Chapter 10

The teaching of thermodynamics today

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Abstract

Although there are several robust theories of 'thermodynamics' operating very successfully over a range of different disciplines, for example, biology, chemistry, geoscience, quantum theory, astrophysics and numerous associated technologies, there are still no unifying foundations for this most important branch of science. Yet, most elementary thermodynamics is taught from an unjustifiable assumption of consistency and certainty. The current inconsistencies that permeate the science community's thinking about 'heat' first appear at the time of Kelvin. This chapter traces some of the early attempts to formulate a theory of 'heat' and indicates a way in which we can improve our approach to the teaching of elementary thermodynamics by attempting to empathise with Kelvin's perspective.

1 Introduction

Heat is a very tricky thing. During the first half of the nineteenth century, despite an industrial revolution powered by coal and the steam engine, the study of heat (thermodynamics) was in very poor shape. Most modern periods of intense technological changes – such as those caused by the introduction of the motor car, the microwave oven, the Internet or the mobile phone – have a science which precedes and drives invention but, peculiarly, this was not true during the development of the steam engine.

Natural Philosophy (Science) was floundering to find a convincing account of the steam engine, and the threads of an understanding only began to come together around 1850. William Thomson brilliantly wove them into the first 'complete theory of the motive power of heat' in his paper of March 1851, 'On the Dynamical Theory of Heat' [1].

2 The technological context of Thomson's 1851 paper

It might be useful to remember that previously, in the sixteenth and seventeenth centuries, the ground water that drained into mining excavations was the major problem facing European industrial development. A typical excavation would have to raise ten times as much water as it did coal or ore. Particularly where coal was easily to hand, the question arose: maybe coal as fuel could be used to raise water?

In this respect, three significant technological developments took place between 1700 and Thomson's 1851 paper: First, in 1702, Thomas Savery [2] introduced his 'Miner's Friend'. Steam

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was introduced into a large egg-like chamber which, when externally dowsed with cold water, sucked mine water up from the floor of the mine. More steam was then pressured into the chamber, forcing out the mine water up to the surface. Unfortunately, it used a lot of coal and it was prone to explode.

Thomas Newcomen [3], on seeing the shortcomings of the Miner's Friend, introduced an enormously improved engine in 1712. It rocked an 8-m lever attached to a conventional stirrup pump. Steam pushed a piston which moved the lever up. Cold water was then flushed into the steam-filled piston chamber, causing the cylinder to contract and the lever to be drawn down. It consumed only a third as much coal as did the Miner's Friend.

Technical improvements continued but a third (and revolutionary) breakthrough came when James Watt [4] realised that the repeated heating and cooling of a chamber was somehow wasting heat. In 1769, he patented an engine that kept the hot chamber warm by flushing the steam into a second chamber before dowsing it to pull the piston back. The scientific principle underlying this leap forward was not really understood for another 50 years or recognised for a further 30 years but, more importantly at the time, this engine used only half the fuel of a Newcomen engine (one-sixth as much as the Miner's Friend).

3 The 'scientific' context of Thomson's 1851 paper

Throughout the eighteenth century, there was still no science or theory to help move the technology along. In fact, the scientific community was still arguing about the nature of heat. In the seventeenth century, Francis Bacon had described heat as quiddity in motion [5] ('quiddity' being used with its Aristotelian meaning as the 'what-it-is-ness' or essence of matter) and both Galileo and Newton, in the eighteenth century, thought heat to be the frictions and movements of tiny particles of which matter is made. However, many scientists/thinkers of the time believed heat to be an indestructible substance – The Caloric – which flowed like a liquid through all matter and from warmer bodies to cooler ones. Wood and coal were believed to have plenty of Caloric, somehow 'frozen' within them, which was released only when they burned. In 1799 Humphrey Davy, arguing for the Bacon camp, described an experiment where he melted two blocks of ice by rubbing them together [6]. Since ice was supposed to be water with its supply of Caloric largely depleted – what could be melting the ice?

But it was Sadi Carnot, a theorist in the Caloric camp, who presented the first incisive analysis of the workings of the motive power of heat in 1824 [7]. His idea was to analyse the changes which took place in a piston chamber as some combination of two separate processes. The first process was the addition of heat (whilst allowing the expansion to push the piston out enough to keep a constant temperature in the chamber) – and, when harnessing the resulting piston movement – to get some work done. The second process was allowing the chamber to expand and reduce its pressure (but allowing no heat to leak in or out of the chamber) – and again getting some work done.

Both these processes (heat change/pressure constant and pressure change/heat constant) are 'reversible' – an important concept in understanding thermodynamics. The first can be reversed by gently pushing on the piston while allowing heat to drain out of the chamber. This gets everything back to where it started. More importantly, it requires exactly the same amount of 'work' to reverse the process as we could have harnessed from the process in the first place. The second process can be reversed by compressing the chamber and increasing its pressure, but not allowing heat to leak out – again it requires exactly the same work to reverse this process as could be harnessed from it in the first place.

Carnot went on to design an engine 'on paper' that completely separated these processes in time. It cycled continuously through four stages: (i) allowing heat into the piston chamber; (ii) allowing the expansion to continue; (iii) cooling the chamber and (iv) allowing the contraction to continue. His engine worked between two heat 'reservoirs' – the heat source and the cooler environment – and it would produce work by virtue of the transfer of heat from the source to the environment.

He then imagined a second engine of identical manufacture driven at the same speed but driven in reverse – it would 'consume' work to carry heat from the environment and back to the heat source. This was an ingenious thought experiment that had the work output of a heat engine harnessed to and driving a reversed engine; together maintaining some kind of heat equilibrium with nil overall work output.

Now comes a surprising implication: If it were possible to have an engine more efficient than a reversible engine – then only a part of its output would be necessary to power Carnot's reversed engine – thus, the heat lost from the source could be infinitely replenished by the reversed engine while the surplus work from the more efficient engine could be infinitely harnessed. Carnot sensibly decided this to be impossible and concluded that a reversible engine must be the most efficient possible. He also concluded that for an engine to work, it is necessary for heat to go out into the environment (be 'dumped' or wasted). His work explained why James Watt's engine was so successful.

However, Carnot's masterpiece of scientific thought was not immediately recognised as such. The French Revolution had given rise to an elite republican generation of mathematicians and scientists (Ampere, Cauchy, Fourier, Gay-Lusac, Poisson, etc.) through the Ecole Polytechnique [8], but they were seen from the other side of the English Channel as somewhat arrogant and over theoretical – especially in the ultra-practical field of engineering.

4 Enter Thomson

William Thomson, on the other hand, admired much of France's achievements. He started at Glasgow University (at the age of 10) where there was a strong interest in the French approach to mathematics and science. When he entered Cambridge (age 17) in 1841, his first published paper was on 'Fourier's expansions of functions in trigonometrical series' [9]. After he left Cambridge, he studied in Paris where he began to work in the physical laboratory of Henri-Victor Regnault and where he began to publish his mathematical works in the *Liouville Mathematical Journal*. When he was elected as a professor of natural philosophy at Glasgow University in 1846 (age 22), he continued to keep an eye on developments in mainland Europe.

Meanwhile, in Britain, James Joule had demonstrated that work could be converted to heat in a consistent way [10]. Although he had published his early results in 1843, he was finding it difficult to be taken seriously. It would have been especially difficult for Thomson to accept that heat and work were somehow equivalent, for which he would have had to abandon his understanding of Carnot's work based upon the theory of indestructible Caloric.

Then, in 1848, Thomson publishes an astounding paper – 'On an Absolute Thermometric Scale' [11]. In this paper, Thomson explains that the problem of measuring temperatures may have been largely solved to all practical purposes. However, because every material used in thermometry behaves with a different heat uniformity, there is no sound theoretical basis for choosing one thermometer over another. He suggests that instead of measuring material expansion, thermometers should be calibrated by determining the amount of work that an idealised Carnot engine can produce from a one degree temperature difference.

In this paper, Thomson feels the need to educate his erudite audience (the Cambridge Philosophical Society) with a description of a Carnot's work. Therefore, it would seem that Thomson had not only come down on the side of Carnot and the Caloric, but that he was using the theory to shore up structural defects in current understanding. Of particular note is his comment that 'the conservation of heat (or caloric) into mechanical effect is probably impossible'. Much as no actual water is lost when a water–wheel produces energy, it would be Carnot's fundamental assumption that the movement of Caloric from a warm reservoir to a cool one would conserve Caloric, even though 'mechanical effect' could be obtained.

However, in a footnote to this comment Thomson states, 'This opinion seems to be nearly universally held by those who have written on the subject. A contrary opinion, however, has been advocated by Mr Joule of Manchester; some very remarkable discoveries which he has made with reference to the generation of heat by the friction of fluids in motion …'. In Joule's view, a steam engine worked by converting some of the heat into 'mechanical effect'. The two theories the Caloric and Joule's 'dynamical theory of heat' were quite incompatible. But this footnote indicates that Thomson was actively, cognitively challenged by the juxtaposition of two seemingly irreconcilable points of view.

5 Death of the Caloric

In early 1850, Rudolph Clausius published a paper 'On the Moving Force of Heat' [12] in Germany, abandoning the Caloric theory. Clausius accepted Joule's results and rejected 'the conservation of Caloric' as a false assumption. He replaced it with 'the conservation of energy' and proclaimed it as the first law of thermodynamics. And he proclaimed the tendency of heat to flow from hot to cold bodies as the second law. However, and significantly, he shows that Carnot's analysis – that no engine is more efficient than a reversible engine – is completely compatible with both these laws.

It is difficult to know at what point Thomson came to the same conclusion – that it was possible to ditch the Caloric but still to keep Carnot. In terms of 'publication', he was clearly beaten to it by Clausius. In his ground-breaking 'On the Dynamical Theory of Heat' [1] presented to the Royal Society of Edinburgh in March 1851, Thomson says 'I may be allowed to add that I have given the demonstration exactly as it occurred to me before I knew that Clausius had either enunciated or demonstrated the proposition'.

Thomson's 'dynamical theory of heat' is founded upon two propositions. First, he attributes to Joule that when work (or mechanical effect) is lost, an equal quantity of heat must be generated somewhere. If work is gained, an equal quantity of heat must be 'put out of existence'. This is an exact (but still clumsy) expression that 'heat is energy' and that 'energy is indestructible'. Attributing to this first principle, his new theory of heat to Joule was an act of fine diplomacy.

Such diplomacy was not lost on Joule who was at last able to join the top echelon; he and Thomson went on to collaborate fruitfully with one another over the next few years.

The second proposition he attributes to Carnot and Clausius that no engine can be more efficient than a reversible engine. This was Carnot's *deduction* from his analysis of heat reservoirs and reversible processes – he did not consider it to be a fundamental principle. Neither did Clausius, who was able to make the same deduction from his two laws.

Even if this was 'exactly as it occurred' to him, his decision to publish this in a quite way can be seen as an act of finely judged politics. Thomson had nailed his colours to Carnot's mast when he proposed his Absolute Thermometric Scale [11] and declared himself a 'Calorist'. Clausius had rescued Carnot from the wreckage of Caloric theory and Thomson was in danger of appearing to need to cling to the same life-ring. Thomson's paper pre-empted any such problems. What it did was to reconcile the new dynamical theory with the best of the old – to make sense of all previous findings – and to raise Carnot's insight above that of Clausius' and to reprieve himself.

Clausius, however, was convinced that he alone had founded thermodynamics and went on over the next two decades to make further ground-breaking contributions, insights and clarifications to a new and successful theory of heat.

6 The second law of thermodynamics

Both these original formulations – by Clausius and by Thomson – of 'the second law of thermodynamics', apparently quite different and unleashed onto the world within months of one another, have weaknesses or drawbacks (and we look at them more closely below). First, however, it is worth making a few comments – from a modern perspective – about that physical phenomenon we call 'the second law'. A 'law' is really only a belief (strongly supported by observation) which, by virtue of its fundamental nature, is given the working status of 'absolute truth' by the scientific community.

In very loose terms, the second law promotes the belief that although the energy around us can be found in concentrations, over time, any such concentrations will tend to disperse. If we (or natural forces) do succeed in collecting energy together by some kind of process, this must be at the expense of some greater dispersal of energy elsewhere. Energy is never destroyed – it just becomes more and more 'dispersed'. For instance, oil or coal is a concentration of stored energy, but the biological and geological processes involved in its formation – of photosynthesis, of building sugars and proteins, of subsequent rotting and geological compression – must (according to this law) disperse more energy than can be stored.

Scientists use the term 'work' for energy employed to lift a weight or to set something in motion. Work is directed energy and, therefore, considered to be equivalent to concentrated, well-ordered energy. When an 'engine' converts heat energy into (concentrated) work, an even greater dispersal of energy must also be taking place, somewhere in the vicinity. Basically, some quantity of unconverted heat energy must be allowed to 'waste away' into the cooler environment – and no matter how inventive we become, any further attempt to 'harness' that wasted energy will result in some yet greater dispersal. It is natural for engineers to see this 'throwing heat away' as an unfortunate reality but, if it were possible to convert heat into energy without waste, then, as Carnot's own proof demonstrated, it would be possible endlessly to concentrate energy and, indeed, to create energy and matter.

Shortly after the events we have described, Thomson published 'On a Universal Tendency in Nature to the Dissipation of Mechanical Energy' [13] in 1852 (where in the introductory passage, Thomson again invokes Carnot as the primary source of thermodynamic thinking). This paper begins a discussion of startling implication; that the universe is irrevocably heading towards a state of total dispersion, which was to be known by the 1860s as 'the heat death of the universe'.

One way to quantify this 'dispersion of energy' during a transfer of heat is with some quite simple arithmetic – by dividing the transferred heat by any temperature change. This measure of dispersal is called 'entropy' (as named by Clausius in 1865 [14]). Indeed, any physical object that has measurable properties like 'volume', 'mass' and 'temperature' can also have measured 'entropy'. When we first pour cool cream into hot coffee, both the cream and the coffee have a distinct temperature and entropy. Adding the entropies gives the combined pre-mix value – but as the cream diffuses into the coffee, and some heat leaves the coffee to enter the cream, the measurable entropy of the mix increases. The total 'dispersion of energy' in the universe has increased – according to its natural tendency.

7 Flawed lawmaking

Clausius' original formulation of the second law, which heat will never spontaneously move from cool to warm bodies, is superbly clear and very easy to understand – but it hides a circular assumption. The relative warmth of two bodies is measured by their temperatures – and a temperature is a measure of a body's propensity to disperse energy. This version of the law can, therefore, be read as 'the body with the greater propensity to spread energy will spread its energy' – which really says nothing at all. By 1865, Clausius had overcome this difficulty with a new statement of the law; that 'the total entropy of the universe tends towards a maximum' [14]. The heat energy in the mug of coffee, as described above, very quickly reaches its maximum dispersion.

Thomson's original formulation (that no engine can be more efficient than a reversible engine) is not quite as simple as Clausius' original formulation. (For the novice student, it would require them to already know about the workings of a heat engine and to understand the concept of reversible process.)

Thomson's formulation is also blemished by a logical problem. It is based upon an ideal (the reversible process) which, according to the law it attempts to define, cannot exist in the real world. Of course, many physical laws only describe behaviour in an ideal situation (if only we had frictionless surfaces, perfectly elastic bodies or 100% vacuums). However, it is the presence of the second law of thermodynamics, solely, which 'spoils' the perfect operating conditions for all these other laws (for instance, if we strike an elastic body it causes an energy transfer and some energy must be lost to dispersal; if we try to create a vacuum there will be a tendency for energy to disperse itself into the vacuum, riding on material bumped off the container walls). To say, 'this particular law works perfectly – if we disregard the effects of the second law of thermodynamics' is quite reasonable because we specify laws in order to help us analyse and separate physical effects. But, to say 'the second law of thermodynamics works perfectly – if we disregard the second law of thermodynamics' is suspect.

Some workers in the field, notably Max Planck [15] in 1897, have tried to keep something of Thomson's formulation, but with the reliance on 'reversibility' removed, by going back to the 1851 paper 'On the Dynamical Theory of Heat' [1]. In this paper, Thomson presented a common sense notion: that no engine could produce work solely by taking heat from the coolest surrounding objects. He then showed that his (reversibility) formulation is the equivalent of this notion. Planck, in 1897, tweaks Thomson's 'common sense' and provides a 'new' formulation of the second law which he credits to Thomson: it is not possible to take heat from a single reservoir and produce work (without dumping some heat at a lower temperature). This became known as the Kelvin-Planck formulation – despite the fact that Carnot made exactly this deduction in 1824.

Today, we have a veritable plethora of ways to view the second law. In 1877, Ludwig Boltzmann gave us a new and completely different perspective on thermodynamics [16]. By treating the heat energy in an object as the aggregate of the small individual energies belonging to a large collection of components, it is possible to use statistical measures of dispersion to represent energy dispersion. In the same way that if a coin is tossed 100 times, getting around 50 'heads' is far more likely than getting near to 100, the most likely distributions of energy are those where the energy is spread evenly through the object. Boltzmann saw the universe's tendency for 'entropy to increase to a maximum' as a tendency for things to shift towards their most likely statistical outcome. Needless to say, in common with the other formulations discussed, a logically satisfying link between statistical dispersion and heat dispersion has yet to be found.

Strangely, despite the situation today where we have no secure or unifying formulation of the second law, there is complete agreement that, however, we might eventually come to formulate it; the second law is a basic foundation stone upon which we must build our understanding of the physical universe. Therefore, imagine a bottle of milk left to stand. Many physicists will see that, as the milk organises itself into cream and whey (losing entropy in the process by 'un-dispersing'), there must be a greater dispersal of heat energy (which is probably radiated away into the environment). Astrophysicists, on the other hand, will choose Boltzmann's perspective and see the gravitational clustering of particles of cream as a more likely outcome, and see the bottle gaining entropy. Their observations and energy calculations will agree. They will both believe that, according to their own standards, the total entropy in the universe will have increased. But they will not agree about whether the new arrangement within the bottle has greater or less entropy.

8 Returning to Thomson's formulation

Therefore, in this context, let us turn to the question how thermodynamics should be taught today, and to what extent Thomson's formulation is of value. We feel that a modern approach to elementary thermodynamics, which looks to the need to educate (rather than being over-concerned to rationalise its choice of foundations), should be based upon the following rules of thumb (each of which we justify below):

- Keep (or reinstate) the heat engine
- Discard attempts at logical consistency
- Use reversibility only as a model

8.1 Keep the heat engine

As we have indicated above, Thomson must have thought long and hard before selecting and presenting his two ‘propositions’ for the 1851 paper [1]. He would have been acutely aware that his second proposition (that no engine can be more efficient than Carnot’s ideal engine) was not very ‘elementary’. Clausius’ earlier, parallel proposition (that heat energy naturally moves from hot to cold) does not refer to ‘engines’ and is clearly a statement about heat, pure and simple. It would seem that Thomson wanted the new science of heat to incorporate some notion of ‘transformation’ – between heat and work. Indeed, he described his theory as one of ‘the motive power of heat’.

Today, at least one school of thought believes that, in an attempt to clarify thinking, students should be told that physical objects have intrinsic energy, one aspect of which is their ‘internal energy’. They should not refer to this ‘internal energy’ as ‘heat’; instead, that word should be reserved to measure a ‘transfer of internal energy’ (when the process of heating/cooling takes place’). An engine may transform ‘internal energy’ into ‘mechanical energy’ – but not into ‘work’; that word should be reserved to measure a ‘transfer of mechanical energy’. All four concepts are measured in ‘Joules’.

Everyday language usage frequently militates against applying this refinement with precision. However, whether we use language with precision or not, it is important that we do not lose sight of the magic that happens when heat is turned into work. Many of us see the pistons in an internal combustion engine (and the steam engine before it) as being driven by a series of small explosions – clever, but quite prosaic. If it were as simple as that, these engines would be about as efficient as the Miner’s Friend. A piston under pressure moves in only one direction and, therefore, is a kind of filter. It acts to extract a single directional component (work) from all of the randomised (heat) energy on either side the piston. Thomson’s principle tells us something about maximising this process.

With today’s economic and environmental concerns about energy, it is even more important that our technologists understand its nature. In temperate climes, our individual energy needs tend to be twofold; we need randomised energy (warmth) and organised energy (work). Work is even needed to drive our computers, TVs and music systems, in order to create a voltage. Individually, we tend to spend more money on heat than on work. But when heat is turned into work (usually to generate electrical power) a significant quantity of heat has to be dumped directly out into the environment. Our motorcars dump *all* of their heat.

Some of us employ electricity (which has come from heat, and much heat was dumped in its production) to generate heat in our homes. We could employ a cheap-to-run ‘reversed engine’ to retrieve energy from the cooler environment and use that to heat our homes – but, in general, we do not. We do not recognise, as Carnot did, that any ‘temperature gradient’, where we allow heat to spread of its own accord down our corridors or out through our walls and roofs, is a lost opportunity.

In short, the magic of the heat engine should be emphasised, not only to challenge and inspire students, but to throw a stark perspective upon the way in which energy around us is utilised.

Thomson, standing at the leading edge of thermodynamic understanding, was aware of the miraculous nature of the heat engine. He chose to keep it as a central principle for understanding the ways of energy and we, maybe for quite different reasons, require that perspective even more today.

8.2 Discard attempts at logical consistency

It is partly because Thomson introduced his second proposition in the face of Clausius that modern thermodynamics is still pre-occupied by the logical equivalence of alternative propositions. A greater reason for this pre-occupation is that we still do not understand the nature of the universe's predisposition to spread its energy and, in denial of this, we cling to pet rationalisations that appeal to some of us, but rarely have more than conventional acceptance. And we visit this rehearsal of historical argument and preferred treatments on to our students.

We frequently run the risk of losing students by introducing pedantry before any need for language precision is clear and then insisting on the performance of logical exercises to satisfy some kind of external standard, usually before immature young minds can grasp their sophisticated abstraction. Thermodynamics can be a lot easier than we make it, and a lot more fun.

It is interesting that Thomson did not try to present a logically complete structure when he presented his two propositions. Mainland European science is often characterised by British commentators as being over-theoretical and it is true that, in this case, Clausius had attempted to present a grand theory of thermodynamics, looking rather like Euclidean geometry, based upon 'laws' and their logical progeny of theorems and demonstrations.

Thomson, with his admiration of French mathematics and science, was well aware of this tradition. Indeed, Carnot's beautifully created arguments and his theoretical heat engine were, in this sense, typically European. However, Thomson's real genius depended upon a quite different approach. He recognised that real progress could be made by facilitating conversation between theory and practice, and he had a special gift for this. He was principally a theorist, but he did not despise practical experiment – he positively encouraged it. His collaboration with James Joule is one example of his approach but, well before that, he had been instrumental in ensuring that laboratory work was known to all 'natural philosophers' coming through the University of Glasgow.

His 1851 paper [1], could be summarised as: 'here are two propositions, which common sense should persuade us to accept, upon which the whole of our understanding of motive power can be based – and here is the experimental data to support this assertion'. He does not call them 'laws' but he does present Carnot's arguments to reinforce our 'common sense'. He uses the power of argument but does not strive for any kind of axiomatic structure or logical completeness.

The second law of thermodynamics still hides a deep truth about our universe which we have not yet penetrated. Until we do, we should not pretend that we have a complete theory of thermodynamics and should not cover for our own lack of understanding by pretending sympathy for the student's confusion. If we present weak, unsubstantiated arguments, then good students should be confused! Instead, let us find ways to talk about second law phenomena, which can improve a student's understanding of what we do know, and instil a genuine fascination for a scientific mystery which is yet to be solved.

8.3 Use reversibility only as a model

In his 1851 paper, Thomson also uses an alternative form of his second proposition (namely, that it is impossible to obtain work from heat by cooling the coolest reservoir in the vicinity). In later years, as we described above, Max Planck developed this idea to formulate what was to become known as the Kelvin–Planck statement of the second law (that it is impossible to obtain work from heat without the existence of a cooler reservoir – in which to dump some of that heat).

Planck went much further and developed a theory which placed the concept of 'reversibility' at the centre of understanding the nature of thermodynamics. Much of British thermodynamics teaching throughout the twentieth century has had this concept at its heart. It might be possible to characterise the difference between Planck and Kelvin in this respect by saying that Planck envisaged circumstances where reversibility was possible (and, consequently, this is still the position of many working engineers today), whereas Thomson saw Carnot's engine more as an ideal to indicate the limits placed upon heat phenomena.

There is some justification for making this characterisation when we look at Thomson's earlier 1849 paper on thermometry [11]. He makes it very clear from the outset that his 'absolute temperature calibration' (which could be determined by placing Carnot engines between a series of heat reservoirs one degree apart) would not provide a better thermometer than already existed. Thomson saw the Carnot engine (and the reversible process) as a tool for thinking about and understanding heat – not as a realistic proposition. Considerable experimentation with various gas thermometers had already provided us with a high degree of confidence in our measurement of temperature; what Thomson did was to provide a theoretical basis for that confidence. In that paper, Thomson suggests experiments to test his theory, but not to develop a better thermometer.

This is 'science as model-making' at its best. Most of us, when we use the term 'degree Kelvin', or 'absolute temperature', see it as interchangeable with the 'degree Celsius' (or 'centigrade' – as it was known in Thomson's time); it is just a question of where the zero lies. However, it can be argued that, whereas the degree Celsius represents temperature seen in terms related to the mean behaviour of expanding substances, the degree Kelvin is a measure which stands outside physical analogue and one which is based upon a Carnot model of the world.

In our teaching, we should celebrate these kinds of opportunities to uncover the nature of scientific thinking. Instead of presenting the second law as 'given', and routinely expounding on its implications, we should say 'this model represents what we think is going on – it is well tested but, even now, we do not have certain proof'.

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