Educating Engineers for a Holistic Approach to Fire Safety

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For the Degree of
Doctor of Philosophy

University of Edinburgh

2013

Declaration

The writing of this thesis, and the research herein was conducted solely by Michael Woodrow under the supervision of Prof. Jose L. Torero and Prof. Luke Bisby. Where other sources are quoted, references are given in full.

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September 2013

Abstract

Problems can be solved using existing knowledge and methods derived from past experiences; and in building design, where buildings are sufficiently similar to those already built, this process can be optimised by creating standardised solutions to common problems.

There is significant demand for specialist engineers who can apply these standardised solutions to established problems quickly and accurately; but novel designs generate entirely new problems for which established solutions are not always applicable. Generalist engineers working on novel designs must first define the problems before they can develop options and if necessary, create optimised solutions.

Fire safety engineering (FSE) is the process of achieving fire safety in our built environment. The field requires both specialists trained in current practice and generalists skilled in creative and critical thinking. Current fire safety engineering education is mostly aimed at producing specialists, yet there is growing demand for generalists in high-end architecture, hindered by a lack of generalist education.

Current education literature in FSE explains in detail what to teach, however they do not explain how to motivate students to learn what is taught; how to create the ‘need to know’ - the purpose that drives learning. The purpose can either be intrinsically motivating (i.e. the subject is interesting) or extrinsically motivating (i.e. if you don’t learn it then you will fail the exam). The former is sustained by autonomy and choice; the latter is sustained by control. Control increases the likelihood that the predicted outcome will be realised, but by definition reduces the likelihood of realising any other outcome, including potential innovation.

Initially a study was created to test the effects of creating an autonomous learning environment within a traditional lecture-based 'fundamentals' course at the University of Edinburgh. This study, along with observations at a range of US universities led to the formation of an overarching theory of education. Ultimately, purpose is the goal students strive to achieve; autonomy creates the opportunity to think and learn independently; and structure provides the constraints that converge students towards an optimised result, supported by sound evidence and reasoning. Thus the key to generalist education was to provide purpose, autonomy and structure (PAS) in that order.

The PAS concept was trialled at EPFL (Switzerland) and the participating students, with no prior knowledge of fire engineering, produced work of exceptional quality.

In summary, the present study offers an observational validation that Purpose, Autonomy & Structure (PAS) can be used to effectively support the generalist way of thinking and although the examples given in this paper are related to fire safety engineering (due to the need for generalists in that field), the qualitative evidence on which the conclusions are based is not subject-specific, implying that the PAS methodology could be applied to other disciplines.

Dedicated to

Will Kingston

Acknowledgments

This thesis represents somewhat of a personal journey, and it would not have been possible were it not for the support of a few amazing people.

Above all I would like to thank Professor Jose Torero, for everything. I feel humbled to have been able to work alongside Jose over these past years, and not just because the man is technically brilliant. The experiences that he has created and I have been a part of – the philosophical discussions, the personal challenges and the professional and educational experiences – have truly changed my life. During my PhD Jose opened doors that allowed me to become a fire fighter, a university lecturer, a postgrad student at Princeton, MIT and Queensland and the first ever fire engineer at Foster + Partners. In each instance he put his faith in me before his own reputation; and asked for nothing in return. I just wish I could figure out a way to pay him back.

I would also like to thank my second supervisor, Luke Bisby, for fulfilling every aspect of the role brilliantly. Through good times and bad, the advice Luke gave was always exactly what I needed to hear; and his timing was perfect.

I would like to thank Roxanne Woodrow, my awesome sister and specialist write up consultant, who's ability to 'not think' helped make writing this thesis not only possible, but enjoyable.

Thanks also to those of you who have given their support and helped make this document a reality. Particular thanks go to Sam Collins for being a sounding board for many of the ideas in this thesis and for teaching me to think (critically) outside the box; Nicolas Bal for teaching me the fundamentals of fire science and Susan McLaren for sharing her knowledge of social science; Maria Garlock and David Billington for hosting me at Princeton, where I became inspired by structural art and by the attitude of the Princeton students; John Ochsendorf for hosting me at MIT and immersing me in their "drinking-from-a-fire-hose" learning philosophy; Peter Sunderland for hosting me at the University of Maryland; Ali Rangwala for hosting me at WPI; Thouria Istephan for creating the fire engineering position at Foster + Partners and Orsi Say for pushing me to the end.

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1.1. Current codes and standards for buildings

1.1.1. Problem-solving or solution-applying?

Designers can solve problems using knowledge from past experiences. Many of the problems they face will have been encountered before and over the years designers/engineers/researchers will have developed and improved a range of available solutions. It is from this list that the most effective solutions are chosen to represent 'best practice' in the form of prescriptive building codes.

If the definition of a 'rule' is '*a statement of what to do or not to do in a particular situation, as issued by an appropriate authority*', then the codes may be described as building *rules.* The first section of this literature review reveals how these rules are created and improved, and then goes on to highlight some of the inherent benefits and limitations of using them.

Despite the best efforts of the regulating authorities, unforseen situations can occur and create problems that prescriptive guidelines are not intended to solve. These problems can be identified through either proactive or reactive research, and the derived information can be used to minimise the risk of designs being either under-dimensioned and dangerous or over-dimensioned and unnecessarily expensive.

The fire safety industry adopts a predominantly reactive approach to identifying new problems (Magnusson, Drysdale, & Fitzgerald, 1995). Natural or man-made events create problems that never previously existed – problems that are only identified *after* the disaster has occurred. The results can be catastrophic in terms of human life and financial losses. Following disasters there is often significant pressure to deliver explanations, leading to investment in investigation, research and future recommendations.

Several disasters have demonstrated that the code-based solutions were not conservative/safe enough. King's Cross, Windsor Tower, TVCC Tower, Triangle Shirtwaist, The Empire Theatre, Piper Alpha, Summerland, numerous tunnel fires (e.g. Mont Blanc), WTC buildings 1, 2, 5, and 7, The great fires of London, Baltimore, San Francisco, etc, Bhopal Sandoz, Buncefield (Woodrow, Bisby, & Torero, 2013; Drysdale, Macmillan, & Shilitto, 1992; Fletcher, *et al.*, 2006; Behrens, 1983; Peterson, 2004). In each of these cases research was carried out to discover the causes of the disaster and rules were changed to limit the possibility of a repeat occurrence.

On rare occasions disasters can highlight aspects of the codes that are *over*-conservative. For example, a fire in the partially completed Broadgate Phase 8 steel-framed building did not damage the steel structure, despite exceeding the prescribed failure temperature for the structural elements (Newman, 1991). This led to investment in research from the steel industry and the subsequent creation of a series of full-scale structural fire tests at Cardington. The results would show that the prescribed failure criteria were too conservative and could be safely reduced (British Steel, 1998).

Proactive research is continuously being carried out at academic institutions and commercial companies, leading to the creation of new information. The sustained, incremental improvement of prescriptive regulations helps building designers move towards the optimum balance between safety and cost-efficiency.

1.1.2. Codes offer solutions to pre-defined problems

Codes represent the culmination of years of experience in solving common problems and over the years several possible solutions have been created. The efficiency of the design process is significantly improved by the compilation and publication of the most effective solutions to these standard problems.

The solutions in the codes have been iterated in light of new experiences involving variations of the identified problem. The constant stream of new information from both real-life experiences and commissioned research leads to an iterative process whereby codes are continuously updated and improved over time.

Additionally there is constant pressure to optimise codes to be more cost-effective. In one direction there is pressure from building designers/developers to increase the flexibility of building codes; while in the other direction there is pressure from insurers and safety authorities to make codes more stringent. Both sides are seeking cost reduction, albeit from different perspectives.

As a result of this rigorous, iterative process the codes usually represent the quickest, most efficient and most cost-effective solutions for standard problems.

1.1.3. Codes have been approved by all safety regulators

Safety regulators are individuals tasked with ensuring safety is achieved; and they accept that the solutions prescribed in the codes represent tried-and-tested methods of achieving an adequate level of safety. Any design utilising standard, code-compliant solutions can be assumed by regulators to deliver a safe result.

The regulator reviews a design to assess whether or not the proposed solution has achieved the "intent" of the code. Regulators understand that the code solutions are intended to solve specific problems and create a desired situation, they therefore must decide if the designers' proposed solution has achieved this.

In this way, minor deviations are allowed provided they are not deemed to be a safety issue by the regulating authority.

It is assumed by building designers that regulators will approve any design that adheres to the prescriptive solutions presented in the codes and will reject any design that deviates significantly from these constraints. If the designers lack understanding of the problems the codes are trying to solve, or the situations they are trying to create i.e. they do not understand the *purpose* of the codes, then they will be limited to applying prescriptive solutions. In the absence of competence, designers have no choice but to follow prescriptive recommendations as closely as possible, and to try and justify any deviations on the basis that they will not make too much difference. Furthermore, if the design can be shown to fulfil the code requirements then a regulator is obligated to approve it. One could therefore conclude that code-compliant designs have the highest probability of achieving regulatory approval.

1.1.4. Fast for standard buildings

Codes are a valuable tool for building designers and provide quick solutions to common safety problems without the need for technical understanding.

In general the codes give clear guidance of what solutions should be used to solve standard safety problems. The codes are written in a way that describes each scenario and gives recommendations of how to make the scenario safe. Some codes are very prescriptive and include sub-clauses that describe minor variations on a particular design. Other codes are more open and include words such as ‘appropriate’ and ‘sufficient’, leaving the actual numbers somewhat open to the designers’ judgement.

Codes are written for an audience with minimal technical understanding or knowledge of subject-specific jargon. In principle the recommendations can be understood by any building designer, however the underlying reasoning, as stated earlier, is not always obvious.

Designers using the codes can seek understanding from other sources however this is unnecessary if the proposed design is similar to the designs on which the codes were based. The codes can still be used regardless of the designers’ technical knowledge.

Designers who apply the codes are able to create solutions without understanding the problems that the codes originally intended to solve. It can be assumed that the problems that exist on a designer’s current design are the same problems that existed when the codes were first developed; therefore it can be further assumed that applying prescriptive solutions will solve these problems and achieve fire safety. Provided the problems are indeed the same as they were in the original code-based buildings, this assumption is valid.

Furthermore, designers do not need to understand why the prescriptive recommendations create safe designs. The assumption is that if the rule is followed, safety will be achieved. Using the example of a car seatbelt, a car designer does not need to understand the mechanics associated with the design and operation of a seatbelt. If it is a rule to install seatbelts in the car, then the designer can ignorantly comply. The designer's understanding, or lack thereof, will not change the level of safety offered to the user.

In the absence of understanding either the problems or the solutions, designers aim to comply with prescriptive solutions as much as possible. In situations where this is not possible, a specialist can be brought in to 'fix' the design and increase the likelihood of approval.

In the absence of technical understanding, it is assumed that any building that is code compliant will be safe. Designers who lack understanding therefore assume safety to be an advantageous and inevitable by-product of achieving regulatory approval.

1.1.5. Responsibility on the system

Not all designers know how to create safe designs. Designers can be educated to a level at which they are considered professionally competent, at which point they can be accredited and held personally accountable for the work they produce. An alternative to education is the creation of a set of legally enforced rules, such as the building codes.

In a prescriptive framework, the *system* is responsible for defining safety; and for developing and enforcing rules/codes. It is assumed that if the rules/codes are followed as they were intended then the design will achieve safety as a by-product. If the design is approved, the responsibility of the success or failure of the solution is on the system, not the individual. In a prescriptive environment individual designers who follow the rules often assume that they cannot be held accountable for a failed design.

The definition of 'safety' is not explicitly stated in the codes. Without technical ability, designers will only be able to define safety in terms of code compliance. Designers can attempt to derive a working definition of safety from the codes. However, very specific technical knowledge and reasoning was used to create the codes and the same knowledge and reasoning would be necessary to reverse the process.

It may seem logical to assume that compliance with the code-based solutions, or their equivalent, *is* the aim. Designers use code-based solutions because, in the absence of viable alternatives, it is the most effective way to achieve regulatory approval and subsequently, a safe design. Designers may be well aware that the code-based solutions are not optimised for their particular design. However, they may lack the competence and confidence to create new, *non*-code-compliant solutions for which they will be fully responsible. The lack of individual accountability creates a strong incentive to engage in unethical behaviour (Ordóñez, *et al.* 2009), and designers may feel pressure to apply code-based recommendations to situations for which they were not intended, if it will achieve code compliance.

1.1.6. Codes do not include background information

Codes do not specify the intended safe outcomes; therefore the definition of success/failure is not explicit. The lack of transparency regarding performance criteria makes it difficult for designers to understand what the codes are trying to achieve.

The codes do not specify or explain the problems they intend to solve. Without knowing what the intended problems are, designers have no way of knowing if the prescribed solutions will actually solve *their* problem(s). Designers often feel pressure to use a prescriptive solution 'just in case' the accompanying problem exists in their structure. For example, many codes specify that sprinklers should be used "throughout" certain building types, such as hotels. Designers who do not understand the problem that sprinklers are intended to solve will most likely feel pressured to install sprinklers in areas that are completely inappropriate – such as atria, electrical rooms or toilet cubicles.

Code-based solutions are based on evidence derived from research and experience. However, codes generally do not contain technical/scientific references and readers have little understanding of the underlying reasoning. It may be the case that comprehensive research was conducted and the prescriptive solutions apply to the majority of designs. For example, if a design is deemed to require sprinklers, prescriptive guidance for sprinkler layouts is highly reliable. The recommendations are based on vast amounts of empirical research conducted by US insurance and sprinkler companies.

Alternatively, prescriptive solutions could be based on very limited information that does not guarantee effectiveness when used in a particular design. For example, the BS-9999 prescriptive requirement that theatres (and other large buildings) should be designed to allow occupants to egress in under 2½ minutes. This requirement was created following the 1911 Empire Theatre fire in Edinburgh, which killed the on-stage performer and several backstage assistants (Haydock, 2000). The fire curtain deployed successfully to shield the auditorium from the blaze. As part of the theatre's fire procedure the band began playing the British National Anthem, which caused the audience to stand up and sing calmly. This allowed theatre staff to usher people out without causing panic and the entire audience was safely evacuated. The length of the British National Anthem (all three verses) is approximately 2½ minutes. This is now a code requirement in countries all over the world, regardless of the building's size, or seemingly, the length of their national anthem.

Without fully understanding the design intent, identifying the specific problems and understanding the proposed solution it is almost impossible to state the conditions in which the solution will be optimised.

1.1.7. Rules are written for standard contexts

Codes are intended to prescribe how to create 'standard' designs proven to be safe. If followed, the codes naturally cause the design to converge towards the standard designs on which they were based, with an allowable level of flexibility for minor variations. The codes therefore cannot be used to converge towards any other design.

The codes assist in the creation of standard designs that have been tried, tested and proven to be safe. Thus standard buildings have no inherent safety problems. Any research conducted on a standard design can be assumed to apply to all buildings of that design. If a certain 'standard' design has been tested rigorously and proven to be safe, any building that can be shown to have that same design will be safe by association.

The layout of any given structure will share similarities with other structures. As stated previously the 'standard' problems created by the most common layouts have been solved and codified to allow building designers to work more efficiently.

Elements of a unique architectural design may include standard elements and therefore code-based solutions may be appropriate. However architects in particular will try to ensure that the structure as a whole is anything but 'standard'. Each time a new structure is designed, architects and structural engineers include new and innovative forms that do not follow convention, have not been researched and for which codified recommendations are wholly inappropriate. Buildings of this type are what may be called innovative or novel designs.

1.2. Novel Designs

1.2.1. Definition of Novel Designs

The majority of buildings are code compliant (Jonsdottir & Rein, 2009). Structural designers however, strive to create novel designs that are unique, innovative and fundamentally different to standard structures. Buildings designed by leading architectural firms are examples of novel designs.

Novel designs are significantly different to the standard designs on which the codes were based so it is impossible to justify their safety on the basis of equivalency. Due to their unique nature, novel designs have never before been assessed holistically in terms of safety. Designers therefore do not know if their design is safe and subsequently, if it can be built.

1.2.2. Improving the tools is not practical

A design must be demonstrated to be safe before it can be built. In some cases that means it must be changed to more closely resemble the code. In other cases the information that would prove safety in a given design could be derived from experimental, numerical or theoretical research, or it could be found in existing literature. This information, when used in conjunction with engineering tools, can be used to demonstrate safety.

Information from research could ultimately be used to improve the codes and provide a valuable tool to designers in future. The time taken for codes to change as a result of research is orders of magnitude longer than the timescale of an individual project. Adapting the codes for each individual case is not a viable option.

A novel design must be assessed and validated to be safe. Designers and engineers must use the limited information available to them and make reasoned assumptions where necessary. It may also be necessary to use tools to improve the accuracy and efficiency of their calculations. In fire safety, the tools available to engineers are sufficient for design purposes, but they could still be improved (Torero & Lane, 2004).

1.2.3. Engineers are responsible for defining 'safety'

Novel designs can create situations that are drastically different from the designs on which the codes were based. There will be no guarantee that the code recommendations will deliver a safe result.

An alternative is for engineers to take responsibility for defining the specific problems associated with the design, and then create bespoke solutions.

1.2.4. The design process

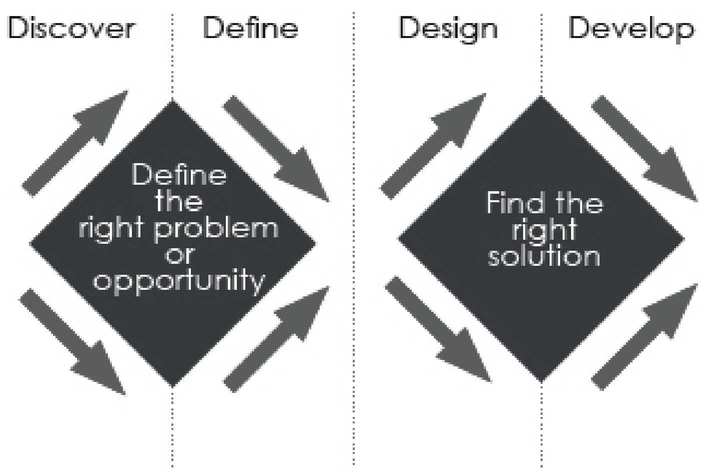

FIGURE 1: THE DOUBLE DIAMOND MODEL (UXBC, N.D.)

The above diagram is known as the Double Diamond model. It shows the process of divergent and convergent thinking - represented by the diverging and converging sides of the two squares - required to define and solve problems.

The first phase of the design process is to view the design situation holistically and think divergently. This is the ‘Discover’ phase of the Double Diamond design model, and consists of being creative and identifying any possible scenarios that could negatively affect the occupants. In fire safety this might be to place a small fire in each area of the floor plate, and visualise the effect it would have on the occupants.

1.2.5. The problems need to be defined

The second phase is to ‘Define’ the problem. This involves critical thinking, reasoned judgement and fundamental knowledge. The aim is to assess the situations outlined in the initial Discover phase and ask “Is this a problem?” In fire safety this may translate to: “If an exit is blocked by fire, is there an alternative way out?” The aim of the process is to clearly define the problems specific to each unique design.

1.2.6. Numerous solutions to every problem

The next phase is to ‘Design’ the solution. The aim is to brainstorm design options that conceptually solve the identified problem(s). During this creative, divergent phase it is important to remember that there are several possible solutions to every problem and that within the existing design constraints, anything is possible.

The problems encountered by designers have in many cases been identified and solved before. Thus it is possible to replicate a solution, or components of it, each time the problem is encountered. In this way, knowledge of previous design solutions can greatly improve efficiency.

The codes are often the most comprehensive sources of previously used solutions. The recommendations from the codes should at this point be included as possible design options – to be assessed holistically during the final phase of the design process.

1.2.7. Narrowing down the options

The final phase is to 'Develop' one or more of the designs. This involves assessing each option against each of the design variables. The aim is to find a balance that meets the needs of all of the design variables; the greater a designer's understanding of the different variables, the greater their ability to combine them into an optimised design.

It is essential that each design option is rigorously assessed against its ability to meet the demands of the particular context, even if a proposed solution has been optimised for previous designs. The variables existing on the new design may be significantly different and render the solution completely inappropriate. For example a very expensive option may have fulfilled all the requirements of a design where cost was not important. The same option may not be possible in other, more cost-conscious designs.

Solutions can be supported using available information. Where the code-based recommendation is used in the context for which it was intended, validation of the design is implicit and no further justification is required.

Occasionally an engineer or designer will lack the necessary information to assess and validate a design. Additional information can be gained using resources such as textbooks, the Internet or libraries; or it may include conducting experiments or computer simulations to produce new evidence for a unique design. The process can be very time-consuming and require specialist skills, however for very unique problems it may be the only way to assess and validate a unique design.

1.2.8. Regulators assess safety

Safety has no fixed definition; and a regulator must make a decision on the extent to which a design is ‘safe enough’ - often defined by limits set by the codes.

A regulator may be willing to accept a non-compliant design if the engineer is able to demonstrate that the problems have been solved and that the design can achieve an adequate level of safety. A pre-requisite is that the regulator has a clear understanding of the complete design process described above.

Regardless of the skill of the engineer and/or the safety of their chosen design, some regulatory frameworks will lack confidence or competence to assess and approve it, and will instead insist on code-compliance. Designers can attempt to minimise the ‘approvals risk’ by engaging early on with the authorities and describing the strategies and solutions that will most likely be used.

Thus the success of a proposed safe solution will depend both on the engineer’s ability to construct a coherent story and communicate it effectively, and the regulator’s ability to understand it.

1.3. Specialist & Generalist

It would appear that there is demand for two roles in professional practice: Generalist roles, where individuals define new, unique problems and think of potential solutions; and specialist roles, where individuals identify common problems and apply established solutions.

Nickols (1981; 2004) describes the differences between specialist and generalist roles with the following diagram.

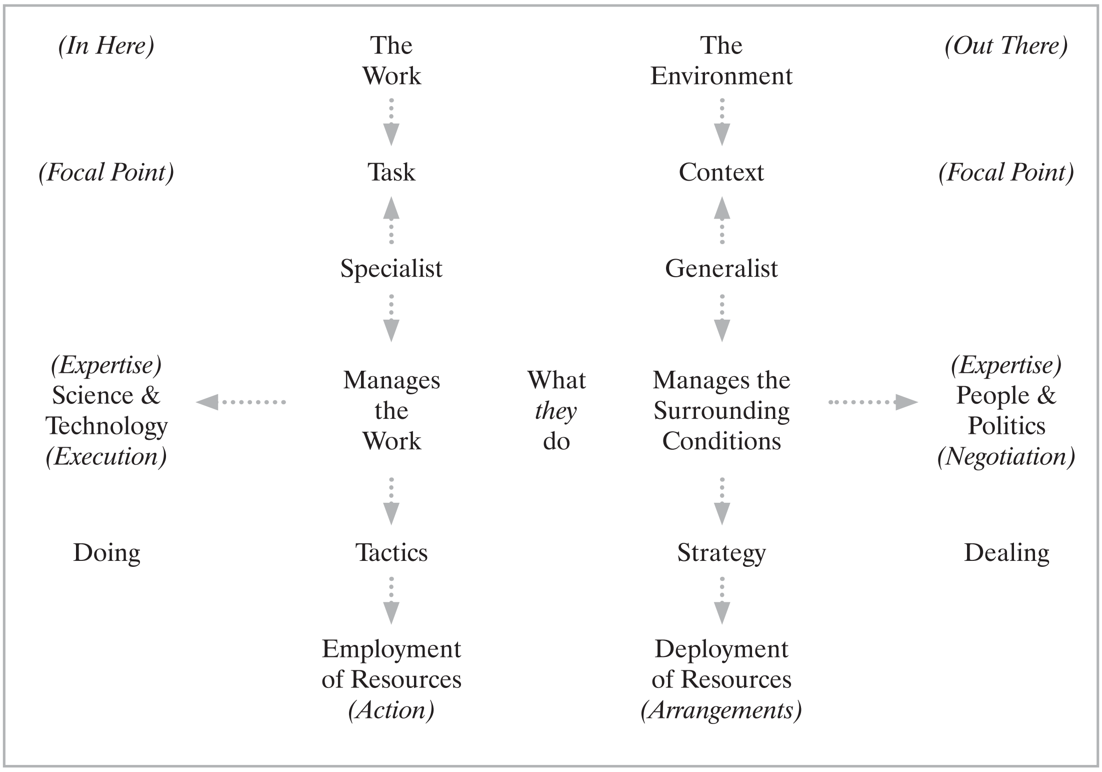

FIGURE 2: SPECIALIST & GENERALIST (NICKOLS, 1981; 2004)

The above diagram shows the differences between Specialists and Generalists, including their aims, strengths and methods of operating.

Specialist jobs are focused on the task (e.g. building a wall), while generalist jobs are focused on understanding the context (e.g. why the wall is being built). The specialist roles involve the use of knowledge and technical skills, while the generalist roles involve the management of people to ensure the work being done is aligned with the global strategy.

Not all people are equally able to complete both specialist and generalist tasks. As Ove Arup stated in his renowned Key Speech: "*It is no good pretending that all are equal - they aren't*" (Arup, 1970).

The two different roles in professional practice require two different mindsets – two different ways of thinking. Individuals in specialist roles should have a specialist mindset; while those in generalist roles should have a generalist mindset. In reality, industrial roles are rarely this segregated, and it is likely that individuals will have to perform both tasks during their professional career.

Likewise people cannot so easily be categorised. An individual's mindset can be partly psychological and influenced by the environment; and partly physiological, and impossible to change. It is likely that an individual will naturally have a preference for one type of mindset, but may change depending on the context. Thus the definitions of the specialist and generalist mindsets should be viewed as opposing ends of a spectrum, rather than being mutually exclusive. For the purposes of this paper however, individuals who demonstrate a strong preference for a particular mindset will be referred to as Specialists and Generalists, as described below.

1.3.1. Specialist

For the purpose of this paper an individual who prefers to focus on the acquisition and application of established knowledge, tools and methods will be called a "Specialist".

Specialists are adept at memorising methods, rules, procedures and large amounts of detailed, often abstract knowledge. Their ability to recall and apply information quickly, accurately and without thinking makes them a hugely powerful resource.

Specialists can work autonomously on tasks for which they have already been trained. However, they have poor reasoning skills and lack the ability to think critically and creatively, meaning that new tasks require constant instruction from a directive manager. Specialists are what Felder describes as sequential learners (Felder & Silverman, 1988).

Specialists regard rules and facts as objective and definitive. The reliance on rules and facts allows specialists to work quickly and accurately. They are focused on the details and cannot or will not see the wider context. There is no incentive to think critically or creatively – "it will not change the facts".

If they have been given sufficient training in following the rules and procedures, Specialists should not need to 'think' during this process. Thinking or reasoning would simply delay the time taken to achieve the prescribed outcome.

Specialists work quickly. Their speed will depend on their accumulated 'database' of established knowledge (how much they have memorised). A specialist will thus be able to recall and apply established knowledge when they recognise the situations for which the knowledge is applicable.

Specialists who value attention to detail will be more accurate and less likely to make mistakes. Given their extensive training in established methods, rules and procedures, and their memory bank of available knowledge, they will be able to operate on autopilot; leaving them to think only about the details e.g. variable numerical values, associated with each situation.

A specialist has the ability to reproduce memorised information including complete solutions to previous problems. In this way they are able to solve problems provided the specialist has learned the established solution(s). If the problem is unique and has not been solved before the specialist will be unable to 'think' through available information and develop an entirely new alternative. This requires the mindset of a generalist.

It is possible for generalists to operate as specialists, however the inverse is not true. "*Not all specialists can or will become generalists but all generalists have demonstrated competency as specialists*" (Nickols, 1981; Nickols, 2004). Specialists who focus only on the details are unable to see the global picture.

1.3.2. Generalist

For the purpose of this paper an individual who is able to understand and integrate available knowledge will be called a "Generalist". Generalists are defined elsewhere as meaning seekers (Wise, 2008), system architects, integrators (McMasters, 2004) and global learners (Felder & Silverman, 1988).

A generalist can see the big picture, can understand and summarise the details and see how all the pieces of the puzzle fit together (Grasso & Brown Burkins, 2010). They can make assumptions and decisions using very limited information, and rely heavily on their reasoning skills to fill in the blanks. Their ability to work without needing to fully understand the details is their greatest strength, but also their greatest weakness; they may be able to describe a conceptually brilliant design, but they may struggle to prove it. It is possible for generalists to go into the details and act as specialists (Nickols, 2004) but their lateral thinking makes it difficult to focus on a single idea for long periods of time; subsequently they will be less efficient at performing specialist tasks than an individual with a purely specialist mindset.

The ability to integrate information in whole or in part makes generalists exceptionally valuable in design situations. "*Although drawings, tools & methods appear to be exact and unequivocal, their precision conceals many informal choices, inarticulate judgements, acts of intuition, and assumptions about the way the world works. The conversion of an idea to an artefact, which engages both the designer and the maker, is a complex and subtle* *process that will always be far closer to art than to science*" (Ferguson, 1992, p. 3).

Generalists have good contextual understanding and can define the global strategy of a system. This strategy will create a purpose for the design and define the minimum standards that must be surpassed for the design to be a success.

Generalists can use their contextual and conceptual understanding to identify and define any problems that must be solved. They can synthesise available information to produce optimised solutions to new, unique problems. The knowledge used can come from a range of information resources including books, the Internet and design codes.

Provided that the Generalist sets very clear limits on the work, Specialists can be employed to quickly and accurately produce information. The Generalist will then be able to integrate the information into the overall strategy.

Where Specialists are not available, Generalists can attempt to learn established knowledge including tools, methods and standard assumptions. They may be able to reproduce information for use in the overall solution; however they would find it more difficult to memorise the information as quickly or as accurately as could a Specialist.

Evidence shows that there is significant demand for generalists in industry (Johnson, Manyika, & Yee, 2005). Nevertheless there is a shortage of generalists in engineering (Wise, 2008). "*Those with a real talent for design (and, by extension, system architecture) apparently do not exist in equal measure in either the general or the engineering populations with those who are good analysts*" (McMasters, 2004).

Many prominent engineers have described how the skills of the engineering Generalist are not valued as they used to be. "*Natural engineering talent is rare today. Public accountability and public responsibility require that everything be calculated, checked and endlessly analysed by computers using* *the latest theories. In such a world the natural genius without formal education moves elsewhere, into boat design maybe, into motor-racing perhaps, somewhere where skill, talent and understanding matter more than proof and where proof can be achieved by performance. It was not always so. In the nineteenth century and before, all the great structures were the work of natural engineers. Gradually their work and the rules that govern it were codified. And slowly that codification became more important than the original fountain from which it sprang. Society demanded that architecture and engineering should only be designed by people who were specially trained in these arts. Natural engineers and builders are being replaced. They have no place in our specialised society. This is sad, as much talent is thereby suppressed. People whose understanding of materials and how they should be used is instinctive and physical, as distinct from mathematical, are not longer able to survive in this climate*" (Rice, 1998, p. 81). Generalist practitioners are not revered and valued as they have been in the past. "*In the Renaissance those who practised engineering in Italy (Brunelleschi, di Giorgio, and da Vinci) had a breadth of vision that encompassed many fields that have now become specialized*" (Heywood, 2005, p. 462).

Armstrong (2009) stated that, "*the creative and analytical skills of engineers are frequently used only to develop or make practical the decisions of others. The importance of engaging engineers in the early decision-making processes of a project is frequently not appreciated, and major decisions are left in the hands of the non-engineering professions*". Peter Rice (1998) explained: "*The problem is that, in the simple world that the media favours, the role of image-making is given to others – to designers, for industrial artefacts such as cars, household goods, and so on; and to architects for the monuments of our built environment. It is not that there is anything wrong with this approach per se; it just ignores the vital role played by engineers in the creation of all the things that are built or made today*" (p. 73). "*It is essential, therefore, that engineers play a full and significant role in ordering the affairs of society, not merely as technicians carrying out the instructions of others*" (Armstrong, 2009).

Some situations are common, the design variables are similar to previous cases and the situation's ability to achieve the success criteria is well understood. If the task therefore is to apply standard solutions to common problems then the Generalists' skills will not be put to use. Unlike Specialists, Generalists will struggle to recall standard processes, and will to some extent have to re-learn the material each time it is applied. It is therefore unlikely that Generalists would work as fast or as accurately as a Specialist in the same situation.

Natural generalists either learn to adopt a specialist mindset in school or drop out. "*However, global learners are the last students who should be lost to higher education and society. They are the synthesizers, the multidisciplinary researchers, the systems thinkers, the ones who see the connections no one else sees. They can be truly outstanding engineers - if they survive the educational process*" (Felder & Silverman, 1988).

1.3.3. Specialist & Generalist

The two extremes complement each other, and together they can produce an optimised solution. Specialists are suited to solving pre-defined problems using established solutions that can be learned and replicated. Generalists are suited to defining new problems and combining available information to create new solutions.

1.4. Fire Engineering

1.4.1. Why fire engineering is necessary

Fires cause billions in dollars each year in direct losses and although the overall cost of fires may be plateauing, or even declining, as a result of improvement in modern building codes, the widespread use of increasingly complex fire protection systems is ensuring the overall cost of fire safety continues to rise (Drysdale, 1999).

The term fire engineering can be subdivided into fire *safety* engineering and fire *protection* engineering. Fire safety engineering originated in the fire service and is concerned primarily with life safety; property protection is largely ignored, provided there is no risk to people. Fire protection engineering has its roots in insurance and the protection of property and, provided the entire building remains protected (e.g. by sprinklers), the occupants are assumed to be safe.

This thesis will focus primarily on fire *safety* engineering.

1.4.2. Author's definition

Fire safety engineering is the process of defining fire safety problems and removing them throughout a holistic design process. A fire engineer's aim is to fulfil the fire safety objectives at the lowest financial, structural and architectural cost. The design process is iterative, with the fire engineer involved throughout, such that the design can be incrementally optimised for all design variables, including fire safety.

1.4.3. Definitions by societies, academic institutions and companies

Societies, companies and academic institutions have established definitions of fire safety engineering.

Definition by institutes & government bodies

The IFE (UK) gives the following definition:

"Fire Engineering is the application of scientific and engineering principles, rules [Codes], and expert judgement, based on an understanding of the phenomena and effects of fire and of the reaction and behaviour of people to

fire, to protect people, property and the environment from the destructive effects of fire" (The Institution of Fire Engineers).

While the SFPE (USA) give the following definition:

"Fire protection engineering is the application of science and engineering principles to protect people and their environment from destructive fire" (Society of Fire Protection Engineers).

Definition by academia

Glasgow Caledonian University describes Fire Risk Engineering as "*the development, evaluation and communication of fire protection strategies and appropriate management systems*" (Glasgow Caledonian University).

At this time, no other academic institution is known to have developed an operational definition for fire safety engineering (Lund University, 2008; University of Edinburgh, 2009; Manchester University, n.d.; University of Maryland, n.d.; Worcester Polytechnic Institute, n.d.).

Definition by Industry

At this time, no company is known to have published a definition of fire safety engineering.

Summary of Definitions

The most interesting conclusion derived from this review of the fire safety engineering literature is the lack of established definitions, and the lack of consistency between the definitions that do exist. The lack of a clear, established definition may explain why the terms *fire safety engineer* & *fire protection engineer* are used to describe a range of different roles (Maluk, Bisby, Woodrow, & Torero, In Press).

1.4.4. Historical Fire Safety

Building designers and engineers have used fire codes for centuries. It is widely believed that the first fire codes were developed in 64AD following The Great Fire of Rome (Cote, 2008). Narrow streets and flammable wooden housing partitions were blamed for spreading the fire and subsequently outlawed in the new building codes. The first American Building Code was written in 1631 and outlawed the construction of wooden chimneys and thatched roofs as these were found to cause fires in the community. The UK created its first fire code following the Great Fire of London in 1666.

Different societies (and even different cultural/socio-economic regions within a society) have different levels of acceptable and affordable fire safety performance (Lucht, 2006).

It is the responsibility of public policymakers to decide the minimally acceptable safety goals, which must be designed against (Lucht, 2006).

Over the years fire safety research has led to the addition of new rules in the building codes. The investigations into large fires in Chicago (1871), Baltimore (1904) and San Francisco (1909) for example led to greater understanding of fires in buildings and a subsequent increase in the level of safety prescribed by building codes (Peterson, 2004; Miller, 1990).

Fire specialists (code consultants) were trained to interpret and apply these codes in industry (Finnegan, 1924).

The MGM Grand Hotel fire for example, led to the requirement of sprinklers in new high-rise buildings. Given that the majority of those killed by smoke-inhalation were in the high-rise tower, this does not at first appear to be a bad solution. However, the fire in the casino never reached the high-rise section of the building, and sprinklers would have done little to save those who were killed by smoke. As Harmathy (1984) says, "*The public cannot be blamed for reaching for simple handles in trying to understand a complex world*".

Harmathy (1984) describes fire science as an alternative to universal solutions, such as sprinklers. "*Fire science has come a long way since its beginnings in the 50s. It cannot offer solutions to every problem, but it does have a fair number of solutions in its repertoire. Most of them were developed at public expense and they are available to the construction industry just for the taking. There is no justification to rely on stereotyped solutions, let alone to force them on the public*" (p. 65).

As building designs became more complex, new situations necessitated clarification of existing codes. In situations such as this, where the rules have no accompanying explanation, a clause is added to improve specificity – as Kripke puts it "*a rule for interpreting a rule*" (1982, p. 54). This remains the preferred process of the US NFPA (2013), which currently has several hundred volumes. There are clear problems associated with this approach, summed up by Margaret Law when she described the fire safety codes as "*very prescriptive and understood mainly by lawyers*" (Law, 1991).

The rapid growth in both size and complexity of the codes necessitated a new individual capable of reading and interpreting the codes. Thus the role of a specialist code consultant was created to inform the architects of the 'intent of the code' and to locate and prescribe the correct fire safety rules to each component of an architects' design. The role saved a significant amount of time and increased the likelihood that the prescriptive requirements would be understood and applied correctly.

Code consultants add value in one of two ways:

1) Code advisor – They either help the designer locate the relevant code requirements applicable to the particular design or;

2) Code interpreter – They help the designer interpret the codes in a way that will convince regulators that the design is safe.

The former approach is generally *proactive*, and gives the architect the constraints within which to design; the latter is generally *reactive*, and is necessary where a design has been created in the absence of fire safety constraints.

Advising designers on code requirements requires good understanding of the underlying science and reasoning. Interpreting the codes requires the skills of an accomplished lawyer – an ability to massage prescriptive wording in order to convince the authorities that the design still falls within the bounds of prescriptive requirements. In either case it is important that the code consultant has extensive knowledge of the wording of the codes.

Prescriptive requirements steadily grew as more scenarios were included; and by 1976 the UK codes had grown in size to a total of 307 pages (Meacham, 1998; Lucht, 2006). The UK *Building Regulations* published in 1985 however decreased in size to just 23 pages, largely due to a change in wording.

The new regulations allowed solutions that did not necessarily meet the code requirements nevertheless achieved 'performance goals' for fire safety. This was called performance-based design and the objectives might well be construed to be "in the eye of the beholder" (Meacham, 1998).

Scaling down the codes so dramatically required reducing the level of prescription and increasing ambiguity. Much of the requirements were left open to interpretation. Meacham (1998) includes the following example of the internal fire spread requirements from Part B of Schedule 1 to the Building Regulations (2006):

Internal fire spread (surfaces)

B2 In order to inhibit the spread of fire within the building, surfaces of materials used on walls and ceilings –

(a) shall offer adequate resistance to the spread of flame over their surfaces; and

(b) shall have, if ignited, a rate of heat release which is reasonable in the circumstances.

Internal fire spread (structure)

B3. – (1) The building shall be so constructed that, in the event of fire, its stability will be maintained for a reasonable period.

The new language in the building codes aimed to increase the responsibility of individual engineers. However, individuals can be reluctant to take personal responsibility for defining safety and still relied on the performance criteria specified in guidance such as the Advanced Building Documents (Meacham, 1998).

Relinquishing some of the responsibility to individuals was intended to create a more reasoned process and reduce the emphasis on regulation. However, as Philip Thomas (1970) noted, "*whilst it is true that it may be sensible to deregulate, one must deregulate into a profession which has competence*".

Harmathy gives his opinion of the way forward: "*It is often claimed that coercive regulations are necessary because fire-safety experts are in short supply. The fact is that even the available expertise is not fully exploited. The blueprint for higher fire safety is this: Use the available experts, give them challenging responsibilities, produce more experts, pay them well and thereby attract even more. This scheme has always worked*" (1984. p. 68). In other words, there are two options available to society: Increase control and regulation, or increase the number of competent, responsible professionals.

Universities, with some notable exceptions, have largely failed to keep up with the rate of change in industry. Many institutions have continued to train students – teaching fundamentals in early years, creating exercises to apply those fundamentals later on (Sheppard, *et al.*, 2008). Students are generally taught in a prescriptive way; a point that is expanded on in Chapter 2.

There is a need for more 'generalists' (Wise, 2008) – individuals capable of participating in a holistic engineering design process. Ove Arup, during his key speech, described holistic engineering design. "*We are led to seek overall quality, fitness for purpose, as well as satisfying or significant forms and economy of construction. To this must be added harmony with the surroundings and the overall plan. We are then led to the ideal of 'Total Architecture'…It is not the wish to expand, but the quest for quality which has brought us to this position, for we have realised that only intimate integration of the various parts or the various disciplines will produce the desired result*" (Arup, 1970).

In fire safety in particular, there is a need for engineers to assume responsibility for defining "fire safety" based on fundamental knowledge and reasoning, and participate in the creation of a fire safe design (Woodrow, Bisby, & Torero, 2013). These individuals would be termed "fire safety engineers" and would take responsibility for creating solutions that achieved performance-criteria for fire safety. Fire safety is, relatively speaking, a new engineering field and as such individuals must be able to operate in the absence of reliable data, standard methodologies or accurate tools; they must develop their own, independent critical judgement.

The fire safety engineering industry requires both specialists who can assist designers in implementing the state-controlled regulations, and generalists who have the competence required to operate independently of prescriptive rules. The roles of each are described in the following section.

1.5. Fire Safety Roles

1.5.1. Specialist Fire Safety Roles

Specialist fire safety roles involve using established methods to quickly and accurately solve prescribed fire safety problems.

Fire fighter

A fire fighter is an individual responsible for controlling and/or extinguishing fires and if necessary rescuing occupants from situations involving fire and smoke.

Although the range of possible fire fighter jobs is diverse, and gives the impression the role requires a generalist capable of tackling fires in all situations, it is more efficient to create specialist roles within fire fighting and to narrow the range of skills and knowledge required. In this way individuals can focus on training for very specific jobs including airport fire fighting, bush fire fighting, township fire fighting, high rise fire fighting etc.

Fire fighters in any discipline must operate in dangerous situations with very tight time constraints. Fire fighters therefore go through extensive training to reach the point where they can complete standard tasks - such as preparing BA or operating a hose reel - quickly and safely. The rigorous training allows fire fighters to carry out many of these standard tasks subconsciously, allowing them to concentrate on unconventional tasks unique to their environment.

Code consultant

A fire safety code consultant is an individual who can help designers understand the ‘intent of the code’, define problems given their experience working with regulators, and advise on how to comply with prescriptive code requirements/rules.

The vast majority of designers lack the capacity to globally integrate fire safety as a variable in a structural design. They will instead attempt to design their structures using fixed constraints; such as the solutions presented in prescriptive building codes and building guidelines (e.g. Approved Document B (2006).

Architects frequently wish to create a considerably 'non-standard' design and there is often ambiguity and confusion about what should be done to achieve 'code-compliance'. The designers will use the codes as much as possible to create their desired design, and approach a code consultant if any potential compliance issues are identified (Torero, 2010).

The role of the code consultant is to validate the designers' interpretations of prescriptive code requirements and, in situations where the requirements appear confusing or ambiguous, to offer further explanations of the underlying 'intent' of the code. An experienced code consultant will be able to quickly and accurately recall the recommended solution for a particular design scenario. Together, designers and code consultants identify, define and solve compliance issues on the basis of performance criteria derived from the codes.

Technical specialist

The technical specialist is an individual with deep understanding of a very narrow subject. Once the design team, including a generalist fire safety engineer, have developed a conceptually fire-safe design, they must provide quantitative information to support their solution. It is the responsibility of the technical specialist to provide this information.

Lab technicians have extensive knowledge of lab equipment and are able to use it to generate experimental evidence. This can be very useful in situations where existing knowledge is insufficient to answer engineering questions.

Researchers have in-depth knowledge and understanding of a particular field of study. Researchers are able to answer very specific, well-defined questions and establish the extent to which the information can be used safely.

Computer modeller

Computer modellers are technical specialists who are able to construct realistic design simulations using computational tools such as Finite-Element Modelling (FEM) and Computational Fluid Dynamics (CFD). They use in-depth understanding of both the program interface and the underlying computational processes to deliver accurate, realistic results.

Regulator (specialist)

Regulators are tasked with reviewing solutions proposed by building designers. Their main task is to ensure buildings achieve the minimum level of safety. As safety is defined implicitly by the codes the aim of the regulators is to ensure the code requirements have been met. Regulators who learn the code requirements are able to identify code infringements quickly and easily, improving the efficiency of the review process.

Where the codes have not been followed the regulator can request evidence from the building designers that demonstrates the design is as safe as it would be if the codes were followed.

In some circumstances where the design is entirely unique, the regulator will not be able to relate the alternative solution to the codes. In these cases the regulator can either reject the solution on the basis that the designer failed to provide a quality argument or they can seek a review by a third-party with greater contextual understanding of the solution.

1.5.2. Generalist Fire Safety Roles

There are currently three main fire safety roles suited for generalists.

Fire investigator

The aim of a fire investigator is to re-construct a chain of events and identify the source of the fire. Conclusions can be derived using evidence gathered from the scene, assumptions made on the basis of established knowledge and computer simulations intended to fill in the blanks. The generalist fire investigator could advise specialists on what data to use in the construction and operation of the computer simulations.

Although it is suited to a generalist mindset and makes use of the same fundamental knowledge, the role of 'fire investigator' necessitates a different style of education and will therefore not be addressed in this paper.

Regulator (generalist)

In contrast to their specialist counterparts, generalist regulators assess *unique* fire strategies in a holistic way using both knowledge and reasoning to decide whether or not a proposal is safe. Unique fire strategies account for only a small proportion of the number of fire strategy proposals submitted each year (Jonsdottir & Rein, 2009) therefore the demand for Generalist Regulators is relatively low. Nevertheless the role of assessment requires a level of understanding equivalent to that of the engineers who produced the design. This is why third-party peer-assessment has been adopted by some fire safety authorities, including the UK & New Zealand. Given this third-party review process, the Generalist Regulator role for the purposes of this paper will be treated as synonymous with the role of Fire Safety Engineer (see below).

Fire Safety Engineer

Fire Safety Engineers define fire safety problems and develop performance criteria on the basis of fundamental assumptions, knowledge and reasoning. Importantly, fire engineers do not view the codes as rules, rather as informational resources.

A fire safety engineer initially educates architects and structural engineers on the criteria that must be met in order to achieve safety in a way that is descriptive, not prescriptive. Importantly, these conditions are derived from scientific principles, not from the building codes. It is possible then to work collaboratively to identify and define the issues associated with the design – situations where the design fails to meet the criteria.

Once the problems have been defined, the designers can iterate their design towards a safer situation. The greater the number of iterations, the greater the likelihood of reaching an optimised design. It may be necessary for the fire engineer to create new, innovative ideas, or it may be appropriate to use solutions recommended in prescriptive building codes. At this stage the intention is to achieve a design that is optimised for all design variables, including fire safety.

The next stage is to prove, quantitatively, that the design fulfils fire safety performance criteria. This validation stage may involve the use of complex tools, many of which can be operated very efficiently by a competent technician.

The SFPE gives a definition of a Fire Engineer:

"The Fire Protection Engineer is a licensed professional engineer who demonstrates sound knowledge and judgment in the application of science and engineering to protect the health, safety and welfare of the public from the impacts of fire. This includes the ability to apply and incorporate a thorough understanding of fundamental systems and practices as they pertain to life safety and to fire protection, detection, alarm, control and extinguishment."

Until now architects have received very little information on fire safety matters (Torero, 2010) and have used prescriptive codes to converge their designs. Fire safety 'solutions' are often applied retrospectively to an otherwise optimised design. However as Harmathy notes, this is not how fire safety should be incorporated: "*Firesafety is not just a patchwork that can be superimposed on the architectural design. Measures to counteract the dangers that some ill-conceived building features may bring are usually very costly; leaving out the problematic features may be much cheaper*" (Harmathy, 1984).

It is not only architects who could benefit from increased integration of fire safety matters. Structural engineers also rely heavily on prescriptive guidance for fire safety. "*The realisation that the geometrical characteristics of a structure can have a significant effect on the evolution of its strength in the event of a fire, opens the door to a much closer interaction between architects, structural and fire safety engineers*" (Torero, 2010).

The design process is moving towards a more integrated approach to fire safety; one that attempts to create a holistically fire safe design. As Torero states: "*There is a strong evolution towards an integrated design process that incorporates fire behaviour into the architectural and structural design processes. The benefits of this approach are significant because it allows optimisation of the structural design to meet the architectural, structural and fire safety needs*" (Torero, 2010).

Fire safety engineers are able to educate designers and engineers, allowing them to identify and solve fire safety problems autonomously. Through improved understanding, fire safety can be treated as a design *variable* and the design can be iterated and optimised holistically.

Fire safety engineers need contextual understanding of fire, smoke and human behaviour in structures in order to identify problems with the design. Additionally the fire safety engineer must have an appreciation of the architectural design brief and any conflicting design variables.

Fire safety engineers can identify problems associated with a design by visualising the user experience. This is a common method used by architects and allows designers to 'see' potential issues associated with various design scenarios. In terms of fire safety the occupants must be able to egress from any area of the floor plan, given a fire in any single location.

As stated above, fire safety engineers help designers create conceptually fire-safe designs. It is also necessary to provide the supporting reasoning to validate a chosen design. For larger, more complex designs it may be necessary (or simply more efficient) to employ specialist technicians, code consultants and computer modellers to produce the relevant information. The role of the fire safety engineer is then to oversee the creation of this information, and to compile it into a complete fire strategy.

1.6. Trial: Generalist fire safety engineer

1.6.1. Established the need for an in-house FSE

It was established at the 2011 LRET Global Technical Leadership Seminar in Fire Safety Engineering that universities should aim "*to produce 'generalist' graduates who understand holistic design, are able to identify and define fire problems, create novel ideas, present available options, perform provisional calculations and manage fire specialists*" (Woodrow, Bisby, & Torero, 2013). It was felt that graduates of this type would be suited to work in large, multi-disciplinary architecture practices.

1.6.2. Trial of internal FSE in an architecture practice

Following the LRET seminar, the author - at the time a PhD student at the BRE Centre for Fire Safety Engineering - approached a representative from Foster+Partners architecture practice to request an internship as an in-house fire safety engineer. The request was approved, and the internship was created.

1.6.3. The role

As the in-house fire safety engineer I was employed by the architectural practice with the sole purpose being to help designers create fundamentally fire safe buildings, rather than simply to create code-compliant buildings (Woodrow, Bisby et al. 2011). The emphasis would be on *integrated* design and the consideration of fire safety principles at every stage of the design process.

The overall aim of the fire safety engineer was to increase architects' contextual understanding of fire safety problems, thus reducing their almost total reliance on prescriptive guidelines (i.e. codes) to converge towards a safe solution. It was hypothesised that this would change the mindset of the architects and encourage them to view the design holistically in terms of fire safety.

As Deru and Torcellini state: *"The design of most buildings is typically driven by the need to meet a set of minimum criteria, including budget constraints, time scheduling, functionality requirements, safety regulations, and energy codes. This process typically produces buildings that just meet these minimum criteria. To achieve better than average or exceptional performance, the design team, which includes the building owner, needs to work together in a focused effort. Performance goals provide direction to these efforts. The earlier in the design process the goal setting begins, the easier it is to implement and the better the results"* (Deru & Torcellini, 2004).

Attempting to achieve fundamental aims associated with the design allowed designers to view fire safety as a *variable* to be incorporated alongside numerous other design variables. The design could then be iterated and optimised holistically. This is in contrast to treating fire safety as a fixed constraint to be designed around or incorporated *after* design decisions have been made.

On a day-to-day basis the fire safety engineer met with architects to review designs and discuss design decisions. Architects would explain the reasoning behind the form and function of the design to date and highlight situations where there may have been issues associated with fire safety.

Prior to the introduction of the in-house fire engineer, architects would limit themselves to either interpreting and applying prescriptive code requirements – thus achieving the implied level of safety – or diverging from the codes and employing a fire engineer to justify any deviations using “performance-based” fire engineering. The in-house fire safety engineer was able to educate the architects, explain the overall goals for fire safety and identify problems on the basis of technical knowledge and reasoning. This increased architects’ contextual understanding of specific fire safety problems and removed many of the prior constraints.

After working with the in-house fire engineer to establish the goals of the design, architects worked autonomously to incorporate fire safety as an integrated variable in an optimised design. The process was iterative; and the fire safety engineer advised, criticised and argued with the architects to improve their understanding of the fire safety problems (if any) associated with their designs. When both the architects and engineers were satisfied that no further problems existed, the design team had succeeded in finding an optimised, fire-safe solution.

In rare circumstances architects became stuck and could not autonomously create conceptual fire safe designs. In these cases the fire safety engineer offered a range of possible options to the architects. The majority of the ideas offered were initially incompatible with the rest of the design. This was unsurprising as the fire safety engineer did not understand, and therefore could not consider, the many other design variables. However, often these suggestions, and the discussions that followed, gave architects the inspiration they needed to create conceptually fire safe designs.

In cases where more accurate or comprehensive evidence was needed to support a chosen solution, the fire safety engineer would perform hand calculations. If further evidence was required, it was necessary to contact external fire safety specialists (e.g. structural fire engineers, lab technicians, sprinkler specialists, CFD modellers) who were able to use complex tools and/or specialist knowledge to provide additional evidence that the proposed design was safe.

Creating a fire safe design was the first challenge, the second was to present it in a way that the regulators would accept. Fire safety engineers – due to their increased technical understanding – could liaise between architects and regulators and effectively communicate the reasoning behind the chosen design. In particular the fire engineer was able to argue for the approval of a fire safe design on the architects' behalf.

In addition to the role described above, the in-house fire safety engineer created a 'Fire Guide' to assist the architects in producing fire safe buildings. The Guide explained the reasoning behind fire safety problems and gave descriptions of proven design solutions. This gave architects an additional, visual design resource and a means to integrate fire safety into their holistic design.

The advisory role of the fire safety engineer, combined with the general Fire Guide allowed architects to treat fire safety as a variable to be optimised, rather than a fixed constraint.

1.7. The need for a generalist education system

The internship demonstrated a demand for generalist fire safety engineers. The following section defines the desirable mindset for this role and describes the system of education intended to support students.

2

EDUCATION

2.1. Introduction

2.1.1. Chapter Summary

This section will review the literature on education, specifically focusing on learning environments to encourage a generalist mindset.

Initially an introduction is given to teacher-centred, specialist training before going into the literature on generalist education.

2.1.2. The specialist & generalist mindset

The terms *specialist* and *generalist* are not intended to be definitive, rather they are intended to label two halves of a spectrum. Furthermore the terms are contextual – one may think and adopt a specialist mindset in some situations and a generalist mindset in others.

The following section aims to define specialists and generalist in the context of learning approaches.

In the 1960s William Perry, an educational psychologist at Harvard, observed that students' attitudes toward the learning process varied considerably. In response, he developed the Perry Model of Intellectual Development, which consists of a hierarchy of nine levels grouped into four categories. Felder (1997) summarises the various levels as follows:

1. Dualism *(Levels 1 & 2)* Knowledge is black and white and the authority is expected to have all the answers. Students at Level 1 believe that their role is to memorise and repeat the correct solutions. Students at Level 2 begin to see that some questions may have multiple answers but they still believe that one of them must be right.
2. Multiplicity *(Levels 3 & 4)* The questions may not have answers now but the answers will eventually be known (Level 3) or responses to some (or most) questions may remain a matter of opinion (Level 4). Individuals at Levels 1-4 perceive knowledge to be externally and objectively based and perform the tasks that are expected of them by the authority (e.g. lecturer, tutor, examiner).

Individuals whose learning preferences lie between Levels 1 – 4 will, for the purposes of this study, be called *Specialists*.

3. Relativism *(Levels 5 & 6)* Knowledge and values depend on context and individual perspective. Students use real evidence to reach and support their conclusions independently (Level 5). Students may feel inclined to use critical judgement to make and support their own decisions on a course of action, despite a lack of certainty (Level 6).

4. Commitment within relativism *(Levels 7 – 9)* Individuals start to make actual commitments in personal direction and values (Level 7), evaluate the consequences and implications of their commitments and attempt to resolve conflicts (Level 8), and finally acknowledge that the conflicts may never be fully resolved and come to terms with the continuing struggle (Level 9).

Individuals whose learning preferences lie between Levels 5 – 9 will be called *Generalists*.

2.2. Aim of Specialist (Teacher-Centred) Training

The specialist graduates' role in industry is pre-defined; It is the responsibility of the academic institution "*to train students to perform known tasks well*" (Grow, 1991, p. 146) and to operate efficiently in that pre-defined role.

The aim of specialist training is either to *transfer* (impart/convey/give) knowledge to students or to *shape* students into a predetermined form (Fox, 1983). "*A general or a vocational training prepares learners either indirectly or directly for the requirements of employment. What is learned can be utilized in work: it is separate and transferable. The changing nature of work may lead to new skills and knowledge being included in training programmes, but it does not impact on the relationship between the two*" (Boud, 2006, p. 77).

'Specialists' view knowledge as objective and separate from the situations in which it is applied (Felder, 1997). The training process is therefore two-fold, to learn knowledge, and to learn how to apply it (Spinks, Silburn, & Birchall, 2006). The assumption being that knowledge is transferrable and non-situation-specific (Harpaz, 2005).

This 'traditional' form of education was created to deliver workers to the factories of the industrial revolution (Robinson, 2001; Pinar, 1992) and is itself modelled on the image of a factory intended to ‘produce’ graduates (Postman & Weingartner, 1971; Bowers & Flinders, 1990). “*Prior to the final quality-control inspection, the student presumably rides the assembly line quietly and dutifully accepting all data transmission in a similar manner as an automobile’s skeletal frame moves towards the new car dealer’s showroom*” (Catalano & Catalano, 1997). Implicit in this model of instruction are the following assumptions:

1. An(y) educational process is considered culturally neutral as well as linear and rationale;
2. Language serves as a conduit for the transmission of information and;
3. The teacher becomes the “manager” of the classroom with the learning process heavily dependent upon the pronouncement and enforcement of rules (*Ibid.* p. 95).

2.2.1. Authority-controlled structure

The transfer of information from a subject authority to students in a classroom is the universally recognised teaching method (Barrows & Tamblyn, 1980, p. 8; Sheppard, *et al.*, 2008, p. 4; Fisher, 1995, p. 184). “*In traditional education, the teacher (or trainer or curriculum committee or somebody) decides in advance what knowledge or skills need to be transmitted, arranges this body of content into logical units, selects the most efficient means for transmitting this content … and then develops a plan for presenting these content units in some sort of sequence*” (Knowles, Holton, & Swanson, 1973, p. 102). Similarly, Barrows & Tamblyn describe how ‘experts’ in the field synthesise difficult subjects into easily digested capsules and readily dispense the information using lectures, seminars and reading assignments (Barrows & Tamblyn, 1980, p. 8).

Traditional classrooms may be described as a 'teacher-centred' (e.g. Catalano & Catalano, 1997) and success as a teacher in a teacher-centred course is dependent on one's knowledge as an expert and one's flair for dispensing this knowledge (Barrows & Tamblyn, 1980). Teachers tend to position themselves at the centre of the classroom as a result of what Finkel and Monk (1983) refer to as the *Atlas complex*. This is defined as "*a state of mind that keeps teachers fixed in the center of their classroom, supporting the entire burden of responsibility for the course on their own shoulders*".

"Kandlbinder and Maufette (2001) found that even student-centred teachers in the sciences had the same goals as their less student-centred colleagues, namely to ensure that students developed a thorough knowledge of the discipline by learning 'basic concepts' at the start of the course. What was particularly interesting about this study was the foundational view of knowledge, whereby the assumption was that students needed to learn and understand a given body of knowledge before they could progress to the next level of the course. However, Kandlbinder and Maufette argued that what many lecturers referred to as 'basic concepts' were in fact far from basic" (Savin-Baden, 2003, p. 55).

In this transmission model of teaching the majority of classroom instruction is passive (Halperin, 1994; Catalano & Catalano, 1997), students' own ideas are unimportant (Fisher, 1995, p. 184) and the voice of authority is to be trusted (Postman & Weingartner, 1971, p. 31).

"*Undergraduate engineering education has been based on the implicit (and foolish) assumption that we somehow need to teach students 'everything they might need to know' before they enter professional practice*" (McMasters, 2004, p. 361). The assumption is still based on the original French model of training, which consists of a formal curriculum of basic sciences, technical subjects, and humanities, with theory taught before application (Sheppard, *et al.*, 2008, p. 4).

There is significant inertia to sustain this philosophy. Professional bodies dictate desirable and necessary skills and knowledge of engineering graduates (Joint Board of Moderators, 2009) and many faculty members feel pressure to cover large amounts of content (Litzinger, *et al.*, 2011, p. 143). "*If a new technological area became important in an engineering discipline, then faculty would add a course on that subject to the curriculum. This 'throw a course at the problem' (reductionist or atomisation) mentality continued until engineering programs were saturated with courses*" (McMasters, 2004, p. 361). "*The solution has always been to add more rather than to consider the overall design*" (Sheppard, *et al.*, 2008, p. 4).

2.2.2. Benefits of teacher-centred "specialist" training

"*The transmission model, "let me show you, or tell you, how to do it", is ideally suited for tasks involving low-level cognitive processing, such as following instructions or orders*" (Fisher, 1995, p. 184). Brownell's studies (1928; 1935) suggested that drill made children faster and better at "immature" and cumbersome procedures. Being told what to do or how to do it can be of vital importance in learning rules, or mastering mechanical and algorithmic tasks, particularly in situations where time is short (Pink, 2010). With sufficient training "*dependent learners become excellent students within a specialised area; they can be systematic, thorough, and disciplined, mastering a settled subject or transmitting a fixed tradition*" (Grow, 1991).

2.2.3. Deficiencies in teacher-centred "specialist" training

Specialist training has been shown to be effective at improving the knowledge and skills of specialist graduates. "*Habituation of action obviously has a function. It reduces the need for choice and enables us to act quickly. However, habits typically reflect the learning environment at the time the habit was formed. As long as the environment is unchanging, this property is fine but in a changing world, such as that which most managers currently experience,* *habits can be troublesome*" (Vroom, 2003). The 'deficiencies' highlighted in the literature are, as will be demonstrated below, associated with its inability to meet the needs of an evolving profession; where technical knowledge grows exponentially (Sheppard, *et al.*, 2008). Universities cannot teach everything that graduates will need to know in future (Boud & Feletti, 1997, p. 4).

Baird (1985), Day & Baskett (1982) argue that education is not in touch with the reality of professional practice and that there is little correlation between success in the workplace (management, leadership, artistic work etc.) and academic achievement. "*A degree certifies the knowledge that graduates have developed when they leave a university, but most graduates use very little of this knowledge in their subsequent careers*" (Laurillard, 2002, p. 134). Students may have differing career aspirations (Barrows & Tamblyn, 1980, p. 8) and will enter evolving fields where knowledge is anything but fixed (Rosenberg, 2009), rendering much of their acquired knowledge-base irrelevant (Postman & Weingartner, 1971; Berryman, 1990).

A common concern amongst educators and professionals alike is that graduates acquire fundamental knowledge - rules, algorithms, and decontextualized definitions - that they cannot use (Brown, Collins, & Duguid, 1989; Mills & Treagust, 2003). This should be unsurprising, as research has shown that learning fundamental facts has little correlation to one's ability to apply those facts in reality (Barrows, 1985).

Perkins suggests that taught knowledge lacks context; that it comes disconnected from the contexts of application that make it meaningful (Perkins, 1986, p. 54). Rules are often presented before the students understand the contexts in which those rules apply (Knight, 2001, p. 277). "*When we learn mindlessly, it does not occur to us to question the information when the context changes*" (Moldoveanu & Langer, 2002, p. 216). This may explain why drilling a student in the technical knowledge does little to improve their conceptual understanding (Glaser, 1983).

Most academics and professionals would agree that application of knowledge in practice is more important than storing facts by rote learning (De Graaf & Kolmos, 2007). Yet surveys of engineering industry found that "*new graduates were technically well prepared but lacked the professional skills for success in a competitive, innovative, global marketplace*" (Lattuca, *et al.*, 2006). This included a lack of communication skills and teamwork experience (Mills & Treagust, 2003); a lack of contextual and conceptual understanding (Nolan, 2009; Owens, 2010), an over-reliance on computing tools (Evans, *et al.,* 1993), and a lack of creativity, problem solving and critical thinking (Glaser, 1983; Perkins, 1986; Felder, 1987; Fisher, 1995).

There is widespread concern that existing lecture-centric programmes are incapable of meeting the needs of engineering industry (Mills & Treagust, 2003). Traditional courses give the misleading impression that knowledge can be divided into discrete, independent subjects (Postman & Weingartner, 1971); yet graduates "*entering today's workforce must be prepared to tackle the multifaceted problems that require more than a single discipline for their solution*" (Christ, 2010) - they must be able to see the big picture.

Lipman argues that, "*We do not sufficiently encourage [the student] to think for himself, to form independent judgements, to be proud of his personal insights, to be proud of having a point of view he can call his own, to be pleased with his prowess in reasoning*" (Lipman, 1982, p. 36).

A specialist system does not encourage students to create reasoned arguments – to identify various perspectives, views, and opinions; develop and select a preferred, reasonable solution; and support the solution with data and evidence (Voss, Lawrence, & Engle, 1991; Kuhn, 1991); as a result, students are not adept at constructing cogent arguments (Cerbin, 1988).

In the absence of critical judgement, graduates are able to work faster (Postman & Weingartner, 1971); but they become fundamentally reliant on a manager's ability to see the global picture and co-ordinate the interactions between individual workers (Hall, *et al*. 1997). As stated previously the traditional system focuses on algorithmic, procedural tasks that can be learned sequentially and applied automatically. In its quest for efficiency and standardisation, specialist education tends to reduce teachers and students to automata (Pinar, *et al.*, 1995).

Pink (2005) warns that specialists from Western nations will become redundant as a result of direct competition from abundance, automation and Asia. Academic institutions are producing more specialist engineers than ever before and there is now an abundance of engineering specialists trained to perform routine tasks (Wise, 2008; McMasters, 2004). The algorithmic tasks that specialists have been trained to perform can be reduced to a set of rules, or broken down into a set of repeatable steps, and can therefore be automated. Regardless of the complexity of the tasks, computers are now able to perform them faster and more accurately than any human. Finally, the training systems of Asia (India & China) produce large numbers of specialists capable of completing routine tasks at very low cost (Pink, 2007).

Specialist training itself is in direct competition with technology. Information can now be transferred to students effectively using digital media – including recorded lectures, videos, online texts or explanatory tutorials (Thompson, 2011); summative assessment (exams) can be fully automated and completed online; students can even obtain degrees via Massive Open Online Courses without even setting foot in a university (Romiszowski, 1997; Daniel, 2012; Pappano, 2012).

In summary, training students to apply de-contextualised fundamental information has been shown to effectively improve the knowledge and skills of specialist graduates. However, this system is unable to meet the needs of an evolving profession, and much of the knowledge that students acquire at university cannot be used in practice. Research has shown that learning fundamental facts has little correlation with the ability to apply those facts in reality, and in general graduates from traditional university systems were found to lack many elemental professional skills; this included a lack of team-working skills and an inability to construct reasoned arguments independently – to develop and defend solutions using information available to them. Moreover, students became reliant on their teachers' ability to see the big picture and co-ordinate their actions. Yet despite its shortcomings, there is still heavy competition for specialist roles, and not just from other specialists. If it can be standardised, it can be automated, meaning graduates are also in competition with machines. Even the process of teaching is being automated, and students are now able to obtain degrees online, without ever entering a lecture theatre.

2.3. Aim of Generalist Education

2.3.1. What is Generalist education?

"A place where people…. learn to reason, learn to understand and above all learn to think for themselves."

Judith (13 years)

(Blishen, 1969)

Education is fundamentally different to training. The central point of education is to teach people to think (Gagne, 1980, p. 85; McMasters, 2004). It presupposes that people are fundamentally capable of thinking for themselves, that they enjoy doing so, and that the structure of an academic system should provide support (Burke & Williams, 2008).

Thinking independently brings a new perspective; it challenges existing norms and could potentially lead to new ideas. To quote Jean Piaget (1954): "*The principal of education is to create men who are capable of doing new things, not simply repeating what other generations have done – men who are creative, inventive and discoverers [sic]. The second goal of education is to form minds which can be critical, can verify, and not accept everything they are offered*".

In a world where information is more abundant and accessible than ever before, students need to learn to differentiate good information from bad. "*What they are seeking to do is not only to help students to be equipped for the world of work but to develop criticality in those students*" (Savin-Baden, 2003). Developing the ability to think critically will help students make better decisions on what information to use, and what to ignore. By learning how to think and learn, students can prepare for their future careers when existing professional knowledge will not fit every case (Laurillard, 2002, p. 138; Harpaz, 2005).

Graduates must be able to apply knowledge as and when it is necessary. As Samuel Johnson said: "*Knowledge is of two kinds. We know a subject ourselves, or we know where we can find information on it*" (quoted in Boswell, 2005). "*It is more important for students to be able to learn quickly, effectively and independently when they need it, than it is for them to have assimilated (at graduation) all the information which their teachers believe is desirable*" (Boud & Feletti, 1997, p. 4)

2.3.2. The benefits of Generalist education

Generalist education encourages students in their personal growth and development (Fox, 1983). It is important that students develop their self-efficacy and an awareness of their own competence as this has been shown to be highly correlated with motivation and learning (Zimmerman, 2000).

"*The ability to make connections among seemingly disparate discoveries, events, and trends, and to integrate them in ways that benefit the world community will be the hallmark of modern leaders*" (Bordogna, Fromm, & Ernst, 1993). Generalist education encourages students to think about a topic holistically, *before* breaking it down into atomised, discrete components. Working with the complete picture increases the likelihood that knowledge will be learned in a meaningful context. As will be discussed later in the chapter, experiential learning (learning by doing) has additional benefits including practicing and improving relevant design skills.

In engineering, a focus on holistic design, and engagement with fundamental knowledge in a meaningful context (Schraw, Dunkle, & Bendixen, 1995, p. 524), could improve graduates' ability to apply theory to practice and to some extent alleviate industry's concerns (Nolan, 2009).

Industry has highlighted several key skills that must be practiced and improved during, and prior to entering, the workplace. "*In terms of professional work, abilities such as critical analysis, professional judgement, self-direction, problem solving, ethical self-regulation, research and a variety of interpersonal skills have all been highlighted as crucial abilities which are of equal importance to the broad knowledge base that underpins professional work*" (Chappell & Hager, 1995). It is important that a generalist education supports students in practicing and improving these skills while at university.

2.3.3. How to implement Generalist education

The aim is to create an authentic learning environment in which students can learn and develop (Laurillard, 2002; Crawley, *et al.*, 2007). In keeping with the studies by Dweck (2006), it was found that the learning approaches adopted by students were not personality characteristics (Biggs, 1999); but were seen to change with the perceived demands of the educational setting (Rust & Gibbs, 1997). University can therefore influence and develop the mindset that individuals will use throughout their career. Those who are given practice being autonomous, self-directed, responsible students are more likely to become autonomous, self-directed, responsible professionals (Taras, 2001).

The literature describes how students approach learning in two qualitatively different ways – a *surface* approach characterised by superficial memorisation of isolated facts, and a *deep* approach intended to derive meaning and understanding (Biggs, 1987; Ramsden & Moses, 1992; Marton & Booth, 1997; Marton & Säljö, 1976; 1984). The two approaches have also been termed learning to *remember* or learning to *know*, respectively (Ames, 1992b; Brophy, 1983; Dweck, 1986; Urdan & Maehr, 1995).

A surface approach to learning (learning to remember) is a superficial method of retaining information in line with the lowest level of Bloom's taxonomy (Krathwohl, 2002). For example, memorising information to pass an exam. Conversely, students who adopt a deep approach to learning (learning to know) aim to understand ideas and seek meanings (Ames, 1992b); they have an intrinsic interest in the task and an expectation of enjoyment in carrying it out. "*They adopt strategies that help satisfy their curiosity, such as making the task coherent with their own experience; relating and distinguishing evidence and argument; looking for patterns and underlying principles; integrating the task with existing awareness; seeing the parts of a task as making up the whole; theorising about it; forming hypotheses; and relating what they understand from other parts of the same subject, and from different subjects*" (Prosser & Trigwell, 1999, p. 3).

Generalist education aims to foster a deep approach to learning. "*Without exception, the results show that deep approaches to learning were more likely to be associated with higher quality learning outcomes*" (Marton & Booth, 1997); and for students to adopt a deep approach to learning they must be intrinsically motivated (Biggs, 1990-91).

It is widely acknowledged that engagement in real world problems is intrinsically motivating (Ramsden and Entwistle, 1981; Felder, 1990). "*Students, and the organizations hiring them, want education to be relevant to the real world they will work in*" (Flint, 2003).

2.3.4. Deficiencies of Generalist education

One potential deficiency of a generalist education is that an individual becomes a "Jack of all trades, master of none" (Various, 2013) and do not obtain mastery of an single subject. Furthermore, individuals learn to spend more time thinking, reasoning and making choices, and take considerably more time to develop solutions. In circumstances where the outcome has already been defined or where time is short, thinking will not add value (students will reach the same, well-established conclusions), and the decrease in productivity will become a significant disadvantage. In cases where students would simply be "reinventing the wheel", a specialist mindset would be preferable.

The generalist mindset alone is not capable of producing complete solutions. Specialist knowledge and skills are required at the later stages of the process to deliver a result. In the words of Glaser (1983): "*General methods are weak because they are applicable to almost any situation, and will not alone provide an evaluation of specific task features that enable a problem to be solved*" (p. 29).

Although not a deficiency, perhaps the biggest difficulty of generalist education lies in accepting the shift from teacher-controlled training to student-controlled learning. "*Most teachers are largely interested to know if it will accomplish the goals that older learning media have tried to achieve: Will students pass exams? Will they get the right answers? Etc*." (Postman & Weingartner, 1971, p. 37). A lack of understanding of the goals of education (as opposed to training) can be a source of confusion and frustration for aspiring educators (Prince, 2004).

Educators may also encounter resistance from students. Litzinger *et al*. (2011) found that students have preconceived expectations of engagement in engineering courses. "*These expectations may represent a hurdle to increasing demands for use of deep learning approaches, which may not be what engineering* *students expect and/or want…Clearly, implementation of deep learning experiences may lead to student dissatisfaction and resistance*" (p. 142).

2.3.5. Generalist Education for engineers

Bordogna *et al.* (1993) state that to be prepared for industry, engineering graduates must be educated to:

- Think across a variety of disciplines functionally (lateral thinking) as well as in terms of disciplinary depth (vertical thinking);
- Couple experience with abstract description;
- Develop ideas and nurture and implement them;
- Understand the functional core of the engineering process;
- Experiment with both design and research and understand their synergy;
- Synthesize and analyze;
- Formulate problems and solve them;
- Act both as a team member and independently;
- Recognize, contribute to, and enjoy the relationship of the engineering enterprise to the social/economic/political/ environmental context in which we live and work.

There are fewer generalists than specialists in engineering. "*Those with a real talent for design (and, by extension, system architecture) apparently do not exist in equal measure in either the general or the engineering populations with those who are good analysts*" (McMasters, 2004, p. 359). It is anticipated that industry will need a greatly increased supply of engineering generalists - 'system integrators' and 'system architects' - in future (*Ibid.*) Wise (2008) also identified the lack of generalists in engineering industry and stated that, "*We need more thinkers, more engineering designers, more people with judgment*".

Grasso & Brown Burkins (2010) also advocate a holistic approach to engineering education. Engineering students trying to meet the demands of the twenty-first century would benefit from a "*more cross-disciplinary, whole systems approach to engineering that emphasizes contextualized problem formulation, the ability to lead team-centred projects, the skills to communicate across disciplines, and the desire for life-long learning of the engineering craft in a rapidly changing world*" (p. 1).

Connections and integration should be at the core of an engineering education (Bordogna, Fromm, & Ernst, 1993). If students are to think holistically, it follows that engineering education "*should aim for an increasingly integrated approach to the formation of students' analytical reasoning, practical skills, and professional judgment*" (Sheppard, *et al.*, 2008).

The paradigm of modern engineering practice is that an individual's role will change and evolve. The graduating engineer must therefore be educated as a generalist (Crawley, *et al*., 2007). Generalist engineers will be able to choose from a range of career paths – each involving a different set of skills and knowledge (Crawley, *et al.*, 2007).

Regardless of the career path followed, engineering graduates need to be prepared to deal with uncertainty, incomplete information and conflicting demands in addition to dealing with an evolving knowledge base (Mills & Treagust, 2003).

"*We need to demonstrate to students that engineering is practiced within a much broader societal context*" (McMasters, 2004). Graduates should acknowledge that engineering is just one component of a much wider process; with a significant number of non-technical drivers (Prados, 1998). "*One element of holistic engineering education is the intimate integration of liberal arts and engineering, which supports the ability to understand problem context and to communicate across disciplines*" (Litzinger, *et al.,* 2011). Engineering curricula should be expanded to include generic skills aimed to improve graduates' ability to interact in an informed way with other professionals (Crawley, *et al.*, 2007, p. 60).

2.4. History of Engineering Education

Engineering has, for the last 500 years depended heavily on nonverbal understanding – that is, the kind of knowledge accumulated through the experience of *doing* engineering (Ferguson, 1992). Thus engineering education has for centuries been based on the hands-on practice-based model, taught by practicing engineers (Bankel, 2005). "*Engineering schools taught an understanding of engineering drawings by teaching how to make such drawings; they built an appreciation of the nature of materials and machines through laboratory experience. They understood that most of an engineers deep understanding is by nature nonverbal, the kind of intuitive knowledge that experts accumulate*" (Ferguson, 1992).

The onset of World War II led to huge investment in engineering science and research at universities; investment that was sustained throughout the Cold War (Prados, 1998). Undergraduate programmes changed to be taught primarily by engineering researchers (Bankel, 2005). "*It laid a strong foundation of fundamentals, but de-emphasised actual engineering practice*" (p. 121). The aim was no longer to figure out how to solve problems – that had already been done – the aim was to apply the right solutions (Woods, 1987). "*The art of engineering has been pushed aside in favour of the analytical "engineering sciences," which are higher in status and easier to teach*" (Ferguson, 1992).

The advent of high-tech innovation in the 1980s caused some to question the relevance of engineering education (Prados, 1998). "*The late 1970s and 1980s became the period in which industry started to recognise the change in the knowledge, skills and attitudes of graduating students. Industry reacted in the 1980s with observations and expressions of concern*" (Crawley, *et* *al*., 2007, p. 15). Students were technically well-prepared, but were lacking in skills essential to engineering practice.

"*It perhaps failed to meet an underlying need – that the university must educate not only technically expert engineers, but also those who can build and operate new value-added engineering systems in a modern, team-based environment*" (Bankel, 2005). The 'teaching fundamentals' way of training is insufficient to meet the demands of today's evolving society (Kemp & Seagraves, 1995; Prados, 1998; Crawley, 2002).

2.5. Motivation

"*One of the most important psychological concepts in education is certainly that of motivation*" (Vallerand, *et al.*, 1992).

2.5.1. Why we learn

Breen & Lindsay (2002) conduct a very thorough literature review of motivational theories and the ways in which they influence learning. A synopsis of their research is given below.

Trait theory of motivation

There are several theories on the origins of motivation in individuals. The pervasive view in the middle of last century was that motivation was a fixed trait and the context in which that individual was operating was irrelevant. Studies such as those of Atkinson (1960) and McClelland, *et al.* (1953) measured the extent of an individual's motivation in terms of dispositional characteristics.

While studies such as that of Entwistle and Wilson (1965; 1977) indicate that trait theories at least partly explain learning outcomes, there are situations in which dispositional motivations do not predict performance

(Ajzen, 1991; Weiner, 1992) and the correlation between individuals' motivational traits and their overall performance are low (Kanfer & Heggestad, 1999).

Accepting the theory that motivation is a fixed trait implies educators can do nothing to change students' motivation to learn their subject. The students are either already motivated, or they are not. The comprehensive literature review by Breen & Lindsay (2002) concluded that motivation could in fact be altered by one's environment, thereby supporting *context* theories of motivation.

Context theory of motivation

More recent research has discussed the ways in which the context of learning has an impact on motivation (Ramsden, 1997; Eccles, Wigfield, & Schiefele, 1998; Theall & Franklin, 1999).

Expectancy-value theory (Eccles, 1983; Vroom, 1964) proposes that people form an expectation of an experience and if that expectation is favourable, they become motivated. A student who thinks a course will be fun will be motivated to study that course.

Attribution theory (Weiner, 1974) proposes that individuals are motivated to feel good about themselves and will attribute the responsibility of their successes and failures accordingly. This theory explains why students would claim credit for achieving high grades and blame assessment methods for achieving low grades.

Self-efficacy theory (Bandura, 1977) relates to an individual's perception of their own ability; and proposes that individuals engage in behaviour if it increases their feelings of competence, control, or effectiveness (Breen & Lindsay, 2002). Some studies claim that self-efficacy theory offers a reliable means to predict academic performance in university students (Bandura, 1987; Lent, Brown, & Larkin, 1987; Siegel, Galassi, & Ware, 1985; Zimmerman, 2000).

Self-determination theory (Deci & Ryan, 1985) proposes that an individual is motivated to make choices without external influences. It claims that an individual is intrinsically motivated when given the opportunity to be autonomous and self-directed (Rotter, 1966). SDT could be viewed as an over-arching theory of intrinsic motivation, relating to all drivers originating from within an individual and encapsulating all of the theories mentioned above.

2.5.2. Reason for pursuing education – reason for learning

Motivation dominates the approaches to teaching and learning (Biggs, 1990-91). It affects not only the type of skills and abilities individuals develop, but also how they use those skills and abilities in practice (Locke & Latham, 2004).

Individuals are motivated to pursue either performance/achievement goals or mastery goals (Ames, 1992b).

Achievement behaviour is characterised in one of two ways. *"First, ability can be judged high or low with reference to the individual's own past performance or knowledge. In this context, gains in mastery indicate competence. Second, ability can be judged as capacity relative to that of others. In this context, a gain in mastery alone does not indicate high ability. To demonstrate high capacity, one must achieve more with equal effort or use less effort than do others for an equal performance*" (Nicholls, 1984). "*Central to a performance goal is a focus on one's ability and sense of self-worth (Covington, 1984; Dweck, 1986; Nicholls, 1984), and ability is evidenced by doing better than others, by surpassing established standards, or by achieving success with little effort (Ames, 1984; Covington, 1984). Above all it is important to those seeking performance goals that there is public recognition that one has done better than others or performed in a superior manner (Covington & Beery, 1976; Meece, Blumenfeld, & Hoyle,* *1988). As a result, learning itself is viewed only as a way to achieve a desired goal (Nicholls, 1979; 1989)*" (Breen & Lindsay (2002 p. 262).

In contrast, those who pursue mastery goals believe that in the long-term, effort is proportional to success. Success – as defined by the individual – is an inevitable by-product of hard work (Ames, 1992a; Ames & Archer, 1988; Dweck, 2006).

In each case the reasons for learning originates either from the *internal* desires of individuals or from the *external* desires of others wishing to control those individuals (Deci, Cascio, & Krusell, 1975).

2.6. Purpose

2.6.1. Definition

Purpose is the reason *why* we do what we do (Deci, 1995). It is the goal we strive to achieve and the justification for expending our time and effort.

"*To be motivated means to behave with the intention of achieving some outcome. However, the types of outcomes one pursues can be very different, as can the reasons one pursues them*" (Deci, Ryan, & Williams, 1996).

2.6.2. Introduction to purpose

Purpose allows students to see where they are going, where they are now, and what they need to do to move forward (Black & Wiliam, 2009; Wiliam & Thompson, 2007). A purpose obliges students to ask what they need to know (Hmelo-Silver, 2004); and learning becomes a means to achieve the desired goal (Nicholls, 1979; 1989; Ames, 1992b).

Purpose creates context and motivation for subsequent learning (Prince, 2004). "*The importance of purpose to understanding finds support in studies where understanding hangs on appreciating what something is for* *and also in the general importance of means-end analysis in human thought*" (Perkins, 1986, p. 21). The purpose provides the context and the framework in which technical knowledge and skills are learned (Crawley, *et al.*, 2008).

The purpose helps students see and understand the 'big picture'. "*Children learn by the gradual accumulation of facts and ideas but perhaps more importantly they learn by seeing situations as a whole, by seeing a pattern of relationships that helps to build up a structure of understanding*" (Fisher, 1995).

All design begins with a clearly defined need (Royal Academy of Engineering, 1999); and it is important that this need is internalised and deemed to be of interest to individual students. "*Unless an inquiry is perceived as relevant by the learner, no significant learning will take place. No one will learn anything he doesn't want to know*" (Postman & Weingartner, 1971, p. 59).

"*For unfamiliar procedures, of course, it is important to make the purpose plain if you are explaining the procedure. Just as with any design, a procedure loses meaning when disconnected from its purpose. Many rote procedures taught in schools seem arbitrary or pointless because the instruction has not richly enough filled in and fleshed out the purpose*" (Perkins, 1986, p. 47).

2.6.3. How purpose can be conveyed

The following section explains how the purpose can be established through effective teaching. "*The art of good teaching is to communicate that need where it is initially lacking. "Motivation" is a product of good teaching, not its prerequisite*" (Biggs, 1999).

One very effective means of establishing purpose is for students to define (or help define) the problem they intend to solve (Getzels, 1982). Involving students in the problem-defining process increases the likelihood that they will be interested and engaged in subsequent problem-solving.

Teachers should determine what it is they really want students to know and do as a result of their course and, more importantly, justify why (Garfield, 1995). The overall purpose of a course can then be broken down into course objectives and conveyed to students through the assessment tasks (Biggs, 1999).

Once the objectives have been defined, students experience a need to get there (Biggs, 1999). The nature of the objectives, in particular whether they are inherently interesting to the students, will have a profound influence on the students' approaches to learning.

"*There are two ways of looking at the work you do to earn a living: One is the way propounded by the late Henry Ford: Work is a necessary evil, but modern technology will reduce it to a minimum. Your life is your leisure lived in your 'free' time. The other is: To make your work interesting and rewarding. You enjoy both your work and your leisure*" (Arup, 1970). These are termed *extrinsic* and *intrinsic* motivation respectively.

2.6.4. Extrinsic

Extrinsic motivation pertains to activities that are engaged in as a means to an end (Deci, 1975). "*Being extrinsically motivated involves performing an activity with the intention of attaining some separable consequence such as receiving a reward, avoiding guilt, or gaining approval. Behaviours that are extrinsically motivated would generally not occur spontaneously, so their occurrence must typically be prompted by some type of instrumentality*" (Deci, Ryan, & Williams, 1996).

"*Hundreds of studies conducted in numerous countries and contexts have consistently demonstrated that setting specific, challenging goals can powerfully drive behaviour and boost performance*" (Ordóñez, *et al.*, 2009); much more so than simple encouragement to "do your best" (Locke & Latham, 2002). In fact, "*so long as a person is committed to the goal, has the requisite ability to attain it, and does not have conflicting goals, there is a positive, linear relationship between goal difficulty and task performance*" (Locke and Latham, 2006). This is particularly true when the goal is challenging and clear, rather than easy and vague (Locke & Latham, 1990; 2002).

Extrinsically defined goals, if they follow the constraints above, have the potential to improve productivity and performance, but may be perceived as controlling. Deci *et al.* (1996) describe how it is possible for extrinsically motivated behaviours, such as pursuing defined goals or following rules and regulations, to become "*self-determined through the closely related developmental processes of internalisation and integration*." Effectively, the more time an individual spends participating in the goal-setting process, the more they will be able to internalise the external constraints; the extent of their involvement will dictate self-determination, and subsequently affect motivation and performance.

Ideally the goals of a course would be fully agreed to by the students to the extent that there is no difference between the desired goals of the student and those of the academic in charge. "*Performance goals are sometimes pursued relatively autonomously, but at other times are experienced as quite controlling. And according to our theory, this could occur either because some individuals have more fully internalized and integrated the performance goals whereas other individuals have remained controlled by them*" (Deci, Ryan, & Williams, 1996).

The following table describes the extent to which a goal is internalised by, or imposed on an individual. Even though the origin of the performance goal comes from an external source, individuals can still maintain their motivation by internalising (and agreeing to) the goal.

Type of Regulation	*Degree of Self Regulation*	*Description*	*Generic Example*	*Specific Example*
External	Very Low	Behaviour controlled by demands or contingencies external to the person	Engaging in a behaviour to obtain a reward or avoid a punishment	The biology student who absorbed little as she sat in front of her textbook because her parents made her was externally regulated
Introjected	Moderately Low	Behaviour controlled by demands or contingencies inside the person such as self-esteem contingencies	One behaves because one thinks one should or because one would feel ashamed if one did not	The girl who studied biology because "she felt like she had to" was regulated by introjects, so her behavior would be classified as controlled
Identified	Moderately High	Behavior chosen because the person identifies with the importance of the activity.	People do not behave simply because they feel they should, but rather because they have identified with the value of the behavior and see its importance for their self-selected goals	The girl who willingly studied for her biology exam because doing well on the exam was important for her becoming a veterinarian had identified with the regulation of that activity.
Integrated	Very High	Behavior experienced as "wholly free" because the regulation has been integrated with the person's sense of self	When an identification has become fully integrated, one will behave with a true sense of volition and willingness	The aspiring veterinarian studied biology because she identified that learning the material could be of benefit in future, would have displayed integrated regulation of her studying
Reference: (Deci, Ryan, & Williams, 1996)				

TABLE 1: SELF-REGULATION THEORY

The table above shows the way in which ones motivation, and subsequent behaviour, changes given the way in which an external goal is perceived and internalised. The examples given for each of the four levels can give educators a better understanding of their students' behaviour towards, for example, coursework problem sets. The motivation for doing the problem sets must come from the lecturer, but the students may adopt the goals for themselves.

Introduction to control – rewards and punishments

Individuals can be *extrinsically* motivated by rewards and punishments imposed by others (Deci, 1995). The promise of reward and the threat of punishment have been shown to increase productivity (Herzburg, 1987). Universities are founded on the belief that students are more productive if they are extrinsically motivated (Wlodkowski, 1999): "*With few exceptions, postsecondary education is a system based on the assumption that human beings will strive to learn when they are externally rewarded for learning or punished for lack of it*" (p. 9).

Strauss and Shiloni (1994) describe how teachers must perform several motivation-raising activities (praising, censuring, stimulating, tempting, threatening, etc.) in order to open the "flaps" in a child's mind and allow the taught knowledge to be absorbed. It is assumed that a child's interest in the subject matter alone is insufficient. These interventions are intended to converge individuals towards the extrinsically defined goal(s). The system is based on the assumption that if good behaviour is rewarded and bad behaviour is punished then the overall result will be good behaviour (Pink, 2010; Herzburg, 1987). It is the responsibility of an authority to define 'good' and 'bad' behaviour in each case. This is the basis of *training*.

Dewey (1938) describes the effect this has on school children, "*The traditional scheme is, in essence, one of imposition from above and from outside. It imposes adult standards, subject-matter, and methods upon those who are only* *growing slowly toward maturity. The gap is so great that the required subject-matter, the methods of learning and of behaving are foreign to the existing capacities of the young. They are beyond the reach of the experience the young learners already possess. Consequently, they must be imposed; even though good teachers will use devices of art to cover up the imposition so as to relieve it of obviously brutal features*" (p. 4).

Ordóñez *et al.* (2009) state that extrinsic goal setting has been over-prescribed. In particular, they warn that: "*goal setting has powerful and predictable side effects. Rather than being offered as an 'over-the-counter' salve for boosting performance, goal setting should be prescribed selectively, presented with a warning label, and closely monitored*" (p. 3).

Goal setting has been found to degrade performance, corrode organizational culture, harm interpersonal relationships, motivate risky and unethical behaviour, shift focus away from important but non-specified goals, and reduce intrinsic motivation (Ordóñez, *et al.*, 2009). In many situations, the damaging effects of goal setting outweigh its benefits.

"*Likewise when an extrinsic goal is paramount – particularly a short-term, measurable one whose achievement delivers a big payoff – its presence can restrict our view of the broader dimensions of our behaviour*" (Pink, 2010). Extrinsic goals restrict students' lateral thinking and creativity (Amabile, 1985).

Extrinsic motivation, as it is intended to do, focuses people's attention on small, short-term tasks and prevents them from having to think about the big picture. This is not always advantageous. "*The very presence of goals may lead employees to focus myopically on short-term gains and to lose sight of the potential devastating long-term effects on the organisation*" (Ordóñez, *et al.*, 2009, p. 7).

Rewards have been shown to reduce creativity and lateral thinking (Amabile, 1985; Bordogna, Fromm, & Ernst, 1993). "*The incentivised participants performed worse than their counterparts because they were so focused on the prize that they failed to glimpse a novel solution on the periphery.*

Rewards, we've seen, can limit the breadth of our thinking. But extrinsic motivators – especially tangible, "if-then" ones – can also reduce the depth of our thinking" (Pink, 2010).

Mills & Blankstein describe the side-effects of working towards socially-prescribed success criteria. "*Socially-prescribed perfectionists are characterised by motivation for recognition by others. This is negatively associated with students' motivation, self-efficacy for learning and performance, and use of adaptive learning strategies, which are in turn related to relatively poorer academic performance*" (Mills & Blankstein, 2000).

Extrinsically-motivated students value grades, praise and others' perception of their intelligence and will try and achieve those goals in the quickest, easiest ways possible (Crooks, 1988; Juwah, *et al.*, 2004; Dweck, 2007). They want to *look* like masters without putting in the effort to attain mastery (Dweck, 2006; Pink, 2010). Expending effort, particularly if that effort does not lead to success, implies a lack of ability (Covington & Omelich, 1979).

Carol Dweck describes how students' who value what other people think of them will focus on the labels and the achievements, rather than the fulfilment and enjoyment of the task itself (Dweck, 2006). "*Look smart at all costs. Don't make mistakes. Don't work hard. If you make mistakes, don't try to correct them. Clearly, these are not rules that foster intellectual growth*" (Dweck, 2007).

The presence of an extrinsically defined goal devalues the process of achieving it. Ordonez *et al.* point out that specific goals may inhibit learning from experience (Earley, Connolly, & Ekegren, 1989; Wood, Bandura, & Bailey, 1990; Cervone, Jiwani, & Wood, 1991).

In summary, the presence of extrinsic goals may lead to unethical behaviour (Jensen, 2003; Schweitzer, Ordóñez, & Douma, 2004), narrowed focus (Simons & Chabris, 1999; Staw & Boettger, 1990), increased risk taking (Larrick, Heath, & Wu, 2009), decreased cooperation (Wright, *et al.*, 1993;

Mitchell & Silver, 1990), and decreased intrinsic motivation (Mossholder, 1980; Rawsthorne & Elliot, 1999; Shalley & Oldham, 1985).

Extrinsic motivation has been shown to conflict with intrinsic desires to perform a task. "*You paint a picture for the sake of the activity and the picture; but you do an assignment to fulfil a course requirement. But what if the assignment is to paint a picture? This mixed case causes trouble. Having an extrinsic motive like meeting course requirements undermines somewhat your perception of the intrinsic worth of the task*" (Perkins, 1986, p. 116).

Grades are an example of extrinsic motivation; they are not an enjoyable, interesting task in their own right. Grades are widely assumed to be the most effective way to motivate students to work at university. "*It has become commonplace to hear lecturers claim that students will not do any work unless it is being assessed – by which they often mean graded*" (Macdonald & Savin-Baden, 2004, p. 5); and, *"Undergraduates in a competitive setting have become adept at learning material in order to pass exams*" (Benware & Deci, 1984). This is only beneficial if it reflects the processes involved in professional practice (Macdonald & Savin-Baden, 2004).

Several studies have highlighted the effects of extrinsic motivation on student achievement. When Atkinson (1999) invited students to perform a task, she found that only 20% of students were (intrinsically) motivated by the task itself, 60% of students were extrinsically motivated towards a result and 20% were unmotivated. The students who were extrinsically motivated (towards a result) achieved higher scores than those students who were unmotivated, although their grades were lower than those students who were intrinsically motivated. In summary, grades are better than nothing, but they have limitations.

Norm-referenced grading systems have the effect of creating competition between students. Like most extrinsic motivators, competition has the potential to yield significant short-term gains. However, several studies have highlighted the debilitating effects of promoting competition in the classroom (Covington, 1992; Amabile, 1982a; Deci, *et al.*, 1981).

Extrinsic incentives have similarly negative side-effects on teachers. A study by Fryer (2011) found that extrinsic incentives increase teachers' *"effort towards short-term increases in test scores but not towards long-term learning"* (p. 7).

2.6.5. Intrinsic

Intrinsic motivation in contrast, is characterised by a genuine interest in the task itself (Deci, *et al.*, 1991). "*Intrinsically motivated behaviours are performed out of interest and require no "separable" consequence, no external or intrapsychic prod, promise, or threat"* (Deci, 1975; Deci, Ryan, & Williams, 1996).

The key difference in goal-orientation is the focus on *process*, rather than *product* (Wlodkowski, 1999); when the purpose of the activity is, in a sense, the activity itself (Csikszentmihalyi, 1975; Deci, Ryan, & Williams, 1996). Henri (1923) gives the following explanation: "*The object of painting a picture is not to make a picture – however unreasonable this may sound. The picture, if a picture results, is a by-product and may be useful, valuable, interesting as a sign of what has passed. The object, which is back of every true work of art, is* the attainment *of a* state of being*, a high state of functioning, a more than ordinary moment of existence*" (p. 157).

"*Henri's point, quite simply, is that being intrinsically motivated has to do with being wholly involved in the activity itself and not with reaching a goal (whether the goal be making money or making a picture)*" (Deci, 1995).

Carol Dweck defines an intrinsically motivating purpose as a "learning goal", where any progress towards the goal will yield learning gains. "*Students don't have to feel that they're already good at something in order to have fun and keep trying. After all, their goal is to learn, not to prove they're smart*" (Dweck, 2006). In an intrinsically motivating environment, the drive for learning comes from in inner desire to *know* what is currently unknown. The feeling of being unable to scratch an itch, being unable to answer a question that has a knowable answer, is a great driving force. Knowledge of one's own incompetence or lack of knowledge creates a feeling of intense psychological discomfort. In the words of Rust & Gibbs (1997): "*little is more important to human survival and progress than converting the intractable unknown into the comfortably predictable*" (p. 32).

People's attitudes towards intellectual challenges vary significantly. Individuals who are extrinsically motivated see challenges as obstacles standing in the way of achieving their goal. Challenges have the potential to cause failure and should therefore be avoided. Intrinsically motivated individuals in contrast view challenges as a goal in their own right. The greater the challenge, the greater the intrinsic desire to know.

Sauermann & Cohen (2008) conducted a study of 11,000 industrial scientists and engineers in the US and found that an individual's attitude had a profound impact on productivity. In fact the best predictor of productivity was found to be the desire for intellectual challenge; that is, the urge to master something new and engaging (Pink, 2010, p. 117).

It has been shown that intrinsic motivation leads people to engage with the process, rather than simply focusing on the task goal. In industry this significantly improves productivity, and it follows that students should be equally engaged in their university work. "*Certainly, no educational goals are more immediate than those which concern the establishment and maintenance of the students' absorption in the task at hand. Almost all other objectives are dependent for their accomplishment upon the attainment of this basic condition*" (Jackson, 1968, p. 85).

Pioneering educators like Dewey (1938) and Montessori (1967) sought to enforce intrinsic motivation by engaging learners in enjoyable, interesting activities. "*If we want to utilise people's intrinsic motivation, we must focus on* *what they are interested in and link the study material to it*" (Marton & Säljö, 1976). To increase intrinsic motivation, educators should identify students' interests (Tyler, 1949, p. 10) and together create opportunities, experiences, or environments that are likely to evoke motivation (Wlodkowski, 1999).

Intrinsic motivation has been shown to relate positively to cognitive outcomes (Grolnick & Ryan, 1987; Utman, 1997; Mills & Blankstein, 2000). For example, there is a strong positive correlation between students' interest/enjoyment (intrinsic motivation) and their subsequent recall of studied material (Ryan, Connell & Plant, 1990); their conceptual understanding (Deci, *et al*., 1991; Deci, Ryan, & Williams, 1996); depth of text processing (Schiefele, 1991); behavioural persistence (Vallerand, Fortier, & Guay, 1997); well-being (Deci, *et al.*, 1981; Ryan & Grolnick, 1986); self-efficacy for learning and performance; problem-solving ability (Deci, *et al.*, 1991); use of adaptive learning strategies; effective resource management; critical thinking; and effort regulation (Mills & Blankstein, 2000).

Intrinsically motivated individuals were found to work as long and as hard as their extrinsically motivated colleagues (Sauerman & Cohen, 2008; Pink, 2010); and were more likely to see interdisciplinary connections (Lattuca & Knight, 2010).

Intrinsic motivation was also found to be conducive to creativity; while controlling extrinsic motivation was found to be detrimental (Amabile, 1985). As Hanna (2008) said, "the desire to do something because you find it deeply satisfying and personally challenging inspires the highest levels of creativity, whether it's in the arts, sciences, or business".

It has also been shown to benefit educators. If the students on a course are intrinsically motivated and actively engaged in the learning process, the teaching time can be significantly reduced. Haidet *et al.* (2004) conducted a course in which content delivery was reduced by 50%, with no detrimental effects on knowledge acquisition or attitude enhancement.

These studies appear to substantiate Montessori's (1967) philosophy; "*The child should love everything that he learns, for his mental and emotional growths are linked…Once this love has been kindled, all problems confronting the educationist will disappear*".

The link between learning and achievement is not always clear. "*Intrinsically motivated people usually achieve more than their reward-seeking counterparts. Alas, that's not always true in the short term. An intense focus on extrinsic rewards can indeed deliver fast results. The trouble is, this approach is difficult to sustain. And it doesn't assist in mastery – which is the source of achievement in the long run*" (Pink, 2010, p. 79).

2.6.6. Problem-Based Learning (PBL)

PBL is focused, experiential learning organized around the investigation, explanation, and resolution of meaningful problems (Barrows, 2000; Torp & Sage, 2002; Hmelo-Silver, 2004). "*In problem-based learning the focus is on organising the curricular content around problem scenarios rather than subjects or disciplines. Students usually work in groups or teams to solve or manage these situations but they are not expected to acquire a predetermined series of 'right answers'. Instead, they are expected to engage with the complex situation presented to them and decide what information they need to acquire and learn and what skills they need to gain in order to manage the situation effectively*" (Macdonald & Savin-Baden, 2004, p. 3).

Problem-Based Learning (PBL) has been developed largely in response to the perceived shortcomings of traditional didactic teaching practices (Andresen, Boud, & Cohen, 1995). The principles of PBL are by no means new, and have been advocated by many prominent education researchers, including: Montessori (1967); Dewey (1910; 1916); Ausubel, Novak, & Hanesian (1978); Bruner (1959; 1961); Piaget (1954) & Rogers (1969a).

Barrows & Kelson (1995) and Hmelo-Silver (2004) state that the main goals of a PBL environment are to:

- Increase intrinsic motivation to learn;
- Develop self-directed, lifelong learning skills;
- Develop effective problem-solving skills;
- Improve effective collaboration;
- Expand and deepen a flexible knowledge base.

Students perceive the learning process to be more meaningful and relevant to them and their lives than many lecture-based programmes they have experienced (Taylor, 1997; Savin Baden, 2000; Savin-Baden, 2003).

It has been argued that the principles of PBL are aligned with the natural process of human intuition (Barrows & Tamblyn, 1980; Duch, Allen, & White, 1999; Felder & Brent, 2004; Gardner, 2011). Traditional education however, is not structured in this way (Chappell & Hager, 1995).

The type of questions students work on are fundamentally different to the well-defined exercise questions used in traditional training. "*In problem-based learning, students are presented with a loosely structured problem – one that has no obvious solution and for which problem-solvers cannot be certain they have the right answer*" (Flint, 2003).

PBL places the emphasis on the learner (Flint, 2003). It creates an opportunity for students to learn by doing (Perkins & Blythe, 1994, p. 6) and could be described as an *active* method of education. "*Problem based learning would be an example of an active method, because it requires [students] to question, to speculate, to generate solutions, to use the higher order cognitive activities that [thinking students] use spontaneously*" (Biggs, 1999).

PBL typically involves significant amounts of self-directed learning on the part of the students (Prince, 2004). It creates an environment in which context is established before knowledge is learned; and students actively learn whatever is deemed to be useful to the task at hand (Benware & Deci, 1984; Bruner, 1966; Rogers, 1969a; Jonassen, 2006).

Blumberg & Michael found that PBL students "*were more likely to use self-chosen learning resources whereas students in the conventional curriculum used faculty-chosen resources*" (Blumberg & Michael, 1992; Hmelo-Silver, 2004). Numerous studies have shown that PBL increases library use, textbook reading, class attendance and studying for meaning rather than simple recall (Vernon & Blake, 1993; Gallagher, 1997; Albanese, 2000; Major & Palmer, 2001; Prince, 2004).

In a PBL environment students learn to be critical of their own knowledge and the knowledge of others (Duch, Allen, & White, 1999). Students assess large quantities of information and make decisions on whether it is trustworthy and valid. The most 'believable' facts are those that have been developed, through a process of reasoning, by the students themselves. "*Facts related to us by others or information we have read ourselves rarely seem to have the tenacity of the information we have gained from our own daily confrontation with problems*" (Barrows & Tamblyn, 1980).

Through the process of inquiry students learn that knowledge is not confined to discrete subjects. "*As they work through real problems, students will be confronted with the realisation that knowledge transcends artificial boundaries*" (Duch, Allen, & White, 1999, p. 2). Students learn to gather information from a wide range of sources, as is the case in professional practice. Furthermore, students are able to recall information equally as well as students taught on traditional courses (Gijbels, *et al.*, 2005).

PBL is not limited to the acquisition of technical knowledge. New graduates require a combination of content knowledge and professional skill (Barrows & Tamblyn, 1980). The study of medical students by Barrows & Tamblyn (1976a) showed that students who had been educated using PBL demonstrated increased skills in problem formulation and self study, as well as a significantly greater intrinsic motivation.

Students don't remember or can't apply the knowledge they learned in traditional, teacher-centred courses because the knowledge was not learned in the context of real-life situations (Barrows, 1985). As Hmelo-Silver (2004) writes: "*Common sense suggests that to encourage students to develop flexible knowledge and effective problem-solving skills we must embed learning in contexts that require the use of these skills (Flint, 2003). Laboratory experiments have demonstrated that this is indeed the case (Needham, 1991; Perfetto, Bransford, & Franks, 1983). Classroom-based research supports these findings as well (Gallagher, Stepien, & Rosenthal, 1992; Hmelo, 1998; Hmelo, Holton, & Kolodner, 2000; Schwartz & Bransford, 1998)" (p. 240)*. In contrast, problem-based learning encourages students to learn fundamental knowledge in context. This increases students' ability to apply knowledge as and when it is needed in practice (Albanese & Mitchell, 1993).

Problem-based learning improves students' intrinsic motivation and life-long learning skills (Hmelo-Silver, 2004). Milà & Sanmartí (1999) for example, note the improvement in transferrable skills resulting from students actively working on real and simulated problems in environmental engineering.

It is not only skills and knowledge that are affected by the context of learning but also the *way* in which students think. Cognitive processing has been shown to be directly influenced by the tasks in which students engage (Astin, 1997; Posner & Rudnitsky, 2001). Students learn effectively when they are actively involved in the context in which the knowledge is to be used (Boud & Feletti, 1997, p. 4); where knowledge can be learned and applied simultaneously; and where students can develop their own understanding by relating concrete experience to existing knowledge (Flint, 2003, p. 2).

Most engineering institutions have realised the value of courses that provide students with real-life engineering design experience and promote engineering skills (Dutson, *et al.*, 1997). Felder & Brent (2003) describe how the proper implementation of PBL can achieve all of the learning outcomes included in the ABET Engineering Criteria (ABET, 2008).

PBL is widely believed to be more time-intensive and costly than traditional teaching practices. However, the costs associated with PBL courses have been shown to be less than conventional courses for class sizes of less than 40; comparable in cost for between 40 and 100 students; and greater in cost for more than 100 students (Albanese & Mitchell, 1993, p. 70).

How is PBL implemented in practice?

There are several ways PBL can be implemented in practice. The major obstacle in implementing this method is the organisational shift required to structure the entire educational programme around projects, rather than disciplines (Bankel, 2005) - many academics find it difficult to "emphasize contextual settings for course subject matter" (Evans, *et al.*, 1993). "*Conversion to PBL requires systemic reform of curricula or at least entire courses. Although they have proven incredibly successful in a range of contexts, the level of commitment to such an innovation is more than most programs or professors are willing to make*" (Jonassen, 2006).

The focal point of a PBL course is fundamentally different to traditional, teacher-based training. "The focus here is in organizing the curricular content around problem scenarios rather than subjects or disciplines" (Savin Baden, 2000). "*The starting point for learning should be a problem, a query or a puzzle that the learner wishes to solve*" (Boud, 1985, p. 13). "*The problem is the focus for acquiring knowledge and reasoning strategies*" (Hmelo-Silver, 2004, p. 237).

The most critical stage of a PBL course is therefore choosing the 'right problems'. A problem should primarily be authentic, relevant and inherently interesting to the students (Flint, 2003). Secondly, it should be closely associated to the subject (Savoie & Hughes, 1994). Overall the problem should be a ‘challenge’ designed to initiate an inquiry-based approach from students (De Graaf & Kolmos, 2007; Litzinger, *et al.*, 2011).

As with any course it is essential to remain current, PBL programmes should establish and apply a systemic process of identifying attributes of workplace problems and should respond to changes in these problems over time (Jonassen, 2006).

Although some struggle initially, most students easily adapt to PBL, especially with appropriate support from a committed tutor (Macdonald & Savin-Baden, 2004). Perhaps above all, it is not what you say to people that counts; it is what you have them *do* (Postman & Weingartner, 1971). The first role of a tutor in PBL is that of facilitator, and second as a knowledge resource (Knowles, 1975).

The challenges are not meant to coerce students into learning authority-defined solutions, rather to become independent, competent learners. As Savin-Baden (2000) says: “*Students work in groups or teams to solve or manage these situations but they are not expected to acquire a predetermined series of ‘right answers’ (Savin-Baden, 2007). Instead they are expected to engage with the complex situation presented to them and decide what information they need to learn and what skills they need to gain in order to manage the situation effectively*” (p. 3).

PBL has now been used successfully in a range of subjects including engineering (Boud & Feletti, 1997). Project-based courses such as ECSEL (Kalonji, Regan, & Walker, 1996) or Keystone (Calabro, *et al.*, 2008) can be viewed as the next level of autonomous learning. Students are presented with a single challenge on which to spend the entire semester, rather than a series of smaller, disconnected challenges as per PBL. Examples of the type of engineering challenges used include designing and building autonomous hovercraft (Calabro, *et al.*, 2008) and solar-powered race cars (Catalano & Tonso, 1996).

A few universities made the transition from the engineering science model to problem-based learning, where projects rather than subjects form the basis for the curriculum (Bankel, 2005). In Aalborg University in Denmark, project-related course make up 75% of the programme (Mills & Treagust, 2003). It is the best-documented example in the literature of integrating PBL into a university curriculum (Kolmos, 1996; De Graaff & Kolmos, 2003; Litzinger, *et al.*, 2011).

"*Employer evaluations comparing Aalborg graduates to students from the Technical University of Denmark (DTU), which does not make extensive use of PBL, show clear superiority on a number of criteria (Kjærsdam, 2004). Forty-one percent of respondents evaluated Aalborg graduates as good or very good at project and people management versus just nine percent for DTU. Aalborg graduates were also rated higher in innovative and creative skills (81%/59%). Graduates of the two programs received equivalent ratings on quality of engineering and technical skills (86%/85%). Thus the intensive focus on PBL seems to have enhanced the Aalborg graduates' ability to apply their knowledge to solve complex problems creatively and collaboratively*" (Litzinger, *et al.*, 2011, p. 135; Creese, 1987).

PBL can create an intrinsically motivating purpose, such that students are naturally interested and willing to work independently. In the absence of an intrinsically motivating purpose, and/or in situations where an authority expects a specific outcome, students must be extrinsically motivated.

2.7. Control

2.7.1. Definition of control

Control is the means by which extrinsic motivation is sustained (Deci, 1995). The curriculum is focused on an authority – a teacher or expert. In this model, "*the teacher is solely responsible for what the student is expected to learn.*

The teacher decides what information and skills the student should learn, how it is to be learned, in what sequence, and at what pace. It is a well-known model that we have been exposed to since kindergarten. Although the teacher's role in this method is to dispense information in lectures, assign readings and provide demonstrations, a modular, self-study or individualised learning curriculum also can be teacher-centred if the teacher determines the modules or resources that are to be studied, the sequence of study, and the learning that is to be mastered. The characteristic that identifies a teacher-centred curriculum is that the student is not responsible for his own education" (Barrows & Tamblyn, 1980, p. 7).

2.7.2. Why control is used

Control is used when an authority does not trust their subordinates to perform satisfactorily. An authority can use their extensive knowledge and experience to define (either implicitly or explicitly) a desirable outcome; in which case control is used to increase the likelihood that that pre-defined outcome will be realised. This creates an underlying expectation (Barrows & Tamblyn, 1980; Deci, 1995). Several businesses operate under this philosophy (Ordóñez, *et al*., 2009), and it has been used to great effect in systems where the process was procedural. The underlying assumption is that students/workers have no intrinsic motivation to work and that they will not work unless they are extrinsically motivated (Deci, 1995). Control is an easy answer; it assumes that the promise of reward or the threat of punishment will make people comply (Pink, 2010).

Most tutors & lecturers were themselves taught in systems that placed the teacher in a position of dominance and power, with almost exclusive authority over and responsibility for making decisions about the students' education (Pratt, 1988). These tutors & lecturers are likely to perpetuate a controlling environment and may ask questions such as: "How do I motivate people to learn this information?"

Some academics find change inconvenient, risky and even intolerable, and feel compelled to conserve the status quo. Such individuals take a paternal view of education – we are the experts and we know best – and therefore do not see value in encouraging students to question, doubt or challenge any part of the society in which they live. Moreover they may even feel threatened by the idea (Postman & Weingartner, 1971, p. 15; Wilson, 2010).

Rice captured the essence of why some engineering educators feel such unease about relinquishing responsibility to their students: "*An engineer must not be wrong, because human life and human safety are dependent on the engineers' work being right*" (Rice, 1998, p. 75). Educators have a duty of care to ensure that the students they graduate are competent and capable of fulfilling an engineering role in industry.

2.7.3. Benefits of control

A controlling environment is primarily intended to increase the likelihood that a predefined outcome is obtained; and it is beneficial when speed, compliance and accuracy are paramount.

In a controlling environment the authority takes full responsibility for thinking and decision-making. This, often unintentionally, promotes dependence on the authority; in a university environment, students become dependent on the tutors & lecturers.

Fostering dependence in students can be beneficial if the intent is to train students to be compliant, and to perform a desired task to a desired standard. A controlling environment has been shown to improve students' mastery of a subject, provided the task is algorithmic and can be memorised and practiced (Deci & Ryan, 1985).

On the whole, it is assumed that a controlling environment is beneficial to learning. Both students and parents rate controlling teachers as significantly more competent than autonomy-supportive teachers (Reeve, 2004, p. 191); subsequently, proponents of traditional training often cite student satisfaction as a reason to maintain the status quo (Felder, 2000).

2.7.4. How control is implemented

"*The view taken by so many educators that the way to get students to learn is through the use of grades, gold stars, and other rewards. Tell them what they should do and then reward them for complying. The answer to how to motivate children's learning, in this view, is quite straightforward: Use the appropriate reward contingencies*" (Deci, 1995).

The way to regulate a controlling environment is to insist on *compliance* (Deci, *et al.*, 1991); rules only work if people follow them. Through compliance, authorities can ensure their standards are met.

2.7.5. Control in engineering

A commonly held assumption is that students need to learn a certain amount of pre-defined knowledge before they are capable of self-directed learning. One's capacity to learn new knowledge certainly does seem to be positively linked to one's level of existing knowledge (Maguire, Frith, & Morris, 1999; Exley & Dennick, 2009). A more contentious question is whether this knowledge must specifically be *taught* or whether it is possible for students to learn it autonomously. Studies by Lambert & McCombs (1998), Deci (1975; 1995), Grow (1991) and others suggest that human beings have the innate ability to derive meaning from the world around them, and can learn without needing to be taught by others.

Extensive research in PBL and self-directed learning would appear to support the theory that students are naturally motivated and capable of self-directed learning regardless of their initial levels of knowledge; and that imposing information on them could undermine their natural motivation for learning. "*In the engineering science and technology courses, the tradition of putting theory before practice and the effort to cover technical knowledge comprehensively allow little opportunity for students to have the kind of deep learning experiences that mirror professional practice and problem solving*" (Sheppard, *et al.*, 2008).

2.7.6. Failings of control

In situations where people or systems fail to meet the expectations of society, greater control seems like the easy answer; if a mistake occurs, improve the rules and compliance. "*In spite of the appeal of control, however, it has become increasingly clear that the approach simply does not work. Attempts to apply stricter discipline have been largely ineffectual, and the widespread reliance on rewards and punishments to motivate responsibility failed to yield the desired results. Indeed, mounting evidence suggests that these so-called solutions, based on the principle of rigid authority, are exacerbating rather than ameliorating the problems*" (Deci, 1995).

The imposition of external constraints on an activity has been shown to undermine intrinsic motivation (Koestner, *et al.*, 1984), decrease creativity (Lepper, Greene, & Nisbett, 1973; Greene & Lepper, 1974; Amabile, 1985; 1986), decrease critical thinking (Pinar, 1992), reduce performance on heuristic activities (Koestner, *et al.*, 1984, p. 246) and hinder personal, social, intellectual and moral development (Dewey, 1938, p. 22; Deci, *et al.,* 1991).

Control increases the likelihood that a predicted outcome will be realised, but by definition reduces the likelihood of any other outcome, including potential improvements (innovation). Any innovation must therefore result, at least to some extent, from breaking the rules. "*Standardisation and convention have such an oppressive effect on creative* *minds that innovation often takes place outside the bounds of what may be considered 'good practice*'" (Postman & Weingartner, 1971, p. 25).

Conflicts occur when there is a misalignment between the aims of the authority and the aims of the individuals being controlled (Macdonald & Savin-Baden, 2004). If both parties actively agree on the defined goals, control will be less likely to induce negative effects (Deci & Ryan, 1994).

It is widely acknowledged that the traditional school environment is controlling and standardised (Pinar, 1992): Pupils learn from a standard curriculum, write standard exams and wear school uniform. Students learn that there is one right answer to questions, and that they do not gain credit for wrong answers (Postman & Weingartner, 1971). "*When the classroom culture focuses on rewards, 'gold stars', grades, or class ranking, then pupils look for ways to obtain the best marks rather than to improve their learning. One reported consequence is that, when they have any choice, pupils avoid difficult tasks. They also spend time and energy looking for clues to the 'right answer'. Indeed, many become reluctant to ask questions out of a fear of failure. Pupils who encounter difficulties are led to believe that they lack ability, and this belief leads them to attribute their difficulties to a defect in themselves about which they cannot do a great deal. Thus they avoid investing effort in learning that can lead only to disappointment, and they try to build up their self-esteem in other ways*" (Black & Wiliam, 1998b).

A controlling environment can have damaging effects on students' self-esteem and work ethic (Lepper & Greene, 1975). "*Not being trusted to do things or allowed to make mistakes, they may be treated or come to see themselves as incapable. Lack of self-confidence induces failure-avoiding behaviour. They use excuses to discount failure, 'nobody told me what to do'. They may seek to avoid failure and achieve minimal success through low aspirations, 'I did as I was told, what more do you want?*" (Fisher, 1995, p. 246). Carol Dweck refers to this mentality as a 'fixed mindset'. This is the belief that one's skills, knowledge and persona are fixed traits that cannot be changed, and that they are either capable or they are not. In contrast, those who have a 'growth mindset' believe that ability can be improved through effort (Dweck, 2006).

Studies conducted by Dweck demonstrated how an individual's mindset can be changed by their environment. This implies that the mindsets Dweck is referring to are not (only) physiological characteristics, but psychological as well.

Rewards and punishments have been shown to work very effectively in some circumstances (Ordóñez, *et al.*, 2009); but they have also been shown to focus attention on ability and achievement rather than on the belief that one's effort can produce success (Black & Wiliam, 1998a). A learning environment that sets goals for students to achieve (e.g. an A-grade) - and offers rewards or punishments on the attainment of those goals - will be more likely to generate fixed mindsets and encourage undesirable behaviour (Dweck, 1986; 2007; Ordóñez, *et al.*, 2009).

In his controversial paper on motivation, Herzberg (1987) describes rewards as a positive KITA (kick-in-the-pants) and punishments as a negative KITA. Rewards are described as coercive, akin to "seduction"; while punishments are a direct attack, akin to "rape". As Herzburg states, "*it is infinitely worse to be seduced than to be raped; the latter is an unfortunate occurrence, while the former signifies that you were a party to your own downfall*" (p. 6).

Individuals who are given engagement-contingent, completion-contingent or performance-contingent rewards lose their intrinsic motivation (Deci, Koestner, & Ryan, 1999). Studies by Suvorov & Van de Ven (2006) on rewards showed that once an individual has been rewarded for doing a task, they will not do it again for free. This even applies if the individual originally enjoyed the task and found it inherently enjoyable (Lepper, Greene, & Nisbett, 1973; Deci, 1995, p. 51). Furthermore, individuals come to view the *rewards* as the purpose of doing a task (Deci, 1971). "*Where the classroom* *culture focuses on rewards, 'gold stars', grades or place-in-the-class ranking, then pupils look for the ways to obtain the best marks rather than at the needs of their learning which these marks ought to reflect*" (Black & Wiliam, 1998b).

Similarly, the threat of punishment has also been shown to have substantially negative long-term effects on intrinsic motivation and task enjoyment (Deci & Cascio, 1972; Deci, Koestner, & Ryan, 1999).

Dan Ariely, along with three colleagues, conducted an experiment into the effects of rewards on performance in Madurai, India. In an article for the NY Times Ariely wrote: "*We presented 87 participants with an array of tasks that demanded attention, memory, concentration and creativity. We asked them, for instance, to fit pieces of metal puzzle into a plastic frame, to play a memory game that required them to reproduce a string of numbers and to throw tennis balls at a target. We promised them payment if they performed the tasks exceptionally well. About a third of the subjects were told they'd be given a small bonus, another third were promised a medium-level bonus, and the last third could earn a high bonus*" (Ariely, 2008).

The result was that "*the people offered medium bonuses performed no better, or worse, than those offered low bonuses. But what was most interesting was that the group offered the biggest bonus did worse than the other two groups across all the tasks*.

"*We replicated these results in a study at the Massachusetts Institute of Technology, where undergraduate students were offered the chance to earn a high bonus ($600) or a lower one ($60) by performing one task that called for some cognitive skill (adding numbers) and another one that required only a mechanical skill (tapping a key as fast as possible). We found that as long as the task involved only mechanical skill, bonuses worked as would be expected: the higher the pay, the better the performance. But when we included a task that required even rudimentary cognitive skill, the outcome was the same as in the India study: the offer of a higher bonus led to poorer performance*" (Ariely, 2008).

Fryer (2011) noted similar results in a university environment: "*I find no evidence that teacher incentives increase student performance, attendance, or graduation, nor do I find any evidence that the incentives change student or teacher behaviour. If anything, teacher incentives may decrease student achievement, especially in larger schools*" (p. 1).

Deci *et al.* note that, in addition to decreasing performance, rewards have a detrimental effect on motivation. "*When people say that money motivates, what they really mean is that money controls. And when it does, people become alienated – they give up some of their authenticity – and they push themselves to do what they think they must do*" (Deci, 1995).

Rewards give implicit value to peoples' actions or achievements, replacing any intrinsic value that the action or achievement may have. This may create short-term motivation but it can have damaging effects on the individual's motivation in the long-term, particularly when it concerns interesting activities (Deci, Koestner, & Ryan, 1999). The value of the reward overrides the implicit value of the task itself.

As Postman says, "*positive judgements, perhaps surprisingly, can also produce undesirable results. For example, if a learner becomes totally dependent upon the positive judgements of an authority (teacher) for both motivation and reward, what you have is an intellectual paraplegic incapable of any independent activity, intellectual or otherwise*" (Postman & Weingartner, 1971, p. 187).

Dan Pink (2010) summarises the negative effects of rewards and punishments (p. 59):

1. They can extinguish intrinsic motivation (Deci, 1971)
2. They can diminish performance (Ariely, 2008)
3. They can crush creativity (Amabile, 1985)
4. They can crowd out good behaviour (Frey, 1997)
5. They can encourage cheating, shortcuts, and unethical behaviour (Ordóñez, *et al.*, 2009)
6. They can become addictive (Suvorov, 2003)

7. They can foster short-term thinking (Deci, Koestner, & Ryan, 1999, p. 659)

2.8. Autonomy

2.8.1. Definition of autonomy

The opposite of control is autonomy; and where control leads to compliance; autonomy leads to engagement (Pink, 2010). The traditional assumption underlying control is that people are not inherently motivated to learn (Deci, 1995), and that if they had freedom they would shirk (Frey, 1997). Research has demonstrated that this is often not the case, as many people actively want to be autonomous, self-directed and individually accountable (Pink, 2010).

The available literature describes the links between autonomy, open-mindedness, independent thought and self-determination theory – all relating to the students' perceptions of themselves, rather than the perceptions of others.

2.8.2. Reasons why autonomy is important

"*Why should we be concerned about creating opportunities for students to develop and exercise autonomy in learning?...Independence in learning may or may not be a desirable personal goal for an individual; it is, nevertheless, a vital requisite for someone to be able to function effectively in modern society. Anyone acting in a responsible position needs to be able to plan his or her own learning and draw upon a variety of resources to assist in putting his or her learning plan into action. He or she needs to draw upon the experience and expertise of others, but it is his or her own responsibility to ensure that the answer needed is found*" (Boud, 1981, p. 12). "*Donald A. Schön (1987), for example, demonstrated the* *need for a "reflective practicum" in universities, where students can prepare for their future careers when existing professional knowledge will not fit every case. Practitioners have to make sense of uncertain, unique, or conflicted situations of practice through "reflection-in-action," and they need to be able to go beyond the rules—devising new methods of reasoning, strategies of action, and ways of framing problems. This presupposes a very different kind of university teaching*" (Laurillard, 2002).

If students are to be intrinsically motivated (Deci, 1995); if they are to gain conceptual understanding (Benware & Deci, 1984); if they are to learn knowledge in context (Biggs, 1999, p. 60); if they are to be open-minded and willing to change (Fisher, 1995, p. 67); if they are to be independent and responsible (Fisher, 1995); if they are to be resourceful (Flint, 2003); if they are to be creative (Amabile, 1986); if they are to be able to think (Flint, 2003), and reason (Toulmin, 1958; Glaser, 1983); then they must be able to learn autonomously.

It has been shown that children in autonomous learning environments learned more as measured by standardised achievement tests (deCharms, 1976; Benware & Deci, 1984), and demonstrated greater productivity in the long-run (Baard, 2004), than children in control-oriented classrooms.

2.8.3. Autonomy is natural

Young children are naturally inquisitive and are able to make decisions and learn autonomously without the need for instruction or extrinsic motivation (Deci, 1975; Grow, 1991). They carelessly explore and manipulate the objects they encounter, and challenge themselves to become competent, apparently just for the enjoyment of doing so (Deci, 1995; Lambert and McCombs, 1998). "*These primary sources of motivation reside in all of us, across all cultures. When students can see that what they are learning is important, their motivation emerges*" (Wlodkowski, 1999).

A study by Miller & Gildea (1987) found that children are capable of learning considerably more on their own than can be taught in the timeframe of a typical school year. In addition to the quantity of information, it was found that the quality of children's learning increased; they were able to associate, categorise and thus give meaning to words far more rapidly than when they were taught. In one experiment a group of five-year olds were able to conceptually understand words after hearing them used in context just once (*Ibid.* p. 95).

Over thirty years ago, education researcher Malcolm Knowles (1980) proposed that a transition from dependency to self-direction was just part of growing up. However, recent research contradicts this and instead suggests that people become more dependent over time as a result of years of depencency training (Grow, 1991).

The traditional school not only encourages individuals to become more dependent, it also encourages a change in attitude. Up to about 10 years of age students generally conceive of ability as learning through effort (Crooks, 1988). Greater effort leads to increased task mastery – an indication of enhanced ability (Dweck, 2006). "*Students with the task mastery concept of ability like challenging tasks that appear reasonably likely to yield success after considerable effort. Such tasks can give them a sense of achievement and thus enhance their perceived ability*" (Crooks, 1988, p. 465).

All children are born with the ability to be creative (Fisher, 1995), but over time that creativity diminishes. In 1968 George Land and Beth Jarman began a study of 1,600 three-to-five year-old children that would prove this phenomenon. He gave the children a series of divergent thinking tests similar to those used by NASA to measure creativity in their engineers and scientists. Of the children who were tested, 98% of them scored in the top tier - a level described as "genius" in divergent, creative thinking. The same children were tested five years later, only this time only 32% of the students scored in the top tier. After another five years, only 10%. By 1992, 200,000 adults had taken the tests and only 2% scored in the top tier (Land & Jarman, 1992). The creative ability that had been so prevalent in kindergarten children had indeed disappeared.

Some (e.g. Postman & Weingartner, 1971) believe that the extrinsically motivating environment of traditional schooling is to blame. Research by Amabile (1985) confirmed that extrinsic motivation does decrease creativity, while individuals working in an environment that supports intrinsic motivation maintain their level of creativity.

2.8.4. How to relinquish control and support autonomy

The issue about how much self-direction students could safely be allowed seems to have emerged as an area of conflict for many staff. Educators feel torn between the ideals of self-directed learning and their perceived duty as responsible teachers to ensure students become safe and competent practitioners (Savin-Baden, 2003, p. 39).

Some faculty members perceive the risks of self-directed learning as too great – the risks that students will not participate or use higher-order thinking, or learn sufficient content; or that faculty members will feel a loss of control, lack necessary skills or be criticized for teaching in unorthodox ways (Bonwell & Eison, 1991; Exley & Dennick, 2009). "*It is rather threatening to relinquish authoritarian control in the classroom and allow what may appear at first glance to be utter chaos*" (Catalano & Catalano, 1997).

Educators have given first hand accounts of their struggles with relinquishing control to their students (Powell, 1981). Catalano & Tonso (1996) encountered negative responses from students ranging from indifference to hostility during an attempt to implement a student-centred design project as the overarching purpose for an engineering course. The faculty members involved did not like the shift of control and the perceived increase in effort required.

Relinquishing control is a pre-requisite for autonomous learning; however, as Dewey notes, "*the mere removal of external control is no guarantee for the production of self-control*" (Dewey, 1938, p. 64). Having control over ones choices does not in itself lead to self-direction, autonomy and acceptance of responsibility (Pratt, 1988; Theall & Franklin, 1999).

Researchers have proposed that the educators' role is changed from 'knowledge expert' to 'facilitator' (Boud, 1981; Flint, 2003; Heywood, 2005). However, learning to facilitate well is a challenge (Derry *et al.*, 2001). Teachers have to learn to 'let go'; "*to stop providing answers to questions when those very questions provide the basis for students' learning activities*" (Macdonald & Savin-Baden, 2004, p. 4); and "*to stop posing as an expert and instead expose oneself as an authentic human being, with feelings, hopes, aspirations, insecurities worries, strengths and weaknesses*" (Knowles, 1975). This shift of roles and responsibilities can make some educators deeply uncomfortable (Macdonald & Savin-Baden, 2004).

The literature indicates that the way to relinquish control and support autonomy is to give students trust and responsibility over their actions. Students can be given the opportunity to choose their own methods and learning resources, and even conduct their own assessment.

2.8.5. How to improve students self-confidence (autonomy)

Learners' self-efficacy – their beliefs about their own capacity as learners – has a significant effect on their achievement (Craven, Marsh, & Debus, 1991; Lan, Bradley, & Parr, 1994; King, 1994; Butler & Winne, 1995; Fernandes & Fontana, 1996). In particular research has shown statistically significant relationships between self-efficacy beliefs and academic performance and persistence (Multon, Brown & Lent, 1991). Yet research suggests that from the age of 10 students' self-esteem decreases significantly (Crooks, 1988); and by the time they reach university, many students have low self-confidence (Felder, *et al.*, 1995). There are several theories why this might be the case. One widely accepted theory is that externally imposed labels of ability replace students' own beliefs about themselves (Deci, 1995; Dweck, 2006). Other research has shown students' self-confidence and motivation decreases when they perceive the subject material as too difficult (Crooks, 1988, p. 455). A lack of self-confidence induces failure-avoiding behaviour (Clifford, 1984; Fisher, 1995), fear of autonomy and responsibility (Stanton, 1981) and blind acceptance of taught information (Exley & Dennick, 2009). These traits are not conducive to learning in an autonomous environment, or to becoming a competent professional.

It has been assumed that confidence, competence and commitment are situational attributes and can therefore be changed by the education environment (Pratt, 1988). Controlling environments have been shown to decrease student confidence, while autonomous environments have been shown to increase it (Deci, *et al.*, 1991). Crawley *et al.* (2007) state that engineering students should have confidence to design and build engineering systems and that this confidence "*can only be developed through the experience of doing it independently*" (p. 37). Working independently is not in itself sufficient; students' confidence only increases when they see *evidence* of self-improvement (Biggs, 1990-91).

Tutors and lecturers can increase students' confidence in several ways; including improving their own self-esteem and self-confidence. "*As Torrance (1973) reminds us: "it takes courage to be creative. Just as soon as you have a new idea, you are a minority of one". A willingness to stand up for one's own ideas and feelings requires a sound basis of self-esteem. This basis is built up not only by the confidence we instil by word and deed, but by the model we present as parents and teachers. We need to raise our own self-esteem and to have* *confidence in our own creativity, for we may teach more by what we are than what we say*" (Fisher, 1995).

2.8.6. How to foster and support autonomy

It has been shown that those who have confidence in their own ability (Pink, 2010) and who feel visible and accountable for their actions (Shulman, 2005) will be intrinsically motivated. Educators should therefore aim to create an environment where individuals are encouraged to assume personal responsibility and accountability for their actions (Blanchard & Johnson, 1986).

Tutors can improve individual accountability by taking a "What-do-you-think" approach to students (Fisher, 1995). Instead of asking students "What is the answer?" an educator who seeks to increase autonomy may ask: "What do *you think* the answer is?" This puts the emphasis on the students' own reasoning (Postman & Weingartner, 1971, p. 183).

It should be noted that students may lack the self-confidence, or simply the desire, to make decisions and take personal responsibility; and may become hostile if they resent the fact that the responsibility for intellectual activity and decision-making has shifted to them (*Ibid.*)

2.8.7. How to create opportunities for choice

Self-directional learning, along with students' enthusiasm, varies with the degree of freedom and choice they have (Grow, 1991; Kilpatrick, 1918; 1921). "*The main thing about meaningful choice is that it engenders willingness. It encourages people to fully endorse what they are doing; it pulls them into the activity and allows them to feel a greater sense of volition; it decreases their alienation. When you provide choice, it leaves them feeling as if you are responsive to them as individuals. And providing choice may very well lead to* *better, more workable, solutions than the ones you would have imposed*" (Deci, 1995, p. 34). "*Providing choice, in the broad sense of that term, is a central feature in supporting a person's autonomy. It is thus important that people in positions of authority begin to consider how to provide more choice. Even in crowded classrooms, fast-paced offices, or harried doctors' offices there are ways, and the more creative one is, the more possibilities one will find*" (Deci, 1995, p. 34).

2.8.8. Benefits of autonomy

There are several notable benefits to autonomous learning. Like many educators, Felder (2004) realised that: "*nobody ever learned anything nontrivial by having someone else tell it to them*" (p. 40). Much of the education literature advocates a shift towards a more student-centred (autonomous) environment (Mills & Treagust, 2003). Some of the reasons are given below:

A study of over 6500 students conducted by Hake (1998) found that students who were actively engaged and self-directed gained far greater conceptual understanding than students who were passive; a conclusion supported by Glaser (1983), Redish *et al.* (1997), Felder *et al.* (1998), Black & Wiliam (1998a) and Laws *et al.* (1999). Grolnick & Ryan (1987) attributed this increase in conceptual understanding to enhanced autonomy and internal locus of control.

The perceived benefits of active learning are not always aligned with reality (Hmelo-Silver, 2004, p. 252). "*In an action research study with gifted high school students, students tended to retain information presented in PBL units better than information from traditional units, despite the fact that the students thought they learned more in lecture-based units (Dods, 1997)*".

Active learning styles have been shown to have both positive and negative effects on students' performance on traditional examinations; the outcome depends on whether the assessment is aligned with the teaching practices. An experiment by Catalano (1995) found that students taught using a student-centred approach achieved higher exam grades than students taught using a traditional, teacher-centred approach (Exam 1: 60/67%; Exam 2: 79/86%).

Autonomy has been shown to improve reasoning skills (Patel, Groen, & Norman, 1991; 1993; Hmelo-Silver, 2004); and subsequently increase students' ability to define and solve ill-structured problems (Gallagher, Stepien, & Rosenthal, 1992; Hmelo, Gotterer, & Bransford, 1997; Hmelo, 1998). Students in an autonomous learning environment come to realise that "*problem solving is the mental process that we use to arrive at a "best" answer to an unknown or some decision, subject to a set of constraints. The problem situation is not one that has been encountered before; we cannot recall from memory a procedure or a solution from past experience. We have to struggle to obtain a "best" answer*" (Woods, 1987, p. 55).

Creativity is the use of imagination to produce meaningful new ideas; and autonomy has been shown to support this process. It is essential to adaptive change; without creativity, mankind would not progress (Csikszentmihalyi, 1997). Any activity that involves imagination and originality, in either the arts or science, can be regarded as creative (Fisher, 1995). Creative ability depends, at least to some extent, on an individual's curiosity (Csikszentmihalyi, 1997) and on their propensity to take risks and view problems in different ways (Hanna, 2008).

Several studies have demonstrated that autonomous learning environments in school and university have a positive influence on students' creative ability (Amabile, 1982b; Fisher, 1995). One component is the nature of the *learning* experience. For example Spendlove (2008) concludes, rather unsurprisingly, that children who partake in creative activities become more creative. Another component is the controlling vs. informational nature of the *teaching* practices, which has been shown to have a profound influence on the level of creativity in an individual's performance (Koestner, *et al.*, 1984, p. 237).

Teachers in autonomy-supporting environments accept that the solutions developed by students could be better than the solutions given in the textbook (Postman & Weingartner, 1971, p. 192). McMasters (2004) for example describes how students answered the creative 'thinking outside the box' problem.

He initially explains that the 'right' answer is five lines, but that with creative thinking it is possible to connect the dots with four lines, three lines, two lines or even – as one 8-year old pupil demonstrated – one line. "*Creativity is not just a question of creating new solutions to problems, but of creating better solutions and this requires critical judgement*" (Fisher, 1995).

"The first key to wisdom is constant questioning…by doubting we are led to enquiry, and by enquiry we discern the truth".

Peter Abelard (1079-1142)

Critical thinking has been described as a main goal of education (Bloom, *et al.*, 1956; King, 1994; Gibson, 1996; Shulman, 2005; Cosgrove, 2009) and a desirable attribute by employers (Flint, 2003).

Critical thinking, like creativity, is a fundamental component of human evolution. "*Our intellectual history is a chronicle of the anguish and suffering of men who tried to help their contemporaries see that some part of their fondest beliefs were misconceptions, faulty assumptions, superstitions and even outright lies. The mileposts along the road of our intellectual development signal those points at which some person developed a new perspective, a new meaning, or a new metaphor. We have in mind a new education that would set out to cultivate just such people*" (Postman & Weingartner, 1971).

Critical thinking is the readiness to challenge the ideas of others (Fisher, 1995) and the act of making informed, reasoned judgments when dealing with uncertainty (Shulman, 2005). Fisher (1995) proposes that students should learn how to question, when to question and what questions to ask; and learn how to reason, when to use reasoning and what reasoning methods to use (p. 66). During their time in higher education students learn how to get information and how to deal effectively with too much of it (McMasters, 2004).

Critical thinking skills are improved through inductive learning (Felder, *et al.*, 2000) – also called the "process of inquiry" – that is to derive or construct a rule or theory for related knowledge using questioning (Glaser, 1983). Fostering critical thinking skills in a classroom environment is by no means a new concept. "*The heart of education lies exactly where traditional advocates of a liberal education always said it was – in the processes of enquiry, learning and thinking rather than in the accumulation of disjointed skills and senescent information*" (Facione, 1990, p. 4). The aim is to create "*an environment where knowledge and skill become objects of interrogation, inquiry, and extrapolation"* (Glaser, 1983).

"*This means that if we wish our children to be critical thinkers then we should try to encourage their challenges to our ideas and ways of thinking*" (Fisher, 1995). Sam Collins, during a lecture to students at the University of Edinburgh, described his version of the "think outside the box" concept (Collins, 2009a). In contrast to the creative problem described above, this was a methodology that encouraged students to be critical - to challenge and assess the validity of available information. See diagram below:

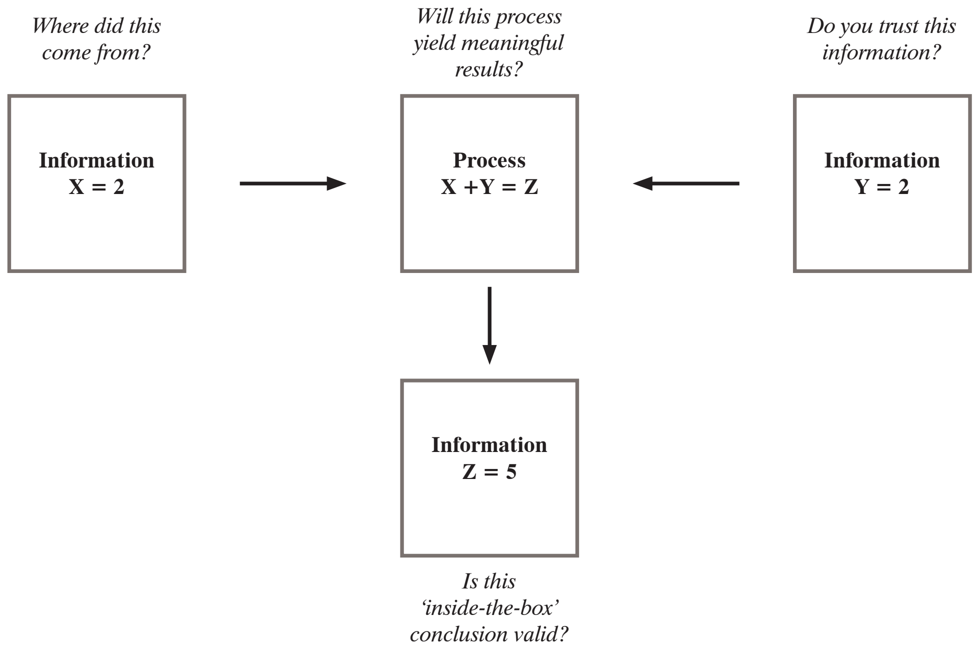

FIGURE 3: "THINKING OUTSIDE THE BOX"

The diagram above represents the process of critical thinking. It describes how every piece of information (e.g. Z = 5) comes in a box; and it is possible to simply accept that statement as fact, or to ask where it came from. In its most basic form, information (e.g. X = 2 and Y = 2) is combined in a process (X + Y = Z) to create yet more information (Z = 5). Two questions regarding the validity of the process, and the input information will allow an individual to see if the information inside the box is trustworthy. In this example, it is not.

Hunt & Minstrell (1994) describe how a teacher should initiate a discussion after presenting their conclusion. "*This part of the discussion is intended to illustrate the point that scientific experiments are seldom conducted to find out "what happens" in the sense of obtaining a definite fact. Rather, they are conducted in order to develop evidence in support of, or to refute, a conclusion*" (p. 59). The intention is to encourage students to formulate their own opinions of the validity of the derived information.

A student's approach to learning depends on the perceived goals of the task (Rust & Gibbs, 1997). Students who pursue goals that are aligned with their own ambitions are less likely to engage in unethical behaviour (Deci, 1995). Conversely, individuals who perceive extrinsically defined goals to be misaligned with their own goals will adopt surface learning strategies to achieve those goals and may engage in unethical behaviour (Ordóñez, *et al.*, 2009). The incentive is particularly strong when people fall just short of reaching their goals (Schweitzer, Ordóñez, & Douma, 2004).

2.8.9. Failings of too much autonomy

Autonomous environments are not suited for all students (Kvan & Yunyan, 2005); some do not have the required skills for autonomous learning (Grow, 1991, p. 139); others simply do not feel confident enough to think critically and learn autonomously and, particularly with unskilled tutors, may feel left behind (Glaser, 1983). There is evidence to suggest that these students need a large amount of reassurance from tutors and peers that they are 'doing the right thing' (Rust & Gibbs, 1997, p. 58).

Students need a minimum level of structure in order to profit from problem-based instruction (Neville, 1999). Koestner (1984) and Ginott (1959) explain that structure – lectures, information, assignments, rules etc. – can *increase* intrinsic motivation and work rate, provided it is offered in an informative, non-controlling way.

2.9. Structure

2.9.1. Definition of structure

Structure is the assembly of limits intended to support autonomous learning. Limits help learners develop a sense of what is possible in our world, and our society (Koestner, *et al.*, 1984). A designer for example is unable to simply *design something*, they first need to set limits within which to design and innovate.

Students appreciate a high degree of organisation, preparation and planning on courses, which in turn increases the likelihood that they will adopt a deep approach to learning (Rust & Gibbs, 1997, p. 17). Even students who are fully autonomous and intrinsically motivated may struggle to learn the skills and find the knowledge they need to progress, and would benefit from being shown established ideas, knowledge, tools and methods. "*It saves the student the agony, frustration, and time that would be squandered if he were forced to work through the subject areas on his own*" (Barrows & Tamblyn, 1980).

Structure can very easily be used as (or at least perceived as) a means to control students, which leads to decreased intrinsic motivation and a shift towards surface learning approaches. Expectation, and an authority's need for control may be subliminal - a lecturer may tout their support of autonomous thinking and learning while subconsciously attempting to ensure that students achieve a 'required level of knowledge'. As Postman points out: "*No teacher ever said: 'Don't value uncertainty and tentativeness. Don't question questions. Above all, don't think.' The message is communicated quietly, insidiously, relentlessly and effectively through the structure of the classroom*" (Postman & Weingartner, 1971, p. 33).

Although the methods used may at first appear identical (e.g. lectures, examinations, curricula, deadlines), structure is fundamentally different to control in that it aims to set limits in an *informative* rather than a controlling way – that is, without implicit or subliminal coercion (Deci, Nezlek, & Sheinman, 1981). Koestner *et al. (*1984) demonstrated that, if offered in an informative way, limits do not have a negative effect on intrinsic motivation; and should support the learner's control over their own learning. Ginott (1959) explains the difference between informational limit setting "Walls are not for painting," and controlling limit setting "You must not paint on the walls" (p. 163). He goes on to explain that universally imposed limits can be very damaging, and that limit-setting should be carried out individually, after gaining insights into the needs of each individual.

Any externally imposed limits e.g. deadlines (Amabile, Dejong, & Lepper, 1976) have the potential to decrease intrinsic motivation and encourage surface approaches to learning (Biggs, 1987, p. 103). As Biggs (1990-91) notes: "*Factors especially powerful in achieving this are out of teachers' hands: examination regulations, prerequisites, time exigencies, and most importantly in professional faculties, the imposition of too high a workload, which they and others see as demanded by accreditation requirements of outside bodies*" (p. 146). It is possible to remove the controlling influence of these factors by discussing them with students, allaying their concerns and putting them in control as much as possible (Ginott, 1959).

2.9.2. Curriculum

Definition: *A curriculum refers to a set of courses and their content.*

Traditional curricula are heavily focussed on accumulating disconnected 'building blocks' of subject-specific knowledge and technical skills (Perkins, 1986; Laurillard, 2002; Mills & Treagust, 2003; Litzinger, *et al.*, 2011; Crawley, *et al.*, 2007). In many engineering schools for example, students have to learn mathematics and science before being "allowed" to frame or solve engineering problems, let alone proceed to build anything (Bordogna, Fromm, & Ernst, 1993; Jonassen, 2000; Mills & Treagust, 2003). Fire safety engineering curricula tend to adopt this philosophy (National Fire Academy, 2008; SFPE, 2010; Lund University, 2008; University of Edinburgh, 2009; University of Maryland, n.d.). The intention is to provide individuals with the knowledge they will need throughout their future careers. However, many educators and industry professionals have come to realise that this philosophy simply does not work (Postman & Weingartner, 1971; Woods, et al., 2000). As Sheppard *et al.* (2008) state: "*Undergraduate engineering education is holding onto an approach to problem solving and knowledge acquisition that is consistent with practices that the profession has left behind. Specifically, undergraduate engineering education in the United States emphasizes primarily the acquisition of technical knowledge, distantly followed by preparation for professional practice*" (p. 6).

The reason for pursuing this philosophy is the pervasive view that knowledge is decontextualized (Savin-Baden & Major, 2004; Boud & Falchikov, 2006; Perkins, 1986); leading to teaching methods that ignore the way situations structure cognition (Seely-Brown, Collins, & Duguid, 1989; Lewis-Peacock & Postle, 2008). Knowledge for example is often presented in a way that is disconnected from the contexts that make it meaningful (Perkins, 1986; Bordogna, Fromm, & Ernst, 1993). The absence of contextual understanding associated with acquired knowledge has been blamed for students' and graduates' difficulties in applying that knowledge to real situations (Glaser, 1983; Spiro, *et al.*, 1988; Perkins & Salomon, 1989; Brown, Collins, & Duguid, 1989).

Assuming that knowledge is de-contextualised implies that context has no effect on the validity of knowledge; it gives the impression that current knowledge is absolute and is unchanging in time or space. However knowledge is not fixed, it does change over time (the world is no longer flat) and it does vary depending on the situations in which it is applied. Thus students who learn existing knowledge as isolated, de-contextualised “facts” will be dangerously ill-prepared to cope with change throughout their careers (Rugarcia, *et al.*, 2000).

Many argue that curricula should move from teaching what is known to teaching how to come to know (Laurillard, 2002). “*We may reject knowledge of the past as the* end *of education and thereby only emphasise its importance as a* means” (Dewey, 1938, p. 23). Robert Zemsky, in an interview on the future of American higher education, stated that: “*We’ve got to move away from talking about a fixed knowledge base that is anything but fixed and talk about ways of accessing that knowledge base over a period of a lifetime*” (Rosenberg, 2009). “*The emphasis on capacities rather than on areas of knowledge in defining a liberal education reflects consciousness of a world in which new knowledge is increasing exponentially, in which disciplinary boundaries are shifting and dissolving, and in which students can expect to have not just multiple jobs but multiple careers...students can no longer expect that mastery of a single set of tools will prepare them well for the world that they will enter. Very few will spend their lives at a single station in the world’s factory*” (Christ, 2010).

In engineering in particular, there is increasing evidence that the traditional knowledge-based system is unlikely to meet the demands of modern engineering industry (Mills & Treagust, 2003; Crawley, *et al.*, 2007). In addition to the researchers above, the US ABET (2008) and UK Engineering Council Education believe education should focus more on enduring qualities – the skills, attitudes, and ways of thinking (Laurillard, 2002). Examples of desirable skills and attributes include: “*critical analysis, professional judgement, self-direction, problem solving, ethical self-regulation, research and a variety of interpersonal skills*” (Chappell & Hager, 1995). As Woods *et al.* (2000) put it, “*the degree to which students develop these skills determines how they solve problems, write reports, function in teams, self-assess and do performance reviews of others, go about learning new knowledge, and manage stress when they have to cope with change*” (p. 108).

It is often assumed that skills and attributes will be improved automatically during the acquisition of fundamental knowledge (Woods, *et al.*, 2000, p. 12) however this is not always the case; and the extent to which students develop their skills and professional attitudes will depend on the *way* in which fundamental knowledge is learned. "*Instructors who wish to help students develop problem-solving, communication, teamwork, self-assessment, and other process skills should explicitly identify their target skills and adopt proven instructional strategies that promote those skills*" (Woods, *et al.*, 2000, p. 12). The curriculum should be designed such that the learning environment is authentic and students are able to pro-actively learn knowledge as and when the need arises (Brown, Collins, & Duguid, 1989; Felder & Silverman, 1988).

2.9.3. CDIO Curriculum (Conceive, Design, Implement & Operate)

In the engineering world, the 1980's brought an expansion in commercial enterprises, and employers rapidly became dissatisfied with the traditional education system (Todd, Sorenson, & Magleby, 1993; McMasters, 2004). "*New graduates were technically well prepared but lacked the professional skills for success in a competitive, innovative, global marketplace*" (Lattuca, *et al.*, 2006). Nolan (2009) describes similar concerns raised by structural engineering employers.

It was agreed that university engineering programmes must educate students in a "*technical discipline as well as in a broad set of personal, interpersonal and system building skills*" (Bankel, 2005). "*In recent years, four leading engineering universities have partnered to create a new engineering education model, named CDIO. Those schools are Chalmers University of Technology, Linkoping University, and the Royal Institute of Technology, in Sweden, and the Massachusetts Institute of Technology in the USA*" (Bankel, 2005). The CDIO initiative set out to formalise this by defining exactly *what* students should learn at university (Brodeur, 2002; Berggren, 2003; Crawley, 2009).

"*Boeing, two MIT docs and ABET EC2000 criteria – as well as others spanning fifty years yields a remarkably consistent image of the desired attributes of young engineers. The required knowledge, skills, and attitudes that companies desire in their engineers consistently include an understanding of engineering fundamentals, design, and manufacturing; the context of engineering practice; and the ability to think critically and creatively, to communicate, and to work in teams*" (Crawley, *et al.*, 2007, p. 48; Boeing, 1995).

Crawley *et al.* (2007) state that new graduates should have "*an insatiable curiosity for understanding how things work, over the broadest spectrum of engineering and nature, underpinned by any necessary understanding of hard science or engineering practice*" (p. 37).

From the various definitions available in literature it was possible for the CDIO authors to define the role of an engineer in our society:

"Graduating engineers should be able to Conceive, Design, Implement and Operate value-added engineering systems in a modern team-based environment" (Crawley, 2001).

An individual's ability to perform in this role will depend on their level of knowledge and skills, as well as their professional attitudes (Crawley, 2001). The CDIO initiative aimed not to devalue the technical fundamentals, but to put those fundamentals in the *context* of engineering practice (Crawley, *et al.*, 2008). Put another way, students on a CDIO programme learn engineering by *doing* engineering - in line with Dewey's (1938) philosophy for effective learning. In a way it reverses the focus. "*In what might be called traditional programs, discipline and topic-based knowledge and understanding dominate. The integrating glue is assumed to be acquired (how is not quite clear), and the capability to make new things happen independently on what has gone before is exercised only through a small input of individual project work*" (Crawley, *et al.*, 2007).

Traditional course curricula are based on domain knowledge (e.g. Magnusson, Drysdale, & Fitzgerald, 1995). Others argue for a curricula focused on improving general skills. Glaser (1983) suggested combining the two: "*rather than switching between general and specific [knowledge], I would also examine…teaching specific knowledge domains in interactive, interrogative ways so that general self-regulatory skills are exercised in the course of acquiring domain-related knowledge*".

The knowledge, skills and attributes of an engineer have been subdivided into four main categories – Technical knowledge, Personal skills, Interpersonal skills and Engineering skills. These categories can be further sub-divided into at least four levels of detail to create learning objectives that are explicit enough to be taught as part of an education system.

The stakeholders must then decide the desired level of proficiency of each of the learning objectives. How important are creativity, critical thinking or knowledge of fluid dynamics? The most significant result found by Crawley, *et al.* (2007) was the similarity of opinion among each university's respective stakeholder groups. "*This degree of consensus in the stakeholder surveys was unexpected, and helped to validate expected levels of proficiency in knowledge and skills for students graduating from CDIO programs*" (*Ibid.* p. 69). Once the learning objectives - and their desired level of proficiency - have been defined, they can be used to develop individual courses within the programme. The entire process is described as:

- Determine a means of engaging the stakeholders and summarising their opinions
- Reach a consensus of the expected levels of proficiency
- These expected levels of proficiency can then be translated into more formally stated learning outcomes that are the basis for instructional design and student learning assessment (*Ibid.* p. 64)

Crawley, *et al.* (2007) explain that the next curriculum design issue to consider is the sequence of content; to allow educators to introduce specific skills and knowledge in a logical order on a programme. If the sequence is properly developed, learning will follow a pattern in which one experience builds upon and reinforces the previous ones (p. 93).

Once the curriculum structure and learning sequence have been developed, learning outcomes are allocated to individual courses. Each course should include an explicit plan to integrate personal and interpersonal skills, and product, process, and system building skills (*Ibid.*, p. 95) as part of the overall programme.

Faculty are encouraged to align their written examination and tutorial questions to course learning outcomes, and to assess students' achievements to the basis of these learning outcomes (*Ibid.*, p. 158).

It becomes clear to any educator who has written learning objectives that different tasks call for dramatically different knowledge and skill levels, with some tasks requiring only rote memorization to complete and others calling for sophisticated analytical skills and creativity (Felder & Brent, 2004). The CDIO initiative developed a system of classifying learning objectives according to their required skill levels (as per stakeholder surveys). This was intended to help instructors make sure they were teaching and testing at an appropriate level for their students.

The levels were aligned with the *Taxonomy of Educational Objectives* (Bloom *et al.,* 1956). The six discrete 'levels of thinking' are described as:

1. Knowledge—repeating memorized information

2. Comprehension—paraphrasing text, explaining concepts in jargon-free terms

3. Application—applying course material to solve straightforward problems

4. Analysis—solving complex problems, developing troubleshooting equipment and system problems

5. *Synthesis*—designing experiments, devices, processes, and products

6. *Evaluation*—choosing from among alternatives and justifying the choice, optimizing processes, making judgments about the environmental impact of engineering decisions, resolving ethical dilemmas

Using Bloom's Taxonomy, along with the CDIO stakeholder surveys, allows educators to be explicit and honest about the level of thinking desired for each learning objective, and subsequently, each assessment task.

Instructors should ask themselves *how* they will know if a student has learned a particular topic. This process of reflection encourages educators to use more explicit verbs to describe the ways in which students can demonstrate their understanding. Vague verbs such as *understand* should be replaced with *recall, describe, explain, analyse* & *evaluate* (Felder, *et al.*, 2000). These words more accurately describe the level of cognitive processing (thinking) that is expected of students when producing their solutions (Felder, 2000).

Summary of CDIO

The CDIO initiative has been shown to effectively improve desirable skills (both technical and non-technical) in graduating engineers (Crawley, *et al.* 2007). As Norman and Schmidt (2000) note however, improvement in graduates' skills comes from more than just curriculum-level intervention. It comes from good teaching.

The following section defines and describes a range of effective teaching methods.

2.9.4. Design studio

A design studio course begins with a complex, open-ended assignment (Jonassen, 2000) and students are encouraged to think about the big picture (Kuhn, 2001). They are responsible for independently developing their own process or method of design; for generating, evaluating, and developing ideas; and ultimately for making decisions and taking action (Gross & Do, 1997). "*Students' design solutions undergo multiple and rapid iterations*" (Kuhn, 2001); akin to 'rapid prototyping' (Raskin, 2011); and is very effective at developing optimised designs through a systematic process of trial-and-improvement (Ibell, 2010).

Students' designs change dramatically over the course of the semester as they acquire new information. In particular, students are encouraged to 'pin-up' their work and invite constructive criticism. "*Critique is frequent, and occurs in both formal and informal ways, from faculty, peers, and visiting experts*" (Kuhn, 2001). Regular presentation of work may at first be difficult for students but they adapt quickly (Savoie & Hughes, 1994; Kuhn, 2001). "*In the highly social environment of the design studio students learn to communicate, to critique and to respond to criticism, and to collaborate*" (Gross & Do, 1997).

Facilitators help students move from the big picture to the details by providing domain-specific knowledge throughout the design studio (Gross & Do, 1997; Kuhn, 2001); and students are encouraged to converge their designs towards a satisfactory solution by imposing appropriate constraints (Kuhn, 2001).

"*Architecture is one of the few subjects where design is the primary focus of university education; therefore architectural education offers valuable lessons for teaching design in other domains*" (Gross & Do, 1997). There have been calls for example for engineering subjects to be taught in the context of design (Joint Board of Moderators, 2009; Ibell, 2010; Woodrow, Bisby, &

Torero, 2013); as often engineering curricula do not include sufficient design experience (Mills & Treagust, 2003).

2.9.5. Lecturing

Lectures were established centuries ago as a means to formally transmit information from an expert to an audience and supplement student learning (Vella, 1992; Swanson & Torraco, 1995; Sullivan & McIntosh, 1996). Lectures have been shown to be very efficient and now predominate as the main method of teaching in university classrooms (Bonwell & Eison, 1991; Saroyan & Snell, 1997; Laurillard, 2002), and increasing student numbers means this is unlikely to change (Exley & Dennick, 2009, p. 11). Furthermore, lack of training in alternative education methods will encourage new faculty to stick to what they know, and perpetuate the use of lectures (Sullivan & McIntosh, 1996).

Ineffective lecturing

Studies show that only about half of the information presented in lectures is retained in the short term and is further halved after just one week (Jones, 1923; McLeish, 1966). Evidence suggests that only 10 percent of the words delivered in a lecture are recorded in the notes of the students (Johnstone & Su, 1994) and that, while writing, students cannot mentally process what the lecturer is saying. They can either listen or write; they cannot do both (Norman & Lindsay, 1977).

It is known that people's attention span in lectures dips after about fifteen to twenty minutes (Johnstone & Percival, 1976). Reasons include: "*The lecturer's monotonous, unmodulated voice; the regular display of slides or overheads that all look the same; the unstimulating presentation of information; the absence of any other presentation modality*" (Exley & Dennick, 2009), yet many lecturers speak for much longer.

New technologies (e.g. clickers, PowerPoint, video-conferencing) are unlikely to lead to any significant change without an accompanying change in the teaching philosophy. "*The academic world has called each new technological device – word processing, interactive video, hypertext, multimedia, the Web – into the service of the transmission model of learning*" (Laurillard, 2002, p. 141).

Many lectures contain too much information (Flint, 2003). "*One of the reasons that lecturers present too much information is the erroneous belief that if they 'cover' an area of knowledge in a lecture the students will automatically learn it. This is simply not true. Learning comes from engaging with the material in a stimulating way, not trying to memorise reams of facts passively*" (Exley & Dennick, 2009). The following cartoon illustrates the problem with assuming that 'covering' material equates to learning.

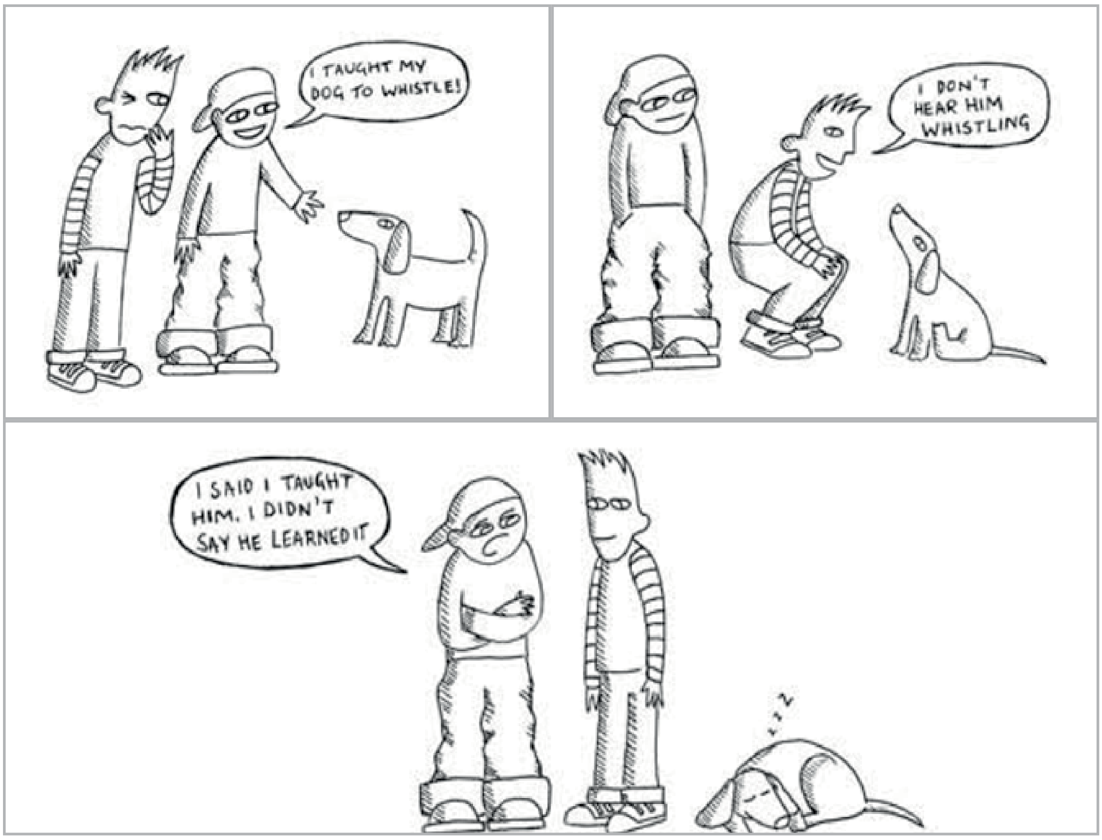

FIGURE 4: TEACHING ≠ LEARNING (LUMINEA, 2013)

Covering information in class does not equate to student learning; even so, lecturers often choose to cover large amounts of factual information at the expense of meaning making and contextual understanding (Johri, 2009; Exley & Dennick, 2009). The result is that students do not understand why the presented information is useful, only that they must learn it. This leads to frustration on the part of the students - who adopt surface learning strategies (Marton & Säljö, 1976) and become dependent on the lecturer for information (Sullivan & McIntosh, 1996).

Some lecturers realise that their talks are ineffective, and that the explanations that were so clear in their mind were not 'transmitted' to the audience. "*It is frustrating to work out a problem elegantly, explaining all the steps clearly, and then find out hardly any of the students understand it*" (Garfield, 1995).

Contextual understanding is a cognitive construct, unique to each individual. Even well presented, informative lectures cannot provide context for information (Barneveld & Strobel, 2011). It is not possible to forcibly change an individual's perception or make them understand (Postman & Weingartner, 1971, pp. 129-133). Hestenes *et al.* (1992) found that students' existing beliefs play a dominant role in the way they learn, and that instruction that does not take students' existing conceptual understanding into account will likely be completely ineffective.

Felder & Silverman describe the misalignment between predominant teaching and learning styles. They explain how the majority of engineering lecturers teach 'deductively'– giving the information, rules and methods *before* context and application. However, this is not conducive to the natural human learning process of 'induction' – deriving facts, information and rules from stories and experiences (Felder & Silverman, 1988).

Students rarely respond to questions asked during lectures, which are often closed or "guess-what-I'm-thinking"-type questions (Postman & Weingartner, 1971). These questions have one 'correct' answer and fear of giving the 'wrong' answer prevents students from responding. Another common problem is that, following a question, teachers do not wait long enough to let students think (Black & Wiliam, 1998b). "*Many teachers wait only one or two seconds after having asked a question before they call on another student, or give the answer to the question themselves*" (Fisher, 1995).

Furthermore, "*the tradition has been to summarise the lecture and then ask: 'are there any questions?' However, experience shows that once students see that the lecture is being summarised they mentally disengage and will start to pack away their pens and notepads. The majority of students now want to leave the lecture theatre and the last thing on their mind is to ask questions*" (Exley & Dennick, 2009, p. 60).

On the whole, new lecturers are given little or no assistance in designing or teaching their course(s), and subsequently revert to teaching the same way they were taught (Stice, *et al.*, 2000; Felder & Brent, 2004). "*The lack of faculty training in presenting effective lectures, rather than the method itself, may be the greatest weakness of the lecture*" (Sullivan & McIntosh, 1996).

Effective lecturing

The definition of an 'effective' lecture is somewhat subjective, and is largely dependent on what the lecturer is trying to achieve. If the aim is to transmit facts and information to a large audience then the standard lecture format described above is effective (Exley & Dennick, 2009). The section above provides some evidence to suggest that in terms of student learning the traditional lecture is not so effective.

This does not need to be the case, and lecturing does not have to be limited in learning potential. Exley & Dennick (2009) believe that lectures should not merely be used to convey large quantities of information that can be read in textbooks or given in handouts. They suggest that lectures can instead be used to achieve the following:

1. Communicating enthusiasm for the topic

This is the best reason for delivering lectures as it is one of the few features that cannot be gained by independent learning. "*The traditional lecture greatly benefits from being delivered by a knowledgeable, prepared and, above all, enthusiastic teacher*" (Exley & Dennick, 2009, p. 9). An effective lecture arouses interest in a topic (Sullivan & McIntosh, 1996).

2. Providing a structure or a framework for the material

Emphasise different points of view, raise issues that will shape the students' thinking about the topic, relate the topic to others in the course, explore practical applications of the central ideas, and so on (Ball, 1988). Exley & Dennick (2009) recommend giving an overview, while Sullivan & McIntosh (1996) suggest presenting visual media such as photos or videos to help students construct a framework for future, more abstract concepts.

3. Tailoring material to the students' needs

Experience might tell you that the textbooks for a topic do not cover the material in sufficient depth or at the right level for your audience. In this case, lectures can serve to 'part digest' the material so that students will be better able to extend their learning using books and other sources.

4. Providing current information

Textbooks are rarely going to be up to date. The lecture provides an opportunity to present recent research to students. This may include your own current work or even ideas you have for research that it would be good to conduct. A lecture is an efficient way of communicating this information to a large audience (Bligh, 1998).

5. Using another format is not viable

This is often the case where you are faced with large student numbers. It is true that giving a lecture is more cost-effective than repeating a small group seminar a large number of times. However, there may also be pedagogic grounds for rejecting other formats (Exley & Dennick, 2009, p. 8).

How to lecture effectively?

Anyone can get up in front of people and present information but only those with experience know how to motivate their students to learn in and beyond the classroom. Fortunately the skills used in teaching can be developed through practice and feedback (Felder, 2004).

Lecturers should establish the purpose of their lecture and ensure that non-essential content is minimised to ensure the purpose remains clear. "*If teachers were asked what they would really like students to know six months or one year after completing an introductory statistics course, most would probably not respond that students should know how to compute a standard deviation by hand, know how to convert normal variables to standard normal variables and look up their probabilities on the table, or compute expected values. Many would indicate that they would like students to understand some basic statistical concepts and ideas, to become statistical thinkers, and to be able to evaluate quantitative information*" (Garfield, 1995, p. 26). Asking *why* a lecture is important will help establish a reason for delivering the lecture (Sullivan & McIntosh, 1996). This is the message that is to be communicated.

Biggs (1999) describes how students who take a deep approach to learning (Marton & Säljö, 1976) arrive to a lecture with relevant background knowledge and a question they want answered. In the lecture, they find an answer to that question; it forms the keystone for a particular arch of knowledge the student is constructing. Students who adopt deep learning strategies virtually teach themselves, and need little help from teachers

(Biggs, 1999). Students should be supported in developing their question - the purpose for learning and their *need to know* - prior to attending a lecture.

Everyone can benefit from the well-timed delivery of useful, usable information, even those who are fully self-directed (Grow, 1991, p. 134). The *way* in which this information is presented, in particular the language used, will have a significant affect on students' motivation and subsequent learning. If the language is controlling ("you must learn this") or demeaning ("you should know this") then it is likely to undermine intrinsic motivation (Deci, *et al.*, 1991). Lectures that are informative ("you may find this useful") and given in response to demand from the students for specific knowledge (Flint, 2003), are more likely to support intrinsic motivation.

"*It is mandatory to introduce the title or the topic of the lecture. At this point it is always worthwhile thinking how you can start with something that will grab the students' attention*" (Exley & Dennick, 2009, p. 47). Regardless of the subject, "*a lecture should aim to interest and stimulate the audience; to make them think*" (*Ibid.* p. 59). "*When it comes to mass communication, it's as simple as two things: arouse and fulfil. You need to first arouse your audience and get them interested in what you have to say; then you need to fulfil their expectations*" (Olson, 2009, p. 69).

"*Within a large group of students there will be a distribution of different learning styles (Felder & Brent, 2004) and different personality types which encourages the view that our students will learn more or less effectively from different learning situations. On these grounds it is therefore necessary to provide a variety of learning situations so that all students have an opportunity to use their preferred learning style at some time during the course*" (Exley & Dennick, 2009).

Felder and Silverman (1988 p. 675) categorised students' learning styles into four dichotomous groups:

- *Sensing learners* (concrete, practical, oriented toward facts and procedures) or *Intuitive learners* (conceptual, innovative, oriented toward theories and meanings).

- *Visual learners* (prefer visual representations of presented material—pictures, diagrams, flow charts, etc.) or *Auditory learners* (prefer written and spoken explanations).
- *Active learners* (tend to learn by trying things out, working with others) or *Reflective learners* (tend to learn by thinking things through, working alone).
- *Sequential learners* (linear, orderly, tend to learn in small incremental steps) *or Global learners* (holistic, systems thinkers, tend to learn in large leaps).

Most engineering lectures are heavily biased toward *intuitive*, *auditory*, *reflective*, and *sequential* learners, although the majority of engineering students are *sensing, visual, active* and *global* (Felder & Silverman, 1988). i.e. the teaching styles of most engineering courses are incompatible with the way most engineering students naturally learn.

Thus commonly used teaching styles would need to be completely inverted to align with the students' learning styles. For example, instead of vocally describing abstract 'building blocks' of subject knowledge to a passive audience, a lecturer should display videos and images that show the big picture, and then engage the audience in active discussion. "*The flow of information in the presentation of course material should generally follow that of the scientific method: begin with induction, proceeding by inference from specifics (facts, observations, data) to generalities (rules, theories, correlations, mathematical models), and then switch to deduction, using the rules and models to generate additional specifics (consequences, applications, predictions)*" (Felder, *et al.*, 2000).

As we have seen previously, the average student's attention span is probably less than twenty minutes; and students regularly become distracted, disengaged or bored during traditional lectures (Johnstone and Parcival

1976); but it is not the length of the lecture that leads to disengagement. The same students will watch entire films without losing focus. "*What keeps an audience awake during a two-hour film or play are constant variations of stimulation*" (Exley & Dennick, 2009, p. 52).

Research has demonstrated, for example, that if a lecturer pauses three times for two minutes each during a lecture, students will learn significantly more information (Ruhl, Hughes, & Schloss, 1987; Bonwell & Eison, 1991). "*It is therefore useful to think of preparing a lecture that limits the formal input from the lecturer to ten to fifteen-minute chunks interspersed with breaks or individual and group-based learning activities.*" (Exley & Dennick, 2009, p. 23).

The way in which teachers interact with their students should support interaction and autonomy. Popular lecturers are clear, tell good jokes, respect the class and provide structure (Brooks, 1984). Part of respecting the audience is to assure them that their opinion is valued. "*There is nothing a student can say that is irrelevant. If a lecturer were to observe that a certain observation is beside the point, how would that change the students' perception? It would mainly have the effect of making the learner feel inadequate*" (Postman & Weingartner, 1971, p. 98).

Hunt & Minstrell (1994) describe how educators can deal with students' preconceived ideas of physical phenomena, particularly if these ideas are not in line with the educators' own understanding. "*Some early research labelled these concepts "misconceptions" or "naïve views," and either implied or directly stated that the purpose of instruction was to stamp out these ideas. The ideas however, do work in appropriate context…The instructor's job, as we see it, is to help the students weave their bits of local knowledge into a coherent whole*" (Hunt & Minstrell, 1994. p. 52).

Lecture styles should vary depending on the number of people in the audience; however, regardless of the size of the class, the beneficial effects of interaction are qualitatively the same (Shulman, 2005). Sullivan & McIntosh

(1996, p. 7) describe several ways in which lecturers can support student interaction in the classroom:

1. *"Use students' names when asking and answering questions—this recognition is a powerful motivator;*
2. *When a student asks a question, the educator can answer the question directly, respond by asking the student a different, related question or offer the question to the other students;*
3. *Repeat students' questions and answers to ensure that all students hear the discussion;*
4. *Provide positive reinforcement when students respond. This praise will help to create a very positive climate and will encourage more students to enter into the discussion"*

If university teachers are to support learning they have to develop their model of the learning process well beyond the traditional transmission model (Laurillard, 2002). James & McCormick (2009) describe how the key challenge for academic leadership is to create a culture of innovation and risk taking. Faculty members should be encouraged through dialogue to test and develop new ideas and to embed and sustain those ideas that are found to work. In the absence of such an evolutionary culture, any changes will be superficial and disappear as soon as the next initiative comes along. Academics must effectively become "researchers in teaching" if they are to adapt and evolve their teaching practices (Laurillard, 2002; Cross, 1986; Heywood, 2005).

Many lecturers tell stories of the greatest failures in engineering history (e.g. Tacoma Narrows) however very few speak of the engineering successes (Ibell, 2010). A small number of lecturers e.g. David Billington (Princeton University) & Michael Dickson (Bath University) have developed courses specifically championing the success stories of structural engineering; and the courses have proven to be very popular amongst students (Riordan, 2006).

Ibell (2010) describes how the lecturer's aim is to inspire the students to pursue a career in engineering, not to cover a curriculum. In keeping with this philosophy, a structural analysis course was redesigned specifically to increase students' motivation and basic conceptual understanding of structural analysis. Much of the course content was removed and replaced with simple mathematics (GCSE level) and visual demonstrations, and the course became highly successful (Ibell, 2010).

Students use knowledge they already possess to understand and structure new information (Albanese & Mitchell, 1993; Lewis-Peacock & Postle, 2008). This is known as the constructivist model of learning (Fosnot & Perry, 1996; Brown, 2004) and implies that *"learning builds upon existing understanding and that new knowledge must be connected to old*" (Exley & Dennick, 2009, p. 48). Lecturers should invest time in understanding first, why the students are there, and second, what is their current level of understanding. This will alow them to better explain and discuss increasingly more sophisticated concepts and relate them to past experiences (Ausubel, 1963; Wlodkowski, 1999; Hmelo-Silver, 2000). As most engineering students are visual learners they will learn more effectively if they can relate new material to images of prior material. Those images could be lab experiments, videos or photographs shown previously in the semester.

Humans do not remember information in the same format as it was presented and; "*rather than 'receiving' material in class as it is given, students restructure the new information to fit into their own cognitive frameworks. In this manner, they actively and individually construct their own knowledge, rather than copying knowledge 'transmitted', 'delivered' or 'conveyed' to them*" (Garfield, 1995, p. 26). The importance of linking new knowledge to old - and thereby giving it context - is highlighted in the following section.

Research shows that humans possess an astonishing ability to recognise previously seen words, sentences and images. The study that attracted most attention, according to a review by Levie & Hathaway (1988), was work by Shepard (1967), which involved picture recognition tests. Until that point experiments indicated that a typical person could only accurately recall lists of about five monosyllabic words (Miller 1956) and it was assumed that the human mind was somewhat limited in its capacity to remember, given a single exposure to a set of stimuli. The Shepard study would fundamentally change that assumption.

The tests still assessed the individuals' ability to remember; but focused on the ability to recognise, rather than recite. The result was that when the subjects were shown two cards side by side – one they had seen before, the other that they hadn't – they were able to recognise which one they had seen previously with remarkable accuracy. They remembered 98% of 748 colour photographs, 90% of 600 common words, and 88% of 1360 short sentences after seeing them just once (Shepard, 1967).

The Shepard tests demonstrated the human brain's remarkable ability to retain almost everything that is seen or heard, but it does not explain why the test subjects performed so badly when asked to recall the information blindly. Glaser (1983), Lewis-Peacock & Postle (2008) and Maguire, Frith, & Morris (1999) provide evidence that our ability to remember depends on our ability to link new information to that which we already know. The cognitive framework existing in each individual's mind acts like a web of interconnected knowledge (Lewis-Peacock & Postle, 2008). Each connection provides a means to locate a specific piece of information – a thread that can be followed – meaning the greater the number of connections, the easier it will be to recall the information. It is the responsibility of educators to help students build these webs of information – connections linking information that may better be described as *context* (Biggs, 1999, p. 60) – such that information given to them throughout their career will act as cues and allow them to remember and use what they have learned (Montessori, 1967; Wlodkowski, 1999).

Information that is learned in context can be retrieved using cues existing in the workplace (Boud & Feletti, 1997, p. 4). However, it is often difficult to know in exactly what circumstances one may use information, or what cues may exist in future. Fluid mechanics is not only used in pipe design, but also in aircraft wing design, or in traffic management. It is therefore essential that educators repeatedly present the same information in different ways and give students the opportunity to work and rework the material in different contexts (Olson, 2009).

2.9.6. Tutorial questions

Tutorial tasks provide a means to learn information; but the type of tasks offered affects how information is learned, and how it can be used in future (Woods, 1987). The 'ideal' tutorial task will therefore vary significantly depending on the aims of the course. Generally speaking, there are two main reasons for setting tutorial tasks during a university course: The first is to train students and improve their capacity to solve established problems accurately and efficiently; the second is to improve their capacity to think and learn independently.

Training tasks are commonly used in engineering education and usually consist of well-defined questions with (so we believe) one correct answer (Felder, 1985). Students are 'drilled' with well-structured exercise questions to give practice in applying the fundamentals (Felder, 1988). "*There is nothing new about the use of problem solving as a method of learning in a variety of educational settings. Unlike what occurs in real-life situations, however, the problem usually is not given to the student first, as a stimulus for active learning. It usually is given to the student after he has been provided with facts* *or principles, either as an example of the importance of this knowledge or as an exercise in which the student can apply this knowledge*" (Barrows & Tamblyn, 1980).

There are advantages to this form of tutorial task. "*Oversimplification, of course, has the effect of allowing action to be taken immediately, without ones' enduring the burden of undergoing a process of extensional ('out there') verification*" (Postman & Weingartner, 1971, p. 110). Students are removed of the burden of thinking independently, allowing them to act immediately, without the need to question.

Students can use these exercises to form connections with existing knowledge in their minds. If this doesn't work, the new knowledge can still be driven into the memory through repetition, rehearsal and practice (Strauss & Shilony, 1994).

The kind of problems most often encountered in engineering programmes (except for capstone and assorted design experiences) is the story (word) problem (Jonassen, 2000; 2006), where the definitive parameters of each problem are specified in the problem statement. *If you walk forwards 4 metres, turn through a right angle and then walk another 3 metres, how far are you from the origin?* Story problems have pre-defined 'correct' solutions that are obtained by applying established solution methods. Furthermore, there are a number of rules and principles that must be applied in a regular, predictive and prescriptive manner to obtain the desired result (Rich, 1960; Jonassen, 1997). "*This linear process implies that solving problems is a procedure to be memorised, practiced, and habituated, a process that emphasizes getting answers over making meaning*" (Wilson, Fernandez, & Hadaway, 1993).

Research has shown that learning to solve well-structured 'exercise' problems does not readily transfer to ill-structured workplace problems (Schraw, Dunkle, & Bendixen, 1995; Cho & Jonassen, 2002; Hong, Jonassen, & McGee, 2003; Jonassen, 2006). Exercise questions do encourage students to demonstrate their ability to recall and apply memorised procedures. "*Smith* *and Good (1985) and Kurlik (1980) call it 'exercise solving'. Thus, students might be excellent solvers of exercises yet be poor problem solvers. However, both faculty and students rarely distinguish between these two processes, and hence the misconception arises that experience gained by solving many exercises develops skills at solving problems*" (Woods, 1987 p. 58).

"*Having students solve many problems and see many worked examples is ineffective in developing problem-solving skill. In a four-year engineering program, students observed professors working more than 1,000 sample problems on the board, solved more than 3,000 assignments for homework, worked problems on the board themselves, and observed faculty demonstrate the process of creating an acceptable internal representation about fifteen times. Yet despite all this activity, they showed negligible improvement in problem-solving skills; the efforts were ineffective (Woods, Crowe, Hoffman, & Wright, 1985). What they did acquire was a set of memorised procedures for about 3,000 problem situations that they could, with varying degrees of success, recall. If they were given a related but different problem situation, they were not able to bring any new thinking or process skills to bear. Caillot (1983) notes similar findings. Similarly, Meiring (1980) finds that having students solve many "problems" does little to promote problem-solving skill*" (Woods, 1987, pp. 58-59).

The aim of convergent tasks is to create what Dan Pink calls "*Goldilocks tasks – challenges that are neither too hot nor too cold, neither overly difficult nor overly simple*" (Pink, 2010, p. 118). People are motivated by 'mastery' i.e. they are motivated when they can see evidence of self-improvement. Conversely they become demotivated when the task is either too easy or too difficult (Deci, 1975; Deci *et al.*, 1996; Csikszentmihalyi, 1997). Biggs (1990-91) describes how "*intrinsic motivation arises when there is an optimal mismatch between level of difficulty of the task and the individual's current competence*" (p. 142).

Closed questions require the authority to define the level of difficulty of the questions. However, as Crooks (1988) states, it is not possible to prescribe evaluation standards that are both high and attainable for all students. Educators in this situation opt for the middle ground. "*Overall, the content, level of demand, and pace of work were most often directed toward children of average ability in the class*" (Bennett, 1988). If variations in competence levels do exist in a given classroom (as they most often do), any convergent question that demands a fixed level of competence will create a non-optimised mismatch (Crooks, 1988).

Closed questions leave out too much to be able to represent our ever-changing reality (Postman & Weingartner, 1971, p. 118). There is not much theory testing or explanation generating, but mainly the application of theory to made-up situations to derive or to prove results (Perkins, 1986, p. 97). "*Most school problems of this sort lack a strong connection to purpose in their disciplines. Although you can calculate the height from which you would have to drop an ice cube to vaporise it or the leverage required to budge the empire state building, who cares? Such problems do not address anything in the real world or the world of theory that is likely to be very important*." (Felder, Woods, Stice, & Rugarcia, 2000).

Closed questions that are formulated around a pre-defined response, answer or solution are substantially different from the kinds of problems that engineering students will solve in their future careers (Jonassen, 2006). "*In the real world…there are many ways to do things and it is not a matter of getting a right answer it's a matter of working for the best solution for your particular situation.*" (Ibid.)

It is not sufficient to include a holistic design project in the final year, after several years of convergent exercise questions, and expect students to develop a global understanding of the subject (Ibell, 2010).

Thought questions – also called divergent, ill-structured and open-ended questions – do not have pre-defined answers; they are a type of game, where the players (students) confront problems that require the discovery of viable solutions (Postman & Weingartner, 1971, p. 172). "*The goal is for students to learn how to use the library, the Internet, their colleagues, and their intellect and common sense to solve real problems*" (Felder, 2004); and in their own time students come to appreciate the complexity and multiplicity of factors that must be considered when making decisions (Postman & Weingartner, 1971, p. 181).

Students, through practice, will become proficient in the tasks they partake in at university. The tasks therefore should reflect those that would be encountered in professional practice (Boud, 2000), and should assume a predominant role in the teaching process (Redfield & Rousseau, 1981).

There have been calls to adopt open-ended problems across the curriculum (Evans, et al., 1993); as they have been shown to increase contextual understanding (Schraw, Dunkle, & Bendixen, 1995; Garfield, 1995), creative thinking (Burke, 2007), critical thinking (Savin-Baden, 2003), interdisciplinary thinking (McKenna, et al., 2011), problem-solving skills and ability to construct coherent arguments (Cerbin, 1988; Cho & Jonassen, 2002). Furthermore, students working on open-ended questions have demonstrated an increased propensity to challenge assumptions (Rosenberg, 2009) and increased engagement in discussions with educators (Felder, 2004).

Note that open-ended questions can be answered by students at every level, irrespective of background knowledge. "*Their answers, as well as their way of answering, will vary depending on their experience*" (Postman & Weingartner, 1971, p. 84). The underlying assumption is that students are capable of thinking and learning without being specifically taught (Felder, 2004). In fact, some will use innovative, unique problem-solving methods when tackling open-ended problems; and "*many of these ways will be beyond the ability of the teacher to imagine, so that the teacher learns from the students*" (Sadler, 1998, p. 81).

The traditional method was to teach the theory first, then create opportunities to apply it later (Barrows & Tamblyn, 1980). Tutorial questions for example, are traditionally handed out after the accompanying lecture. However, it has been shown that this method does not work (Barrows & Tamblyn, 1980); that students benefit from working on tutorial questions beforehand (Hmelo-Silver, 2004); and that the information contained in lectures, class notes and textbooks would be more useful to students if it were presented at a time when it is immediately useful (Postman & Weingartner, 1971, p. 145). Hmelo-Silver (2004) describes a study by Schwartz and Bransford (1998) that lends weight to this argument: "*They found that students who solved problems prior to the lecture performed better on a problem-solving task than students who read the chapter or those who just solved problems. This finding suggests that attempting to solve a problem helps create a readiness to learn from a lecture*" (p. 251). These results suggest that tutorial questions should be handed out before lectures.

2.9.7. Tutorial classes

Tutorials create opportunities for students to engage with course material and, if used carefully, offer good opportunities for formative discussion (Macdonald & Savin-Baden, 2004). As Bonwell & Eison (1991) explain; "*If the objectives of a course are to promote long-term retention of information, to motivate students toward further learning, to allow students to apply information in new settings, or to develop students' thinking skills, then discussion is preferable to lecture (McKeachie, et al., 1986; Bligh, 1998)*". They go on to state that a tutorial should "*create a supportive intellectual and emotional environment that encourages students to take risks (Lowman, 1984)*".

Fisher (1995) describes how the success of seminar/classroom discussions depends on the tutor's skill in facilitating dialogue (p. 132) and goes on to explain in detail how to effectively manage a classroom discussion.

For example: "*One way to encourage the child's efforts in constructing understanding is to question their thinking*" (Fisher, 1995, p. 191). Asking divergent questions helps encourage students to think broadly and pursue alternative possibilities. Crucially, the questions must be seen to support the students' own thought processes, rather than those of the tutor.

Discussions are not only a time for tutors to ask questions of students, but for students to ask questions of the tutor, of themselves and of each other. As Postman & Weingartner (1971) say: "*The art and science of asking questions is the source of all knowledge*" (p. 84). Learning to ask pertinent questions improves students thinking and reasoning skills.

Several exemplary tutorial systems already fulfil many of the above objectives, including the Oxford and Cambridge liberal-arts-based tutorial systems. These tutorials are renowned for encouraging critical and creative thought (Palfreyman, 2008; Cosgrove, 2009).

The aim of a tutorial class in generalist education is not to promote the memorisation of correct procedures and answers, but instead to encourage students to develop their own way of thinking and reasoning (Hunt & Minstrell, 1994; Cho & Jonassen, 2002) through active engagement in higher-order thinking tasks such as analysis, synthesis, and evaluation (Bonwell & Eison, 1991).

The majority of college students are naturally active learners who require learning experiences that engage their senses (Sullivan & McIntosh, 1996; Hake, 1998). It has been shown that active learning environments are more effective than passive ones at promoting intrinsic motivation and improving conceptual understanding (Benware & Deci, 1984).

It is important to consider the amount of direction and support that is given to students during a course. Some have even attempted to determine the most effective levels of intervention required while teaching (De Grave et al. 1998, 1999; Savin-Baden, 2003). The most effective tutors are able to adapt their teaching style to suit the variations in student learning styles.

Some students need some direction or structure or they may flounder, while others flourish in an unstructured environment. "*Indeed, directive tutoring for the latter may frustrate and antagonize such students*" (Neville, 1999).

In his paper, Teaching Learners to be Self-Directed (1991), Gerald Grow classified students into four categories depending on their level of self-direction. The four categories were:

Stage	Level of Self-Direction	Teaching Style
1	Low	Coaching
2	Moderate	Motivating
3	Intermediate	Facilitating
4	High	Delegating

TABLE 2: TEACHING STYLES (GROW, 1991)

The above table divides the level of students' self-direction into four discrete groups. Those who have low self-direction (Stage 1) will want/need coaching and a high degree of structure; while those with high self-direction (Stage 4) will want/need a more delegating style of teaching. The four learning groups and they're accompanying teaching style are described below.

Stage 1 – Coaching

Students at this level are entirely dependent, which in some contexts can be a serious limitation (Grow, 1991). It is the responsibility of the tutor to get the students to a pre-defined destination by showing them how to take each step. "*Novice students, with little experience of PBL or prior knowledge, probably benefit from directive and knowledge expert tutors to provide the* *necessary structure or foundation upon which to build their learning*" (Neville, 1999).

To use the coaching method, the tutor must first gain the students' trust and establish credibility and authority. The tutor must demonstrate genuine mastery and prove himself or herself as an expert. Dependent learners dislike choice and respond best to discipline, direction, and a clearly organised, rigorous approach to the subject (Grow, 1991).

Stage 2 – Motivating

Students at this level are willing to do assignments if they can see the purpose; and will have the confidence to attempt prescribed tasks even if they lack knowledge (Grow, 1991). These students are willing to work autonomously towards an authority-defined goal but will gladly allow a tutor to guide them.

A teacher at this level should be motivational and enthusiastic, and should "*persuade, explain, and sell, using a directive but highly supportive approach that reinforces learner willingness and enthusiasm*" (Grow, 1991, p. 131).

Stage 3 – Facilitating

Stage 3 learners like to take some responsibility for deciding which tasks to pursue. They have the skills, knowledge and confidence to explore a subject on their own – requesting help only when they get stuck. They are somewhat critical – of others and of themselves – and will change their opinion if evidence proves them wrong. Students see themselves as future equals to the teacher, but may not be experienced or motivated enough to continue on their own (Grow, 1991).

"*The student comes to grips with the material in the classroom and is committed, via small group exercises and other active strategies, to 'owning' the material. This turns the student into an active, more effective learner*" (Exley

& Dennick, 2009, p. 86). Students seek meaning through asking questions and naturally pursue answers from all sources, not just the subject material available to them as part of a disciplinary course (Postman & Weingartner, 1971, p. 81).

Teaching Stage 3 learners requires a combination of structure and flexibility. The teaching protocol itself will remain the same; but the content that is taught will be uncertain and entirely dependent on the avenue of enquiry the students have chosen to pursue (Shulman, 2005).

Those who have defined the role say that the aim of the facilitator is to empower students by negotiating goals and standards rather than imposing them (Savoie & Hughes, 1994); to provide opportunities for students to actively construct knowledge rather than 'giving' knowledge to them (Barrows & Tamblyn, 1980; Neville, 1999; Garfield, 1995); to be an active participant in the learning experience (Knowles, 1975); to tell stories and to present tools, methods & techniques as resources to help students advance on their own (Grow, 1991; Cavanagh, Hogan, & Ramgopal, 1995; Hmelo-Silver, 2004). "*The teacher rarely tells the student what he thinks they ought to know. He believes that telling, when used as a basic teaching strategy, deprives students of the excitement of doing their own finding and of the opportunity for increasing their power as learners*" (Postman & Weingartner, 1971, p. 43).

Stage 4 – Delegating

Self-directed learners establish and pursue their own goals and standards; and use experts, institutions, and other resources to pursue these goals (Grow, 1991). They decide both the mountain they will climb and the path they will take to the top.

The students' drive to learn independently stems at least in part from an attitude of doubt – from an inability to blindly accept information presented to them (Fisher, 1995). Initially however, they may lack the confidence to learn independently and may require some guidance from tutors (Margetson, 1993; Savin-baden, 2003). "*As students mature, in knowledge as well as familiarity with PBL, the tutor should become more participatory or delegatory, allowing the students more leeway in deciding what and how they will learn*" (Neville, 1999). Delegating responsibility for making decisions about what students will do and how they should do it is only one form of tutoring at this stage; tutors could also challenge and provoke, criticise and evaluate, or play Devil's advocate. Eventually Stage 4 learners will actively seek responsibility for defining what and how they should learn (Grow, 1991, p. 134). "*The ultimate task of a Stage 4 teacher is to become unnecessary*" (Grow, 1991).

Becoming 'unnecessary' involves removing oneself from the critical path to learning, such that the student may decide whether or not they wish to listen. "*The most mature Stage 4 learners can learn from any teacher, although they prefer an atmosphere of autonomy…Interestingly, Stage 4 learning does not completely do away with teachers*" (Grow, 1991, p. 134). As Candy (1987) explains: "*There are certain skills and other bodies of knowledge which are best and most easily mastered under the tutelage of an expert*" (p. 229). Even the most autonomous students can benefit from a well delivered explanation of a concept or idea.

Mismatches between teaching and learning

Problems arise when the teaching style is not matched to the learner's degree of self-direction. The following table shows the potential mismatches between students (on the left) and tutors (along the base).

S4: Self-Directed Learner	**Severe Mismatch** Students resent authoritarian teacher	**Mismatch**	**Near Match**	**Match**
S3: Involved Learner	**Mismatch**	**Near Match**	**Match**	**Near Match**
S2: Interested Learner	**Near Match**	**Match**	**Near Match**	**Mismatch**
S1: Dependent Learner	**Match**	**Near Match**	**Mismatch**	**Severe Mismatch** Students may resent freedom they are not ready for
	T1: Authority, Expert	T2: Salesperson, Motivator	T3: Facilitator	T4: Delegator

TABLE 3: ALIGNING LEARNER STAGES WITH TEACHER STYLES (GROW, 1991)

The above table shows the mismatches that can occur between teaching and learning styles. In principle, the level of direction given by a tutor should be aligned with the level of direction that students actively *want*. i.e. dependent learners should be taught by an authority/expert; and self-directed students should be given responsibility by a delegator. A mismatch between a student's learning style and a tutor's teaching style will be stressful for both. The students may become frustrated, bored or rebellious while the tutor may fail to attribute the students' behaviour to the mismatch and instead assume that the student is not serious about learning (Grow, 1991). "*The most severe problems occur when dependent learners are mismatched with non-directive teachers and when self-directed learners are mismatched with directive teachers*" (Grow, 1991, p. 137).

Fox (1983) explains how to identify a severe mismatch between teaching and learning. "*One kind of mismatch will be that in which the student sees teaching and learning in the light of developed theories whilst the teacher has fairly simple theories. The student will feel constrained and frustrated at having to sit hour after boring hour in lectures having, as he sees it, an enormous amount of material 'pumped' into him with very little time or opportunity to range for himself over different ground and to get the material into a meaningful context. He will be disillusioned to find that success in assignments and examinations can be achieved by a fairly simple regurgitation of what has been given. The teacher will possibly see the student as surly, uncooperative and unprepared to get down to the hard graft of learning the basic facts.*

The other kind of mismatch is probably more common. In this case it is the students who view the teaching and learning process as a transfer of knowledge. They will expect well-structured lectures which leave them with a set of comprehensive notes which they can learn and later reproduce in an examination. Such students will be impatient with any attempts at introducing experiential learning such as projects, simulations and games. They will see such exercises as a waste of time because they know that the information transferred in such procedures can be transferred much more rapidly in lectures and duplicated notes. Sometimes students see some of the more creative exercises (which they have to work on independently or in groups) as an abdication of responsibility by the teacher. The students are resistant to activities designed to help them 'learn for themselves' because they see it as the teacher's job to teach them. 'Why should we do his job for him? It is not our job to teach ourselves--that is what he is paid for.' A situation in which the student is in effect saying 'Here I am, give me the knowledge' and the teacher is saying something like 'Let's take a journey together.

Do you fancy climbing that hill over there?' is bound to lead to frustration for both of them" (Fox, 1983, p. 160).

Rewards, praise & punishment

Praise and rewards have the potential to be either controlling or informational; the difference does not appear to be the words or the rewards, per se, rather the underlying intentions of the authority (Ryan, Mims, & Koestner, 1983; Deci, et al., 1991; Deci, Koestner, & Ryan, 1999). Positive verbal reinforcements (Deci & Cascio, 1972) and positive feedback (Deci, 1971) that are given in response to students' own assertions of their performance, or when the rewards are administered with a more autonomy-supportive style (e.g. without pressuring language) are likely to have a positive effect on intrinsic motivation (Deci, Ryan, & Williams, 1996). In contrast, any attempt to coerce or pressure individuals towards a specified outcome will be perceived as controlling (Lepper, Greene, & Nisbett, 1973) and will undermine intrinsic motivation (Koestner, et al., 1984, p. 234).

A controlling environment – where students are rewarded or praised for fulfilling the expectations of the authority – can have significant, negative side-effects (Black & Wiliam, 1998a); including perpetuating student dependency (Deci, Cascio, & Krusell, 1975), promoting surface learning strategies (Dweck, 2006) and undermining both interest and motivation (Deci, 1971; Lepper, Greene, & Nisbett, 1973; Lepper & Hodell, 1989).

In general, praise should be used sparingly and where used should be task specific (Crooks, 1988). Fisher (1995) recommends using the following autonomy-supportive phrases:

- That's an interesting idea
- Tell me about it
- How did you reach that conclusion?
- Have you thought of some alternatives?

- Whatever you decide is fine with me
- Try it yourself first, if you need help tell me
- That's an imaginative idea
- That's a good question

Feedback

Informative feedback has been shown to increase student learning from questions and tests (Kulhavy, 1977; Crooks, 1988); it helps students identify areas of their argument that do not make sense; and encourages them to elevate their thinking by fully justifying their own decisions for selecting a particular option (Postman & Weingartner, 1971; Cho & Jonassen, 2002).

Feedback should be given to students soon after the task is completed and opportunities should be created to allow students to use the feedback to improve their work (Crooks, 1988). "*Feedback is most effective if it focuses students' attention on their progress in mastering educational tasks. Such emphasis on personal progress enhances self-efficacy, encourages effort attributions, and reduces attention to social comparison*" (Crooks, 1988). "*Positive feedback tends to strengthen perceived competence and enhance intrinsic motivation if it is presented with a non-controlling style (Ryan 1982; Usui 1991). Positive feedback that used controlling locution (e.g., "Good, you did just as you should") tended to undermine intrinsic motivation (Ryan 1982)"* (Deci, Ryan, & Williams, 1996). "*Although negative feedback may not always undermine intrinsic motivation, studies suggest that it does tend to have a detrimental motivational effect*" (Deci, Ryan, & Williams, 1996).

Personal interactions

"I try to talk at least once to each child in my class as if they were the only child in the world"

- Student Teacher (Fisher, 1995, p. 203)

Trust and personal interactions are very important in education (Sadler, 1998). In large, traditional classes, "*students are disengaged, invisible, unaccountable, and emotionally disconnected most of the time*" (Shulman, 2005); they have a negative view of teaching and are more likely to adopt surface learning approaches (Sheppard & Gilbert, 1991; Rust & Gibbs, 1997). Yet intrinsic motivation can be increased significantly by acknowledging the individuality and feelings of each student (Deci, *et al*., 1991; Deci, Ryan, & Williams, 1996). In effect, "*learning requires that students feel visible and accountable*" (Shulman, 2005).

As Barrows & Tamblyn (1980) point out: "*Students are not homogeneous in background knowledge or experience, nor are they homogeneous in their learning abilities in different areas or in their pace and style of learning. Each has different career aspirations*" (Barrows & Tamblyn, 1980, p. 8); and acknowledging and supporting each student individually can have a significant positive impact on their learning (Grow, 1991).

Teachers should begin by learning their students' names (Felder, et al., 2000). "*The better you know your students as individuals the more they will feel that they matter and their views are respected. The larger the student groups, the more necessary it is to make a real effort to learn students' names and remember who they are*" (Habeshaw, Gibbs, & Habeshaw, 1992, p. 46). "*In a climate of respect, intrinsic motivation emerges easily because people are able to be authentic and spontaneous and to accept full responsibility for their actions. These are the qualities of self-determination, which is a hallmark of intrinsic motivation; they are qualities that fear and alienation quickly suppress*" (Ginsberg & Wlodkowski, 2009, p. 75).

A student's ability to learn is heavily influenced by the tutor's perceptions about their ability to learn. Rosenthal & Jacobson (1968a; 1968b) conducted a study into the effects of teachers' preconceptions of their pupils' ability. Teachers at a San Francisco primary school were informed that some of their first- and second-grade children had taken the 'Harvard Test of Inflected Acquisition' and had been identified as 'growth spurters' with potential to make dramatic gains in schoolwork. The teachers did not know that the test was fictitious and these 'special' students had in fact been chosen at random. Nevertheless those students went on to make the predicted gains, while the rest of the student body did not.

The opposite is true of children who were not part of the 'special' group. They were not predicted to make intellectual gains, and the more they gained, the less favourably they were viewed by the teachers; their unexpected progress was viewed as undesirable (Rosenthal & Jacobson, 1968a; 1968b). Negative perception of students' ability can be just as much a self-fulfilling prophecy as a positive perception.

Deci et al. (1991) reports similar findings: "*Teachers who had been led to believe that the students were extrinsically motivated were very controlling toward the students, which in turn led the students to display low levels of intrinsic motivation toward the puzzles. On the other hand, teachers who thought that they were interacting with intrinsically motivated students were more autonomy supportive, and their students showed high levels of intrinsic motivation. Thus, the teachers' beliefs about the student's motivation (which had been randomly assigned) actually created their own reality*" (p. 341). This implies that students must always be treated as if they will succeed, or else, they won't (Boud, 2000).

Teaching for thinking

Education is an admirable thing, but it is well to remember from time to time that nothing that is worth knowing can be taught.

- Oscar Wilde

Students learn better when they teach themselves, even if they perceive otherwise (Dods, 1997). Furthermore, many tasks may be within a students' capabilities before he or she has been taught anything (Perkins, 1986). "*Children are usually quite willing to let teachers, or other children, do their thinking for them. It is easier that way. They are more likely to get it "right", or at least to get it "done" and out of the way*" (Fisher, 1995, p. 199); but does this deprive the child of the very thinking that education is intended to support? As Maria Montessori once said: "*Never help a child with a task which he feels he can succeed*"; to do so is to increase their dependency on others and prevent them from pursuing their own creative ideas (Grow, 1991).

Teaching for thinking can make education more interesting and challenging (Fisher, 1995, p. 252); but it requires the teacher to take a secondary role in the education process - that of facilitator, rather than subject expert (Knowles, 1975). Many struggle with the transition; "*Don't underestimate how difficult it is for a teacher to move from being a requirement to being just one among many choices in how to learn*" (Grow, 1991, p. 142).

Stories can be used to great effect to convey the importance and relevance of ideas. "*A number of research studies have illustrated the importance of stories in workplace problem solving. Klein & Calderwood (1988) found that experts (e.g. fire commanders, system designers) relied more heavily on cases based on past experience than on abstract principles when making decisions in situations with a high degree or uncertainty*" (Jonassen, 2006).

Questioning is perhaps the greatest teaching tool as it creates a means to provide feedback to the teacher on the students current level of understanding. As Ausubel (1968) says, *"the most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly."* A student-centred tutor should therefore pause at frequent intervals, ask a 'what do you think?' question that encourages students to voice their own ideas, and then wait patiently (Catalano & Catalano, 1997).

One very important tool that is often over-looked, is the use of silence (Fisher, 1995). "*Many teachers wait only one or two seconds after having asked a question before they give the answer to the question themselves. It is easy to feel that unless someone is talking no one is learning. A short waiting time encourages short answers. If the adult waits for longer periods children tend to respond in whole sentences and complete thoughts*" (Fisher, 1995, p. 78).

"*When asked a difficult question the temptation is too great for parents or teachers to bluff their way out with vague generalisations or hopeful guesses. But this does not help children. A positive response might be "how can we find out?*" (Fisher, 1995). Again, the use of silence will increase the likelihood that students engage with the subject material and discuss their ideas with others in the room. As Fisher (1995) says, "*When I talk no one listens, when I listen everyone talks!*" (p. 248).

"*The teacher admits uncertainty, 'we are not quite sure about that, people have different ideas', and welcomes challenge. The teacher conveys his belief in the value of thinking, and emphasises that education is as much about exploring the unknown as it is about repeating the known. In the enquiring classroom the teacher is a learner alongside the child*" (Fisher, 1995, p. 250).

Tutors in a generalist-supportive classroom should withhold information (including textbooks, lecture notes etc) from students and encourage them to think and reason independently. Given that throughout school they have been conditioned to depend on an authority to provide them with answers, the students' first reaction will be to attack the tutor for refusing to teach them anything (Postman & Weingartner, 1971, p. 140).

Grow (1991) observed that specialist-type teachers and generalist-type teachers have an almost innate antipathy for one another's methods, and often, for one another's personalities. Generalist educators often ridicule or reject specialist methods of training because they miss the 'big picture'. Conversely, specialist tutors who value 'the fundamentals' consider the generalists' methods waffly and non-directional (p. 140).

Group work

In group work, students work in teams discussing alternatives, examining possible options and sharing information, opinions and ideas with other students (Flint, 2003). Available research demonstrates that collaboration is a key factor in student motivation and learning (Hmelo-Silver, 2004). "*Cooperative learning approaches can be effective in facilitating student learning and motivation and in developing good interpersonal skills and relationships. They are particularly appropriate for more complex tasks where the different perspectives and skills of group members can complement each other*" (Crooks, 1988).

Team working and collaboration are essential to engineers and are among the skills specified in ABET EC2000; and as skills can only be improved through practice, it stands to reason that students should work in teams at university (Prince, 2004, p. 5). Some students do not like working in teams and resent being made to do it, however most change their opinion once they realise the benefits of the process (Felder, 2004).

Learning in small groups leads to increased productivity, improved attitudes and greater academic achievement (Garfield, 1995; Fisher, 1995; Savoie & Hughes, 1994; Springer et al., 1999). Prince (2004) concludes that collaboration is more effective than either competition or individual work at improving students' conceptual understanding, self-esteem and perceptions of social support (Johnson, Johnson, & Smith 1998a; 1998b; Prince, 2004); furthermore, it is more effective than individual work at improving social skills (Johnson & Johnson, 1989), team skills (Terenzini, et al., 2001) and a range of interpersonal skills (Panitz, 1999).

Students can be given tasks to work on in groups during class, with a summary review period at the end of the session (Rust & Gibbs, 1997). Tutors can manage multiple groups by 'roving' between them – spending no more than 5-10 minutes with each group (Duch, Allen, & White, 1999). Asking students to develop and defend their own ideas generates an emotional investment; and "*the presence of emotion, even a modicum of passion, is quite striking…No emotional investment, no intellectual or formational yield*" (Shulman, 2005, p. 22).

Hunt & Minstrell (1994) provide an example method of conducting a worked example that allows the students to think, reason, argue and hypothesise prior to the tutor/teacher revealing available information. They note that the emphasis must be kept at all times on the students' reasoning; and that the teacher "*most importantly, does not present a voice of authority*" (p. 59). The aim of the teacher, acting as a facilitator during the discussion, is to encourage students to think and reason as much as possible and foster a desire for information. It is only at this point that the data is revealed/ provided by the teacher, and even then it is open to criticism (Van Rossum & Taylor, 1987).

Peer-tutoring

Peer-learning is often more effective than other forms of learning environments (Catalano & Catalano, 1997). "*The best answer to the question, 'What is the most effective method of teaching?", is that it depends on the goal, the student, the content, and the teacher. But the next best answer is, "Students teaching other students." There is a wealth of evidence that peer teaching is extremely effective for a wide range of goals, content, and students of different levels and personalities*" (McKeachie, *et al.*, 1986)

A study by Moust & Schmidt found that: "*Student tutors were better at understanding the nature of the problems students face in attempting to master the subject-matter. Student tutors were also more interested in students' daily lives, study experiences and personalities. In addition, student tutors referred to end-of-course examinations more frequently than staff tutors to direct student learning. Alternatively, staff tutors used their subject-matter expertise more often and displayed more authoritarian behaviour than student tutors. No differences were found with respect to tutors' focus on cooperation among group members*" (Moust & Schmidt, 1995).

Tutoring is intrinsically interesting and has been shown to positively effect the tutor (Benware & Deci, 1984). Experiments by Cloward (1967) and Allen & Feldman (1973) found that the tutor learned more of the subject material than the students. Zajonc (1960) suggests that the increase in conceptual understanding (from learning to teach) is a result of using a different set of cognitive processes; from adopting deep learning approaches (Marton & Säljö, 1976); and from "learning how to learn" (Bargh & Schul, 1980). Student tutors were also found to gain self-esteem, motivation and perceived competence as a result of teaching (Benware & Deci, 1984).

2.9.8. Lab classes

Lab classes create meaningful context and generate motivation to learn new information (Felder, *et al.* 2000). Research has shown that students in engineering are visual, active learners and respond well to lab work (Felder & Brent, 2004). Additionally, research has demonstrated that experiences such as these help students structure a cognitive framework that provides context for future theoretical knowledge (Schmidt, *et al.*, 1989; Goodhew & Bullough, 2005). In effect, students will be able to learn associated knowledge (e.g. from lectures) more effectively if they can relate it to their own experiential knowledge (Bransford & McCarrell, 1977).

Most lab experiments are set up prior to the students' arrival, thus allowing the students to begin experimenting immediately upon entering the lab. This, combined with the tutor's over-enthusiasm to recall knowledge from long-term memory, means that most prepared lab experiments do not allow for much independent thought (Brooks, 1984). The students' experience could be improved with the use of more open-ended experiments/projects (Evans, *et al.*, 1993).

2.9.9. Assessment (General)

Assessment has the single strongest influence on student learning; even the form of an examination question or essay topic influences what is learned and how it is taught (Scott, 1990; Gipps, 1990; Atkinson, 1999; Entwistle, 1996; Boud, 2000). The quickest way to change student learning is to change the assessment system (Elton & Laurillard, 1979, p. 100). Students themselves have described how their study behaviour was entirely dominated by the perceived demands of the assessment system (Snyder, 1971; Miller & Parlett, 1974).

"*Examinations tell them our real aims, at least so they believe. If we stress clear understanding and aim at a growing knowledge of physics, we may completely sabotage our teaching by a final examination that asks for numbers to be put into memorised formulas. However loud our sermons, however intriguing the experiments, students will judge by that examination – and so will next year's students who hear about it*" (Rogers, 1969b, p. 956). "*Snyder (1971) described how students encouraged to be creative at Massachusetts Institute of Technology abandoned any such aspiration on discovering that most of the marks were derived from rote memorization of material for multiple choice tests*" (Gibbs & Simpson, 2004/2005).

Macdonald & Savin-Baden (2004) state the aim of assessment is (in order of importance): "*to support learning, to measure learning and provide* *certification, and to assure standards*". "*Most important in this is the need for a view that considers teaching, learning and assessment as a whole and rejects treating assessment as separate from the processes of learning…based on the premise that learning must be integrative and lasting, and that the overall system of education must be coherent*" (Boud & Falchikov, 2005). "*The ultimate goal of assessment for learning and learning how to learn is to promote learning autonomy. Learners (whether pupils or teachers themselves) need to take responsibility for their learning and develop strategies that enable them to learn both on their own and with others*" (James & McCormick, 2009).

"*Biggs (1999), amongst others, stresses the need to align curriculum objectives, teaching and learning activities and assessment tasks, particularly where the intention is to encourage deep, rather than surface, approaches to learning*" (Macdonald & Savin-Baden, 2004, p. 5). "*Traditionally, assessment has been about finding out how much students know, usually in terms of knowledge or content. Increasingly, skills are seen as being important for students' future employability*" (*Ibid.*, p. 8).

Assessment should "*assess what the professional does in their practice, which is largely process-based professional activity, underpinned by appropriate knowledge, skills and attitudes*" (Macdonald & Savin-Baden, 2004, p. 7). The closer the practicum is to the real thing, the greater its validity (Macdonald & Savin-Baden, 2004; Baird, 1985). "*In PBL what we are really interested in is the students' ability to perform in a professional context, to recognise their need to acquire new knowledge and skills, and to view learning holistically rather than atomistically*" (Macdonald & Savin-Baden, 2004, p. 8). This is in keeping with generalist education. Unlike specialist skills and knowledge, generalist competence cannot be atomised. As Kimbell (1994) says, "*Holistic capability is greater than the sum of its parts and cannot be reduced to any intellectual formula; as greatness in footballers or violinists cannot ultimately be reduced to 'performance indicators' (Satterly, 1989, p. 147)*". Or as Evans et al. (1993) say "*Behaviours cannot be analysed and broken down to a myriad of components* *that adequately represent professional practice. Measuring instruments and rules cannot be developed to codify and produce correct professional practices*".

"*Difficulties are emerging as many people retain the assessment methods they used in their traditional approaches resulting in a misalignment between their objectives and student learning outcomes, the learning and teaching methods adopted and the assessment of student learning*" (Macdonald & Savin-Baden, 2004).

"*It has long been assumed that there are two main purposes of assessment. The first is to provide certification of achievement…The second purpose of assessment is to facilitate learning…These two purposes have been associated with two sets of practices: summative and formative assessment respectively"* (Boud & Falchikov, 2006, p. 401). As Biggs (1998) explains, *"When the chef tastes, it's formative assessment; when the customer tastes, it's summative*".

2.9.10. Summative assessment

Summative assessment by evaluators predominantly aims to establish the extent to which students achieve the pre-specified outcomes (Black & Wiliam, 1998a) - to certificate one's ability to perform a set of chosen tasks. Summative assessment can be in the form of self-assessment, peer-assessment or assessment by an authority.

It is most common in universities for lecturers, examiners and tutors to assume full responsibility for assessment practices (Black & Wiliam, 1998a). As Heron (1981) explains, *"The prevailing model for assessing student work is an authoritarian one. Staff exercise unilateral intellectual authority, they decide what students shall learn, they design the programme of learning, they determine criteria of assessment and make the assessment of the student. The student does not participate in decision-making at all about his learning objectives or* *his learning programme, nor in setting criteria and applying them in assessment procedures. He is subject to the intellectual authority of an academic elite who have the power to exercise a high degree of social control on the exercise of his intelligence and on his future social destiny by intellectual grading"* (p. 33).

Students may be reluctant to accept innovative assessment methods (Carless, 2007); particularly when they do not feel that the evaluations are important or accurately reflect their level of performance and effort (Natriello & Dornbusch, 1984; Crooks, 1988).

Assessing actual learning is perhaps the most daunting challenge facing engineering educators (Catalano & Catalano, 1997). As Biggs (1999a) says, "*How can students' performance be graded qualitatively when the results have to be reported in percentages?*" (p. 1).

Assessment questions

Assessment questions can be described as either convergent or divergent depending on whether they converge to a single answer, or diverge to many (Torrance and Pryor 1998, 2001).

Convergent questions are used to assess students' capacity to achieve pre-specified solutions to well-defined problems (Felder, 1985; Rugarcia, Felder, Woods, & Stice, 2000). Convergent assessment practices – such as multiple-choice exams – are seen as convenient, assumed to be objective, more scientific, and less prone to error (Macdonald & Savin-Baden, 2004). However, the subjectivity is not removed, only moved onto the assessor, who must design questions that demonstrate conceptual understanding (Biggs, 1999). "*Written examinations continue to be effective and efficient means to assess students' conceptual understanding. A large number of students can be assessed in the same time period, and student achievement is documented; however, good questions are difficult to construct, and students' answers do not always reveal the causes of their errors or the sources of their misconceptions*" (Crawley, *et al.*, 2007, p. 158).

Divergent questions in contrast, have no single, correct answers (Macdonald & Savin-Baden, 2004), only better or worse ones (Biggs, 1999, p. 2); and students are encouraged to develop a range of different solutions to each question (Flint, 2003). Each solution must therefore be assessed on the quality of the proposed argument (Cho & Jonassen, 2002).

It is possible for students to deliver creative answers to divergent questions during a timed exam, however, they must be given the questions and allowed to prepare their answers beforehand. In fact Biggs (1999) and Blanchard, Zigarmi & Zigarmi (1999) suggest giving out the final exam questions at the beginning of the semester.

Why summative assessment is used

Summative assessment is primarily used for certification (Boud, 2000; Carless, 2007) as it is perceived to be a standardised, fair and equal means to categorise students (Brown & Knight, 1994).

Summative assessment can also be used as a form of extrinsic motivation (Theall & Franklin, 1999); and as a mechanism of control (Boud, 2000). Grades promise reward (high grades/pass) or punishment (low grades/fail) and motivate students to perform the tasks that are expected of them by the examiner (Deci & Ryan, 1994; Amabile, 1985). An assumed by-product of fulfilling these tasks is student learning.

Negative aspects of summative assessment

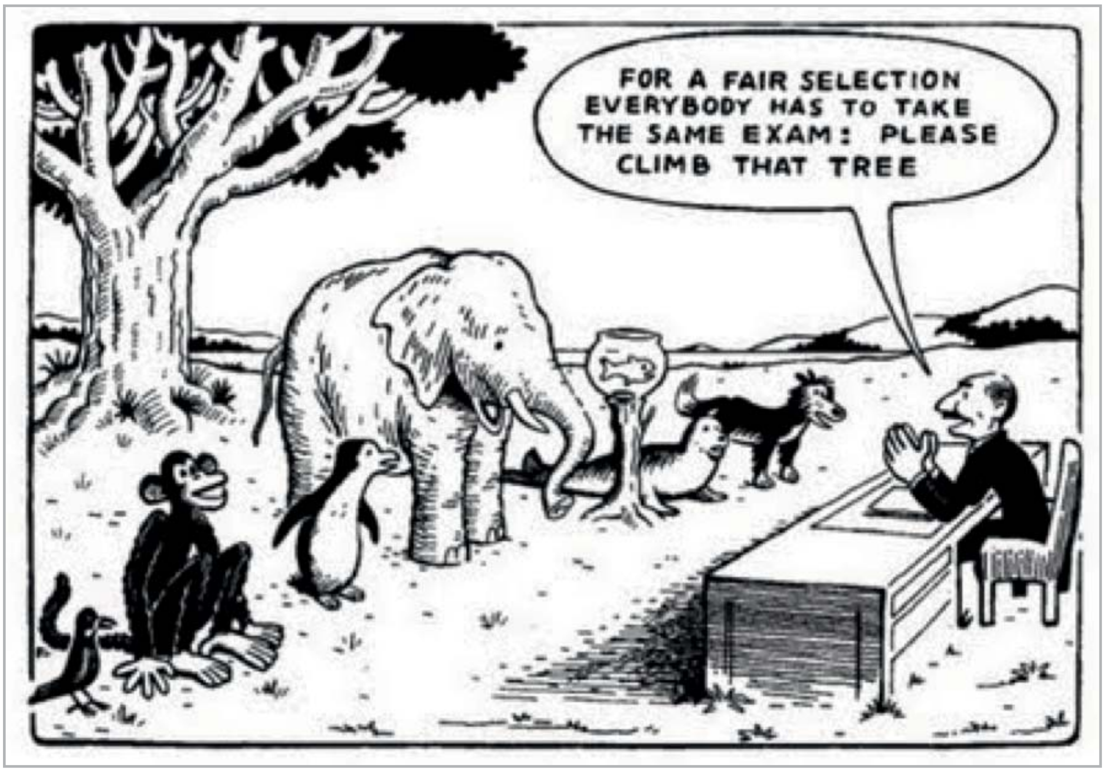

FIGURE 5: THE EQUAL TREATMENT OF UNEQUALS (ABYAPTA, 2012)

"Everybody is a genius. But if you judge a fish by its ability to climb a tree, it will live its whole life believing that it is stupid."

- Albert Einstein

Standardised, teacher-made tests are assumed to be fair as they treat everyone the same; they measure everyone against the same yard-stick; but by definition they ignore the individuality of each student and ultimately benefit some more than others (Boud, 1981; Pinar, 1992; Brown & Knight, 1994). Postman & Weingartner (1971) describe how any educator who views students as individuals "*would resent 'standardised' examinations which devalue, even denigrate, the uniqueness of each learner's perceptions*" (p. 95).

Boud (2000) describes how, "*Ironically, summative assessment drives out learning at the same time it seeks to measure it. It does this by taking* *responsibility for judgements about learning away from the only person who can learn (the student) and placing it unilaterally in the hands of others*". Consequently the students' own opinions of themselves become unimportant; and they learn to value and depend on assessment by an authority - the better the grade, the more they have learned and the better they are (Biggs, 1990-91).

As with any form of extrinsic motivation, summative assessment has a detrimental effect on learning in both the short-term (Crooks, 1988; Biggs, 1990-91) and long-term (Harlen & Crick, 2003; Boud; 2000). "*The most reliable, rigorous and cheat-proof assessment systems are often accompanied by dull and lifeless learning that has short lasting outcomes - indeed they often directly lead to such learning*" (Gibbs & Simpson, 2004/2005).

Many forms of existing assessment fail to encourage the type of thinking that education seeks to support. "*Students are not in practice encouraged to look for relating ideas, broad principles or functioning knowledge*" (Macdonald & Savin-Baden, 2004). Emphasis is placed on low cognitive level activities such as the speed and accuracy of knowledge recall, which encourages surface approaches to learning (Crooks, 1988; Redfield & Rousseau, 1981; Biggs, 1998; 1990-91). Such examinations, where students are expected to memorize the right answers, are at odds with problem-based learning (Boud, 2000; Savin-Baden, 2003; Macdonald & Savin-Baden, 2004).

When the assessment is closed, students participate in what Miller & Parlett (1974) describe as 'cue-seeking'. i.e. students will spend most of the class time trying to spot cues as to what they will be assessed on and, if possible, the answer that the lecturer wants (Gibbs & Simpson, 2004/2005; Macdonald & Savin-Baden, 2004, p. 8). The assessment will elicit memorisation-related activities such as rote learning, question spotting and going through past papers (Biggs, 1999; Tang, 1994). Students focus on marks rather than the learning they purport to represent (Boud & Falchikov, 1989,

p. 403). Many of these students resent being assessed in ways that they feel do not do justice to their learning (Biggs, 1999, p. 3).

Switching to convergent summative assessment, e.g. multiple-choice questions, will shift all students toward surface approaches to learning; in particular those students who use deep approaches to learning (Entwistle & Tait, 1990). Scouller (1996, 1998) found that students who tried to use deep learning approaches on multiple choice tests did poorly. As Macdonald & Savin-Baden (2004) said, "*The message is clear. Get a nodding acquaintance with as many details as you can, but do not be so foolish as to attempt to learn anything in depth*" (p. 11).

Summative assessment has been shown to encourage students "*to play up what they do know or can do to cover up as much as possible what they do not know or cannot do*" (MacDonald & Savin-Baden, 2004). Assessment should, in contrast, try and encourage learners to be open and honest about their ability (MacDonald & Savin-Baden, 2004. p. 5).

Time constraints are used for several, predominantly administrative reasons: convenience, invigilation, to create standardised conditions and to reflect the time constraints existing in real life. However, these arguments are unconvincing and cannot easily be justified from an educational perspective (Biggs, 1999).

The results of norm-referenced summative assessment (a means to compare one student to his or her peers) can have significant, and often negative, psychological effects. "*Norm-referencing places major barriers in the way of improving the quality of learning as it focuses on discrimination between different students, not on discrimination between different levels of learning achievement*" (Boud, 2000). Butler (1988) found that after being allocated a grade, students were more interested in comparing themselves with their peers than on understanding their mistakes and improving their work. In other words, "*norm referencing was unreliable and unhelpful because it did not identify in clear and positive terms what pupils were capable of doing*" (Kimbell, 1994). "*When normative grading is de-emphasized, cooperative learning is predictably more easy to establish*" (Crooks, 1988).

In summary; "*requiring results to fit some predetermined distribution, normal, rectangular or whatever, cannot be justified on educational grounds*" (Macdonald & Savin-Baden, 2004). "*If a teacher is employed in an institution where summative results really are required to adhere closely to some predetermined curve, there is a problem. The solution then can only be political: lobby to get the policy changed*" (*Ibid.*)

The grades assigned by evaluators can be interpreted in multiple different ways, thus students may derive incorrect assumptions about their learning (Knight, 2001; Boud, 2000). Furthermore, the use of grades and value-laden, judgemental words has been identified as a mechanism for damaging self-esteem and inhibiting learning (Boud, 1995a; 2000).

A student who receives a low score because they did not understand what was expected of them may come to the erroneous conclusion that they lack ability (Yorke, 2003; Biggs, 1998). This is assumed by many to be a primary cause of learner helplessness, which in turn has led to grade inflation and other failure-avoiding processes (Clifford, 1984).

Summative assessment has been shown to yield inaccurate results when used to classify students' ability (Knight, 2002; Boud & Falchikov, 2006). "*Evidence that pupils' responses to such tests do not represent their best performance has been obtained by interviews based on pupil responses to APU test items: Gauld (1980) found that pupils often misread the demand of a question, seem incompetent because of a single slip in a complex process, fail to use what they know because they judge it irrelevant, and may be marked down because the marker can't understand the quality of thinking behind non-standard responses*" (Black, 1993, p. 62). "*Many investigations have shown that assessments of practical work do not correlate closely with written theory* *assessments, and that written tests of practical skills cannot be used as surrogates for practical assessments*" (Black, 1993, p. 62).

Black (1993, p. 52) summarised the detrimental effects of narrow external testing on science teaching as follows:-

- science is reduced to learning of isolated facts and skills;
- the cognitive level of classroom work is lowered;
- pupils have to work at too great a pace for effective learning;
- in particular, ground is 'covered' by a race through a textbook;
- much teaching time is devoted to direct test preparation;
- pupils' questioning is inhibited;
- learning follows testing in focusing on aspects that are easy to test;
- laboratory work stops unless tests include laboratory tests;
- creative, innovative methods and topical content are dropped;
- teachers' autonomy is constrained and their methods revert to a uniform style;
- teachers are led to violate their own standards of good teaching. (Duschl and Wright, 1989, Herr, 1992, Smith *et al.* 1992, Tobin, Espinet *et al.*, 1988, Yager and McCormack, 1989, Wood, 1988).

How to implement summative assessment in practice

Where grades are an unavoidable necessity assessment reliability can be improved by assessing more often, with more varying assessments (Brown & Knight 1994; Davis & McLeod 1996). For example, observing students in oral communication or teamwork (Crawley, *et al*. 2007, p. 158). Where written assessments are used, Macdonald & Savin-Baden (2004) suggest the following methods to promote fair assessment (pp. 9-10):

- All assessment should be 'blind', with the identity of the student concealed.

- All rechecking should likewise be blind, with the original mark concealed.
- Each question should be marked across students, so that a standard for each question is set. Marking by the student rather than by the question allows more room for halo effects, a high or low mark on one question influencing your judgement on the student's answers to other questions.
- Between questions, the papers should be shuffled to prevent systematic order effects.
- Grade coarsely (qualitatively) at first, say into 'excellent', 'pass' and 'fail', or directly into the grading categories. It is then much easier to discriminate more finely within these categories.

The aims of summative assessment must be clear and transparent (Taras, 2001). If the aim is to assess de-contextualized knowledge i.e. information recall without conscious thought, then exams with convergent questions can be very effective (Biggs, 1999).

If the aim is to promote higher order critical and creative thinking, then authority-controlled summative assessment should be used only with careful consideration. It is possible to assess thinking skills using summative assessment (Fahy, 2005); however if the summative assessment is deemed to be controlling it will have substantial negative effects on learning.

Authority-imposed assessment, particularly those with norm-referenced grades, have been shown to improve compliance, generate competition, promise reward and instill fear (Amabile 1982; 1985; Amabile, Dejong & Lepper, 1976; Deci, 1995); and in doing so has been shown to systematically undermine intrinsic motivation, a pre-requisite for higher level thinking (Deci, *et al.*, 1991). In summary, intrinsic motivation and higher level thinking are in most cases suppressed by summative assessment, implying that summative assessment can in many cases have a significant negative effect on generalist education.

One way to maintain intrinsic motivation is to discuss summative assessment criteria openly with students, to share the responsibility of defining 'good work' and to ensure that students fully internalise and agree with the criteria (Deci, Ryan & Williams, 1996).

Students' opinions can be incorporated into summative assessment in several ways. Felder (1985) describes a course involving a quiz (test) written by the students themselves. The students were asked to create a class quiz for the subject they were studying and were given specific criteria that had to be met. The quality of the students' submitted test questions ranged from good to spectacular (Felder, 1987, p. 222). The students enjoyed the experience and developed some extremely creative, technically sound questions together with their worked solutions. Additionally the students were summatively assessed using a final, authority-controlled exam at the end of the semester. The average score on this final exam was 15% higher than the previous tests on the course (aside from the student-written one). Carless (2007) reported similar results in a study of student-designed tests.

Another alternative that has been shown to encourage students to engage with the assessment criteria - and subsequently maintain their intrinsic motivation - is self-assessment. This will be discussed in the section below.

Summative self-assessment

Student self-assessment is when learners make judgements about aspects of their own performance (Boud & Falchikov, 1989) and assess and grade their own work (Biggs, 1999). It works very effectively however it is rare (Biggs, 1998). "*Assessment practices are often the major barrier to developing increasing student responsibility: if students always look to others for judgements of their competence, how can they develop their own ability to assess their own learning?*" (Heron, 1981). If they are excluded from assessment then they are excluded from any real responsibility (Boud, 1995b; Boud, 1995a).

"*Many lecturers/tutors express great fear of handing any of the power of assessment over to students*" (Stefani, 1994, p. 74); the fear is that students will not assess themselves accurately. However, Barrows & Tamblyn (1976b) found that when students' self-assessment was compared with that of expert evaluators, the students "*rarely missed any of the concerns the evaluators had about their performance and, in fact, seemed even more critical*" (p. 335). In a study by Boud & Falchikov (1989), students assessed themselves in a way that was identical to the way in which they would have been rated by an authority and were in some cases very critical of their own work. Later studies also demonstrated good agreement with teachers' assessments (Black & Wiliam, 1998; Stefani, 1994; McGourty, Dominick, & Reilly, 1998).

Self/peer-assessment can be fair and democratic (Taras, 2001) and promote lifelong learning, by helping students take more responsibility for evaluating their own and their peers achievements, not just encouraging them always to rely on (tutor) evaluation from on high (Macdonald & Savin-Baden, 2004).

Stefani reported that 100% of students who participated in a self/peer-assessment exercise said that the scheme made them think more, 85% said it made them learn more and 97% said that it was challenging. These responses were given despite the fact that 100% of the students said that it was more time consuming and over 75% said that it was hard (Stefani, 1992; 1994).

Self/peer-assessment does not mean that students always have full control (Nicol & Macfarlane-Dick, 2005); assessment techniques still require a degree of organisational structure by the teacher. Boud (1986), Macdonald & Savin-Baden (2004) estimate however, that it can cut the teacher's workload by at least 30 percent.

The success of self-assessment improves proportionally to the level of understanding of what constitutes 'good work' (Boud, 2000). An educator can assist students (if needs be) by giving more information: "*This is what an A* *requires. If you can prove to me that you can demonstrate those qualities in your learning, then an A is what you will get*" (Biggs, 1999).

Barrows & Tamblyn (1976) found the students were unable to review and critique their own work immediately after completing it. They developed an iterative process, whereby students received additional information from a subject expert before being asked to assess their own work. The process worked very effectively and demonstrated good agreement with the teachers' assessments.

Summative peer-assessment

Peer-assessment has also been shown to encourage students to internalise standards of competence, which in turn enables reflective thinking and self-direction (Boud 1995; Gibbs 1998; Macdonald & Savin-Baden, 2004).

Brown, Rust and Gibbs (1994), Zariski (1996), Race (1998) and Bostock (2000) have described numerous potential advantages of peer assessment for students, including:

- Giving a sense of ownership of the assessment process, improving motivation;
- Encouraging students to take responsibility for their own learning, developing them as autonomous learners;
- Treating assessment as part of learning, so that mistakes are opportunities rather than failures;
- Practising the transferable skills needed for life-long learning, especially evaluation skills;
- Using external evaluation to provide a model for internal self-assessment of a student's own learning (metacognition), and;
- Encouraging deep rather than surface learning.

Ballantyne, Hughes, & Mylonas (2002) list the following benefits of peer-assessment:

"Encouraging students to consider the objectives and purposes of the assessment task as well as the course itself (Boud, 1995; Topping et al., 2000); Forcing student assessors to contemplate the question of what constitutes a good or poor piece of work (Searby & Ewers, 1997); Taking the mystery out of the assessment process, thereby enabling students to appreciate why and how marks are awarded (Brindley & Scoffield, 1998); Providing students with a better understanding of what is required to achieve a particular standard and what academic staff are looking for when conducting assessment (Falchikov, 1995; Hanrahan & Isaacs, 2001; Race, 1998); Enabling students to view and critique a range of writing styles, techniques, ideas and abilities, thus encouraging them to learn from both the mistakes and exemplary performances of their peers (Race, 1998); Alerting students to the dilemmas tutors face in assigning marks (Billington, 1997; Hanrahan & Isaacs, 2001) and highlighting the importance of presenting work in a clear, logical format (Brindley & Scoffield, 1998; Race, 1998); Encouraging students to reflect on their own approaches to assessment tasks (Dochy et al., 1999); and Improving students' understanding and self-confidence, as well as the quality of subsequent work (Dochy et al., 1999; Mowl & Pain, 1995; Topping et al., 2000)".

Summative peer-assessment, as with self-assessment, has been shown to have good agreement with teachers' grades (Black & Wiliam, 1998; Hughes & Large, 1993).

There are however some negative aspects of summative peer-assessment. Boud (2000) for example warns that, "*having peers rate each other on relatively uninformative scales to produce marks which are used primarily for classificatory purposes tends to disrupt learning together.*" Ballantyne, Hughes, & Mylonas (2002) go on to describe several further downsides to summative peer-assessment:

"Orsmond & Merry (1996) found that students were uncomfortable with peer assessment because they felt unqualified to mark others' work; Falchikov (1995) and Mowl & Pain (1995) report that the majority of their students found

assigning marks to their peers' work difficult; Topping et al.'s (2000) students rated the cognitive challenge and strain of peer assessment as one of its least liked features; McDowell's (1995) students expressed concerns about their ability to provide constructive feedback and mark fairly and, consequently, although they were prepared to participate in the process, they also wanted staff to provide additional feedback; Cheng and Warren (1997) report that although students agreed in principle with peer assessment, most were not supportive of first-year students being involved. Furthermore, some students found it difficult to be objective and tended to award higher marks to friends; Brindley and Scoffield (1998) and Falchikov (1995) note that students were generally reluctant to award low marks to peers even when they were deserved; McDowell (1995) found that students were not convinced their peers would mark fairly; and Orsmond & Merry (1996) report that many of their students were sceptical about the worth of peers' comments".

2.9.11. Formative assessment

Formative assessment is an iterative process that encourages students to modify and improve their solutions in light of new information (McLaren, 2007). The ability to use information from the assessment process to further guide learning is what distinguishes formative from summative assessment (Black, 1993).

Many educators view assessment as synonymous with grading (Carless, 2007), but it should instead be viewed as a tool for learning; as a safe environment in which to make – and learn from – mistakes (Dochy & McDowell, 1997; Sadler, 1998; Nicol & Macfarlane-Dick, 2005; Boud, 2000; Crawley, *et al*, 2007; McLaren, 2007).

The results of frequent formative assessment can be used by educators to generate cumulative information on students' levels of understanding and skill, and allow them to adapt their teaching accordingly (Nicol & Macfarlane-Dick, 2005; Crawley, *et al*. 2007, p. 152).

Engaging with formative assessment has been shown to cause students to focus on self-improvement (Savin-Baden, 2003, p. 25) and lead to lifelong learning (Boud, 2000); furthermore it has been shown to be effective in virtually all educational settings (Sadler, 1998).

Black and Wiliam conducted a review of the formative assessment literature, with studies involving a range of ages, subjects and countries. "*All of these studies show that innovations which include strengthening the practice of formative assessment produce significant, and often substantial, learning gains*" (Black & Wiliam, 2001, p. 3).

Formative feedback is more effective than grades at increasing intrinsic motivation and fostering deep learning approaches (Butler, 1988). "*A student's desire to know more about a subject is more important than a measure of performance at any point in time*" (Caine & Caine, 1991). We should therefore design assessment primarily to support worthwhile learning, and worry about reliability later (Gibbs & Simpson, 2004/2005).

How to implement formative assessment in practice

Formative assessment questions should be open-ended/divergent to create multiple opportunities for enquiry (Yorke, 2003). Students should be able to develop a response immediately, but continue to improve their answer over time. Formative assessment is therefore iterative - it is a process of action, reflection and refined action (Ballantyne, Hughes, & Mylonas, 2002) - and it has been shown to develop learning outcomes significantly through the provision of informative feedback (Macdonald & Savin-Baden, 2004, p. 9; Deci, Ryan & Williams, 1996). As Tishman, Perkins, & Jay (1995) say; "*In a culture of thinking, feedback should be informative and learning-centred. That is, it should provide students with useful information about their thinking behaviours – information that can help them learn how to think better*" (p. 4).

Nicol & Macfarlane-Dick (2005, p. 7) state that good feedback practice:

- helps clarify what good performance is (goals, criteria, expected standards);
- facilitates the development of self-assessment (reflection) in learning;
- delivers high quality information to students about their learning;
- encourages teacher and peer dialogue around learning;
- encourages positive motivational beliefs and self-esteem;
- provides opportunities to close the gap between current and desired performance;
- provides information to teachers that can be used to help shape the teaching.

In general, feedback should be private, linked to opportunities for improvement, and should encourage the view that mistakes are a part of learning (Ames, 1992b; Black & Wiliam, 1998a). Students should receive feedback that they can learn from and apply immediately (Boud, 2000; Nicol & Macfarlane-Dick, 2004; Carless, 2007); and it has been shown that significant learning benefits – for both teachers and students – result from re-doing and re-submitting assignments after receiving formative feedback (Boud, 2000).

Specific feedback messages can sometimes be complex and difficult to decipher (Nicol & Macfarlane-Dick, 2005). Students should therefore be given the opportunity to discuss the feedback, internalise the meaning and adjust their thinking accordingly (Higgins, Hartley & Skelton, 2001; Ivanic, Clark and Rimmershaw, 2000).

It is important to consider that grades are the most difficult form of feedback to interpret, and if used in formative assessment can act as a barrier to student understanding (Boud, 2000). Grades have been shown to distract students from engaging with feedback (Boud & Falchikov, 2006); and feedback given without grades was shown to lead to greater learning than feedback with grades (Black & Wiliam, 1998b). Marks on written work should therefore only be provided after students have responded to feedback (Gibbs, 1999).

Some studies have criticised formative assessment practices and their influence on student learning (Sadler, 1998; Hounsell, 2003; Yorke, 2003; Boud & Falchikov, 2006). Others believe it is not the assessment practices themselves, rather the context in which they take place. "*I believe that the culprits threatening learning are not so much failure and error-making as they are inappropriate goal setting, ineffective goal awareness, undesirable performance conditions, ineffective task assessment and evaluation, and unproductive attributions for failure*" (Clifford, 1984, p. 118).

Sadler explains how many students learn coping strategies to deal with defective formative assessment; and changing their attitudes may be difficult (Sadler, 1998). *"Some students are particularly vulnerable to a sense of personal failure… 'I am a failure' may erroneously come to dominate over something like 'I didn't understand what was expected of me', for example. Such a reaction is edging towards learned helplessness*" (Yorke, 2003). A study by Dweck (1975) showed that when a group of students were trained to attribute their failure to lack of effort they demonstrated subsequent learning gains. Students who were given no such training attributed their failures to their ability (something they could not change), which perpetuated learner-helplessness.

"*The detrimental effects of failure can be anticipated when the goal is not inherently associated with the activity. Finally, I predict that the more meaningful the goal (i.e. the more closely it is linked to other relevant goals), the more likely it is that failure will result in constructive effects*" (Clifford, 1984).

Students should be encouraged to actively engage with the performance criteria (Carless, 2007). "*The effectiveness of formative assessment depends on whether students actually perceive the gap between where they currently are* *and where they should be: and then if they do, what they are willing to do about closing it*" (Biggs, 1998).

Formative assessment encourages the assessor to use and develop critical thinking skills (Shulman, 2008). "*If formative assessment is exclusively in the hands of teachers, then it is difficult to see how students can become empowered and develop the self-regulation skills needed to prepare them for learning outside university and throughout life*" (Nicol & Macfarlane-Dick, 2005). Formative self-assessment supports life-long learning (Boud & Falchikov, 2005) as it encourages individuals to engage actively with the required standards and to self-monitor their own work (Carless, 2007). The critical reasoning skills used in assessment must be developed through practice (McGourty, Dominick, & Reilly, 1998) and are essential if individuals are to cope with change in future (Boud, 2000, p. 160).

Students already assess their own work and higher education should build on this ability. In particular it should support students in developing a clear understanding of the goals to be achieved against which performance can be compared and assessed (Nicol & Macfarlane-Dick, 2005).

Sadler (1998, p. 78) describes how the thinking behind formative assessment has evolved. Originally, feedback was intended to reinforce or remedy correct or incorrect answers, respectively; it was a mechanism by which teachers could guide students towards the 'right answer', and in doing so increase extrinsic motivation and achievement. The nature of feedback evolved to focus on praise of effort and critical thinking, which would lead to higher self-esteem, more effort and finally higher achievement (Dweck, 1986; Sadler, 1998; Savin-Baden, 2003). Finally it was acknowledged that students could use informative, personalised feedback to improve their understanding of what constitutes high quality work. They could then develop strategies to attain high standards, and subsequently high achievement. Feedback of this form empowers students to take control of their own learning – to become self-regulated learners (Nicol & Macfarlane-Dick, 2005).

2.10. Education conclusions

The review of education literature above yields several, very significant conclusions. The first is that students in a controlled, teacher-centred environment become extrinsically motivated and subsequently adopt surface-learning strategies. This has been proven to be effective at improving students' mechanical skills and ability to perform low-level cognitive tasks, but is completely ineffective at improving higher-level skills such as critical or creative thinking.

Conversely, if students are to adopt deep learning approaches and develop their skills and contextual understanding, i.e. to become generalist engineers, then intrinsic motivation is a prerequisite. The majority of the literature on motivation describes either the positive effects of intrinsic motivation or the undermining effects of extrinsic control. There is limited information on how to support intrinsic motivation in a university environment, even less on how to do so while achieving the stringent requirements of engineering accreditation, and there is no literature whatsoever on how to achieve this in a fire safety engineering programme.

The limited information that is available states that learning goals should be established collaboratively rather than be imposed in a controlling way. This leads to the second major conclusion from the literature review, which was that assessment defines the learning goals and will therefore have the greatest impact on students' motivation and subsequent learning. The assessment effectively provides the aim - the purpose - of the course and it is essential therefore that students fully internalise the assessment criteria.

The literature suggests that there is potential for problem-based learning (PBL) to form the framework for generalist education in university of marasdfasdf. PBL creates an environment in which individuals pursue task goals largely independently, and iterate and optimise their solutions in response to formative assessment. Very few PBL courses exist in fire safety engineering, and none have been documented in the literature.

Finally, the literature states that when knowledge is presented in an informative, non-controlling way, it will not have an undermining effect on intrinsic motivation. It is clear that a certain quantity of structured information should be presented to students by the course authorities (tutors, lecturers etc.); but what is not clear from the literature is *how much* should be given to students and at what *time* during the learning process. Establishing the quantity and timing of information delivery will be a key aim of this thesis.

3

DATA COLLECTION

3.1. Introduction

Given the conclusions above it was decided to trial PBL teaching methods and observe student learning; the aim being to identify and define specific methods that increase intrinsic motivation and support the generalist mindset. The research was conducted over a period of three years and incorporated courses at the University of Edinburgh, Princeton University, Massachusetts Institute of Technology (MIT), University of Maryland, Worcester Polytechnic Institute (WPI) & École Polytechnique Fédérale de Lausanne (EPFL).

The data collection and analysis was used to derive an over-arching theory of generalist education and specific methods that are effective at supporting a generalist mindset. This qualitative process is well documented in the social science literature and is termed 'Grounded Theory' (Strauss & Corbin, 2008). Surveys, semi-structured interviews and participant observation were the main methods of data collection; again these methods have been well documented in the literature (Olds, Moskal, & Miller, 2005).

The main source of data collection was case studies (Case & Light, 2011), predominantly fire safety engineering courses at the University of Edinburgh between 2009-2011. The data gathered was combined with observations from U.S. universities to develop a universal teaching philosophy that could then be applied to any course, including fire safety engineering. This universal teaching philosophy was used to develop a course, which was then trialled at EPFL.

The data collected here is not intended to provide conclusive evidence of educational theories, although much of it supports the theories presented in the earlier literature review; furthermore it is not the intention to deal with qualitative problems in quantitative terms – a common mistake in education research (Postman & Weingartner, 1971, p. 14). Instead, the case studies in this paper are intended to test practical applications of those theories in the context of fire engineering courses.

The fire science and fire dynamics (FSFD4) course was chosen for data collection because it is based on teaching the fundamentals using a traditional system of lectures and tutorials. The conclusions are therefore widely applicable.

The FSFD4 course was compulsory for fourth-year fire safety engineering undergraduates and was made available to civil, mechanical and chemical engineering students to be taken as an elective in their fourth or fifth year of study. The fire safety undergraduates had completed only one prior introductory course in fire safety engineering, while all the other students were yet to be introduced to the subject.

3.2. 2009 FSFD4

3.2.1. Method

The 2009 FSFD4 course was based on the structured delivery of a very thorough curriculum by an individual recognised as an effective lecturer. The aim of the class was to teach students a large amount of subject-specific, fundamental knowledge to provide a foundation for learning. The lecturer had made a decision on what information should be taught to the students on this course as a component of an overall degree programme. Each one of the programme courses was designed to teach students one component of the entire list of technical knowledge deemed to be necessary for a practicing engineer. The process of dividing knowledge into individual courses was subjective but it was assumed that any student who learned all of the components would be able to recall, synthesise and then apply the taught knowledge to any situation they encountered. It was also assumed that students would develop engineering skills such as creativity and critical thought as a by-product of learning subject specific knowledge.

Thus the aims and objectives of the class were given as:

This course is intended to provide the knowledge required for quantitative fire hazard analysis. Physical and chemical behaviour of combustion systems as well as the impact of fire on structures and materials will be addressed. The student will acquire skills for quantitative estimation of the different variables of fire growth. Basic principles of fire dynamics will be used to provide analytical formulations and empirical correlations that can serve as tools for design calculations and fire reconstruction. Focus will be given to the scientific aspects of fire but some basic features of fire safety engineering will be also developed.

And the learning objectives were:

Demonstrate an understanding of the following combustion principles, all of which contribute to fire and smoke behaviour in a compartment:-

- ***Pre-mixed flames:*** *laminar flame speed, stoichiometry, deflagration, explosion, flammability limits and flame extinction.*
- ***Diffusion flames:*** *Burke-Schumann formulation, flame location and mixture fraction*
- ***Soot and Thermal radiation:*** *factors influencing the production of soot and the radiation emitted by flames, the effect of turbulence, turbulence modelling, demonstrate an understanding of the processes of fire growth and fire modelling*
- ***Ignition:*** *ignition of solid, liquids and gases -*
- ***Spontaneous ignition and smouldering:*** *Semenov and Frank-Kamenetskii models, diffusion-controlled ignition (smouldering) and gasification-controlled ignition (flames)*
- ***Flame spread:*** *mechanisms of flame spread, upward, downward and lateral spread, thermal models for flame spread and the blow-off limit*
- ***Burning rate:*** *pyrolysis and gasification, heat feedback and the mass transfer number - non-charring, charring, fire-retardent materials*
- ***Combustible liquids:*** *flash point and fire point, flame spread over liquid*
- ***Pool fires:*** *turbulent plumes, flame height correlations, ceiling jets - air entrainment and entrainment correlations, virtual origin*
- ***Production of smoke:*** *quantitative and qualitative analysis of smoke, CO, toxics and irritants, the concept of obscuration, extinction coefficients and its application to detection and visibility*
- ***Effect of a compartment:*** *heat feedback effects on burning and burning rates, the concept of ventilation - fuel-limited fire/oxygen-limited fire, flashover and backdraught - identify methods to quantify smoke movement and smoke management, passive and forced smoke evacuation calculations*

The course objectives and associated learning outcomes were not dissimilar to other engineering courses inasmuch as it was structured around technical topics with no clear indication of what linked those topics together. The aim of the course according to the lecturer was to teach fundamental knowledge that could be applied to more tangible fire safety engineering scenarios later in the degree programme and/or after graduation.

The course was structured around a curriculum of fundamental knowledge (the learning outcomes); to be 'delivered' sequentially to the students in the form of lectures. In previous years the same (or similar) knowledge had been presented by Professor Dougal Drysdale – who founded the programme and subsequently created a textbook based on the lectures (Drysdale, 1999). The combination of lectures and a textbook was deemed to provide sufficient transfer of information to the students.

Students attending the class came from a range of different backgrounds (student numbers in brackets); including undergraduate chemical (10), mechanical (8) and civil engineers (13). Furthermore the students were at different stages of their degrees – some were 4^{th} and 5^{th} year undergraduate students while others were international postgraduate students (6) with degrees in engineering from other institutions.

The lecturer intended to transfer the information defined in the learning outcomes to all of these students over the course of ten 1½ hr lectures. The lecturer's method included interacting with the audience and asking questions to gauge students' prior understanding of the concepts. A strategy proposed by Ausubel (1963), Wlodowski (1999) and Hmelo-Silver (2000).

The lecturer realised the detrimental impact of stating that a student was "wrong". He acknowledged that it would decrease the student's confidence, impose the lecturer's beliefs and undermine intrinsic motivation. Therefore regardless of their answers, the lecturer stated that the students' responses were correct, albeit for a specific *context* – and would proceed to explain the context in detail. This method was advocated by Hunt & Minstrell (1994, p. 52) as a means of sustaining intrinsic motivation through classroom discussion.

The lecturer began each lecture by telling a story that described the concept he was about to teach. In addition he referred several times to that concept throughout the lecture and cited real world examples of how that concept could be applied in practice – to put it in context.

In addition to the main series of lectures, the students were given a guest lecture by Sam Collins (2009b) – a former University of Edinburgh fire engineering student. The talk described a real application of fire science and demonstrated the need to 'think outside the box' and be critical of available information. The intention was that students would begin to doubt the information presented by the lecturer and tutors, and would question the validity of taught material instead of applying it blindly to the tutorial questions.

The aim of problem sets in the 2009 FSFD4 tutorial questions was to ensure they read, applied and subsequently learned the information contained in the course notes. This was fundamentally different to the subsequent 2010 FSFD4 course described in the next chapter. The 2009 problem set questions were technically very difficult and written in such a way that they could be answered using methods presented in lectures and course notes. Convergent questions of this type are common in engineering education (Felder, 1985).

It was assumed that students would need to be taught the details *before* they were capable of solving problems on their own. The problem set questions were therefore distributed and collected *after* the lectures that covered the topics. This assumption would be tested in the 2010 course.

Tutorial classes

The tutorial classes were 1hr long, and were attended by up to forty students and two tutors each week. The students sat in rows while the tutors stood at the front of the room. When a student raised their hand the tutor approached the student and asked if they had a question. The majority of students formed informal groups of between two and five students who worked together to solve the problem set questions. In these cases the tutor provided assistance to the whole group.

Due to the convergent nature of the questions, there was a pre-defined answer that the students needed to find. The tutors had a copy of the pre-defined solutions, including methods, and were therefore able to answer any questions relating to the problem-solving process. Prior to giving the prescribed solution, tutors would ask the student how they *thought* they should answer the question. It was intended that this would encourage the student to explore the material and locate the solutions autonomously.

A separate tutorial class was arranged for ten mechanical engineering students due to timetabling issues. The format of the tutorial did not change except for there being only one tutor present.

Summative assessment

The students' problem sets were assessed by the tutors using a marking scheme of pre-defined solutions. The marking scheme allowed grading to be carried out very quickly; if the intended method and numbers were used, the solution would be identical to the marking scheme and would gain full credit. If the expected method and numbers were not used, the solution would be different and the student would lose marks. The amount of marks the student lost was subjective and dependent on the tutor.

Assessment was summative, meaning students could not re-submit their solutions and gain credit for amending their mistakes. Furthermore the submission date was final and non-negotiable; late submissions were penalised 5% for each day late (a University of Edinburgh requirement).

The final summative assessment was an open book 1.5hr written exam consisting of three questions.

3.2.2. Results

The lecturer explained the purpose and relevance of learning the knowledge presented in each lecture. Despite this, the students demonstrated very poor recall of taught information and lacked contextual and conceptual understanding.

The students were either able to do the tutorial questions very easily or they were unable to start. This is characteristic of closed questions and was a source of intense frustration for many of the students. The vast majority of students found the questions were either too easy or too difficult; very few found the questions optimally challenging and intrinsically motivating. Most chemical engineering students for example found the first chemistry-based tutorial very easy, while some civil engineering students were unable to even understand the question.

The chemical engineering students also complained about the taught material. One student said: "*I found the first four classes very boring – mostly covered information that was basic for chemical engineers. In the future you should tell the chemical engineers they don't need to attend these classes*".

In contrast, a group of three civil engineering students had moved themselves from the back of the lecture theatre to the front row to try and gain some level of understanding of the chemistry lectures. Following a 1½ hr lecture on stoichiometry and how to calculate the heat of combustion these students were asked if they understood it. They replied that they "*didn't have a clue*". The tutor then began asking questions about how they would go about balancing a chemical formula e.g.:

$$\mathbf{CH_4 + O_2 \text{ -> } CO_2 + H_2O}$$

When it became obvious (from their blank faces) that the students did not understand, the tutor asked if they knew what a "mole" was. All three students shook their heads. This is the chemical equivalent of asking what a "metre" was. Needless to say the preceding lecture gave explanations of significantly more complex chemical phenomena, based on the assumption that the students already understood "the fundamentals". This was clearly not the case for these three students, whose definition of "fundamental" was clearly different to that of the lecturer.

The huge variance in background knowledge and understanding meant that, even though they were presented very well, the lectures were pitched at an inappropriate level for many of the students. Although there was no before-and-after evidence, it is unlikely that the lectures improved the conceptual understanding of either the civil or chemical engineering students.

As the tutorial questions were convergent, the explanations given to each student on how to converge towards the predefined solution were always the same. The tutors therefore had to repeat themselves with every student who asked a question; quite an inefficient process. It may have been more efficient to give another lecture, explaining the convergent thought process required to reach the pre-defined solutions. Students would have been able to copy and memorise the method for later application.

Students were more interactive when being taught by another student rather than by the tutor. In one particular class the tutor explained a concept on the blackboard and asked repeatedly if the students understood. The students either gave no response or nodded. The tutor realised that the students did not understand and stopped explaining. The tutor then asked one of the students who had created a solution to the question if he would like to explain it on the board. After some encouragement, the student agreed and presented the same solution in the same way; only this time the other students immediately started questioning and challenging the student presenting at the board. "*Why did you do that? What do you mean?*" The student was then able to respond and explain his solution in a way that his peers understood, and he himself was forced to think more deeply in order to justify and explain his solution effectively.

Many of the students submitted identical pieces of work implying either collaboration or plagiarism. Without further information, there was no way to establish whether or not the *individual* students had actually learned anything. And it posed a further problem for the assessors – if a student reproduced the 'correct' solution, the assessor had to award the available credit regardless of how the student achieved that solution. This is another inherent problem with convergent questions and pre-defined solutions.

We already know from the literature that in the absence of an interesting, intrinsically-motivating purpose, the goal becomes 'to get a good grade'. The only way to achieve that goal in this case was to reproduce the pre-defined solutions as shown in the marking scheme. Some students knew that it would take less time and yield a higher probability of success if they copied solutions from their peers, rather than spend time completing the work on their own.

One response can be to implement yet more control, and force students to work on their own, thus reducing their capacity to copy solutions from each other. However this is ultimately counterproductive. For example, it denies students the opportunity to practice communication and collaboration skills necessary for a future career in multi-disciplinary team environments. Tighter control increases the likelihood of a particular outcome but stifles the very skills an education is meant to support.

An alternative response could be to go the other direction, to reduce control and to re-orient the assessment such that the aim is to support student learning. Students are still encouraged to achieve the goal by the most efficient means possible. It is largely irrelevant whether this is by working with peers, by 'cheating', by reading books or by asking tutors. As long as they learn, the tutors should support them on their chosen path.

In some cases students worked hard on the questions but became stuck at a particular obstacle. Other students would give up very easily, knowing that they could just wait and ask the tutor. It was very difficult to differentiate between these two groups so the tutors would ask the question: "*What have you done so far?*" Those students who had already attempted the question would describe in detail how they became stuck, while those who had not invested much time or thought gave very superficial answers.

The students who had put in effort and become stuck knew roughly what solution they were being asked to find, but had failed to reproduce it on their own. These students were given enough information by the tutors to help them over the obstacle (often only a mathematical error) and continue on the linear problem-solving process. Throughout the process, all the students converged towards the same, pre-defined 'correct' solution.

Other students who had given up were asked by the tutors what they thought was the purpose of the question – what were they trying to find? The students would give their interpretation of what was being asked of them and the tutor would encourage them to think of how they could get there. Many of the students struggled to describe a problem-solving process and expected the tutor to define a method for them. One of them said: "*I don't know what to do, that's why I'm asking*." Often the tutor was reluctant to give students a prescriptive problem-solving method without the student expending some energy first. In such cases the tutor refused to give any solutions and instead told the student(s) to think about it on their own. This initially caused many students to become hostile towards the tutors. Similarly negative reactions were reported by Catalano & Tonso (1996).

By the end of the semester the same students came to see the tutor very often, and were more interested in the subject than were any of the other students, implying that they were intrinsically motivated to learn.

A small number of students were determined to be autonomous and self-directed, despite the tutorial questions leaving little room for independent thought. One of the students was even prepared to criticise her friend for following the rules and fulfilling the expectations of others rather than thinking for himself.

The major problem with convergent, linear problem solving is achieving the optimal level of difficulty. If a problem is too easy, the students can reproduce the solutions from memory and therefore do not learn; if a problem is too difficult, the students do not know where to begin, rapidly become stuck and therefore do not learn. Questions must neither be too difficult nor too easy. With a homogenous audience this is achievable as the diversity of intelligence is very low and questions can be designed to suit a normal distribution of students (ignoring the extreme outliers at the top and bottom end). Fire safety engineering courses by their nature have very diverse audiences, with huge variances in technical competency, making it almost impossible to satisfy the majority of individuals.

3.2.3. Discussion

In the FSFD4 course, the lecturer taught what he deemed to be important, interesting and necessary to fire engineers. This seemed logical to the lecturer, but may not have been viewed as such by the students. Although the lecturer had designed the lectures around the single concept of a compartment fire, the way in which the knowledge had been broken down into individual lectures made it difficult to see how the knowledge was holistically connected. The students would have to reverse the teaching process – to 'abstract' meaning from presented knowledge – in order to derive the purpose that the organiser had originally intended.

The purpose of teaching each lecture was clear to the lecturer, who understood the context in which the information could be applied. Students did not have this contextual understanding and thus had not internalised the learning goals to the same extent; there was no intrinsic 'need' to learn the taught information. This is despite the fact that the lecturer explicitly stated the purpose – and used real examples to provide context – throughout every lecture. The results imply that the purpose of learning could not be communicated verbally. This was found by Barneveld & Strobel (2011).

The low attendance in tutorial classes along with the type of questions asked by students indicated very low interest in the subject material. The students were inclined to use equations and calculations from either the course notes or from their peers. They were not interested in understanding the validity of these equations and instead focused on achieving the highest grade. This implied that, had the problem set questions or the exam been removed, the students would have done little or no work on the course.

The lecturer used extrinsic motivation in the form of summative assessment (tutorial questions and final exam) to impose an extrinsic purpose on students in a controlling way.

There were some students who internalised the extrinsic purpose and became self-regulated and motivated to learn; a phenomenon described by Deci, Ryan, & Williams (1996, p. 167). These students are still described as extrinsically motivated because the origin of the motivation was still external i.e. to get a good grade or avoid a bad one.

The more extrinsically motivated students adopted surface approaches to learning i.e. they attempted to memorise seemingly disconnected facts and methods 'just in case' they were needed for summative assessment. This was not conducive to the generalist mindset, which requires understanding information in context. The environment was more conducive to a specialist mindset.

The low attendance at tutorial classes may have been because there were not enough tutors compared with the number of students. It was observed that many students were unable to ask more than one question during an entire tutorial class and had to sit for large portions of the tutorial waiting for the tutor to reach them. It may also have been because the tutors were seen as unhelpful, as occasionally they were unable to answer complex technical questions, giving the impression that they lacked competence. For many students it was quicker, easier and more effective to ask their peers on the course for help, rather than the tutors.

In this course the lectures were intended to generate an intrinsically motivating purpose, however this proved unsuccessful. The type of tutorial questions limited the extent to which students could think critically and creatively. The majority were closed questions with a single predefined solution, thus there was no choice but to follow the prescriptive method and achieve the intended solution.

Furthermore the level of difficulty was fixed for each question, therefore it was impossible to cater for all students with a single set of questions.

The open-ended 'bonus' questions seemed to generate greater interest from the students, implying that the problem set questions could be used to foster intrinsic motivation.

3.2.4. Conclusion

- The purpose was imposed on students in a controlling way, without allowing them time to develop their own 'need-to-know'
- Stating the purpose in lectures was not enough to generate intrinsic motivation in students therefore they did not work independently and did not gain contextual understanding
- Closed tutorial questions were either too difficult or too easy and limited students' ability to think critically and creatively

3.3. 2010 FSFD4

3.3.1. Hypothesis

Hypothesis: students are intrinsically motivated and capable enough to think, learn and fulfil the assigned tasks *autonomously* i.e. without being taught.

3.3.2. Method

The course in 2010 was altered, reducing the fundamental knowledge delivered via lectures and modifying the structure of the tutorials. The learning objectives were redefined to:

"This course is intended to teach students about the science behind compartment fires. Particular focus will be placed on understanding fire behaviour and the mathematical tools used to predict it. These same concepts are the basis of computer models used in building design so, if the results are to be accurate, an understanding of the physical and chemical properties of fire is essential."

From the experimenters' perspective, the aim was to compare two teaching philosophies (one controlled, one autonomous) to establish which one would have the greatest success in improving the knowledge, skills and attitudes of a generalist engineer.

Due to ethical considerations and institutional constraints, the majority of the variables on the course were consistent for all students in the study. The main independent variable was the teaching style (either controlling or non-controlling).

All students attended the same lectures, given by the same course lecturer as the year before. The course included two guest lectures by University of Edinburgh academics. Additionally, students were taken to the fire lab at the start of the semester and shown demonstrations including: a flashover, a 'fire tornado' and a visualisation of smoke movement in a confined space (Yao & Marshall, 2006).

Problem Sets

The purpose of the course was relayed not through the lectures, but through the problem sets (Appendix B). The literature has demonstrated that students derive purpose – the 'need-to-know' – from the tasks in which they are actively engaged (Montessori 1967; Marton & Säljö 1984) and assessed (Barrows & Tamblyn, 1976a; Boud, 2000). The knowledge that students learn throughout a course is therefore governed by what they deem necessary to complete the problem sets. If students are to learn the type of knowledge required to overcome real engineering challenges, they should be assigned similar tasks in their problem sets.

University policy required that all students on the course be given the same problem sets and assessed using the same assessment criteria. This was intended to ensure that the student group is treated homogeneously and assessed uniformly. It may be argued that uniform assessment is in fact unethical as it does not consider differences in students' preferred learning styles (Felder & Silverman, 1988); a single task could be seen to unfairly favour some students over others. Nevertheless university policy was adhered to and uniform assessment was used.

The aim of the course was to educate generalist engineering students therefore the problem set tasks were designed to be intrinsically motivating, and open-ended/divergent. The tasks would provide a purpose, would generate a 'need to know' and would encourage autonomous learning.

The problem set tasks were designed specifically to support the generalist mindset, therefore those students who had a specialist mindset were at an immediate disadvantage. Due to university policy it was not possible to alter the assessment criteria to support individuals. The negative impact on students with a specialist mindset was reduced somewhat by providing highly technical 'tutorial questions' designed to give training in the technical details of the course (Appendix C).

The problem sets were designed to create a need-to-know – driving students to pursue the purpose autonomously. It was critical that the problem sets were designed in such a way that they would interest the students and foster the skills and knowledge associated with professional fire safety engineering.

In order to develop the problem sets for the fire engineering courses a stakeholder survey was carried out as described by Bankel (2003). The survey (see Appendix A) consisted of a standard CDIO syllabus, supplemented with a section on desirable technical knowledge in fire safety engineering derived from Drysdale's Introduction to Fire Dynamics (1999). Programme stakeholders were invited to rate each topic on the syllabus with values of between 1 and 5 depending on the desired level of proficiency.

The responses to the survey were consistent with the responses of previous CDIO stakeholder surveys (Wyss, et al., 2005). The results gave programme organisers a clear understanding of *what* skills and knowledge should be learned, and to what *extent*. The courses could be evaluated to establish if they were teaching at the desired level and problem set tasks could be altered such that the desired level of proficiency was more explicit (e.g. *Explain* the difference; *Create* a design etc.) This method is advocated by Felder (2000) & Crawley (2001).

The intention of this process was to more openly define the purpose of each course, and subsequently each tutorial question; thus removing ambiguity and reducing dependence on instructors. For students to become self-determined and autonomous, it was essential that they fully internalised and agreed to what was being asked of them (Deci & Ryan, 1994). Understanding and agreeing to the purpose – the problem set tasks – was a pre-requisite for students to take control of their own learning.

The problem sets were given out as early as possible and students were encouraged to work on the problem sets autonomously prior to the accompanying lecture. The students could submit their work and gain feedback from tutors each week; in this way students had the opportunity to work on the problems *before* being given a lecture on the topic.

The class was divided into two tutorial groups to compare the following two opposing teaching philosophies:

- Group A – Teaching knowledge and then creating a need to apply that knowledge, or;
- Group B – Creating a need to apply knowledge followed by teaching.

"*Proving that changing one aspect of teaching in large and complex curriculum is beneficial for all the students in a diverse class is clearly very difficult to do. There are so many variables and potential points of bias"* (Exley & Dennick, 2009, p. 86). *"In short, absolute proof of impact is difficult to obtain, cause and effect being notoriously difficult to pin down in a multi-variable experimental condition*" (Exley & Dennick, 2009, p. 87).

Qualitative evidence of teaching effectiveness was obtained via:

1. Interviews with students to find out how much they rate the teaching effectiveness,
2. Observing attendance rates at classes,
3. Comparing performance in examinations,
4. Recording students' future course choices and expressions of interest in the subject in the future (Exley & Dennick, 2009, p. 86).

Group A (Specialist) Method

Students in Group A were taught significant amounts of fundamental knowledge in a clear, sequential way before being given an opportunity to apply it during tutorials. The aim was to 'cover' all the necessary fundamental knowledge outlined in the curriculum and to give students practice in applying that knowledge. The assumption was that students would then be able to use that knowledge independently at a later date. This encouraged the specialist mindset and therefore supported the naturally Specialist students.

Furthermore, it was assumed that the students would not study unless they were extrinsically motivated by rewards (favourable grades, praise) and punishments (poor grades, embarrassment).

The tutor took the course curriculum and divided up the major topics into smaller, more detailed sections to be taught sequentially. The intention was for students to retain and reproduce the detailed knowledge on which all larger concepts were based – the 'fundamentals' so to speak.

The tutor informed the students that the problem sets were homework and should not be worked on during class. Instead, exercise questions were given out and students were told to work on them. It was intended that these questions would help students memorise knowledge. The tutor would have made the questions compulsory, however they were not graded and the tutor's controlling influence was limited only to what the students worked on during class.

Problem set tasks were viewed by the tutor as too open-ended and offered no guarantee that the students would actually learn the fundamentals. The tutor assumed that the students needed assistance *before* they would be competent enough to solve the problems on their own.

Tutor A formatively assessed each student's problem set submission. It was intended that the students would use the feedback from the tutor to further refine their solution and get closer to achieving 100%. In this way feedback was intended to improve students' knowledge and grades.

It was assumed that if the students did not autonomously learn the taught topics then they would need to be incentivised to study harder. This was done using rewards and punishments.

Group B (Generalists) Method

Students in Group B already had the open-ended problem sets to work on and therefore had an intrinsically motivating reason to learn. There was no need therefore to incentivise the students to learn specific knowledge in a particular order. The tutor assumed that the students would naturally gravitate towards learning the fundamentals as they identified the gaps in their knowledge.

As the students were already motivated by a tangible purpose created by the problem sets, autonomy was deemed to be the most important characteristic of the tutorial environment. The tutor therefore encouraged students to work on any part of the course they liked, including problem sets, practice tutorial questions, work from other fire courses or discussion of fire-related news.

The tutor made the assumption that *all* students wanted autonomy, choice and responsibility for their own learning. The tutor would therefore attempt to de-emphasise the role of the tutor and place responsibility squarely in the hands of the students. The students were even offered the opportunity to assess their own work. This was because it was felt that the assessor ultimately has control over the individual being assessed. It followed that if students were to be autonomous and be in control of what they learn then they must be able to control their assessment.

It was assumed that students would find the questions inherently interesting and challenging and that there would be no need for extrinsic motivators. The students were encouraged to work autonomously and build confidence in their own ability to make decisions and be self-directed.

The tutor also learned the students' names to increase responsibility and accountability of each individual.

The tutor explained that a team consisting of students from different academic backgrounds would be more capable of solving a diverse range of fire safety problems than students from a single discipline. Students were encouraged to work in teams consisting of a mix of chemical, civil, mechanical, fire engineering and IMFSE students if possible. The use of tutor-formed, heterogeneous student groups was advocated by Felder (2000), who gives an explanation of why it is useful.

The tutor would not be a primary source of information and would advise the students on where to find the information they needed. In this way the tutor's role was that of a facilitator, not an expert.

The tutor would give formative assessment on students' problem sets. The aim of the feedback was to increase students' confidence in their ability and to support them in achieving their own solutions. The process included removing any external incentives for improving solutions, such as achieving higher grades or pleasing the tutor.

The tutor made further efforts to de-emphasise their role as a subject expert. Peer tutoring and peer assessment was used to create an understanding that there were several possible ways of solving the same problem and that the 'best' solution was entirely subjective.

Group C (both Specialists and Generalists) Method

The students in Group C were taught by both a specialist tutor (A) and a generalist tutor (B). The tutors would take it in turns to teach the class, alternating each week. The students would therefore be taught using the two methods outlined above.

All Groups Summative Assessment

The lecturer – a widely respected generalist fire engineer – conducted the final, anonymous, summative assessment. The aim was to assess the students' contextual understanding of subject knowledge. The lecturer created and graded the exam independently of either tutor and sought to assess the knowledge and reasoning of each student.

Due to academic constraints the final assessment was in the form of a 1.5hr written exam.

3.3.3. Results

Results for Group A - Specialist Group

Group A Personal Attitudes:

Confidence - Many of the students initially lacked confidence in their own ability. Many felt uncomfortable submitting solutions that they knew contained mistakes. Students' confidence improved when they produced solutions that the tutor was happy with/praised them for. Students' confidence was reduced when given too much information to learn. The students were not confident enough to argue with their peers, the tutor and the lecturer on the problem set solutions.

Motivation - The tutor felt that the students did not know enough and the only way to get them to learn was to scare them into doing the work (extrinsic motivation). Students may have been intrinsically motivated initially but given the way that they were taught, they quickly lost it.

Group A Tutor Teaching (Skills):

Attendance - Attendance during tutorial classes increased throughout the semester.

Group discussion - There was very little discussion during tutorial sessions. Students sat in rows facing the front of the class, they took notes on what was being taught and occasionally answered closed questions put to them by the tutor. Interaction between students was limited to the groups that existed before the semester started, i.e. friends talked to each other.

Peer tutoring - Some students were capable of teaching other students. The tutor used this as an assessment tool - where students were asked to present solutions on the board. The student was expected to give the same explanation as the tutor would have given for each concept and most had very little confidence when giving their explanation. There was no improvement in the learning process than if the tutor had been explaining the same material.

Student opinions - Students enjoyed the lab visit and found it useful for visualising the concepts.

Some students treated every question as if there was only one solution; they liked to be told that they had got the answers wrong and to be given the correct answer by the tutor. Furthermore they would only hand in work when they were confident it met the expectations of the tutor.

Students were impressed and sometimes overwhelmed by the breadth and depth of information presented during tutorials. The students were taught considerably more than the students in Group B in terms of fundamental knowledge. Many students appreciated the emphasis on teaching as it covered a breadth and depth of additional information in addition to the existing course lectures. The students did not feel that their work load was too high compared to other courses.

Learning Tool - The tutor spent the majority of the class teaching the students – explaining concepts. Often several students had the same problem and the tutor would collect the students together to teach them as a group.

The tutor gave very detailed explanations of fundamental knowledge and the students saw the tutor as a useful learning resource.

The tutor spent a considerable amount of time giving feedback on tutorial submissions. The students found it very useful and much more comprehensive than other courses.

Very few students came to the see the tutor to request assistance during the semester despite being told that the tutor would be available any time. However, many students came to see the tutor in the days immediately before the exam and were interested in hearing detailed explanations of the concepts and assistance getting the ‘right’ answers.

Referencing - Several of the students copied entire sections of textbooks, including appropriate references. Others copied work from other students, particularly on numerical questions.

The more work the students were given the more work they did. However, there was a point where the students became overwhelmed by the volume of work and their work rate dropped significantly, almost to zero.

Group A Academic results:

Almost all of the students had created solutions prior to the lecture intended to teach those solutions, implying that the students were motivated to study. However, very few of the students answered the bonus questions. This could imply the students were not intrinsically motivated.

Many students submitted their work to the tutor for formative assessment prior to the final deadline and were more likely to use solutions given to them by the tutor or from a textbook than create solutions themselves. Almost half of the students by the end of the semester copied entire sections from the textbook, including references, rather than develop their own ideas.

The students did significantly more work, and learned significantly more than students in previous years, however the average final grade of Group A was the lowest of all 3 tutorial groups.

Results for Group B - Generalist Group

Group B Personal Attitudes:

Motivation - The students were intrinsically motivated and interested in solving the tutorials. The students' intrinsic motivation was undermined by an incorrect amount of taught information (too much or too little) and by the release of the exam timetable.

Confidence - Many of the students initially lacked confidence in their own ability. Some students' confidence improved as the course progressed, particularly when they could see themselves improving at the subject. Students' confidence was reduced when they were not given the information they asked for or when they were given too much information without asking for it. Some of the students were confident enough to argue with their peers, the tutor and the lecturer on the tutorial solutions.

Individual Responsibility & Accountability – Through observation it was found that the majority of students (there were exceptions) were more intrinsically motivated to study when they felt individually accountable for their work. Learning the students' names had a significant impact on their motivation. The personalisation of the interaction between tutor and student clearly meant a lot to some of the students. On meeting the tutor outside the university one student turned to his friends and said: "[My tutor] is one of the only people in this whole university who's actually bothered to learn my name." It was not easy learning the names of almost fifty students, but the effect on their motivation and the quality/quantity of work more than made up for the time invested to do so.

Initially it was made clear to the tutor that the students had a level of *expectation* on the tutor's performance, in particular in their ability to give students the 'correct' answers. The students believed that it was the tutor's responsibility to decide what was a 'good' solution.

The tutor began the course with the assumption that *all* students wanted to be autonomous and independent and during the first tutorial class the tutor explained the issue with using percentages to grade students' work. It implied that the students had attained a certain percentage of pre-defined, and entirely subjective criteria. To illustrate the point, the tutor asked the students what "100%" meant. One of the students responded: "It means you've got the right answer". The tutor then asked who decides what the 'right answer' should be. The student looked confused and replied, "you do". The tutor acknowledged the comment and summarised the point – that the students would be graded based on how close their opinion reflected that of the tutor, 100% indicating pure agreement. The students looked quite offended and asked if the tutor had a better suggestion. The tutor suggested the students graded their own work. A heated debate ensued and ten minutes later the tutor asked if the students would just prefer to be given an arbitrary grade based on the tutor's subjective opinion. The most vocal student in the above interaction had quite extreme views on the matter, and believed that the assessment criteria was not subjective, that the solutions to each question could be clearly defined and that the tutor should be responsible for grading students' work.

It is interesting to note that this student had benefited very well from the established system, and had until that point achieved the highest average grade of any student in the year. It followed that this student would resent any attempt to deviate from the status quo.

Group B Tutor teaching (skill):

Attendance - Attendance during tutorial classes was good.

Peer Tutoring - Some students were capable of teaching other students and the tutor used this as a learning tool. Some of the students who had already grasped the concepts were able to assist the tutor in explaining those concepts to other students. When asked by the tutor if they would like to help out with teaching the majority of students did so willingly and their teaching was appreciated by the other students. It was found that generally students were more likely to question their peers rather than the tutor. Initially the student volunteers repeatedly asked the tutor if what they were doing was 'correct', but as their confidence grew they stopped asking.

Their confidence was reduced and they made more mistakes any time the tutor criticised their teaching.

Peer Assessment - Peer assessment was difficult in practice. Some students found it useful, and were able to use the feedback they received from others. The majority of students however did not find it useful, and some actively disliked it. The issues the students raised were:

- Discomfort with allowing their peers to see their mistakes. At least one student actively disliked peer assessment and the idea that other people would see her work because they may think less of her.
- When reviewing a piece of work that was far more complex than their own, students came to believe that they were 'behind'. This lowered their confidence and motivation.
- When reviewing a piece of work that was far more basic than their own, students were unable to learn anything new.

One student felt he benefitted from the process and felt improved confidence from viewing others' work. Seeing the work of others allowed him to gain a point of reference and realise how much he had learned. This had the effect of improving confidence and self-efficacy.

Another student did not want to take part in the process and said she would not hand in any work if it was going to be seen by others. She did not want others to laugh at her work and wanted instead for the authority to tell her if her work was right or wrong.

<u>Group discussion</u> - At the beginning of each weekly tutorial the students were quiet, sat in rows facing the front of the class and did not engage in discussion. By the end of each class they were sitting in groups and actively engaged in discussion. During the class students stopped talking as soon as the tutor started.

<u>Learning tool</u> - Providing feedback took a long time. The students found the feedback very useful and much more comprehensive than other courses. Many students came to see the tutor throughout the semester without being told to and showed genuine interest in the subject material. These students liked the stories told by the tutor to give contextual understanding of a particular concept. Some students did not like the lack of tutor teaching, the low level of information presented during lectures or the amount of information presented during tutorials. These students did not appreciate the lack of teaching, and subsequently did not see the tutor as a useful learning tool.

<u>Student opinions</u> - Students enjoyed the lab visit and found it useful for visualising the concepts.

The students felt that the work load was too high compared to other courses. When asked if that was a bad thing they replied no because they enjoyed the work but it was taking up a lot of their time.

Students complained that not enough information was given to them during the course. Also some students wanted to be told that they had got the answers wrong and wanted to be given the 'correct' answer by the tutor.

Initially the students were uncomfortable submitting work that they felt was not perfect. As the course progressed the students became more comfortable submitting incomplete work and became more comfortable with the feedback they received.

Referencing - There was an extremely low number of instances of students copying from other students. Students referenced sources however they did not include full sections of those sources in their answer, instead they used their own words.

The more work the students were given the more work they did. However, there was a point where the students were given ‘too much’ work at which point they became overwhelmed and their work rate dropped significantly, almost to zero.

Regarding the knowledge based questions there were some students who became bored because the level of difficulty was too low and others, who struggled because the difficulty of the same question was too high. The same was found in 2009.

One of the students had already learned the knowledge presented on the course to an extremely detailed level. Thus, she felt she had not learned anything on the course. However, she acknowledged that she had gained contextual understanding of that knowledge through its application to real problems.

Group B Assessment

It was clear from the students’ reaction to the release of the exam timetable that summative assessment was viewed as a form of control. The students had no idea what was expected of them and the uncertainty led to fear and panic. The effect was an instantaneous drop in intrinsic motivation and an increase in extrinsically motivated behaviours such as ‘cue seeking’, as observed by Miller & Parlett (1974).

Students in Group B learned significantly more than students in previous years. Many were disappointed with the level of difficulty of the final exam, which they felt did not let them demonstrate how much they knew. The following exchange took place after the final examination:

Tutor: “How did it go?”

Student: “I actually really enjoyed that, I’m not kidding. Like, it was completely different to all of the past papers and I looked at it and went f**k, why did he do that? And then I sat down and just went for it and it was actually quite enjoyable. ‘Cos you actually realise you can do something haha. So I’m really happy. Thanks for all your help, it’s been thoroughly enjoyable.”

Tutor: “So you feel like you learned something?”

Student: “Yeah, I feel like, you know, I didn’t know anything about chemistry before I started this, now I feel like I can do it all again.”

Group B Academic Results:

The students appeared to enjoy the lectures more than the previous year. Students from all groups found the lectures useful and interesting. Through observation it was found that students in Group B were more likely to ask questions during lectures. As the course progressed, the questions asked became predominantly knowledge-based (“would cancelling the viscosity term not make the result unrealistic?”), rather than administrative (“will this be in the exam?”) Such questions were indicative of deep learning approaches and were significantly different to the types of questions asked by students in Group A, or by any students in 2009.

The students preferred answering problem set questions that involved describing concepts, rather than completing calculations. Many of the students answered the bonus questions given in tutorials and took part in long intellectual discussions with the tutor over some of the more challenging questions.

Students' work improved significantly following formative feedback from the tutor. Many submitted their work several times prior to the final deadline.

In the problem sets, the students were confident in creating solutions that they had not been taught during the course. Furthermore, many developed solutions that were better than those offered by the tutor. One student did not attend any of the lectures or tutorial classes, nevertheless he submitted excellent tutorial work and achieved the highest exam grade of any student. After the final exam the tutor asked him:

Tutor: "I was wondering how you went about learning on the course?"

Student: "I used Google a lot. The problem sets were quite useful so I just did those basically, and then you know revised a bit towards the exam."

Tutor: "Yeah but you didn't use any of the methods the other students used"

Student: "I used Google a lot. Just Google".

Tutor: "Yeah but there was a lot of conceptual ideas to do with balancing energy equations and..."

Student: "Err yeah I mean, what can I say, I used Google, and the textbook - the Drysdale book - and I just worked through it".

Results for Group C

Students enjoyed taking part in discussion, but most lacked the confidence to contradict or argue with the tutor. When the tutor spoke, the students did not.

Students were given two sets of tutorial questions to work on during class. One set had been handed out prior to the class, the other one was given to them during the class. Every student preferred to work on the problems that they had had more time to think about.

Some students attended some tutorials but not others. There were several reasons why this was the case, but it is possible that the students were choosing to attend only the tutorials with their preferred tutor.

Overall this group achieved the highest average grades in the final exam. When faced with the problem of estimating the temperature profile in a large room, students realised the deficiencies of using the standard methods and came up with excellent concepts on their own. One of their ideas had only recently been proposed by a team of leading academic researchers (Stern-Gottfried, Rein, & Torero, 2009).

Exam Results for All Groups

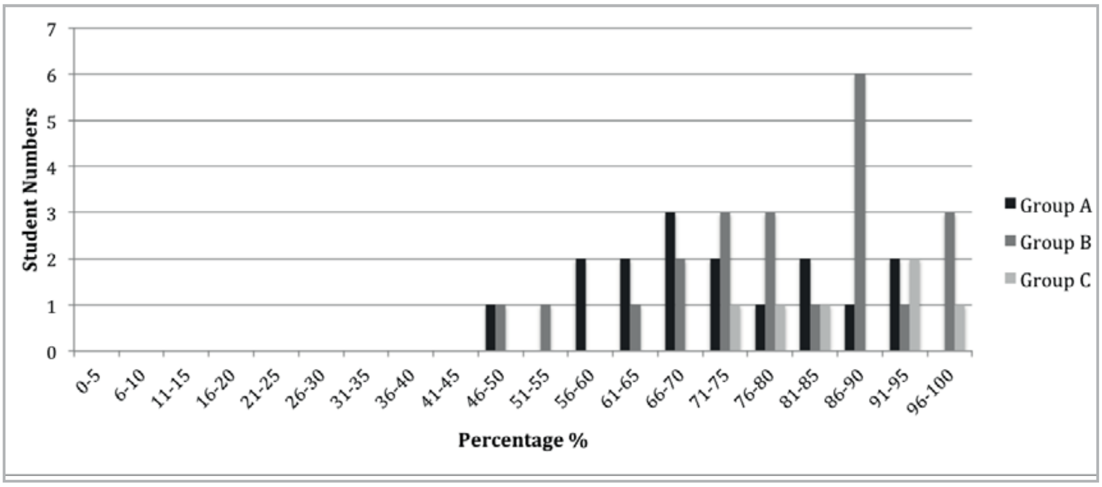

FIGURE 6: EXAM GRADES

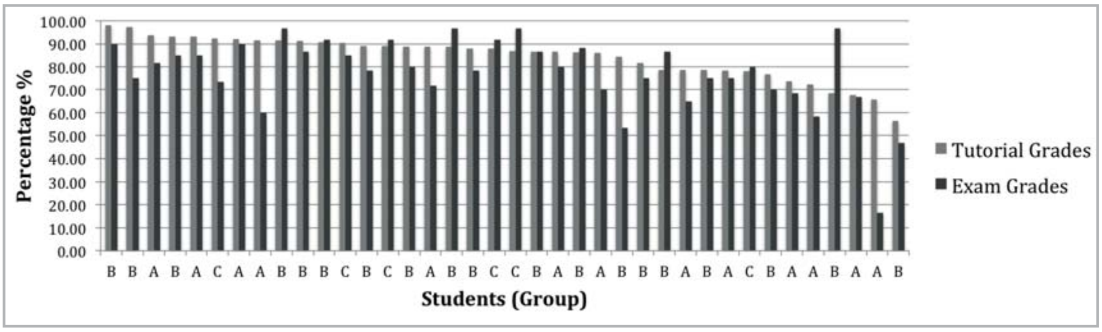

FIGURE 7: EXAM AND TUTORIAL GRADE DIFFERENCE

	Tutorial		Exam		Overall		
Group	**Mean**	**Median**	**Mean**	**Median**	**Mean**	**Median**	**Std Dev**
A	80	86	73	71	75	75	13
B	85	87	79	80	81	82	11
C	87	88	86	88	87	89	7

TABLE 4: FSFD4 2010 GRADES

Figure 6 above shows the exam grades for students on the 2010 FSFD4 course. The results show that students in Groups B & C, which included a large percentage of autonomy and very little structure, performed noticably better in the final exam than students in the highly structured environment of Group A.

Figure 7 shows the students ranking by their tutorial grades, with the exam grades overlaid. The graph shows the variation in the students' performance between the two forms of assessment. In particular this graph shows how some students can deliver consistent high quality work throughout the semester only to perform poorly in the final 1.5hr exam. Very few students achieved the opposite.

Table 5 shows the average grades for each group, including the tutorial grades, exam grades and final grade (composed of 25% coursework, 75% exam).

3.3.4. Discussion

The results suggest that students were more likely to copy from the tutor, from literature or from each other in a controlled environment. Conversely, those in an autonomy-supportive environment demonstrated greater intrinsic motivation to learn, came to see the tutor in their free time and became excited about solving bonus problems. Many of these students were able to develop exceptionally creative solutions.

Students did not attend tutorial classes for several reasons. Some students found the controlling environment of Group A very stressful; they felt like they would be judged for not 'knowing enough'. Others stated that they preferred to work through the material on their own, or that they simply "don't learn well in tutorials". One student described how he did not like when someone told him an answer; he preferred to work it out for himself.

The release of the exam schedule significantly undermined students' intrinsic motivation to learn. Throughout the semester, students in groups B and C became more confident, more autonomous and adopted deeper approaches to learning – all indicative of intrinsic motivation - but with the release of the exam schedule, the students realised that ultimately, others would define the extent of their competence on the basis of their performance in the final exam. Their own opinion was not valid.

There are several possible reasons why students in Group C performed the best during the exam and it was not possible in this case to attribute their success to just one variable. It may have been due to the fact that all students were mechanical engineers, or it could have been the personal attitudes of the individuals in the group. One possible explanation is that the students benefitted from the combination of both specialist and generalist tutors. It was the case that the students received both autonomy (from Tutor B) and structure (from Tutor A) iteratively throughout the semester.

Group discussion:

The reason for encouraging group discussion was to decrease dependency on the tutor to create solutions, to improve contextual understanding through reasoned explanation, to teach concepts to a larger group of students more efficiently, to allow students to see that there are a range of possible solutions and to improve students' ability to construct a coherent argument.

Students in group B were more confident in their understanding of the concepts i.e. have greater contextual understanding of the concepts. They did not see the tutor as the only person who could make a decision on the best solution. They accepted that the tutor was not going to give them a definitive answer; they would need to do the work for themselves. They accepted that there was a range of possible solutions and were therefore comfortable discussing various options. In this way they acknowledged there was no right or wrong answer. Occasionally the tutor would take part in group discussions and assume the role of an equal, sometimes playing devil's advocate and sometimes admitting that he did not know a good answer; a method used by Knowles (1975). Each time a student proposed a solution the tutor would agree and would ask them to elaborate on it or think of another. Tutor B would join a group and question their understanding of the problem. He would also explain that there were many different solutions and that there were pro's and con's about each one.

In contrast there was no group discussion in group A. Any interaction between the tutor and students was predefined and controlled by the tutor. The students learned that there was only one way of solving each problem and that the tutor could give them that answer. They learned to trust the information given to them by the tutor and accept it without question, and if they had the 'right' answer there was no incentive to discuss alternative methods. The students were inclined to focus on finding solutions (looking through textbooks etc.) before they fully understood the problem.

Peer tutoring:

The tutor B realised two things while teaching, the first was that many students encountered the same problem therefore the tutor had to repeat his explanations to several students. This was an inefficient use of the (very limited) time available during class. The second reason was that each time the tutor gave the explanation it improved the tutor's conceptual understanding of the knowledge being presented. It was felt that there was an opportunity for students to teach others and subsequently improve *their* conceptual understanding.

Some students were identified by the tutor as having a high level of knowledge and/or very good conceptual understanding, in some cases surpassing that of the tutor. These students would find large sections of the tutorials very easy and would not learn anything new. The tutor explained this to the individual student and then asked if they would be willing to help out their peers. Every student who was asked agreed however initially they lacked confidence and looked to the tutor for validation. As the semester progressed students became less dependent on the tutor and more confident giving explanations on their own. In one instance two students approached the tutor independently each asking for assistance with tutorial questions. Both had done 3 out of the 4 questions but the questions that they were stuck on were different. Instead of teaching each student in turn, the tutor introduced the two students and asked if they could teach each other. Although the tutor was sitting next to them, neither student sought further assistance or validation from the tutor. This implied the students were confident in their ability to explain the solutions and did not need the tutor. Both students were comfortable challenging the explanations of the other, and when challenged both were equally happy to explain in a different way. The two students left the tutor's office content that they understood how to solve the problems they were stuck on.

Tutor A used peer tutoring as a means to extrinsically motivate students to learn. The reasoning was that if a student knew they may be picked at random to explain a concept in front of the rest of the class then they would be scared enough to learn it. Thus students were told by the tutor to stand at the board and teach the other students regardless of whether or not they wanted to. Throughout their explanation the tutor asked convergent questions to keep them on the 'right' track i.e. to ensure their explanation was the same as the one the tutor would have given. The process was used to motivate students to learn predefined information.

Peer assessment:

Peer assessment was used to give students an alternative perspective on how to solve each problem and to give additional feedback on other students' work.

The process had mixed reviews – some people liked it others didn't. Some students really appreciated the opportunity to see an alternative way of thinking. They received a confidence boost when they were able to understand the reasoning behind the alternative solutions, particularly ones that were not as good as their chosen solution.

Other students however did not appreciate peer assessment for several possible reasons. One student was unable to understand another student's work, made the assumption that he would never understand it, and subsequently lost confidence in his own ability. Other students were not confident in showing their work to their peers due to fear of criticism and some stopped handing in work altogether. These students preferred the tutor to take responsibility, and assess and grade the work as an authority. The students would then trust the tutor's singular assessment.

Self-assessment:

At the start of the semester the tutor asked the students if they would like to assess their own submitted tutorial work and the students rejected the idea. There were several possible reasons why the students rejected the proposal of summative self-assessment. The main reason given by the students was that they had no idea what constituted 'good' work; there was no benchmark, no criteria on which to base their grade. They would have benefited from hearing an expert's opinion (Barrows & Tamblyn, 1976b).

The students had, until this point in their education, been given questions that converged to a single, pre-defined answer. Thus they had not been able to develop the critical thinking skills necessary to assess and/or justify a proposed solution. It is possible that some students would have been prepared to grade themselves later in the semester; and after they had been given an opportunity to develop their understanding of what constituted a quality answer.

Shulman (2005) describes how unexpected deviations from standard ideas such as this are unlikely to be well received by students, and that "to spring it on students without preparation" (p.22) is a common mistake.

Teacher-Assessment (Exam)

The students in tutorial Group B (student-centred) on average obtained higher exam grades than those in teacher-centred tutorial Group A. Similar findings were reported by Catalano (1995) where students obtained higher grades with a student-centred approach, rather than a traditional approach (86%/79% respectively). The highest average grades were achieved by students in Group C, who were given both autonomy support and highly structured lessons. Very similar results were reported by Schmidt *et al*. (1993), who found that tutoring skill (facilitating) and content knowledge were closed linked and necessary for effective tutoring.

Teacher-Assessment (Problem Sets)

Many students submitted work for formative assessment prior to the final deadline. Almost all of the students had created good solutions autonomously prior to the lecture intended to give them those solutions. The students subsequently attended lectures with a deep approach to learning. The amount of work students did on the problem sets and their susequent level of understanding was increased by the presence of intermediate deadlines (opportunities for students to submit their work for formative feedback).

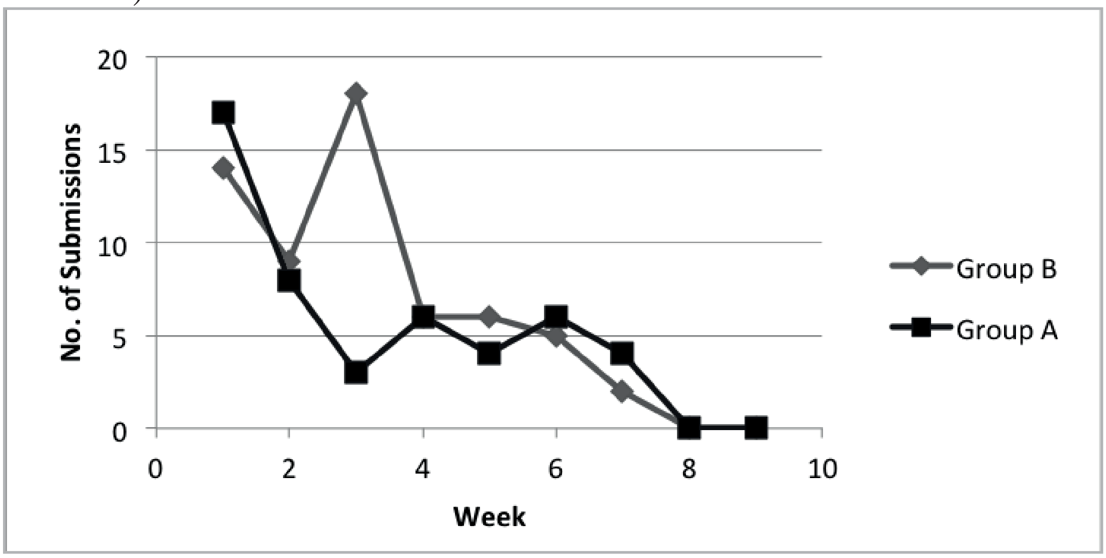

FIGURE 8: STUDENT WORK SUBMISSION

Figure 8 above shows the number of problem sets that were submitted *early* and in time for feedback. This does not include the problem sets that were submitted for summative assessment on their final due date, for which almost all students submitted work.

The two course tutors each assessed the work of the students in their groups (A & B) as well as half the students in Group C. The number of submissions from each group were consistent, and showed a steady decline in the number of submissions each week; with the exception of week three. At the end of week 2, the Group B tutor sent personalised emails to ten students who had not yet handed in any work to gain formative feedback. The email began with their name and explained that the tutor had noticed that the student had not handed in any work yet, and if they needed any help they could ask any time. Of these students, only three did not submit any work for formative assessment the following week. Given the strong correlation between the submission numbers of both groups, it is likely that the emails had an effect on the students. It is also likely that the three students who did not submit any subsequent work either felt confident enough to continue working autonomously, or lacked the confidence to submit work they knew was not perfect.

For many of the students it was the first time they had been contacted directly by a tutor in their (4 or 5) years at university; and many assumed initially that they were in trouble. Thus it appeared that the students who submitted their work following the emails appeared to be extrinsically motivated, although they may have internalised the value of gaining feedback. Thus it might be the case that contacting students individually will increase the quantity of work submitted, but the effect appears to be short-lived.

Referencing:

Several students in Group A copied from the course textbook (referenced), and copied from peers (not referenced) on numerical questions.

Students in Group B and C used textbooks and included references but in almost all cases used their own words. Blumberg and Michael (1992) published similar results. They showed that students who were taught in a conventional manner were more likely to choose faculty-chosen resources; while students taught in an autonomy-supportive PBL environment were more likely to choose their own learning resources.

Seeking information from other sources and providing references is a standard process in education and should be encouraged. There are a few reasons why a student would choose to do this rather than work it out on their own. Some reasons are very positive; it may be faster for example to look up a book than construct an experiment; or the information could be written more succinctly than the individual was capable of writing. Other reasons are negative. An individual may quote a reference because they are too lazy to think, or are not confident in their ability to create ideas on their own.

An education based exclusively on the acquisition of established knowledge will limit an individual to reproducing only that knowledge. An education system that involves creating an opportunity for students to both develop and apply their own knowledge will better prepare students to deal with situations for which new knowledge is required.

Obtaining information from reliable sources is highly beneficial and is the aim of specialist training. However, it is only one component of generalist education as it alone does not encourage the kind of creative, critical thinking skills that education aims to promote.

Student opinions:

Students from all groups enjoyed the visit to the fire lab at the beginning of the semester. They said it allowed them to visualise the concepts and improve their conceptual understanding of the information presented later during lectures. This fits with Felder & Silverman's (1988) observation that the majority of engineering students are visual learners.

Entwistle & Tait (1990) note that students with either deep or surface learning orientations "*are likely to define effective teaching in ways which reflect those orientations*" (p. 169). A student with a specialist mindset is likely to favour rote learning and reject procedures that promote understanding. It is important therefore to understand the mindset of a student before adding weight to their definition of 'effective teaching'.

Students in Group A were taught considerably more knowledge than the students in group B. Feedback at the end of the semester indicated that a very large percentage of group A students were very impressed by the breadth and depth of information presented by the tutor during tutorial classes. In comparison the students in group B complained that their tutor did not present enough information during class.

This should mean that students in Group A *learned* considerably more but the results in the final exam indicate that this was not the case. This is supported in the literature (Johri, 2009; Exley & Dennick, 2009).

The results of a mid-semester survey indicated that students who were taught considerably more knowledge in group A did not believe that the workload was too high compared to other courses. Students in group B, who were encouraged to think for themselves and develop their own solutions felt that the workload was too high.

When asked if it was a bad thing that the workload was too high, students in Group B replied that it was not; they enjoyed the work but it was taking up a lot of their time. This indicated that their enjoyment of the subject outweighed any stress caused by the large volume of work.

Students who were given information did not feel the need to seek additional information on their own. This may seem obvious but it is an important point. Giving a person information without allowing them to develop contextual understanding creates an island of disassociated knowledge. While the individual may be capable of recalling that knowledge, the lack of contextual understanding will limit their ability to connect and synthesise ideas – the basis for creativity.

Students in Group A had no incentive to find information on their own while Group B had no choice but to do so. Group A felt a sense of security that they had all the answers and were prepared for any problem. Group B realised that they did not yet have all the answers and would not be prepared for any problem. Group A students allowed the tutor to take responsibility for preparing them with the necessary information. Any shortcomings in the students' knowledge would be a failure of the tutor. Group B students felt personal responsibility to find and learn the information they needed. They realised that they would have to think autonomously and make decisions on what to learn, with only minimal support from the tutor.

Initially students in both groups were uncomfortable submitting work that they felt was not perfect. Many would give excuses and blame others for the lack of perfection. This is because the students were used to having only one opportunity to submit their graded work, and their first attempt must be perfect. Furthermore, many students felt embarrassed to demonstrate that they did not know the 'right' answer. This is not surprising in an environment where people are 'expected to know' information that has been taught to them. These individuals fear being seen to fail by others and the level of expectation is what drives them to work. This is extrinsic motivation.

As the course progressed some students, particularly in Group A, remained reluctant to submit non-perfect work while others, particularly in Group B became more comfortable doing so. The students who knowingly submitted incomplete work did not feel pressure to fulfil any external expectation; while those who strived to deliver a 'perfect' answer at the first attempt were trying to fulfil the expectations of the authority.

In both groups throughout, there were students who preferred to be told that they had got the answers 'wrong' and wanted to be given the 'correct' answer by the tutor. They wanted the tutor to take responsibility for the success or failure work because they did not want to use their own judgement.

Written feedback:

In both groups the tutors provided comprehensive written feedback on submitted work. The type of feedback varied between the tutors although the emphasis of both tutors was on asking students to further justify their solutions. Both tutors gave little feedback on solutions consisting of fire safety definitions. The degree of variation in the students' answers was too large to be able to give appropriate suggestions of how to improve.

The main difference between the two groups was that feedback given to students in Group B was personalised. This included using the student's name when making a comment and occasionally referring to previous conversations from tutorial class. The tutor would also praise students' ability to create new methods of solving problems without being taught. This encouraged them to trust their own problem-solving ability.

The Group B tutor also attempted to create and support a "growth-oriented" attitude (Dweck, 2006) amongst students by de-emphasising the importance of 'getting the right answer'. This was done by praising effort rather than achievement and by challenging the accuracy of the technical information. The tutor would apologise for setting questions that were too easy if a student felt as though they had reached an optimised solution very quickly. Students would also be praised for pursuing a new method of solving a problem, even if the idea did not work. The reasoning was that there were no negative consequences if the student failed to create a viable solution to a university tutorial question. The questions that asked the student to justify their answer would inevitably lead them to the conclusion that the idea did or did not work. Through this process they would learn very effectively whether solutions were viable or not and most importantly, they would understand why.

The Group A tutor gave feedback specifically on the work presented – the accuracy and validity of the solutions – rather than on the student as an individual. The aim was to ensure the student achieved the aims of the written course curriculum.

The amount of time invested by tutors to provide this level of feedback was very high – significantly more than on courses involving closed questions with a definitive marking scheme. The investment had a high rate of return however, with the majority of students submitting considerably more work than would be expected of them on a 10-credit course. Furthermore, a large number of students commented that the feedback was the best they had received at university.

Tutor as a learning tool:

The tutors had fundamentally different roles:

- Tutor A was an authority
- Tutor B was a facilitator

Students in Group A viewed the tutor as a valuable learning resource as he was able to give clear, detailed responses to any of the students' technical questions. This in itself is conducive to a generalist education provided the student views the tutor as a resource among many, rather than the purveyor of the 'right answer'. There were however students who viewed the tutor as the latter and this implies that the students valued the tutor's opinion of what constituted a 'good answer' over their own. All students value producing technically complex solutions and find it very motivating to see themselves improving at a subject. A problem arises however when the the students learn to value the tutor's opinion of quality work more than their own.

There were students in both groups who would accept the tutor's opinion without question. These students seemed content to submit work that they knew they did not fully understand or confidently explain, provided it was accepted by the tutor. It was therefore entirely the tutor's responsibility to develop a quality solution and ensure the students were able to replicate it. It is unsurprising, given the way in which our education system operates, that students would value an unfounded perception of high technical competence over confidence in one's own ability.

All students in Group A were very supportive of the quantity of information given to them by the tutor, however many generalist students were unknowingly limited in their ability to create innovative new solutions. The human mind always looks for the path of least resistance. If a tutor explains how to answer a question, a student will be less likely to spend hours trying to figure out how to answer that question on their own. The only way generalists would go through the process of finding an alternative is if they had a reason to pursue an alternative e.g. if they doubt what the tutor was presenting. For this to happen they would need to spend time thinking about the problem and understand the purpose. If a tutor gives an extremely confident, detailed explanation of a solution to students before they are given time to think about the problem, the students will have no reason to doubt and no reason to believe they could create a better alternative. Thus education focused exclusively on providing information does not promote autonomous thinking and learning, particularly amongst generalist students.

Conversely many students in Group B did not appreciate the lack of tutor teaching or the tutor's refusal to 'give them the answer'. These students had become used to the standard style of teaching in university, where tutorial questions can be answered entirely using information available in course notes. The standard role of the tutor was to help them apply that information to the tutorial questions. The 2010 FSFD4 course was different in that many of the tasks were designed such that students could find answers using the Internet, books & lectures rather than from course notes. The students lacked practice in resource-investigating and did not know how to find information that wasn't specifically given to them.

Several students who complained at the lack of information provided to them by Tutor B. They did not want to think autonomously and did not need to understand the context of the information they were applying. This was observed by Litzinger *et al.* (2011). The tutor assumed this was due to laziness – it was easier to ask the tutor for an answer than spend time looking through piles of textbooks or searching on the Internet. The majority of the students did respond, albeit grudgingly, to the tutor's insistence that they work autonomously and decide for themselves what the most effective solution would be to each question. This implied that the majority of students were capable of contextual thinking and understanding.

There were a small number of students however who could not adapt. They complained frequently and were clearly unhappy with the way the tutor was running the tutorial classes. These students were extreme Specialists and therefore it was not about laziness or not wanting to use reasoning to work out a solution, it was about their poor reasoning skills and subsequent inability to think holistically or contextually. These students could only work in situations where they were given a procedure or rule to follow, or asked to memorise small amounts of detailed information in a sequential order. In the standard education format they usually thrive and the Specialists on this course were no different. The students who were least capable of thinking contextually about an engineering problem were the ones with the highest average exam grades. These students did not question why they needed to know any of the information they were being asked to learn at university. They were not able to think of how they could synthesise the information and apply it in reality, they just knew what they had to do to get a good grade. These specialists were therefore not creating their own definition of success and were entirely dependent on the tutor to define success. Thus they were totally lost without clear, sequential guidance throughout the semester. Tutor A provided this clear, sequential guidance.

When a number of students in Group A encountered the same problem the tutor would stand at the board and explain the solution to the entire class. This is an effective way of transferring a single piece of information to a large number of students at the same time.

In contrast, when a number of students in Group B encountered a problem the tutor grouped them with students who had worked out solutions to the problems on their own. This had several benefits including increasing student confidence, increasing discussion, increasing motivation to work autonomously, exposing a range of possible solutions. If none of the students could answer the question then either the question had to be discussed and/or re-phrased, or the students needed more information that was not yet available to them. In the latter case a lecture may be entirely appropriate.

Students in Group B liked the stories told by the tutor. It increased their interest in the subject and increased their contextual understanding of a particular concept. However the more specialist students did not see value in the stories or the subsequent discussions and would have preferred simply to be told what to do.

All students were told by their tutor that they were welcome to come to the tutors' office and ask questions at any time.

Many students came to see Tutor B of their own accord. They came throughout the semester and showed genuine interest in the subject material. The students engaged in detailed discussion of the problem set tasks and asked for help with questions they were stuck on. Felder *et al.* (2000) describe a similar experience. The tutor tried hard not to give students answers he suspected they were capable of giving themselves. In most cases where a student asked how to answer a question the tutor replied: "How do you *think* you answer the question?" In most cases the student launched into a comprehensive explanation of their ideas and in almost every case the tutor ended up agreeing with them that their reasoning was good and that their solution would work. The tutor gave suggestions for information sources or gave additional information himself, caveated by saying ‘this is just one idea but…’ In a few cases the students’ reasoning was flawed; in these cases the tutor would challenge their assumptions until the student realised why their solution would not work.

Only a handful of students came to see Tutor A to request assistance throughout the semester; despite being told that the tutor would be available any time, and despite the tutor having a very high level of technical understanding. The students were intimidated by the tutor and were not comfortable revealing their level of understanding as they knew the tutor had a level of expectation that they may not live up to. The only exception was in the days immediately before the exam when several students came to see the tutor and request assistance in answering the past exam papers. The students’ fear of underperforming in the exam exceeded the fear of embarrassment of revealing their level of knowledge.

Summary of the above section

- Group A was more conducive to specialist training.
- Specialists in Group A loved being given the solutions, they wanted to copy and paste the solutions because if the tutor’s explanations were good then their answers were also good.
- Generalists in Group A were blinded to the alternatives by being given only one solution before being given the opportunity to think about it.
- Group B was more conducive to generalist education.
- Generalists in Group B were comfortable developing their own ideas.
- Specialists in Group B did not like the lack of teaching; they did not want to think and take responsibility for their own work.

Student Motivation

Many generalist students were intrinsically motivated to solve the problem sets because they found the questions inherently interesting. Other students were not intrinsically motivated and complained about the tutorial questions, some stating that they were not specific enough. These students were extrinsically motivated specialists and did not like the fact that the method to achieve the highest grades was not clearly defined. Finally there were those who were disengaged, uninterested and unmotivated with respect to answering the questions – these students may have been subjected to a long list of boring subjects while at university and had brought similar preconceptions to this course. It was easy to differentiate between the groups. The generalists handed in work and did not complain, the specialists handed in work and complained a lot while the disengaged students handed in nothing and said nothing. The tutor encouraged the students' interest in the subject by telling stories and describing fire phenomena. As the semester progressed, many of the disengaged students did work without being told to do so, implying that their intrinsic motivation had increased.

Many students in Group A responded well to extrinsic motivation and produced large amounts of work. However much of the work lacked creative originality or critical reasoning. This was in keeping with the results of studies carried out by Deci & Ryan, who found that extrinsic motivation led to a decrease in quality and quantity of work involving higher cognitive processes. Other students did not respond well to extrinsic motivation; and being scared by the tutor into learning complex information had a significantly negative effect on the students' intrinsic motivation and productivity.

Students in Group B also had their intrinsic motivation unintentionally undermined in several cases. Most often it was caused by the tutor giving too much information thus giving the impression that the students should know more than they did, and that they were incapable of producing a solution on their own. The second, and more noticeable reason why students' intrinsic motivation plummeted during the semester was the day the exam timetable was issued. Until this point students had been happy to spend large amounts of time discussing the problem set tasks and other fire-related topics and had become confident in their ability to answer questions. Hearing about the exam date shifted their focus onto what they needed to know for the exam and the subsequent realisation that they had little idea what was expected of them caused panic. The tutor tried to explain to the students that they should just focus on the subject, that the exam was irrelevant and a good grade was an inevitable by-product of learning. However the students replied, “that’s easy for you to say, you’re not sitting the exam, and the only thing we have to show from this course is a grade”.

Student Confidence

In both groups many of the students initially lacked confidence in their own ability. This is most likely due the way in which they had been assessed throughout university. Assessment at university is almost exclusively summative, where the students’ ability is criticised and categorized by another, usually by an authority on a particular subject. The only way a student can change the label of themselves is if they convince the authority to change their mind. The *students* had until this point been unable to practice self-assessment and improve their confidence and self-efficacy. The result was that many students lacked self-esteem.

Students felt uncomfortable submitting solutions that they knew contained mistakes and did not have the confidence to knowingly be ‘wrong’. Consistent summative assessment had enforced the idea that they had only one opportunity to submit an answer and that there was no benefit to iterating and improving their solution once it had been submitted. The students were therefore reluctant to submit work that they knew was unfinished and could be improved, preferring instead to hold onto it until the deadline where they had to submit it regardless. Seth Godin (2010) describes this phenomenon.

The students responded very well when they were encouraged (not forced) to submit work for formative assessment. Many were surprised to be given the opportunity to improve their work.

By the end of the semester there were students in both groups who felt the tutor had helped improve their confidence. The teaching styles were completely different but the overall effect on some students' confidence was almost identical. It is unclear from the data what exactly the students were more confident about. It is likely, given the different teaching styles, that the students would be confident about very different aspects of the course e.g. grades vs. understanding.

Students received a confidence boost when they got an answer 'right'. They enjoyed the feeling of closure, and the confirmation of achievement. All students appreciate being told they have done well, however the more specialist students *needed* to be told. Specialist students in Group A had their confidence improved when they produced solutions that the tutor was happy with/praised them for. Specialist students' confidence remained low in Group B where the tutor refused to tell them whether their solution was good or not.

Every student's confidence improved when they could see themselves improving at the subject. The feeling of mastery is one that should be explored more carefully. The tutor in Group B avoided making the decision of what constituted a good answer in order to avoid undermining students' autonomy. However, the lack of information meant that often students did not get the feedback they needed to experience the motivational effects of mastery.

Group A students were not as confident as their Group B colleagues with respect to arguing with their peers, the tutor and the lecturer on the problem set solutions, particularly regarding information they had not specifically been taught. One of the more generalist students in Group B was confident enough to argue with both tutors about the problem set questions and in one case was confident enough to admit that his argument was flawed.

In both groups the students' work rate increased proportionally to the amount of work they were given - more problem sets led to more time spent working on the material, however each student reached a limit when they were asked to do too much, they became overwhelmed, the task became too difficult and their work rate fell to zero.

In addition to the quantity of work students were given, the quantity of information had an optimum too. If the students were given too little information they simply asked for more, and their confidence was sustained if not increased. If on the other hand the students were given too much information, they became stressed, their intrinsic motivation and confidence dropped, and they resorted to surface learning strategies.

For example, one student in Group B came to see the tutor two days before the exam. While waiting to ask a question he stood behind a group of students who were in the office to see Tutor A. The tutor was going through a detailed explanation of the energy equation, which included a significant amount of complicated calculus. The student realised that he was not able to understand anything the tutor was writing on the board and yet he only had one day in which to learn it. The student became visibly stressed, his confidence decreased and he began to panic. Tutor B asked the student to take a seat and calm down. The tutor then gave him a whiteboard pen and asked him to write out the energy equation on the whiteboard. The student's first response was "I can't". The tutor responded by asking him very low level questions about how he would go about figuring out how long it would take for a heater to ignite a wooden table. The student described the process and the tutor helped him turn his words into symbols to be used in an equation. The tutor did not write anything down, nor tell the student what to write. If the tutor noticed a mistake he did not say anything, but let the student continue until he realised his mistake or asked for help. After 20 minutes the student had written a complex energy equation to a level that was appropriate for the exam and was confident in his ability to reproduce it. He left the office and returned half an hour later to prove to the tutor that he could do it on his own. He was very proud of himself and significantly more confident than he had been one hour before.

3.3.5. Conclusion

1. Autonomous learning led to excellent contextual understanding of the subject and improved students' ability to define and solve new problems
2. Although the quantity of information presented was far less, students learned more and had greater contextual understanding than in the 2009 course.
3. This greater contextual understanding indicated that the course encouraged the generalist mindset.
4. Neither Group A nor Group B was optimised for specialists or generalists as neither provided enough support. Group C was the only group that encouraged both the generalist and specialist mindset and the students in this group performed very well in the exam. The combination of both generalist and specialist support is worth pursuing in future studies.

3.4. 2011 US Fire Courses

3.4.1. Introduction

The aim of this section was to discover improvements in the way fire safety engineering is taught at university, by better understanding alternative teaching methods through observing teaching practices in American Universities.

The hypothesis was that although teaching methods vary widely, there are certain key features of teaching that will have a profound effect on students' intrinsic motivation to learn. This section assesses only the teaching methods used on fire protection engineering (FPE) courses.

3.4.2. Method

The method was to gather information from current, leading programmes in fire protection engineering (FPE). It is widely acknowledged that the most advanced undergraduate and postgraduate programmes in the U.S. are at the University of Maryland and Worcester Polytechnic Institute (WPI) respectively.

Observation in classrooms

Data was gathered through observation in classrooms and through semi-structured interviews of students and faculty members. In total, five course lectures (two at WPI, three at Maryland) and one lab class (Maryland) were observed and qualitative data was recorded.

Observation of the students focused on student engagement and perceived interest in the subject material. It was assumed that students were actively engaged and pursuing a deep approach to learning if they were:

- Asking questions to improve their understanding of the subject material;

- Discussing the subject material with other students;
- Focusing on and reacting to the lecturer (e.g. facial expressions depicting emotion).

Conversely it was assumed that students were actively disengaged and pursuing a surface approach to learning if they were:

- Using their laptops or phones to browse social media or play games;
- Asking superficial questions related to administration or process (e.g. asking the lecturer to clarify a symbol on the board, or whether the information will be in the exam);
- Staring at the lecturer without any facial expression;
- Sleeping.

Observation of the teachers focused on:

- The material being presented;
- Relation of concepts to reality;
- The use of either controlling or autonomy-supportive language.

The material being presented was all related to fire and should therefore be inherently interesting to students who intend to become fire protection engineers.

Semi-structured interviews

Semi-structured interviews were conducted with faculty members and students. The intention of the student interviews was to find out which courses were intrinsically motivating to students (which ones they enjoyed); and which courses they felt they learned the most from. The intention of faculty interviews was to find out what the faculty members valued most on their course - what they felt was important for students to learn.

3.4.3. Results/Discussion

The following qualitative information was gathered from interviews and classroom observations.

University of Maryland

Lecturers at UM had good working relationships with their students. Many of the students would work at desks outside the academics' offices and ask questions when they needed help. Work was submitted and collected directly from the lecturer's office.

Faculty stated that the overall aim of the FPE programme was to increase students' understanding of 'the fundamentals'. The majority of lectures therefore involved large quantities of fundamental knowledge and students were assessed on their ability to recall and/or apply it accurately.

Many students were noticeably disengaged during lectures, and from discussions with the students it appeared that many had adopted surface learning strategies for learning technical information. Thus it appeared that lectures did not succeed in fostering intrinsic motivation and contextual understanding, an observation supported in the literature (Perkins, 1986; Barneveld & Strobel, 2011).

Several students stated that their favourite course was a sprinkler design course where they were taught fundamentals at the same time as they applied them. i.e. lectures during a project. It was interesting that even though students expressed a preference for this iterative process of knowledge acquisition and application, they did not fully understand why it worked. The same students, when asked how they should be taught felt that they needed the fundamentals first, *before* they could do a project. This was also the opinion shared by the majority of the faculty.

One lecturer said that he once tried giving open-ended questions without a clear marking scheme and that the results were disastrous. It is likely that the lecturer changed the assessment method without changing the underlying philosophy, and that the students still perceived the environment to be controlling. Not having clearly defined expectations would be viewed by students as being incredibly unfair. An example would be asking open-ended questions with an infinite number of solutions, then assessing students against the 'right' answer (as defined by the lecturer), but not revealing what that 'right' answer is.

In contrast to the very prescriptive fire protection courses, the University of Maryland runs an open-ended design course for all first-year engineering students. The 'Keystone' project, as it is known, is intended to introduce students to engineering design at the start of their degree. Each year students are given a very clear purpose: to design and build a hovercraft capable of navigating an obstacle course autonomously. The course has proven to be very popular, and students have demonstrated their ability to learn and apply complex technical knowledge from technical lectures delivered throughout the semester (Calabro, *et al.* 2008). Similar courses at MIT and Princeton are discussed in Section 3.5.

Worcester Polytechnic Institute (WPI)

Faculty Interview #1

The lecturer believed that until the fire protection industry creates tools with high fidelity, fire practitioners will need to understand the building codes. CFD is still unreliable therefore the students should learn to engineer using prescriptive guidance. The faculty member did not consider an alternative strategy involving educating competent engineers to be capable of defining and solving problems without using prior examples.

The lecturer found that it was difficult to break students out of a passive rut, and to get them to think for themselves. He said he knew that the students had to be more confident and more comfortable making mistakes but said he found it difficult to encourage autonomy when standardised testing was "trying to produce robots". He was unaware that formative assessment as an alternative to standard testing could achieve his aims in practice.

Fire dynamics at WPI is example driven, i.e. students learn an example of how to use a method (codes and engineering science), and then apply it to practice problems in homework. This learn-by-example style of teaching is conducive to a specialist mindset as students learn to value conformity over autonomy. It allows students to practice using the equations but does not encourage them to think about the context and understand the big picture. The eventual aim was for people to think for themselves however individuals are unlikely to develop their own reasoning once they have been given a solution that has been shown to work.

The lecturer thought that the difference between students was their ability to 'abstract', the ability to derive context from individual isolated pieces of information. "Maths is an exercise in abstraction" he said. In his eyes the role of the lecturer was to provide fundamental information, the role of the student was to figure out how that information applied to reality. Teaching styles were not seen to have an effect on student learning and they were just a "flavor of the month". This implies that all students have a specialist mindset and that the only way to derive context is through this process of "abstraction". If this was the case then changing the type of tutorial questions would not lead to increased contextual understanding nor increased knowledge. This assumption was proven false in the FSFD4 2009/2010 courses.

Classroom Observation #1

During a 3hr fire science class the lecturer attempted to create a discussion with the students. However the lecturer only asked closed-ended questions i.e. questions that converged to a single answer. That meant only the students who were confident they had the 'right' answer gave responses.

The students did not engage in discussion because their opinion was not relevant.

Faculty Interview #2

This faculty member believed that his role was “to give students a string to follow” - a method to learn. The students were then assessed on whether or not they could reproduce the method, even if they failed to produce the expected numerical solutions. This teaching philosophy demonstrates to students that numerical accuracy is not always essential and also suggests that there is only one way of solving each problem. The aim therefore is to learn to identify problems and apply the established problem-solving method from memory.

Classroom Observation #2

One method of teaching at WPI was distance-learning. The class had three students present, while the remainder of the course viewed the lecture online. The concept of recording and streaming lectures is not new and has been shown to be a very efficient method of delivering information to large audiences (MIT, 2013; Udacity, 2013). The issue with distance learning is the lack of interaction between the lecturer and the audience. The lecturer has no immediate feedback on whether or not the information has been communicated in a way that the audience understand.

Faculty Interview #3

The lecturer found that students were not thinking critically and were just accepting the information they were given without question. He had not considered encouraging students to doubt the validity of some of the concepts by revealing some situations in which they do not apply and to question the origin of information.

"Fire Dynamics" is a tool. The fire dynamics course is a series of lectures aimed at providing students with knowledge about how to use the tool more effectively. On its own it lacks purpose, and therefore students lack intrinsic motivation to learn the subject.

3.4.4. Conclusion

The fire courses at WPI and Maryland create a controlled, specialist environment similar to that of the US fire protection industry.

3.5. 2011 US General Education

3.5.1. Introduction

The aim was to gain an understanding of innovative teaching philosophies and methods, irrespective of the subject material, and combine them with fire engineering content developed at the University of Edinburgh.

The study would primarily focus on observing teaching and learning behaviour on structural engineering courses. The reason being that for decades structural engineering has strived to move away from prescription and it was believed that the programmes were aimed at providing a more generalist education in line with the demands of structural engineering industry.

3.5.2. Method

The primary form of data collection during the study was observation and semi-structured interviews, from which a grounded theory could be inductively derived (Jorgensen, 1989; Bogdan & Biklen, 1992; Charmaz, 2003).

Princeton

Princeton University was chosen primarily because it is based on a liberal arts education perceived to support the generalist mindset. This style of education exposes students to a wide variety of subjects and encourages them to develop their own way of thinking about the taught material. This is fundamentally different to the European polytechnic model, which is intended to train students to fulfil pre-defined professional criteria (Sheppard, Macatangay, Colby, & Sullivan, 2008).

Princeton's teaching philosophy is evident from their tutorial classes or 'precepts' (Princeton University, 2003). During these classes up to six students participate in discussions and debate on papers, lab experiments and news stories; while an academic or post-graduate tutor (preceptor) chairs each session. This philosophy extends to traditionally prescriptive subjects such as structural engineering.

MIT

MIT was chosen as it has a reputation for being a very practical, hands-on engineering university where students 'learn by doing'.

As with Princeton, information on teaching was gathered through participant observation. The researcher attended lectures and observed both students' and lecturers' behaviour before deriving an overall theory to provide an explanation.

Additional qualitative information was gathered from interviews with student and faculty members. In particular the interviews aimed at discovering the motivations for both teaching and learning in a class.

3.5.3. Results & Discussion

Teaching holistic design

Students at Princeton and MIT were encouraged to take a range of subjects and understand the global picture. In Princeton in particular students are not confined to a specific degree programme until after their second year and even then it is very flexible. During the initial two years students are encouraged to take a range of subjects to help them decide which path they would like to pursue. All courses are offered to all students with recommended pre-requisite courses stated in the course outline. This helps students select the right courses for them.

At Princeton it is common for courses to incorporate several subjects. This allows students to see the connections between different fields and in doing so better understand the global picture. Courses include: Structural Art, Economics of Criminology, Stochastic Calculus of Brownian Motion, High Tech Entrepreneurship, Democracy in Architecture & Mathematical Biology.

In the Structural Art course, the lecturer believed that structural engineers rely too heavily on architects for creativity; and that engineering is now (incorrectly) perceived as being the calculations part that follows on from the architect's design. The lecturer wants to go back to the point where structural engineers designed beautiful buildings on their own – without architects.

In class the lecturer told stories and spoke of the structural engineers as people driven by the social, cultural and political influences of the era. This was essential to understand the driving forces that shaped their designs. The students were also given the opportunity to design and build their own models of structures to gain a better understanding of how it could actually be built (this can't be done on paper).

MIT students were also encouraged to choose from a range of elective subjects. Some degree programmes were professionally accredited e.g.

engineering, and therefore students were required to take certain subjects. However, MIT students were allowed to create their own degree path and, if successful, the student would be awarded a unique, unaccredited degree.

Engineering students were also encouraged to take part in lab-based courses that involved designing, constructing and testing prototype models. Thus the students were able to take responsibility for their own learning and experience what it was like to be a professional engineer. Below are examples of design courses from Princeton, MIT and Maryland:

The 2.007 course (MIT)

The 2.007 course is the most well-known engineering design course at MIT. A plaque in the MIT museum gives the following description:

*Prof. Woodie Flowers handed a syllabus to students enrolled in course 2.70, the Mechanical Engineering "Introduction to design" class, with a simple but maddening challenge: "Design and build a robotic system for putting a round peg in a square hole, while a competing system tries to put another peg into the same hole." Students received a box of supplies – a variety of cardboard tubes, cords, two motors, sprockets, and rubber bands – and a series of lectures that introduced the fundamentals of design. The course is demanding, but students love it. Hundreds now pack the "final competition" cheering on friends, the most elegant contraption, or even the biggest failure. For four decades, this hands-on course has taught "gracious professionalism." Recently renamed course 2.007 *Design and Manufacturing," it has become one of MIT's iconic classes.*

Entrepreneurship video game project (Princeton)

On the Princeton entrepreneurship course students were asked to create a concept for a new video game involving a peripheral (gun, glove, glasses etc). The students were asked to present their game to the class at the end of the semester and were given a range of informative lectures throughout the course to help them improve their design and increase the likelihood that it would be commercially successful.

Form-finding (Princeton)

The form-finding course at Princeton involved students designing and building a prototype structure using form-finding. i.e. developing the most structurally efficient shape for a design. The students created some very innovative forms inspired by lectures they had received throughout the semester.

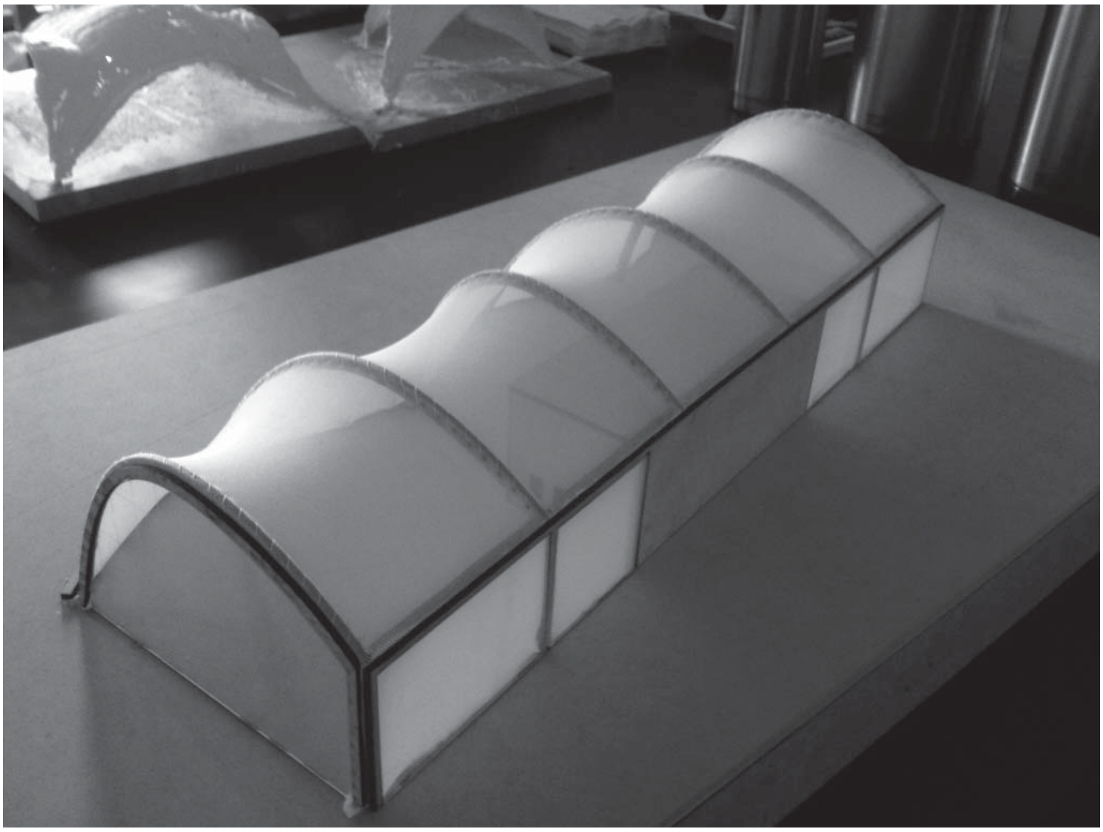

FIGURE 9: FORM FINDING AT PRINCETON

Figure 9 above shows one of the models made by students enrolled on the form-finding course at Princeton. Several other models were made, including forms made by draping plaster of Paris over a suspended form (background of Fig. 9). These plaster models are hung in tension and, once inverted, are very strong under compression loading. There was a significant amount of variation in the students' designs, indicating a high level of autonomy and creativity.

Column design, build, test (MIT)

A structural engineering class at MIT set an open-ended challenge to students. The purpose was to design and build a structural column to achieve one of the following goals: the greatest load capacity, the greatest load/weight ratio and/or the most accurate load capacity prediction. The limitations were that it had to be 1ft – 2ft high, max 5in wide, constructed using only balsa wood, dental floss and wood glue and could not have any solid wood sections greater than 1sq.in. The lecturer told the students: "don't limit yourself to I-beams. They can be any shape you want".

After they were given the challenge (but prior to the lab class) the students were given a lecture describing the internal forces – tension & compression within a beam. The lecturer described the form-finding methods used by Gallileo to minimise internal stresses and maximise efficiency. The lecturer then moved on to shear force diagrams (SFD) and bending moment diagrams (BMD) and explained how they could be useful in developing a structurally optimised design. When the lecturer began explaining more complex mathematical formulae associated with BMDs and SFDs the students became disengaged. The lecturer acknowledged this and said: "I feel a great gulf has opened up between me and you after I've explained this". It was evident from the students' eventual designs, that the students had been able to understand the global concepts but they were not ready for the details. They had not yet discovered a *need* for those details.

The students worked in teams of two to design and build the column. Construction and testing took place in a lab in a single day, nevertheless some of the columns looked very professional, particularly ones made using the laser cutter. The columns were crushed using load-testing apparatus.

During testing one student stepped in front of the data-logger and began commentating on the force/strain curve; shouting out the force and deflection as it changed; the atmosphere was quite exciting. Because each slope will be different for each failure mode, the students were able to learn what type of failure leads to what type of graph, and vice versa.

One group had developed a tiny 0.5oz. (15g) column based on a form-finding lecture given earlier in the course. It had a triangular cross-section and fins on each face that were formed in the exact shape of the bending moment diagram. The two students were asked to predict what load the column could take. One of the students had done the calculations but they predicted a failure load of over 800lbs (360kg) so he wasn't sure, he assumed his calculations must have been wrong to have such a high failure point. During the test the column did not fail at 800lbs; it failed at 900lbs (410kg). The students were visibly excited about exceeding their load calculations, and achieving such a high load-to-weight ratio.

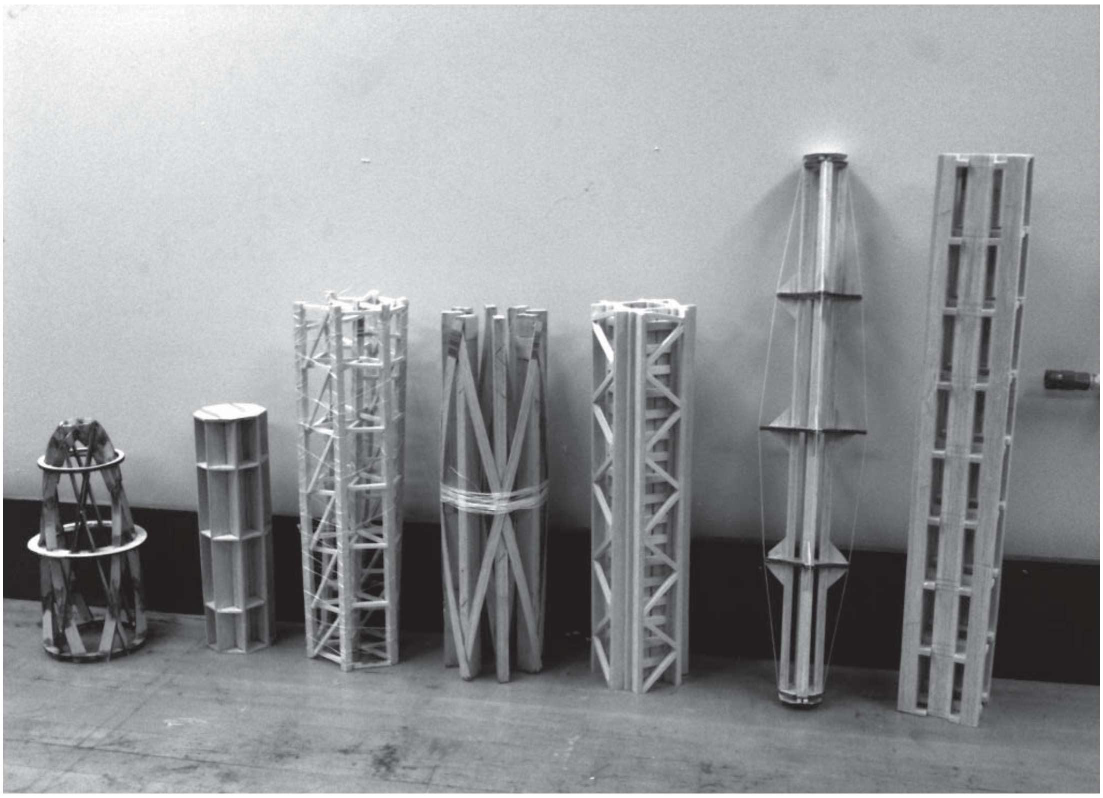

FIGURE 10: COLUMN DESIGN, BUILD, TEST AT MIT

Figure 10 shows a range of columns designed and built by students on the MIT structural engineering course described above. One of the larger columns (far right) held an incredible 4000lbs (1800kg), although it did not obtain the strength-to-weight ratio of the 15g column described above (not pictured).

Bridge design course (Princeton)

Princeton offered a bridge-building lab where students designed, built and tested models of bridges.

David Billington explained to students that "*the art form of structure lies in discipline and play*" (Billington, 1985) and that they should follow this philosophy when designing their own model bridge.

The 'discipline' that Billington was referring to was in maintaining scientific rigour during a design, ensuring that, whatever form the structure takes, it will be structurally optimised. Billington described how the great engineers had historically had very good understanding of scientific principles and were rigorous in their attention to detail.

'Play' on the other hand is the intrinsically motivated, and autonomous act of creating something, just for the enjoyment of doing it. Csikszentmihalyi (1975; 1997) offers an appropriate definition of 'play', which he describes as "autotelic experiences" – from the Greek *auto* (self) and *telos* (goal or purpose). He describes how, in the midst of an autotelic experience, the goal is self-fulfilling; the activity is its own reward. He observed how painters were so enthralled in what they were doing that they seemed to be in a trance. For them, time passed quickly and self-consciousness dissolved (Pink, 2010).

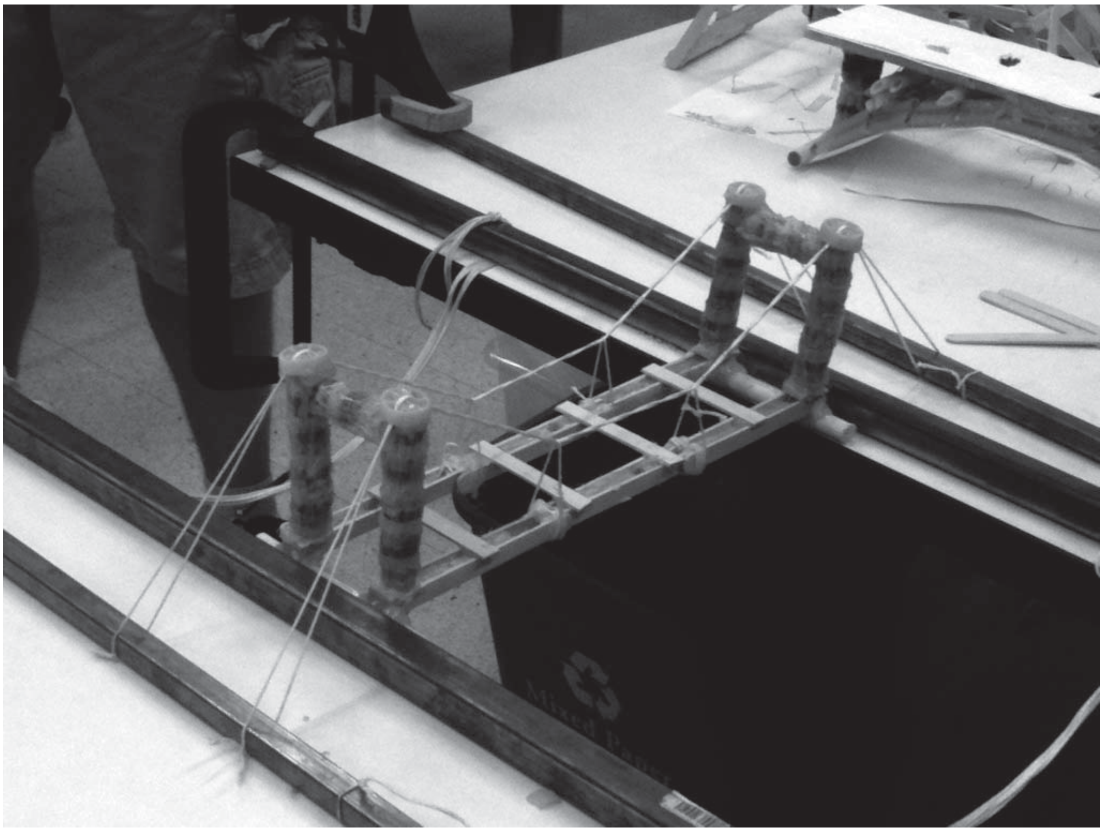

FIGURE 11: BRIDGE DESIGN COURSE AT PRINCETON

The above bridge model was constructed using string, lollipop sticks, circular pasta shapes and string; and tested to destruction under linearly-increasing vertical loading. The students designed a wide range of unique bridges although most were based on designs that had been presented in lectures. Thus students were employing the notion of play (autonomy) and discipline (structure) in their designs.

It was interesting that none of the US courses reviewed as part of this study relied on tutorial questions to generate an intrinsically motivating purpose prior to lectures. Even the courses with world-class lectures had very prescriptive tutorial questions that required students to memorise and recall information. These tutorial questions would likely not generate intrinsic motivation to learn, and at best would create internalised extrinsic motivation (students accept that grades are the purpose of studying).

Teaching

Lectures can be used to *support* an intrinsically motivating purpose. Billington used lectures to great effect by telling stories and communicating passion for the subject. As it was discovered in the 2009 FSFD4 course however, students cannot derive purpose from lectures and will lose motivation when a lecturer presents information before the students internalise the reason to learn that information.

Many lecturers began talking about knowledge without first allowing the students to develop their contextual understanding. Thus students did not see the relevance of the information and had no immediate incentive to learn.

The students at these top universities were by their nature incredibly hard-working. In one particular lecture, students arrived at the class, sat evenly throughout the room and spoke quietly amongst themselves until the lecturer arrived. At that point they stopped speaking, took their notebooks out and listened intently. They were clearly intrinsically motivated to learn, and were listening to the lecturer to gain the answers that they were looking for. The lecturer immediately began writing large quantities of knowledge on the blackboard, which he copied from a set of notes in his hand. As he wrote he spoke out loud and explained what each of the symbols and equations represented. The students still seemed very motivated.

It was clear that the lecturer expected his audience to follow his equations without any difficulty. Indeed many of the students followed closely (and even corrected his mathematical mistakes).

The lecturer asked convergent questions about the material and used ‘right’ and ‘wrong’ when referring to the students’ responses. At one point he asked if there were any questions and one of the students asked a question on torsional vibrations. He gave an explanation and said “does that make sense?” The student replied, “I’m sorry I’m still confused.” This clearly annoyed the lecturer, who gave the same explanation again, word-for-word, albeit in a slightly more clipped voice. The student still looked confused.

The lecturer was very focused on presenting the details. He began talking about shear stresses in a cube. This drew blank looks from the class, or at least stopped them speaking. He also said, “The shear stress will of course, be zero”, assuming that it was obvious. Then one student asked, “So, why is the shear stress zero?” His answer did not satisfy the students, and two girls asked him to repeat his explanation. Even after he explained for the third time saying, “of course we know that…” the students still looked confused. Even so, he was eager to move on to the next topic. He didn’t ask any further questions of the students, or do anything to try and understand how much/little his audience knew (he had no feedback loop).

The lecturer had assumed that the students had an understanding of steps A, B, C, D & E and therefore moved on to explain F on the board. The students asked several questions which amounted to: “Where did that come from?” or “how did you arrive at that equation?”

The students did not understand the context therefore there was no clear reason to learn the presented information; nevertheless the lecturer was determined to ‘cover’ the information that was assigned for this lecture. It was clear that the information he had presented on the board could have been obtained by reading a textbook. He had not taken the opportunity to interact with the audience and give them something different.

After such an enthusiastic start, most of the students looked bored after 20 minutes. Their eyes were glazed and they were yawning. Some were doing homework from other courses or playing on their smartphones and it was clear that it is the lecturing style rather than the students’ lack of intrinsic motivation had caused them to mentally ‘switch off’.

Even the students who understood him (and asked detailed, challenging, relevant questions) looked bored and were rolling their heads back. One girl was asleep. The students on the back row were discussing with each other what the equations meant and were deciding if they wanted to ask a question. Not a single student managed to retain the enthusiasm and motivation they had when they came in.

The lack of context, and application to the real world (i.e. purpose) had the biggest impact on motivation; there was no explanation of the lecturer's reasoning, just explanations of what each of the terms meant.

The above example is just one of many lectures where the lecturer failed to justify the need to learn the information being presented. The vast majority of lecturers transcribed notes onto the board for the students to copy without answering the fundamental question of *why* that knowledge was important; and, more importantly, what the students would *not* be able to do if they *didn't* have that knowledge. It was not the quality of the presentation – some lecturers could communicate very effectively – it was the lack of meaningful purpose. Without contextual understanding, the students could not make a decision about what was worth learning and what was not.

Many engineering lecturers for example were quick to present 'the solution' without giving students the chance to think about and define the problem. The lack of contextual understanding of the presented solution however meant that students were limited in their ability to apply it to complex real world problems. If the problem was changed slightly, the student would not be able to adapt their solution in an appropriate way.

It was easy in most cases to identify if students lacked purpose; the students would ask questions beginning with the word *why* e.g. "why is this important?" along with other questions that attempted to derive meaning. For example, in one class the lecturer gave a very clear, detailed explanation of a technical concept and a girl asked, "so what are you like, trying to show?"

Two Princeton preceptors (tutors) were tasked with preparing for a tutorial class that was intended to ensure students 'covered' information from the structural engineering syllabus. The course had two different lab experiments, however due to the number of enrolled students each student was only able to attend one class. It was up to the preceptors to ensure the students covered the information from both lab experiments; this included concepts such as torsional stiffness and the forces created by distributed and point loads.

One preceptor knew that the students would find the class boring and had developed several forms of *extrinsic* motivation to encourage them to cover the information. This included asking individual students to stand at the board and describe what they had done during their lab class while the preceptor asked closed-ended questions. It was assumed then that every student had heard what the class was about and had therefore covered the information. The result was that the students were bored, were not confident explaining what they had done and did not appear to engage with the material. Furthermore, many seemed scared that the answers they were giving to the closed questions were not what the preceptor wanted to hear. Many asked repeatedly: "Is that right?"

The other preceptor developed an *intrinsically* motivating purpose to the same tutorial class through active discussion. At the start of the class he asked the students to sit in groups with students from a different lab class. The aim was to ask and answer the following question: "*Why did you spend your Wednesday afternoon doing a lab class?"* The students would present on behalf of students from the other group, such that students from lab group A would argue and justify why students from lab group B spent time doing their experiments. The discussion was lively and the students reached very high levels of understanding very quickly by asking direct questions of the other students. Intererstingly one student interrupted another student during their explanation to ask an extremely trivial question. The other student gave a simple, informative answer, checked if it was understood and then continued with the explanation. There was no embarassment or judgement from either student.

Self-directed MIT students who were intrinsically motivated and who wanted to take responsibility for their own learning were encouraged to do so. One mechanical engineering student described how she wanted to be a toy-designer. She chose several courses in education and child psychology that were not part of the mechanical engineering programme and dropped several courses that were. In all only half of the courses she studied were mechanical engineering classes meaning she would not graduate with an accredited degree. This fact did not concern her at all; in fact she believed the specialisation and uniqueness of her degree made her more employable. It is likely that she is correct. John Ochsendorf, an MIT professor, constructed a similarly unique degree when he dropped half of the required civil engineering classes to study archaeology. He too ended graduated without an accredited degree and is now one of the world's foremost experts in the analysis and renovation of ancient structures.

In an interview for MIT 150 Ochsendorf says: "*I think inventing your own path in life is key. There are paths that are so well trod that there is very little innovation left in them. But you can combine Maths and Music and cover new, innovative ground*" (MIT, 2011).

The ability to choose one's own courses was cited by one student as the biggest (intrinsic) motivator for her to work. The increased motivation appears to have a positive influence on all chosen courses, not only for the courses that are deemed to be enjoyable. As one MIT student put it, "I try and get those subjects out of the way quickly so I can spend more time working on the subjects I really like".

Giving students the opportunity to pursue a range of different subjects allows them to answer questions about their future and formulate their own ideas about the direction they want to take. Princeton was particularly good at offering multi-disciplinary courses that blurred the lines between subjects. Studying a variety of subjects gives students a more holistic view of education and undermines the assumption that knowledge is specific to individual disciplines.

Students often see their competence as a limiting factor in their subject choices; “am I really smart enough to take a psychology course?” Several US universities developed systems to encourage students to participate in courses that interest them without being penalised. Students at Princeton for example can enrol for Credit, P/D/F or Audit. A credit enrolment means the students’ grades will count towards their GPA – compulsory courses are taken as credit. If a student knows they will not do well academically on a course they may lower the enrolment to P/D/F (Pass/D-grade/Fail) and avoid negatively effecting their GPA. Lastly, students may audit a course and only participate in lectures, discussions and occasionally assignments. Auditing students do not participate in final exams.

Student self-assessment

Students doing a very creative course at the MIT Media Lab were asked by the course organisers to give themselves a final grade and justify to the rest of the class why they deserved that grade. The majority of the students did not give themselves the top grade. One student who gave herself a B-minus said: “I feel like I didn’t do as much work as I could have on the course”. Another student gave herself a B because she hadn’t done all the readings in the class.

This contradicts the widely held belief that students will automatically award themselves the highest grade if given the opportunity to grade themselves. This may be true in cases where students do not understand or do not agree with the criteria against which they are to be assessed. Literature shows that where students have internalised the assessment criteria the results of self-assessment are very accurate (Stefani, 1994).

Deadlines

Several lecturers always granted requests for deadline extensions. The reason for this was to increase the students’ responsibility for managing their own time. As one lecturer said, "I always grant deadline extensions, because I don't know the student's circumstances and I trust that they have a good reason."

Students did not take advantage of this system and only a very small percentage of students requested deadline extensions; creating very little additional workload for lecturers. When one MIT student was asked why she did not simply ask for extensions all the time she looked confused. "You still have to do the work", she replied, "if you ask for too many extensions you'll run out of time by the end of the semester". This is in contrast to the University of Edinburgh, where late submissions were very common, regardless of the harsh penalties. This observation suggests that giving students the responsibility of managing their time actually *improves* the probability that work is handed in on time, while punishing students for not following the rules has the opposite effect. Similar observations were recorded by Frey (1997; 2001) and Deci (1995).

Creating an autonomous environment

An autonomous environment can be supported in several ways. Instead of asking closed (single-answer) questions, lecturers can ask open-ended questions that encourage students to think. The easiest method of doing this is simply to ask the same, closed question but include the word "think". Thus "what is the answer?" becomes "what do you *think* the answer is?" The two questions are fundamentally different. The former implies one correct answer, as defined by the question asker. The latter implies the answer is subjective and a matter of opinion, therefore students cannot get the answer wrong (Postman & Weingartner, 1971).

Whether a student will be autonomous or not depends on the students' perception of whose opinion is valued. If a student does not feel their opinion is valued then they will not be likely to share it, and in some cases will actively suppress it. A lecturer can improve students' confidence by asking for their opinion, ensuring them that their contribution is valued and then discussing the opinion in class. If students learn to value their own opinion then they will be more likely to develop their own ideas (creativity) and challenge the ideas of others (critical thinking).

Lecturers can let students choose the learning material and be confident that it will be appropriate. Giving students control over *what* they learn can have a significant effect on motivation. If the students are intrinsically motivated to achieve a purpose, they will know what they need to learn and will actively seek it out. Likewise students who internalised an extrinsically motivating purpose, and learned in order to gain mastery of the subject, were more likely to adopt a deep approach to learning.

In one example, a lecturer asked students to choose a topic to teach to their peers later on in the semester. Those students who enjoyed presenting were intrinsically motivated to teach. For other students this was a form of indirect extrinsic motivation where they felt compelled to make a good impression and avoid embarrassment. Deci *et al.* (1991) explain this phenomenon, and describe how individuals who 'internalise' imposed goals become motivated to learn without feeling external pressure. The students knew that the success of their presentation was directly proportional to the amount of time they spent learning the material.

Professors in the business classes at Princeton University printed name-cards for each of the students in their class. The name-cards had the students' first names in large font, with their surname in smaller font beneath. At the beginning of the first lecture of the semester the lecturer asked the students to come down and collect their name cards. From then on he addressed them by name each time he spoke to them.

Using students' first names made them feel valued as individuals and subsequently increased responsibility, autonomy and intrinsic motivation. It did not seem to matter that the lecturer was reading the names rather than remembering them, the overall effect was the same.

The learning environment should encourage students' creativity. Control and extrinsic motivation have been shown to stifle creativity (Amabile, 1985; Deci, 1995). This was intuitively understood by one Princeton lecturer who said, "*I understand there's a large element of creativity associated with this tutorial so I'm not going to mark it too harshly*". The lecturer wanted to ensure that students' effort was focused on creating new ideas rather than getting a good grade.

The lecturer encouraged students to think broadly by saying, "Creativity is the diversity of ideas". This encouraged students to develop a wide range of ideas and helped remove any negativity regardless of how strange the ideas were. The lecturer further supported the process by asking questions that challenged the established assumptions made by students. "Does a paper clip have to look like a paper clip?" Discussing a diverse range of subjects (as stated above in teaching holistic design) could potentially lead to increased synthesis of information and the formulation of new ideas.

A postgraduate engineering student described his experience of moving from a British university to Princeton. He said previously his classes had been passive, and he "got a slap" when he arrived at Princeton and wasn't allowed to be passive. He was given recently published scientific papers and told to critique them and describe what was wrong with the author's argument. He said it was difficult to change from a system where he had learned to always trust the textbook, to a system where you are encouraged to tell published academics why they were wrong.

This was one method used at Princeton to encourage students to 'think outside the box'. Critical thinking undermines blind acceptance of others' work and increases students dependence on their own judgement.

One course organiser felt that an undergraduate course was about making people "think in a way they hadn't thought of before". He didn't want idealists or debates about prior issues the students felt strongly about. He wanted his course to be about thinking differently.

Lecturers can create doubt in students' minds that they have all the answers, to become critical of available information, regardless of the source. The process of discussing and debating ideas allows students to see that often decisions are not black and white. Listening to others can help students develop their own argument – to see where their reasoning is flawed and give them the information they need to improve their argument. Through this iterative process students develop better understanding of the topic and are more likely to make appropriate assumptions.

Entrepreneurship course – the lecturer encouraged students to discuss and debate different ideas. He asked open-ended questions and wanted to hear the students' answers, to learn from them. Students learned that their peers often disagreed with their argument; and they were able to listen to the reasons for the disagreement and subsequently change and improve their own argument.

Architecture course – The course organiser wanted students to try and incorporate social, scientific and political values into architecture. Instead of teaching these components individually the course organiser created discussions during the seminars each week. The discussions were loosely based on the ways in which democracy could be influenced by the design of architectural space. Various topics were discussed including architectural landmarks such as Central park, Capitol Hill and their relevance to the Egyptian revolution in Tahrir Square. The discussion encouraged students to see the connections between topics, and to use those connections to improve their understanding.

Effective Structure

The main component of effective teaching was found to be autonomy support (student-centred), whereas ineffective tutorials were based on control (teacher-centred). This finding is not new and is widely acknowledged in education literature; but it is rarely acknowledged in practice. Only a small proportion of classes observed during the course of this study were autonomy-supportive.

Lectures were only effective when given in response to students' demand for more information.

MIT – students had been given a project to design and build a structural column. The students realised the need to understand structural mechanics in order to develop an effective structure. In response to this need the students were given lectures showing them how to do basic structural calculations.

Princeton entrepreneurship – the lecturer showed the students that he could accurately predict from a range of video games which game each student would buy. This 'magic trick' made the students very interested and created a need to know. They wanted to know how it was possible that the lecturer knew what they were thinking. The lecturer went on to explain that it was not magic, it was conjoint analysis, and over the next few lectures he was going to explain to them how they could do it.

Princeton lectures have very little technical content compared to lectures in other universities, yet students seemed to learn far more. This supports the studies of Exley & Dennick (2009), who found that teaching too much content can have a negative effect on learning.

It was found that lectures were effective at clarifying the knowledge that students struggled to learn. Design courses in particular required students to learn a significant amount of information, much of which had to be learned quickly, thus students gained conceptual understanding before learning the details.

Some lecturers focused on inspiring their students and generating interest in the subject. Professor David Billington of Princeton University for example inspired many people to pursue careers in structural engineering.

Stories proved to be a very effective means to both inspire an audience and to improve contextual understanding. Billington demonstrated through stories exactly how and why engineering fundamentals were essential to structural design, however his lectures contained no explanation of these fundamentals.

David Billington used only photo slides and told stories about each one. Eli Dahan - of Princeton's Entrepreneurship course - used well-designed PowerPoint slides and a very engaging, interactive style of teaching that included discussion with the students and 'magic tricks' to get the students engaged and eager to hear the secrets. Again, the aim was to demonstrate the need to learn the fundamentals without actually teaching them. The fact that these two lecturing styles are so different and yet had the same positive effect shows that the methods can vary widely, but the underlying principles are fundamentally the same.

The first common component of these lectures was that they told a story. The lectures had a single purpose – one point that the lecturer wanted students to remember. The entire lecture was focused on this one idea; and that idea was interesting. One of Prof. Billington's lectures for example was on the design of the Eiffel Tower. He described the social and political drivers and the structural form of the design. Throughout the story the audience got into the mind-set of Gustav Eiffel and understood the complexities and inter-disciplinary nature of the design. A slide show of images was used to visually illustrate the story.

It was found that good lecturers constantly iterated and refined their lectures; they never gave the same lecture twice. Prof. Billington has taught the same course for over 30 years and has iterated and changed his lectures every single year, constantly improving them.

In one example of an effective tutorial, students at Princeton were encouraged to think more deeply about *why* they were learning subject knowledge. The topic of the tutorial was the lab classes that had preceded it. The large number of students on the course meant that they had to be divided up into two groups, and take part in two separate experiments. However the final exam would assess students on both. It was therefore important that the students learned about the other group's experiments.

The tutorial classes consisted of students from both lab Group 1 and lab Group 2. The tutor asked students from one lab group to defend why they had done the lab work to students from the other group. The roles were then reversed so every student could reciprocate and defend their own lab work. The explanations and discussions that followed were far more involved and active than previous tutorial sessions. The students were able to explain the concepts to a very detailed level but in a way that their peers were able to understand. Where further clarification was needed the students felt comfortable challenging their peers and asking questions. The tutor did not need to take part in these discussions, and was largely ignored by the students.

The process of asking students to teach other students was successful because it was in the students' best interests to teach and learn. One group learned so that they were able to confidently explain the principles and help their peers. The other group had an incentive to ask pertinent questions and felt confident in doing so because it was their peers and not the tutor.

An example of an effective design course was the Keystone project in Maryland university, which gave students a clear purpose (design an autonomous hovercraft) and then encouraged them to work independently while still providing lectures, guidance and deadlines where needed (Calabro, *et al.* 2008).

Attendance

Some lecturers believed that the aim of assessment (quizzes, exams) was to differentiate those students who had been to lectures from those who had not. This was a form of control, as it was clear that the *lecturer* valued attendance at lectures, however that may not have been the viewpoint of the students.

The lecturer effectively used assessment as an extrinsic motivator to force students to attend class. There was some logic to this. The lecturer believed that to become a competent professional, individuals needed to know the information that was presented during lectures. For this reason they valued lectures very highly, and it was assumed that students who did not attend lectures had no way of learning the information that was presented. The lecturers also believed that only information presented during lectures was assessable and that asking students to use any additional information was unfair. Thus the lecturer gave all students the same information and an equal opportunity to do well in the exam.

The above would appear to make sense, however, there is no way of 'ensuring' that students learn taught information; therefore forcing students to attend lectures has no guaranteed effect on learning. Furthermore many students do not learn effectively from listening to someone else speak (Felder, 1988). There is no reason to penalise these students while giving so much support to those who do learn effectively in lectures. There are also several examples of cases where students learned information that was not taught during class. The student who received the highest average grade in the 2010 FSFD4 course did not attend a single lecture for example. Finally, if a lecturer is interested in knowing who is attending lectures, they can ask their tutor/TA to discretly take attendance during class. Thus the same goal is achieved in a non-controlling way.

3.5.4. Conclusion

- Purpose is essential to maintain intrinsic motivation
- Students who were intrinsically motivated to learn were more innovative in their use of fundamental principles
- The methods used encouraged students to be independent thinkers and take responsibility for their own learning

- Lecturers can tell stories as a very effective means to inspire and clarify knowledge

3.5.5. Purpose, Autonomy & Structure (PAS)

Teaching at the University of Edinburgh and observation of teaching practices in the US – in particular the Keystone project – led to the understanding that education is entirely dependent on students' motivation to learn. This is in keeping with previous work (Dewey, 1916; Montessori, 1967; Postman & Weingartner, 1971; Felder, 2004).

Students who are intrinsically motivated will adopt deep learning strategies while those who are extrinsically motivated will adopt surface learning approaches.

It was hypothesised that there were three components to create an intrinsically motivating environment in university:

Establish Relevance

Purpose first – students need a reason to learn that will clearly benefit each individual. In MIT and Princeton students were asked to build and test a model. In Edinburgh the problem sets created interesting challenges.

Offer Choice and Encourage Responsibility

Autonomy comes next – students should be given choice and responsibility as often as possible. Autonomy is necessary if students are to think and learn information in context. Many students want to think and be self-directed; they have the confidence to learn without support and are simply waiting for the opportunity. Others will not want responsibility and will actively request support from the course academics. Either way it is the students' choice about what information they need. Students who are given information by an authority before they have had a chance to think and understand the context are likely to forgo the opportunity to think independently and adopt surface learning strategies instead. i.e. attempt to memorise the information out of context.

Descriptive, not Prescriptive

Structure is last – students are not always able to operate independently and will occasionally request help. This should be informative (lectures, textbooks etc.), or organisational (deadlines, formative assessment etc.) and not controlling.

It was intended that the PAS concept be trialled at the 2011 FSFD4 course at the University of Edinburgh.

3.6. 2011 FSFD4

3.6.1. Method

The 2011 FSFD4 course had a different course organiser/lecturer than previous years, therefore the teaching philosophy changed. The course aim and objectives were described as:

<u>Aim</u>

This course is intended to provide the knowledge required for quantitative fire hazard analysis. The student will acquire skills for quantitative estimation of the different variables on physical and chemical behaviour of fire. Basic principles of fire dynamics will be used to provide analytical formulations and empirical correlations that can serve as tools for engineering calculations and fire reconstruction. Focus will be given to *the scientific aspects of fire but some basic features of fire safety engineering will be also developed. Introductions to materials flammability and the impact of fire on structures will be addressed as well.*

Learning outcomes

Demonstrate an understanding of combustion principles:

- pre-mixed flames: stoichiometry, flame temperature, laminar flame speed, and flammability limits

- diffusion flames: flame location, mixture fraction, flame height, Burke-Schumann formulation

- thermal radiation: soot production and flame radiation

Demonstrate an understanding of the processes of fire growth and fire modelling:

- ignition: Semenov and Frank-Kamenetskii theory.

- liquids fuels: flash point and fire point, flame spread

- flame spread: mechanisms, thermal models and the blow-off limit

- materials flammability: pyrolysis and gasification, heat feedback, and the mass transfer number, charring

Identify and quantify the impact of a compartment on a fire

- pool fires: turbulent plumes, flame height correlations, Ceiling jets

- air entrainment and entrainment correlations

- smoke: production, CO, toxicity, obscuration, detection and visibility

- compartments: heat feedback and ventilation

- fuel-limited and oxygen-limited fires

- flashover

- fully developed fire

Identify methods to quantify smoke movement

- smoke management to control its movement, Passive and forced smoke evacuation calculations

The course was initially structured around lectures; where students were given information and then graded on their ability to apply that information to practice questions. This was deemed to be the standard format of most lecture-based courses. The final exam aimed to assess the extent to which the students had achieved the learning goals as defined by the lecturer.

As the course progressed, the problem sets were adapted to include more open-ended questions with a clearer purpose. It was hypothesised that when given more open-ended questions with no predefined solutions the students would be more intrinsically motivated to complete the questions autonomously. Furthermore, it was hypothesised that the students would need less structure when working on the open-ended problems.

The aim, from a social science perspective, was to see the effect the change would have on students' intrinsic motivation. The method of changing the tutorial questions from convergent to divergent during a single semester allowed the differences in the students' attitudes towards learning to be compared directly.

The students' contextual understanding was assessed subjectively through summative assessment (tutorial questions); while semi-structured interviews were used to assess their intrinsic motivation.

The students were divided into two tutorial groups (~25 students per group), to make teaching more manageable.

3.6.2. Results

The students initially responded very well to the lectures and were clearly interested and intrinsically motivated by the subject material.

On being given convergent problem set questions however, students resorted to surface learning strategies, and were inclined to wait for a tutor or lecturer to give them structure. Another observation was that students were less likely to be critical or creative when given convergent questions. This was in stark contrast to the students' behaviour at the end of the course when they were presented with challenging, open-ended questions.

On being given convergent questions that they were initially unable to do, students became very agitated and stressed until they were given the 'correct' answer (as with 2009). In contrast, the divergent questions allowed students to create an answer very quickly (minimising stress), and gradually improve their solution as their understanding increased.

The students required much more assistance during class when the questions were convergent; and the number of students made it very difficult to give the students the help they needed. As one tutor said: "*They raised their hands and like, twenty minutes later I was able to go and answer their questions.*" Conversely, on being given open-ended questions towards the end of the semester, several of the students were able to create solutions independently.

When students worked on convergent questions, they were less likely to respond well to criticism of their solutions. This supports Carol Dweck's theory of a 'fixed mindset' (Dweck, 2006), whereby students believe their knowledge as fixed and unchangeable; therefore criticism of their work is taken as criticism of them as individuals. In contrast, when students were criticised for their work on divergent questions they were more open, and viewed feedback as potential for improvement. This behaviour is indicative of a 'growth mindset'.

One student highlighted a very interesting psychological trait that was unexpected prior to this study. Regardless of the type of tutorial question asked, this student claimed to be incapable of developing a solution without being given an example solution to copy, and became visibly distressed when the tutor refused to give a prescriptive solution. The student did not *want* to think, did not want to be autonomous and self-directed; the student *wanted* to be controlled.

3.6.3. Discussion

The coursework on the 2011 FSFD4 course transitioned from convergent to divergent questions as the course progressed. It was found that a controlled environment with convergent tutorial questions was significantly more resource intensive than an autonomy-supportive environment with divergent questions. This is probably because convergent questions with a pre-defined answer place the tutors and/or the lecturer on the critical path to learning. When the coursework questions were convergent, the tutors quickly became overwhelmed by the quantity and complexity of the students' questions during class; and many students were limited by the lack of teaching resources available to them.

Changing the tutorial questions to include more open-ended/divergent questions decreased the demand on teaching resources significantly, as students were able to work autonomously without the need to find the 'right' answer from the tutor or lecturer. Nevertheless many of the students remained frustrated, albeit for different reasons. The lack of structure gave too much choice and not enough direction, which overwhelmed many students.

Each student required different levels of support from tutors to reach their optimised solution. Those students who were independent, intrinsically motivated, resourceful and ultimately knowledgeable were able to develop solutions to the open-ended problems given later in the semester with little or no help from the tutor; thus supporting the idea that purpose leads to autonomy. But when structure was offered *before* autonomy it narrowed students' focus and undermined intrinsic motivation; students did not need to think of alternatives if they already knew 'the answer'. Conversely, when structure was offered *after* autonomy it did not narrow students' focus nor undermine intrinsic motivation.

This was also found during the previous year (2010 FSFD4 course), where the vast majority of students were very satisfied by the level of information provided during the course, despite the open-ended nature of the tutorial questions. This is because the lectures on the 2010 course not only included more information than in 2011, but were intended specifically to answer questions generated by the tutorial questions. Thus the lectures supported the open-ended tutorials, and vice versa. Structure, and the timely delivery of useable information, appears to be a critical component of maintaining intrinsic motivation.

Other extrinsically-motivated students preferred the specialist way of teaching however and were frustrated by autonomy and the absence of structure. This small group of students reached the point of requiring assistance very quickly and complained to the tutor to distribute a prescriptive solution. These students did not want to make their own decisions and create their own solutions independently, and preferred to rely entirely on the tutor, lecturer, textbook or other students for their solutions; a phenomenon observed by Felder (2004) and Exley & Dennick (2009, p. 86).

As in the 2010 FSFD4 course, many of the "good" students with very high average grades fell into this category, implying that traditional teaching supports the specialist mindset. These students had become very good at following instructions and memorising information but had very poor reasoning, creative and critical thinking skills. One particularly frustrated student assured the tutor that he was very good at memorising, and suggested that the tutor should just "*tell me what to write and I'll write it*".

The interaction with these small number of 'good' students appeared to indicate that they were 'dependent learners' on Perry's scale (1999) and were extrinsically motivated by the grade-based reward. When the course was adapted to become more autonomy-supportive, a mismatch was created between teaching and learning styles. These students did not want to think for themselves, did not want to move up to higher levels of thinking and, because they viewed their mindset as fixed, the result was that they could not. On being asked to think and use reasoning to figure out possible solutions to a given problem one student replied: "*I can't. It's like you're asking me to run the 100m in less than 10 seconds. I just can't do it*."

Prior to this study the hypothesis, based on the work by Deci, was that greater choice led to increased confidence, productivity and work satisfaction and ultimately supported intrinsic motivation. But the results of student surveys revealed that many of the students found the level of autonomy (and lack of structure) overwhelming. This may be because the students did not want to be intrinsically motivated and responsible for making decisions; or it may be because they still felt controlled, and did not know what was expected of them. For example, in the latter half of the semester the students were given open-ended question with several possible answers, yet only one opportunity to submit the work to a tutor for assessment. The students understandably did not know the criteria against which they were being assessed; they did not have the opportunity for iterations and feedback that would have improved their understanding and helped them form a clearer definition of a 'good' answer. The students were not given meaningful choice and responsibility; the tutor's assessment was still final. Subsequently the tutors received a significant amount of questions about what was expected for each question.

The combination of the two FSFD4 studies (2010 & 2011) appeared to disprove the hypothesis that greater choice is always liberating and beneficial. In fact, too much choice can *decrease* motivation. As Barry Schwartz (2004) explains in his book *The Paradox of Choice,* having some choice is better than none, but having too much choice can be paralysing. There is therefore an optimum level of choice for each individual, in each situation, before someone else needs to make a choice for them. Schwartz did not know what the optimum level of choice was. The findings of the FSFD4 2011 course however demonstrated that the optimum level can be found quite simply: After being given autonomy and choice, the optimum moment to give structure (i.e. when the student is most likely to benefit from it and not perceive it as controlling) is when they *ask* for it.

3.6.4. Conclusion

- Extrinsic motivation is resource intensive as it puts tutors and lecturers on the critical path to learning
- Establishing an intrinsically motivating purpose was a means to relinquish control and encourage students to work autonomously and create solutions on their own
- It was possible to create an intrinsically motivating purpose using open-ended, fun tutorial questions
- Divergent questions must be supported by the structured delivery of information if they are not to become a source of frustration to students
- It is possible to transition from a controlling to a non-controlling environment within the time frame of an individual course
- The process of Purpose, Autonomy and Structure repeats itself every time the purpose is redefined
- The timing of support was critical to maintain intrinsic motivation. The optimum moment to give students support is when they ask for it.

3.7. 2012 EPFL

As part of their degree programme, engineering and architecture students at L'École Polytechnique Fédérale de Lausanne (EPFL) were given the opportunity to be involved in a one-week environmental design course during their second year at university. The aim of the 'Semaine ENAC' learning week was to gain experience working with students from other disciplines on an integrated design project; something they would not normally be able to do during their regular studies. The 200 enrolled students were able to choose from a wide range of environmental design projects located in various countries; one of these projects was the *Integrated Analysis of the Renovation of the Bastions Buildings at the University of Geneva*.

From the students' perspective the aim of the project was to analyse the existing, listed building to establish if it met the required standards for fire safety and environmental sustainability and, if not, to propose a strategy for its imminent renovation.

During its lifetime the building had experienced two fires (1899 & 2008) and initial assessments by Swiss professionals found the building to be unsafe in fire and below the Minergie requirements for environmental sustainability. Thus there was an opportunity for the 16 enrolled students to analyse the existing building, establish whether or not there were any problems and subsequently to solve those problems using engineering and architectural tools.

With the exception of a site visit, the course was based in EPFL and involved 16 students, including civil & mechanical engineering & architecture students, all of whom had no prior knowledge of fire safety engineering.

From an education perspective, the challenge was intended to provide an intrinsically-motivating purpose that students could pursue autonomously. In doing so they would be able to experience working in interdisciplinary teams, improve their creative and critical thinking skills and to learn and apply fundamental knowledge from available resources as and when it was necessary.

FIGURE 12: BASTIONS BUILDINGS AT THE UNIVERSITY OF GENEVA

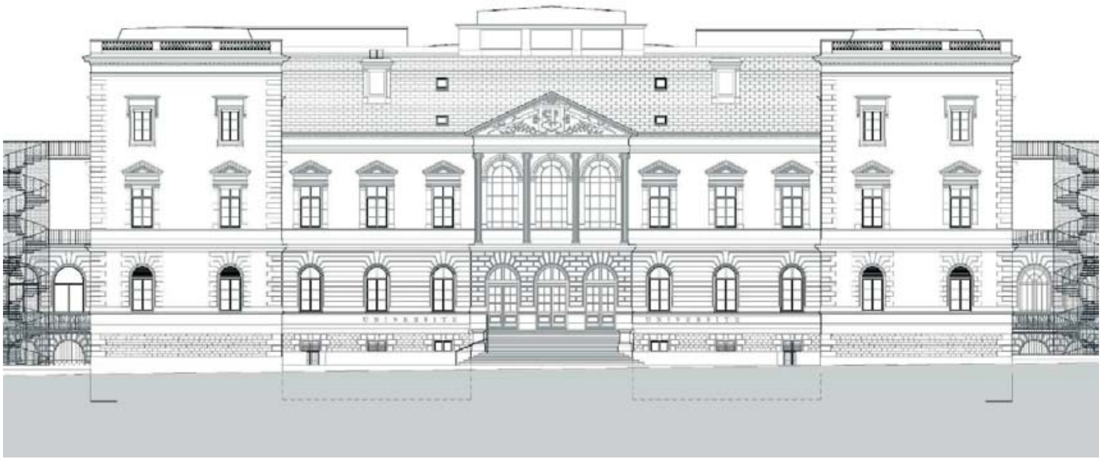

FIGURE 13: PROPOSED RENOVATION INCLUDING EXTERNAL STEEL FIRE ESCAPES

The above figures show the Bastions building in Geneva: Figure 12 shows the building as it was at the time of the 2012 course; while Figure 13 shows the renovation design proposed by the professional Swiss engineers, including the addition of two external steel fire-escapes on either side of the building.

3.7.1. Method

The course had a very structured itinerary and timetable. The course was introduced on April 17th during a presentation to students. The intensive learning week ran from Monday April 30th – Friday May 4th (five days). Each day the students were given a specific purpose to aid the overall purpose of achieving an optimised solution for the building renovation.

Day 1 (Apr 30th): Visualising the situation
Day 2 (May 1st): Defining the problem
Day 3 (May 2nd): Creating solution options
Day 4 (May 3rd): Researching solution options and choosing one
Day 5 (May 4th): Detailed work validating solution

Date	Time	Location	Topic	Presenter
April 17th, 2012	13:15-15:15	CM09	Introduction to the project	M. Jose Torero
April 24th, 2012	13:15 -15:15	CM09	Conservation of Patrimony (in French)	M. Yves Peçon
April 30th, 2012	08:00-08:30	AAC231	Departure to Geneva by bus	
	9:30-15:30	Bastions Building	Visit of Site	M. Marc Brunn
	15:30-16:00	Bastions Building	Departure to EPFL by bus	
May 1st, 2012	09:00-11:00	AAC231	Fire Safety Regulations in Switzerland and Fire Safety Engineering (in French)	M. Eric Tonicello
	11:00-17:00		Guided work	M. Jose Torero M. Michael Woodrow
May 2nd, 2012	09:00-17:00	CM1113	Guided work	M. Jose Torero M. Michael Woodrow
May 3rd, 2012	09:00-17:00	AAC231	Guided work	M. Jose Torero M. Michael Woodrow
May 4th, 2012	09:00-17:00	DIA003	Guided work	M. Jose Torero M. Michael Woodrow
May 8th, 2012	13:15 -15:15	TBA	Final Questions	M. Jose Torero
May 15th, 2012	2 hours (TBA)	TBA	Presentations	Plénum

TABLE 5: ITINERARY AND TIMETABLE

Monday: The first day of the learning week, the students were taken by bus to Geneva to meet the renovation architect and view the building. The architect explained the situation and gave the students the following design brief (i.e. the overall purpose of the project):

- Respect the building patrimony by preserving its original form and function;
- Achieve Minergie standards for low energy consumption and;
- Fulfil modern fire safety requirements.

It was explained that optimising a design to suit one variable in isolation would have negative effects on the other variables (e.g. very efficient thermal insulation may be highly flammable). The aim was therefore to produce a solution that was holistically optimised for all of the criteria stated in the brief. A secondary constraint was that the solution should fulfil the brief at the lowest possible cost.

The students were then given a tour of a nearby sister building that had already undergone renovations. Here students were shown potential options to consider, including 'invisible' fire doors (see Fig. 14). Finally the students were taken to the building to be studied - the main Bastion building - where they were able to take notes of each of the rooms and potential problems with fulfilling each of the design criteria.

FIGURE 14: 'INVISIBLE' FIRE DOORS

Tuesday: the students were given an introductory lecture by Eric Tonicello – Switzerland's most prominent fire engineer. They were then asked to split up into smaller working groups of four, and would remain in these groups throughout the week. The students were given the responsibility for choosing their own teams as it was felt that assigning teams on their behalf would undermine intrinsic motivation. After the students had chosen their groups they were asked to 'define the problem', requiring a global analysis of the building and the design constraints. At this point, and throughout the rest of the week, two fire safety engineering academics acted as facilitators to structure the course and provide knowledge as and when students requested it. At the end of the session one representative of each group was asked to come forward and present and justify why they had chosen their particular problem.

Wednesday: The students were asked to brainstorm solution options for their particular problem. Facilitators helped students as required throughout the session and at the end of the day each group presented the option(s) they had decided to pursue.

Thursday: The students were asked to justify their chosen solutions using scientific evidence i.e. to produce engineered solutions. Again they were asked to present these solutions to the class.

Friday: The students were asked to iterate and optimise their solutions in response to questions and queries from within their group, from the facilitators or from other students. In the afternoon they presented their solution. At this point they were told that the group with the best presentation would be asked to present to the architect, professional fire engineer and local authority involved in the project the following week.

The students were asked to grade themselves as they had, over the course of the week, developed a clear understanding of the quality of their work. Furthermore the differences between students' background knowledge, and the type of work they did for the course would have made it impossible to assess them fairly using unilateral teacher-controlled assessment criteria. The facilitator would ultimately award the grade, but the students' opinions were assumed to be final. Finally, the students were asked to grade the facilitators on the course and to give feedback on the teaching.

3.7.2. Results

Monday: The students enjoyed the site visit with the architect and were very interested by the project. They were able to ask questions throughout the tour and were able to look around the building and take photos in their own time during the afternoon.

Tuesday: Each group worked independently and identified a range of different problems. Initially the students jumped straight into proposing solutions (fire stairs, insulation, extra doors etc.). However, the facilitators kept bringing the students back to defining the problem; asking questions that encouraged the students to think more critically. This gave the students an opportunity to think more deeply and consider all the constraints. One group informed the tutor that they had chosen their problem, but were confused because it was so obvious to them. “Isn’t everyone going to be solving the same problem?” In reality each group’s chosen problem was different.

One group decided to look at the energy requirements for the building. They defined the problem as the building’s failure to meet the Minergie environmental requirements. This involved defining the exact levels of energy loss that were acceptable in the Bastion building. Another group identified issues with egress, particularly from the upper floor lecture theatres (for which the professionals’ proposed solution was two external steel fire escapes). One group comprising mainly architecture students found that there was no physical problem with the main theatre, however there were over-conservative code requirements that would negatively impact the overall design. Their defined problem was therefore the prescriptive requirements of the Swiss regulations. The strategy for solving the problem therefore was to provide necessary evidence to convince the authorities that the prescriptive solutions were not necessary. This allowed them to create an alternative, more architecturally appropriate solution.

By the end of the day every student group had identified and defined components of the design that they believed did not meet the design criteria stated in the brief. Throughout the day students needed very little assistance from facilitators and were able to work at their own pace in a very relaxed environment.

The students were very efficient at defining the existing problems. There was only one problem that the student groups did not consider – fire compartmentation – and this was worked on by the facilitators.

Wednesday: The students developed initial solutions that worked conceptually, and began developing strategies for how those solutions could be validated. Again the students needed very little assistance from facilitators and were very innovative in creating strategies for proving that their solutions worked. The facilitators questioned and challenged the students' reasoning to ensure that they had fully thought about their chosen strategy.

Thursday: The students pursued their chosen strategy and began learning more detailed information as necessary, including fire science fundamentals. The facilitators did not lecture the students, but instead waited for the students to ask specific questions before giving an informative answer.

At one point during the day one of the facilitators presented the problem of fire compartmentation. The authorities had stated that the existing ceilings underneath the roof on the top floor were insufficient to meet Swiss regulations for fire protection, and that 60-minute fire-rated ceilings were necessary. The facilitator wanted to demonstrate that the largest real fire that could exist in the upper floor space would be far less than the fire that is assumed by the regulations, but he wanted the students to come to this conclusion on their own. The presentation therefore involved a lot of questioning and interaction, guiding the students towards a conceptual solution. As the presentation progressed however it became clear from their body language and lack of interaction that the students were no longer able to follow the facilitator's logic. The facilitator was asking detailed questions associated with the concepts and none of the students were confident enough to answer. The facilitator was just about to give up and tell the students his answer to give them *structure*, when he was interrupted.

The other facilitator turned to ask the students a global question that would establish a clear *purpose*. He pointed at the image of the proposed false ceiling that was a prescriptive requirement to protect the roof above. He then said "the client doesn't want that false ceiling, at all. How would you argue that you don't need it?" The students waited a couple of seconds and then one of them said, "well you could look at the temperature of the smoke at the ceiling given a normal fire". Another one of them said that the smoke temp would probably be 30–50^{o}C as he had calculated it to be in another room.

All they had to do then was to check that the structure could withstand that temperature for 60 mins. This was *autonomy*.

The lecturer was then able to present the same solution as he was about to give before, only this time it came across in a way that the students fully understood. This was *structure*; and overall this demonstrated a clear example of establishing purpose, autonomy and structure.

Friday: The students continued to iterate and develop each component of their analysis and proposed design. The level of detail that the students were able to go to was quite staggering. Many of the students were able to learn and apply fundamental fire science concepts normally taught in the fourth year of a fire safety engineering programme at the University of Edinburgh.

Throughout the week the atmosphere was very friendly, students were allowed to come and go as they pleased and were able to spend as much time working on the project as they liked. None of the students found the week stressful.

3.7.3. Discussion

The students knew exactly what they were trying to achieve, they had clearly defined the aims of their group. They had a clear, intrinsically motivating purpose and were both competent and confident enough to pursue that purpose autonomously. They advanced at their own pace, only moving forward when they were confident and competent enough to do so.

Occasionally the students needed new information that they were not able to find on their own – in particular related to fundamental fire science. There were clear signals that the students had reached this point (had become 'stuck') and needed to ask for assistance; signals such as checking social network sites and playing with mobile phones. At this point the tutor would approach the students and ask how they were doing. In every case the students had specific questions that they needed answered before they were able to progress further.

The results indicate that although the facilitators spent a large amount of time supporting the students in pursuing their own ideas, it was necessary for the facilitators to have a very high level of competence in the subject. The level of divergence in the problems allowed the students to develop a very wide range of methods for defining and solving problems. In order to provide technical support the facilitators had to be able to understand each method and adapt their own way of thinking.

Autonomous learning

The students required very little assistance throughout the week, and were able to find and use information from a range of different sources. The facilitators largely aimed to give students the confidence to continue on their own. As Knowles (1975) discovered in his studies in the 70s, the educators in the ENAC course were functioning primarily as procedural guides and only secondarily as information resources.

The students learned considerably more than was anticipated by the course organisers. The solutions presented were evaluated and deemed of the highest standard by leading Swiss fire safety consultants and building regulators.

It was clear that the students' existing knowledge did influence their work, the architecture students focused on architecture, the mechanical engineers on heat transfer, the civil engineers on structural elements etc. This supports the theory that existing knowledge affects our ability to learn new knowledge (Lewis-Peacock & Postle, 2008), however it does not support the theory that an existing level of knowledge must specifically be *taught*.

None of the students had been exposed to fire safety engineering prior to the week. The fundamentals were entirely new to the students, some of whom were architecture students with very little understanding of maths and physics. Nevertheless their understanding of fundamental fire science was beyond that of experienced fire engineering professionals. (An experienced senior lecturer in structural fire engineering was unable to understand the equations used in the students' proposed solutions). The result demonstrated that the students were able to learn very effectively and create technically brilliant solutions, despite not being taught 'the fundamentals' beforehand. This appears to contradict the common assumption that a 'baseline level of knowledge' must be acquired before a project-based course can be attempted (Savin-Baden, 2007).

Student self-assessment

Despite achieving such high levels of success in their work, not a single student awarded themselves the top grade (Grade 6) for the week; and instead graded themselves either 5 or 5.5. As the course organiser made the final decision on grades he awarded all of the students even higher grades than they awarded themselves. It was interesting to note that each student's self-assessment was more critical than the assessment carried out by the subject authority. This could be for several reasons; it could be a result of the authority's lack of understanding of the intricacies involved in the task; or of the students' true capability; or it could be a result of students' lack of knowledge or 'competency awareness'. The subject matter was largely new to the students, and it was possible that their lack of experience made it difficult for them to accurately assess how well they did. Finally, the lower self-assigned grades could be a result of low self-esteem. A lack of self-esteem could result from several years of authority-controlled assessment (Boud & Falchikov, 1989), or could again result from a lack of knowledge/experience, and a lack of understanding of what constitutes 'good work'. This could have led the students to believe that they could have done better, even if they did not know how.

Student feedback

The following emails were sent by the students to give their personal feedback and assessment of the course teaching:

Student #1:

> *As you have asked us for a personal feedback, I will share my impressions of last week. I have also attached the feedback sheet for the coordinators.*
>
> *Even though I didn't expect too much, I have thoroughly enjoyed this week. It was great to take a brake [sic] from our regular studies and work in a completely different way for once. I also enjoyed working with students from other sections for once and after having talked to a number of students from other projects, it seems that this project was one of the few that really incorporated elements from architecture, civil and environmental engineering.*
>
> *I also liked the balance between individual group work, discussions with everybody and presentations. The amount of assistance for the group work enabled us to work on our own while still getting all the information and help that we needed. I think the workload was adequate and the schedule allowed us to get some work done while still spending a pleasant week (where I even managed to get enough sleep for a change).*
>
> *While at the beginning I had the feeling that the project, while being interesting, had nothing to do with my studies, I realized that the fire safety calculations were exactly the kind of work that's often used in environmental engineering and that represents the part of my studies that I currently like the most. I wasn't really aware of this field of studies beforehand and now I could even imagine choosing it as a future career path.*
>
> *While the learning outcomes are probably hard to quantify, I have the feeling of having learned a lot during this week and I enjoyed it very much.*
>
> *So my impressions of this week have been throughout positive, apart from the scarcity of information beforehand perhaps. I appreciated both you*

and Michael as highly competent instructors and I was impressed by the clarity of your comments and presentations.

Thus, I thank you for an excellent week and look forward to meeting you again someday.

Student #2:

First of all I would like to thank you and Mike a lot for this week. The subject was very interesting and challenging, and the organization was very good. You and Mike were great: the work process was clear and you gave us the keys we needed to proceed – as much as possible – on our own. It was also very rewarding to see that all our "options" and proposals (of all 4 groups) were well-appreciated, even today by Mr. Tonicello! Regarding the marks, we talked today and came up with a grade between 5 and 5.5. We think that we got the purpose of this week, and we were able to propose quite reliable solutions for the renovation. Again, thanks to you and thanks to Mike. Wish you all the best for the future!

Student #3:

The theme of the week was interesting because I will inevitably be involved at one time or another with a renovation problem. We saw how the problem was seen differently from the point of view of the engineer, fire engineer, Heritage Officer, architect etc ...

I appreciated the self-learning side while having teachers able to answer our questions and able to guide us in our project.

A downside was having to spend the week at EPFL when other parties were in France, Germany, Italy or elsewhere in Switzerland...

Regarding the teachers. Messrs Torero and Woodrow were competent, friendly, interested, listened etc… Super!

Student #4:

You asked us to make a personal comment on the semaine ENAC. I'd like to say that your way of approaching the problems of the renovation was very interesting, and making us focus on "why we do that" instead of "how *we do it" was what made this week quite enriching. We have a computer science teacher who often says that computer scientists tend to develop softwares that are supposed to give the solution to a problem, but engineers don't want solutions, they want options. Now I truly know what he meant. You received the mail from [my colleague] that said we thought we deserved a grade between 5 and 5.5. I agree with him.*

Student #5:

Hello,

I write you to tell you about the mark we gave ourselves and about what I thought about the course.

First, about the mark, we gave ourselves 5.

About the course I really liked it, for a couple of reasons. First of all the fact that it was the first time for everyone (architects and engineers) that we had to deal with that kind of problem so we all were at the same level. There is also the fact that it wasn't a Semaine ENAC for a specific section but we needed both points of view to solve a given problem.

I have to admit that after the first presentation and what the visit was like I feared that we would have a boring week and at the end of the second day I was a bit lost but then everything went really well.

The help you and Michael provided was pretty useful even though sometimes there were too many options (but I guess giving us a simple answer wouldn't really have helped us considering all the possibilities).

So, thanks for this really interesting week and I'll let you know as soon as we have something for the presentation.

Student #6:

Hello,

First of all, thank you again for this week. We agreed in the group to rate our work between 5 and 5,5...

As for the feedback, I really enjoyed this week, for various reasons;

- The subject was interesting and unknown to us, so we

were all at the same level and there was no separation of tasks between architects and engineers (and that's good).
- I think we all understood the purpose of this project and it was well articulated/constructed to give us the proper "sensibilisation" (I don't know the english word for that) on the subject.
- I had the impression that we worked independently and at the same time you knew when to give the right input so we don't stagnate to much.
- Even if the week was short I have the impression that we managed to actually DO something, unfortunately I'm not sure how the architect could take our work into account, maybe we intervened too late in the process of his project...

But I would totally advise this ENAC week to future students if you do something similar again next year. So thanks again.

Student #7

The only negative thing from my point of view was the fact that during the course (presentations of the speakers, especially in the case of fire) the presentation was addressed to architects, while half of the students were engineers. It was quite interesting, but it is a detail that bothered me.

Apart from that, I loved the week ENAC, because I liked working in small groups on a specific subject. I learned a lot. It was not always easy, sometimes we were a bit stuck. In these situations, discussions with the teachers were very helpful.

Student #8

For our own self-marking, we thought about a grade between 5 and 5,5. This would be considering the deep thermic analysis of the subject and the rigorous apply [sic] of physical calculations we managed to do. However, we are conscious that we had some weaknesses in making our presentation visually understandable for an external person.

Student #9

As you ask for, here is the mark to the work group: 5

It was a really interesting week, we learned a lot of things which will be very useful in the future.
Thank you.

All students except one graded the facilitators 6/6 – the highest grades awarded to teachers on the Semaine ENAC projects. Many gave further feedback on the facilitators which was similarly positive.

Limitations:

The course could have been improved if the students had been able to visit the building at the end of the week and visualise how their solutions would work in practice. The course was also limited in the type of help the professionals could give i.e. specific to their own field, although this will be a limitation of any course.

3.7.4. Conclusion

Students created optimised solutions that fulfilled the requirements for form and function, energy, efficiency and fire safety as specified in the design brief. Furthermore the solutions were assessed by professionals and deemed to be of very high quality.

The course showed that, using the purpose-autonomy-structure (PAS) teaching methodology, students – with no prior knowledge of fire safety engineering – could produce fire safety solutions to unique problems, without the need for extrinsic motivation. Furthermore they could support their solutions using fundamental discipline-specific knowledge.

4

SUMMARY, LIMITATIONS & FUTURE STUDIES

4.1. Summary

4.1.1. Purpose

The literature describes the need for individuals to be motivated towards achieving a purpose. The literature also describes the difference between an intrinsically motivating purpose and an extrinsically motivating purpose; both can be beneficial depending on the context. It was found that intrinsic motivation was preferable for generalist education where the outcome is unknown, while extrinsic motivation was preferable for specialist training where the outcome is predefined.

Students who were intrinsically motivated to learn were more likely to adopt deep learning approaches and were more innovative in their application of fundamental principles than students who were extrinsically motivated.

It was found that lectures had little effect on establishing purpose, while assessment had the greatest effect. Tutorial questions were shown to foster intrinsic motivation if the questions were open-ended and extrinsic motivation if the questions were closed.

Qualitative evidence collected during fire science courses at the University of Edinburgh demonstrated that when students were given clear, open-ended tasks that were relevant to them, the students adopted deep approaches to learning; several students were able to develop innovative conceptual methods of solving problems without being taught.

The Keystone course at the University of Maryland, the Semaine ENAC course at EPFL and the Entrepreneurship course at Princeton University all used projects to create a clear purpose that students found interesting and intrinsically motivating.

Evidence from literature showed that extrinsic motivation must be sustained using rewards and punishments, and by establishing expectation; but control - particularly in the form of subliminal or explicit expectation - has been shown to destroy intrinsic motivation. Naturally (intrinsically) motivated students therefore do not benefit from external control and would benefit instead from autonomy support.

4.1.2. Autonomy

Autonomy is the ability to make one's own decisions, to be self-directed.

The literature states that intrinsic motivation is sustained in environments where people feel in control of their own decisions; a hypothesis that was supported by the current study. To support intrinsic motivation students should be given choice and responsibility for their actions, even if they choose to relinquish that responsibility to others.

During the EPFL course, the facilitators offered choice and shifted the learning responsibility onto students in a number of different ways, including:

- Asking students to form their own groups
- Asking each group to identify the problem they wanted to work on
- Asking each group to develop their own solutions to their chosen problem
- Encouraging the students to manage their own time
- Asking students to assess and grade themselves

The results of the Semaine ENAC course at EPFL demonstrated that autonomous learning led to a high level of contextual understanding of the fundamentals and an improved ability to define and solve new problems; results supported by existing literature (Schraw, Dunkle, & Bendixen, 1995; Savin-Baden, 2003; Exley & Dennick, 2009; Garfield, 2010; Barneveld & Strobel, 2011).

The controlling aspects of traditional teaching have been shown to undermine students' intrinsic motivation to learn. This does not mean that structure should be removed. The 2010 FSFD4 course demonstrated that the complete removal of structure and the offer of unlimited choice inhibited many students from learning just as much as too much control – a finding supported in the literature (Schwartz, 2004). What was realised was the that structure is viewed as non-controlling and beneficial if the student *wants* to have it.

The FSFD4 course demonstrated that when structure was given before autonomy students became less intrinsically motivated, and became less creative. It seemed that students did not feel motivated to find an answer on their own if they already had an answer. Conversely, when students were given time to think about a problem autonomously they formulated their own ideas and were more likely to be critical of presented information.

4.1.3. Structure

Fiske (1991) argues for a "complete frontal assault on the entire school system". The FSFD4 2010 course demonstrated that this is not necessary, and could actually be counterproductive. The same structure – the same curriculum, the same lectures the same deadlines etc. – can be used and the lecturer does not need to be anything other than be an expert in their subject. What is required is a different teaching philosophy, and for the same structure to be delivered in a different context, *after* the students have had an opportunity to gain a need-to-know and a chance to work it out on their own.

It was found that structure did not undermine students' intrinsic motivation if it was informational and intended to support the students' natural learning process. In particular, students appreciated a well-organised timetable and interesting, informative lectures.

It was discovered on the EPFL course that the optimum time to teach students the fundamentals was when they asked for it. At this point the students had moved from asking "why?" to asking "how?" and the educators were able to be *descriptive*, not prescriptive.

4.1.4. Purpose, Autonomy & Structure

The system of purpose, autonomy and structure can be used to establish and support intrinsic motivation at all levels of a degree programme. For example, an educator can define a singular purpose for an entire degree (e.g. "become a fire engineer"), then give students choice on how they wish to achieve that purpose ("it's up to you what courses you take"), and finally to offer students tried-and-tested methods of how to achieve it ("these courses have been shown to include useful information for fire engineers"). The individual courses can be subdivided in the same way. For example in the FSFD4 2010 course, the aim of the course was to work out how to create a design fire - a commonly used tool in fire engineering. This purpose (create a design fire) was then subdivided into more detailed "sub-purposes" (e.g. describe how flames spread); each requiring some degree of autonomy and structure.

It is important to always maintain the link between the overall goal of the curriculum and what is being taught on a course. Even the most fundamental details can be linked back to the original purpose by asking "*why?*" For example: "*Why would one need to know the fundamentals?*" Provided the questions lead to an overall purpose that is intrinsically motivating and interesting to each student (e.g. being a competent fire engineer) then those students will have the potential to be intrinsically motivated.

4.2. Limitations of the research

4.2.1. Limitations in the data collection & analysis

The data would benefit from better profiling of students in order to map potential changes in their mindset throughout the semester e.g. using an increased number of surveys.

The assessment of students' contextual understanding on the FSFD4 courses was very subjective and assessed mainly through tutorial questions. The final summative assessment (exam) also assessed contextual understanding however it presented a source of control that appeared to have an undermining effect on students' intrinsic motivation. The final exam however could not be changed given the constraints of the University of Edinburgh. In future studies it may be possible to change the method of assessing students' conceptual and contextual understanding to include a series of personal interviews to assess each student separately. The time investment can be similar to the length of time taken to grade an exam script.

Interviews have been shown to be an effective way of assessing students on fire engineering courses at Ghent University.

This study did not focus on any one specific variable in part due to ethical considerations, but also to avoid detracting from the overall aim of the thesis, which was to lay the foundations for a generalist education programme applicable to fire safety engineering. Therefore this work intended to be qualitative and to provide some descriptive preliminary evidence. The following variables were not assessed: stress levels, previous experience, goal orientation, personality, language ability, self-esteem, learning disorders, learning approaches, creativity, flexibility and cognitive style etc. to establish the effect they may have had on learning outcomes. Additionally the effects of specific feedback, rewards, instructional styles and interactions with instructors and other students were not quantified either.

This study defines the fundamental principles of a generalist programme and gives examples of situations where these principles have been used successfully in practice. There is now significant opportunity to carry out additional case studies that provide statistically valid evidence to either corroborate or refute the results.

4.2.2. Limitations in the system (University of Edinburgh)

Students came from a range of engineering disiplines and at various stages in their degree. There was no way of knowing what level of understanding the students had prior to the course, or what kind of mindset they had.

The university fixed the lecture and tutorial times. Lectures were scheduled at 9am on Monday morning in the FSFD4 2010/11 courses and many of the students were tired or didn't come to class because of the time. This may have had a negative effect on their learning and motivation.

The tutors were limited in the amount of formative feedback they could provide to students given that there was only 48 hrs between the lectures (where work was submitted) and tutorials (where work was returned to students).

In all three FSFD4 courses there was a scheduling conflict for the mechanical engineering students that meant that a third tutorial group had to be created for a small number of students.

In 2010 the course schedule was released late and the date of the lecture changed from the year before meaning that the lecturer was unable to attend 3 weeks of classes.

The final examination date, percentage weighting, question format and time duration were all fixed by the university. The convention at the University of Edinburgh was for students to be assessed using a written exam (1.5-2 hrs) that made up 75 % of the final grade. This was not in keeping with the philosophy of the course.

The FSFD4 course was designated as a lecture-only course and therefore students could not gain credit for lab-based work.

University administration

At the University of Edinburgh the process of gaining feedback on assignment solutions was complicated and involved an administrative "middle-man" in the form of the Engineering Teaching Office (ETO). The office insulated the academics from the students and reduced face-to-face contact almost to zero. The process had very rigid rules, students were penalised for late submissions and extensions were rare.

This heavily controlling, time-consuming system had significant negative effects on students' intrinsic motivation and subsequent learning. Students did not have autonomy over their own time and were unable to arrange individual deadline extensions with the lecturer or tutor.

The ETO was incapable of answering the students' questions related to feedback. Most students did not know where to find the tutor who assessed their work and had no choice but to accept the feedback and grade they have been given.

Some students on the FSFD4 courses produced work that was over-and-above the level that was expected of them by tutors. Due to the rules, tutors were unable to allocate additional 'bonus' marks to students who excelled in a particular piece of work, even if they had been given approval from the course organiser. Thus students learned that there was a limit to how much credit they could receive and that there was no immediate benefit to completing additional work.

Tutors were paid by the hour to teach and assess work. It has been shown that the way people are financially compensated can have a significant impact on their motivation (Ariely, 2008), on their teaching practices and subsequently on student learning.

4.3. Future studies

Conduct additional social science studies to gather quantitative and qualitative data with greater statistical validity. Although there is qualitative evidence to support the effectiveness of the PAS methodology in practice, this study lacks the quantity of data necessary for statistical validity. For this reason additional studies could be carried out to corroborate the findings in this study.

Studies could be carried out to establish if/how the PAS methodology could be applied to other engineering disciplines, or in these other managerial contexts:

- Other University programmes
- Primary or Secondary School programmes
- Sports coaching

- Business management
- Language programmes
- Parenting

The last point is quite contentious, however it has been researched in the past. *"Parenting. The finding that autonomy support plays an important role in increasing students' intrinsic motivation and internalization, and in turn their learning and adjustment, is not limited to the influence of teachers. Grolnick and Ryan (1989) used in-home, structured interviews with parents to examine the impact of parental autonomy support versus control on children's capacity to be autonomously self-regulating of their school work. An autonomy-supportive parenting style was evidenced by a willingness to offer choice and to consider the child's perspective when making decisions. In contrast, a controlling parental style was characterized by the use of extrinsic contingencies such as rewards, punishments, and pressures to motivate the child. Children of these parents completed the self-regulation questionnaire (ASRQ) and various other self-report measures in their classrooms. Regression analyses revealed that parental autonomy support was positively related to children's intrinsic motivation and internalization of regulations for school-related activities. Further, parental autonomy support was also positively related to children's being rated by their teachers as being more capable and better adjusted, and to the children's school achievement"* (Deci, Ryan, & Williams, 1996).

4.3.1. Mindset survey

During this study, a small percentage of students were identified to be at the extreme ends of the spectrum. These students could not adapt to, and were severely limited by, teaching practices that were not aligned with their way of thinking.

A further study could be to develop a survey to accurately predict the specialist/generalist mindset of students, thus allowing the university and the students to make informed decisions about teaching styles. An example questionnaire is given in Appendix D.

Individuals with a naturally Specialist mindset would be likely to answer (a) to questions 4, 7, 10, 13, 16, 19 & 22; while those individuals with a naturally Generalist mindset would be likely to answer (b).

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APPENDIX

CDIO Stakeholder Survey Results

	CDIO Previous Study	Edinburgh FSE Academics					Average	Diff	Std Dev
		JT	LB	DD	GR	SW			
1 DISCIPLINARY KNOWLEDGE AND REASONING									
1.1 KNOWLEDGE OF UNDERLYING MATHEMATICS AND SCIENCES	**3.0**	2.3	3.0	3.3	3.0	3.7	**3.1**	**0.1**	0.49
1.1.1 Mathematics		3	3	4	3	4	**3.4**		
1.1.2 Physics		2	4	3	4	4	**3.4**		
1.1.3 Chemistry		2	2	3	2	3	**2.4**		
1.2 CORE ENGINEERING FUNDAMENTAL KNOWLEDGE	**3.0**	2.4	4.2	2.6	3.2	3.4	**3.2**	**0.2**	0.71
1.2.1 Fire Chemistry and Combustion		2							
1.2.2 Fire Dynamics		3	5	4	4	4	**4.0**		
1.2.3 Fluid Mechanics		3	4	3	3	3	**3.2**		
1.2.4 Human Behaviour		2	3	1	3	3	**2.4**		
1.2.5 Solid Mechanics and Materials		2	5	3	3	4	**3.4**		
1.2.6 Architecture		2							
1.2.7 Computers and Computation			4	2	3	3	**3.0**		
1.2.8 Structural Behaviour		3							
1.3 ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE, METHODS AND TOOLS	**3.0**	2.3	2.7	2.7	2.5	4.0	**2.8**	**-0.2**	0.67
1.3.1 Fire Chemistry and Combustion		2	2	3	3	4	**2.8**		
1.3.2 Heat Transfer		3	4	4	3	5	**3.8**		
1.3.3 Human Egress		2	2	1	2	3	**2.0**		
1.3.4 Structural Mechanics		3	2	3	2	4	**2.8**		
1.3.5 Structural Materials		2	4	3	3	4	**3.2**		
1.3.6 Computational Techniques		2	2	2	2	4	**2.4**		
1.3.9.1 Computational Fluid Dynamics		2							

1.3.9.2 Finite Element Methods		3							
1.3.9.3 Egress Modelling		1							
2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES									
2.1 ANALYTICAL REASONING AND PROBLEM SOLVING	**4.2**	3.6	5.0	2.4	3.8	4.6	**3.9**	**-0.3**	1.01
2.1.1 Problem Identification and Formulation		5	5	3	4	4	**4.2**		
2.1.2 Simplification and Modelling		3	5	2	3	5	**3.6**		
2.1.3 Estimation and Qualitative Analysis		4	5	2	4	5	**4.0**		
2.1.4 Analysis With Uncertainty		3	5	2	3	5	**3.6**		
2.1.5 Solution and Recommendation		3	5	3	5	4	**4.0**		
2.2 EXPERIMENTATION, INVESTIGATION AND KNOWLEDGE DISCOVERY	**3.3**	3.8	4.0	4.0	2.3	3.3	**3.5**	**0.2**	0.74
2.2.1 Hypothesis Formulation		5	5	4	3	3	**4.0**		
2.2.2 Survey of Print and Electronic Literature		3	4	4	2	4	**3.4**		
2.2.3 Experimental Inquiry		3	3	4	2	3	**3.0**		
2.2.4 Hypothesis Test, and Defence		4	4	4	2	3	**3.4**		
2.3 SYSTEM THINKING	**3.5**	4.3	3.3	3.5	3.3	4.3	**3.7**	**0.2**	0.51
2.3.1 Thinking Holistically		4	4	3	4	4	**3.8**		
2.3.2 Emergence and Interactions in Systems		3	2	3	2	4	**2.8**		
2.3.3 Prioritization and Focus		5	3	4	3	4	**3.8**		
2.3.4 Trade-offs, Judgement and Balance in Resolution		5	4	4	4	5	**4.4**		

2.4 CREATIVE AND CRITICAL THINKING, LEARNING AND PERSONAL RESOURCES	**3.5**	4.4	4.2	3.8	3.2	4.0	**3.9**	**0.4**	0.46
2.4.3 Creative Thinking		5	4	3	3	4	**3.8**		
2.4.4 Critical Thinking		4	4	4	4	5	**4.2**		
2.4.5 Awareness of One's Personal Knowledge, Skills and Attitudes		5	5	4	3	4	**4.2**		
2.4.6 Curiosity and Lifelong Learning		5	5	4	3	4	**4.2**		
2.4.7 Time and Resource Management		3	3	4	3	3	**3.2**		
2.5 ETHICS, PROFESSIONAL RESPONSIBILITY, EQUITY AND OTHER CORE PERSONAL VALUES	**3.0**	3.0	2.8	3.4	3.3	4.1	**3.3**	**0.3**	0.53
2.5.1 Ethics, Integrity and Social Responsibility		3	3	3		5	**3.5**		
2.5.2 Professional Behaviour and Responsibility		3	3	3	4	5	**3.6**		
2.5.3 Proactively Planning for One's Career		3	2	4	3	3	**3.0**		
2.5.4 Staying Current on World of Engineering		3	3	4	3	4	**3.4**		
2.5.5 Initiative and Willingness to Take Risks		3		3		4	**3.3**		
2.5.6 Urgency and the Will to Deliver		3		3		4	**3.3**		
2.5.7 Resourcefulness and Flexibility		3		4		4	**3.7**		
3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION									
3.1 TEAMWORK	**3.4**	3.0	1.8	2.6	3.8	3.4	**2.9**	**-0.5**	0.76
3.1.1 Forming Effective Teams		4	3	2	4	4	**3.4**		

3.1.2 Team Operation		3	1	3	4	3	**2.8**		
3.1.3 Team Growth and Evolution		3	1	3	3	3	**2.6**		
3.1.4 Team Leadership		2	1	3	4	3	**2.6**		
3.1.5 Multi-disciplinary Teaming		3	3	2		4	**3.0**		
3.2 STRUCTURED COMMUNICATIONS	**3.5**	2.0	3.3	3.7	3.2	3.8	**3.2**	**-0.3**	0.72
3.2.1 Communications Strategy		2	4	3	4	4	**3.4**		
3.2.2 Communications Structure		2	2	3	2	4	**2.6**		
3.2.3 Written Communication		2	4	4	2	4	**3.2**		
3.2.4 Electronic/Multimedia Communication		2	2	4	3	4	**3.0**		
3.2.5 Graphical Communication		2	4	3	4	3	**3.2**		
3.2.6 Oral Presentation		2	4	5	4	4	**3.8**		
3.3 COMMUNICATIONS IN FOREIGN LANGUAGES	**3.5**	2.3	2.3	3.3	2.7	2.3	**2.6**	**-0.9**	0.43
3.3.1 Communications in English		3	3	5	4	4	**3.8**		
3.3.2 Communications in Languages of Regional Industrialized Nations		2	1	3	2	2	**2.0**		
3.3.3 Communications in Other Languages		2	3	2	2	1	**2.0**		
4 CONCEIVING, DESIGNING, IMPLEMENTING AND OPERATING SYSTEMS IN THE ENTERPRISE, SOCIETAL AND ENVIRONMENTAL CONTEXT									
4.1 EXTERNAL, SOCIETAL, ECONOMIC AND ENVIRONMENTAL CONTEXT	**2.3**	3.0	4.5	2.3	2.7	3.4	**3.2**	**0.9**	0.85
4.1.1 Roles and Responsibility of Engineers		3	5	3	2	4	**3.4**		
4.1.2 The Impact of Engineering on Society and the Environment		2	4	3	4	4	**3.4**		

4.1.3 Society's Regulation of Engineering		3	5	2	2	3	**3.0**		
4.1.4 The Historical and Cultural Context		4	4	2	2	3	**3.0**		
4.1.5 Contemporary Issues and Values		4	5	2	2	3	**3.2**		
4.1.6 Developing a Global Perspective		2	4	2	4	3	**3.0**		
4.1.7 Sustainability and the Need for Sustainable Development		3		2		4	**3.0**		
4.1.8 Societal Responsibility and its Manifestations in Engineering		4							
4.2 ENTERPRISE AND BUSINESS CONTEXT	**2.4**	3.0	3.0	2.2	2.0	3.2	**2.7**	**0.3**	0.54
4.2.1 Appreciating Different Enterprise Cultures		3	3	3	2	3	**2.8**		
4.2.2 Enterprise Stakeholders, Strategy and Goals		3	3	2	2	3	**2.6**		
4.2.3 Technical Entrepreneurship		2	2	2	2	3	**2.2**		
4.2.4 Working Successfully in Organizations		4	4	3	2	3	**3.2**		
4.2.5 Engineering Project Finance and Economics		3		2		4	**3.0**		
4.2.6 New Technology Development, Assessment and Infusion		3		1		3	**2.3**		
4.3 CONCEIVING, SYSTEMS ENGINEERING AND MANAGEMENT	**3.0**	2.8	2.8	2.5	2.8	3.8	**2.9**	**-0.1**	0.49
4.3.1 Understanding Needs and Setting Goals		4	4	2	4	4	**3.6**		
4.3.2 Defining Function, Concept and Architecture		2	3	3	2	4	**2.8**		

4.3.3 Modelling of System and Ensuring Goals Can Be Met		3	2	2	2	4	**2.6**		
4.3.4 Development Project Management		2	2	3	3	3	**2.6**		
4.4 DESIGNING	**3.2**	3.2	3.8	2.5	3.0	3.7	**3.2**	**0.0**	0.53
4.4.1 The Design Process		4	3	2	3	3	**3.0**		
4.4.2 The Design Process Phasing and Approaches		3	3	2	4	4	**3.2**		
4.4.3 Utilization of Knowledge in Design		3	5	3	3	3	**3.4**		
4.4.4 Multidisciplinary Design		2	5	3	2	3	**3.0**		
4.4.5 Fulfilment of Legal Obligations		4	4	3	4	4	**3.8**		
4.4.6 Design for Sustainability, Safety, Operability, Aesthetics and other Objectives		3	3	2	2	5	**3.0**		
4.5 IMPLEMENTING	**2.7**	4.0	4.0	2.3	2.3	3.3	**3.2**	**0.5**	0.84
4.5.1 Designing the Implementation/Construction Process		2	4	2	2	3	**2.6**		
4.5.2 Test, Verification, Validation and Certification to Standards		3	4	3	3	4	**3.4**		
4.5.3 Implementation/Construction Management		2	4	2	2	3	**2.6**		
4.6 OPERATING	**2.5**	2.2	2.5	2.5	1.2	3.0	**2.3**	**-0.2**	0.68
4.6.1 Designing and Optimizing Sustainable and Safe Operations		2	3	3	2	3	**2.6**		
4.6.2 Training and Operations		1	3	3	1	3	**2.2**		
4.6.3 Supporting the System Lifecycle			3	2	1	3	**2.3**		

4.6.4 System Improvement and Evolution		3	2	2	1	3	**2.2**		
4.6.5 Management, Ageing and Maintenance of Systems		4							
4.6.6 Disposal and Life-End Issues			1	2	1	3	**1.8**		
4.6.7 Operations Management		1	3	3	1	3	**2.2**		

b

APPENDIX

Problem Sets

2010 Fire Science and Fire Dynamics 4

Fire Science and Fire Dynamics 4

Problem Set #1

Due Date: 3rd November 2010

Question 1

(a) Describe in your own words what is meant by a "fire strategy". Describe the fire strategy for the flat/house that you live in.

(b) Explain the shape of a flame on a burning match. What would the same flame look like in a space ship? Try explaining the difference.

(c) Define the terms: 'laminar flame speed' and 'blow-off limit'.

(d) Define 'stoichiometry' and 'flammability limits' of a fuel in your own words.

(e) Calculate ΔHc for a stoichiometric mixture of methane (CH_4) and air.

(f) Recall what percentage of a flame's energy is released in the form of radiation.

Question 2

(a) Recall the meaning of 'flash point' and 'fire point' of a volatile liquid.

(b) Describe the difference between a 'deflagration' and a 'detonation'.

(c) Describe what a 'combustible liquid' means, in your own words.

(d) Explain at a level understandable by a non-technical person, what is meant by 'pyrolysis'.

Question 3

(a) 1.45kg of gaseous propane (C_3H_8) has leaked into an informatics clean room containing extremely valuable computing equipment. The room measures 3x3x2m, is kept at stp and is almost completely sealed (no external ventilation). Demonstrate a safe and cost-effective method of protecting the computer equipment. Assume 1mole = 22.4L at standard temperature and pressure.

References that may help you:

1. Drysdale, D.D. Introduction to fire Dynamics, 2nd Edition, John Wiley and Sons, 1998.

Please hand in your solutions at the start of the next lecture (Mon). You will be given it back in the following tutorial (Wed) to make changes and improve your solution.

Fire Science and Fire Dynamics 4

Problem Set #2

Due Date: 10th November 2010

Question 1

(a) Define a 'diffusion flame' and give examples.
(b) Define the factors influencing the location of a diffusion flame between fuel and air.
(c) Describe the factors that increase soot production and radiation emission from flames.
(d) Describe in detail how a flame moves along the surface of a wooden table.
(e) Flame tornadoes are highly dangerous occurrences in wild fires. Explain what causes them.

Question 2

(a) Create a formula to work out the heat release rate of a liquid pool fire. How much of this will be transferred via convection?
(b) Demonstrate how you would calculate the temperature at a sprinkler head that is 2m above and 1.5m to the side of a heptane pool fire.

Question 3

(a) Explain, in as much detail as possible, how a candle works.
(b) Explain why it is possible to blow out a candle.

(c) Assuming a candle is made with a type of paraffin wax, calculate the mass and volume of air required to burn a standard candle completely.

(d) Bonus: Calculate the time to burn the candle completely.

Question 4

(a) A self-proclaimed fire safety expert has been asked to design a storage unit for a canister containing 10kg of propane gas for use in one the University of Edinburgh laboratories. He designs an airtight, 4x4x4m reinforced concrete room and claims that "the situation would not be at risk of explosion unless the room was filled up with greater than 28.5% by volume of propane gas, any less than this would be safe".

Do you trust him? Show reasoning for your answer.

Reference that may help you:

1. Drysdale, D.D. Introduction to fire Dynamics, 2nd Edition, John Wiley and Sons, 1998.

Fire Science and Fire Dynamics 4

Problem Set #3

Due Date: 17th November 2010

Question 1

(a) A heater provides a constant heat source (Q) as it is held against a table leg. Model the table leg as a block of wood and derive an equation to calculate the time to ignition (assume conduction dominates).

(b) Explain the conditions necessary for spontaneous ignition to occur, e.g. in hay bales (research Semenov and Frank-Kamenetskii).

(c) The Deepwater Horizon was the world's largest oil spill. Discuss whether or not burning the oil would have been a viable option.

Question 2

(a) Describe in your own words the difference between smouldering (diffusion-controlled ignition) and flaming (gasification-controlled ignition).

(b) Describe what is done to materials to make them 'fire-retardant' and discuss the effectiveness of this process.

(c) If the temperature is 200°C on one side of a steel beam and 20°C on the other, estimate the temperature of the beam after reaching steady state conditions. Describe how you would model the temperature in the beam before steady state conditions are reached.

Question 3

(a) A vertical strip of fabric, 1m long, 30cm wide and 0.7mm thick is suspended by one short edge. It is exposed uniformly on one side to a radiant heat flux of 25 kW/m2. Will the fabric achieve its pilot ignition temperature of 300°C and if so, approximately how long will this take?

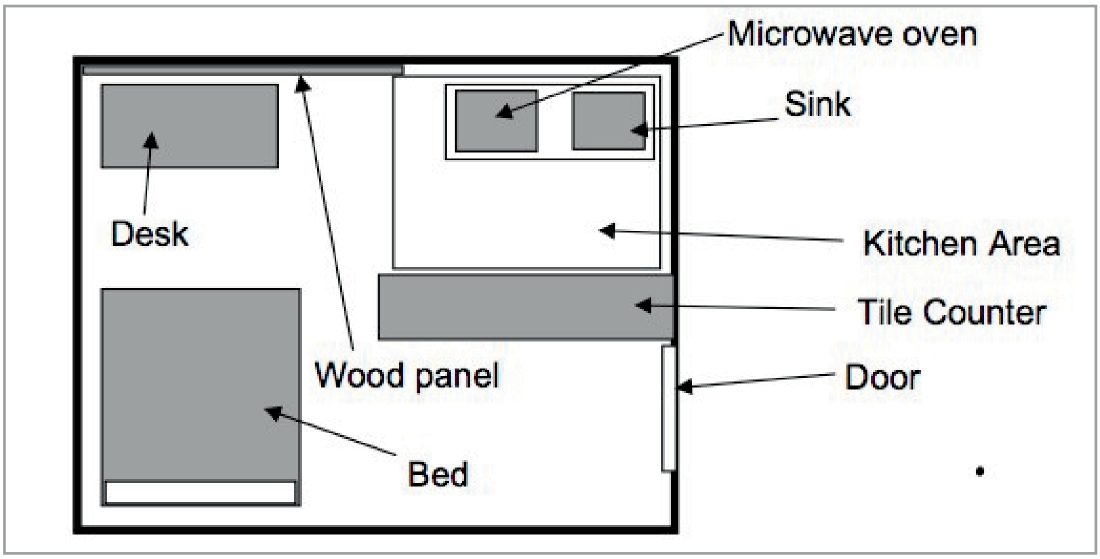
Assume that the convective heat transfer coefficient $h = 12$ W/m^{2}K, $c = 1400$ J/kgK and $\rho = 350$ kg/m^3 and that the fabric surface has an emissivity of 0.9. The initial temperature is 20°C.

Question 4

A fire occurred in a hotel room that resulted in several million dollars in losses, the death of a firefighter and of two guests of the hotel. The insurance company hired a fire investigator to determine the cause of the fire. The fire investigator issued a report that provided the following explanation.

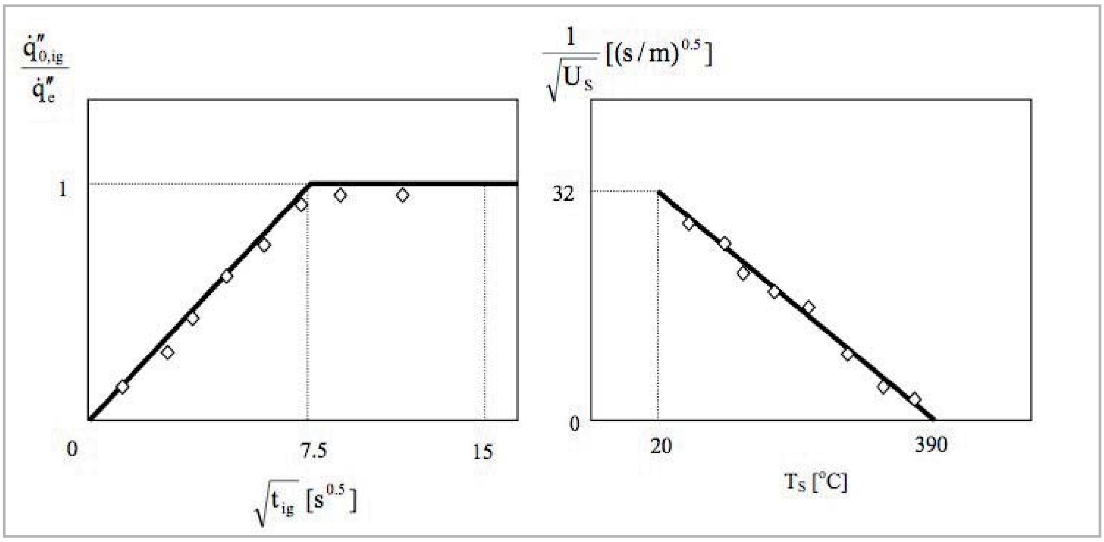
- The hotel room had a small kitchen facility and the fire was initiated there.
- An electrical short circuit resulted in the ignition of a microwave oven.
- The microwave oven ignited a wood panel in the adjacent wall.
- Once the wood panel had ignited the fire grew beyond possible control. All other furnishings were involved and flash over occurred in a period of less than 4 minutes.
- The hotel room did not have sprinklers (old construction in the process of being remodelled).

Ignition of the wood panel is the critical event since there is no other fuel surrounding the microwave oven. The ceilings are very high and made out of concrete panels therefore cannot ignite.



The insurance company claims that the microwave oven should have not been placed next to the wood panel since in case of a short circuit that microwave oven can provide an incident heat flux of approximately 12,000 W/m^2 to the wood panel, which will result in its ignition. The insurance company provided data on similar materials that verifies that 12,000 W/m^2 is enough to ignite the wood panel. The insurance company, thus, blames the hotel and refuses payment of damages.

The hotel, throughout the remodeling process had determined that the heat released from the microwave is not enough to ignite that specific type of wood panel and had hired a Fire Protection Company to conduct a series of LIFT tests to back their calculations. The data provided by the company is as follows:



Where T_s is the surface temperature of the wood panel, U_s the flame spread velocity, t_{ig} the ignition delay time, $q''_{o,ig}$ the critical heat flux for ignition and q'_c the external heat flux applied to the surface. The company says that all tests were conducted at 20°C ambient temperature, that the calculated value for φ= 13 x 106 (W^2/m^3) and that all tests were conducted rigorously following ASTME-1321. No further information is provided and the Company does not want any further involvement in this case (lets call it conflict of interests!). You are hired by the Fire Marshall to decide who is right on this issue.

The absorptivity (a) can be taken as a=1 and the 12,000 W/m^2 is assumed to be an adequate estimate of the heat imposed by the burning oven.

From the data provided determine if the board should or should have not ignited. Show all your calculations in detail. You will be graded based on your work not on the final answer.

Fire Science and Fire Dynamics 4

Problem Set #4

Due Date: 24th November 2010

Question 1

(a) Describe how flames spread upward, downward and laterally.

(b) Explain, in as much detail as possible, how sprinklers control a fire.

(c) Define 'fuel-limited' fire and 'ventilation-limited' fire and describe the effects of ventilation on burning rates.

(d) Define 'heat feedback' and describe how radiation (particularly from the smoke layer) affects flame spread.

(e) Try and define 'flashover' and a 'fully developed fire' in your own words.

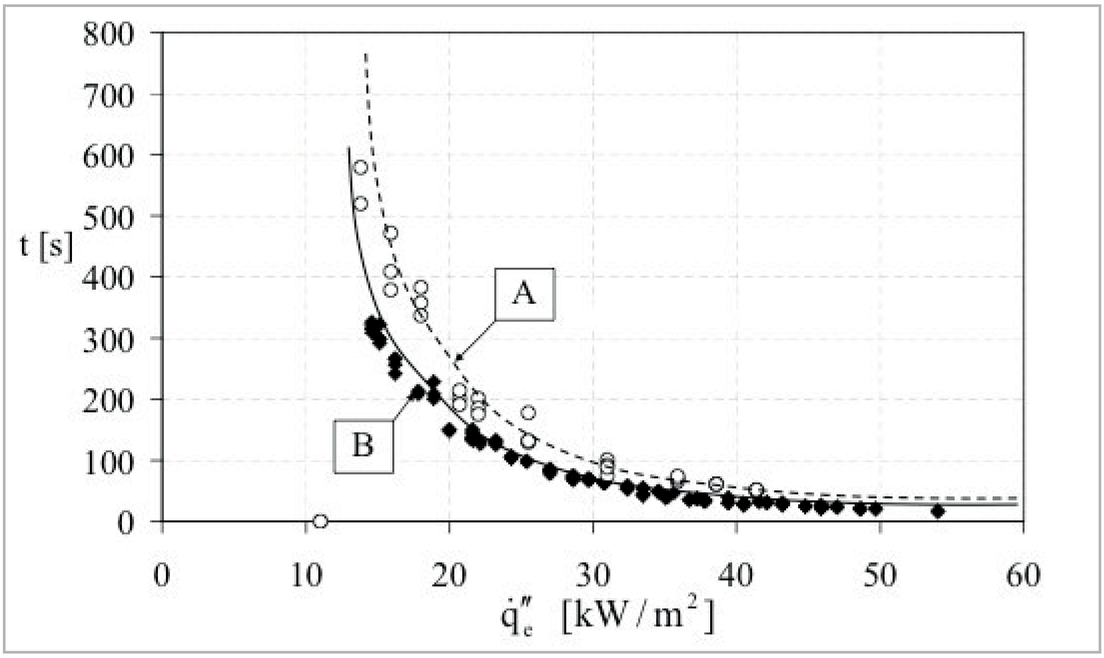
(f) Define 'backdraught' in your own words.

Question 2

(a) Design an experiment to measure how quickly a sofa burns. Discuss whether the results of this experiment would be useful for a fire strategy.

(b) Create a design fire (the fire used to design structural components and the fire strategy) for your own dorm room/bedroom. Present it as a graph of Q (on y-axis) vs. time (on x-axis). Data for different materials can be found in the SFPE handbook or from websites e.g. www.fire.nist.gov/fire/fires/

Discuss possible problems with your chosen fire.



Question 3 – Bonus

(a) Describe how tall buildings (skyscrapers) can be designed to limit vertical flame spread.

(b) Describe how you would calculate the minimum distance required between town houses to prevent flame spread from one house to the next.

Fire Science and Fire Dynamics 4

Problem Set #5

Due Date: 1st December 2010

Question 1

(a) Calculate how much time you would have to escape from your kitchen if a pool of octane (diameter ~50cm) were to ignite on the floor. Assume the critical point is where the smoke reaches your head height. (Feel free to simplify the dimensions of your kitchen.)

a. Plot the evolution of the smoke layer height as a function of time.

b. Plot the evolution of the smoke layer temperature as a function of time.

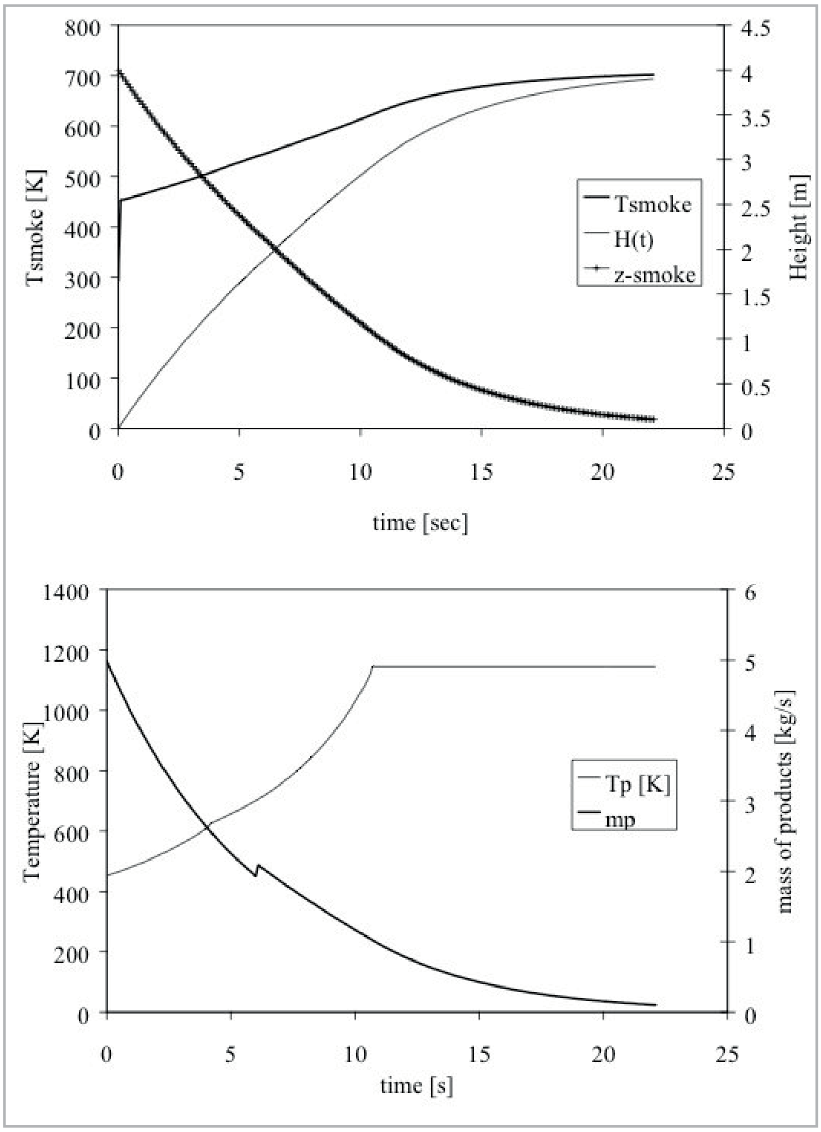
c. Plot the evolution of the oxygen concentration in the smoke layer as a function of time.

d. Plot the evolution of the mass of products entering the smoke layer as a function of time.

e. Plot the evolution of the temperature of the products entering the smoke layer as a function of time.

f. Analyse assumptions and sources of bias in your model

For your information, example solutions for (a), (b), (d) and (e) are presented below.



(b) Bonus: Discuss whether a pool of octane is a realistic design fire for your kitchen and suggest an alternative.

C

APPENDIX

Tutorials

2010 Fire Science and Fire Dynamics 4

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Tutorial #1 (20/10/10): Thermochemistry

Question 1:

A compartment contains a volume V of air. The volume of oxygen is estimated to be 10 m^3.

a) Calculate for each of the component:
- the number of moles;
- the mass;
- the mass fraction;

b) Calculate the total number of moles.

c) Calculate the molar mass of air.

d) Calculate the density of air at {0, 20, 100, 200, 500} °C.

e) Determinate the coefficient of thermal expansion.

f) Calculate the Cp of air thanks to the relative Cp of oxygen and nitrogen.

Question 2:

a) Calculate the specific heat of a mixture of ethylene C2H4 with oxygen at stoichiometry at 298K.

b) Once the reaction of combustion occurs, what is the cp of the mixture if you consider that the products are still at 298K?

c) Assess the error done in b) if the real temperature of the products is at 1000K.

d) Calculate the specific heat of the product mixture for the combustion reaction of propane C_3H_8 and benzene C_6H_6 at 298 and 1000K.

Question 3:

a) Determine thanks to the heat of formation, the heat of combustion of the following chemicals:
- Heptane C_7H_{16};
- Methanol CH_4O;
- Propane C_3H_8;
- Propene C_3H_6;
- Benzene C_6H_6;

The heat of combustion should be given in kJ/mol_{FUEL} ; MJ/kg_{FUEL}, MJ/kg_{AIR} ; MJ/kg_{OXYGEN}.

b) Calculate the heat of combustion of the elements from a) using the constant E = 13.1 MJ/kg_{OXYGEN}. Assess the uncertainty bringing by using this constant.

c) Calculate the heat of combustion in kJ/mol_{FUEL} and MJ/kg_{FUEL} of Propylbutyrate $C_7H_{14}O_2$.

Question 4:

a) Calculate the adiabatic flame temperature of the following mixture supposed at stoichiometry using the :

CH_4 / O_2	CH_4 / Air
C_6H_6 / O_2	C_6H_6 / Air
C_8H_{18} / O_2	C_8H_{18} / Air
C_2H_6 / O_2	C_2H_6 / Air
C_3H_8 / O_2	C_3H_8 / Air

b)Repeat the same question than a) by using Cp = 1000 kJ/kg.K.

c) Repeat the same question than a) but this time by considering the mixture at the lean flammability limit.

Question 5:

An experimentalist carried out some experiments and measured the production of CO and Soot (considered here as pure Carbon) as a function of the equivalence ratio of the mixture. His results are reported in the following table. The material used for the experiments is polyethylene (PE – $(C_2H_4)_n$).

Determine the heat of combustion for each of the mixture composition. It is assume that the only products are CO_2, H_2O, CO and C (soot).

ϕ	y_{CO} [g/g]	y_C [g/g]
0.1	0.013	0.05
0.5	0.013	0.05
1	0.024	0.082
1.5	0.071	0.071
2	0.104	0.082

Tables

Table 1: Lower flammability limit and Heat of combustion at 25°C

Substance	Formula	LFL [% Vol]	$-\Delta h_c$ [kJ/mol]
Methane	CH_4	5	800
Ethane	C2H6	3	1423
Propane	C_3H_8	2.1	2044
Octane	C_7H_{16}	0.95	5104
Benzene	C_6H_6	1.3	3120

Table 2: Heat of formation in kJ/mol (at 25°C and 1 atm)

Substance	Formula	Sate	Δh_f
Oxygen	O_2	g	0
Nitrogen	N_2	g	0
Graphite	C	g	0
Carbon dioxide	CO_2	g	-393.5
Carbon monoxide	CO	g	-110.5
Water	H_2O	g	-241.8
Water	H_2O	l	-285.9
Methane	CH_4	g	-74.9
Propane	C_3H_8	g	-103.8
Heptane	C_7H_{16}	g	-187.8
Ethylene	C_2H_4	g	+52.6
Propene	C_3H_6	g	+20.7
Benzene	C_6H_6	g	+82.9
Methanol	CH_4O	g	-201.2
Methanol	CH_4O	l	-238.6

Table 3: Specific heat at constant pressure [J/(mol.K)]

T. [K]	C	CH_4	C_2H_4	O_2	N_2	H_2O	CO_2	CO
298	8.5	35.8	42.9	29.4	29.1	33.6	37.1	29.1
600	16.8	52.2	10.7	32.1	30.1	36.3	47.3	30.4
1000	21.6	71.8	110.0	34.9	32.7	41.3	54.3	33.2
1600	24.2	88.5	112.1	36.8	35.1	48.1	58.9	35.5
2500	25.9	98.8	123.1	38.9	36.6	53.9	61.5	36.8

Tutorial #2 (27/10/10): Premixed flames

Question 1:

A compartment of dimension 3x2x5 m^3 contains a premixed mixture of propane C_3H_8 and air. Initially the compartment is NTP conditions.

a) Stoichiometric mixture:

- Equilibrate the chemical reaction assuming that CO_2 and H_2O are the only product of the reaction.
- Assess the final pressure inside the compartment in an isothermal case at 20 °C.
- Calculate the adiabatic flame temperature of the mixture
- Assess the final pressure inside the compartment at the adiabatic flame temperature.

b) Lean flammability Limit mixture:

- Repeat a), given that the mixture is not at stoichiometric proportion but at its LFL.

Question 2:

a) CV I: Pre-heating zone: (NO reaction)

- Thank to a schematic, indicates the different components of the energy conservation law over a control volume of thickness dx taken inside CV I.

H_1: No radiation component is considered.

H_2: The system is in the referential II attached to the flame.

- Establish the Partial Differential Equation (PDE) governing the energy conservation.

H_3: Use a Taylor series expansion of order 1.

- Determinate the initial condition and the boundary conditions at $X=x_0$ and $X=x_{ign}$
- Integrate the PDE between x_0 and x_{ign}.

You should find something similar at the equation in your Notes.

b) CV II: Reacting zone:

- Repeat the same steps than a) but this time integrate between x_{ign} and x_f.

H_4: Assume an Arrhenius model of order zero

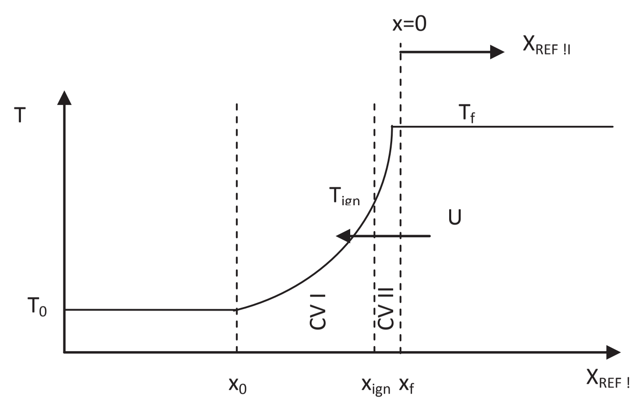


Figure 1

c) Continuity between CVI and CV II:

-Pose $\left.\frac{dT}{dx}\right|_{x=x_{ign\ CVI}} = \left.\frac{dT}{dx}\right|_{x=x_{ign\ CVII}}$

- Express U as a function of T_f, E, A, ΔH, α, ρ and C_P.

- Apply the value from the Table 1 to estimate the flame speed velocity of a pre-mixed flame of methane.
H_5: Assume stoichiometric proportion.
- The adiabatic flame temperature measured is 2210K. Compare the flame speed limit found with the previous answer. Explain where the difference comes from

Question 3:

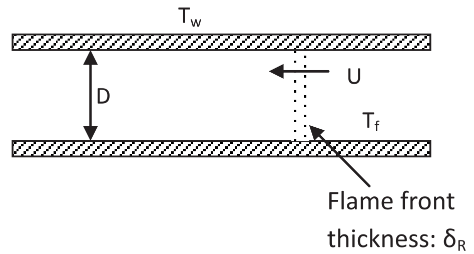


Figure 2

a) Energy balance:
Establish ONLY with the following variables an energy conservation law for the control volume CV_{II}.

- ρ : gas density [kg/m^3];
- c_p : gas specific heat [J/(kg.K)];
- δ_R : flame thickness [m];
- D : duct diameter [m];
- $^{dT}/_{dx}$: change of temperature inside CV_{II}.
- $\dot{Q}_R$: heat released per combustion reaction [W/m^2].
- $\dot{Q}_L$: Heat losses per convection through the wall [W/m^2].

H_1: No radiation component is considered.
H_2: Material properties are considered invariant with Temperature.

b) Heat released $\dot{Q}_R$:
Determine the heat released by the reaction of combustion.

c) Heat losses $\dot{Q}_L$:
Determine the heat losses transferred by convection from the flame to the wall per unit surface area of the flame.

H_3: No heat loss to the pre-heating zone.

d) Quenching diameter for steady state problem:
Determine the quenching diameter in the case of a methane melange where the heat released follow the curvature express in the schematic on Fig. 3.

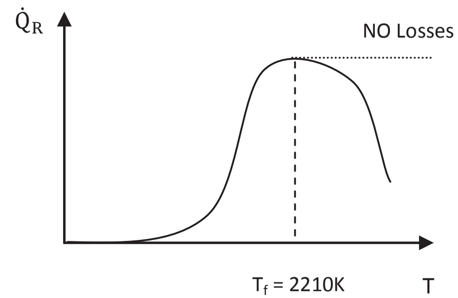


Figure 3

f) According to H_1 and H_3, conclude on the real quenching diameter

Question 4:

In a refinery a pipe containing a mixture of methane and air at stoichiometric proportion is crossing a confined room. This room has a uniform temperature T_r and the movement of air is negligible. Due to a technical problem, the flow inside the pipe is blocked.

a) Establish a conservation energy equation with the same type of component than Question 3 a).

H_1: V : volume of the pipe.

b) Express $\dot{Q}_L$.

H_2: System losses heat only by convection.

c) Express $\dot{Q}_R$

d) With the relation given in appendix, estimate the heat transfer coefficient h for a diameter of 0.1 m.

e) Plot on a schematic the curves corresponding to $\dot{Q}_L$ and $\dot{Q}_R$ as a function of the temperature.

f) By considering that the heat transfer coefficient is not a function of the temperature, plot on the schematic of e) the critical scenario where the mixture does not ignite.

g) Estimate the ambient temperature that should not be beyond to avoid auto-ignition of the mixture (AIT_{CH4} =540°C).

h) With the Biot number, determine if we can consider the temperature of the mixture methane air as uniform in the pipe.

Appendix

NTP: Normal Temperature and Pressure: 20 °C and 1 atm.

Pressure: 1 atm = 1.01325 bar = 760 mm Hg
= 101.325 kN/m^2 = 1013.25 10^2 Pa

Ideal gas law constant R = 8.31431 J/(K.mol) (V in m^3 and P in Pa)

$$\frac{d}{dx}\left(\frac{dT}{dx}\right)^2 = 2\frac{dT}{dx}\frac{d^2T}{dx^2} \quad (1)$$

$$\int_{\varphi(a)}^{\varphi(b)} f(t)dt = \int_a^b f(\varphi(x))\varphi'(x)\,dx \quad (2)$$

$$\int_{T_i}^{T_f} \exp\left(\frac{-E}{RT}\right) = \frac{RT_f^2}{E}\exp\left(\frac{-E}{RT_f}\right)\exp\left(\frac{-E}{RT_f^2}(T_f - T_i)\right) \quad (3)$$

$$Nu = \frac{hD}{k} = 3.66 \text{ (for a laminar flow in a duct of diameter D)} \quad (4)$$

Empirical correlation for free convection around horizontal cylinder:

$$Nu = \left[0.60 + \frac{0.387\,Ra_D^{1/6}}{\left(1+(0.559/Pr)^{9/16}\right)^{8/27}}\right]^2, Ra_D \le 10^{12} \quad (5)$$

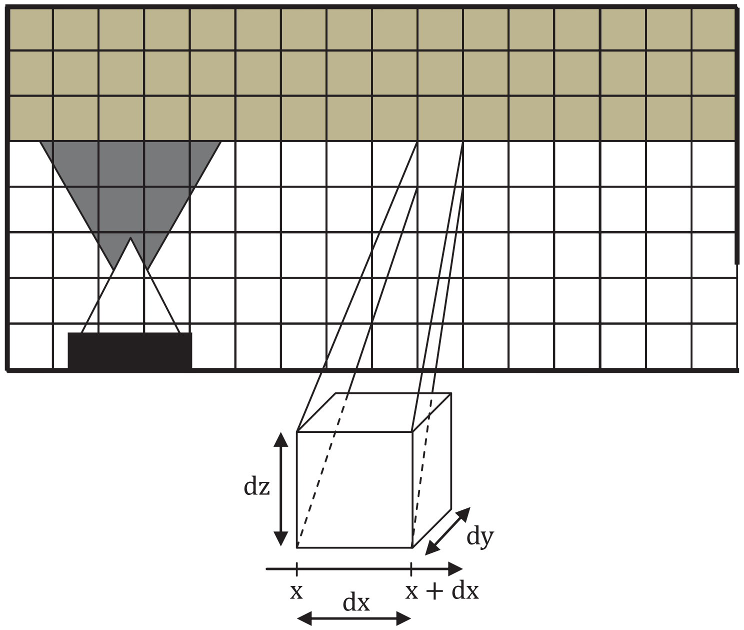
$$Ra_D = \frac{2g(T_s - T_\infty)D^3\rho c_P}{\nu k(T_s + T_\infty)} \quad (6)$$

$$Bi_D = \frac{hD}{2k} \quad (7)$$

Table 1: Kinetic parameters for Methane pre-mixed flames

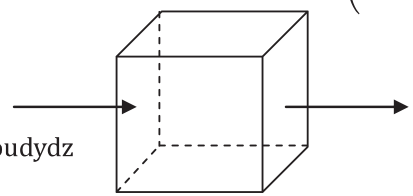
Parameter	Unit	Value	Parameter	Unit	Value
ΔH	kJ/mol$_{CH4}$	802.860	T_0	°C	20
R	J/(mol.K)	8.314	ρ	Kg/m^3	0.348
E	J/mol	121417.2	C_P	J/(kg.K)	1141
A	Mol$_{CH4}$/(s.m^3)	8.125 10^6	k	W/(m.K)	0.0667
ν (300K)	m^2.s	3.22 10^{-5}	Pr (300K)	-	0.74

Tutorial #3 (01/11/10): CFD governing equations



Question 1: Continuity equation

$$\dot{m}_{OUT\,x} = \left(\rho u + \frac{\partial(\rho u)}{\partial x}dx\right)dydz$$



$$\dot{m}_{IN\,x} = \rho udydz$$

$$\dot{\phi}_{IN} + \dot{\phi}_{GEN} = \dot{\phi}_{OUT} + \dot{\phi}_{ST}$$

$$\phi = m$$

$\dot{\phi}_{IN\,x} = \dot{m}_{IN\,x} = \rho udydz$
$\dot{\phi}_{GEN} = 0$
$\dot{\phi}_{OUT\,x} = \dot{m}_{OUT\,x} = \left(\rho u + \frac{\partial(\rho u)}{\partial x}dx\right)dydz$
$\dot{\phi}_{ST} = \frac{dm}{dt}$

$$\left(-\frac{\partial(\rho u)}{\partial x} - \frac{\partial(\rho v)}{\partial y} - \frac{\partial(\rho w)}{\partial z}\right)dxdydz = \frac{\partial m}{\partial t}$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

Incompressible flow: $\rho = \text{constant}$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = \text{div}(\vec{\mathbf{u}}) = \nabla \cdot \vec{\mathbf{u}} = 0$$

Question 2: Momentum equation

Momentum: $\vec{\mathbf{p}} = m\vec{\mathbf{u}}$

Newton's second law: $\sum F_i = m\,a_i = m\frac{Du_i}{Dt}$ with $i = \{x; y; z\}$

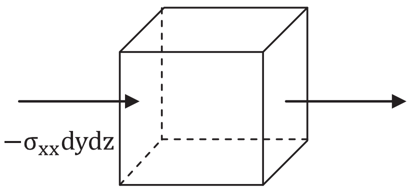
$$\dot{\phi}_{IN} + \dot{\phi}_{GEN} = \dot{\phi}_{OUT} + \dot{\phi}_{ST}$$

$$\phi_x = mu \Rightarrow F_x = \frac{\partial mu}{\partial t}$$

$$\dot{\phi}_{IN\,x} = F_{surf\,IN\,xx} + F_{surf\,IN\,xy} + F_{surf\,IN\,xz}$$
$$\dot{\phi}_{GEN} = F_{Body}$$
$$\dot{\phi}_{OUT\,x} = F_{surf\,OUT\,xx} + F_{surf\,OUT\,xy} + F_{surf\,OUT\,xz}$$
$$\dot{\phi}_{ST} = \frac{Dmu}{Dt} = \left(\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho vu)}{\partial y} + \frac{\partial(\rho wu)}{\partial z}\right) dxdydz$$

Normal stress:

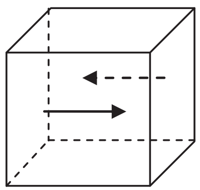
$$F_{surf\,OUT\,xx} = -\left(\sigma_{xx} + \frac{\partial \sigma_{xx}}{\partial x} dx\right) dydz$$



$$F_{surf\,IN\,xx} = -\sigma_{xx} dydz$$

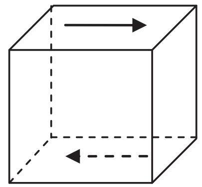
Tangential stress:

$$F_{surf\,OUT\,xy} = -\left(\tau_{xy} + \frac{\partial \tau_{xy}}{\partial y} dy\right) dxdz$$



$$F_{surf\,IN\,xy} = -\tau_{xy} dxdz$$

$$F_{surf\,OUT\,xz} = -\left(\tau_{xz} + \frac{\partial \tau_{xz}}{\partial z} dz\right) dxdy$$



$$F_{surf\,IN\,xz} = -\tau_{xz} dxdy$$

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + \rho g_x = \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho vu)}{\partial y} + \frac{\partial(\rho wu)}{\partial z}$$

Newtonian fluid:

$$\sigma_{xx} = -P + \tau_{xx}$$
$$\tau_{xx} = \mu\left(\frac{\partial u}{\partial x} + \frac{\partial u}{\partial x}\right) = 2\mu\frac{\partial u}{\partial x}$$
$$\tau_{xy} = \mu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$$
$$\tau_{xz} = \mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)$$
$$\mu = f(T, P)$$

$$-\frac{\partial P}{\partial x} + 2\mu\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}\right) + \mu\frac{\partial}{\partial y}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) + \mu\frac{\partial}{\partial z}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) + \rho g_x = \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho vu)}{\partial y} + \frac{\partial(\rho wu)}{\partial z}$$

Incompressible flow: $\rho = \text{constant}$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

$$2\mu\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}\right) + \mu\frac{\partial}{\partial y}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) + \mu\frac{\partial}{\partial z}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) \quad = \mu\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right] + \mu\left[\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{\partial w}{\partial x}\right)\right]$$

$$= \mu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right]+\mu\left[\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)\right]$$

$$= \mu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right]$$

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho vu)}{\partial y}+\frac{\partial(\rho wu)}{\partial z} = \rho\left[\frac{\partial u}{\partial t}+u\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right]$$

$$= \rho\left[\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right]$$

$$-\frac{\partial P}{\partial x}+\mu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right]+\rho g_x = \rho\left[\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right]$$

Question 3: Energy equation

First low of thermodynamics: $\frac{\partial E}{\partial t} = \sum \dot{E}_{IN-OUT} + \sum \dot{W} + \sum \dot{Q}$

$$\dot{\phi}_{IN} + \dot{\phi}_{GEN} = \dot{\phi}_{OUT} + \dot{\phi}_{ST}$$

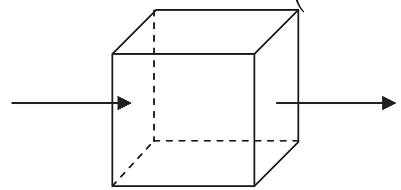
$$\phi = E$$

$\dot{\phi}_{IN\,x} = \dot{E}_{CONV\,IN\,xx} + \dot{E}_{COND\,IN\,xy}$
$\dot{\phi}_{GEN} = \dot{E}_{RAD} + \dot{Q}_{REAC} + \dot{W}$
$\dot{\phi}_{OUT\,x} = \dot{E}_{CONV\,OUT\,xx} + \dot{E}_{COND\,OUT\,xy}$
$\dot{\phi}_{ST} = \frac{\partial E}{\partial t}dxdydz$

CONVECTION:

$$E_{CONV} = \rho c_P uT|_x dA$$

$$\dot{E}_{CONV\,OUT\,x} = \left(\rho c_P uT|_x + \left.\frac{\partial(\rho c_P uT)}{\partial x}\right|_x dx\right)dydz$$

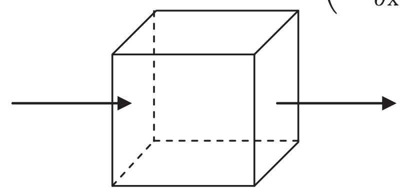


$$\dot{E}_{CONV\,IN\,x} = \rho c_P uT|_x dydz$$

CONDUCTION:

$$E_{COND} = -k\left.\frac{\partial T}{\partial x}\right|_x dA$$

$$\dot{E}_{COND\,OUT\,x} = \left(-k\left.\frac{\partial T}{\partial x}\right|_x - k\left.\frac{\partial^2 T}{\partial x^2}\right|_x dx\right)dydz$$



$$\dot{E}_{COND\,IN\,x} = -k\left.\frac{\partial T}{\partial x}\right|_x dydz$$

$$\dot{E}_{IN} + \dot{E}_{GEN} = \dot{E}_{OUT} + \dot{E}_{ST}$$

$$k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)-\frac{\partial(\rho c_P uT)}{\partial x}-\frac{\partial(\rho c_P vT)}{\partial y}-\frac{\partial(\rho c_P wT)}{\partial z}+\dot{E}_{RAD}+\dot{Q}_{REAC}+\dot{W}=\frac{\partial \rho c_P T}{\partial t}$$

$$\dot{W} = \dot{W}_{Surf\,x} + \dot{W}_{Surf\,y} + \dot{W}_{Surf\,z} + \dot{W}_{Body}$$

$$\dot{W}_{Surf\,x} = \left[\frac{\partial(u\sigma_{xx})}{\partial x} + \frac{\partial(u\tau_{xy})}{\partial y} + \frac{\partial(u\tau_{xz})}{\partial z}\right] dxdydz$$

Incompressible flow: $\rho = \text{constant}$

$$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \dot{E}_{RAD} + \dot{Q}_{REAC} + \dot{W} = \rho c_P \left[\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial t} + w\frac{\partial T}{\partial t}\right]$$

Question 4: Specie Equation

$$\dot{\phi}_{IN} + \dot{\phi}_{GEN} = \dot{\phi}_{OUT} + \dot{\phi}_{ST}$$

$$\phi = mY_i$$

$$\dot{\phi}_{IN\,x} = \rho u Y_i dydz - D\left.\frac{\partial \rho Y_i}{\partial x}\right|_x ydz$$

$$\dot{\phi}_{GEN} = \dot{S}_i$$

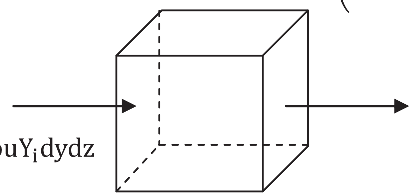
$$\dot{\phi}_{OUT\,x} = \left(\rho u Y_i + \frac{\partial(\rho u Y_i)}{\partial x}dx\right)dydz - \left(-D\left.\frac{\partial \rho Y_i}{\partial x}\right|_x - D\frac{\partial^2 \rho Y_i}{\partial x^2}dx\right)dydz$$

$$\dot{\phi}_{ST} = \frac{\partial \rho Y_i}{\partial t} dxdydz$$

CONVECTION:

$$E_{CONV} = \rho Y_i u\, dA$$

$$m\dot{Y}_{i\,OUT\,x} = \left(\rho u Y_i + \frac{\partial(\rho u Y_i)}{\partial x}dx\right)dydz$$

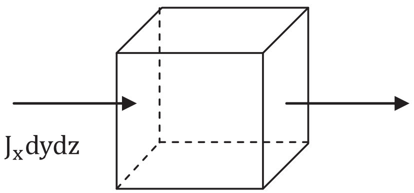


$$m\dot{Y}_{i\,IN\,x} = \rho u Y_i dydz$$

DIFFUSION:

$$E_{DIFF} = -D\left.\frac{\partial \rho Y_i}{\partial x}\right|_x dA$$

$$m\dot{Y}_{i\,OUT\,x} = \left(J_x + \frac{\partial J_x}{\partial x}dx\right)dydz$$



$$m\dot{Y}_{i\,IN\,x} = J_x dydz$$

Fick's law diffusion:

$$J_i = -D\frac{\partial(\rho Y_i)}{\partial x}$$

$$D\left(\frac{\partial^2 \rho Y_i}{\partial x^2} + \frac{\partial^2 \rho Y_i}{\partial y^2} + \frac{\partial^2 \rho Y_i}{\partial z^2}\right) - \frac{\partial(\rho u Y_i)}{\partial x} - \frac{\partial(\rho v Y_i)}{\partial y} - \frac{\partial(\rho w Y_i)}{\partial z} + \dot{S}_i = \frac{\partial \rho Y_i}{\partial t}$$

Incompressible flow: $\rho = \text{constant}$

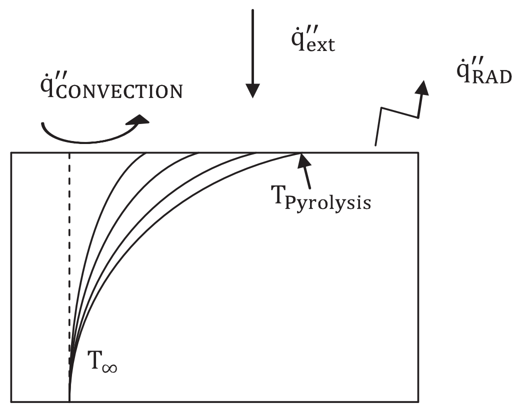
$$\rho D\left(\frac{\partial^2 Y_i}{\partial x^2}+\frac{\partial^2 Y_i}{\partial y^2}+\frac{\partial^2 Y_i}{\partial z^2}\right)-\rho\left[u\frac{\partial(Y_i)}{\partial x}+v\frac{\partial(Y_i)}{\partial y}+w\frac{\partial(Y_i)}{\partial z}\right]+\dot{S}_i=\rho\frac{\partial Y_i}{\partial t}$$

Nomenclature

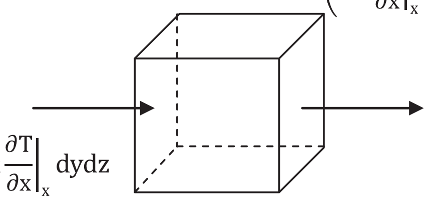
$\{x, y, z\}$: Cartesian coordinate [m];
m: Mass of the control volume [kg];
ρ: Density [kg/m^3];
$\vec{\mathbf{u}} = u\vec{\mathbf{i}} + v\vec{\mathbf{j}} + w\vec{\mathbf{k}}$: Velocity vector [m/s];
σ_{ii}: Normal stress [N/m^2];
τ_{ji}: Tangential stress [N/m^2];
μ: Dynamic viscosity [kg/(m.s)]
F: Force [N];
P: Pressure [N/m^2]
$\vec{\mathbf{g}} = g_x\vec{\mathbf{i}} + g_z\vec{\mathbf{j}} + g_z\vec{\mathbf{k}}$: Gravity acceleration [m/s^2];
c_P: Specific heat [J/(kg.K)];
k: Thermal conductivity [W/(m^2.K)];
T: Temperature [K]
E: Internal energy [J];
W: Work [J];
Q: Heat [J]
D: Diffusion coefficient [m^2/s];
Y_i: Mass fraction of specie i [kg/kg];
$\dot{S}_i$: Source term of specie i production or destruction;

Tutorial #4 (01/11/10): Solid Fuel ignition_Theory

Question 1: Solid thermally thick



$$E_{OUT} = \left(-k\frac{\partial T}{\partial x}\bigg|_x - k\frac{\partial^2 T}{\partial x^2}\bigg|_x dx\right) dydz$$



$$E_{IN} = -k\frac{\partial T}{\partial x}\bigg|_x dydz$$

]

$$\dot{\phi}_{IN} + \dot{\phi}_{GEN} = \dot{\phi}_{OUT} + \dot{\phi}_{ST}$$

$$\dot{\phi} = \dot{E}$$

$$\dot{\phi}_{IN\,x} = \dot{q}_{e\,IN\,x} = -k\frac{\partial T}{\partial x}\bigg|_x dydz$$

$$\dot{\phi}_{GEN} = \dot{E}_{RAD} + \dot{Q}_{REAC}$$

$$\dot{\phi}_{OUT\,x} = \dot{q}_{e\,OUT\,x} = -k\frac{\partial T}{\partial x}\bigg|_{x+dx} dydz == \left[-k\frac{\partial T}{\partial x}\bigg|_x + \frac{\partial}{dx}\left(-k\frac{\partial T}{\partial x}\bigg|_x\right)dx\right] dydz$$

$$\dot{\phi}_{ST} = \frac{dmc_PT}{dt} = \frac{d\rho c_PT}{dt} dxdydz$$

General formal of Energy conservation equation:

$$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) - \frac{\partial(\rho c_P uT)}{\partial x} - \frac{\partial(\rho c_P vT)}{\partial y} - \frac{\partial(\rho c_P wT)}{\partial z} + \dot{E}_{RAD} + \dot{Q}_{REAC} + \dot{W} = \frac{\partial \rho c_P T}{\partial t}$$

Expression 1:

$$\frac{d\rho c_P T}{dt} = \frac{\partial}{dx}\left(k\frac{\partial T}{\partial x}\bigg|_x\right) + \dot{E}_{RAD} + \dot{Q}_{REAC}$$

Initial condition:

$T(\forall x, t = 0) = T_\infty;$

Boundary conditions:

$-k\frac{\partial T}{\partial x}\Big|_{x=0} = -h_c(T_{Surf} - T_\infty) - \sigma\varepsilon\left(T_{Surf}^4 - T_\infty^4\right);$

$-k\frac{\partial T}{\partial x}\Big|_{x=L} = 0;$

Expression 2:

$$\frac{d\rho c_P T}{dt} = \frac{\partial}{dx}\left(k\frac{\partial T}{\partial x}\bigg|_x\right)$$

<u>Initial condition:</u>
$T(\forall x, t=0) = T_\infty;$
<u>Boundary conditions:</u>
$-k\frac{\partial T}{\partial x}\Big\vert_{x=0} = \alpha\dot{q}_e'' - h_c(T_{Surf} - T_\infty) - \sigma\varepsilon\left(T_{Surf}^4 - T_\infty^4\right);$
$-k\frac{\partial T}{\partial x}\Big\vert_{x=L} = 0;$
 	
<u>Expression 3:</u>
 	
$\bar{\rho}\bar{c}_P\frac{dT}{dt} = -\bar{k}\frac{\partial^2 T}{dx^2}$
 	
<u>Initial condition:</u>
$T(\forall x, t=0) = T_\infty;$
<u>Boundary conditions:</u>
$-k\frac{\partial T}{\partial x}\Big\vert_{x=0} = \dot{q}_e'' - h_c(T_{Surf} - T_\infty) - \sigma\left(T_{Surf}^4 - T_\infty^4\right);$
$-k\frac{\partial T}{\partial x}\Big\vert_{x=L} = 0;$
 	
<u>Expression 4:</u>
 	
$\bar{\rho}\bar{c}_P\frac{dT}{dt} = -\bar{k}\frac{\partial^2 T}{dx^2}$
 	
<u>Initial condition:</u>
$T(\forall x, t=0) = T_\infty;$
<u>Boundary conditions:</u>
$-k\frac{\partial T}{\partial x}\Big\vert_{x=0} = \dot{q}_e'' - (h_c + h_r)(T_{Surf} - T_\infty);$
$-k\frac{\partial T}{\partial x}\Big\vert_{x=L} = 0;$
	<u>Laplace transformation:</u>
	$T(x,t) = T_\infty + \frac{\dot{q}_e''}{(h_c+h_r)}\left[\mathrm{erfc}\left(\frac{x}{\sqrt{4\alpha t}}\right) - \exp\left(\frac{(h_c+h_r)}{\sqrt{\alpha}\sqrt{\bar{k}\bar{\rho}\bar{c}_P}}x + \frac{(h_c+h_r)^2}{\bar{k}\bar{\rho}\bar{c}_P}t\right).\mathrm{erfc}\left(\frac{(h_c+h_r)}{\sqrt{\bar{k}\bar{\rho}\bar{c}_P}}t^{1/2} + \frac{x}{\sqrt{4\alpha t}}\right)\right]$
	$T(0,t) = T_\infty + \frac{\dot{q}_e''}{(h_c+h_r)}\left[1 - \exp\left(\frac{(h_c+h_r)^2}{\bar{k}\bar{\rho}\bar{c}_P}t\right).\mathrm{erfc}\left(\frac{(h_c+h_r)}{\sqrt{\bar{k}\bar{\rho}\bar{c}_P}}t^{1/2}\right)\right]$
	$T(0,t) = T_0 + \bar{T}\left[1 - \exp\left(\frac{t}{t_c}\right).\mathrm{erfc}\left(\left(\frac{t}{t_c}\right)^{1/2}\right)\right]$
	$T(0,t_{Pyrolysis}) = T_\infty + \bar{T}\left[1 - \exp\left(\frac{t_{Pyrolysis}}{t_c}\right).\mathrm{erfc}\left(\left(\frac{t_{Pyrolysis}}{t_c}\right)^{1/2}\right)\right]$
	
	<u>Expression 5:</u>
	
	if $\frac{t_{Pyrolysis}}{t_c} \to 0$, Taylor series expansion:
	$\frac{1}{\sqrt{t_{Pyrolysis}}} = \frac{2}{\sqrt{\pi}.\sqrt{\bar{k}\bar{\rho}\bar{c}_P}}.\frac{\dot{q}_e''}{T_{Pyrolysis} - T_\infty}$
	
	if $\frac{t_{Pyrolysis}}{t_c} \to \infty$, asymptotic expansion:
	$\frac{1}{\sqrt{t_{Pyrolysis}}} = \frac{(h_c+h_r).\sqrt{\pi}}{\sqrt{\bar{k}\bar{\rho}\bar{c}_P}}.\left[1 - \frac{(h_c+h_r).(T_{Pyrolysis} - T_\infty)}{\dot{q}_e''}\right]$

a) At each step of the demonstration, explain the explicit assumptions carried out in order to obtain the new expression.

b) What is the value of the heat flux if $\frac{1}{\sqrt{t_{Pyrolysis}}}$ is equal to 0?

<u>Question 2:</u> Solid thermally thin

a) A solid is considered thermally thin when its physical thickness is smaller than the thermal penetration depth δ_T.

$$\delta_T \approx \sqrt{t \times \alpha}$$

What is the consequence on the temperature profile of the material heated? As Figure 1, draw the temperature profile of the sample heated.

b) With a similar path to the one follow in Question 1, it is possible to obtain an equation of the temperature of the solid:

$$T(t) = T_\infty + \frac{\dot{q}_e''}{(h_c + h_r)}\left[1 - \exp\left(\frac{(h_c + h_r)}{d\bar{\rho}\bar{c}_P}t\right)\right]$$

With d the thickness of the sample.

Express a relation for the time to pyrolysis for high heat fluxes and one for law heat fluxes.

c) In the case of high heat fluxes applied, how is the ratio between the external heat fluxes and the heat losses by convection and radiation?

<u>Question 3:</u>

$$t_{Ignition} = t_{Pyrolysis} + t_{Mixing} + t_{Induction}$$

$t_{Ignition}$: Time before ignition of solid sample.
$t_{Pyrolysis}$: Time to reach the pyrolysis temperature.
t_{Mixing}: Diffusion or transport time needed for the flammable fuel concentration and oxygen to reach the pilot.
$t_{Induction}$: Time needed for the flammable mixture to proceed to combustion once at the pilot.

a) <u>Induction time:</u>

Thanks to the theory of ignition of flammable gases (spherical volume), the induction time could be estimated with the following eauqtion:

$$t_{Induction} = 0.7\frac{kT_f}{\alpha}\frac{E}{RT_f}\frac{1}{A\Delta H_C \exp\left(-E/RT_f\right)}$$

Estimate the induction time with the value of Table I.

<u>Mixing time:</u>

It is assumed that the pilot is situated inside the boundary layer created on top of the solid sample heated. The mixing time corresponds therefore to the time required for the flammable mixture to cross the boundary layer (δ_{BL}) by diffusion. These two parameters are linked to the diffusion coefficient (D) thanks to the following approximation:

$$\delta_{BL} \approx \sqrt{t_{Mixing} \times D}$$

In order to assess the order of magnitude of the boundary layer the simple following relation is used:

$$h_c \approx \frac{k}{\delta_{BL}}$$

Where k is the thermal conductivity of the mixture which compends the boundary layer and h_c is the heat transfer coefficient associated to this boundary layer.

The Nusselt number for laminar natural condition along a vertical plate of height l is:

$$Nu = 0.59(Gr \times Pr)^{1/4} \quad \text{for } 10^4 < (Gr \times Pr) < 10^9$$

Estimate the mixing time for a solid sample of height $l = 0.5\text{m}$ with the value of Table 1.

Pyrolysis time:

The solid is considered as inert until it reaches a pyrolysis temperature $T_{Pyrolysis}$. As a consequence, assessing the time to pyrolysis corresponds to evaluate the time required to reach this temperature at the surface according to the heat flux applied.

If the convection and the re-radiation at the surface are neglected, the boundary condition at the surface is:

$$-k\frac{\partial T}{\partial x}\bigg|_{x=0} = \dot{q}_e''$$

The derivative could be approximate as:

$$\frac{\partial T}{\partial x}\bigg|_{x=0} = \frac{T_{Surf} - T_\infty}{\delta_T}$$

Where δ_T is the thermal penetration depth (Thickness of the solid heated). This thermal penetration is varying according to the time (for sufficiently thick material) as:

$$\delta_T \approx \sqrt{t \times \alpha}$$

where α is the thermal diffusivity of the material.

Thanks to the properties presented in Table 2, estimate the order of magnitude of the pyrolysis time for a heat flux of 20 kW/m^2.

Ignition time:

At the sight of the three different times composing the delay time to ignition, is it possible to identify a main mechanism and therefore to simplify the ignition theory?

Tables

Table 1: Flammability characteristics of Methane mixture at stoichiometry

Activation energy	E	kJ/mol	121.4172
Pre-exponential factor	A	$g/m^3.s$	$1.3\ 10^8$
Thermal conductivity	k	W/(m.K)	0.0667
Thermal diffusivity	α	m^2/s	$168\ 10^{-6}$
Heat of Combustion	ΔH_C	kJ/g	50.1
Adiabatic flame temperature	T_f	K	2210
Prandtl number (300K)	Pr	-	0.74
Kinematic viscosity (300K)	ν	m^2/s	$3.22\ 10^{-5}$
Diffusivity coefficient	D	m^2/s	$2.2\ 10^{-5}$

Table 2: Ignition characteristic of wood

Thermal conductivity	k	W/(m.K)	0.2
Density	ρ	kg/m3	500
Specific heat	c_P	J/(kg.K)	1952
Pyrolysis temperature	$T_{Pyrolysis}$	K	650

$$Gr = \frac{2g(T_S - T_\infty)l^3}{\nu^2(T_S + T_\infty)} \qquad (1)$$

Tutorial #5 (03/11/10): Solid Fuel ignition

Question 1:

a) Given Figure 1 where the inverse square root of the time to ignition is plotted versus the applied heat flux, determine:

- The critical heat flux;
- The surface temperature at ignition;
- The thermal inertia I;

b) Propose a methodology to determine the different components of the thermal inertia.

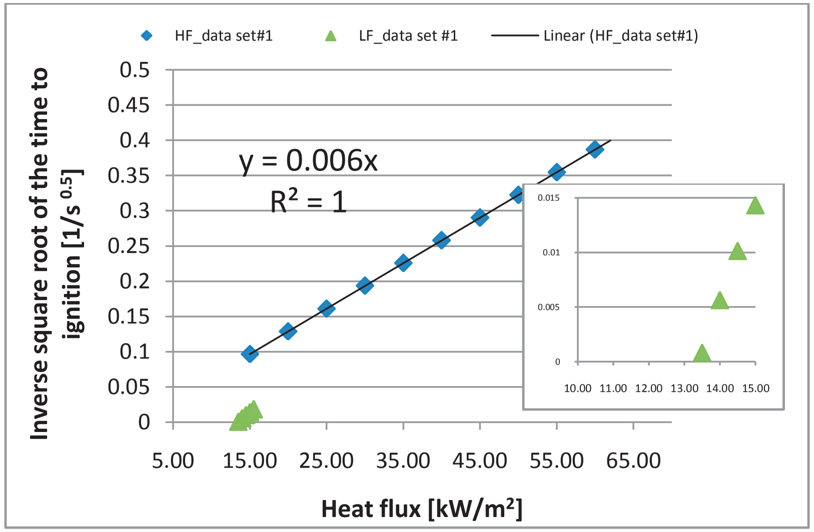


Figure 1

Question 2:

a) The surface temperature of a sample was recorded and plotted in Figure 2. From it, determine the surface temperature at ignition.

b) Assuming that the surface temperature found at ignition in a) is the criterion of ignition; calculate the total heat transfer coefficient at ignition given Figure 3.

c) Calculate the heat transfer coefficient for radiation at ignition (see expression #4 in Tutorial #4).

d) The heat transfer coefficient for convection is generally taken for this type of test equals to a value in the range [8 -15] $W/(m^2.K)$. How do you explain the difference between the heat transfer coefficient for convection found in this example?

Question 3:

a) Figure 4 represents the results from an analysis of time to ignition data. Assuming that the surface temperature at ignition is constant and equals to 300°C, assess the variation of the thermal inertia between the different set of lines. The best linear fit equation of each dataset is reported in Table 1.

$$Y = aX + b$$

Table 1: Linear fit equation from Figure 4			
C#	A	b	R^2
1	6.3002E-06	0	1
2	5.9120E-06	- 7.4287E-02	0.9994
3_Iaverage	6.3473E-06	- 4.2766E-02	0.99988
3_I20	7.1016E-06	- 4.8015E-02	0.99990
3_ign	6.5691E-06	- 4.3640E-02	0.99980
5	6.2103E-06	- 3.8199E-02	0.99970
7	3.5574E-06	- 1.0541E-02	0.98629

b) Each of the C#, from Figure 4, corresponds to one of the expression seen in Tutorial #4 to develop the thermally thick solid ignition theory. Table 2 indicates the match between the C#s and the expressions. Comment on the impact of the different assumptions on the thermal inertia.

Table 2: Match C# - expression in Tutorial #4	
C#	Expression
1	Expression 5
2	Expression 4
3_Iaverage	Expression 3 with I averaged on [T_∞ ; T_{ign}]
3_I20	Expression 3 with I at T=300K
3_ign	Expression 3 with I at $T=T_{ign}$
5	Expression 2
7	Expression 1

Appendix

$$I = \sqrt{k\rho c} \qquad (1)$$

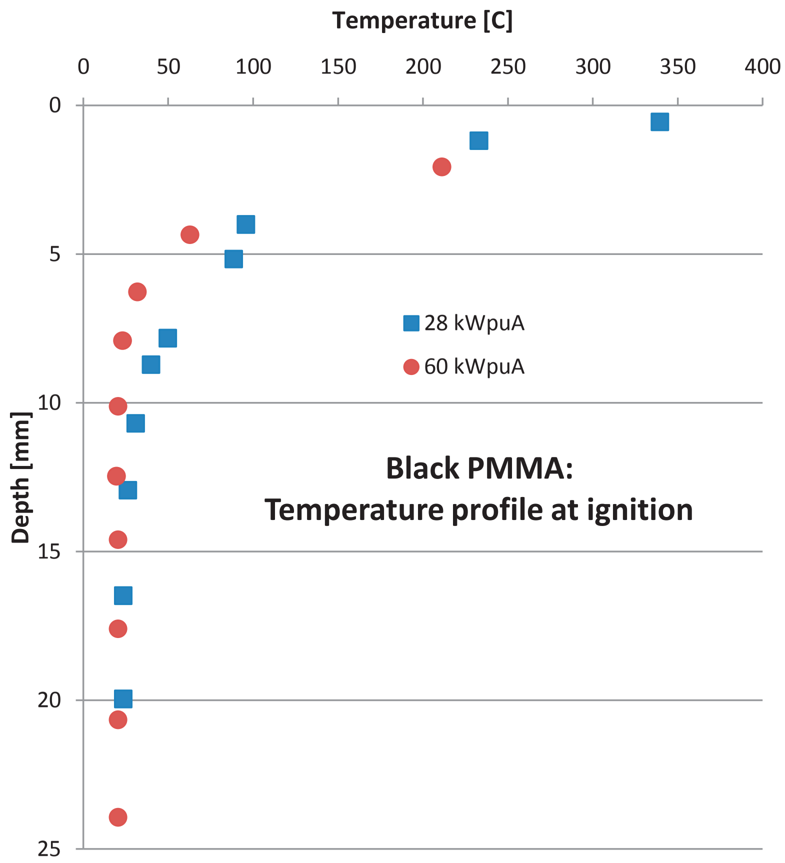


Figure 2

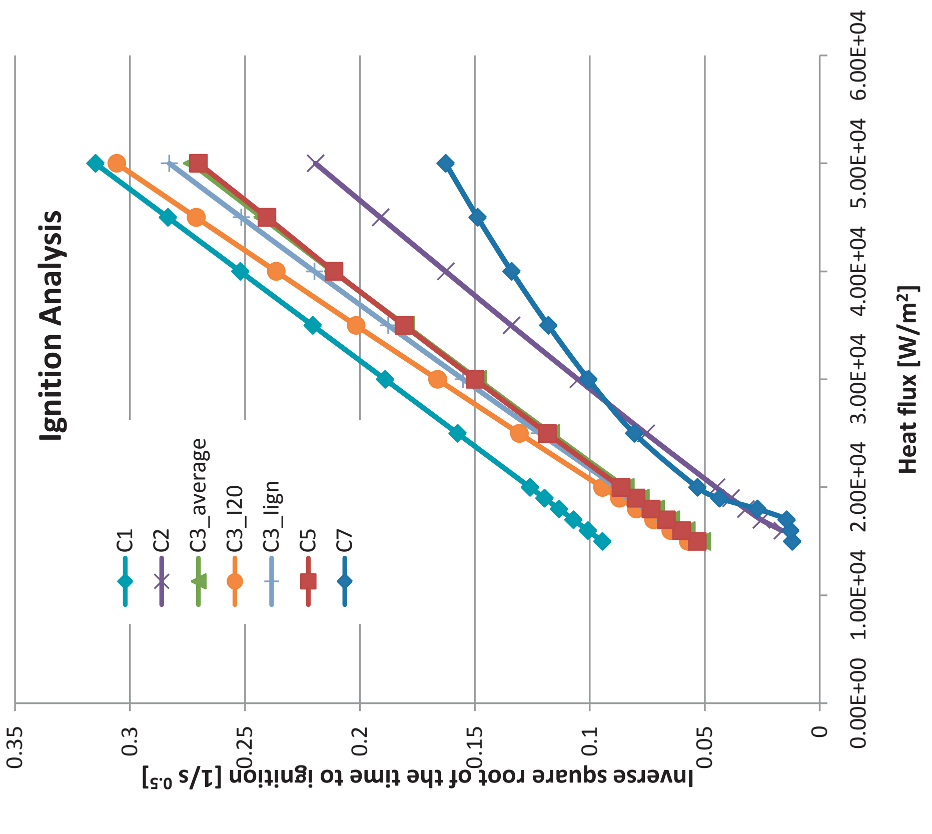


Figure 4

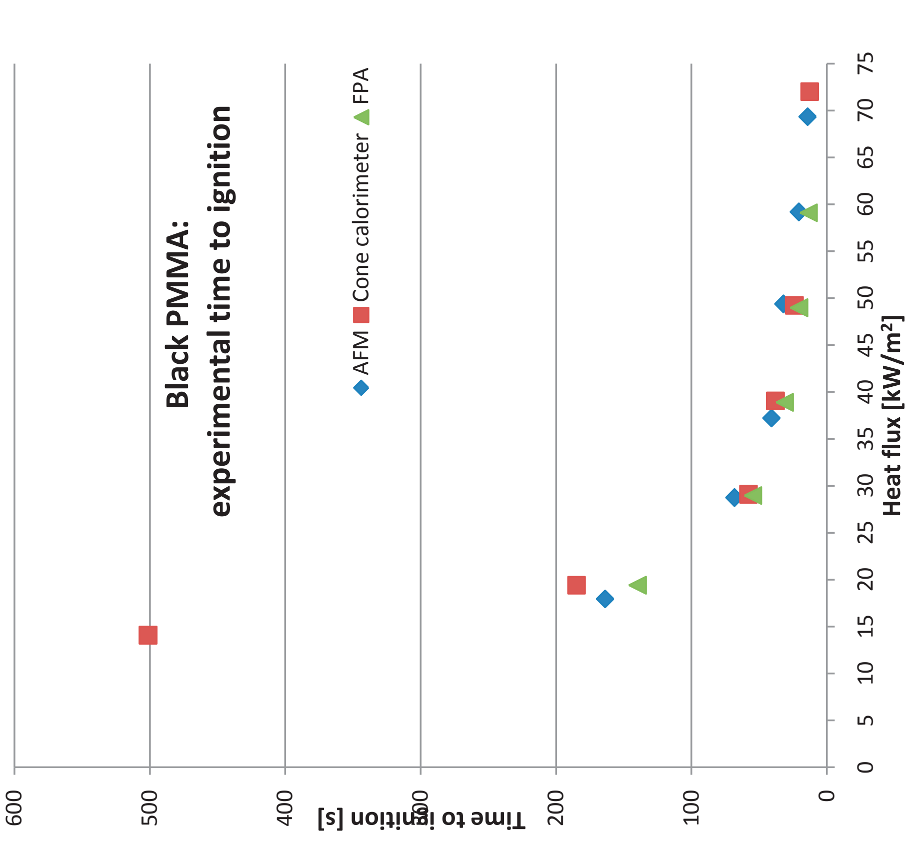


Figure 3

Tutorial #6 (10/11/10): Flame spread

Question 1:

The heat released rate is calculated by the following equation;

$$\dot{Q} = \dot{m}_f \Delta H_C \qquad (1)$$

By decomposing this equation to the highest level you can, list the parameters that you need to calculate the heat released rate of a fire over a solid sample. For each of them, explain how you get them.

Question 2:

a) From Figure 1, determine the critical heat flux for ignition and the surface temperature at ignition for both materials.

c) From Figure 2, determine the thermal inertia of the material.

d) From Figure 3, determine the flame spread parameter and the critical heat flux for spread.

Question 3:

a) From Figure 4, determine the surface temperature at ignition and the thermal inertia of black PMMA.

b) From Figure 5, determine the flame spread parameter for black PMMA.

c) From Figure 6, 7 and 8, plot a graph representing the steady mass loss rate as a function of the heat flux applied.

d) Thanks to the previous elements, assess the α parameter for a t^2 fire for an assumed non-pre-heated solid and a heat flux from the flame of $28kW/m^2$ (measured experimentally).

e) Repeat d) by now assuming that the solid is pre-heated by the smoke layer at 100°C.

f) Repeat d) by now assuming that the solid is pre-heated by the smoke layer at 200°C.

g) Assuming that a fire start in the middle of a circular table (diameter = 1m) composed of a surface layer of black PMMA, plot the HRR curve as a function of time from t= 0 to t = 5000s for the different α found in d), e) and f).

> H_1: The surface layer of black PMMA is thick enough to not be consumed entirely by the fire during the time required in the question.

Appendix

$$I = \sqrt{k\rho c} \qquad (2)$$

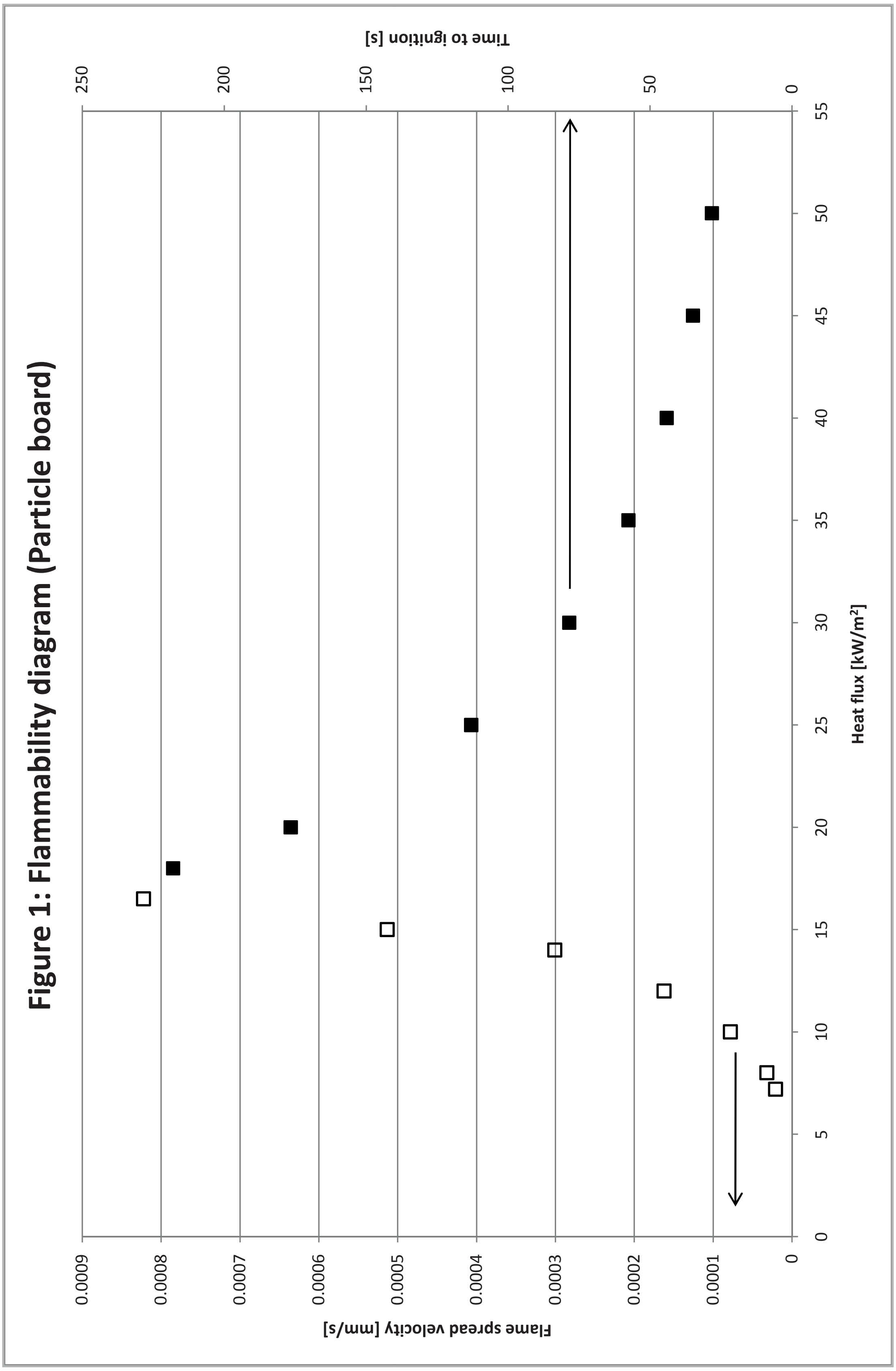


Figure 1: Flammability diagram (Particle board)
Time to ignition [s]
0
50
100
150
200
250
Flame spread velocity [mm/s]
0
0.0001
0.0002
0.0003
0.0004
0.0005
0.0006
0.0007
0.0008
0.0009
Heat flux [kW/m²]
0
5
10
15
20
25
30
35
40
45
50
55

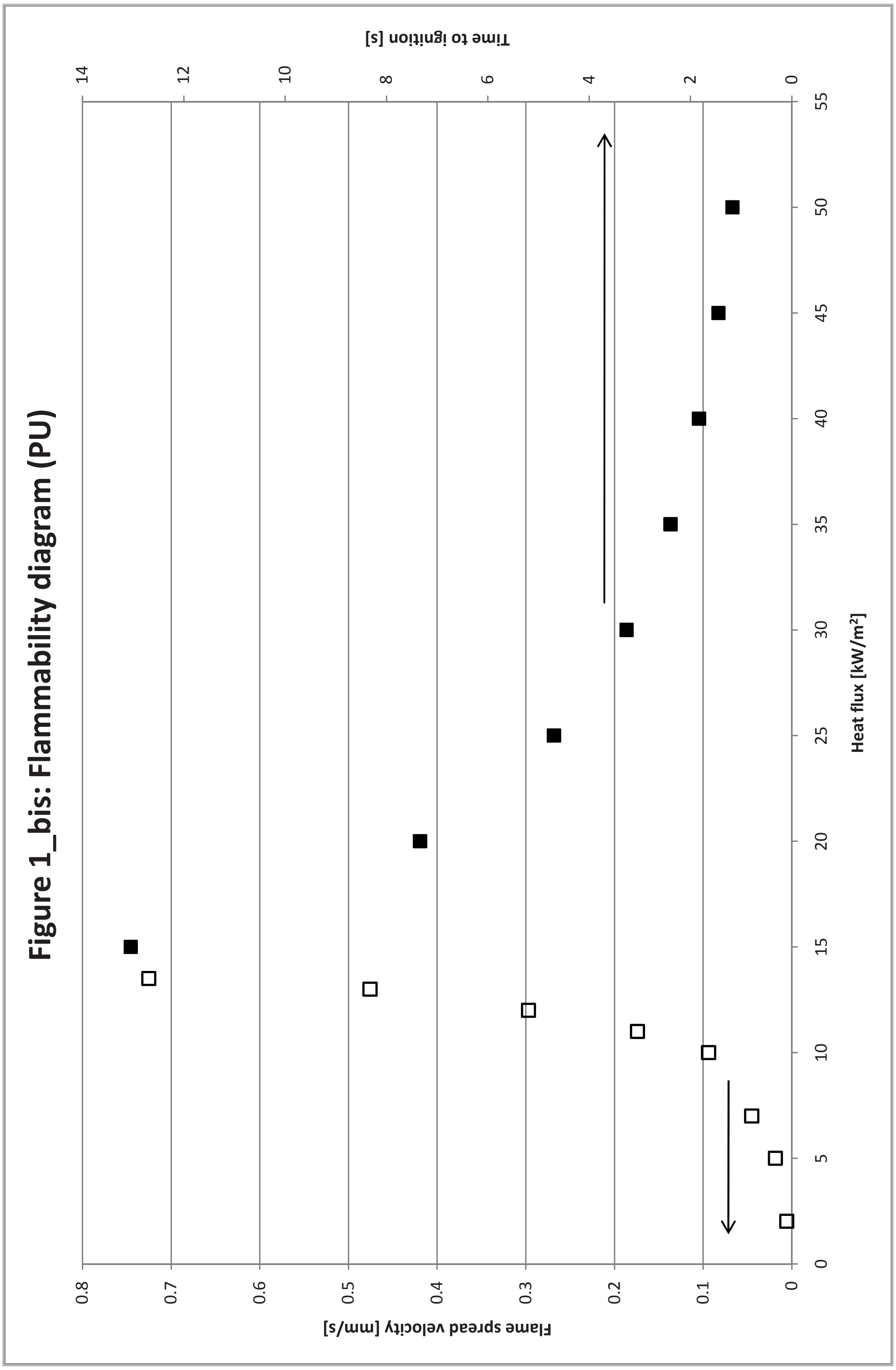


Figure 1_bis: Flammability diagram (PU)
Flame spread velocity [mm/s]
Time to ignition [s]
Heat flux [kW/m²]

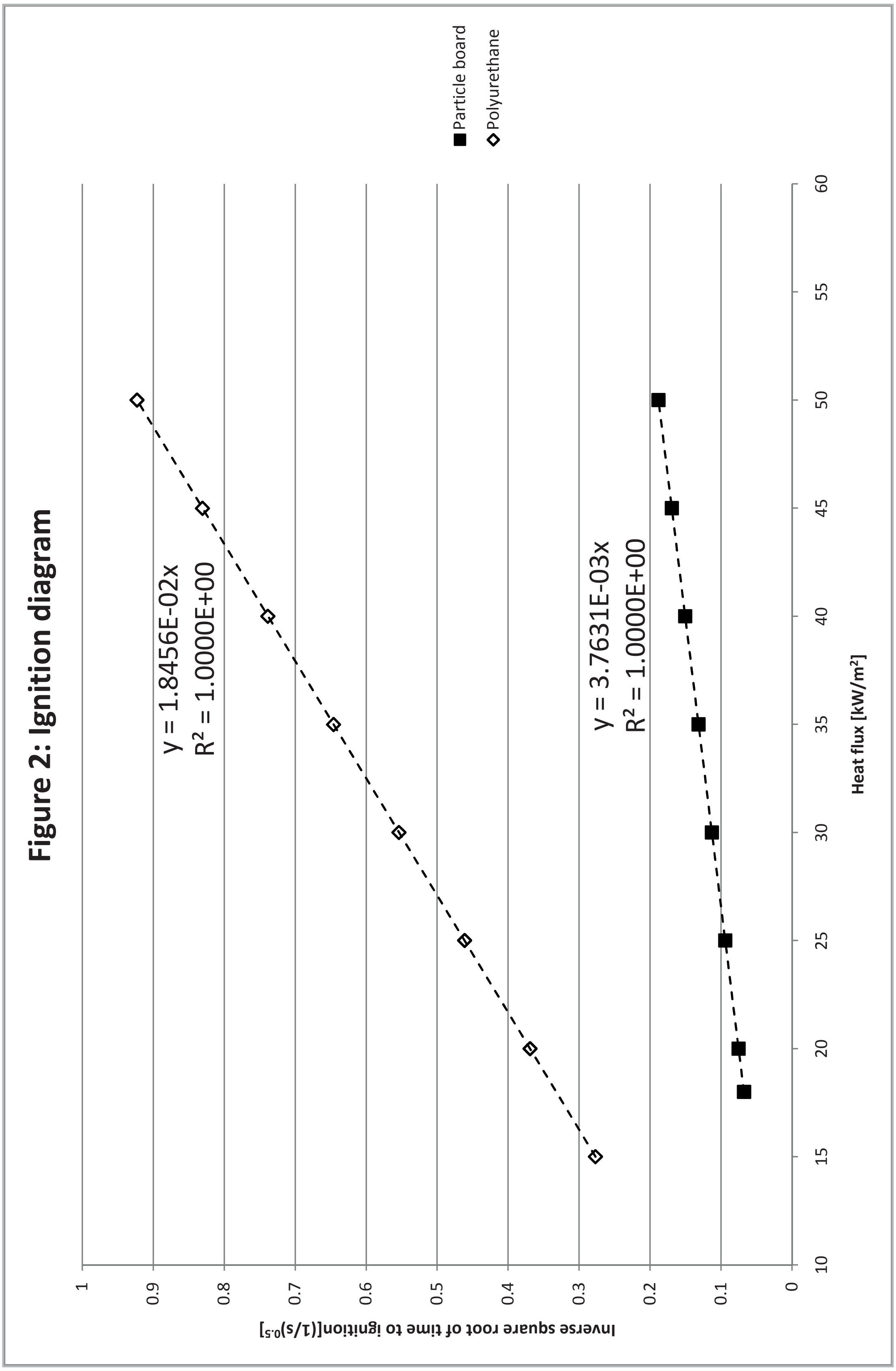


Figure 2: Ignition diagram
y = 1.8456E-02x
R² = 1.0000E+00
y = 3.7631E-03x
R² = 1.0000E+00
Particle board
Polyurethane
Heat flux [kW/m²]
Inverse square root of time to ignition[(1/s)0.5]
10
15
20
25
30
35
40
45
50
55
60
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

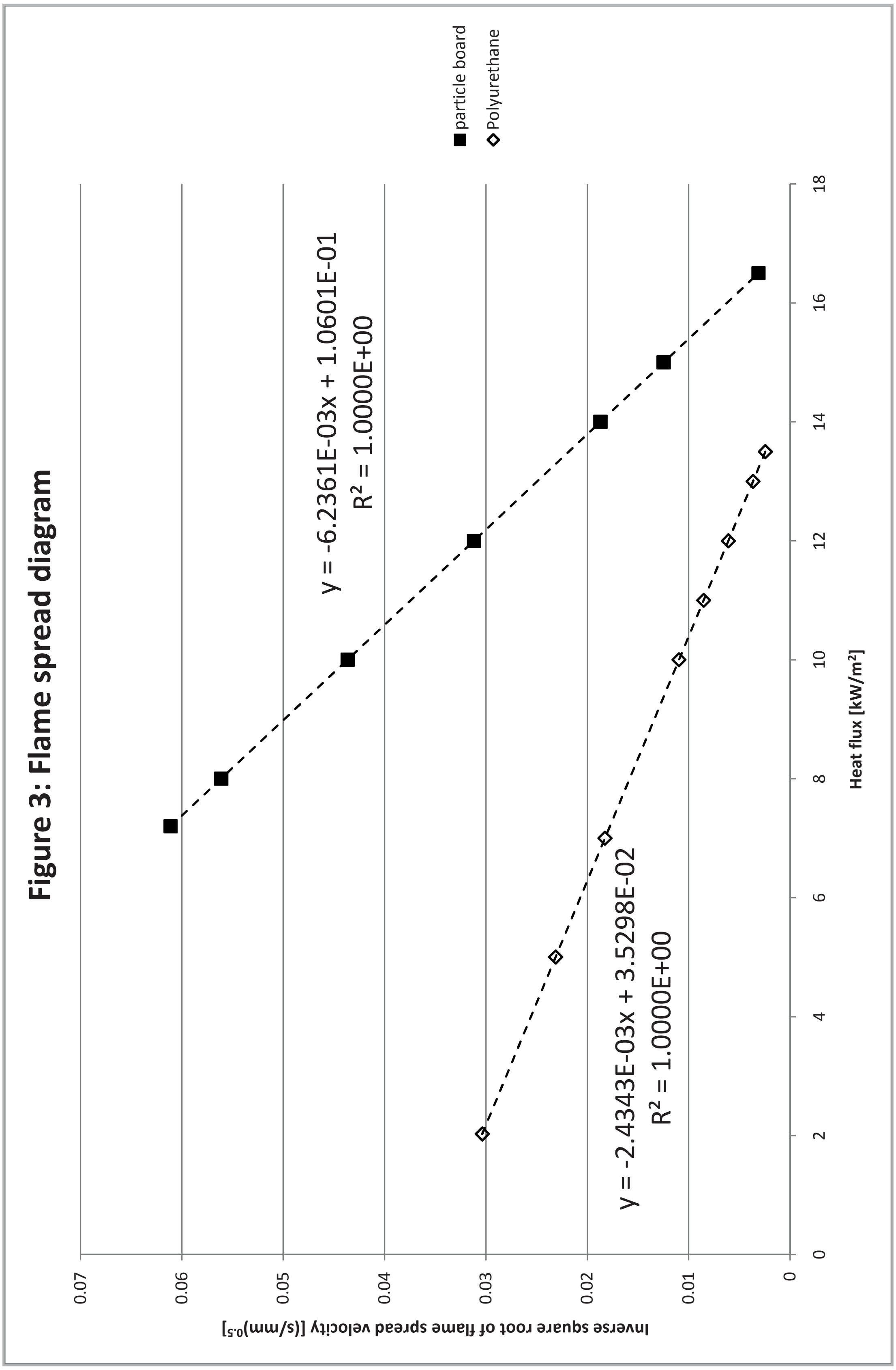


Figure 3: Flame spread diagram
y = -6.2361E-03x + 1.0601E-01
R² = 1.0000E+00
y = -2.4343E-03x + 3.5298E-02
R² = 1.0000E+00
particle board
Polyurethane
Heat flux [kW/m²]
Inverse square root of flame spread velocity [(s/mm)0.5]
0
2
4
6
8
10
12
14
16
18
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07

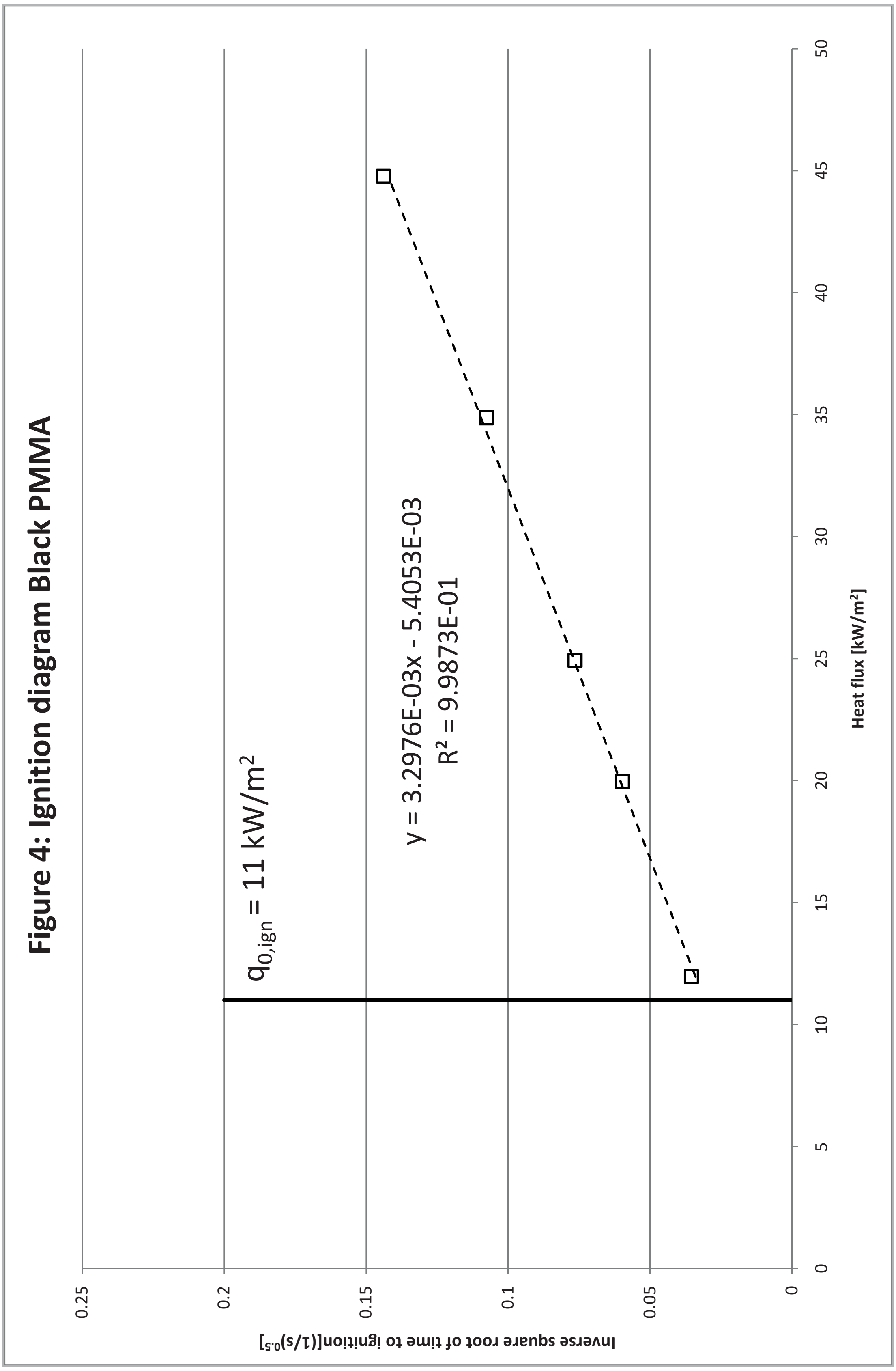


Figure 4: Ignition diagram Black PMMA
$q_{0,ign}$ = 11 kW/m²
y = 3.2976E-03x - 5.4053E-03
R² = 9.9873E-01
Inverse square root of time to ignition[(1/s)0.5]
Heat flux [kW/m²]
0
0.05
0.1
0.15
0.2
0.25
0
5
10
15
20
25
30
35
40
45
50

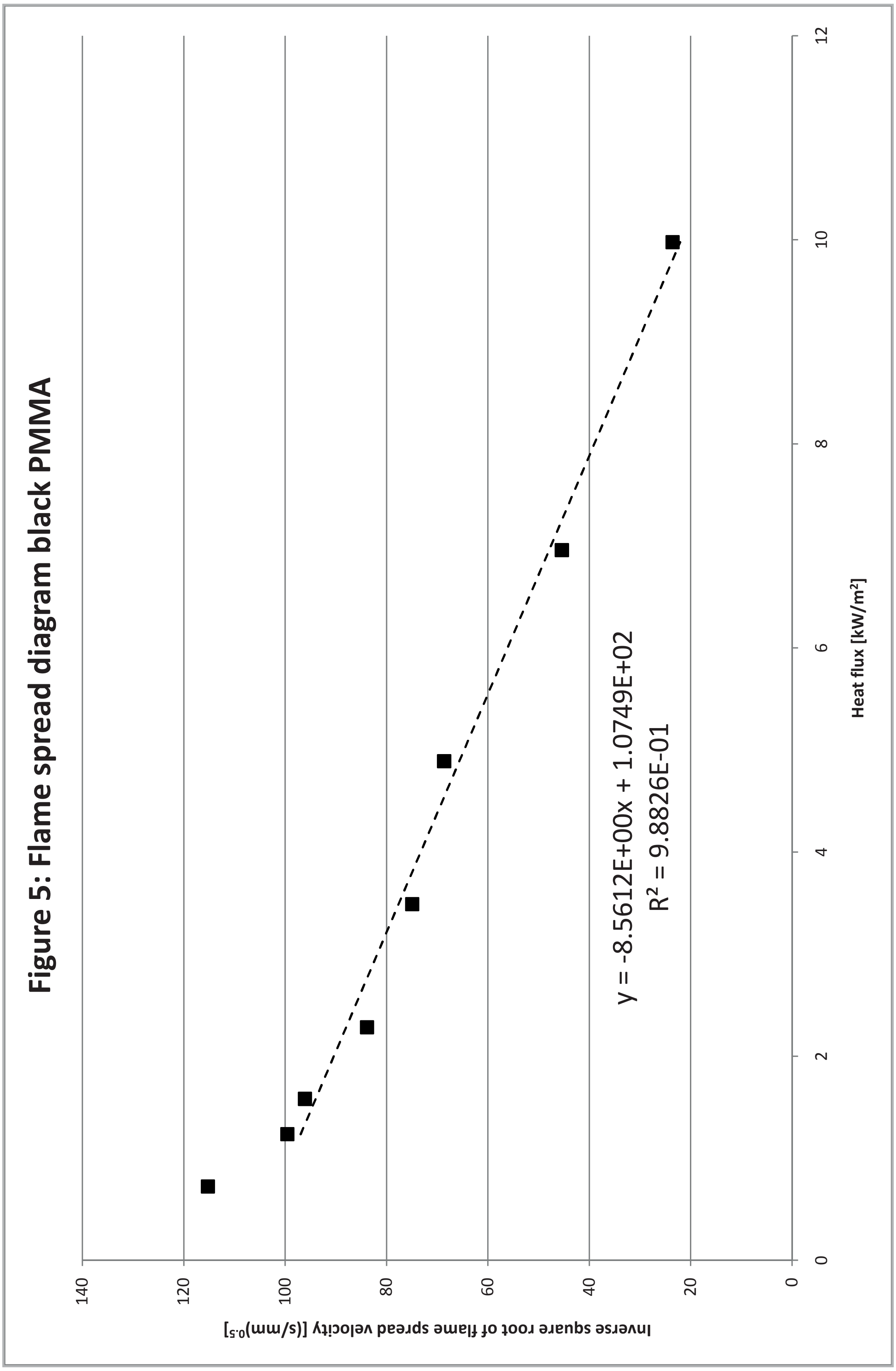


Figure 5: Flame spread diagram black PMMA
y = -8.5612E+00x + 1.0749E+02
R² = 9.8826E-01
Inverse square root of flame spread velocity [(s/mm)0.5]
Heat flux [kW/m²]
0
20
40
60
80
100
120
140
0
2
4
6
8
10
12

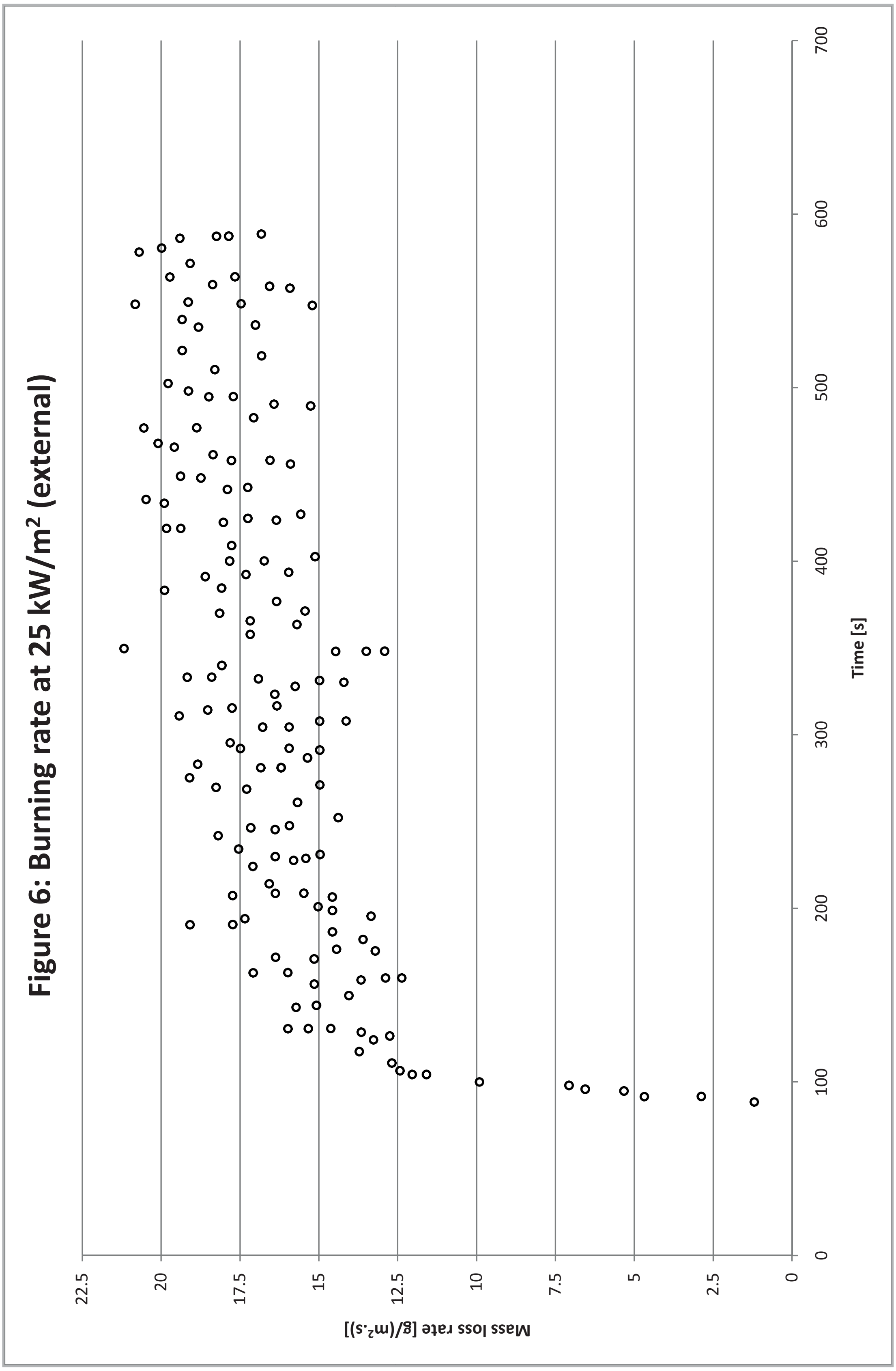


Figure 6: Burning rate at 25 kW/m² (external)

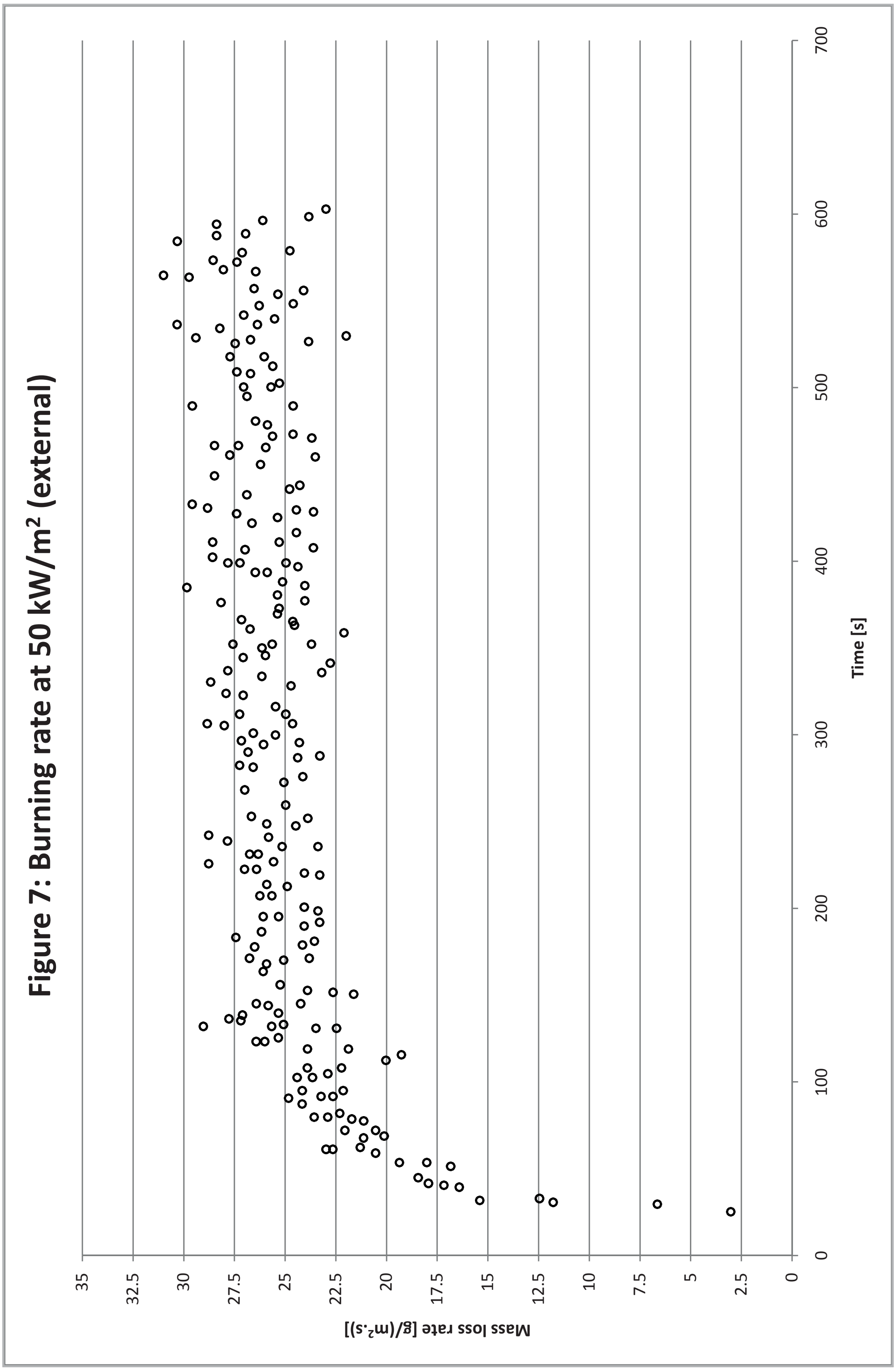


Figure 7: Burning rate at 50 kW/m² (external)
Mass loss rate [g/(m²·s)]
35
32.5
30
27.5
25
22.5
20
17.5
15
12.5
10
7.5
5
2.5
0
Time [s]
0
100
200
300
400
500
600
700

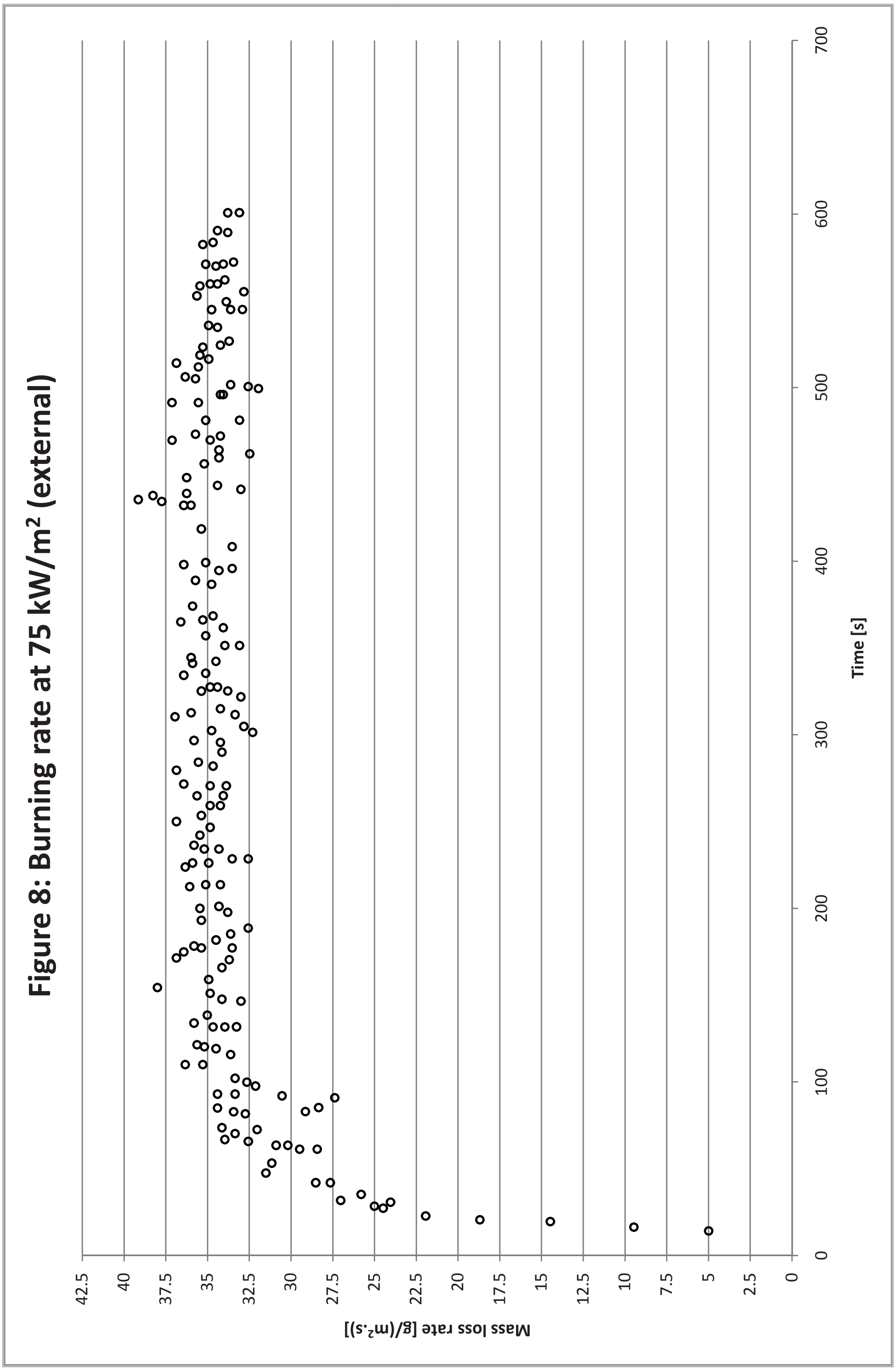


Figure 8: Burning rate at 75 kW/m² (external)

Tutorial #7 (17/11/10): Burning rate

Question 1:

Figure 1 to 4 represent different Heat Release Rates (HRR) measured experimentally. Associate one curve to each of the following items:

- Sofa;
- TV set (no Fire Retardant);
- TV set (with Fire retardant);
- Pillows;
- Christmas tree;
- Heptane Pool fire (D = 80 cm);
- School bus;
- Bunk bed;

Data from:

[1]NIST websit: http://www.fire.nist.gov/

[2]V. Babrauskas, in: P.J. DiNenno et al. (Eds.), The SFPE Handbook of Fire Protection Engineering, third ed., National Fire Protection Association, 2002.

Question 2:

The steady mass loss rate for a pool fire can be calculated with the following formula:

$$\dot{m}'' = \dot{m}''_{\infty}\left(1 - e^{-k\beta D}\right) \quad (1)$$

Where k is the extinction-absorption coefficient of the flame, β is the mean length corrector and D is the diameter of the pool.

a) Given Eq. (1), express what $\dot{m}''_{\infty}$ represents.

b) What are the units of $\dot{m}''_{\infty}$ and of the product $k\beta$?

c) Given the data given in Table 1, calculate the steady mass loss rate of a pool fire of heptanes, gasoline and LPG for a circular pool with a diameter of 1m.

d) Repeat c) for a rectangular pool fire of side 2 m by 1m.

e) A pump breakdown causes 20 l of transformer oil to spill into a circular pan of 2 m^2 floor area. The oil is warm and ignites. Estimate the energy and the duration of the fire for a combustion efficiency of 100%

f) Repeat for a combustion efficiency of 70%

Appendix

$$D_H = \frac{4\ \text{Area}}{\text{Perimiter}} \quad (2)$$

Table 1: Burning rate data for pool fire

	$\dot{m}''_{\infty}$	$k\beta$	$-\Delta h_c$
Substance	[kg/(m^2.s)]	[1/m]	[MJ/kg]
Heptane	0.101	1.1	44.6
Gasoline	0.055	2.1	43.7
LPG	0.099	1.4	46.0
Transformer oil	0.039	0.7	46.4

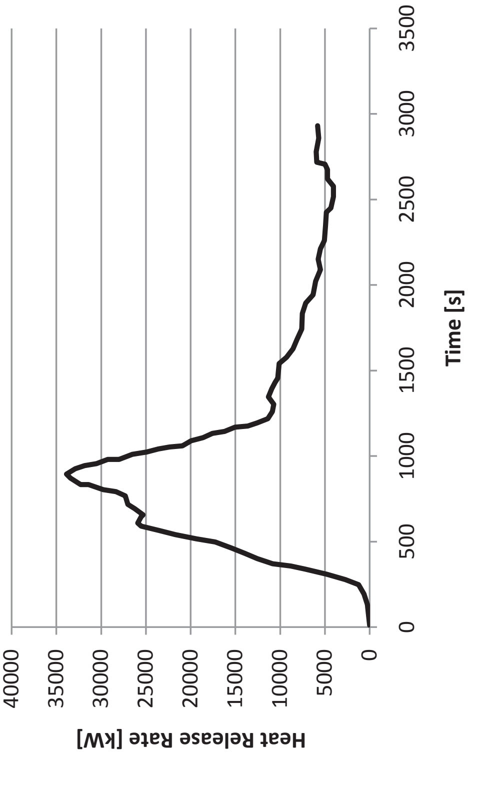


Figure 1

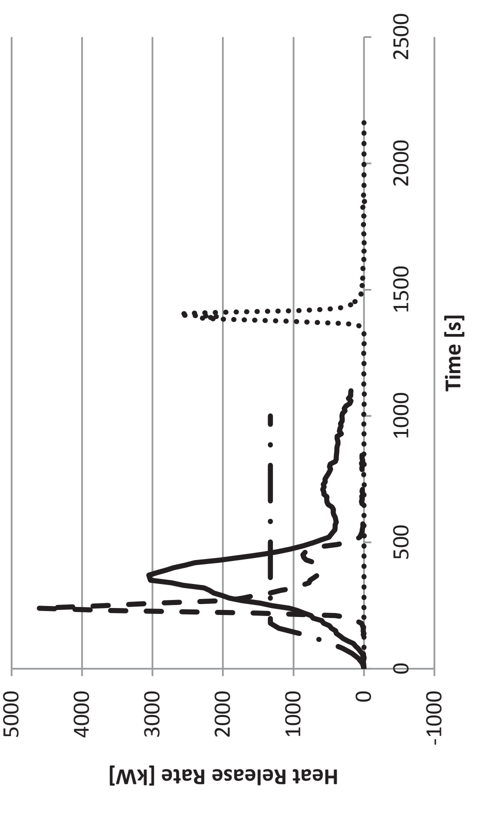


Figure 2

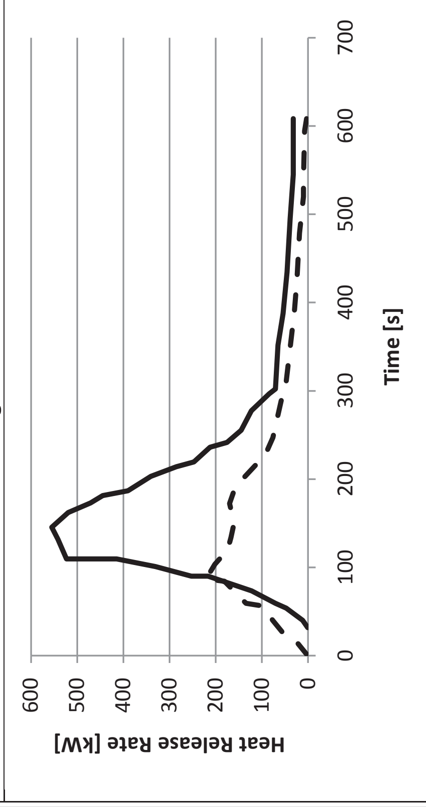


Figure 3

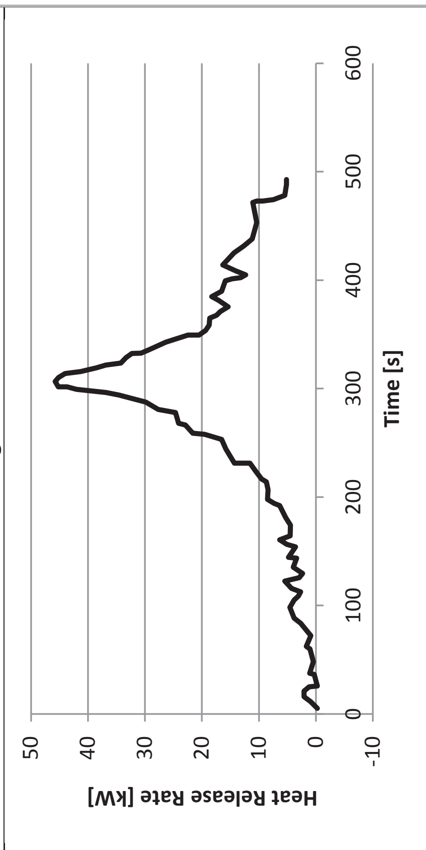


Figure 4

Tutorial #8 (24/11/10): Fire plume

Question 1:

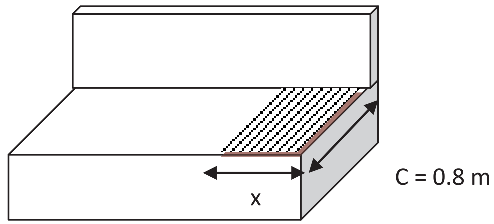


Figure 1

Experimental results conducted in laboratory suggest that the sofa on Figure 1 burns in such way that it rapidly reaches a steady mass loss rate of 5 g/s. Moreover, oxygen consumption measurements reveal that the mass flow rate of O_2 consumed in the steady mass loss rate period is 6.87 10^{-3} g/s.

a) Determine the Heat Release Rate of the sofa.

b) What is the effective heat of combustion of the sofa?

c) Given Eq. (1), estimate the mean flame height of the flame for the following value of x (Figure1): 0.1; 0.5; 1 and 1.2 m.

$$L = 0.235\,\dot{Q}^{2/5} - 1.02\,D \qquad (1)$$

d) Why it is important in a fire scenario to know the approximate value of x (Figure 1)?

f) Consider that a desk and a bookshelf situated respectively at 20 cm and 1 m away from the sofa. Assume that they are composed of a material which has a critical heat flux of 12 kW/m^2. Given Eqs. (2-3), estimate if they can be ignited.

$$\dot{Q}_{desk} = 0.75\,\dot{Q}_{flame} \qquad (2)$$

$$\dot{Q}_{bookself} = 0.23\,\dot{Q}_{flame} \qquad (2)$$

Question 2: Zukoski's plume theory

Main assumptions:

- Density and temperature variations throughout the plume height are small (Weak plume);
- Temperature and velocity have a "top hat" profile (constant over all the horizontal section);
- Air entrainment velocity is proportional to the upward plume velocity ($v = \alpha\, u$).

$$\dot{m}_e = 0.21\left(\frac{\rho_\infty^2 g}{c_P T_\infty}\right)^{1/3}\dot{Q}^{1/3}\,z^{5/3} \qquad (3)$$

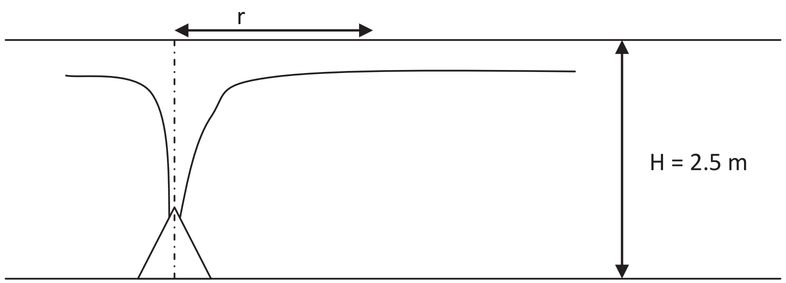
$$u = 1.94\left(\frac{g}{c_P T_\infty \rho_\infty}\right)^{1/3}\dot{Q}^{1/3}\,z^{-1/3} \qquad (4)$$

$$\Delta T = 5.0\left(\frac{T_\infty}{g c_p^2 \rho_\infty^2}\right)^{1/3} \dot{Q}^{2/3} z^{-5/3} \quad (5)$$

Assess the mass flow in the plume, the temperature and the velocity centreline at 2, 3, 4 and 5 m above the floor.

Question 3: Alpert's correlation

A fire of a constant HRR (1000kW) is started in the classroom. The plume reaches the ceiling and spread radially over the ceiling.



The maximum temperature of an unconfined ceiling jet is obtained thanks to Eqs. (6-7):

$$\frac{r}{H} < 0.18 \qquad T_{max} = \frac{16.9\,\dot{Q}^{2/3}}{H^{2/3}} + T_\infty \quad (6)$$

$$\frac{r}{H} > 0.18 \qquad T_{max} = \frac{5.38\left(\frac{\dot{Q}}{r}\right)^{2/3}}{H} + T_\infty \quad (7)$$

The maximum velocity of an unconfined ceiling jet is obtained thanks to Eqs. (8-9):

$$\frac{r}{H} < 0.15 \qquad u_{max} = 0.96\left(\frac{\dot{Q}}{H}\right)^{1/3} \quad (8)$$

$$\frac{r}{H} > 0.15 \qquad u_{max} = \frac{0.195\,\dot{Q}^{1/3} H^{1/2}}{r^{5/6}} \quad (9)$$

a) If we consider two sprinkler heads situated at 0.9 m and 1.2 m respectively from the centreline of the fire. Only one of them explodes due to the temperature. Assess the temperature at which the bubble from a sprinkler should explode?

d) If a sprinkler is situated at a distance of 37 cm from the centreline of the fire, how long before it is activated?

c) If the diameter of the fire is equals to 0.2 m, what physical phenomenon occurs?

e) If the room is circular (Diameter = 6 m) and the fire is situated at the centre of the room, determine the time at which Eqs. (6- 9) are no longer valid (Do a conservative case).

Appendix

$$D_H = \frac{4\,\text{Area}}{\text{Perimeter}} \quad (10)$$

d

APPENDIX

FSFD4 Questionnaire

FSFD4 Questionnaire

This questionnaire asks 22 questions to find out about your personal learning styles. The results will be used to tailor our teaching methods to suit YOU as an individual. It is therefore completely subjective and there are no right or wrong answers.

1. Name:

2. If I were a teacher, I would rather teach a course…

☐ a) that focuses on facts and real life situations.

☐ b) that explores ideas and new concepts.

☐ c) both.

3. I prefer…

☐ a) being given choice.

☐ b) being given instructions.

☐ c) both.

4. When I begin working on a tutorial problem, I am more likely to…

☐ a) start working out a solution immediately.

☐ b) try to fully understand the problem first.

☐ c) both.

5. I am good at…

☐ a) memorising facts.

☐ b) learning new concepts quickly.

☐ c) both.

6. When I am given a series of problems, I prefer…

☐ a) figuring it out by myself until I ask for help.

☐ b) being given an example solution by an expert.

☐ c) both.

7. When I solve maths problems…

☐ a) I usually work my way to the solutions one step at a time.

☐ b) I often just see the solutions but then have to struggle to figure out the steps to get to them.

☐ c) both.

8. When reading non-fiction, I prefer a book…

- ☐ a) that teaches me new facts or tells me how to do something.
- ☐ b) that gives me new ideas to think about.
- ☐ c) both.

9. If I go into industry I want to…

- ☐ a) be self-employed.
- ☐ b) have a manager.
- ☐ c) both.

10. It is more important for me that an instructor…

- ☐ a) lay out the material in clear sequential steps.
- ☐ b) give me an overall picture and relate the material to other subjects.
- ☐ c) both.

11. I am more likely to be…

- ☐ a) careful about the details of my work.
- ☐ b) creative and careless when I do my work.
- ☐ c) both.

12. When my work is assessed, I would prefer…

- ☐ a) to grade myself and convince the tutor/lecturer that the grade is fair.
- ☐ b) a tutor/lecturer to grade my work.
- ☐ c) both.

13. I learn…

- ☐ a) at a fairly regular pace. If I study hard I'll "get it".
- ☐ b) in fits and starts. I'll be totally confused and then suddenly it all "clicks".
- ☐ c) both.

14. When I am reading for enjoyment, I like writers to…

- ☐ a) clearly say what they mean.
- ☐ b) say things in creative, interesting ways.
- ☐ c) both.

15. If I encounter a rule/law that I don't necessarily agree with…

- ☐ a) I usually challenge it.
- ☐ b) I usually accept it.

☐ c) both.

16. When considering a body of information, I am more likely to…

☐ a) focus on details and then build the big picture.

☐ b) try to understand the big picture before getting into the details.

☐ c) both.

17. When I have to perform a task, I prefer to…

☐ a) master one way of doing it.

☐ b) come up with new ways of doing it.

☐ c) both.

18. When people criticise my work…

☐ a) I find it useful.

☐ b) I feel bad.

☐ c) both.

19. When writing a paper, I am more likely to…

☐ a) work on (think about or write) the beginning of the paper and progress forward.

☐ b) work on (think about or write) different parts of the paper and then order them.

☐ c) both.

20. When solving problems I would rather …

☐ a) learn how to apply methods from the textbook.

☐ b) come up with my own methods.

☐ c) both.

21. I prefer the idea that…

☐ a) there are millions of solutions that could be 'right'.

☐ b) there is one right solution.

☐ c) both.

22. I would rather work on…

☐ a) exercises that let me practice taught methods.

☐ b) open-ended problems with no known solutions.

☐ c) both.