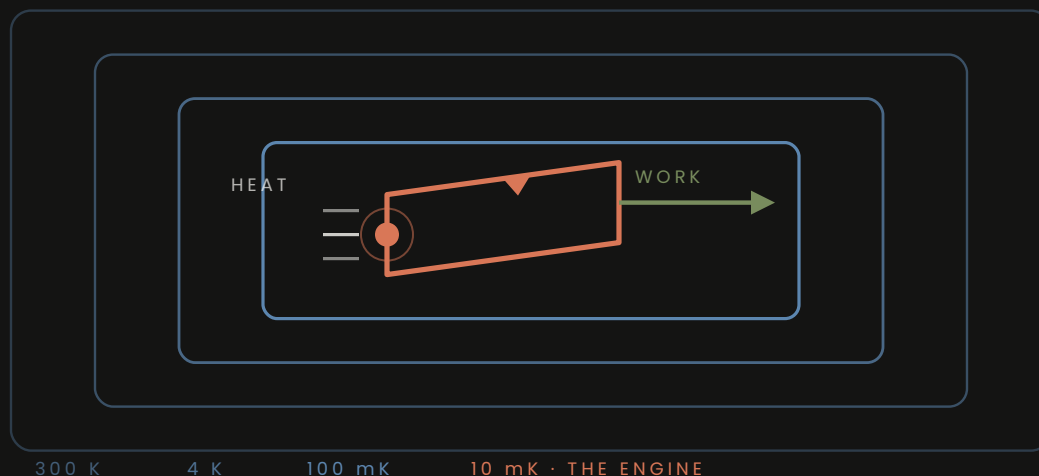


INFLECTION.

THE WEEKLY MAGAZINE OF INNOVATION

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DEEP DIVE — QUANTUM THERMODYNAMICS



THE MOVE 37 READ

Physics just put an engine inside the **coldest** place on Earth

A Finnish team ran a working Otto cycle inside a superconducting quantum processor — near absolute zero, on heat so faint it is usually treated as contamination. The point is not the engine. The point is that the wall blocking million-qubit machines was never the qubit. It was the wiring.

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THIS ISSUE IN ONE LINE

The hardest problem in quantum computing is currently a plumbing problem — and somebody just proposed replacing the plumbing with an engine.

DISPATCH

The constraint migrates.

FROM THE EDITOR

Every computing era has a headline constraint and a real one, and they are almost never the same thing. In the vacuum-tube years the headline was switching speed; the real constraint was heat and burnt filaments. In the mainframe years the headline was clock rate; the real constraint was memory bandwidth. In this decade the headline is model scale; the real constraint is power delivery and interconnect. The pattern is stubborn: the physics is glamorous, the plumbing decides.

Quantum computing is now living through its own version of this. For fifteen years the public story has been coherence — how long a fragile quantum state survives before the universe notices it. That problem is not solved, but it has become tractable enough that a different one has quietly moved into first place. To control a superconducting qubit you run a coaxial cable from a room-temperature rack down through the thermal stages of a dilution refrigerator to a chip at roughly ten thousandths of a degree above absolute zero. Every cable carries signal down and heat down with it. The coldest stage of a commercial machine has a thermal budget measured in tens of microwatts. You cannot cable your way to a million qubits. You run out of cold long before you run out of qubits.

So this week's feature is not really a thermodynamics story, though it is a lovely one. It is a story about a team that looked at the heat leaking into the coldest machine humans have ever built and asked the question nobody in the field was asking: what if we stopped removing it and started spending it? Read on with one lens in hand — *the bottleneck is rarely where the marketing is.*

One housekeeping note. Inflection rotates its deep dive every week and does not return to a domain until the field has moved. Issue 01 covered photonic computing; this issue turns to quantum thermodynamics. Every figure printed here has been checked against a named primary source, and the full list appears on page nine. Where a claim could not be verified, it was cut rather than hedged.

The Engine in the Freezer

Aalto University physicists have run the first cyclic heat engine ever built inside a superconducting circuit. It produces an amount of work too small to matter. It may nonetheless be the most strategically interesting quantum result of the year.

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Near absolute zero, heat does not vanish. It thins. At ten millikelvin — the operating temperature of a superconducting quantum processor — there is still a residue of thermal energy sloshing through the circuit, and for the entire history of the field that residue has been the enemy. It scrambles qubits. It is the thing the refrigerator exists to fight. On 13 July, a group led by Academy Professor Mikko Möttönen reported in *Nature Communications* that they had built a machine that eats it. Their device runs an Otto cycle — the same four-stroke thermodynamic loop that turns over in a petrol engine — using a transmon qubit as the working substance, and it produces net positive work, cycle after cycle. It is the first cyclic quantum heat engine ever demonstrated in superconducting circuits.

The problem nobody puts on a slide

Quantum computing roadmaps are published in qubits. Almost none of them are published in watts, which is unfortunate, because watts are what will decide the outcome.

A superconducting qubit must sit between roughly 10 and 20 millikelvin to hold coherence. Getting it there requires a dilution refrigerator, a nested set of thermal stages descending from room temperature through 4 kelvin down to the base plate. The control electronics, however, live at the top, at 300 K, because conventional semiconductors do not work at millikelvin. So each qubit's control and readout lines are physical coaxial cables threaded down through every stage.

Each of those cables is a thermal short circuit. It conducts heat downward into a stage whose entire cooling capacity, in a commercial machine, is on the order of twenty microwatts — about a millionth of the power drawn by a phone charger. Engineering studies of hundred-qubit

cryogenic setups spend most of their pages on this single budget line.

Arithmetic that does not close

Finland's national Quantum Technology Strategy targets a machine with one thousand *logical* qubits by 2035. Under current error-correction overheads that implies hundreds of thousands of physical qubits — and, Möttönen notes, on the order of millions of microwave cables, each costing roughly a thousand euros. The capital cost alone is absurd. The thermal cost is impossible. And the cables do not merely carry heat: they carry noise, which is the very thing the qubits cannot tolerate.

The field's answer so far has been to move the electronics closer to the cold: cryo-CMOS controllers at 4 K, multiplexers at base temperature, optical links replacing coax. All of these reduce the cable count. None of them change the underlying premise, which is that useful action must be imported into the fridge from somewhere warmer.

The Aalto result is interesting precisely because it attacks the premise.

A four-stroke engine, one atom-sized cylinder

One refrigerator, two temperatures

A heat engine classically needs two reservoirs: something hot to draw from, something cold to dump into. The elegance of the Aalto device is that it has only one. At its centre sits a transmon qubit — the workhorse element of nearly every superconducting quantum computer on Earth — coupled to a resonator and to a quantum-circuit refrigerator, or QCR.

A QCR is a tunable dissipative element: bias it one way and it drains energy out of the qubit; bias it the other and it pumps energy in. In other words, the same component can be dialled hot or cold on demand, in nanoseconds. The team used it as both reservoirs of the engine, alternating its character with timed control pulses rather than moving the qubit between two physically separate baths.

"Using a single controllable quantum refrigerator as both the hot and cold environment of the engine makes it simpler and more versatile," said Tuomas Uusnäkki, the study's first author.

"This is the first experimental demonstration of a cyclic quantum heat engine in superconducting circuits."

TUOMAS UUSNÄKKI · AALTO UNIVERSITY

Why cyclic is the whole point

Quantum heat engines have been demonstrated before — in trapped ions, in nitrogen-vacancy centres, in single atoms. Most were single-shot: a demonstration that one stroke could extract work, not that a loop could repeat

and keep repeating. Cyclic operation is the difference between a spark and an engine, and it is the property that matters if the device is ever to power something.

The team monitored the qubit state continuously as the cycle ran, and measured that heat flowing through the qubit was converted to positive work across the full loop. The experiment was fabricated and run at OtaNano, Finland's national nano- and quantum-technology infrastructure, with funding from the Research Council of Finland and the Finnish Cultural Foundation.

The interesting failure mode

Note what this device does *not* do. It does not cool anything better than a dilution refrigerator. It does not deliver useful power in any engineering sense; the energies involved are at the scale of single microwave photons. Judged as a machine, it is a toy.

Judged as a proof of principle, it is a claim that thermodynamic work can be generated *locally, on-chip, at base temperature*, from energy that is already present and currently wasted. Everything strategic follows from that sentence.

Where this sits in the literature

Quantum thermodynamics has been an active theoretical field for decades and an experimental one for about ten years. What has been missing is a demonstration in the one platform industry has actually committed to at scale. Superconducting circuits are where the money, the fabs and the roadmaps are; a result in trapped ions is beautiful physics, a result in transmons is a supply-chain conversation.

From lab bench to fab floor

The application the Aalto team is chasing is autonomous qubit readout. Today, measuring a qubit means generating a microwave pulse at room temperature, sending it down a cable to the chip, and sending the reflected signal back up through amplifiers to be digitised. The round trip crosses five orders of magnitude of temperature. An autonomous on-chip engine would let a readout event be powered by the local thermal environment instead — the measurement paying for itself out of the ambient noise.

If that works, the cable count stops scaling with the qubit count. That is the whole prize. It converts a linear-in-

hardware problem into a fabrication problem, and fabrication problems are the kind the semiconductor industry knows how to win. The market that appears is not "quantum heat engines." It is cryogenic on-chip power and control — a component layer that every superconducting quantum computer would need, supplied by whoever gets the process node right.

The honest timeline is long. A fully autonomous engine has not been demonstrated; the team says it is what they are building next. Treat this as a 2030s component thesis, not a 2027 procurement decision.

FIELD NOTES • HOW IT WORKS

1 • HEAT

The quantum-circuit refrigerator is biased to inject energy, driving the transmon qubit into an excited, "hot" state. This is the intake stroke.

2 • COMPRESS

With the qubit now isolated from the reservoir, a control pulse widens the energy gap between its two levels — the quantum equivalent of squeezing a cylinder. The stored energy per excitation rises.

3 • EXHAUST

The same refrigerator is re-tuned cold and absorbs the excitation at the wider gap. More energy leaves than went in at the narrow gap. The difference, summed over the loop, is net positive work.

GLOSSARY

Transmon — a superconducting circuit engineered to behave like a controllable two-level atom. The dominant qubit design in industry today.

Quantum-circuit refrigerator (QCR) — an on-chip element that removes or adds energy quanta to a nearby circuit on command. Here, it plays both reservoirs of the engine.

Otto cycle — heat in, compress, heat out, expand. The four-stroke loop in a petrol engine, reproduced here with a single qubit as the working fluid.

Millikelvin — thousandths of a degree above absolute zero. Superconducting qubits need 10–20 mK; the cooling budget there is roughly 20 microwatts.

WATCH LIST • THREE FALSIFIABLE MILESTONES

01 • AUTONOMY

An engine that runs without externally timed control pulses. Until that exists, the device still needs the cables it aims to remove.

02 • COHERENCE COST

A published measurement of how much qubit lifetime is lost by sitting next to a QCR. That number decides the whole trade.

03 • A CABLE REMOVED

One readout line eliminated from a working processor by an on-chip device. One is enough. One proves the scaling law has changed.

Quantum computing just became a *thermal* engineering industry.

Which sounds like a demotion. It is the opposite.

Here is the move that looks wrong. If you are allocating capital in quantum computing today, the consensus advice is to buy qubit quality: gate fidelity, error-correction overhead, logical-qubit milestones. The contrarian position after this paper is that the decisive competitive variable over the next decade is not fidelity per qubit but *useful work per microwatt at base temperature* — and almost nobody is underwriting that.

The reasoning is structural. Fidelity improvements are asymptotic and broadly shared; every serious lab is climbing the same curve with the same materials tricks. Thermal budget is not shared. It is a hard, per-cryostat physical ceiling that sits between today's few-hundred-qubit modules and any commercially meaningful machine, and the company that moves that ceiling by an order of magnitude does not win a benchmark — it wins the platform. This is the same shape as the shift from transistor-count competition to power-delivery and packaging competition in classical silicon, which is where most of the last decade's actual margin went.

An on-chip engine is a small piece of evidence for a large claim: that the fridge can be made to do work rather than only to absorb it. Once that is possible in principle, the design space opens — autonomous readout, self-powered control logic, error-correction primitives that never talk to a room-temperature rack. The unit of competition becomes the cryogenic component library.

Why the consensus disagrees — fairly

The counter-arguments are strong and should be stated plainly. First, scale: the work extracted here is at the level

of individual microwave photons. Nothing in the paper demonstrates that this can be amplified to power anything, and there are thermodynamic reasons to expect the efficiency of such engines to be poor.

Second, the QCR is itself a dissipative element deliberately coupled to a qubit. Every such coupling is a decoherence channel. Adding engines to a processor may cost more coherence than the removed cables save — that trade has not been measured.

Third, the autonomous device that would matter does not exist yet. The demonstrated engine still runs on externally timed control pulses, which means it currently needs the very cables it aspires to eliminate.

Fourth, the competition is real and closer to market. Cryo-CMOS control chips and base-temperature multiplexing already cut cable counts by large factors today, with conventional supply chains. A component that works now beats a component that is elegant later.

All four objections are correct. None of them touch the premise, which is what makes this worth watching: they are objections about maturity, not about direction.

The test that settles it

So ignore the qubit-count press releases for a decade and track one number instead: control and readout lines per physical qubit. If it falls below one, the industry has a path to a million qubits. If it does not, no amount of fidelity will rescue the roadmap — and the winners will be whoever learns to own the cold.

Three developments from elsewhere in the week, each with one number worth remembering.

\$4.48B

ENERGY

Fusion's best fundraising year on record

The Fusion Industry Association's 2026 survey reports that 56 private fusion companies raised \$4.48 billion over the past twelve months — a 69% jump on 2025 and the largest annual total since the association began tracking in 2021. Cumulative private investment now stands at \$14.24 billion and the sector employs more than 16,000 people. The largest individual raises were Commonwealth Fusion Systems (\$863m), Proxima Fusion (\$518m), Helion Energy (\$465m) and Inertia Enterprises (\$450m). Approach diversity remains wide — 48% magnetic confinement, 21% inertial, 14% magneto-inertial — and while 28 of the companies are American, twelve other nations are now represented.

SOURCE · FUSION INDUSTRY ASSOCIATION, 2026 GLOBAL FUSION INDUSTRY REPORT

¥1T

SEMICONDUCTORS

Sony and TSMC put a trillion yen into seeing

Sony Semiconductor Solutions and TSMC announced agreement on a joint venture to develop and manufacture next-generation CMOS image sensors, with total investment of roughly ¥1 trillion (about \$6.3 billion). Sony will hold approximately 60% and TSMC 40%; Sony contributes around ¥465 billion in cash and transferred assets, TSMC around ¥282 billion in cash. Production is targeted at Sony's new fab in Koshi, Kumamoto Prefecture, as early as 2029. Read it as a bet that the sensor — not the processor — is the next contested layer of the physical AI stack: the pairing of Sony's imaging architecture with TSMC's leading-edge logic process is aimed squarely at putting compute inside the pixel.

SOURCE · SONY SEMICONDUCTOR SOLUTIONS NEWS RELEASE, 11 AUGUST 2026

1st

BIOMEDICINE

The brain is not the closed system we taught

A Stanford team reported in *Nature* that immune cells from the bloodstream enter the human brain in large numbers beginning as early as middle age, and once inside, become microglia — the brain's resident immune cells, long assumed to be a self-renewing population established at birth. The team proved ancestry by matching somatic mutations between paired blood and post-mortem brain samples, using accumulated mutations as a genetic family tree. Strikingly, the process does not appear to occur in mice or non-human primates, making it a uniquely human feature of ageing — and opening a delivery route for engineered immune cells aimed at amyloid and tau.

SOURCE · BELK ET AL., NATURE, 2026 · DOI 10.1038/S41586-026-10939-0

BY THE NUMBERS

Seven figures from the week, each verified against a named source.

20 μ W

Typical total cooling power at the base stage of a commercial dilution refrigerator — the entire thermal budget a quantum processor gets.

€1,000

Approximate cost of a single microwave control cable. Millions would be needed for a machine at national-strategy scale.

1,000

Logical qubits by 2035 — the target in Finland's national Quantum Technology Strategy, implying hundreds of thousands of physical qubits.

\$14.24B

Cumulative private investment in fusion energy, after a record \$4.48bn year across 56 companies and 16,000+ employees.

3,000,000

New spectra released in SDSS-V Data Release 20, covering 1.5 million stars and the survey's first southern-hemisphere optical observations.

2029

Earliest commercial production date for the Sony-TSMC image-sensor joint venture in Kumamoto, capitalised at roughly ¥1 trillion.

69%

Year-on-year growth in annual fusion fundraising — the steepest increase the sector has recorded since tracking began in 2021.

What you do with the waste

There is a thread running through this issue that is easy to miss because the stories look unrelated. A Finnish lab finds work in heat that everyone else was throwing away. A Stanford lab finds that the brain has been quietly recruiting immune cells from the bloodstream for decades, in a traffic pattern the field had explicitly ruled out. Fusion investors put \$4.48 billion into a technology whose defining problem, for seventy years, has been that it produces more waste heat than useful output.

The common structure is a category error being corrected. In each case a flow was labelled noise — contamination, leakage, loss — and the labelling was load-bearing. It shaped what people measured, what they funded, and what they did not bother to look at. When the label came off, the same physical system turned out to contain a resource nobody had budgeted.

This is worth naming because it is a repeatable move rather than a lucky one. In most mature technical systems, the largest untouched reserve is not a new capability but a

reclassified one. The engineer's instinct is to remove the anomaly; the strategist's instinct should be to ask what the anomaly is made of. Twenty microwatts of parasitic heat is not much. But it is twenty microwatts that somebody is already paying for, sitting exactly where the next generation of hardware needs power.

None of this makes the Aalto engine a product. It makes it a hypothesis with a working prototype attached, which is the most valuable form an idea can take. The right posture is neither the press-release enthusiasm nor the reflexive dismissal, but a specific question, asked annually: has anyone demonstrated an autonomous on-chip device that removes a cable? The year the answer is yes, the roadmaps get redrawn.

Until then, the useful discipline is to run the same audit on your own systems. Find the flow you are paying somebody to remove. Ask what it is made of. The answer is occasionally an engine.

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THE WEEKLY MAGAZINE OF INNOVATION

THE LENS

What is the plumbing problem hiding behind your physics problem — and who on your team is paid to notice it?

NEXT ISSUE · FRIDAY

A new deep dive, three fresh Signals, and the numbers that moved. Rotating domains — no repeats.

COLOPHON

Researched, written & designed with Claude.
Typeset in Poppins & Lora on the Anthropic palette.
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