Title: Quantum steampunk: Quantum information meets thermodynamics

Speakers: Nicole Yunger Halpern

Series: Colloquium

Date: May 18, 2022 - 2:00 PM

URL: https://pirsa.org/22050002

Abstract: Thermodynamics has shed light on engines, efficiency, and time's arrow since the Industrial Revolution. But the steam engines that powered the Industrial Revolution were large and classical. Much of today's technology and experiments are small-scale, quantum, far from equilibrium, and processing information. Nineteenth-century thermodynamics needs re-envisioning for the 21st century. Guidance has come from the mathematical toolkit of quantum information theory. Applying quantum information theory to thermodynamics sheds light on fundamental questions (e.g., how does entanglement spread during quantum thermalization? How can we distinguish quantum heat from quantum work?) and practicalities (e.g., quantum engines and the thermodynamic value of coherences). I will overview how quantum information theory is being used to revolutionize thermodynamics in quantum steampunk, named for the steampunk genre of literature, art, and cinema that juxtaposes futuristic technologies with 19th-century settings.

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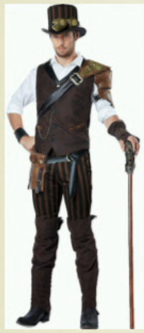
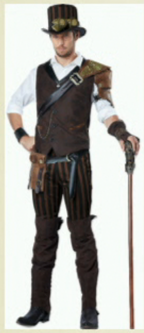


STEAMPUNK

- Literary, artistic, and cinematographic genre
- "Set in the late 19th century, it encompasses all of the romanticism of the Victorian Era . . . then cranks up the technological level . . . to eleven."

  - Steampunktrain



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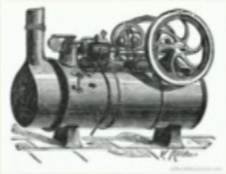
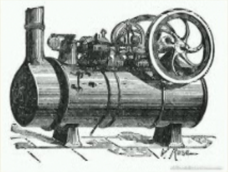
  - Steampunktrain
- Steam power + grimy cities + top hats
  + time machines + automata + dirigibles

THERMODYNAMICS



THERMODYNAMICS



- The study of energy
- Invented during the steampunk era (1800s)

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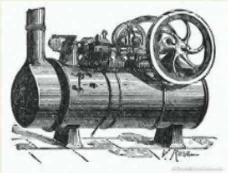
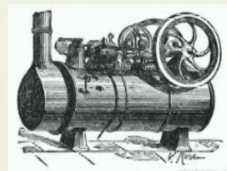


- The study of energy
- Invented during the steampunk era (1800s)
- Technological motivations ⟶ Fundamental physics
- Describes large, classical systems

Steam engine

THERMODYNAMICS NO LONGER SUFFICES.



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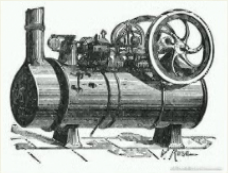

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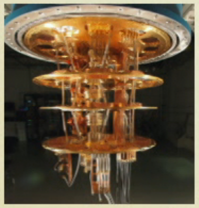
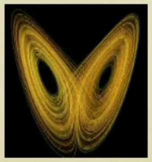


Quantum

Information-processing



Out of equilibrium

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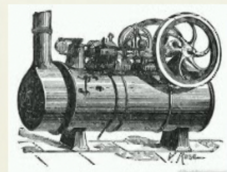

Small

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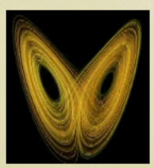

Out of equilibrium

- New settings
- But work, efficiency, etc. relevant

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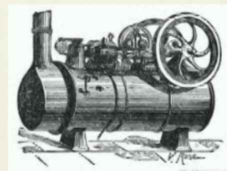

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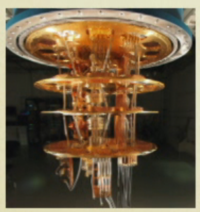


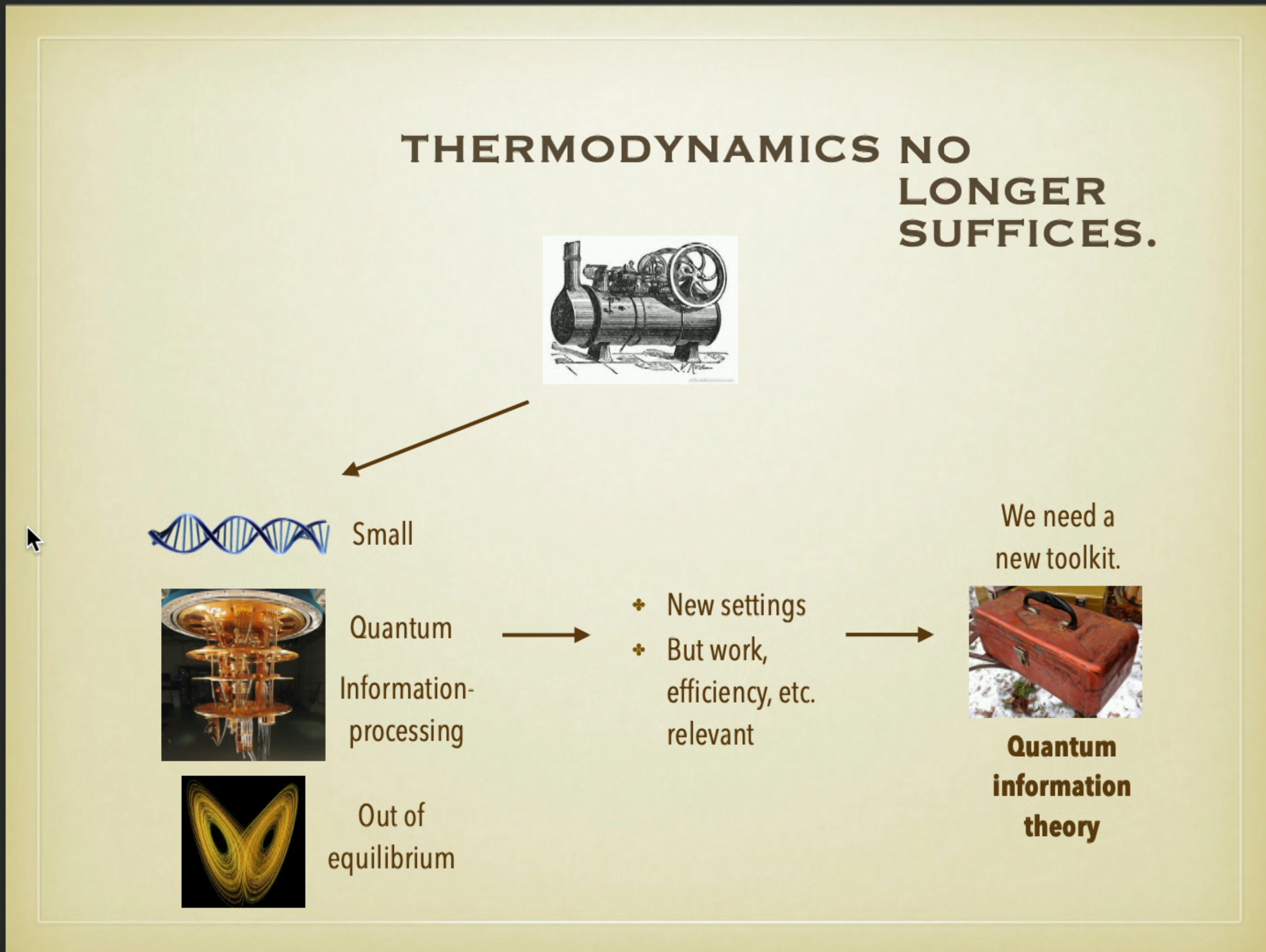
Quantum

Information-processing

Out of equilibrium

- New settings
- But work, efficiency, etc. relevant

We need a new toolkit.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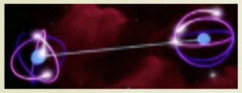
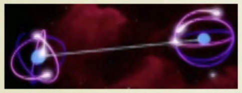
Quantum information theory

Quantum information theory

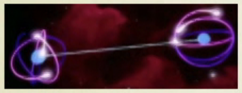
 + 

Quantum information theory

 + 

The use of quantum phenomena to process information in ways impossible with classical systems

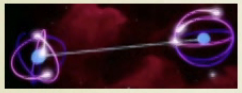
Quantum information theory

 + 

The use of quantum phenomena to process information in ways impossible with classical systems

- Entanglement

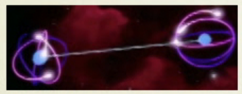
Quantum information theory

 + 

The use of quantum phenomena to process information in ways impossible with classical systems

- Entanglement
- Noncommutation
- Discreteness
- Disturbance by measurement
- ...

Quantum information theory



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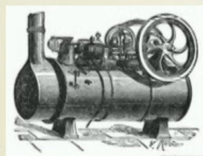
- Mathematical toolkit being applied across science:
- Condensed matter; atomic, molecular, and optical physics; chemistry; high-energy physics; computer science; thermodynamics; …

Thermodynamics



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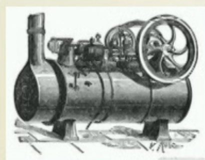
Quantum information

- Re-envisioning the laws of thermodynamics for small, quantum, far-from-equilibrium, and information-processing systems

Thermodynamics



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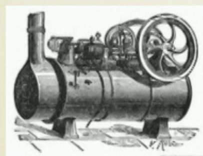
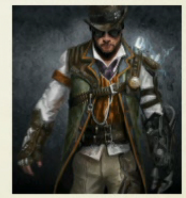
Quantum information

- Re-envisioning the laws of thermodynamics for small, quantum, far-from-equilibrium, and information-processing systems
- How can nonclassical resources enhance thermodynamic tasks?
- Which features of thermodynamics are truly nonclassical?

Thermodynamics + Quantum information = Quantum steampunk

 +  = 

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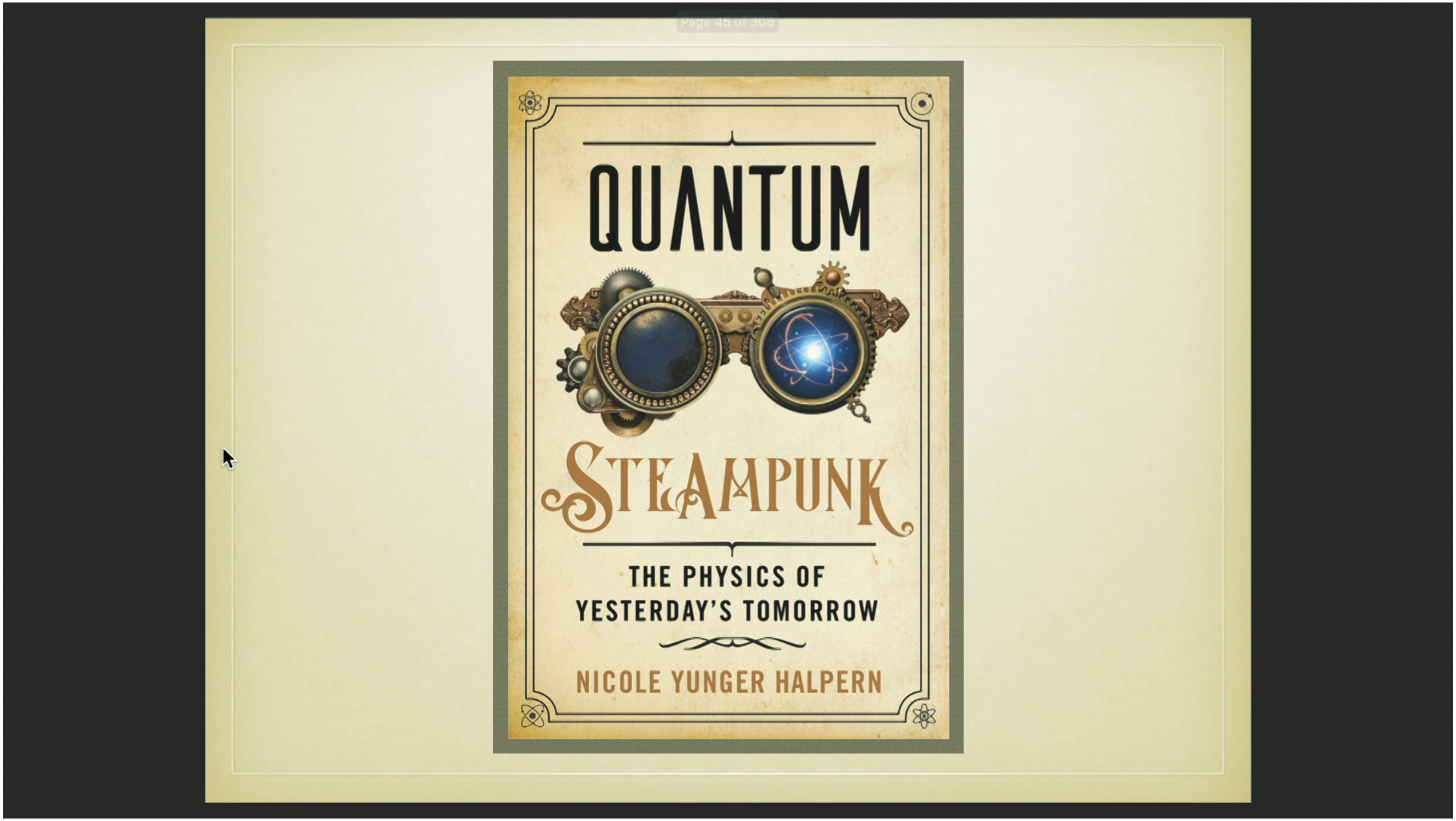
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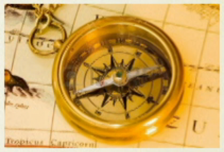
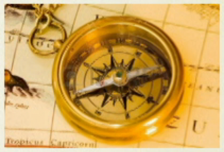
QUANTUM
STEAMPUNK
THE PHYSICS OF
YESTERDAY'S TOMORROW
NICOLE YUNGER HALPERN

WHERE WE'RE HEADED



- Why quantum information theory + thermodynamics?

WHERE WE'RE HEADED



- Why quantum information theory + thermodynamics?
- Work and information as resources in thermodynamics and computation
- Quantum many-body engine ⟶ 
  - NYH, White, Gopalakrishnan, and Refael, Phys. Rev. B **99**, 024203 (2019).

WHY COMBINE QUANTUM INFORMATION THEORY WITH THERMODYNAMICS?

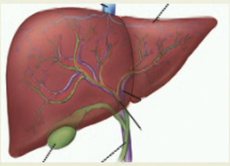
Quantum information

Thermodynamics

BIG QUESTION IN INFORMATION THEORY:

How efficiently can we process information?

- "The liver of information theory"



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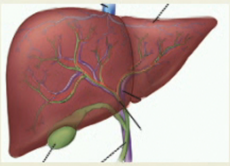

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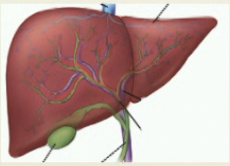
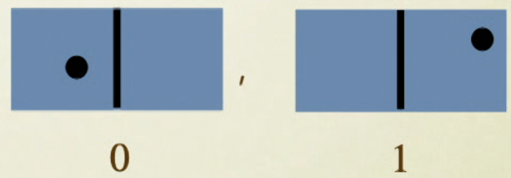


- Typical answer: function of an entropy
    - Function of a probability distribution or a quantum state
    - Quantifies the uncertainty in the outcome of a measurement

QUICK REVIEW: QUBITS

- Basic units of quantum information
- Quantum analogues of bits:

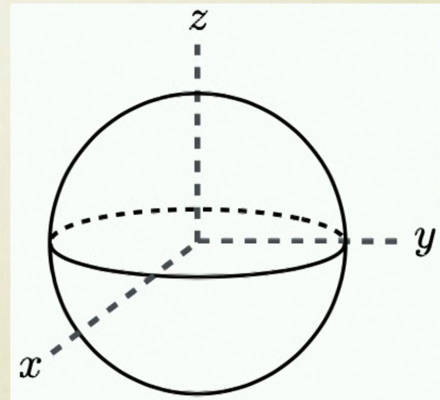


- Quantum 2-level systems
  - Example: spin degree of freedom with $s = 1/2$

QUICK REVIEW: QUBIT STATES

- ρ
- Density operator (matrix)
- Trace-1 positive-semidefinite linear operator
- **Pure** state: $\rho = |\psi\rangle\langle\psi|$
  - Vector in Hilbert space
  - Arrow meets the Bloch sphere

Bloch sphere



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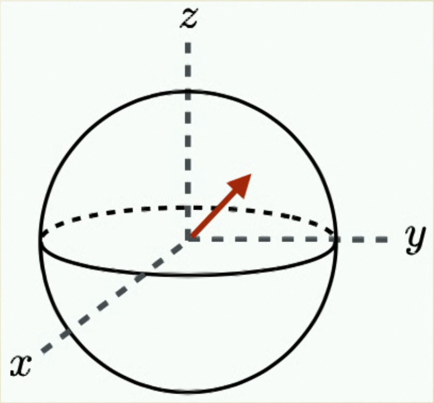

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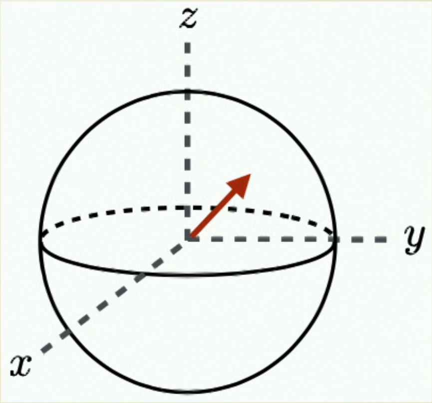
  - Example: quantum thermal state, $\exp(-\beta H)/Z$

Bloch sphere



LET'S CONFRONT AN ENTROPY FACE TO FACE.

ENTROPY AS OPTIMAL EFFICIENCY

- 
-  ⟶ $|a\rangle, |b\rangle, \dots$
- Probabilities: $p_a, p_b, \dots$
- Quantum state: $\rho = \sum_j p_j |j\rangle\langle j|$
-  ⟶ n copies of ρ ⟶ $\rho^{\otimes n}$
- Into how few qubits can I squeeze the total message? ⟶ **data compression**

ENTROPY AS OPTIMAL EFFICIENCY

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  $\uparrow$
  von Neumann entropy

ENTROPY AS OPTIMAL EFFICIENCY

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WHY IS THIS FUNCTION CALLED "ENTROPY"?

Shannon

SHANNON (1961): "VON NEUMANN TOLD ME..."

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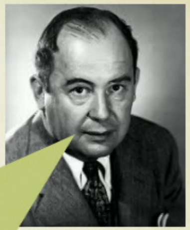


"You should call it entropy, for two reasons.
In the first place your uncertainty function has been used
in statistical mechanics under that name,
so it already has a name.
In the second place, and more important,
no one knows what entropy really is,
so in a debate you will always have the advantage."
(*Scientific American*)

$$dE = TdS + \mu dN + \dots$$

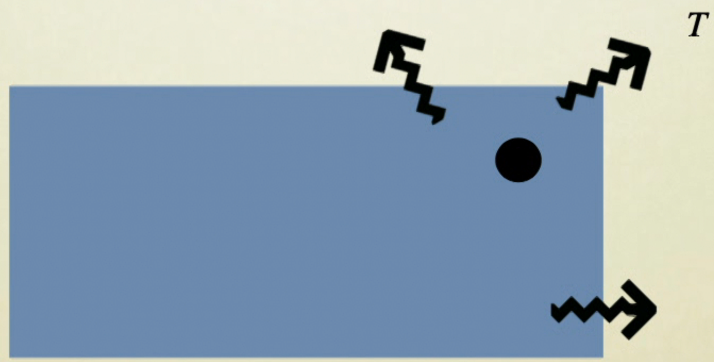
$$dE = T\,d\boxed{S} + \mu dN + \dots$$

Spread of probability density across phase space

ILLUSTRATION:
INFORMATION ⟷ WORK

SZILÁRD'S ENGINE: INFORMATION + HEAT → WORK

- Classical particle in a box ⟶ oversimplified ideal gas
- Exchanges heat with temperature-T bath
- Begin with 1 bit of information



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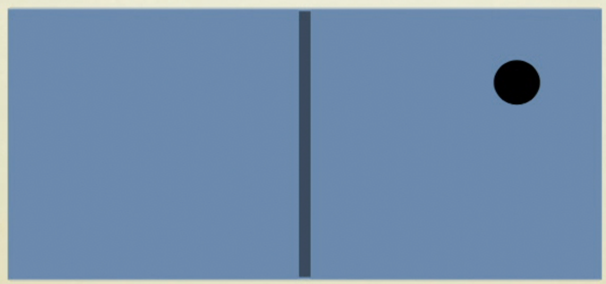

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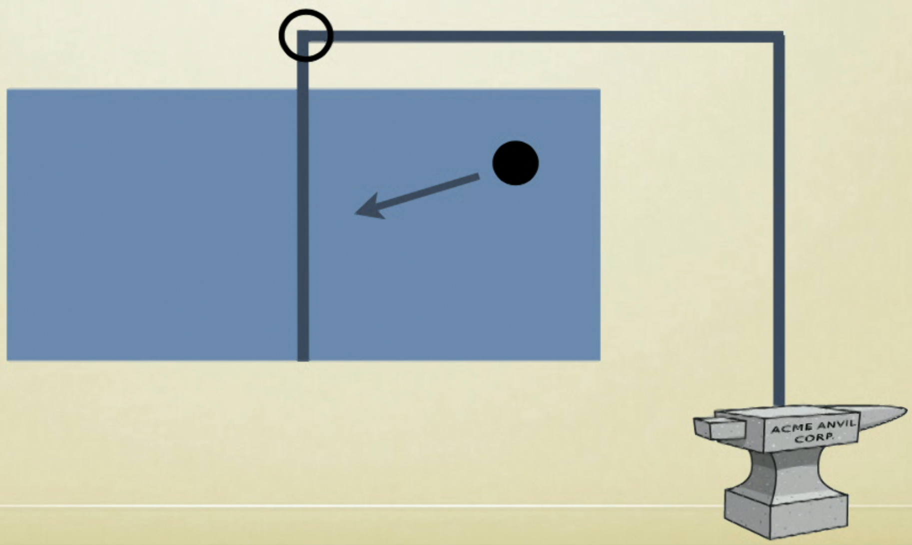
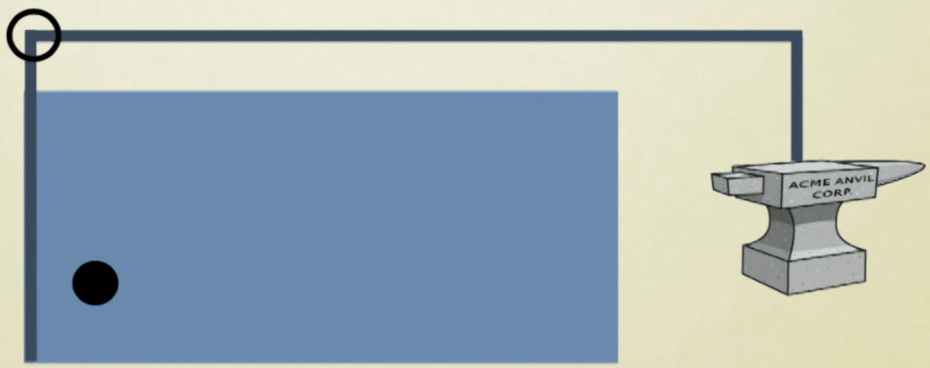


SZILÁRD'S ENGINE: INFORMATION + HEAT → WORK

- Anvil gains potential energy
- Heat converted into work



HOW MUCH WORK HAS THE PARTICLE PERFORMED (ON AVERAGE, IDEALLY)?

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- Pressure-volume work: $W = \int_{V_i}^{V_f} p \, dV$
- Ideal gas law: $pV = nk_BT \quad \Rightarrow \quad p = \frac{k_BT}{V}$
- Substitute in: $W = k_BT \int_{V/2}^{V} \frac{dV'}{V'}$

$$= k_BT \ln |V'| \Big|_{V/2}^{V}$$

$$= k_BT \ln 2$$

REVERSING SZILÁRD'S ENGINE: LANDAUER ERASURE

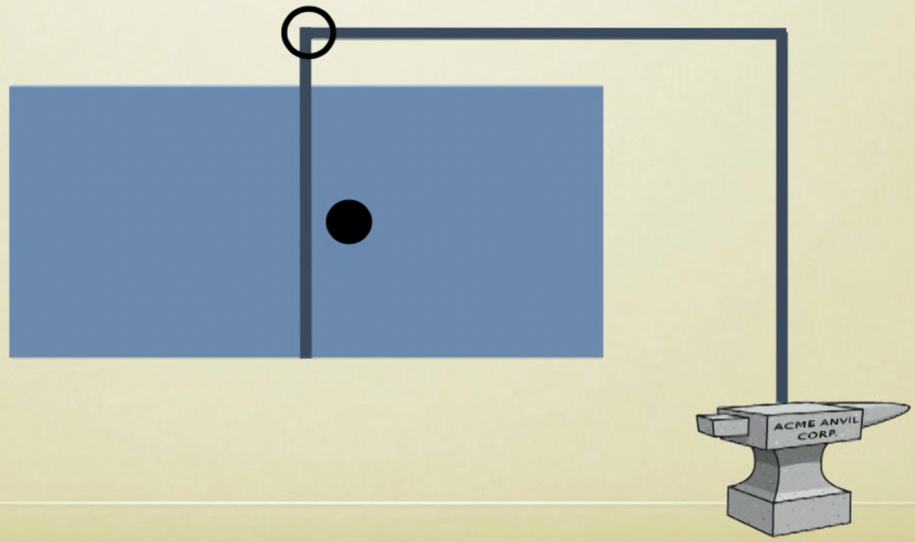
- Landauer, IBM J. Res. Develop. **5**, 183-191 (1961).

REVERSING SZILÁRD'S ENGINE: LANDAUER ERASURE

- Landauer, IBM J. Res. Develop. **5**, 183-191 (1961).
  - Begin with potential energy
  - Particle location unknown

REVERSING SZILÁRD'S ENGINE: LANDAUER ERASURE

- Performed work: $W \geq k_B T \ln 2$
- Returned the bit to a known state



BACKGROUND: ENTANGLEMENT

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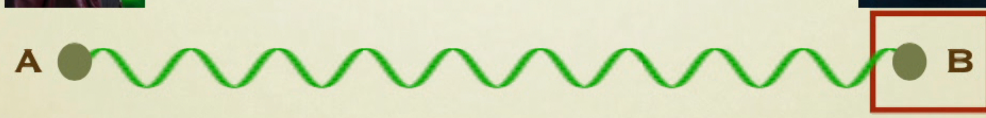
- Manifests in correlations between measurement outcomes
- Stronger than any correlations achievable with classical systems
- Example: **singlet** state of 2 qubits: $|\psi\rangle = (|0\rangle \otimes |1\rangle - |1\rangle \otimes |0\rangle)/\sqrt{2}$



If we measure either system **locally**,
we have no idea which outcome will obtain.

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If we measure both subsystems **locally**,
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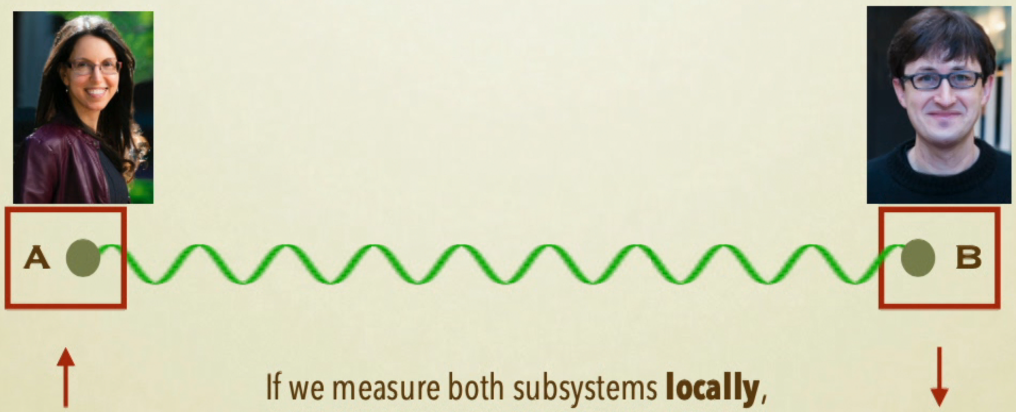

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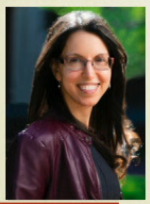
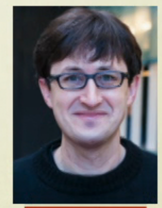
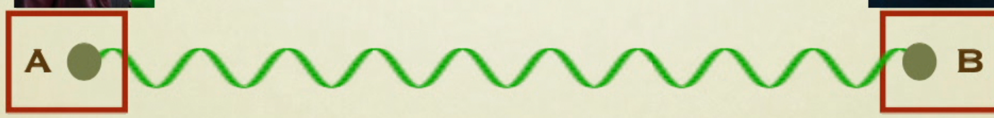


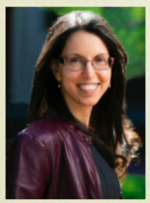


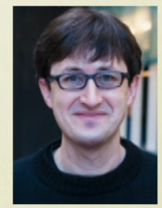


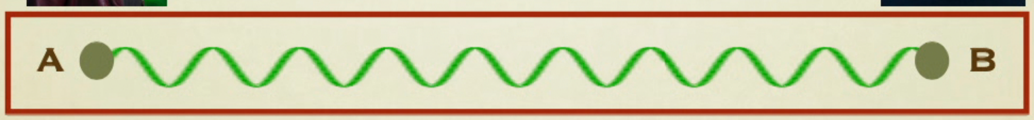
If we measure both subsystems **locally**,
we might be able to predict a property
of the joint outcome.

BACKGROUND: ENTANGLEMENT

- Manifests in correlations between measurement outcomes
- Stronger than any correlations achievable with classical systems
- Example: **singlet** state of 2 qubits: $|\psi\rangle = (|0\rangle \otimes |1\rangle - |1\rangle \otimes |0\rangle)/\sqrt{2}$



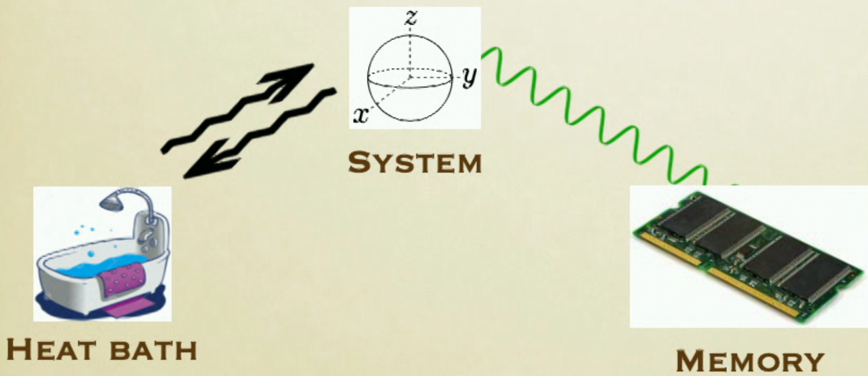




There exists a certain **whole-system** measurement whose outcome we can predict exactly.

ENTANGLEMENT & ERASURE IN THERMODYNAMICS

- Del Rio *et al.*, *Nature* **474**, 61 (2011).
- <u>Goal</u>: reset to $|0\rangle$ a qubit entangled with a memory in a heat bath's presence
- While erasing the system and keeping the memory's state fixed, you can extract work.



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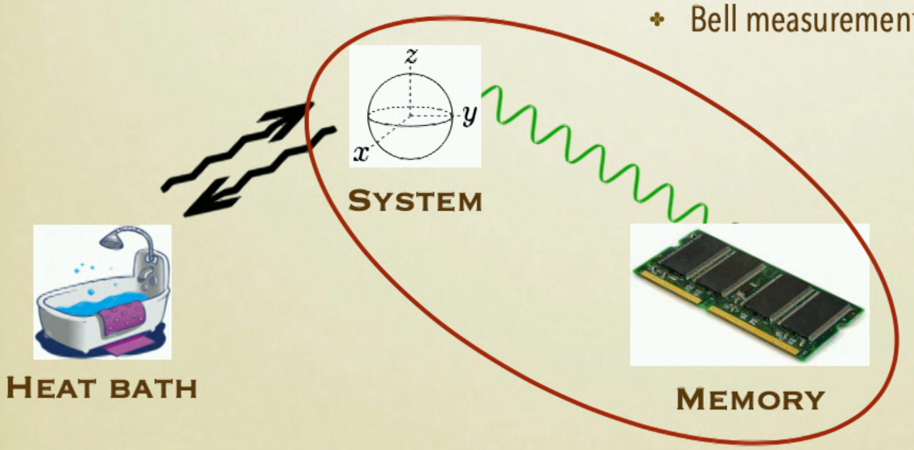
- Trick: "Burn" the correlations between system and memory.

- Bell measurement



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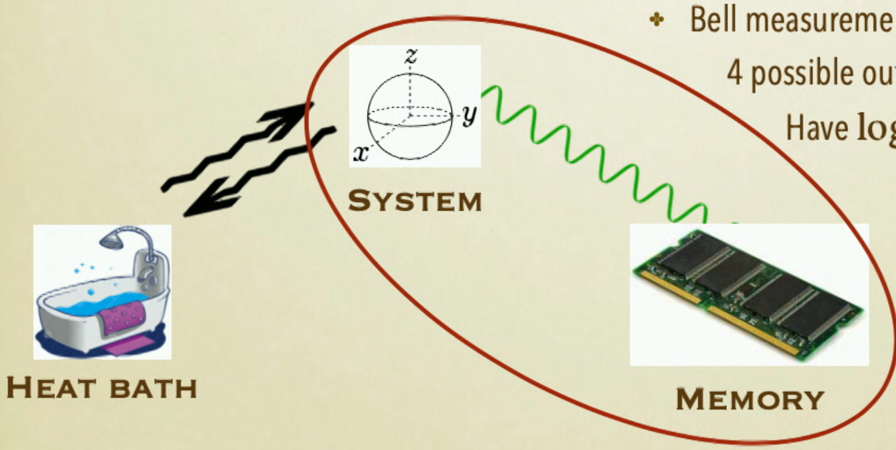

- Bell measurement →
  - 4 possible outcomes, 1 known with certainty →
    - Have $\log_2(4) = 2$ bits

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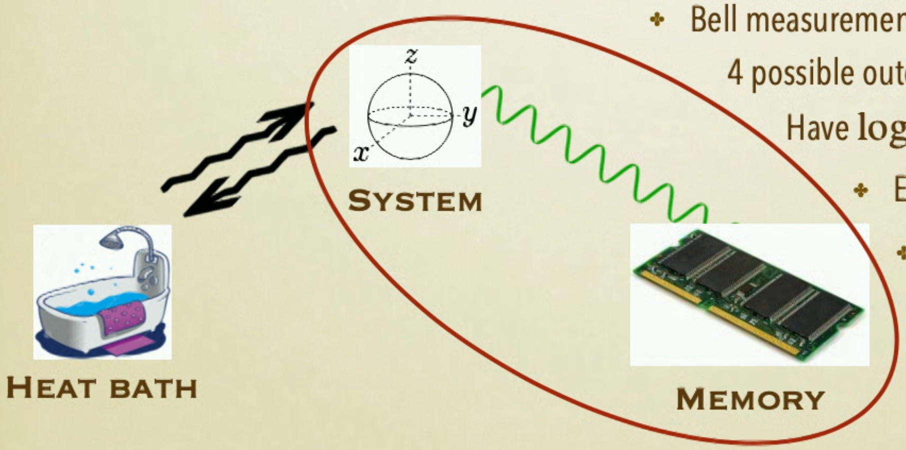
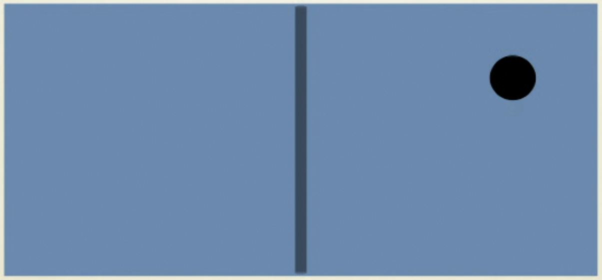


- Bell measurement →
  4 possible outcomes, 1 known with certainty →
  Have $\log_2(4) = 2$ bits
  - Extract $W = 2k_B T \ln 2$
    - Use $k_B T \ln 2$ to erase
      - Have $k_B T \ln 2$ left over

TAKEAWAYS



- Information can be used to turn heat into work.

ENTANGLEMENT & ERASURE IN THERMODYNAMICS

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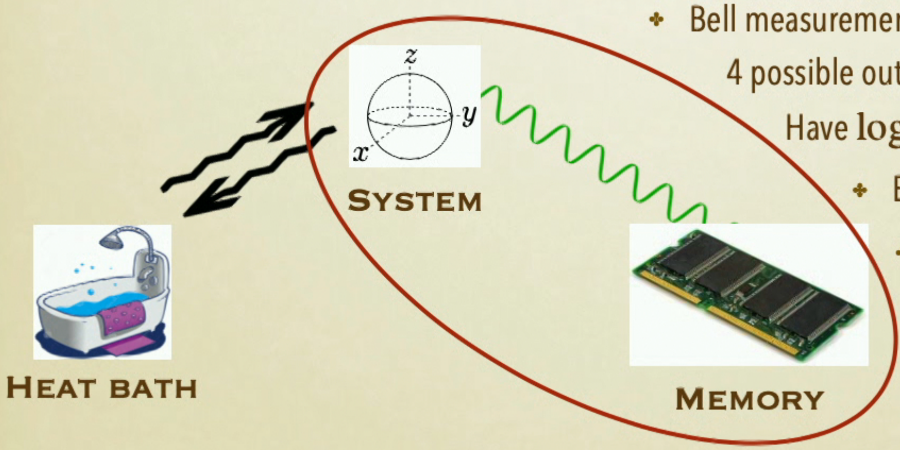
- Trick: "Burn" the correlations between system and memory.

  ⟶ Quantum information/entanglement as a thermodynamic "fuel"



- Bell measurement ⟶

  4 possible outcomes, 1 known with certainty ⟶

  Have $\log_2(4) = 2$ bits

  - Extract $W = 2k_BT\ln 2$
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    - Have $k_BT\ln 2$ left over

QUANTUM MANY-BODY ENGINE

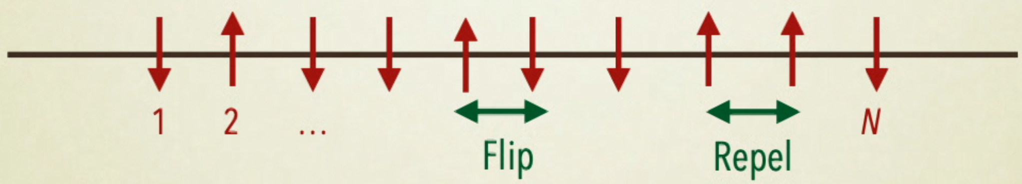
PHYSICAL REVIEW B **99**, 024203 (2019)

Editors' Suggestion | Featured in Physics

Quantum engine based on many-body localization

Nicole Yunger Halpern,[1,2,*] Christopher David White,[1,2,†] Sarang Gopalakrishnan,[1,2,3,4,‡] and Gil Refael[1,2,3,§]

Many-body localization (MBL)



$$H = \sum_{j=1}^{N-1} \vec{\sigma}_j \cdot \vec{\sigma}_{j+1}$$

- Phase of quantum many-body systems
- Review: Abanin *et al.*, Rev. Mod. Phys. **91**, 021001 (2019).

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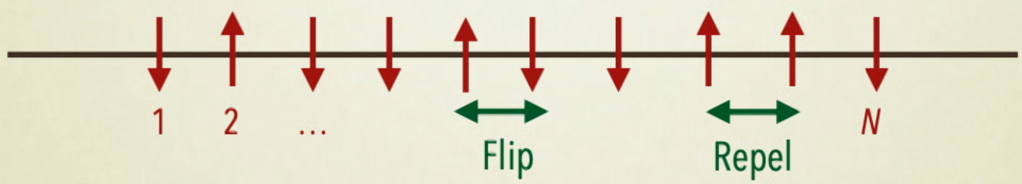

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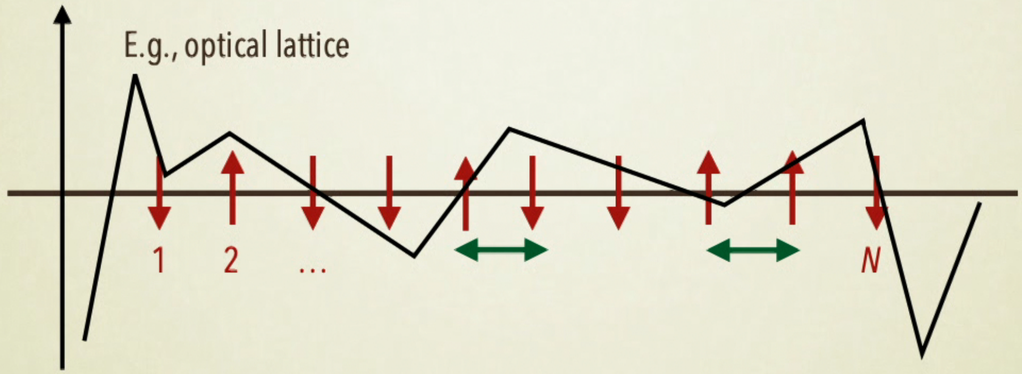

$$H = J\sum_{j=1}^{N-1} \vec{\sigma}_j \cdot \vec{\sigma}_{j+1} + h\sum_{j=1}^{N} h_j \sigma_j^z$$

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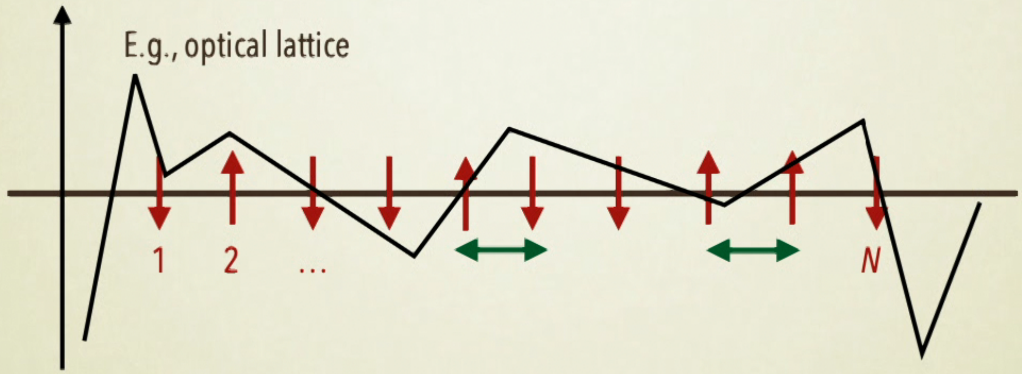

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- Phase of quantum many-body systems
- Review: Abanin *et al.*, Rev. Mod. Phys. **91**, 021001 (2019).
- If $h \gg J$ and you measure the particles' positions, the particles will stay ~static for a long time afterward.

NYH, White, Gopalakrishnan, Refael, Phys. Rev. B 99, 024203 (2019).

"Sarang specializes in everything that involves [quantum many-body systems], as well as in a blend of snideness, dark humor, and resignation that's oddly endearing."

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MBL-MOBILE

NYH, White, Gopalakrishnan, Refael, Phys. Rev. B 99, 024203 (2019).

MBL-mobile

NYH, White, Gopalakrishnan, Refael, Phys. Rev. B 99, 024203 (2019).

- Quantum many-body engine
- Run on an Otto cycle

MBL-MOBILE

NYH, White, Gopalakrishnan, Refael, Phys. Rev. B 99, 024203 (2019).

- Quantum many-body engine
- Run on an Otto cycle →

- 4 strokes: 2 isentropic, 2 isochoric

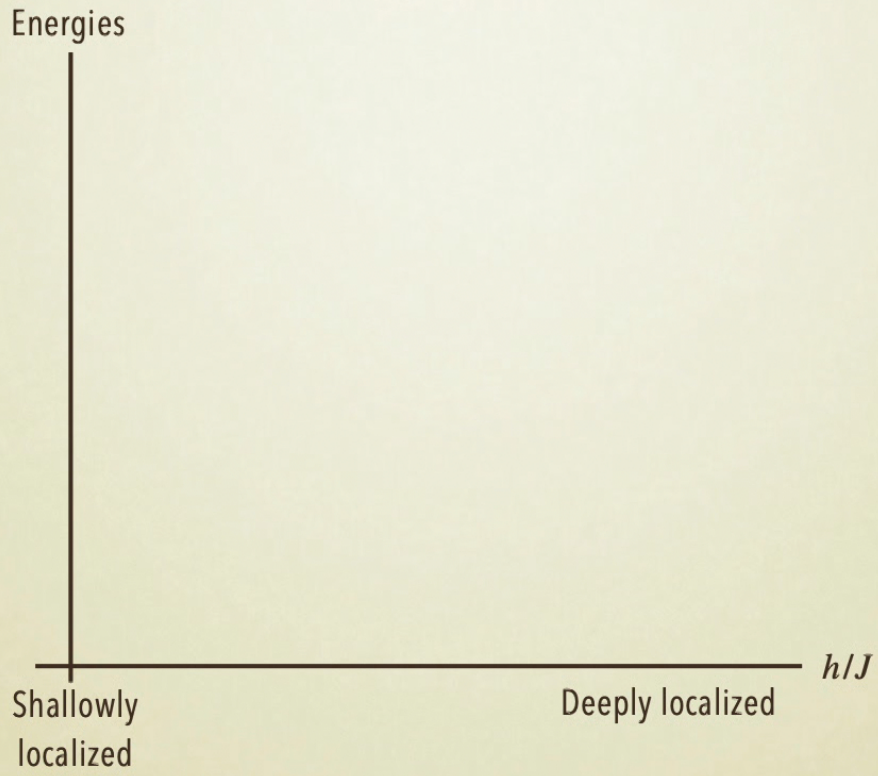
MBL Otto cycle

h/J

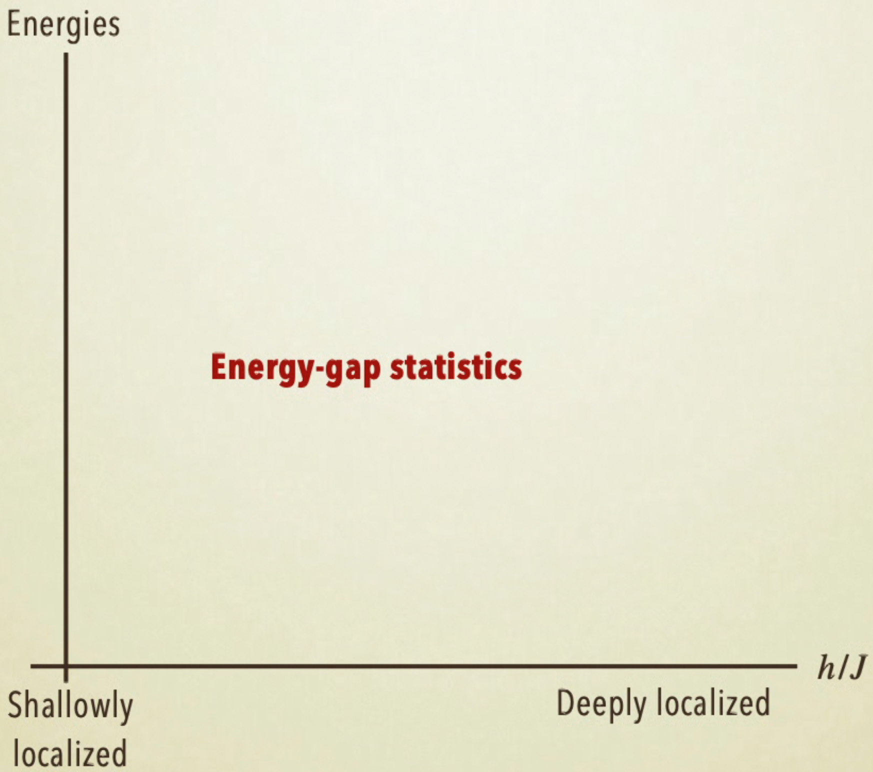
Shallowly
localized
(thermal)

Ask me about my favorite symmetries!

MBL Otto cycle



MBL Otto cycle



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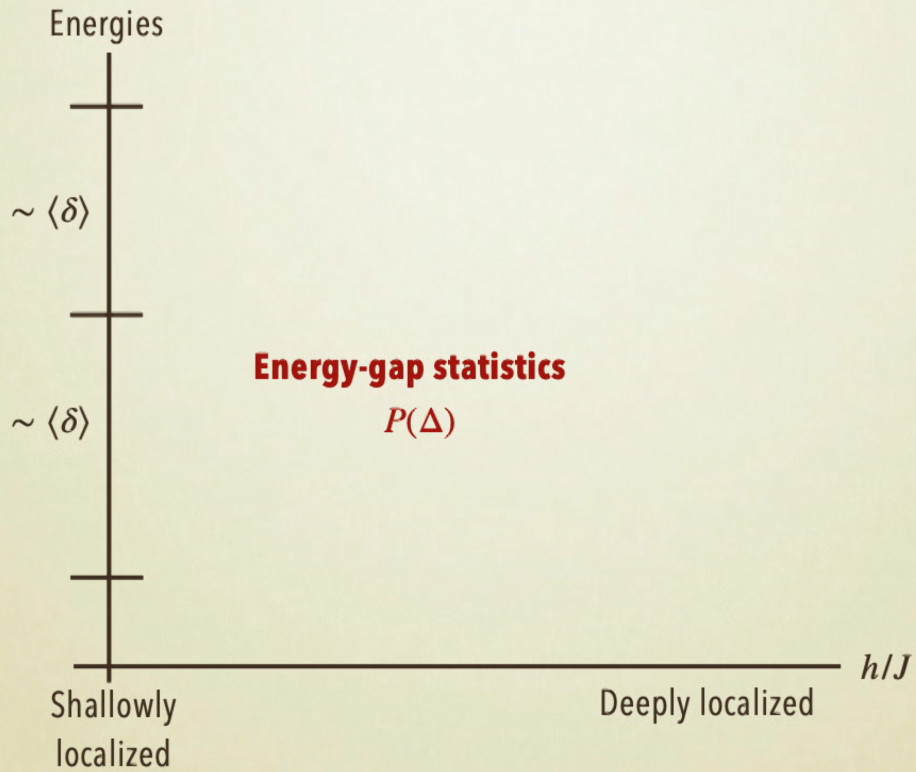
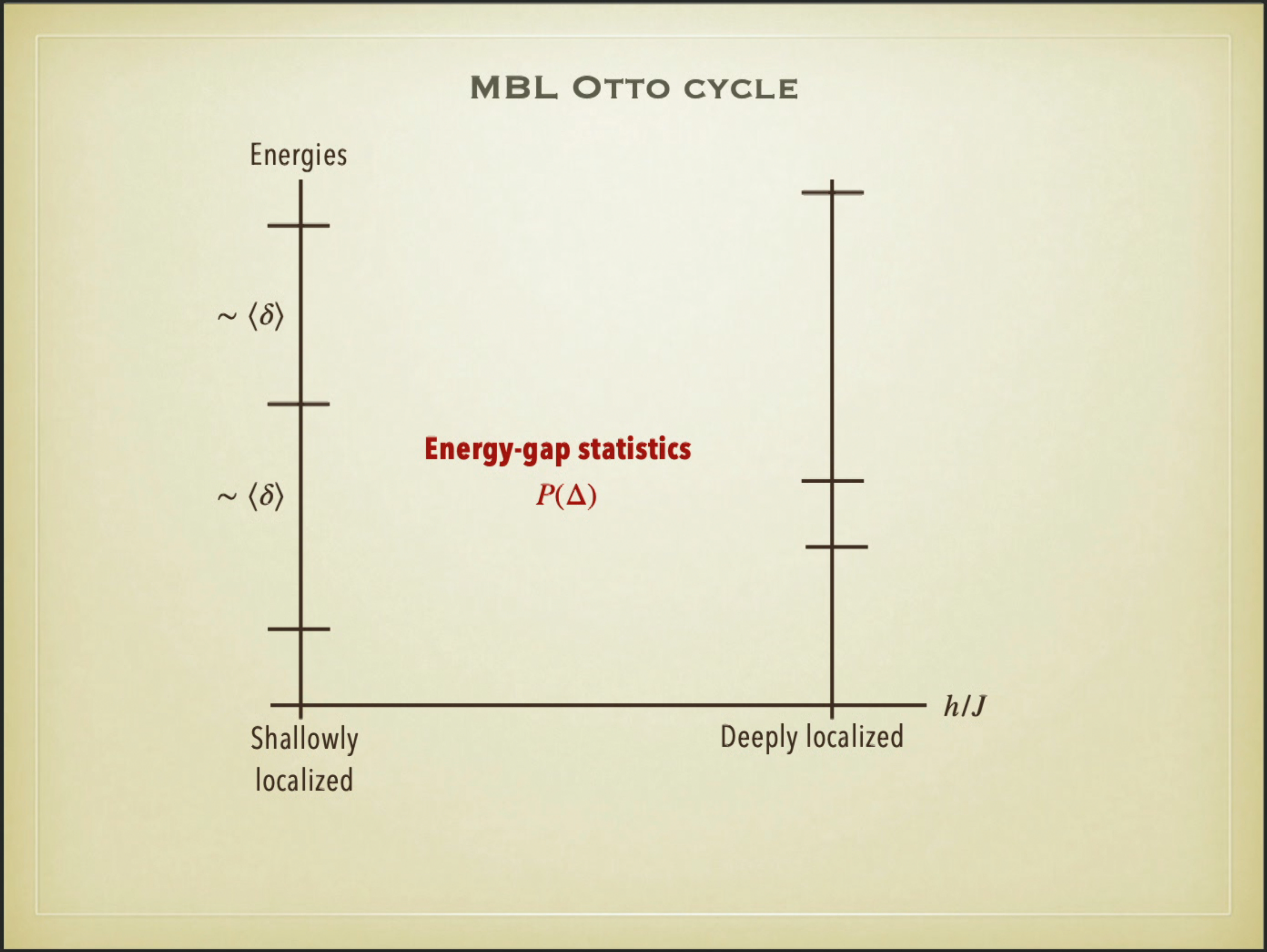
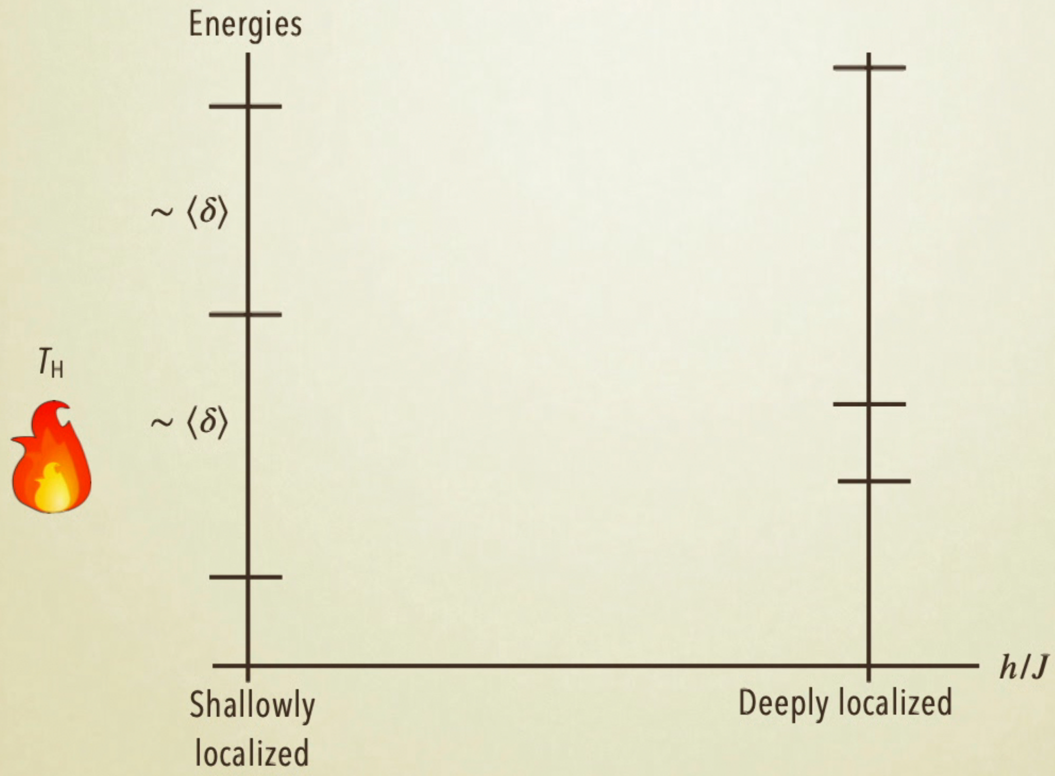



MBL Otto cycle
Energies
$\sim \langle\delta\rangle$
$\sim \langle\delta\rangle$
Energy-gap statistics
$P(\Delta)$
h/J
Shallowly localized
Deeply localized

MBL Otto cycle



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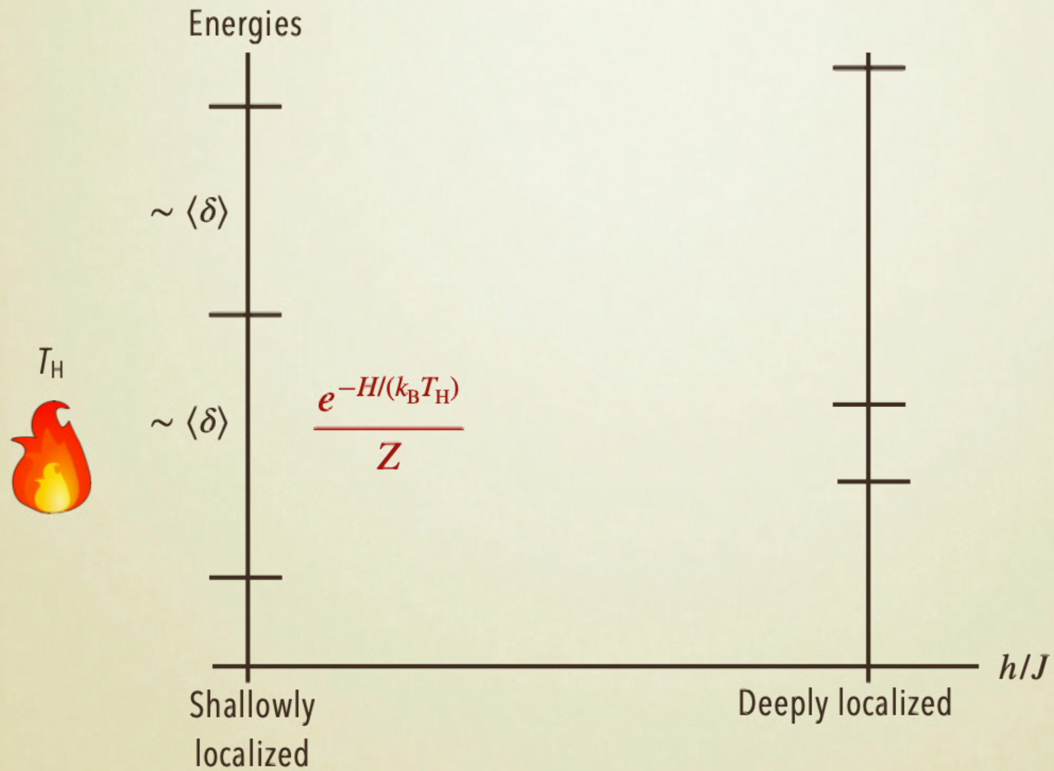

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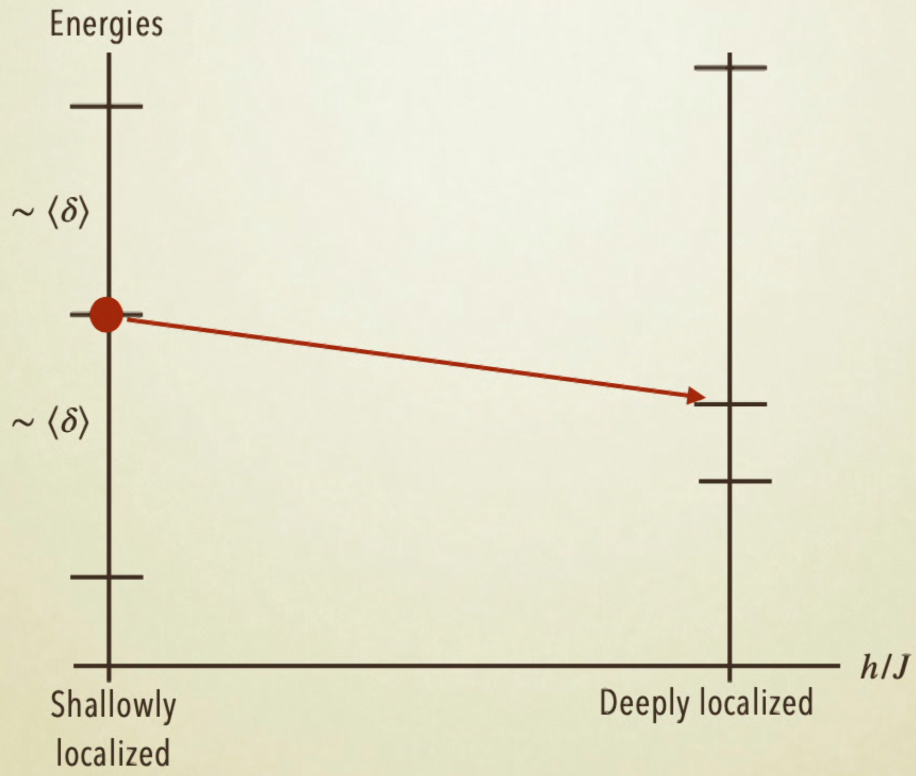

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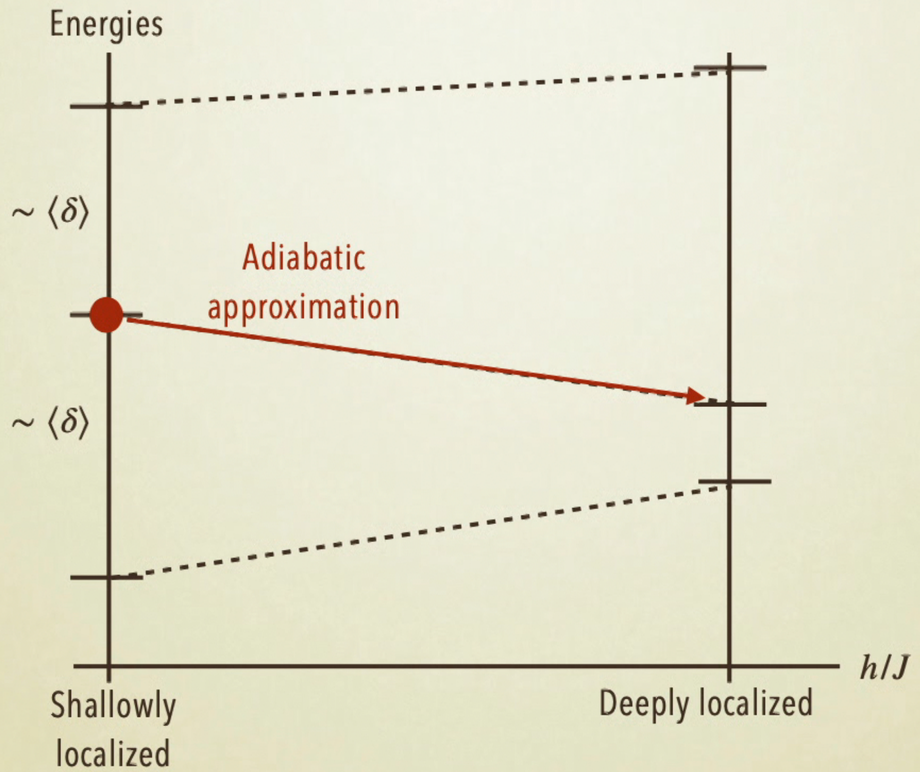

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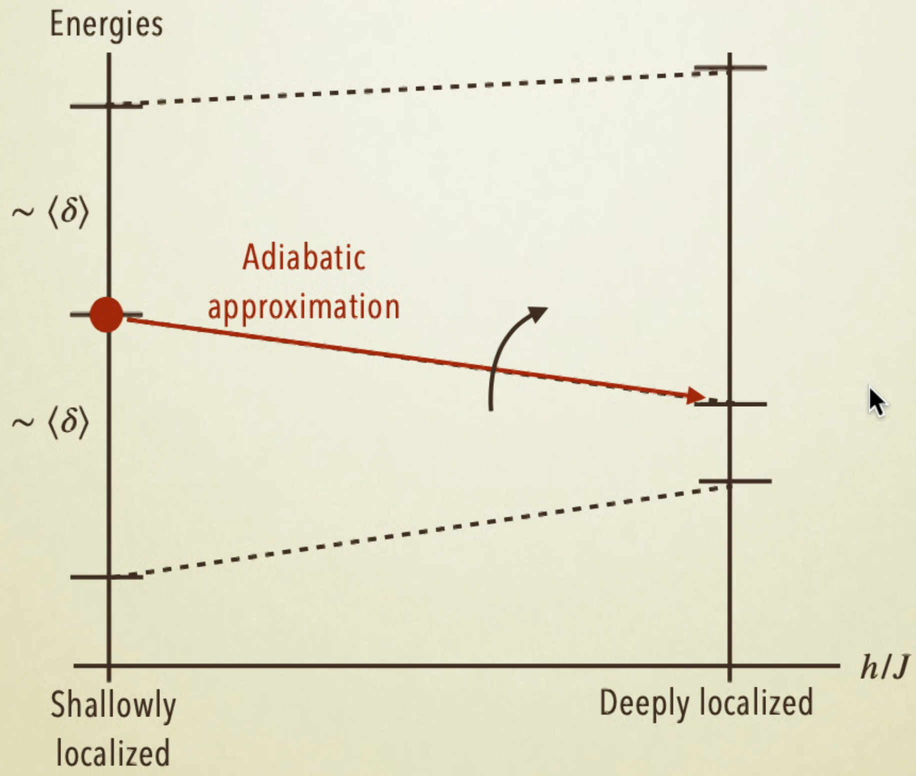

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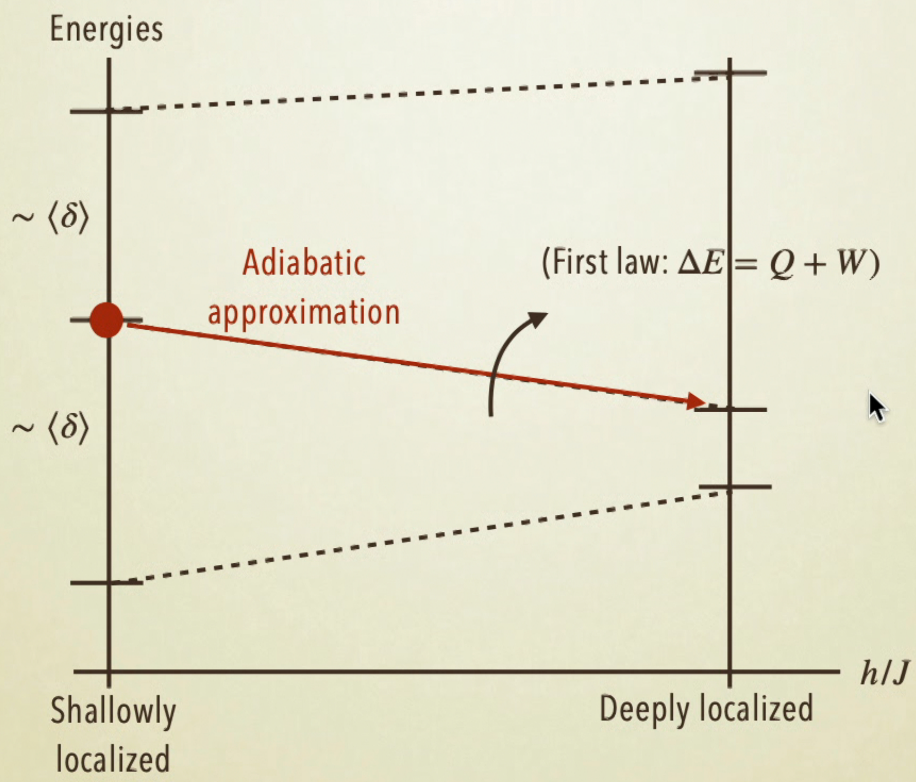

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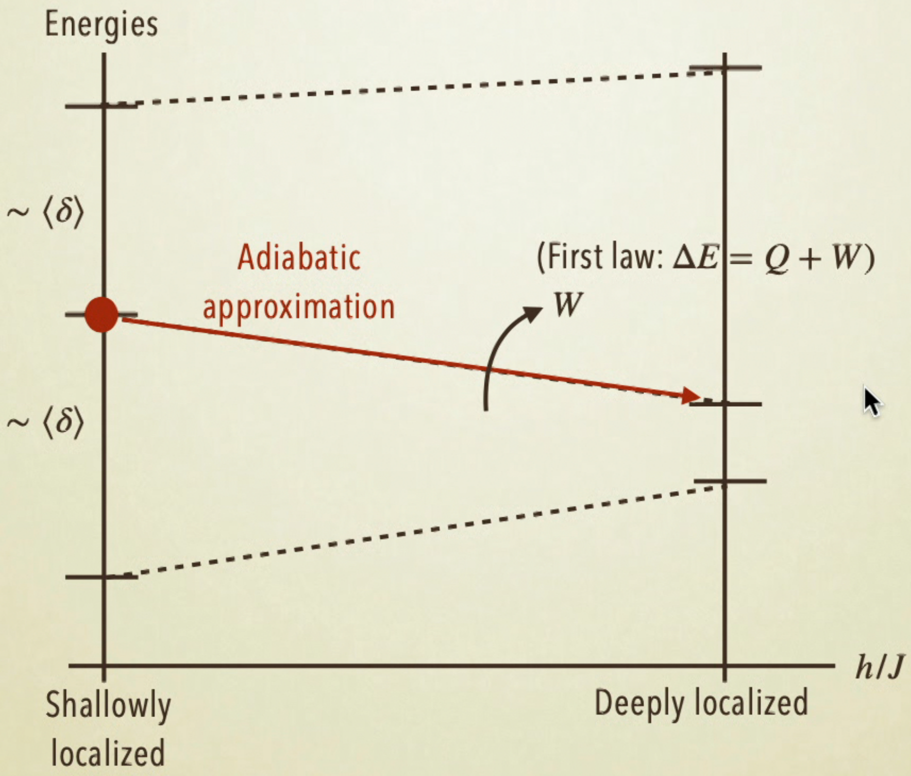

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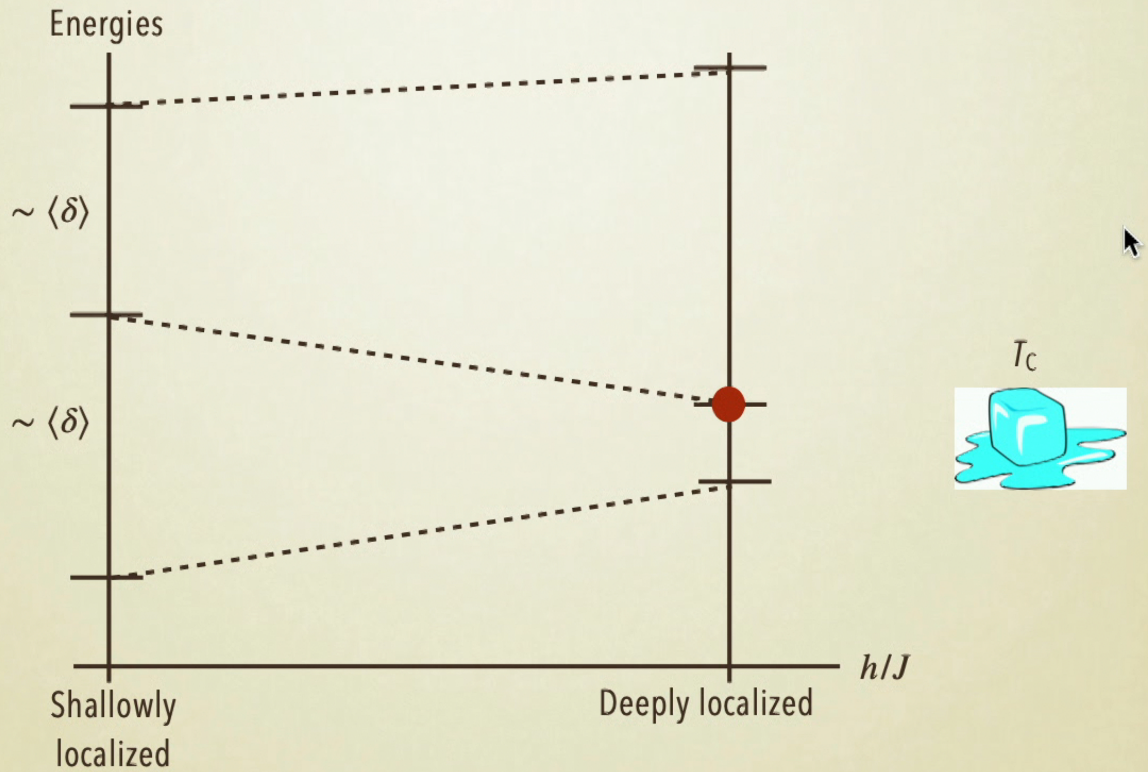

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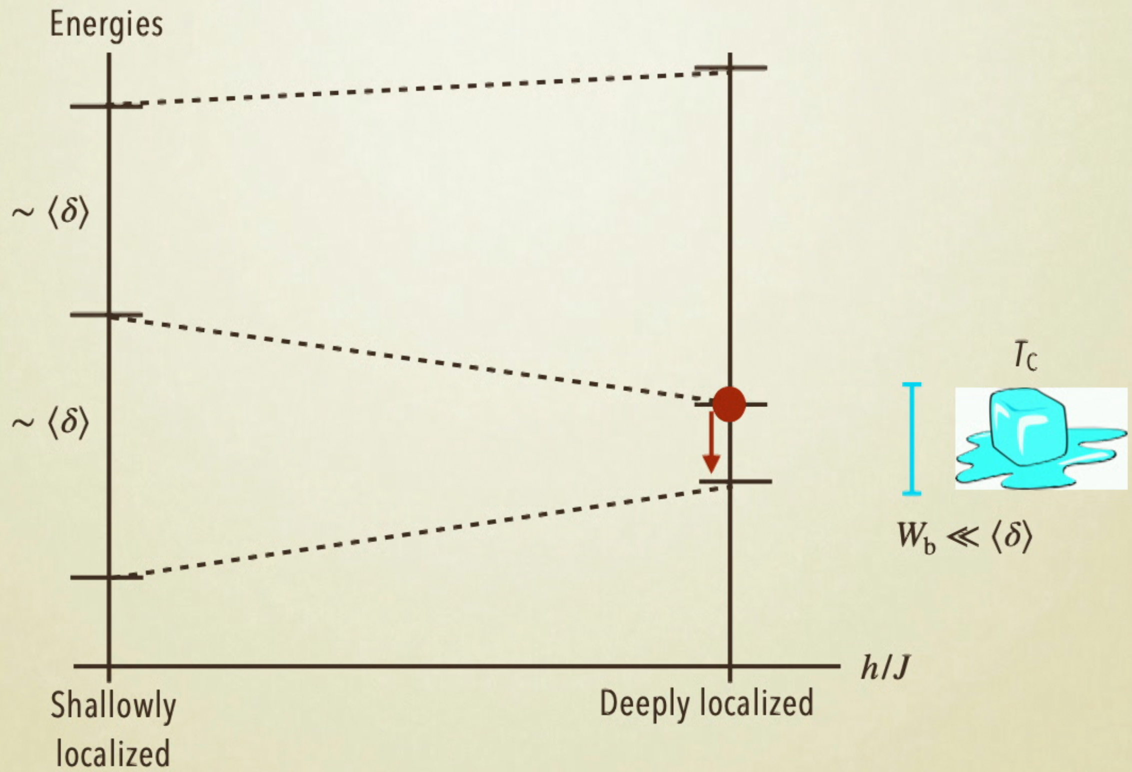

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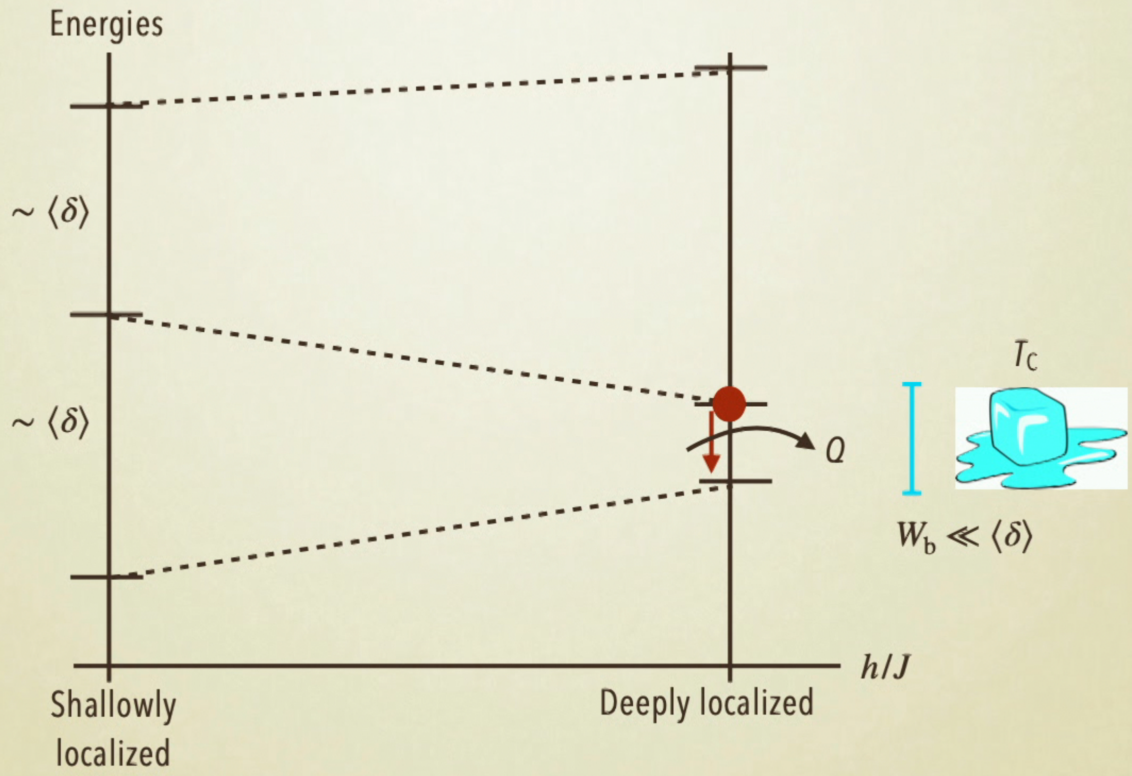

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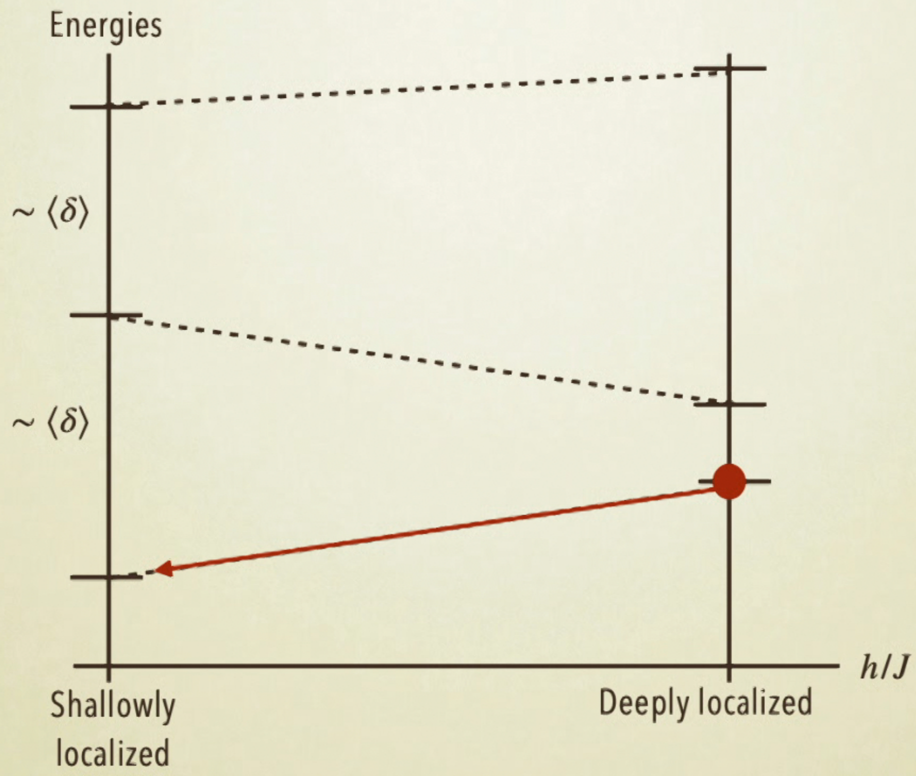

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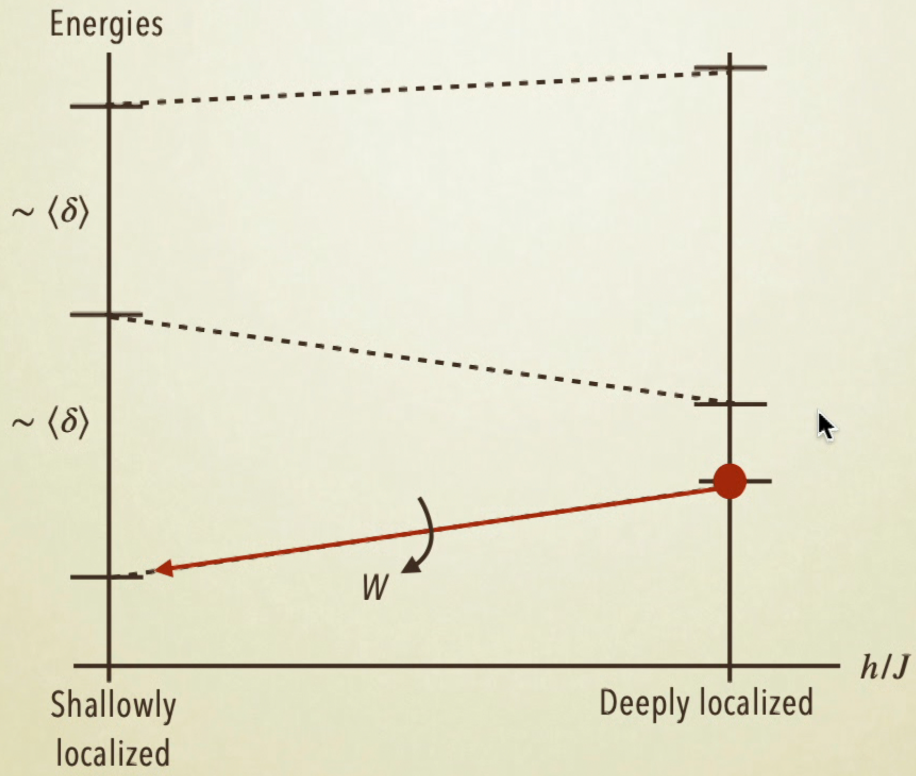

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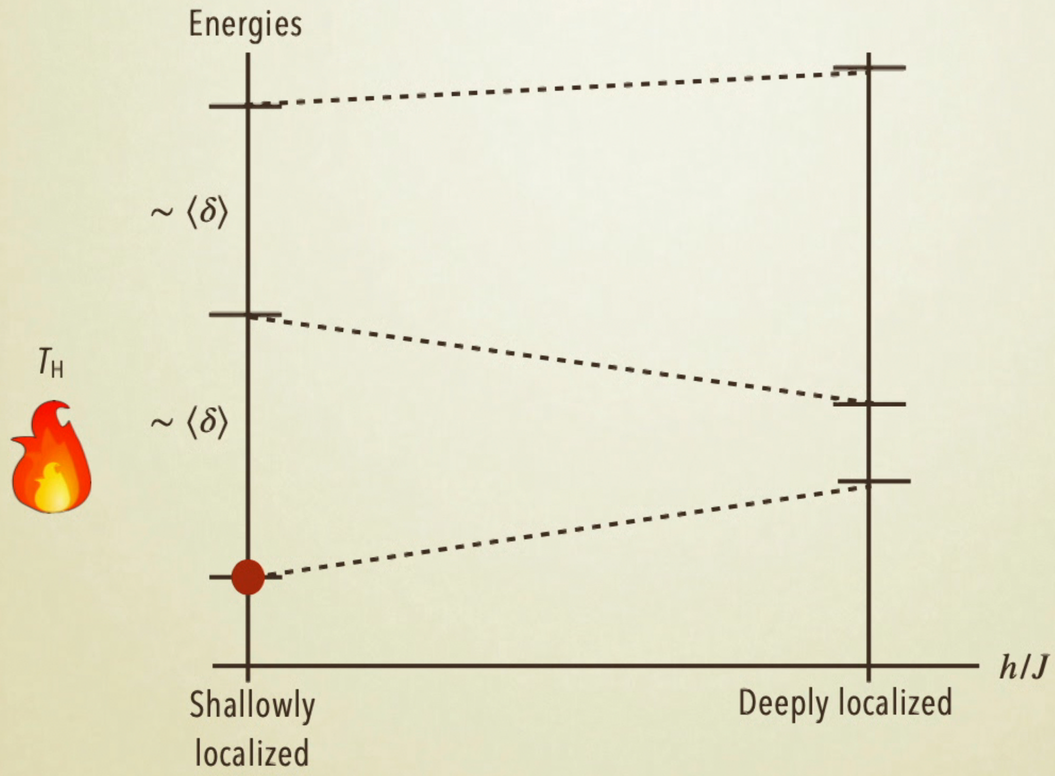

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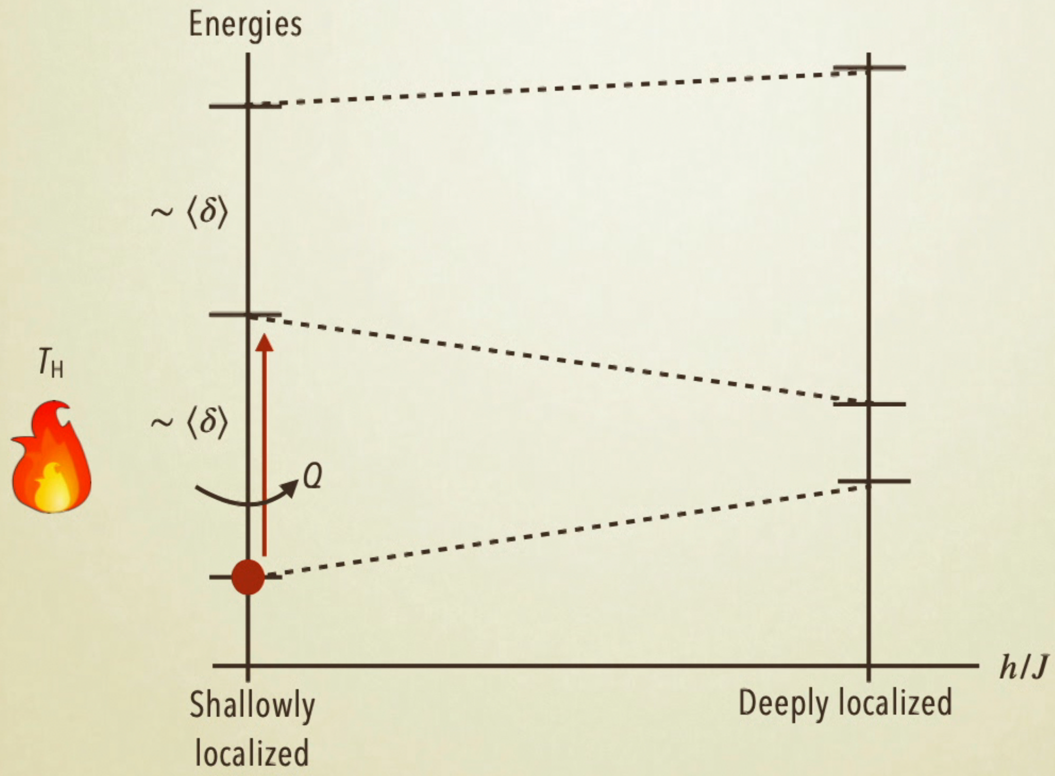

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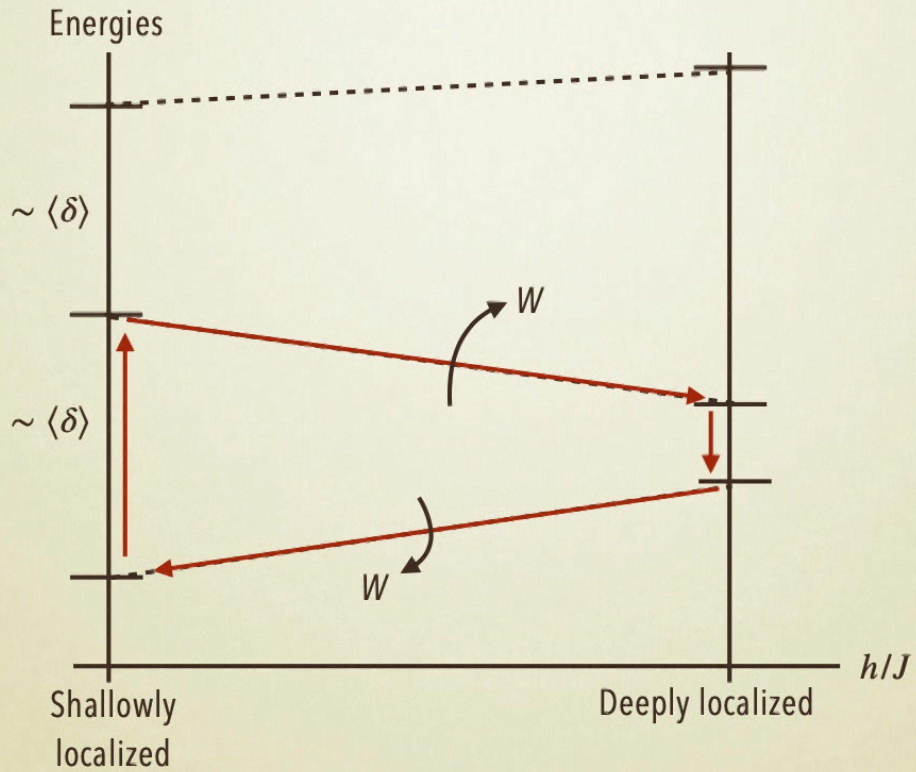

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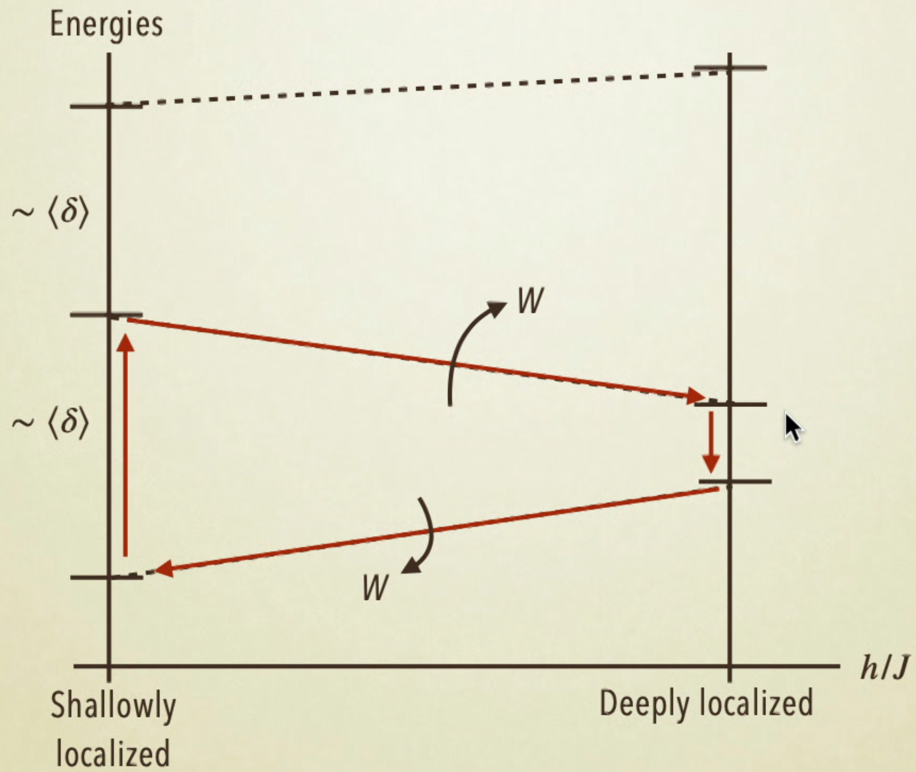

Why $\langle W_{\text{out}} \rangle > 0$: We take advantage of MBL's athermal gap statistics.

Scaling up to the thermodynamic limit

Scaling up to the thermodynamic limit

- Number of sites: N
- Size of energy band: $\sim N$
- Number of energy levels: 2^N
- Size of average gap: $\sim N/2^N > \langle W_{\text{tot}} \rangle$

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  $\rightarrow 0$ in the thermodynamic limit

Scaling up to the thermodynamic limit

Mesoscopic subengine

N_{sub} ~10 sites ⟵ The power is exponentially small in this constant.

N_{tot} sites ⟵ The power grows linearly with this.

♠♦♣♥

WHAT HAPPENS IN

~~VEGAS~~ a subengine

STAYS IN

~~VEGAS~~ a subengine.

Power and efficiency

Average work out per cycle $\sim N_{\text{tot}} W_{\text{b}}$ – (finite-temperature corrections) – (diabatic corrections)

- Estimate with phosphorus-doped silicon:
- Power $\sim 10^{-16}\,\text{W} \sim 10\Big($ power of  $\Big)$
- Power density

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- Estimate with phosphorus-doped silicon:
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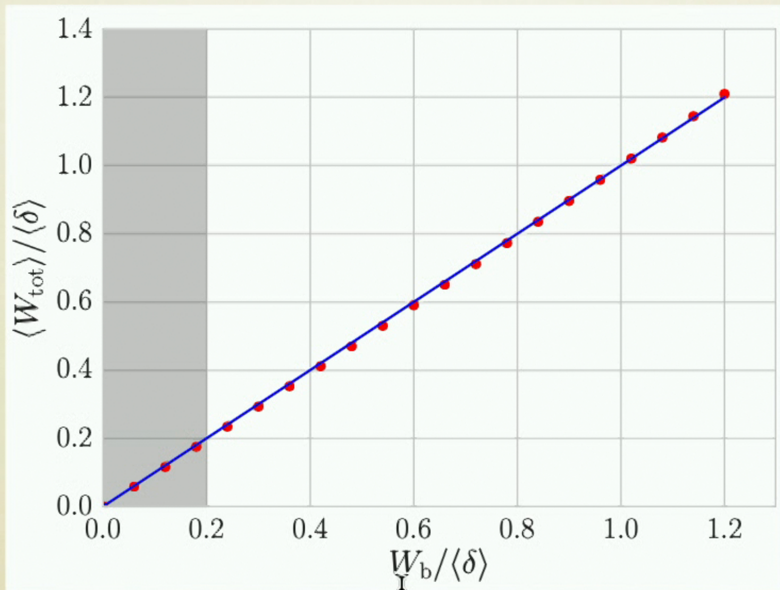
- Power density ~ 100 kW/m^3 $\sim 10^{-1}$ (power density of )

Numerical simulations

- 1D chain of 12 qubits
- Exact diagonalization



$$\langle W_{\mathrm{tot}} \rangle \approx W_{\mathrm{b}}$$

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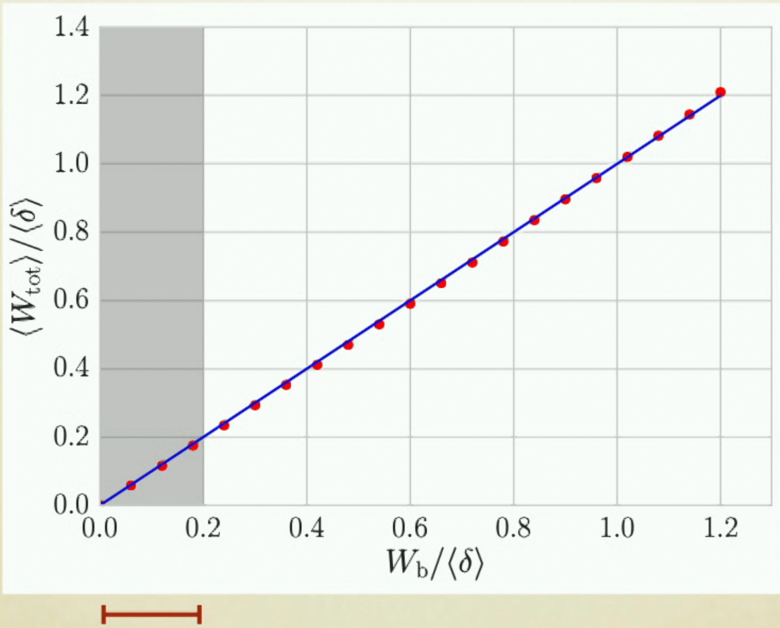

$$\langle W_{\text{tot}} \rangle \approx W_{\text{b}}$$

Power and efficiency

- **Efficiency:** $\eta := \dfrac{\langle W_{\mathrm{tot}} \rangle}{\langle Q_{\mathrm{in}} \rangle}$

$$= \boxed{1 - \frac{W_{\mathrm{b}}}{2\langle \delta \rangle}}$$

$$= \eta_{\mathrm{ideal-gas}} = 1 - \frac{1}{\left(V_+/V_-\right)^{(C_{\mathrm{P}}/C_{\mathrm{V}})-1}}$$

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Heat capacities

Power and efficiency

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$$= \eta_{\rm ideal-gas} = 1 - \frac{1}{\left(V_+/V_-\right)^{(C_{\rm P}/C_{\rm V})-1}}$$

Heat capacities

$$\leq \eta_{\rm Carnot} = 1 - \frac{T_{\rm C}}{T_{\rm H}}$$

Advantages of the MBL-mobile

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- **Robust scaling**
- **High power density** (*P/V*)
- **Reliability** (small fluctuations in work outputted during successful trials)

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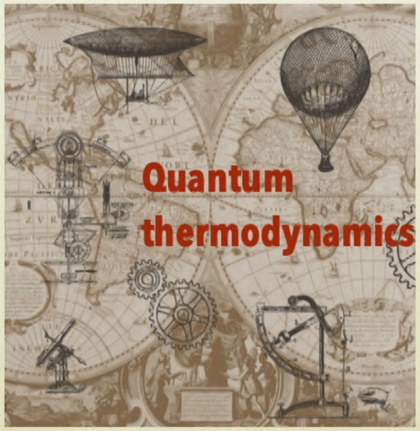
- **Robust scaling**
- **High power density** (*P/V*)
- **Reliability** (small fluctuations in work outputted during successful trials)
- **Few worst-case trials** ($W_{out} < 0$)

PEEKING INTO THE FUTURE

Bring quantum thermodynamics outside to meet the neighbors.

Yunger Halpern, in *Information and Interaction: Eddington, Wheeler, and the Limits of Knowledge*, Springer (2017).



PEEKING INTO THE FUTURE

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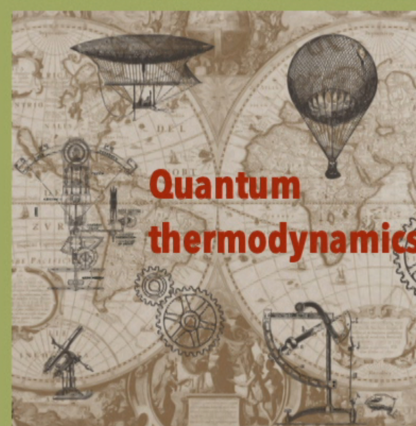
Atomic, molecular, and optical physics

Condensed matter

Chemistry



Biophysics

High-energy physics

PEEKING INTO THE FUTURE
OF QUANTUM STEAMPUNK BROADLY

Yunger Halpern, in *Information and Interaction: Eddington, Wheeler, and the Limits of Knowledge*, Springer (2017).

- **Answer pre-existing questions in other fields.**
  - Photosynthesis, photovoltaics, exciton hopping in quantum dots, …

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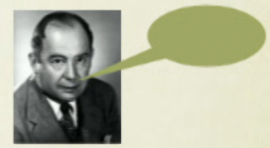
- **Integrate with other fields' toolkits.**
  - Eigenstate thermalization, quantum chaos, out-of-time-ordered correlators, Doob transforms, black-hole information paradox, …
- **Extend from abstract theory to experiments and technologies.**

RECAP

- Quantum information theory as a toolkit for re-envisioning thermodynamics →



- Information and work as resources in thermodynamics and computation →

- MBL-mobile →

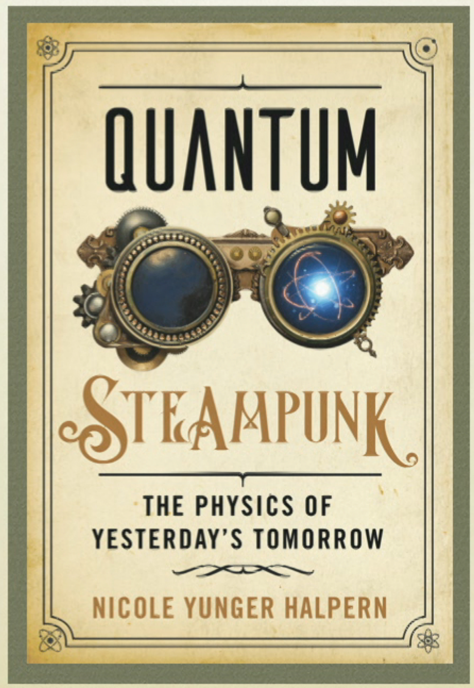
  - Many-body localization as athermal
  - Otto cycle
  - Power, efficiency, and 4 advantages

- Peek into the future →

IN CASE YOU'RE HOOKED...

Goold *et al.*, J. Phys. A **49**, 143001 (2016).

Vinjanampathy and Anders, Contemp. Phys. **57**, 4 (2016).



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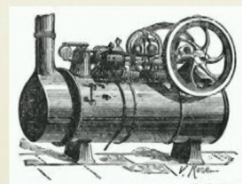

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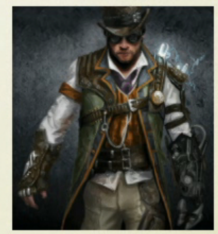
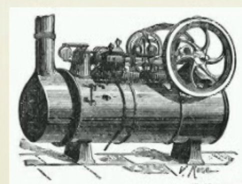


STEAMPUNK FANS DREAM IT.

+



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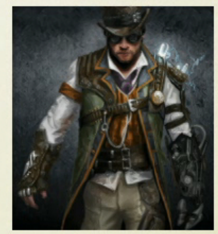

QUANTUM-INFORMATION THERMODYNAMICISTS LIVE IT.