The Teaching of Thermodynamics

5th December 2012, IOP Higher Education Group Meeting, Institute of Physics, London

Last December's meeting of the Higher Education Group focused on the teaching of thermodynamics. The programme was organised jointly by me and *Professor Brian Cowan*, from Royal Holloway. Brian has taught thermodynamics and statistical mechanics for many years and, like many of us, has spent much of that time grappling with the subtleties, inconsistencies and conceptual difficulties of this field. He opened the programme with a presentation addressing the question of whether the teaching of classical thermodynamics and statistical mechanics should be integrated or not. Brian wittily proffered a caution that thermodynamics can be bad for the health, citing as evidence the unfortunate and untimely demise of people such as Ludwig Boltzmann, Paul Ehrenfest and others. However, Brian's answer to the underlying question of whether we should regard thermodynamics as distinct from statistical mechanics was quite unexpected. He suggested that, as modern treatments of thermodynamics have moved on from the classical approach favoured by the likes of Zemansky to include the non-affine geometry of first Brillouin and later Lieb and Yngvason, statistical mechanics is now conceptually easier than thermodynamics and, if anything, it is thermodynamics that should be taught as advanced material.

A different view was presented by *Jeremy Dunning-Davies* (Hull), with whom I have worked closely in recent years. Jeremy is a mathematician who researched for his PhD under Peter Landsberg. As a mathematician he taught thermodynamics to mathematics students for many years at Hull before moving over to physics towards the end of his career. Jeremy is therefore well placed to provide an insight into the different ways that students of these two disciplines regard the subject, and in particular entropy. Entropy is widely regarded by physicists as a mysterious quantity, but not so by the mathematician, for whom entropy appears as a mathematical consequence of finding an integrating factor for the inexact differentials within the First Law. For the student of mathematics, then, the physical interpretation of entropy is not something that causes any concern. For the students of physics, however, the small matter of just what entropy is looms very large. Jeremy focused very much on the classical view of thermodynamics and the Second Law in particular. Both Kelvin and Clausius stressed cyclic processes in their formulations of this law, and basing a course on thermodynamics on cycles sidesteps the question of the meaning of entropy to a great extent: entropy is something that is conserved in an ideal reversible cyclic process but not in an irreversible cyclic process. Of course, Clausius later went on to extend the Second Law to non-cyclic processes and thus the idea that entropy always increases, along with much of the confusion in thermodynamics, was born.

The question of just what entropy is cannot be answered with reference to thermodynamics alone and *Professor Ian Ford*, from UCL, offered a statistical view based on information theory. The notion that entropy is a measure of disorder is very common, but incorrect when considered in the light of information theory. Ian's message was that entropy is associated with uncertainty, which comes from the idea that entropy is a property of a probability distribution rather than a particular arrangement of the constituent particles. The recourse to probability to describe the microscopic properties of a material arises through a lack of knowledge about the arrangement of its constituents rather than the arrangement itself, so information entropy is very clearly associated with uncertainty. Still on the theme of entropy, *Professor Mick Brown*, from Cambridge, gave a short presentation on entropy and self-organised criticality in which he used the working of ductile metals to illustrate the doctrine of maximum entropy. In essence, complex mechanical systems tend to maximise the number of pathways available in response to large external forces, hence the entropy is maximised.

Following lunch, *Charles Tracy*, Head of pre-19 education at the Institute, gave a presentation on ideas being formulated about the teaching of energy in schools. There is growing concern over the inconsistencies in terminology and usage of the word 'energy' among different sciences within schools. Charles demonstrated some of the confusion that can arise and welcomed the opinions of the audience on some of the ideas being developed. This was a very interesting and stimulating contribution and possibly provides a model for future consultations of this sort.

Sarah Harris, from the University of Leeds, then gave what was universally agreed to have been a most inspiring talk. Sarah's interests lie in the physics, and especially the thermodynamics, of large bio-molecules and she showed how these can be used to illustrate some basic ideas in thermodynamics. The one disadvantage to this approach is the need for the very large computing resources that are used in this research area, so if this kind of material is to be used in teaching it will be necessary to generate resources that can be used independently of the research being undertaken.

I closed the meeting with a presentation on the statistical interpretation of entropy and how I think it should be taught. I have had a deep mistrust of some of the foundations of thermodynamics for a number of years now: I don't believe, for example, that there is any justification for believing entropy to be a property of a body. This was, I believe, an error of Clausius' that was never properly scrutinized at the time and which has simply come down to us as a "fact" supported by several unfortunate coincidences. In consequence, inconsistencies can be found throughout thermodynamics and statistical mechanics. One such concerns the famous Gibbs paradox of the entropy of expansion. Actually, it is not a paradox in the true sense of the word, as the inconsistency is not internal. Two very different things, statistical and thermodynamic entropy, are being compared, but rather than recognise that perhaps this points to a fundamental difference between the two, attempts have been made to fix the paradox by making the entropies agree. This is the point about Clausius' error: if entropy is not a property of a body, there is no thermodynamic entropy and therefore nothing with which to compare the statistical entropy. I showed that if one considers physically representative distributions, that is, distributions containing a density of states characteristic of the system, which the canonical distribution does not, the statistical entropy contains apparently non-thermodynamic terms. I finished off with the conclusion that entropy is a very important property of statistical distributions, but it should be taught as such within statistical physics rather than thermodynamics and statistical mechanics.

The feedback from participants indicated that the meeting was very interesting and stimulated a lot of thought. As the various presentations showed, there is a lot of confusion, misunderstanding, as well as different, and strongly held, opinions within thermodynamics. I was surprised that I received no argument, even to my assertion that the most common derivation of the canonical distribution is fundamentally flawed in as much as a fluctuation in entropy is assumed in order to derive the distribution when in fact the entropy contains no terms that fluctuate. Whether the day caused anyone to change their approach to thermodynamics or their teaching of it I wouldn't care to say, but it was a lively and very enjoyable meeting and gave rise to a lot of things to think about, even for a sceptic like me.

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