CHAPTER 21

TEACHING SSIS—AN EPISTEMOLOGY BASED ON SOCIAL JUSTICE THROUGH THE META THEORY OF CRITICAL REALISM

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Abstract: Teaching socioscientific issues presupposes integrating normative concepts with descriptive facts. Historically this has proved problematic firstly because science public examinations tend to focus on factual explanations, and secondly, facts are often treated separately from value-oriented knowledge. Critical Realism is based on explaining real open systems through the use of causal powers, tendencies of bodies to act under actuating circumstances, and emergent structures so that events can be explained through a range of interacting causes: physico-chemical, biological, socio-psychological, politico-economic. The manufacture of aluminum is discussed through a critical realist perspective and it is suggested that both production and consumption, and an awareness of social justice, are central to understanding SSIs.

Keywords: Socioscientific Issues, Critical Realism, Social justice, Manufacture

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21.1 Introduction

About ten years ago a technology was developed that drew on chemical knowledge and research, art, and design and a prospect of environmental improvement. This project, Catalytic Clothing (Brown 2012) aimed to design beautiful clothes which purified the air, a creative use of scientific research for the public good, one which demonstrates in the best possible way the blending of science and society, and science and the arts. For science teachers it was an ideal socioscientific issue (SSI).

Catalytic clothing is a project likely to enthuse high school students: it captures interesting aspects of science for environmental betterment at the same time as creating an aesthetic product likely to appeal to young people. The science works like this. Textile materials are chemically configured to adsorb a nano-material photocatalyst, Titanium Dioxide, TiO_2, which can be integrated into washing powders. As the clothes are washed the catalyst adheres to the material. When the clothes are worn outside the titanium dioxide, activated by light, catalyzes the decomposition of water molecules in the moisture in the air into highly reactive hydroxide and peroxide free radicals. These free radicals in turn react with NOx molecules produced by car emissions converting them into the relatively harmless dilute nitric acid which washes off the clothes. Questions remain about the efficacy of the process but the idea is surely beneficial. It is consistent with the European Union's advocacy of Science & Technology in its Responsible Research & Innovation framework, that technoscientific products should be ethically acceptable, socially desirable and sustainable (European Commission 2015). On all three counts catalytic clothing should pass with flying colors.

Titanium dioxide is also a component of toothpaste, it helps to produce the shine in gloss paints, and it sterilizes dirty water, particularly useful in areas where obtaining clean water for drinking is not always possible (Royal Society of Chemistry 2014). How can there possibly be a fly in this ointment?

Later in this article I discuss the metatheory of Critical Realism (CR) which I will propose as the main epistemological justification for SSIs. CR is concerned with causation and absence as a cause. For example, a car accident can be caused by the absence of friction on an icy road. Absence can also apply to social theory, that the absence of certain conditions might contribute towards poverty or racism. In terms of catalytic clothing what could be the problem? Even if the product was not as efficacious as the researchers and designers hoped its sum effect on human happiness is still positive.

One aspect which is missing, perhaps because it is not relevant to the science conceptual knowledge needed to explain the process, is the origin of the photocatalyst, titanium dioxide. Like many minerals on which we depend, titanium dioxide is obtained from an ore, in this case rutile, which is mined mainly in the West African republic of Sierra Leone. Sierra Leone is one the world's poorest countries, positioned 182 out of 187 countries on the Human Development Index (UNDP 2020). In 2014 an outbreak of Ebola in Sierra Leone resulted in many deaths, some of which need not have happened if the country had had a health infrastructure which could cope (O'Hare 2015).

Given the extensive use of the land by global corporates in Sierra Leone, not just rutile but diamonds and timber, the question is raised as to how a country so rich in raw materials, which are of use to the world in general, is so prone to being ravaged by disease and war (there was a major civil war in Sierra Leone at the turn of the millennium). Reading the literature on this topic generates different versions of events. Wilson (2019) argues from his interviews, with a representative sample of interested parties, that mining rutile has contributed to impoverishment rather than prosperity, the loss of fruit farming land without compensation, increased unemployment and unequal power relations. A report from the National Advocacy Coalition on Extractives (NACE) argues that mining conglomerates are not paying the required royalties to the government based on their profits, as well as a lack of safety regulations, loss of farmland and lack of proper compensation by the mining companies (NACE 2009). NACE does report some benefits although these appear to have been outweighed by the harms. There are conflicting accounts on the social good established by the rutile mining company, hence it becomes a socioscientific controversial issue (Levinson 2006).

In fact, controversies abound surrounding companies, usually multinationals, that supply many of the commodities for our everyday life yet rarely, if ever, appear in socioscientific issues. Examples from mining are the extraction of coltan, the mineral that supplies the valuable and rare metals essential for the functioning of the semi-conductors in computers and cell phones, in the Democratic Republic of Congo under conditions of slave labor (Lalji 2007), and diamond mines in Sierra Leone (Frynas and Buur 2020). But it is not only mining. A highly detailed and informed article in the London Review of Books exposed the exploitative conditions of cheap labor for the manufacture of wind turbines (Meek 2021). Chemicals used in the thin layer coatings of solar cells, a central solution to harnessing sunlight for electricity supplies, have hazardous health and environmental properties which need to be taken into account in their manufacture (Nkuissi et al. 2020). Low-cost solar cells might well be at the expense of workers exposed to toxic materials. The question remains why these issues remain absent from discussions of socioscientific issues. Is it because they are not really science?

So my central question is: What is the epistemological difficulty in incorporating social factors, particularly those pertaining to social justice, in SSIs?

To address this question we need to consider an epistemological problem, that is the is/ought problem, or the fact-value dichotomy.

21.2 Fact-Value

When I have introduced SSIs to my group of science beginning teachers I often hear the understandable refrain: “Our degree is in Natural Science. We don’t have the background to deal with moral and ethical issues.” “And anyway,” they add, “these are too complex to deal with at school.” I have a great deal of sympathy with their views. This is an important pedagogical barrier and needs solutions. Another problem is that teachers will introduce the social context of an issue before getting down to what they see as the real science: the laws, concepts, facts, theories that are mainly addressed in assessment materials.

The is/ought problem states that you cannot infer an ‘ought’ statement from an ‘is’ statement, in other words the fact-value dichotomy. Empirically derived descriptions of the world have no intrinsic social or emotional value attached to them. That hydrogen has an atomic number of one, the moon rotates around the Earth, that heat flows along an energy gradient are matters of fact, they are not ideological or a matter of opinion. Photosynthesis will continue to occur in plants whether we live in communitarian or individualist societies, under authoritarian regimes or open democracies, in a society driven by neoliberalism or one that is wholly egalitarian. To say the moon ‘ought’ to rotate around the Earth is a nonsensical statement. It does so whether we like it or not. When uranium atoms are compressed in a critical mass a highly destructive fission reaction results which can destroy whole cities. As one educator has observed, Critical Mass is a descriptive proposition. It can tell us nothing about the rights and wrongs of holding a fissile bomb above a highly-populated city. The latter is a matter of morality not science (Hall 1999). Nonetheless, one should add, it would be a very odd class of high school teenagers who did not raise any question about its morality even in science lessons.

A significant part of the science education community has held the position that a focus on core science knowledge is the main aim of science education and a school science curriculum, and that a broader social context can provide an illustration of application. Tim Oates, a UK Government curriculum advisor, has pointed out that "we have believed we have needed to keep the National Curriculum up to date with topical issues but oxidation and gravity don't date…we are taking it back to the core stuff" (Shepherd 2011). Roberts (2011) identifies two 'Visions' of the science curriculum. Vision I focuses on the core concepts in science: the facts, laws, principles, theories that are the result of accumulated scientific knowledge over the years, whereas Vision II situates science in its social and historical context. Simonneaux (2014) has devised a spectrum of objectives in SSIs; one that moves from knowledge of and about science at the 'cold' end of the spectrum to activism at the 'hot' end. At the cold end of the spectrum, what Sund and Wickman (2011) broadly refer to as the 'fact-based tradition', decision making or action about an SSI presupposes scientific knowledge. Indeed a solid body of science education research is devoted to identifying what scientific knowledge is necessary for informed decision making. They use as their data student and teacher misconceptions about climate science (Arslan et al. 2012; Gungordu et al. 2017), and, contemporarily, scientific knowledge needed to know what action to take about COVID (Blandford and Thorne 2020; Braund 2020).

Such an approach is consistent with curriculum policy. For Hirst and Peters (1970) the concepts taught in science are distinct and different from those taught in the humanities. The fact-value dichotomy has produced a question, therefore, as to how to integrate knowledge into socioscientific issues. Addressing this problem depends very largely on context. Lee and Roth (2003) and Layton et al. (1993) have demonstrated that when dealing with such issues as local water pollution, caring for Down Syndrome babies, avoiding toxic fumes from a local chemistry factory, lay people draw on anecdotal and situated knowledge as more effective than knowledge transmitted by experts. Jho et al. (2014) in a study sample of Korean undergraduate students who underwent instruction on a course of nuclear energy, found there was no relationship between science content knowledge and quality of decision making. Lewis and Leach (2006) reported that school students aged 14-16 could use knowledge of genetics to discuss a social issue relating to the science when the relevant knowledge was taught in a way contextualized to the problem. Research on a similar issue did demonstrate that content knowledge of genetics in undergraduate students was linked to a higher quality of informal reasoning on SSIs (Sadler and Zeidler 2005). My argument, however, is not that academic content knowledge is irrelevant to decision making but that it is a contextualized component of a broader range of knowledges or knowings. What counts as knowledge in discussing and acting on an SSI is contentious, and that essentializing science conceptual knowledge can miss crucial issues of social justice.

But the fact-value dichotomy is, I claim, rather over-egged. First there are values intrinsic to science, for example, when scientists comment on the 'beauty' of a model. To say copper is a better conductor than plastic is a value statement but it is the way scientists talk all the time. As discussed above, to make sense of the role of science in any social context, facts and values are invariably entangled.

21.3 Critical Realism

A difficulty in using science knowledge, specifically school science knowledge, in real world contexts, is that much of this knowledge is gleaned from an un-real world. The laws, theories, and principles learned in the physical sciences at school relate to closed systems. This can be seen in names such as the Ideal Gas Laws. These reflect ideal systems where collisions between molecules are perfectly elastic and there are no attractions between the molecules. Adjustments have to be made for applications to real gases. Some years ago, I reported on a teaching activity carried out by a beginning teacher I observed (Levinson 2018). He asked a class of 11 year-olds to very carefully measure the temperature of water as it was heated from room temperature to boiling point. Half the class drew a perfect boiling point curve on their graphs because they knew what the answer should have been under ideal conditions. Others followed the data but their resulting graphs had no clear pattern. The valuable lesson students learned is that our world is patterned, but imperfectly. We cannot directly infer patterns from data alone. We need theories and models; data is driven by theory. The world does not reveal itself automatically to us.

The leading theoretician of CR, Roy Bhaskar, wondered what reality would have to be like for scientific knowledge to be possible (Bhaskar 2008). To answer that question there are a trio of fundamental concepts relating to CR. The first is an ontologically real world that scientists and social scientists are endeavoring to explain, it needs to lend itself to description and explanation. That, if you like, is the good news. Now comes the bad news. The second concept is that it is impossible to access that world directly, we are limited by theory, culture, language, instrumentation, and history. Knowledge about that world is relative because we are human, i.e., epistemological relativism. Now here's better news. Because knowledge is relative it does not follow that all theories about Nature and social structures are equally valid. Scientists use *judgmental rationality* to decide which theories carry validity and which do not. Hence CR avoids the traps of naïve realism in that it recognizes there is a world to be explained but knows there will never be perfect understanding. It avoids pure idealism because it recognizes a world beyond discursive interactions and forms of representation.

An important concept in CR, and central to my account, is that of emergence. Emergence occurs where a structure is more than the properties of its parts. A school is an example. It consists of buildings, texts, hardware, software, students, and teachers but it is more than these separate parts. It cannot be wholly explained only by describing these components. The formation of liquid water from its elements is another example. Liquid water is formed from the elements hydrogen and oxygen which are both inflammable gases at room temperature. When they are combined they form a non-flammable liquid water with completely different properties to its constituent elements. Hence liquid water is emergent. This is also true of biological systems which are emergent from physico-chemical systems, and psychological and social systems from biological systems. The brain is a biological system but more than its physicochemical components. Similarly, Mind and Consciousness presuppose a functional brain but are more than its biological structures. We cannot determine a priori the nature and properties of a structure from its constituent parts. However, it is possible to conclude that the potential to reflect is impaired if a balanced and varied diet is not available for biological systems to function to full potential.

A CR account of science starts from the assumption that Nature is an open system, not closed. The laws school students learn in physics and chemistry such as the Law of Falling Bodies and the Ideal Gas Laws can only be explained in closed systems. The Law of Falling Bodies assumes the presence of a vacuum; the Ideal Gas Law, assumes literally ideal conditions in a world of perfectly elastic collisions and zero loss of kinetic energy after intermolecular impact. But the world we live in is open, although such laws powerfully help make important predictions under certain conditions. As the students measuring the temperature of heated water found effects such as cooling, conduction, and convection influence the collection of data. These would all have to be eliminated as variables to obtain a perfect graph.

Another way of explaining natural phenomena is to start from the fact that we live in an open system, and rather than adapt physical laws based on closed systems, to start accounting for the world in situ. So, take the case of the Law of Falling Bodies. Everyone knows that if you drop a metal block and a feather at the same time the metal block will reach the ground first every time even though the law tells you otherwise. Hence CR deploys causal powers or tendencies (Archer et al. 1998; Chalmers 2007). A causal power is an intrinsic tendency of a body to act when triggered by an interaction. So, a feather has a tendency to accelerate towards the center of the Earth when released. However, air currents have a tendency to resist the fall of objects. If we take into account the causal powers of air currents, the Earth's mass and feathers, we can then account for their interactions. We take into account the interacting entities in the real world.

In conceptualizing causation CR draws on three domains: the empirical, the actual, and the real. When things happen in open systems this is due to a multiplicity of interacting causal mechanisms, each of which can be isolated in closed controlled conditions. These happenings, or events, are *actual* and *experienced*. However, they happen because of unseen causal mechanisms. For example, experiencing the pleasure of sitting by a pond. At the empirical level our senses respond, we see the pond, hear bird life, perhaps smell wild flowers which grow by the edge. The actual *accounts for* the empirical. There are, however, underlying mechanisms which explain the life of the pond: chlorophyll capturing sunlight for photosynthesis to take place, concentration gradients which set up a diffusion path for gases to flow. But what is experienced is more than the physico-chemical and biological mechanisms although these are a part of it. The pond needs to be maintained, and this means that social and political interactions need to occur to support its maintenance. In other words, any event, such as the pleasure taken in sitting by a pond, is explained by causal mechanisms at different levels. These causal mechanisms, often hidden (for example, the electronic sequence of interactions that accounts for photosynthesis) are in the domain of the real.

CR is a useful frame to explain events. This does not negate the fact that there are important concepts to learn in science but that to understand the world in its complexity, the real open world, we need to deploy different strata of knowledge, i.e., transdisciplinary approaches to explain events. To explain how people come to wear catalytic clothing we can draw on physico-chemical concepts, economic concepts (costs of research and production, extraction and shipping costs of the catalyst), and socio-political concepts (power relations in enabling the extraction). The effect of the catalytic clothing could not be realized without an understanding of the interconnections between different strata of explanation: physico-chemical, biological, sociological, economic, etc., the higher strata carrying normative values.

In the next section I will explain the thinking about an EU project, Promoting Attainment in Responsible Research & Innovation (PARRISE) (www.parrise.eu), in which I was involved in devising before discussing the way CR can be applied to a particular topic, the extraction of aluminum.

21.4 Socioscientific Inquiry Based Learning (SSIBL)

PARRISE is an EU funded project designed to support teachers in Socioscientific Inquiry Based Learning (SSIBL) (Amos et al. 2020). Social justice is built into its core rationale. Its aim is to support students in building their knowledge through inquiry into socioscientific issues.

The framework for SSIBL draws on three main cyclical stages: Researching authentic questions (ASK); Inquiry (FIND OUT) and Action (ACT) (See Figure 21.1).

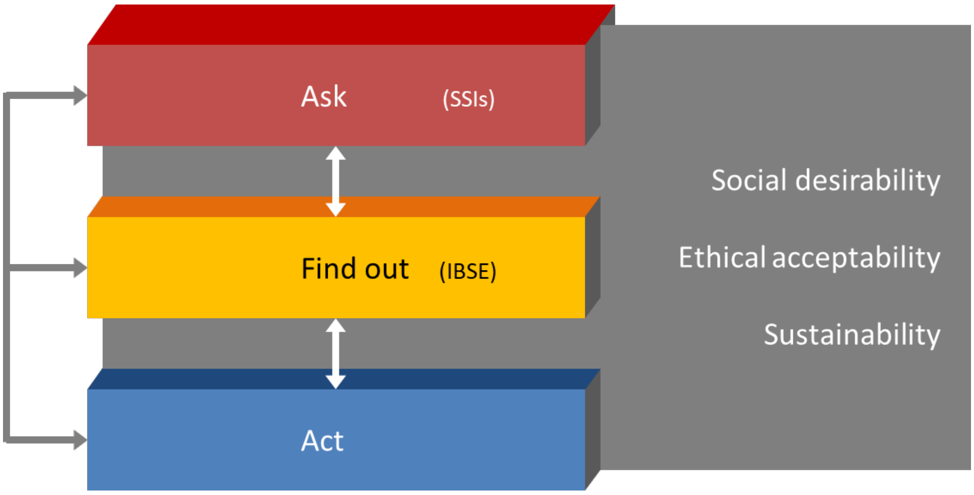

Fig. 21.1 SSIBL framework

While there has been a lot of evidence to show teachers' positive responses to this approach, one of the barriers has been the structure of a Vision I based curriculum. A single subject disciplinary curriculum therefore is something of a hurdle in supporting SSIBL (Levinson and PARRISE consortium 2017). CR underpins SSIBL in accounting for events through a transdisciplinary approach.

One contemporary example is student inquiry into the efficacy of face masks in preventing infection from the SARS-COVID 2 virus. Students researched various aspects: raw materials used to make the masks, conditions of production, transport routes, and modes of disposability. They did experiments to analyze the masks' permeability by spraying colored liquids onto them from various distances, checking pathogenicity by finding out how long it took for pieces of fruit to become infected when placed at various distances from a piece of moldy fruit. Researching this information through social inquiry and scientific investigation enabled them to take action in publicizing their evidence in suggesting suitable protective equipment[1].

21.5 A Way Forward

The promise of CR in a science context is that its starting point is inquiry into this open messy world around us and demonstrating the importance of a transdisciplinary approach in understanding emergent phenomena. My suggestion is that while understanding our world is important in grasping fundamental scientific concepts, meaning is more readily addressed by structuring the curriculum in terms of events rather than concepts. The use of masks, for example, is an event which draws together interlocking multidisciplinary knowledge. I would like to demonstrate this through an

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[1] I am indebted to Marta Romero-Ariza, a colleague on the PARRISE project, who furnished me with details of this activity. You can see a video of Marta's presentation on https://www.youtube.com/watch?v=-d_eRqEtwYM&ab_channel=ISDDE

example I have been working on in recent years, and I draw on it in particular because quite often science teachers see it as a hurdle to get over rather than a way of developing understandings both about science and social justice.

The topic I refer to is the manufacture of aluminum, to see this as an event, rather than a series of concepts to master for an examination. In the curriculum students learn about the electrolysis of pure alumina to manufacture pure primary aluminum. If this process is explored as a series of events which raise socio-political and scientific questions, the understanding of the science concepts and its social meaning will be enhanced. As will, I suggest, interest and motivation.

Aluminum is the world's most abundant metal and it has many uses due to its physical properties. It has a low density, is corrosion and heat resistant, and durable. It therefore it is used in aircraft manufacture, drink cans, and food wrapping. There are two main events in preparing aluminum for distribution:

1. Purification of the electrolyte
2. Electrolysis of the electrolyte to generate aluminum metal.

21.5.1 Purification of the Alumina

There are many different compounds found in bauxite, alumina (aluminum oxide) does not come out of the ground in a pure state. It has to be separated from other metal minerals. The particular property of aluminum oxide is that it is amphoteric. It can be dissolved in acids or alkalis. Given Al_2O_3's particular status, the bauxite can be washed with concentrated alkali, usually sodium hydroxide, which dissolves the alumina, separating it off from other chemicals, in particular other metal oxides. The resulting solution is filtered and evaporated and the pure alumina obtained. This process looks fairly straightforward but when carried out for manufacture certain problems arise.

On October 4, 2010, the retaining wall of a dam, owned by the Ajka Aluminum plant in Hungary, containing waste formed by treating bauxite with caustic sodium hydroxide, collapsed, and millions of liters of toxic red sludge was released killing ten people and injuring over a hundred more. The injuries to humans were bad enough but homes and many acres of farmland were destroyed, thousands of people lost their livelihoods, waterways were poisoned and livestock killed.

Three billion tons of red mud waste are stored around the world and 150 million tons of waste are produced each year through this process. Dealing with such a problem raises questions about consumer choices and technoscientific fixes.

Much of the aluminum produced is used for cans for fizzy drinks and food wrapping, for example sweet candies such as chocolate eggs. Since the market for aluminum products does depend on patterns of consumption, are there questions here about personal and communal responsibility for sustainability? Technoscientific solutions include tapping red mud for scandium since scandium-aluminum alloys have greater strength than pure aluminum, and help in the construction of lighter aircraft burning less fuel. There are prospects for industries using red mud as a source for scandium, however, there are only 140 parts per million of scandium in red mud so much of the residue will remain and the extraction process will generate other technical problems to address (Service 2020).

Looking more closely at the science explanation for producing pure alumina, implications become clear. Where will the waste red sludge be stored? Who will be responsible for it? What responsibilities do the owners of the plant have to the local population? What are the risks of such an accident taking place, and are infrastructures in place to deal with the consequences?

Meaning is therefore given to the science explanation if we understand the Ajka disaster as an event with different layers of interconnected knowledge. Not all of these questions can be addressed in depth but it does raise questions about the purposes of production and our own responsibilities for consumption.

21.5.2 Electrolysis

Aluminum metal is generated in the smelter by electrolyzing pure alumina dissolved in the mineral cryolite. There are interesting stories to be told about extracting and utilizing cryolite (Levinson 2014) but the focus here is on the electricity generation for the smelter.

Aluminum has an atomic number of 13 and is in group three of the Periodic table. We can infer from this that aluminum is a small atom and has an ionic charge of 3+. This helps to explain why a huge amount of electricity is needed to reduce aluminum ions at the cathode. The equation is:

$Al^{3+} + 3e = Al$

Hence three moles of electricity (coulombs of charge) are needed to reduce the aluminum ions; the approximate electrical energy used globally in manufacturing aluminum is between 600 billion and 700 billion kilowatt-hours of electricity annually which is about 3% of the world total production of electrical energy. The energy needed now comes almost entirely from hydro-electric power stations which are regarded as a source of clean, carbon-free energy. Aluminum producers are keen to make their environmental credentials very clear. *Hydro* maintain their hydroelectric plants provide around “10 TWh of clean and renewable energy annually for our aluminium production” (Hydro 2021).

‘Clean’ and ‘renewable’ energy is obviously very desirable. But basic knowledge of the principles of hydro-electricity would allow any student to contest this claim.

A hydro-electric plant needs two important geographical features: mountains for water to fall on a turbine from a great height and, of course, plenty of running water. Although huge dams can be constructed to produce these features (questions can be raised about the amount of carbon needed to construct these dams) most hydro-electric plants are in areas of great natural beauty. The generation of electricity caused by the rotation of the turbines generate waste heat which raises the temperature of the water. Fish are poikilotherms and thrive in cold water, hence the rise in temperature is not likely to be conducive for life. As the temperature of water rises oxygen solubility decreases threatening aquatic plant and animal life and promoting the growth of anaerobic bacteria and fungi. What can ‘clean’ mean in those conditions?

Situating the scientific explanation of hydroelectricity within a broader socio-political context raises significant questions about sustainability and consumption. Scientific explanations are embedded in social, psychological, and economic ideas pointing to multidisciplinary causal mechanisms.

21.6 Conclusion

Resources and strategies for teaching SSIs are proliferating, some of which such as STEPWISE (Bencze 2018) and Socially Acute Questions (Morin et al. 2017) deal with important aspects of social justice and power distribution. The many empirical studies on using knowledge for personal and social purposes suggest that experience and situated knowledge play a more important role than the decontextualized value-free concepts learned in school science.

I want to draw attention to the fact that the goods consumed in the West are often found in science curricula–Catalytic Clothing, aluminum, electronic goods–and the emphasis is often on their utility rather than the human and environmental costs of production. These are choices made by curriculum designers, politicians, educationalists, and so forth; the focus on consumption rather than production is value-laden. Throughout the process of manufacture to consumption are socio-political causal mechanisms which are as central to production as, for example, the electronic structure of aluminum.

By looking first at events or questions about events the meaning of science concepts within the context of that event becomes clearer. This enhances the means of linking scientific knowledge to personal and social experience. And as a final note it answers the question when pupils ask in science lessons ‘what are we learning this for?’

Applying scientific knowledge to society can be a misleading epistemic barrier for SSIs. If we recognize that we live in an open system and that an event has multiple causes, including scientific ones, then ‘events’, by which I include socio-scientific happenings, become more intelligible. Nor need that gain be at the expense of scientific knowledge; in fact, an understanding of the role of science in explaining any event is likely to enhance the motivation to know.

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