Quantum Science and Technology - Argentina 2019

XXI GIAMBIAGI WINTER SCHOOL

Quantum simulations and quantum metrology with cold trapped ions – July 15-24

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Quantum Thermodynamics



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I - Work extraction from quantum coherences (long)

- II Maxwell's demon and his exorcism experimental evidence (short)
- III Thermodynamics beyond the weak coupling limit (long)

IV - Optional: Non-equilib. temperature of levitated nanospheres (short)



Second Law of thermodynamics & Maxwell's demon & information

Previous Maxwell demon experiments

Superconducting qubit Maxwell demon experiment

Reading the demon's mind

Second law of thermodynamics







1824-1907 Thomson/Kelvin

Kelvin-Planck statement of 2nd law:

It is impossible to devise a **cyclically** operating device, the sole effect of which is to absorb energy in the form of **heat** from a single thermal reservoir and to deliver an **equivalent amount of work**.





gas in equilibrium



insert wall (no heat, no work)



select and open door (no heat, no work)





1831-1879 - James Clerk Maxwell









Heat from heat bath is completely converted into work.





Heat from heat bath is completely converted into work.

Breaks the 2nd law of thermodynamics!

Clausius inequality $\Delta S \geq rac{Q}{T}$

But here:
$$\Delta S = 0 < \frac{Q}{T}$$

So is the **2nd law of thermodynamics broken**?

I.e. can one really create a **cyclic process** in which heat is **fully** transferred into work?

The answer is No - but understanding why that is so took physicists more than a hundred years.

The resolution invokes Landauer's erasure principle.













Information is stored in the demon's memory and this makes the cycle not closed.





1) Demon's action on the **gas** converts heat completely into work



2) Erasure of demon's memory requires work and generates heat



$$\Delta U = 0$$

$$0 = -Q_{diss} + W_{\text{cost erasure}}$$



$$W_{\text{cost erasure}} - W_{ext} \ge 0$$

total work required to do process is positive

for a cycle with one heat bath at temperature T

In total there is no net work extracted. (in the best case)

So 2nd law intact.



Second Law of thermodynamics & Maxwell's demon & information

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Reading the demon's mind

Recent demon experiments



classical demons





classical autonomous demons



Proposal: use superconducting qubits! H.T. Quan, et al, PRL 97, 180402 (2006)

Staircase Maxwell demon



classical demons







Brownian motion (heat bath) drives particle up/down the potential staircase.

Feedback stops particle from returning down after going up.

Staircase Maxwell demon





 classical experiment
 work inferred from particle position in applied potential not extracted into a "bucket"

b

 no attention on information in demon's memory

se.

Feedback stops particle from returning down after going up.



Second Law of thermodynamics & Maxwell's demon & information

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Superconducting circuit experiment





+ microwave cavity = c = D







superconducting transmon qubit = q = S



$$\hat{H} = \frac{\hat{q}^2}{2C_J} - E_J \cos \frac{\hat{\phi}}{\hbar/2e} = \frac{\hat{q}^2}{2C_J} + \frac{\hat{\phi}^2}{2L_J} + H_{\text{non-lin}}(\hat{\phi})$$

$$H_q \approx 0 |g\rangle \langle g| + \hbar\omega_q |e\rangle \langle e|$$

$$h\omega_q$$

Maxwell's demon: Preparation





Superconducting circuit experiment





Step 1: **Prepare** transmon qubit S in thermal state at temperature T or in superposition state.



- \bullet initially at T = 103mK
- ✦ flip by π -pulse with certain probability to make any thermal state
- ♦ or flip by π /2-pulse to make a superposition state

Maxwell's demon: Read out





Superconducting circuit experiment





- Step 1: **Prepare** transmon qubit S in thermal state at temperature T or in superposition state.
- Step 2: **Encode** system state in demon's memory:

Coupling between qubit and cavity





qubit + cavity Hamiltonian

$$H = hf_c a^{\dagger}a + hf_q |e\rangle \langle e| - h\chi a^{\dagger}a |e\rangle \langle e|$$

$$\int_{7.9 \text{ GHz}} 7.1 \text{ GHz} 33 \text{ MHz}$$

Cavity frequency depends on qubit excitation

$$f_c \mapsto f_c - \chi |e\rangle \langle e|$$

Qubit frequency depends on photon number

$$f_q \mapsto f_q - \chi N$$

Correlating qubit and cavity (demon)





qubit + cavity Hamiltonian $H = h f_c a^{\dagger} a + h f_a |e\rangle \langle e| - h \chi a^{\dagger} a |e\rangle \langle e|$ 33 MHz 7.9 GHz 7.1 GHz Cavity frequency depends on qubit excitation $f_c \mapsto f_c - \chi |e\rangle \langle e|$ Qubit frequency depends on photon number $f_a \mapsto f_a - \chi N$ Driving at fc results in state evolution

 $|e
angle_q|0
angle_c
ightarrow |e
angle_q|0
angle_c$ (since detuned) $|g
angle_q|0
angle_c
ightarrow |g
angle_q|lpha
angle_c$

Superconducting circuit experiment





Step 1: **Prepare** transmon qubit S in thermal state at temperature T or in superposition state.

Step 2: **Encode** system state in demon's memory: $c_g |g\rangle_q |0\rangle_c + c_e |e\rangle_q |0\rangle_c \rightarrow c_g |g\rangle_q |\alpha\rangle_c + c_e |e\rangle_q |0\rangle_c$

Maxwell's demon: Work extraction





Superconducting circuit experiment



Step 1: **Prepare** transmon qubit S in thermal state at temperature T or in superposition state.

Step 2: **Encode** system state in demon's memory: $c_g |g\rangle_q |0\rangle_c + c_e |e\rangle_q |0\rangle_c \rightarrow c_g |g\rangle_q |\alpha\rangle_c + c_e |e\rangle_q |0\rangle_c$

Step 3: adaptive Work extraction to battery.

Deterministic work extraction





qubit + cavity Hamiltonian

$$H = hf_c a^{\dagger}a + hf_q |e\rangle \langle e| - h\chi a^{\dagger}a |e\rangle \langle e|$$

$$\int_{7.9 \text{ GHz}} \int_{7.1 \text{ GHz}} \int_{33 \text{ MHz}}$$

Cavity frequency depends on qubit excitation

$$f_c \mapsto f_c - \chi |e\rangle \langle e|$$

Qubit frequency depends on photon number

$$f_q \mapsto f_q - \chi N$$

 π -pulse at f_q results in state evolution $|e\rangle_q|0\rangle_c \rightarrow |g\rangle_q|0\rangle_c$ $|g\rangle_q|\alpha\rangle_c \rightarrow |g\rangle_q|\alpha\rangle_c$ (since detuned)

Where does the work go?





Work extracted as **amplification** of light pulse of $f_q = f_s$

Work extraction to battery







Power extracted from qubit over pulse time for 4 different initial qubit states:

ground state = low temp. state
medium temp state
high temp state = fully mixed state

superposition state

=> extracted work is positive
 + higher for higher Temp.



Step 2: **Encode** system state in demon's memory: $c_g |g\rangle_q |0\rangle_c + c_e |e\rangle_q |0\rangle_c \rightarrow c_g |g\rangle_q |\alpha\rangle_c + c_e |e\rangle_q |0\rangle_c$

Note: encoding is only good if average photon number is large enough $\bar{n} = \langle \alpha | \hat{n} | \alpha \rangle >> 0$

Work extraction to battery







Power extracted from qubit over pulse time for 4 different initial qubit states:

ground state = low temp. state
medium temp state
high temp state = fully mixed state
superposition state

=> extracted work is positive
 + higher for higher Temp.

Same experiment but for "**blind**" demon, i.e. cavity state is the same for either initial qubit state $|e\rangle_q|0\rangle_c \rightarrow |e\rangle_q|0\rangle_c$ $|g\rangle_q|0\rangle_c \rightarrow |g\rangle_q|\alpha\rangle_c$

=> extracted work is **zero** or less on average for all initial qubit states

Transfer of energy from qubit to battery





A - Work extracted to battery as a function of the demon's ability to distinguish qubit energy states (0 = "blind" ... 3 = distinguishes well) ground state = low temp. state medium temp state high temp state = fully mixed state superposition state

=> extracted work is only **positive** when demon has **information** to distinguish

Transfer of energy from qubit to battery



A - Work extracted to battery as a function of the demon's ability to distinguish qubit energy states (0 = "blind" ... 3 = distinguishes well) ground state = low temp. state medium temp state high temp state = fully mixed state superposition state

E

=> extracted work is only **positive** when demon has **information** to distinguish

B - **Energy of qubit** after and before demon's intervention.

=> energy lost by qubit is indeed work collected in battery.



Second Law of thermodynamics & Maxwell's demon & information

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Reading the demon's mind





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brain tomography (image PNAS Phelps (2000))

Here: quantum state tomography!

Reading the demon's mind



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Tomography of the demon's state after the feedback protocol. initial qubit state: $\begin{array}{l} A \text{- ground state} \\ |g\rangle_q |0\rangle_c \rightarrow |g\rangle_q |\alpha\rangle_c \rightarrow |g\rangle_q |\alpha\rangle_c \\ B \text{- excited state} \\ |e\rangle_q |0\rangle_c \rightarrow |e\rangle_q |0\rangle_c \rightarrow |g\rangle_q |0\rangle_c \end{array}$

Reading the demon's mind

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Tomography of the demon's state after the feedback protocol. initial qubit state: A - ground state $|g\rangle_q|0\rangle_c \rightarrow |g\rangle_q|\alpha\rangle_c \rightarrow |g\rangle_q|\alpha\rangle_c$ B - excited state $|e\rangle_q|0\rangle_c \rightarrow |e\rangle_q|0\rangle_c \rightarrow |g\rangle_q|0\rangle_c$ C - superposition stateD - fully mixed state

=> demon's state shows "memory" of the transmon qubit state

To close cycle need to erase demon state, **costing more work than was extracted.**





First realisation of **autonomous quantum** Maxwell demon.

$$H = hf_c a^{\dagger}a + hf_q |e\rangle \langle e| - h\chi a^{\dagger}a |e\rangle \langle e|$$

Α

0.5

Work is directly measured (photons), not inferred (phase space position).





Information stored by demon is unveiled, evidencing resolution of paradox for the first time.





Observing a Quantum Maxwell Demon at Work

PNAS, **114**, 7561(2017)



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Further reading:

Toyabe, et al, Nature Physics **6**, 988 (2010)

Koski, et al, PRL **115**, 260602 (2015)

Thank you!

