WALTER SCRIPTUNAS II

Steam engines convert heat into work; physicists are debating the rules that govern how quantum-level machines could do the same thing.

THERMODYNAMICS

Clash of the physics laws

The debate over how the laws of heat and energy apply at the quantum level is hotting up.

BY DAVIDE CASTELVECCHI

The young field of quantum thermodynamics, which tries to reconcile quantum theory with the 200-year-old science of heat and entropy, is booming. It's also causing some heated disputes.

Many physicists hope that rebuilding thermodynamics from the laws of quantum mechanics will help to settle long-debated conundrums. There are practical implications, too. The field could help to resolve whether the concepts of heat and efficiency apply to tiny electronic components and even atom-sized machines.

But despite proliferating approaches — many of which were presented at the Fifth Quantum Thermodynamics Conference this month in Oxford, UK — the field is as contentious as ever. The crux of the issue is whether the fundamental laws that govern heat and energy on large scales also dictate the behaviour of nanoscale systems — or whether new laws are needed.

Interest is growing: this year, more than 100 scientists attended the quantum thermodynamics conference, says co-organizer Vlatko Vedral, a physicist at the University of Oxford. That is double the attendance in previous years.

Such meetings bring together researchers from subfields that use different technical languages, says co-organizer Felix Binder, a theoretician at Nanyang Technological University in Singapore. "There are a lot of barriers being broken between different approaches."

But a few physicists, such as Peter Hänggi of the University of Augsburg, Germany, caution that some of the work is misguided. "The field is growing rapidly, but also a lot of nonsense is written (and talked) about," he says.

Physicists have argued over the meaning of the three laws of thermodynamics since they were written in the nineteenth and early twentieth centuries. The laws say that energy cannot be created or destroyed; that the amount of disorder, or entropy, in an isolated system can ▶

never decrease; and that it is impossible to cool an object to absolute zero. But thermodynamics is paradoxical. The second law, which also puts limits on how efficiently heat can be converted into work — as happens in a steam engine — is particularly controversial.

The law says that the production of disorder is irreversible. But some physicists argue that at the microscopic level, this seems to conflict with the laws of mechanics — be they those of Newton or of quantum physics. Mechanical laws, say these researchers, prescribe that all processes can be reversed.

Researchers have come up with different approaches to solving this conundrum, but none has satisfied everyone. "This has always been a bit of a dirty business," says Christian Gogolin, a physicist at the Institute of Photonic Sciences in Castelldefels, Spain.

Gogolin's work involves taking statistical mechanics, in which quantities such as temperature or heat are averaged properties of systems made of many particles, and developing a quantum version of it. Some physicists maintain that this statistical-mechanics approach suggests that quantities such as entropy or heat depend on the information an observer possesses. In particular, an all-seeing, 'godlike' being could know the positions and motions of each particle and calculate their evolution, and this level of order would be in the eye of the beholder.

This approach has been revived in recent years, as many physicists have come to regard information as something quantifiable, and with physical significance.

Statistical mechanics is even murkier in systems made of relatively few particles and governed by quantum laws. For example, if the tendency towards disorder is a purely statistical phenomenon, it might in principle not apply to a single molecule. Yet in the past decade, theorists have suggested that quantum systems tend to reach and maintain a state of equilibrium — or maximum disorder — even when they have just a handful of components. Experiments confirmed this with small numbers of atoms trapped by laser light in a vacuum[1].

"This has always been a bit of a dirty business."

And in a 2011 theory paper in *Nature*, Vedral and his collaborators showed that quantum correlations — the ability of particles to share an 'entangled' quantum state when far apart — can be harnessed to produce mechanical work[2].

More recently, physicists have made progress with the third law. In a paper published on 14 March in *Nature Communications*[3], Lluis Masanes and Jonathan Oppenheim at University College London showed that the laws of quantum mechanics limit how fast heat can be extracted from an object, and that reaching absolute zero would take an infinite amount of time. Their work seems to confirm that the third law emerges from quantum mechanics.

A more radical proposal, by Oxford theoretical physicists Chiara Marletto and David Deutsch, suggests a set of principles that all physics theories have to satisfy, a sort of a 'theory of everything' from which laws such as quantum mechanics should follow. And in a 2016 preprint[4], Marletto sketched out how this set of meta-laws leads to a redefiniton of thermodynamic concepts in terms of rules that physical transformations have to obey.

Whatever the outcome of these debates, they may have implications for future technologies. Physicists have made 'quantum heat engines' — that can turn heat into work at the quantum level[5]. Applications such as quantum computing are moving from the theoretical to the real world, so understanding thermodynamics on a tiny scale could be crucial. "You need to design algorithms that are not just faster," says Renner, "but also thermodynamically optimized." ■

1. Trotzky, S. *et al. Nature Phys.* **8,** 325–330 (2012).
2. del Rio, L., Åberg, J., Renner, R., Dahlsten, O. & Vedral, V. *Nature* **474,** 61–63 (2011).
3. Masanes, L. & Oppenheim, J. *Nature Commun.* **8,** 14538 (2017).
4. Marletto, C. Preprint at https://arxiv.org/abs/1608.02625 (2016).
5. Roßnagel, J. *et al. Science* **352,** 325–329 (2016).

FUNDING

Canada budget falls flat

Emphasis on innovation overshadowed by funding freeze for key research councils.

BY NICOLA JONES

The budget that Canadian Prime Minister Justin Trudeau's government released on 22 March lives up to his promises to emphasize innovation, and to encourage links between industry and academia. But it also presents scientists with a depressing, and unexpected, freeze on the main funding streams for basic research.

"This budget is really focused on innovation and skills," science minister Kirsty Duncan told *Nature*. "Last year we had over $2 billion for science, and this year over a billion for innovation. This is a government that respects research and science."

The plan promises to establish Innovation Canada, a new central platform to co-ordinate and simplify support for Canadian entrepreneurs. And there will be Can$950 million (US$710 million) available over five years to support "superclusters": areas dense with companies and academics, similar to California's Silicon Valley, that are designed to push forwards innovative industries such as clean technology.

But critics note that much of this money isn't new; the Can$950 million, for example, is reallocated from pots set aside in last year's budget. And there is little in this year's announcement for basic research. In particular, no mention is made of annual budgets for Canada's three major research councils, which deal with the natural, health and social sciences. This means that they will have no budget increase at all this year.

"The tri-councils get something every year for cost of inflation. I can't remember when they got nothing," says James Woodgett, a biomedical researcher and director of research at the Lunenfeld-Tanenbaum Research Institute in Toronto. "It sends the wrong message, especially with what's going on in the US."

The flat funding for the three research councils is odd given the emphasis that Trudeau's middle-left Liberal government has placed on science. The prime minister's first budget, released last year, injected badly needed cash into those granting agencies, more than doubling the meagre annual increases they had received under the former Conservative government.

MISSING PIECES

Trudeau's government is probably sticking to the status quo while it waits for the results of the Fundamental Science Review, an independent assessment of the country's systems for supporting science, says Paul Davidson, president of the Ottawa-based advocacy group Universities Canada. That analysis will be released in the coming months, the budget notes. "In the interim, the granting councils can continue to do their work at current levels," Davidson says.

The budget does set aside Can$2 million to fund the post of chief government science adviser. The decision to create that post, which will provide independent scientific advice to ministers, was one of the Liberal party's main