Discussion on "Foundations of the Second Law"

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Abstract. This article reports an open discussion that took place during the Keenan Symposium "Meeting the Entropy Challenge" (held in Cambridge, Massachusetts, on October 4, 2007) following the short presentations – each reported as a separate article in the present volume – by Seth Lloyd, Owen Maroney, Silviu Guiasu, Ping Ao, Jochen Gemmer, Bernard Guy, Gian Paolo Beretta, Speranta Gheorghiu-Svirschevski, and Dorion Sagan.

All panelists and the audience were asked to address the following questions

- Why is the second law true? Is it an inviolable law of nature? If not, is it possible to develop a perpetual motion machine of the second kind?
- Are second law limitations objective or subjective, real or apparent, due to the nature of physical states or the representation and manipulation of information? Is entropy a physical property in the same sense as energy is universally understood to be an intrinsic property of matter?
- Does the second law conflict with quantum mechanics? Are the differences between mechanical and thermodynamic descriptions of physical phenomena reconcilable? Does the reversible law of motion of hamiltonian mechanics and quantum mechanics conflict with the empirical observation of irreversible phenomena?

ROBERT SILBEY: So far I didn't hear a lot of common ground from the nine speakers. So maybe we can have the audience get in on this. And then maybe the speakers can start fighting among each other.

STEVE FREEDMAN : I'd like to make a comment leading to a question. One word that I didn't hear in any of the speakers' presentations was the word temperature. Now there are several of us with gray or missing hair who remember the good old days and Keenan's 1941 book, which is entirely classical continuum thermodynamics, and which involves entropy as a property of matter that changes as the temperature changes. And we've got it (temperature) in the first question up there about the PMM2, and I assume

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everybody knows what a PMM2 is. Now, I've been looking at the table up there, and nobody's water bottle separated into ice floating on top and warmer water on the bottom during the half hour or hour that you've been talking about. Most of the presentations are on computational techniques that don't involve temperature. The item that would be most useful for society today, and personally I don't think it exists, is a perpetual motion machine of the second kind. A first kind wouldn't be too bad either. But a PMM2 would be really great. Now, does the computational discussions that most of you, Professor Guy and Mr. Sagan spoke about involve the continuum approach to entropy, as distinguished from the computational approach to entropy from statistical mechanics. Now that I've made my speech the question is, to what extent is the statistical computation dependent upon its own assumptions and is divorced from what you measure with a thermometer?

PING AO : I think I can answer some parts of the comment here, since I had made kind of a big defense on Darwin and Wallace, by stating Darwinian dynamics [P. Ao, present proceedings]. First, I don't believe that the framework of Darwinian dynamics can be classified merely as a computational tool. That is, what discussed by many of us here today are not simply computational tools. So I put this issue aside. And since I claim Darwinian dynamics implies a whole set of dynamics, of course, the very first question one needs to address is about "temperature". So where is the concept "temperature" in this framework? I think the temperature concept in the framework of evolution theory is embedded in the concept about variation [P. Ao, "Emerging of Stochastic Dynamical Equalities and Steady State Thermodynamics from Darwinian Dynamics," *Communications in Theoretical Physics*, in press (2008)]. That means, if you have a noise, and anything similar like that, you've got to define a quantity, whether you call it temperature or not. There is something just like that in there. So basically, I think, the variation itself, as Nature suggests to us, contains something like temperature.

GIAN PAOLO BERETTA: My view of the reason why we're not talking about temperature is that temperature is a property defined only for stable equilibrium states, whereas the main emphasis now in the frontiers of the subject is in studying non-equilibrium states where temperature is not defined.

SILBEY: It's not clear that entropy is defined in non-equilibrium states, either, but we'll keep going. Go ahead.

RODERICH GRAEFF: I agree, temperature wasn't mentioned, and experiments were not mentioned. What we are hearing here are all very interesting theoretical discussions, but we don't hear about experiments. And as Dick Bedeaux said this morning, only experiments can give us final answers.

Loschmidt proposed in 1877 that a rod, a metal rod like this aluminum post before me, would show a temperature difference in an isolated system, cold at the top and warm at the bottom [L. Loschmidt, Über den Zustand des Wärmegleichgewichts eines Systems von Körpern mit Rücksicht auf die Schwerkraft, Sitzungsberichte der Mathematisch-Naturwissenschaftl, Klasse der Kaiserlichen Akademie der Wissenschaften 73.2, p. 135 (1876); Trupp, A., Energy, Entropy: On the Occasion of the 100th Anniversary of Josef LoschmidtŠs Death in 1895: Is LoschmidtŠs Greatest Discovery Still Waiting for Its Discovery?, Physics Essays, Vol. 12, No. 4, 614 (1999)]]. I have a small physics laboratory in Germany where I measure these temperature differences since about ten years, not only in metals, but also in gases and in liquids. I find in very-well-insulated test setups temperature gradients of about ten to 100 mK/meter. [Details in R.W. Graeff, *Gravity Machine*, www.firstgravitymachine.com; R.W. Graeff, Measuring the temperature distribution in gas columns, CP 643, *Quantum Limits to the Second Law*, American Institute of Physics, AIP Conference Proceedings, Vol. 643, New York 2002,] Apparently these are created by the effect of gravity, as the gradients increase proportional to the height of the experiment. This means that I produce energy out of heat bath. Seth (who gets a Nobel Prize for fast speaking, I'm sure) said no to the question, if it is possible to develop a perpetual motion machine of the second kind. Well, my test setups represent, in my opinion, perpetual motion machines of the second kind. Thermocouples in the form of thermopiles produce electricity without the introduction of outside energy, not enough to heat my house, but they demonstrate the principle.

Loschmidt predicted these temperature gradients. Boltzmann calculated for gases that there should be equal temperatures over height, but of course, he calculated only for ideal gases, not for real gases [L. Boltzmann, Wissenschaftliche Abhandlungen, Vol. 2, edited by F. Hasenoehrl, Leipzig, 1909]. And Maxwell stated very clearly, if these temperature differences would occur in vertical columns, it would violate the second law, because you would be able to produce work out of a heat bath [J.C. Maxwell, *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, Vol. 35, 215 (1868)].

My question to the panel is, how do these results fit into your theoretical thoughts?

My interest is also to find somebody here who might want to repeat these measurements in your own laboratory. It's certainly a very exciting and interesting field.

SETH LLOYD : And I will try to speak more slowly. Well, let me paraphrase our moderator here. If it were possible to build a perpetual motion machine of the second kind, I'm rather surprised that Exxon hasn't done this already. I have been involved with quite a few experiments at the very microscopic level, at the level of individual atoms, molecules, photons. These experiments have been mainly to build quantum computers, but we also built a nice little two-spin Maxwell's demon at one point, where we used one spin as the working fluid, and the other spin was the demon that got information about this. In all of these experiments, we find that the laws of quantum mechanics are confirmed. That means that we never find an unexplained decrease in entropy. But we also find that there's no increase in entropy that cannot be explained simply by interaction with the environment. And these experiments are just one out of hundreds of millions of experiments that are done in which the laws of quantum mechanics are confirmed. So I'd actually add my voice to asking questions from some of the other members of this panel, why do you think it's worthwhile to pursue these non-standard versions of quantum mechanics in which entropy increases, when there are no experiments that actually suggest that quantum mechanics is wrong to the slightest degree?

YUNUS CENGEL : I just wanted to make a brief comment on the question whether entropy and exergy are physical quantities in the same sense that mass and energy are. Mass and energy are conserved quantities and are associated with the 1st law of thermodynamics, while entropy and exergy are non-conserved quantities, and are associated with the 2nd law. The big bang theory about the origin of the universe gives rise to the notion that this is a material universe, and everything is made of matter (mass-energy is a better phrase) and matter only. As conserved quantities, mass and energy fit into the description of truly physical properties, but entropy and exergy do not since entropy can be created and exergy can be destroyed. Thus they are not truly physical quantities although they are closely related to the physical quantity energy. Therefore, the 2nd law deals with properties that are of a different kind of existence, and points to a universe that is beyond the material universe we know of. The 1st law of thermodynamics is kind of dull since it deals with conserved quantities, but the 2nd law is exciting since it intrigues the imagination by dealing with properties that are in this world and beyond at the same time. As such, the 2nd law has far reaching philosophical implications. Also, mass and energy – at least some forms it – can be perceived by the 5 physical senses, but this is not the case for entropy and exergy. Let us consider the question "What is 2 + 2?" The 1st law would answer this questing by simply saying 4, using the conservation principle. But the 2nd law will say that the answer can be 1, 3, 4, 7, or something else – with endless possibilities. The 2nd law coincides with the 1st law and gives the answer 4 only for reversible processes. Entropy can be brought into existence from nothing and exergy can disappear into nothingness, and thus they are existences of different kind. The existence of entropy and exergy is not limited by their material existence, and they are at least partially non-matter or meaning. As such, the 2nd law opens a new window for viewing the existence and examining the nature of things. With the 2nd law glasses put on, the universe may look quite different.

MIKE WEISSMAN : This is a comment for response mainly from Dr. Gheorghiu-Svirschevski, and also probably for an opposite response from Seth Lloyd. You raise the issue of whether essentially non-linear decoherence processes could account for second law. And that sounds a little bit ad hoc, except that many people feel that it's hard to obtain the Born rule in ordinary quantum mechanics without adding something. Ghirardi, Rimini, Weber, Pearle and various other people have tried adding non-linear decoherence plus collapse, and David Albert, a philosopher at Columbia, has shown that if you do that, the time reversible dynamics of the collapse lead rather naturally to the second law. Since the collapse is very ugly and hard to reconcile with locality. I've done a version (on the archive: arXiv:quant-ph/9906127, arXiv:quant-ph/0605031) in which you leave out the collapse, so you live with many worlds, but use the non-linear decoherence to generate the right number of worlds to get the Born rule out. It's obviously speculative. So my question is whether you've looked into this sort of stuff, non-linear things that might work for the probability issue as well. And the question for Seth, or really the answer to your challenge, is perhaps every time we measure the Born rule, we're already seeing a violation of strict unitary dynamics in Hilbert space, so in some sense, we may be swimming in violation of those dynamics.

LLOYD: I guess my problem with that is that there are also explanations of the Born rule, there was a rather lovely one by Jim Hartle from about 20 years ago. And then the more recent one by Woijciech Zurek, in which everything –

WEISSMAN: There's an error in his proof.

LLOYD: Which one, Zurek or Hartle?

WEISSMAN: The one where he says he's assuming he had additivity. He's actually assuming context independence, inter-subjective agreement.

SILBEY: Who is he in this case?

WEISSMAN: Wojciech Zurek. He's made many wonderful contributions, but that wasn't one of them.

LLOYD: At least, so let me comment on the Hartle paper at any rate. The Born rule, which says that probability is the square of the amplitude, was a footnote in a paper. One of the most famous footnotes in quantum mechanics. Hartle tried to explain this (and Sydney Coleman worked on this as well) in terms of an ensemble approach. You simply look at the frequency with which these different histories show up in the wave function. And then you get the Born rule. I don't see why some kind of non-linearity or collapse is required for this.

WEISSMAN: To get frequencies in a strictly linear dynamics without some sort of implicit non-linearity from competition with the background is very hard. That doesn't mean that there couldn't be a background and some implicit non-linear competition with it, but that theory has not been worked out, and I don't think that Hartle really –

SILBEY: Are we talking about a measurement of an isolated system? Or are we talking about a measurement of a system which is in contact with the environment, and therefore a macroscopic device, in which there is going to be decoherence, and therefore one can understand the collapse?

WEISSMAN: We're assuming ordinary Schroedinger type decoherence. But the question is whether that gives the right numerosity to account for the probabilities. However, if you have any kind of collapse process, we're assuming something other than unitary dynamics. If you don't have a collapse process, you don't have an extra non-unitary place to insert the Born rule. Then the question is whether the correct numerosities are generated in any natural way.

NIEUWENHUIZEN: Sorry for this, but with my collaborators I worked it out some time ago [A.E. Allahverdyan, R. Balian and Th.M. Nieuwenhuizen, "The quantum measurement process: Lessons from an exactly solvable model," quant-ph/0702135, in *Beyond the Quantum*, eds. Th.M. Nieuwenhuizen, V. Spicka, B. Mehmani, M. Jafar-Aghdami, and A. Yu. Khrennikov (World Scientific, 2007); A.E. Allahverdyan, R. Balian and Th.M. Nieuwenhuizen, "Curie-Weiss model of the quantum measurement process," *Europhys. Lett.* **61**, 452 (2003)]. The Born rule is OK, and the physical reason is that it is based on the connection to what a quantum formalism means for the experimentalist in his lab. And it's just frequencies of occurrences. There is an answer.

SILBEY: OK, so Hartle's proof, and Nieuwenhuizen's proof gives you the answer, Professor Weissman.

JAMES KECK: To come back to the question of temperature, I should point out that the translational temperature does appear in the expression for the Maxwell–Boltzmann velocity distribution. However, in real gases, there is more than one temperature. We have a translational temperature, which describes the translational state, the rotational temperature, the vibrational temperature, and the electronic temperature. These are not necessarily the same. Only if the system is allowed to relax over a long period of time will we eventually end up with a common temperature. One example of a steady state system, in which you can have two temperatures that are vastly different is a fluorescent light, where the electronic temperature is around 10,000 kelvin and the translational temperature of the heavy particles is 300 or 400 K. I think this issue of multiple temperatures is something that has been largely overlooked in classical thermodynamics. However, aerodynamicists who deal with shock waves are well aware of multiple temperatures because behind shock waves there is a large vibrational temperature lag and a corresponding translational temperature overshoot. This is an issue which I wanted to bring up and to point out that. In general, we can have as many temperatures in a single system as there are separable degrees of freedom.

SILBEY: Partially separable.

KECK: Partially separable.

SILBEY: They're not really separable. In the long time limit, we have one temperature. So we have quasi-equilibrium in various degrees of freedom.

KECK: No, they are never really separable, but the separation can be pretty good. We know we have stars at vastly different temperatures.

NIEUWENHUIZEN: I want to make one remark, because it's maybe not well known, but it was already alluded by Owen Maroney in his talk that the Landauer principal is actually a reformulation of the Clausius inequality. And if we have a small quantum system coupled to a bath, then this Clausius inequality can be violated [A.E. Allahverdyan and Th.M. Nieuwenhuizen, "On testing the violation of the Clausius inequality in nanoscale electric circuits," *Phys. Rev. B* **66**, 115309 (2002)]. And an experiment has already been done that confirmed this [A.E. Allahverdyan and Th.M. Nieuwenhuizen, "Breakdown of the Landauer bound for information erasure in the quantum regime," *Phys. Rev. E* **64**, 056117 (2001); A.E. Allahverdyan and Th.M. Nieuwenhuizen, "Extracting work from a single thermal bath in the quantum regime," *Phys. Rev. Lett.* **85**, 1799 (2000)]. Thus also the Landauer principle can be violated, and I suspect that it will be violated just when it becomes interesting, because nowadays we are still far away from the Landauer bound. That's one statement I want to make.

I also have another question to Owen Maroney, namely, if you have all these Maxwell demon stuff, and you do, I'm thinking for quantum systems, somehow you're going to measure on which side your particle is. But a quantum measurement is a costly system. If you know any person doing a quantum measurement, you know he has an apparatus as big as half of this room, and huge power supplies. At the end of the measurement, you have to reset the apparatus. That costs you a lot of energy, because this apparatus is macroscopic. In many discussions, this cost of reset of the apparatus is left out, although it is a macroscopic part of the energy of the whole process. You only focus on this little $k_B T$ which is ten to the nothing, how to say. It's ten to the minus infinity. But anyhow, the big part is left out of discussion. So I just miss all the sense of these discussions. Maybe you can go against this.

OWEN MARONEY: Well, I can make a partial response, I suppose. I think the idea of building a microscopic Maxwell's demon is based on the assumption that these are essentially very small microscopic systems that are well modeled by unitary dynamics. Now the interactions of those are simply correlating unitary interactions, so the idea of actually having to do quantum measurement by having a large macroscopic apparatus, I don't think is playing a part in these kind of discussions. In the end, if you actually did manage to build some Maxwell demon type system, constructed out of small, interacting microscopic degrees of freedom, and it could reliably cause even a small quantify of heat to flow from a colder to a hotter heat bath, and simply continues to do so, the fact that it was actually a very small quantity wouldn't really be the point. You would just leave it running, and eventually you would get as much energy as you wanted.

SILBEY: You'll have to finish it in private. Maybe there will be some people standing around listening. Gian Paolo, did you want to say something?

GIAN PAOLO BERETTA: My view of the reason why we're not talking about temperature is that temperature is a property defined only for stable equilibrium states, whereas the main emphasis now in the frontiers of the subject is in studying non-equilibrium states where temperature is not defined.

ANDREW FOLEY: I would just like to comment on Maxwell's demon and the property of temperature. The problem I have is that when we talk about temperature before and after the demon has done his work, the temperature is the same. So we all agree the energy is unchanged. So the only reason that we consider entropy to be reduced in the newfound demon's corner box is that we have squashed all these particles together, and we can then expand them. So the reason we are saying entropy is actually reduced is because energy, basically the pV term, can expand, and we can get energy back that was previously unobtainable. The reality is, though, that we could conceivably come up with a ratchet in the big volume, and extract the energy by direct molecular impact in more or less the same way. So effectively entropy hasn't changed before and after. It's our definition of entropy that's causing the problem again. Entropy change for a gas equals $c_p \ln(T_2/T_1) - MR\ln(p_2/p_1)$. As the temperature is unchanged in our new small volume, it's the pressure term that is causing the entropy reduction. If we can take those out and just consider internal energy, in this case as "reclaimable" energy, then the entropy hasn't changed at all, so Maxwell's demon isn't really an issue. It's a cool name though, "Maxwell's Demon". Thank you.

SILBEY : OK, thank you. Well, now you see that we're all in agreement about the foundations of the second law up here, and it has been a very interesting discussion. I think we are really clearly in need of more research and thought about these interesting questions, and they're still alive and well, and I think that's the main point here.