Raising attainment in post-compulsory physics through collaborative problem solving

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ABSTRACT This article examines how students taking a post-compulsory physics course for 16- to 19-year-olds (A-level physics) benefited from a change in pedagogy which meant that they spent more time problem solving in collaborative groups. Video analysis of these collaborative problem-solving sessions revealed that the students improved a number of key competences, including their use of metacognition. As a result, the students improved in their learning of physics, although the reasons for this differed from student to student.

This article examines how the teaching of strategies to solve paper-and-pencil problems, the solutions to which do not simply involve following a standard procedure, might benefit from the use of collaborative problem-solving approaches. For this study, collaborative problem-solving competency is defined as the capacity of an individual to engage effectively in a process where two or more individuals attempt to solve a problem by sharing the understanding and effort required to come to a solution and pooling their knowledge, skills and effort to reach that solution (OECD, 2014).

Many studies argue that competence in problem solving is raised by explicitly teaching problem-solving strategies to students (e.g. Jonassen, 2011). This study advances the case for collaborative group problem solving to help enhance post-16 physics problem solving.

The importance of problem solving within the learning process

Problems can differ greatly, from well-defined ones that clearly state the given and desired goal, and for which all information needed to solve the problem correctly is presented, to ones where the desired goal may be uncertain, some necessary information is absent or to which there may be several possible solutions (Pretz, Naples and Sternberg, 2003). To some extent, whether the problem is well defined or ill defined depends on the problem solver's expertise. In this study, the problems used are well-defined ones. These are the sorts of problems found in physics textbooks and examination papers.

Problem solving is characterised by a complex interaction of factual knowledge, cognitive and metacognitive strategies, experiences, belief systems and social factors (Rogoff, 1990). Some argue that competence in problem solving is the most important outcome of learning, since knowledge created in the context of problem solving is better understood, retained and more transferable (Jonassen, 2011).

Within the context of science learning, problem solving is an essential tool for predicting and explaining many diverse phenomena, emphasising the active nature of thinking and extending cognition beyond simple acquisition of knowledge (Reif, 2008). Problem solving is widely viewed as an approach to developing higher-order cognitive skills; most physics courses use problem-solving activities to assess the depth of conceptual understanding and the extent of transfer of acquired scientific knowledge. Sternberg (1996) argues that problem solving represents a form of inquiry learning where existing knowledge is applied to an unfamiliar situation in order to gain new knowledge.

Challenges within the curriculum

Larkin *et al.* (1980) noted that many novices began solving a physics problem by generating an equation that solves for the desired quantity. If the selected equation contained an unknown variable, then another equation was selected to solve for this variable. This is the observed case with many post-16 physics students.

Effective learning of physics is reflected by a transition from a novice approach to an expert-like approach during problem solving. This entails shifting from suggesting solutions and equations soon after reading the problem statement to first engaging in a kind of qualitative analysis (Larkin and Reif, 1979). The expert approach means that students employ a working-forward strategy, with clear, logical and coherent stages that integrate related physics principles (Simon and Simon, 1978). At the same time, metacognitive strategies such as monitoring develop (Flavell, 1979).

Metacognition determines the ability to consciously deploy one's cognitive forces with changing needs and circumstances during any activity (Flavell, 1979). Schoenfeld (1985) argues that competence in problem solving relies on the individual's conceptual model of the situation or problem at hand, as well as effective deployment of cognitive and metacognitive strategies.

An argument for teaching problem solving through collaboration

Metacognitive monitoring during problem solving is evidenced in good solvers through the maintenance of internal dialogue regarding the development of the solution. Plans are sought and evaluated against possible plans, solutions are tested and evaluated for accuracy within the problem context and progress is monitored. Socio-cultural theory argues that human cognition is a product of collaborative social activity (Vygotsky, 1978).

A socio-cultural perspective to knowledge construction emphasises the relationship between the learner and the context in which the learner develops. People are seen as active learners if they develop knowledge for themselves through interaction with others and in situations that require acquisition and refinement of skills and knowledge (Schunk, 2012). During these interactions, guided by adults or more skilled individuals, cognitive processes are modelled before internalisation (Rogoff, 1990).

The argument is therefore that all higher cognitive functions, such as analysis, modelling, evaluation and metacognitive monitoring, originate on the social level and are then internalised at the individual level. From a pedagogic perspective, a collaborative context is developed on the basis of a cognitive apprenticeship model, typified by the teacher modelling the steps to successful problem solving with mastery guidance, peer and teacher prompting and the provision of constructive feedback. A shift in problem-solving competence is evidenced by solvers having an internal dialogue regarding the way their solution evolves, arguing with oneself at every stage of the solution: planning, strategy selection and deployment and checking of solutions. Key to organising collaborative group problem solving is the teacher's knowledge of the distance between students' actual development levels and their potential levels – determining the zone of proximal development (ZPD) (Vygotsky, 1978).

The intervention pedagogy of collaborative problem solving

Teachers should teach students the tools for problem solving, such as metacognitive self-questioning, and then provide opportunities for using these tools (Schunk, 2012). During the learning process, initially through cooperative group activities and cognitive apprenticeship, the teacher models the deployment of the problem-solving strategies, providing structure and guidelines on how to accomplish the problem-solving task, demonstrating the proper expected performance of successfully solving problems. Students can model statements to guide action in the form of questions such as '*What is it that we have to do in this problem?*', '*To what aspects do we need to pay attention?*' and '*How are we doing so far?*' Strategy mastery hinges on frequent, timely and focused feedback on students' progress (Meichenbaum, 1977). Scaffolding is gradually removed as competence increases and activities become predominantly collaborative.

Summarising, from a socio-cultural perspective, the contexts for a positive shift in problem-solving competence include:

- **Collaboration within the ZPD** – which allows co-construction through strategies such as peer tutoring, reciprocal teaching and collaborative cooperative learning.
- **Cognitive apprenticeship** – where the teacher or more able students provide scaffolding through clues, reminders, encouragement, breaking the problems into steps, providing examples and modelling the use of cognitive and metacognitive strategies. These forms of support are gradually withdrawn as each student progresses.

The mechanisms that are triggered include:

- **Argumentation** – a central aspect of social exchange that involves a divergence of understanding, followed by group efforts to resolve and reach a shared understanding (Miller, 1987).
- **Appropriation** – students bring forth their ideas to the collaborative activity, consider alternatives, and recast these ideas in an effort to build an individual understanding. The shared knowledge is taken in to extend the existing knowledge structures (Rogoff, 1990).
- **Private speech** – a mechanism for the appropriation of shared knowledge and self-regulation (Rogoff, 1990). Private speech, self-talk (overt verbalisation) or inner speech (covert verbalisation) illustrates the internalisation of the acquired cognitive tools, that is, the use of language and problem-solving strategies.
- **Individual agency** – the active role of the individual student during collaboration. Agency, though socially organised, is exercised through individual acts of thinking, evaluation, analysis, synthesising and abstraction.

Methods for data collection

The study that this article presents sought answers to the following research question: *Can students' performance in problem solving be improved through collaborative group problem-solving activities?* The research took place in an 11–18 state school in London. All fieldwork was undertaken by the first author while studying for his doctorate; the second author was the first author's supervisor.

The context for this study was a physics department with poor GCE A-level physics grades, to the extent that there was no A2 group. There was little evidence of a culture of independent study and a clear absence of self-regulatory practices such as use of learner diaries to plan the weekly tasks to enhance retention and transfer of physics concepts. An intervention, through collaborative group problem solving, was undertaken to develop self-regulation strategies, build an appreciation of the impact of collaborative group work and foster an understanding that problem solving is a lifelong transferable skill that has to be nurtured and developed over time.

An action research methodology, consisting of two cycles, was adopted. Data were collected before the intervention and at the end of each cycle. The data were in the form of video recordings. The participants initially consisted of the ten AS students (eight boys and two girls) on an OCR A-level GCE physics A course (Mazorodze, 2016). The predicted grades for this group ranged from U (unclassified) to B. Initially, the whole group participated; later, only the four students who had proceeded to the final year of the course took part in the study. This small sample limits the generalisability of our conclusions. The problem of small cohorts for post-16 physics is common in schools in areas of low socio-economic status in London.

Informed consent was sought from the school authorities, the participating learners and their parents or guardians. Where this was not obtained, the relevant students were not video-recorded.

Data were collected using external assessments and video recordings of individual and collaborative group problem-solving sessions. For the video data, the group solved a minimum of two problems in collaborative and individual sessions in the first action research cycle. In the second cycle, the sessions involved solving an equivalent of a full examination paper, lasting about an hour. For group sessions, this allowed up to five problems to be tackled. Two group and three individual sessions were videoed. In addition, parts of other sessions were videoed to allow playback and feedback to the participants.

Analysis of video data for collaborative competences

Assessing collaborative competences required the capturing of the communication stream during collaborative group problem solving. After the video data, both actions and verbalisations, were transcribed, they were examined to infer the underlying processes. Examination of students' conversations and activity as they worked together illuminated, to some extent, how social interactions affected the course and outcome of problem solving. Competencies are inferred from the actions performed by the individuals, communications made to others, intermediate and final products of the problem-solving tasks, and open-ended reflections on problem-solving representations and activities.

The main categories adopted for the framework for assessing collaborative competences were: *positive interdependence*, *promotive interaction*, *individual accountability* and *group processing* (Roschelle and Teasley, 1995; OECD, 2014) (see Table 1). The subcategories were derived from all the four frameworks.

To illustrate the application of this framework, low collaborative competence was evidenced by: communications irrelevant to the task; providing redundant, repetitive or incorrect information to other group members; random actions or communications that do not reflect any meaningful role; a trial-and-error approach

Table 1 A framework for assessing collaborative competences

A Positive interdependence	**a** **Constructive feedback**. Members give constructive feedback to facilitate reflection and evaluation on the success of the group organisation in solving the problem. **b** **Coordination of language and action.** Team members' discussion shows collaborative turn sequences, specific turn-taking and narrations. **c** **Establishing and maintaining team organisation.** Students assume different roles for the effective functioning of the group, monitor the group organisation and progress, and facilitate changes needed to handle communication breakdowns, obstacles to the problem, and performance optimisation.
B Promotive interaction	**a** **Constructive discussions.** Students' input related to the problem to be solved results in content being added, explained, evaluated, summarised or transformed. **b** **Monitoring and maintaining the shared understanding.** Students establish or negotiate shared meanings, verifying what each other knows, and taking actions to repair deficits in shared knowledge. **c** **Collaborative argumentation.** Students put forward suggestions for the analysis and solution of the problem, challenge their proposals, back them up with theory, rebut opposing views on theoretical grounds, and weigh the available evidence that favours or disfavours possible solutions. The meaning of each other's information is negotiated. Students critically and constructively analyse others´ contributions through argumentation sequences.
C Individual accountability	**a** **Assumption of different roles.** Students respond to requests or take actions that are relevant to any progress towards goals. **b** **Consistent engagement.** Reduced or no instances of social loafing (i.e. participating less in a group than when on one's own).
D Group processing	**a** **Establishing and maintaining shared understanding.** In establishing the joint problem space, students identify the mutual knowledge (what each other knows about the problem) and the perspectives of other agents in the collaboration, and establish a shared vision of the problem states and activities. Group efficacy is established by comparing confidence levels. **b** **A shared focus.** Students use conceptual knowledge to explore and propose a strategy to solve a problem or to support a claim. Students plan how to start the task, time management, how to carry out the task, etc. **c** **Repairs.** The group collectively explores the weaknesses and merits of each proposal, and individual ideas are negotiated with respect to the shared work. Students resolve dissension or conflict among group members and identify and rectify errors committed by group members. **d** **Taking appropriate action to solve the problem.** The group identifies and describes the problem to be solved, creating a shared understanding of the problem state, goals and descriptions of the current problem state. The group agrees on the strategies to adopt and enact to solve the problem. The group monitors the results of actions and evaluates success in solving the problem.

that moves the problem away from the solution; and/or taking actions that are independent or inappropriate for the assumed role or tasks. When assessing collaboration, solving a problem alone was deemed to be evidence of low collaborative competence. The group could then be asked to discuss how collaboration could have enhanced their progress.

For this study, a highly collaborative student was one who participated in modification of plans and tasks by initiating the modifications. A medium collaborative student did not take the initiative but responded positively to requests to clarify problem goals, problem constraints and task requirements. A low collaborative student participated very little and might make less effort than when working alone.

For the analysis, high collaboration included identifying efficient pathways to goal resolution and taking an initiative to build and maintain the agreed group goals. This also included enquiring about the abilities and perspectives of other group members. In following the agreed plan, the student initiated requests to clarify problem goals, common goals, problem constraints and task requirements when contextually appropriate. When enacting agreed plans, high collaboration was evidenced by detecting deficits (gaps or errors) in shared understanding and taking the initiative to perform actions to solve these deficits (Table 2).

During collaborative problem solving, students can assume different roles (Heller and Heller, 2000; Mazorodze, 2016):

- **Facilitator (F)**: invites participation, monitors the group's progress and promotes group harmony by tempering conflicts, building group harmony, and so on.
- **Proposer (P)**: suggests new ideas that support a chosen approach, citing advantages and disadvantages of the proposed strategy.
- **Supporter (S)**: tries to justify a claim, elaborates it and tends to reinforce the direction of the current problem-solving approach.
- **Critic (C):** challenges the original claim and identifies errors and weaknesses, suggesting related alternatives that tend to alter the course of the problem-solving process. A critic usually triggers the argumentation process.
- **Scribe (S)**: 'distils' and summarises the jointly constructed solution path.

Table 2 illustrates how the designed framework was used to analyse the video data and illustrates certain findings of interest when the collaborative group was engaged in solving problems in mechanics and kinetic theory. The letter outside the brackets denotes the role and the initial of the participant is in the brackets, so, for example, P(S) means Sue is playing the role of the proposer. Four codes are used for collaborative competencies:

I positive interdependence;
II promotive interaction;
III individual accountability;
IV group processing.

All names are pseudonyms. Each episode is identified by shading and the student responsible for the episode is identified by the first letter of their pseudonym.

Regularities found from the video data analysis

Regularities (patterns) were sought for each individual student and the collaborative group. Video data from the entry (pre-intervention) video for Jamal, where he is working in a pair with Mik, show a low *positive interdependence*, with very little collaborative turn-taking. Jamal, a high-ability student, starts the problem individually before initiating an initial shared understanding of the task to establish the joint problem space. Consequently, there is no joint co-construction of the problem-solving strategy. *Promotive interaction* is low as Jamal fails to establish what Mik knows to allow for collaborative turn-taking. The interaction is reduced to prompting and asking for opinions from Mik during those moments when Jamal feels stuck.

Encouragingly, the exit (post-intervention) data (Table 3) show a high level of collaboration as Jamal initiates the establishment of the joint problem space within the group of four students. He requires each group member to rate their self-efficacy for each problem before attempting the task. *Promotive interaction* is further shown when Jamal engages in collaborative argument with Nik on the applications of resonance. In monitoring group progress, Jamal suggests a checklist of all the problems successfully solved in order of confidence rating and completion. Overall, Jamal shows a shift from being a low collaborative group member to a high collaborative member,

Table 2 Coding data from a video of students working in a group on a problem; participants: Jamal (J), Sue (S), Mik (M) and Nik (N); date: 18 October 2013

Time (mins:secs)	Actions (plain text), verbalisations (in quotation marks in italics) and commentary (in bold)	Role	Collaborative competencies			
			I	II	III	IV
0:00	Group allocates initial roles					
01:00	Jamal reads question 1					J
	Sue: '*kinetic energy is not conserved*'	P(S)				S
	Mik: '*yeah that means momentum is conserved*'	S(M)		M		
	Sue: '*the second … is not … become in inelastic collisions KE is conserved*' [**quick retrieval – evidence of schema**]					S
	Nik: '*does it mean the same as before or the same for each?*'					N
	Jamal: '*let's do the confidence ratings for each question first*' [**shift from general approach to strategic planning**]		J			
02:30	Nik: '*right question A*'	N(M)				
	Sue: '*you don't have to do all of it, do part*'	C(S)				
	Nik [reads question]: '*kinetic model of ideal gases*'					
	Jamal: '*I will say 50%*' Mik: '*I will say 60%*'	P(M&J)				
	Jamal [explains how lift force maintains . . .] Sue: '*I think that's 70%*'					
03:00	Jamal: '*I think that's over 70%, 80%*'					
	Mik: '*I will give that 70%*' Sue: '*yeah that's 70%*'					
03:00	Nik: '*let's go to B*'					
	Sue: '*I think that's all right . . . that's just dividing the equations*'	P(S)				
	Jamal: '*I would say 80%*'					
	Mik: '*I would say 80%*'					
	Sue: '*that's easy . . . it's easy . . .* [reads on] *. . . not actually*'					
	[**reassessment of knowledge after re-establishing problem demands**]					
03:30	Nik: '*simple harmonic motion*'	P(N)				
	Sue: '*not that one, we haven't done C*'					
	Jamal: '*I would say 75, whole C I will say 65%*'					
	Mik: '*second part I would give that 70%*'					
04:00	Mik [reads]: '*will give that 10%*'					
	Jamal: '*3a*'					
	Nik: '*yeah that's pretty much . . .*'	S(N)				
	Sue: '*it has to move from equilibrium position*'	S(S)	N			
	Nik: '*and directly towards it and proportional to the displacement.*' [**good definition but use of equation would have helped further exploration**]	S(N)	S			
04:30	Jamal: '*that's the definition? Fair enough*'					
	Sue: '*part C … 90 to 95% confidence level*' [group scans question]	F(S)				
	Mik: '*Yeah, I think it's fine*'	S(M)				
05:00	Jamal: '*use of resonance?*'					
	Nik: '*I think it's when we have to . . .*'	P(N)				
	Jamal: '*but that's not useful*'	C(J)		J		
	Nik: '*but I thought resonance . . . there has to be the same frequency*'			N		
	Jamal: '*Yeah . . . which means the amplitude . . .*' [Mik explains]			M		
	[**argumentation between Nik and Jamal on resonance**]					
	Nik: '*I think we can say we have 50% here . . . we can get half the question*'	F(N)				
06:00	Sue: '*we start solving the problems . . . the first one has the highest rating*'	F(S)				S
	[**adoption of strategy, problems with highest confidence rating first**]					

assuming different roles but mainly acting as a facilitator, facilitating group interactions and managing group progress.

An excerpt is given to exemplify positive interaction. Jamal says: '*right, give me all the confidence ratings and I will order them*'. A notable shift in group processing occurs when Jamal enquires about each group member's confidence rating to build group efficacy.

Another noted shift in collaborative competence is that of Nik. Initial data revealed low collaborative competence with a high frequency of social loafing (when an individual makes less effort in a group than when on their own). Nik was observed to wander off task more than five times in a given 15 minute task. In the recorded task, Nik's group demonstrates a low positive interdependence, scoring just 6 out of the possible 15 marks.

While the exit data show the persistence of incomplete knowledge structures in some physics domains and inadequate comprehension of the problem demands, there is a marked change in Nik's level of collaboration. This is positively correlated with attainment in physics problem solving. Nik participates in the initial establishment of the joint problem space and, assuming the role of scribe, subsequently 'distils' the group discussions. This indicates a much deeper understanding of the physics concepts compared with that revealed by the entry video data. In contrast to the entry data on collaboration, Nik participates in establishing team organisation and formulation of strategy through assuming a role as a scribe and a proposer, a major shift in collaborative competences. He engages in co-construction of the solution path. An extract (Table 3) illustrates where the students participate in specific turn-taking.

Discussion

Entry (i.e. pre-intervention) data revealed low levels of collaboration among these students when problem solving in groups. Yet, learning is a social activity and successful collaboration generally sustains learners' motivation. Successful collaboration involves a large degree of mutual engagement, joint decision making and discussions (Roschelle and Teasley, 1995). In one of the collaborative problem-solving groups, members failed to engage with the set tasks and build a joint problem space, with individuals often making less effort in the group than when on their own.

Overall, entry data showed a novice approach to problem solving with little to no metacognitive processing. Mechanisms that enable competent problem solving, such as self-efficacy and collaboration, were inadequate or non-existent. For this GCE A-level physics group, success was limited to low-level 'problems' requiring basic recall, such as stating definitions or recalling basic physics principles, and straightforward quantitative 'problems' where students only had to apply a basic linear heuristic approach (read → extract data → equations → substitution → solution).

The study revealed how the change in pedagogy impacted differently on the various students. For Jamal, a highly efficacious and good mathematician with a physics target grade of B, it meant an increase in the second external examination from grade B to grade A. Individual videos of problem solving showed that the use of language abilities developed during the collaborative group problem-solving sessions. The self-directed verbalisations in the form of questions served the role of metacognitive prompts.

For Mik, a highly efficacious but slow student, with a physics target grade of C, the intervention led to increased take-up of group roles and greater

Table 3 Turn-taking during collaborative group problem solving

06:00	Nik: '*I think we can say we have 50% here... we can get half the question*' Sue: '*we start solving the problems... the first one has the highest rating ... question Part B*' Nik: '*no we have got another one with 100%* [flips through] *yeah 100 right here*'
07:00	Sue: '*why didn't we do b?*' Nik: '*because this one has the highest confidence rating*'
11:00	Nik: '*so magnitude of the average force...*' Sue: '*F delta P over delta t?*' Jamal: '*so the change in momentum is...*' Sue: '*is mv minus mu*' Nik: '*so change in speed is 21...*'

use of argumentation; his time management skills also improved. Evidence pointed to incomplete tasks but high attainment as he adopted the strategy of prioritising problems with high confidence ratings.

For Sue, who would opt out of problems that required a deeper analysis, a notable shift in self-efficacy and good grasp of relevant physics concepts was observed. She adopted a strategy of deriving equations from first principles, reducing the equation to the specific physics for the given problem context. This is in contrast to abandoning the problem as evidenced by her entry data. Sue contributed during the collaborative group problem solving efficaciously. While the challenge to attaining full marks on qualitative problems that required deep analysis persisted for Sue, her increased self-efficacy and adoption of strategies taught during collaborative group problem solving resulted in higher attainment.

Nik shifted from being a near drop-out to a diligent and focused collaborator. The language and other cognitive tools used during collaborative group problem solving were eventually appropriated by Nik, and group expectations on him to regulate his behaviour eventually passed into his own self-regulation.

In summary, different shifts in regularities were observed for the different students. The resultant high level of collaboration was correlated with increased levels of attainment for each of the students involved in the study. Enhancements of metacognitive processing and increases in self-efficacy were observed. The intervention through collaborative group problem solving produced shifts in all the students, with marked positive shifts in collaborative competences, cognitive competences, metacognitive processing and increased self-efficacy positively correlating with attainment in problem solving in physics.

Implications for practice

While the small sample size for this study limits the generalisability of the findings, the findings present a strong argument for further exploration of such a pedagogic shift to promote competence in physics problem solving.

The GCE A-level curriculum that the students were studying (OCR GCE A-level physics A H158/H558) identifies problem solving as one of the six key skills to develop. However, little literature exists as to how this skill should be taught by teachers, with students consequently relying on standard textbooks and other materials with worked examples. Recent changes in the A-level curriculum have focused on structure and the nature of assessments. The shift from modular courses to linear, two-year courses and greater emphasis on the mathematical aspects of science (Ofqual, 2014) have not done much to support collaborative problem solving among students. Little can be done by teachers in terms of policy but, at a classroom level, a pedagogic shift to collaborative group problem solving can be adopted.

Assessments should include context-rich problems that encourage the development of problem-solving skills. Context-rich problems are realistic but more complex than traditional problems, reflecting the real world, and may include excess information or require the student to recall important background information (Docktor and Heller, 2009).

In the early stages of the proposed pedagogic shift, a scaffolded approach is recommended. With this approach, students are provided with a problem-solving framework that makes explicit the metacognitive processes involved, in the form of metacognitive prompts. Metacognitive processes are largely implicit; hence, explicit labelling of metacognition for students should be part of the modelling process. The discussion of metacognitive processes must be made part of the everyday discourse of the classroom to help foster a language for students to talk about their own cognition.

Finally, it may be helpful for students to have sessions when they video record their progress in competence and functioning in problem solving as collaborative groups.

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