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The Science Thought Experiment: How Might it be Used Profitably in the Classroom?

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Abstract. It is well established that thought experiments are both scientifically and philosophically significant, and even that they are pedagogically significant. However, the basis and methodology for their pedagogical use is not as well established. Pedagogical thought experiments are defined as mental simulations with special features to isolate certain conceptual elements. It is argued that thought experiments are made pedagogically effective through the process of re–enactment of the thought–experimental process. The process of re–enactment is best captured by rewriting thought experiments as stories. Several examples of thought experiments are analysed for their narrative content and an example is given of a pedagogical thought experiment re–written as a story. Recommendations are made as to how such thought experimental stories can be used effectively.

Introduction

High grade thinking in science can provide for us examples to emulate in their typology, albeit on a lesser scale. Such inspiration is certainly provided by the famous thought experiments in science, especially the examples provided by Galileo Galilei. Galileo infuses his thought experiments (TEs) with drama in the arguments between Salviato and Simplicio in his *Dialogues Concerning Two New Sciences*. An example of that debate which readily comes to mind is Salviato's disproof of the Aristotelian premise that heavier objects free–fall faster than lighter ones. The TE unfolds in the form of a dramatic interchange in which the character Simplicio plays the role of the Aristotelian. Simplicio works through the TE and ends with the contradiction that a heavier stone must fall both faster and slower than a lighter one. At that point he reveals a state of cognitive dissonance when he says, "I am all at sea because it appears to me that the smaller stone when added to the larger increases its weight and by adding weight I do not see how it can fail to increase its speed or, at least, not to diminish it" (Galilei, 1638/1954, p. 63). TEs such as this have played an important role in the development of science. Popper credited Galileo with having made "one of the simplest and most ingenious arguments in the history of rational thought" (1934/1959, p. 442) and Koyré credited Galileo with "having known how to dispense with experiments" (1968, p. 75).

It is well established that TEs are both scientifically and philosophically significant. Galileo's example, cited above, suggests that TEs may also be pedagogically significant. Simplicio provides for us an interesting model of learning, namely, 'science student as Simplicio'. The implied metaphor of student as Aristotelian is one possible connection between the TE and its pedagogical application. However, another connection to pedagogy is possible. I will argue, based on the analysis of several other TEs, that pedagogical effectiveness arises from the story–like nature of TEs. When they are artfully retold, TEs are story–like re–enactments of idealized experiments which, by nature, inspire in the teller or hearer the reaction "But, how could it be otherwise?" But, what is it about the nature of TEs that is likely to inform the development of a model for their pedagogical use?

The Nature of Thought Experiments

The origin of the modern philosophical discussion on TEs in science is frequently attributed to Ernst Mach (1838–1916) who used the term "Gedankenexperiment". However, contrary to popular belief, Mach was not the first to use the term. The term was already used by Hans Christian Örsted (1777–1851) in his essay "Prolegomenon to the General Theory of Nature" (1811). More recently, a concerted discussion on the nature of TEs appears to have been initiated by Thomas Kuhn's seminal essay "A function for thought experiments" which was included in his *Essential Tension* published in 1977. I would like to identify several questions that have arisen during the course of the discussion on TEs from Örsted up to the present that will have a bearing on their pedagogical use. These are

1. How certain are the explanations produced by thought experiments?
2. How are thought experiments related to real experiments?
3. What are some of the unique features of thought experiments?
4. How are thought experiments related to learning?

THOUGHT EXPERIMENTS AS EXPLANATIONS

Is it possible to discover new scientific knowledge by means of TEs or do they merely provide clarification, or at best, disconfirmation, of existing scientific theories? Örsted would likely have answered in the affirmative, as he wrote that by means of thought experiments "one will find out whether or not an event can be explained by a definite supposition together with the other [known] laws of nature" (in Witt–Hansen, 1976, p. 56). The "suppositions" advanced by TEs, Örsted believed, are the basis for new scientific theories. James Brown (1986, 1992) claims that some TEs are, indeed, able to make an original contribution to a theory in science. Brown observes that there are some TEs that are both destructive and constructive of theories. These, he claims, may provide the grounds for an *a priori* transition from one theory to another. John Norton (1996) disagrees with Brown's position, arguing that all TEs can be reconstructed as logical arguments and that TEs are nothing more than imaginatively situated arguments. In Norton's view, since TEs build on existing knowledge by means of logical arguments, they can never produce new knowledge. Ian Winchester (1990) takes an intermediate position, maintaining that TEs are arguments about nature that proceed from "everyday" type certainties in a particular area of science. These arguments function to make concepts, already suspected of being true, more plausible. Concepts are made more certain by TEs, thereby contributing to the formation of "everyday certainties" in science that are sometimes called metaphysical propositions (Winchester, 1990, p. 74). Brown's and Winchester's positions differ on the degree of certainty that TEs may contribute to the acceptance of metaphysical propositions.

THOUGHT EXPERIMENTS AND REAL EXPERIMENTS

Many writers on TEs (Brown, 1986; Bunzl, 1996; Gooding, 1992; Kujundzic, 1992; Nersessian, 1992) think that TEs obviate the need for physical (real) experiments (REs). TEs either make

REs unnecessary due to their conclusive nature or they employ imaginary situations that are impossible to duplicate in the real world. If REs cannot or, need not, be employed to add further support for the TE, then such TEs are likely definitive in supporting or disproving some element of theory (Brown, 1986). However, others (Atkinson, 2001; Mach, 1926; Sorensen, 1991) maintain that often TEs need to be followed by REs that confirm the TE or that TEs and REs differ in methodology but not in kind (McAllister, 1996; Reiner & Gilbert, 2000). If TEs merely make some propositions about nature more plausible, then they need to be followed by REs in order to add a higher degree of certainty to the issue. Mach believed that TEs rely on physical experiment for their validation and that TEs "are a necessary precondition for physical experiment in science" (1926/1976, p. 136). Based on the range of arguments that exist for and against the ability of TEs to generate new knowledge, it seems that the conclusions of TEs can range in certainty. On one end of the spectrum, the outcome is little more than an educated guess, necessitating a physical experiment. On the other end of the spectrum, the outcome is definitive and seemingly conclusive so that the thought experimenter feels justified in dispensing with any further physical experiments.

IMPORTANT FEATURES OF THOUGHT EXPERIMENTS

The philosophical discussion on TEs tends to set certain limits on what could be considered "*thought experiments proper*" (Stinner, 1990, p. 248). One such issue of demarcation is whether TEs are "merely imagined experiments" (Brown, 1986, p. 3). Brown, and also Bunzl (1996) maintain that TEs are not merely experiments that *could* have been carried out as REs but were *instead* carried out in thought because the results are obvious. Experiments that can be carried out either in practise or in thought at the discretion of the experimenter are "philosophically uninteresting" (Bunzl, 1996, p. 228). That is because such TEs have no obvious advantage over REs. The TE achieves philosophical interest, according to Mach, by varying the conditions of a process in such a way so as to isolate certain features and show that one conclusion should be chosen over another. A typical method of isolating features is to consider limiting cases.

Another characteristic of TEs, claimed by some, is that they are, in fact, a type of narrative (Hacking, 1992; McAllister, 1996; Nersessian, 1992). It is not clear, however, whether the claim of narrative is contradicted by the assertion of Norton (1996) that TEs are simply picturesque arguments.

THE RELATION OF THOUGHT EXPERIMENTS TO LEARNING

Many commentators on TEs have pointed out that TEs hold considerable potential for contributing to student learning of scientific concepts (Helm, Gilbert, & Watts, 1985; Mach, 1926; Matthews, 1994; Nersessian, 1992; Reiner & Gilbert, 2000; Stinner, 1990; Winchester, 1990). Reiner and Gilbert have shown that "thought experimentation in which students construct imaginary situations are a frequently–used strategy for problem solving" (2000, p. 502). According to these educators, the general feature of TEs that contributes to learning is the ability to contribute to conceptual clarity. Mach is possibly the earliest to write about this and he categorizes speculative questions as a type of pedagogical TE that may give rise to real experiments that enhance student learning through individual investigations (Mach, 1926, p. 142). Mach published a large number of speculative thought questions that are particularly interesting for students. These "Denkaufgaben" or "thought assignments" were featured throughout the pedagogical journal *Zeitschrift für den Physikalischen und Chemischen Unterricht* that Mach co–edited for many years, beginning in 1886. How, specifically, TEs relate to the individual learning process has, however, not been discussed in the literature other than in the work of Reiner and Gilbert (2000).

Thought Experiments and Learning Science

In order to gain understanding, students must engage, actively, with their learning materials and situations. Learning for understanding, sometimes called "cognitive change", must consist of purposeful mental, verbal, or physical activities by the student. Cognitive scientists claim that meaningful learning arises as a side effect of activity (Barsalou, 1995; Ohlsson, 2000). Activity–based learning produces understanding which, by nature, students must *express* by means of explanation—either to themselves or to others. Such processes of explanation are really re–enactments of processes based on trial theories, models, or laws (Ohlsson, 1992, 1999, 2000; Schwitzgebel, 1999). If the trial theory, model, or law works well in producing a particular observation, then it serves as a good explanation, thereby producing a higher level of understanding of the concept involved.

It is interesting to compare the learning–as–re–enactment model to descriptions of TEs. Bunzl (1996, p. 229) writes, that in performing TEs, "we set up an experimental situation in our mind and then let the experiment 'run', 'observing' the consequences". The imagined consequences do not "just appear", but they obey the relevant principles about nature that we already know. Brown maintains that "The burden of any constructive thought experiment consists in establishing (in the imagination) the thought–experimental phenomenon. This phenomenon then acts as fairly conclusive evidence for some theory" (1991, p. 45). Whether the TE is seen as conclusive, or not, the theory of the TE is, at least initially, a trial theory and its success in producing the thought–phenomenon is a measure of its viability. Both learning for understanding and the TE process involve re–enactment. The processes of explanation in learning and in performing a TE in the mind, as described above are, evidently, very similar.

A DEFINITION OF THE PEDAGOGICAL THOUGHT EXPERIMENT

Before considering examples of pedagogical TEs, it would be useful to adopt a provisional definition of the TE. I define pedagogical thought experiments as mental re–enactments of natural processes for the purpose of clarifying concepts in science or providing answers to students' questions about science. Students may imagine the behaviour of such natural processes with the help of intuitions about nature that have become "everyday certainties" (Winchester, 1990, p. 74). On the other hand, students may not yet have arrived at the point of having developed "everyday certainties" about concepts or processes. In that case, the purpose of a TE will be to help develop such certainties. Furthermore, TEs are not just any re–enactment of a natural process. They need to be able to answer a question or produce clarification by introducing a special feature or variation, to use Mach's term, on the process that isolates the feature of interest. Often TEs will employ limiting cases. Not only will the TEs employ special design features, but the thought experimenter must imagine or re–enact the experiment in a way that eliminates experimental error such as may be present in real experimentation.

EXAMPLES OF PEDAGOGICAL THOUGHT EXPERIMENTS

Einstein Riding on a Light Beam

In recalling his reflection on a universal principal underlying physics, already at the age of 16, Einstein recounts his famous thought experiment on the velocity of light:

> If I pursue a beam of light with the velocity *c* (velocity of light in a vacuum), I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest. However, there seems to be no such thing, whether on the basis of experience or according to Maxwell's equations. (in Schlipp, 1970, p. 53)

The objective of this TE is to observe the nature of a light wave and the ingenious variation employed is to increase the velocity of the observer so as to approach the velocity of the light wave. Maxwell's equations, however, dictate that an electromagnetic wave in a vacuum must have a definite speed, *c*. The observed wave seems to be stationary, which contradicts Maxwell's equations. At the superficial level, the violated principle appears to be Maxwell's equations. However, the issue is deeper. As Einstein explains, ". . . judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to the earth, was at rest" (in Schlipp, 1970, p. 53). The more fundamental principle is that the laws of physics must be the same in all inertial frames of reference. Since the TE violates that fundamental principle, the assumption that the observer may assume a speed as large as that of light must be incorrect. As Einstein, says, the seeds of the special theory of relativity are already contained in this TE.

If students merely recapitulate the problem, this TE has limited pedagogical value. It does explain an aspect of the origin of the special theory of relativity. Moreover, for students simply to reason through Einstein's thought process does not produce the active student engagement that we wish to achieve in teaching for understanding. Obtaining a genuine understanding requires more than a brief class discussion (Westbrook & Rogers, 1996). Students would need to be encouraged to arrive at a conclusion similar to Einstein's based on their own through further investigations of the concept. However, students do not arrive at a thorough understanding of Maxwell's equations even in the senior university years. Moreover, students would likely already have heard of this TE at some point and it would not be possible to have them discover the principle, independently.

Mach's Thought Problems[1]

Mach co–edited the first science pedagogical journal, *Zeitschrift für den Physikalischen und Chemischen Unterricht*. Each issue contained a selection of *Denkaufgaben* or "thought assignments" designed to produce student discussion of a scientific concept. I include a translation of one example from this journal (available only in German) to illustrate that the feature of *variation* must be present in order for the problem to be considered a TE.

> A person climbs on a motor-driven treadmill so that he remains at the same location. How is it that he is able to do work by lifting his body, seeing that he remains at the same elevation? In this thought investigation he feels the work, since it results in the loss of a caloric equivalent. He feels work which, instead of depending on his speed of climbing,

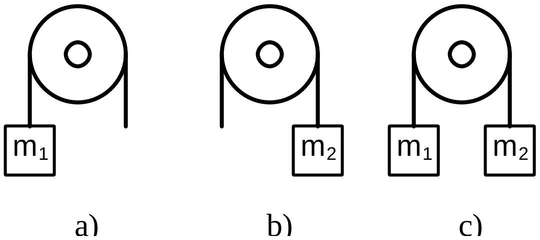

Figure 1: Two masses and a pulley

> depends on the relative speed of his body mass along the incline. But where does the work actually take place? (Mach, 1888, p. 211, S. Klassen, Trans.)

Although this example is clearly a mental re–enactment, it does not include any special variation to aid in the isolation of a particular conceptual feature. The problem encourages the student to investigate the component of work resulting from walking up an incline, which results from efforts other than the normal caloric expenditure in walking. The element of variation can be introduced into the above example, easily. I have re–written it as follows:

> Susan walks, in place, along a motor–driven treadmill that she has adjusted to have a zero incline. She notices that she expends a certain amount of caloric work at a particular pace. If, now, Susan adjusts the treadmill to have an incline, ?, and she still walks at the same pace along the surface, does the amount of work expended increase, and if so, where does the extra expenditure originate?

The re–formulated problem includes the feature of a limiting case (zero incline) and thereby clarifies the distinction between work due to walking on a level and work due to walking up an incline. The solution is that the person lifts her body from the lower position to which the treadmill incline has moved, over a short time, to a higher position, thereby maintaining the same elevation. The person works against the normal force exerted by the treadmill on the feet with each step, which is equivalent to lifting the body on each step.

In its second form, the problem more clearly adheres to the pedagogical TE guidelines. Mach’s *Denkaufgaben* include many examples that students could use as simple TEs for the purpose of conceptual clarification.

An Original Example[2]

In the following example, the student is encouraged to use limiting cases and common–sense assumptions to arrive at an expression *without using Newton’s laws.*

> *You connect two masses by a thin inextensible string which passes over a massless and frictionless pulley. What is the downward acceleration of the heavier mass?*

The analysis proceeds in the following fashion (see Figure 1). The acceleration must depend on the values of the masses, call them m_1 and m_2, in some way. Assume that m_1 is greater than m_2. The simplest relationship between the masses and the acceleration will be linear. If either of the two masses, in turn, were allowed to be zero, then the expression of acceleration would be proportional to either m_1 or m_2 —see Figure 1(a) and (b). On the other hand, if the masses were allowed to be equal, then the acceleration would be zero—see Figure 1(c). This condition is only met if the acceleration, in general, is proportional to m_1 minus m_2. But we also expect that the acceleration would depend on the value of g, the gravitational acceleration. We also assume a linear dependency on g, since it is the simplest relationship. There are no other variables upon which this problem appears to depend. On this basis, it is likely that the acceleration is proportional to $(m_1 - m_2)g$.

At this point, the solution requires either a check for unit consistency or directional consistency. We choose the latter approach. The problem requires a uniform definition of the positive direction of motion, since the masses move together. This is achieved by letting the downward direction of m_1 and the upward direction of m_2 be positive. Finally, we note that if m_2 is zero, then the acceleration must be g, and if m_1 is zero then the acceleration must be $-g$. That is only achieved if we divide the above expression proportional to acceleration by $m_1 + m_2$ to yield the final expression for acceleration $\frac{(m_1 - m_2)}{(m_1 + m_2)}g$. It is interesting to note that the above solution could also have been obtained using Newton's Second Law. The expression for acceleration is, in fact, a means of motivating the form of Newton's Second Law, $Ma = F_{net}$.

The limiting cases, considered above, are constructed so as to match the solution to the everyday world in the most easily discerned manner. Our (and the students') understanding of the world—a type of everyday certainty—constitutes a means of arriving at the proposed solution. One might view the choice of a linear relationship as deriving from the "principle of simplicity" which is an extension of Occam's principle. The assumption that masses connected by a string behave as one derives from Leibniz's "Principle of Sufficient Reason" which implies that "when no reason can be given why things which should be the same are not, then we ought to treat them as the same" (Winchester, 1990, p. 78). The assumption of dimensional consistency in an expression is another illustration of Leibniz's principle. Although students are, likely, not aware of the philosophical dimension to their reasoning, simple TEs, like the example above, can result in remarkable learning episodes. By using "everyday certainties" like the condition of simplicity (using a linear relationship) or by requiring dimensional consistency in an expression, students can be motivated to "discover" basic concepts on their own.

Are Thought Experiments Narratives?

As I mentioned earlier, several authors have singled out narrative as a central feature of TEs. Whether TEs are narratives is an important issue from the pedagogical perspective. When the arguments of TEs are realized as re-enactments, they automatically become narrative sequences (Klassen, 2002). Furthermore, story–narratives are significantly more engaging to students than bare arguments. If TEs, or at least their mental re–enactment, are story–narrative sequences, then they become learning sequences, by definition.

One cannot, automatically, assume that TEs are narratives, as there are some potential objections to the premise. The work of Norton (1996) showing that he can express any TE as a logical argument presents one possible objection to the assumption that TEs are narratives. The objection arises from the argument of Bruner (1996), that narratives are fundamentally different from scientific arguments in that the scientific argument appeals to logic whereas story–narratives appeal to our sense of human identity. If TEs are presented as arguments rather than

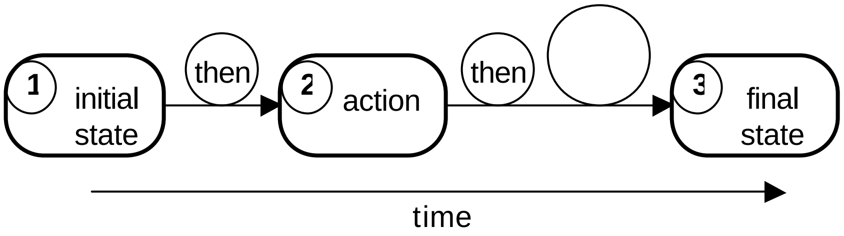

Figure 2: The Minimal Story Sequence

stories, then they may have mathematical appeal but they lose their human appeal upon which we rely to hold students' attention and engender better learning. We know that TEs can be expressed as arguments. Can they also be expressed as story–narratives?

TEs must conform to conventional narrative structure in order for us to consider them to be narratives, in the first place. Andrew Harrison describes the essential structure of stories in the following way:

> It is an interesting question what the minimal complexity of a story might be. . . . The answer seems to be that it tells of a sequence of events that lead to a certain consequence. . . . One thing happened, then another and the outcome was so and so—a mere list of events, real or imaginary, won't do. . . . there needs to be a reason why what happened did happen. (Harrison, 1997, pp. 157-158)

It is also possible to represent this minimal story structure (Klassen, 2002) in a diagrammatic fashion (see Figure 2). The rule of the story structure is that the final state must be a type of variation on the initial state in order to preserve the narrative flow.

Let us re–examine the preceding TE examples in the light of the restrictions placed by narrative structure. The example of Einstein's TE can be broken into the following components: 1) A proposition: I pursue a beam of light with the velocity *c*, [then] 2) A hypothetical observation: I observe such a beam of light as a spatially oscillatory electromagnetic field at rest, [and then, as a result] 3) I make a deduction: There is no such thing as pursuing a beam of light with the velocity *c*. The correspondence to a story structure is marginal, since the final deduction is not, strictly speaking, a variation of the initial state.

The second example, in its revised form, can be broken into the following components: 1) Susan walks, in place, along a motor–driven treadmill that she has adjusted to have a zero incline; [then] 2) she notices that she expends a certain amount of caloric work at a particular pace; [then] 3) Susan adjusts the treadmill to have an incline, *?*; [then] 4) she still walks at the same pace along the surface; [and then] 5) she asks: does the amount of work expended increase, and if so, where does the extra expenditure originate? It is interesting to note that if the example is left as a problem, the element of causation is not present, but that when it is changed into a problem–solution, the causation enters. The last component, above, could be stated as: [and then, as a result] the amount of work expended increases. Although it is possible to have a story–narrative structure, when the narrative element is present, it is only the barest of structure.

The third example can be broken into the following components: 1) You connect two masses by a thin inextensible string which passes over a massless and frictionless pulley, [and then] 2) you ask the question: What is the downward acceleration of the heavier mass? Here the narrative structure is trivial.

Based on my analysis of these examples and my reading of a number of other examples, I am unable to justify the claim that narrative structure is a major feature of published TEs. On the other hand, it is commonly believed that the human mind naturally superimposes narrative structure on events (Bruner, 1996) and we could think of TEs as *capable of becoming narratives*.

TEs are presented in a particularly condensed form and their narrative elements, where present, are extraordinarily sparse. But, far from being a negative characteristic, sparseness makes the TEs more powerful devices. Philosopher Andrew Harrison notes that "virtually any story may be made convincing so long as you tell it sparsely enough, and so long as it is received sparsely enough" (Harrison, 1997, pp. 167–8). TEs have their sparse, pithy nature in common with the anecdote. It is interesting to note that anecdotes invite the listener to "infer recklessly" (Shrigley & Koballa, 1989, p. 296) by their very sparse nature. A similar invitation to infer a particular solution is also contained in TEs. Ian Hacking has said that TEs are like jokes—very well worked–out items with a punch line (Hacking, 1992). As an alternative, I suggest that TEs are like anecdotes—terse accounts of novel scientific episodes pointing the hearer or reader towards an obvious solution.

Thought experiments contain both arguments and the elements of narrative. The narrative, whether in story form, or not, is the seed of the human element, whereas the argument comprises the scientific element. These two aspects may be separated for the sake of analysis, but in the effective pedagogical use of the TE the scientific element is embedded within the story and both are necessary.

A THOUGHT EXPERIMENT EXPRESSED AS A STORY

To test the hypothesis that TEs can be constructed as genuine stories, I have written a story about an episode in the life of Ben Franklin (1706–1790). It is based on experiments that Franklin conducted and what is known about his life, at the time (Cohen, 1966; Heilbron, 1979). Franklin designed an experiment to determine where electrical charge, which he considered to be a fluid, resided in a Leyden jar condenser. The first version of the Leyden jar consisted of a water–filled glass medicine bottle with a stem (a nail placed into the bottle). The electrician charged the bottle by induction by holding it in the hand and touching a charged glass rod to the stem. It is known that Franklin experimented with such arrangements around 1747 in order to formulate his theory of electricity. Franklin likely asked himself the question "What would happen to the charge if I were to replace the water in a Leyden jar with fresh, uncharged water?"

A TE may be elaborated around Franklin's supposed question in the following way:

Assume that charges of the same sign repel, charges of opposite sign attract, and that glass is impervious to the movement of electrical charge, but not to the electrical force. This implies that the charge in a positively–charged Leyden jar resides on the surface—positive charge on the inside and negative charge on the outside—if the jar were charged with a glass rod rubbed with silk. Imagine that you charge the stem of the Leyden jar positively while holding the jar in your hand. If a leaf electroscope is touched to the stem, it would register the presence of charge. If water conducts electrical charge, then the only role of the water is to conduct the charge to the inner surface of the glass. Removing and replacing the water should have no effect. If the leaf electroscope is again touched to the stem, it should again show a charged state.

This TE shows that the role of water in the original Leyden jar is non–essential to the maintenance of its charged state. It led Franklin to construct condensers of other shape and composition. In the re–enactment of the process, the replacement of the water serves as the variational element. The function of the TE is either to show the role of water or to support the underlying theory of electricity. If the purpose is to support the underlying theory, then a RE must follow the TE, since the TE supposes an outcome based on a proposed theory of electricity.

If students are to engage with the Franklin TE, the teacher cannot disclose the fact that replacing the water will have no effect. In the following story version of the TE, the teacher invites the students to provide the conclusion. The teacher might incorporate such a story into a larger account of the history of electricity.

Fire and Water

Ben Franklin was a thinker. Those who did not know him well would not have thought so. One glance at his electrical room, with its Leyden jars, electrical machines, and wires, would have convinced the casual observer that Ben was, rather, a tinkerer, at heart. But now, as was the case nearly every day, with a late dinner under his recently-expanding belt, Ben sat in his favourite chair, staring into the distance. Suddenly, he shuddered as he recalled the force of the shock he had received, earlier in the day, when he inadvertently touched the stem of his most recently-constructed Leyden jar with his finger. How to explain the presence of such a force of electrical fire in such a small jar of water—that was all he could think about, lately. Ben imagined filling the jar, charging it, and measuring its charge with an electroscope. Tonight, he was preoccupied with the question: “Where, exactly, does the charge in the jar reside?” Then an idea struck him—what if he were to empty the water after the jar was charged and replace it with different, uncharged, water? What would the charge on the stem be then? In his mind, he removed the stem and poured out the water without touching anything with his hands. Then he added different water from a tin cup that was not charged. Finally, he replaced the stem, all the time not touching any part with his hands. Now came the deciding moment—what would the electroscope show? Dare he try it? Yes! He knew what to expect. The electroscope touched the stem and voilà . . . a sense of relief flooded his mind. It was just as he had expected. Ben Franklin shook himself out of his daydream. Could he devise a way of actually replacing the water in his Leyden jar? Only the next day would tell.

It is possible to represent the heart of the Franklin story by means of a minimal story sequence, as follows:

Initial state: the Leyden jar is charged [and then]

Action: the water is replaced with uncharged water [and then, as a result]

Final state: the Leyden jar is/is not charged.

Clearly, the sequence lends itself to re–enactment. The student may offer a tentative model for the process in order to arrive at a trial solution. Ultimately, however, students must follow this TE by a RE in order to arrive at a conclusion about the validity of their personal model of electricity. Although group discussion may be useful in helping students clarify their solutions to the TE, it is, by itself, not likely to result in genuine learning. This assumption rests on my earlier observation that student activity facilitates genuine learning. Classroom discussions do not have nearly the same impact on learning as student laboratory investigations designed to test the students’ own hypotheses (Westbrook & Rogers, 1996).

It is clear that it is possible to express TEs either as arguments or as story–narratives. In the normally–expressed form of TEs, the narrative element is extraordinarily sparse in nature.

The sparse narrative characteristic encourages the experienced scientist to infer the solution with confidence. The student, however, who is, at best, a novice scientist, will require guidance in constructing a solution to the TE and even more assistance in developing a good understanding of that solution. For that purpose, the story form of the TE is more appropriate. Furthermore, the pedagogical TE will often result in a confirmatory student investigation.

Conclusion

I began this paper by pointing out the convincing nature of Galileo's famous TE on free fall. Many have found this to be conclusive evidence for rejecting the Aristotelian view. Yet, countless practical investigations of free fall have followed Galileo's argument. Einstein's TEs on the speed of light are illuminating and suggestive of the special theory of relativity. Yet, their convincing nature has never prevented physical experimental investigations from being carried out. There has probably never been a TE in the history of science that has not inspired at least someone to attempt a real experimental investigation to test the theoretical conclusions of the TE, further. In science education, TEs, similarly, serve as a stimulus towards further investigation of the concept involved. Further investigations of concepts need to be largely student–initiated in order to encourage genuine learning.

Given that TEs are to serve as stimulus, how are teachers to present them to students? I have argued that TEs are best rewritten in a story–narrative fashion so that they can encourage active student engagement and result in learning situations that support the creation of significant student understanding. The history of science can provide such stories as in the Franklin example I have constructed. In other instances, Machian "thought assignments" can be rewritten so as to place on them a human face.

TEs can have a wide range of characteristics. In every instance, however, they must encourage mental re–enactment of the thought–experimental situation and they must employ special features in order to produce a higher than ordinary degree of conceptual clarification. The dominant characteristic of TEs is the sparse nature of their communication. Andrew Harrison remarks that "mostly, their being sparse is honoured by the philosophically resonant concept of idealization: idealization directs us towards mathematical, or at least conceptual abstractions, thus teaches us what is truly conceivable behind the veil of the merely imaginable" (Harrison, 1997, p. 169).

Can thought experiments be used profitably in the classroom? Miriam Reiner (2000) and others have already provided evidence for a positive answer. Ultimately, the most productive method of harnessing TEs for pedagogical purposes will capitalize on their underlying story–like nature. However, in order to achieve this, TEs need to be re–fashioned into explicit story–narratives from their original skeletal form.

Notes

[1] Michael Matthews brought to my attention the existence of Mach's thought problems and Nahum Kipnis kindly supplied examples from which the problem used is taken.

[2] Arthur Stinner suggested this problem to me.

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