Quantum thermodynamics

— a primer for the curious quantum mechanic

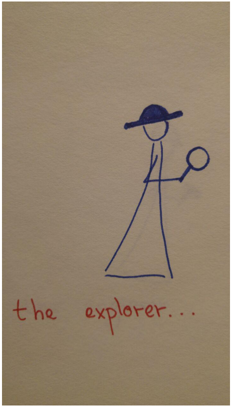
Lídia del Rio, ETH Zurich

QIP 2017 Seattle

Why quantum thermodynamics?

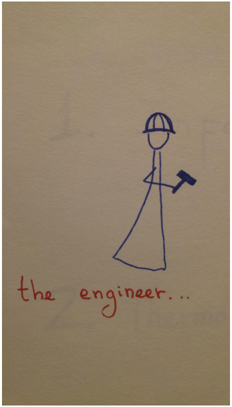
- Why is thermodynamics so effective?
- Emergent theory?
- Axiomatic formulation?

Why quantum thermodynamics?



- Do quantum systems obey the laws of thermodynamics?
- Correction terms: small or quantum?
- Can we explore new effects?

Why quantum thermodynamics?



- Heat dissipation in (quantum) computers
- Microscopic heat engines
- "Thermodynamics" of relevant parameters at the nano scale?

This lecture

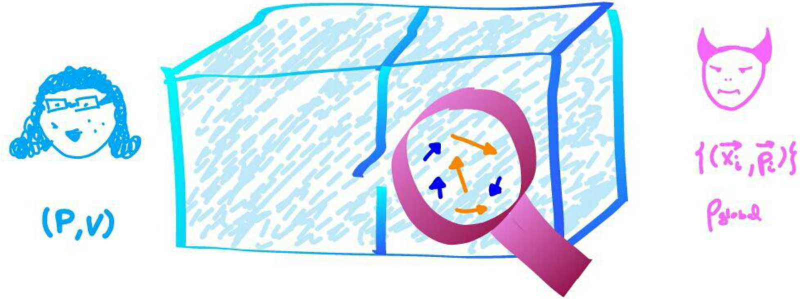
Information and thermodynamics

- Work cost of classical information processing
- Quantum work extraction and erasure

Axiomatic quantum thermodynamics

- Resource theory of thermal operations
- Insights and results
- Directions

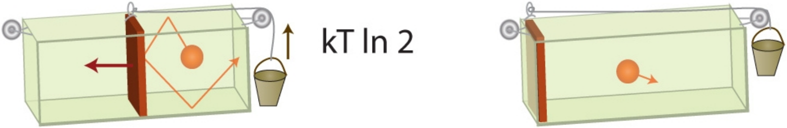
Maxwell's demon



Thermodynamics of information processing

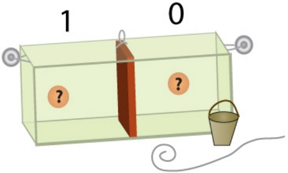
- How much work must we supply to compute a function?
- Must (quantum) computers always dissipate heat?

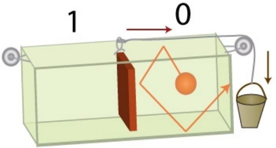
Szilard boxes



$$1 \text{ bit} + \text{heat bath } (T) \Rightarrow \text{work } kT \ln 2$$

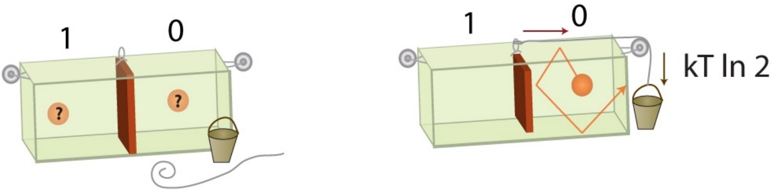
Szilard boxes





$$1 \text{ bit} + \text{heat bath } (T) \Leftarrow \text{work } kT \ln 2$$

Szilard boxes



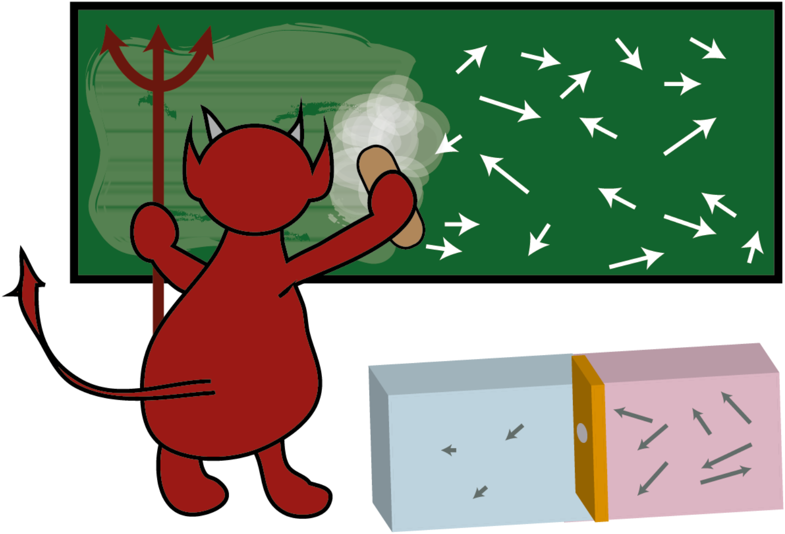
$$1 \text{ bit} + \text{heat bath } (T) \Leftrightarrow \text{work } kT \ln 2$$

Landauer's principle [1973]

Information + heat $\Leftrightarrow$ work

- rate: $kT \ln 2$ per bit

Maxwell's demon



Cost of computations [Bennett 1992]

Must computers dissipate heat?

- Irreversible computation: reversible + erasure
- $\mathcal{E}(\rho_S) = \mathrm{Tr}_{A'}(U\ \rho_S \otimes \sigma_A\ U)$

Cost of computations [Bennett 1992]

Must computers dissipate heat?

- Irreversible computation: reversible + erasure
- $\mathcal{E}(\rho_S) = \mathrm{Tr}_{A'}(U\ \rho_S \otimes \sigma_A\ U)$
- Reversible computations: free in principle
- Work cost: cost of erasure

Work cost of erasure

$$kT \ln 2 \text{ per bit}$$

Erasure

- Formatting a hard drive:

$$0?10101??1 \to 000000000$$

- Resetting a quantum system: $\rho_S \to |0\rangle_S$

Work cost of erasure

$$kT \ln 2 \text{ per bit}$$

Erasure

- Formatting a hard drive:

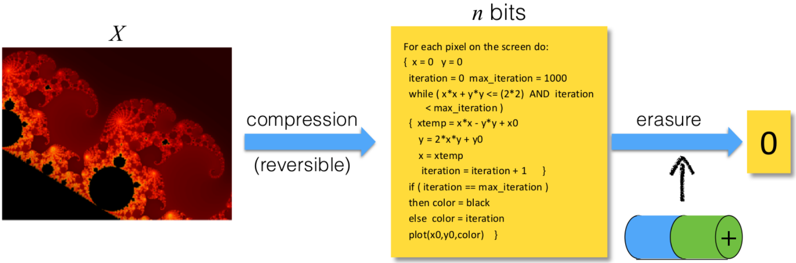
$$0?10101??1 \rightarrow 000000000$$

- Resetting a quantum system: $\rho_S \rightarrow |0\rangle_S$

In numbers

- $k = 1.38.10^{-23}\ J/K$
- Erasure of $16TB$ hard drive at room temperature: $0.4\mu J$
- Lifting a tomato by 1m on Earth: $1J$.

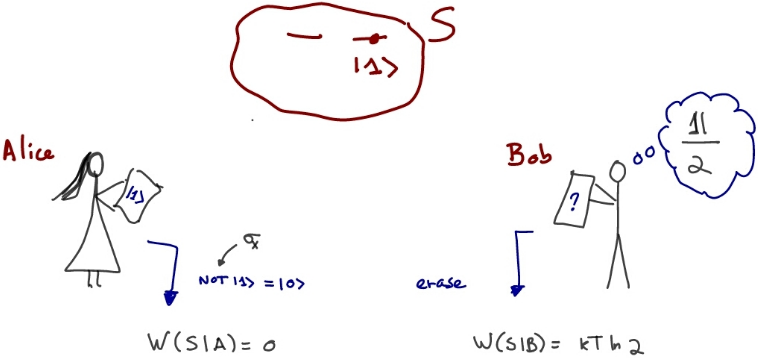
Information compression



Compression length: $n = H(\rho)$ bits

$$W(S) = H(S)\ kT \ln 2$$

(Subjective) side information



$$W(S|M) = H(S|M)\ kT \ln 2$$

What about quantum information?

- Szilard box for quantum systems?
  - How do we even measure work?

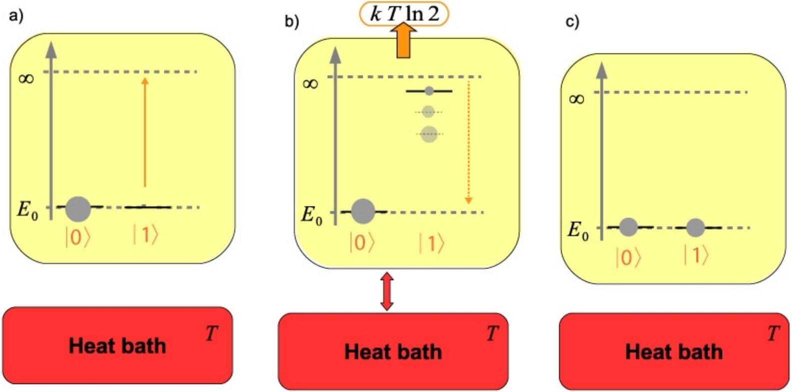
What about quantum information?

- Szilard box for quantum systems?
  - How do we even measure work?
- How to use quantum memories?
  - Reading $\implies$ disturbing contents

What about quantum information?

- Szilard box for quantum systems?
  - How do we even measure work?
- How to use quantum memories?
  - Reading $\implies$ disturbing contents
- Entropy $H(S|M)$ can be negative!
  - but does that mean anything?

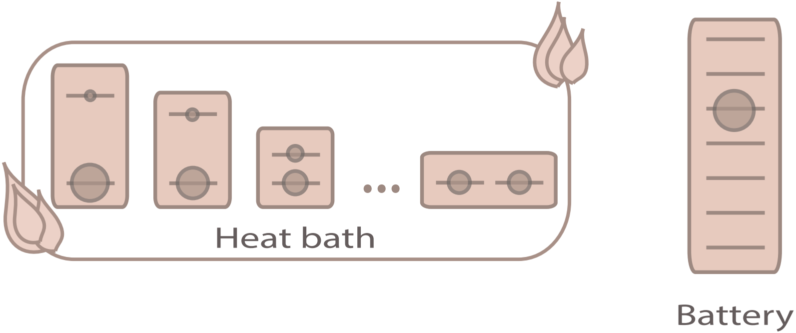
Quantum Szilard box



Semi-classical model [Alicki *et al.*]

- Manipulating H: moving energy level by δE costs δE if state is occupied
- Thermalizing: system relaxes to $G(T) = \frac{1}{Z} e^{\frac{H}{kT}}$

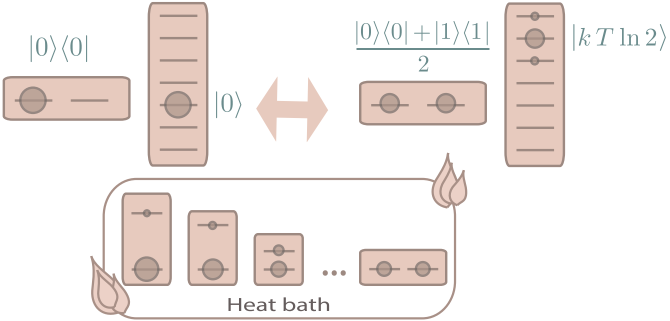
Quantum Szilard box



Quantum model [Skrzypczyk *et al.*]

- Free unitaries if $[U, H] = 0$
- Explicit heat bath and battery

Quantum Szilard box



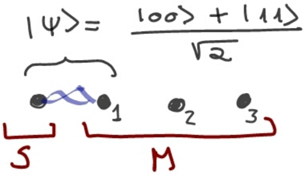
Quantum model [Skrzypczyk *et al.*]

- Free unitaries if $[U, H] = 0$
- Explicit heat bath and battery

Erasure with quantum side information

Memory preservation

Erase the first qubit, preserving the others:

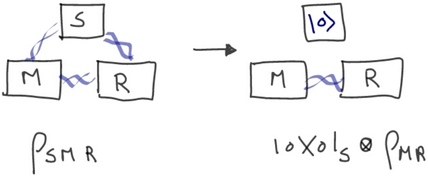


$$|\Psi\rangle\langle\Psi|_{S1} \otimes \rho_{2,3} \quad \to \quad |0\rangle\langle 0|_S \otimes \underbrace{\frac{\mathbb{1}_1}{2} \otimes \rho_{2,3}}_{\rho_M}$$

Erasure with quantum side information

Memory preservation

Generally: Erase S, preserving M (and correlations)



Erasure with quantum side information

We can still use the memory optimally:

$$W(S|M) = H(S|M)\ kT \ln 2$$

where $H(S|M) = H(SM) - H(M)$. [1]

[1] [LdR et al. 2011]

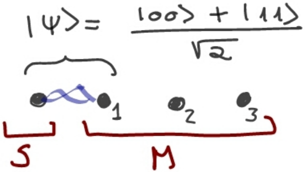
Erasure with quantum side information

We can still use the memory optimally:

$$W(S|M) = H(S|M)\ kT \ln 2$$

where $H(S|M) = H(SM) - H(M)$. [1]

Example



$$\underbrace{|\Psi\rangle\langle\Psi|_{S1} \otimes \rho_{2,3}}_{H(S|M)=-1} \quad \rightarrow \quad |0\rangle\langle 0|_S \otimes \underbrace{\frac{\mathbb{1}_1}{2} \otimes \rho_{2,3}}_{\rho_M}$$

---

[1] [LdR et al. 2011]

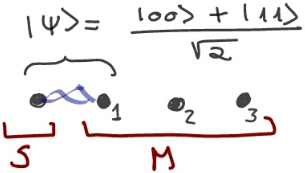
Erasure with quantum side information

We can still use the memory optimally:

$$W(S|M) = H(S|M)\ kT \ln 2$$

where $H(S|M) = H(SM) - H(M)$. [1]

Example



$|\Psi\rangle\langle\Psi|_{S1} \to \frac{\mathbb{1}_S}{2} \otimes \frac{\mathbb{1}_1}{2}$ + work $2kT \ln 2$

[1] [LdR et al. 2011]

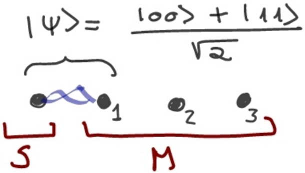
Erasure with quantum side information

We can still use the memory optimally:

$$W(S|M) = H(S|M)\ kT \ln 2$$

where $H(S|M) = H(SM) - H(M)$. [1]

Example



$\frac{\mathbb{1}_S}{2} \to |0\rangle\langle 0|_S$ – work $kT \ln 2$

[1] [LdR et al. 2011]

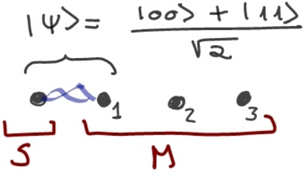
Erasure with quantum side information

We can still use the memory optimally:

$$W(S|M) = H(S|M)\ kT \ln 2$$

where $H(S|M) = H(SM) - H(M)$. [1]

Example



Total: $W(S|M) = -kT \ln 2 = H(S|M)\ kT \ln 2$

[1] [LdR et al. 2011]

Work cost of computations

Cost of implementing a map $\mathcal{E}$

- $\mathcal{E} : X \to X'$
- unitary dilation $X \to X' \otimes E$
- $W = H(E|X')_{\mathcal{E}(\rho)}\ kT \ln 2$ [2]

[2] [Faist et al. 2015]

Work cost of computations

Cost of implementing a map $\mathcal{E}$

- $\mathcal{E} : X \to X'$
- unitary dilation $X \to X' \otimes E$
- $W = H(E|X')_{\mathcal{E}(\rho)}\ kT \ln 2$ [2]

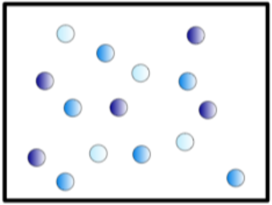
In numbers

- AND gate: $1.6\ kT \ln 2$
- Running a 20 Petaflops computation: $1W$

[2] [Faist et al. 2015]

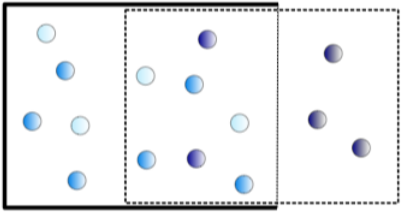
von Neumann entropy [1932]

Goal: erasure $\left(\sum_k p_k \, |\phi_k\rangle\langle\phi_k|\right)^{\otimes N} \to |\phi_1\rangle^{\otimes N}$



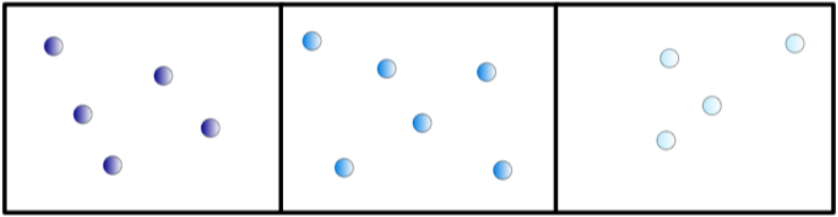
von Neumann entropy [1932]

Goal: erasure $\left(\sum_k p_k \, |\phi_k\rangle\langle\phi_k|\right)^{\otimes N} \to |\phi_1\rangle^{\otimes N}$



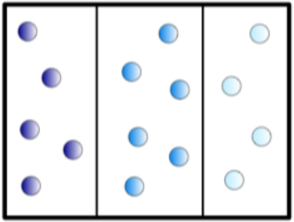
von Neumann entropy [1932]

Goal: erasure $\left(\sum_k p_k \, |\phi_k\rangle\langle\phi_k|\right)^{\otimes N} \to |\phi_1\rangle^{\otimes N}$



von Neumann entropy [1932]

Goal: erasure $\quad \left(\sum_k p_k \, |\phi_k\rangle\langle\phi_k|\right)^{\otimes N} \to |\phi_1\rangle^{\otimes N}$

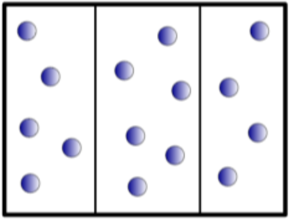


$$V_k = p_k \; V \implies W_k = N_k \ln(V_k/V) = N \; p_k \ln p_k$$

$$\frac{W}{N} = \sum_k p_k \ln p_k \qquad \implies \qquad S(\rho) = -\operatorname{Tr}(\rho \ln \rho)$$

von Neumann entropy [1932]

Goal: erasure $\quad \left(\sum_k p_k \, |\phi_k\rangle\langle\phi_k|\right)^{\otimes N} \to |\phi_1\rangle^{\otimes N}$



$$V_k = p_k \; V \implies W_k = N_k \ln(V_k/V) = N \; p_k \ln p_k$$

$$\frac{W}{N} = \sum_k p_k \ln p_k \qquad \implies \qquad S(\rho) = -\operatorname{Tr}(\rho \ln \rho)$$

Why is thermodynamics so effective?

- ~~microscopic details~~
- Identifies:
  - easy and hard operations
  - freely available resources

Why is thermodynamics so effective?

- ~~microscopic details~~
- Identifies:
  - easy and hard operations
  - freely available resources
- Efficient exploitation:
  - steam engines, fridges
  - cost of state transformations

Why is thermodynamics so effective?

- ~~microscopic details~~
- Identifies:
  - easy and hard operations
  - freely available resources
- Efficient exploitation:
  - steam engines, fridges
  - cost of state transformations
- Operational approach: resource theory

Why is thermodynamics so effective?

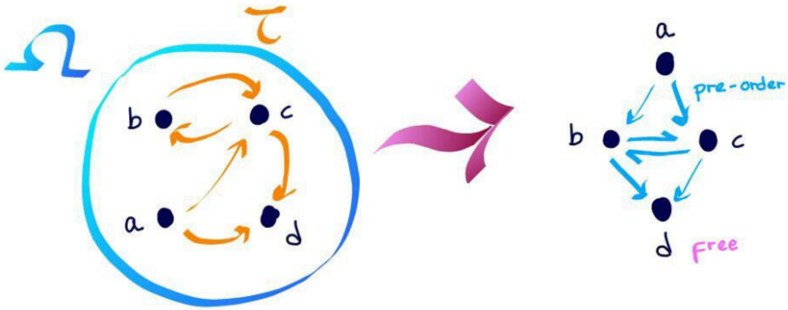
- ~~microscopic details~~
- Identifies:
  - easy and hard operations
  - freely available resources
- Efficient exploitation:
  - steam engines, fridges
  - cost of state transformations
- Operational approach: resource theory (just like LOCC)

Resource theories

Operational questions

- Can one achieve $X \to Y$?
- Monotones: characterizing pre-order
- Useful and useless resources?

Resource theories



Example: LOCC

- Allowed operations: local operations and classical communication
- Monotones: formation and distillation entanglement, squashed entanglement...
- Free resources: separable states. Currency: Bell states

Thermodynamics as a resource theory

- Limitations:
  - lack of knowledge: (N, V, T), (N, V, E), ...
  - conservation laws: energy, momentum, ...
  - limited control of operations

[3] [Carathéodory 1909] [Giles 1964] [Lieb and Yngvason 1998, 1999, 2003]

Thermodynamics as a resource theory

- Limitations:
  - lack of knowledge: (N, V, T), (N, V, E), ...
  - conservation laws: energy, momentum, ...
  - limited control of operations
- Resources: macroscopic descriptions of systems (hot gas, cold bodies)
- Operations: adiabatic, isothermal, ...
- Insights: laws of thermodynamics, free energy as a monotone, Carnot efficiency, ...[3]

[3] [Carathéodory 1909] [Giles 1964] [Lieb and Yngvason 1998, 1999, 2003]

Thermal operations

- Resources: quantum descriptions of systems (ρ_S, H_S)

[4] [Janzing 200] [Brandao *et al* 2011]

Thermal operations

- Resources: quantum descriptions of systems (ρ_S, H_S)
- Account for entropy: $U\rho_S U^\dagger$

[4] [Janzing 200] [Brandao *et al* 2011]

Thermal operations

- Resources: quantum descriptions of systems (ρ_S, H_S)
- Account for entropy: $U\rho_S U^\dagger$
- Account for energy: $U\rho_S U^\dagger, \quad [U, H_S] = 0$

[4] [Janzing 200] [Brandao *et al* 2011]

Thermal operations

- Resources: quantum descriptions of systems (ρ_S, H_S)
- Account for entropy: $U\rho_S U^\dagger$
- Account for energy: $U\rho_S U^\dagger, \quad [U, H_S] = 0$
- Free environment: $U(\rho_S \otimes \mathrm{Gibbs}(T))U^\dagger, \quad [U, H_{SB}] = 0$

[4] [Janzing 200] [Brandao *et al* 2011]

Thermal operations

- Resources: quantum descriptions of systems (ρ_S, H_S)
- Account for entropy: $U\rho_S U^\dagger$
- Account for energy: $U\rho_S U^\dagger, \quad [U, H_S] = 0$
- Free environment: $U(\rho_S \otimes \mathrm{Gibbs}(T))U^\dagger, \quad [U, H_{SB}] = 0$
- Free forgetting: $\mathrm{Tr}_A[U(\rho_S \otimes \mathrm{Gibbs}(T))U^\dagger], \quad [U, H_{SB}] = 0$

[4] [Janzing 200] [Brandao *et al* 2011]

Thermal operations

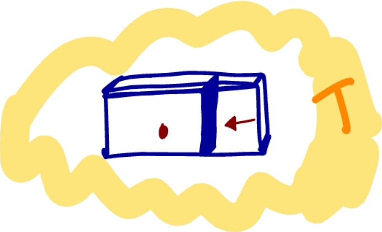
- Resources: quantum descriptions of systems (ρ_S, H_S)
- Account for entropy: $U\rho_S U^\dagger$
- Account for energy: $U\rho_S U^\dagger, \quad [U, H_S] = 0$
- Free environment: $U(\rho_S \otimes \mathrm{Gibbs}(T))U^\dagger, \quad [U, H_{SB}] = 0$
- Free forgetting: $\mathrm{Tr}_A[U(\rho_S \otimes \mathrm{Gibbs}(T))U^\dagger], \quad [U, H_{SB}] = 0$
- Toy model [4]

[4] [Janzing 200] [Brandao *et al* 2011]

Why thermal states?

$$G(T) = \frac{1}{Z} e^{-\frac{H}{kT}}$$

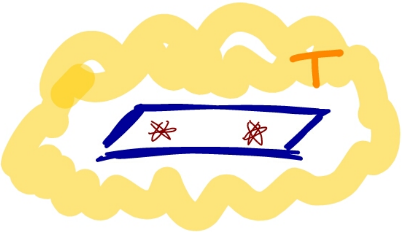
Landauer's principle



Why thermal states?

$$G(T) = \frac{1}{Z} e^{-\frac{H}{kT}}$$

Noise models



Why thermal states?

$$G(T) = \frac{1}{Z} e^{-\frac{H}{kT}}$$

Reduced description

- Large system composed of independent parts: $H = H_S + H_E$
- Energy shell Ω_E of fixed energy
- Global state of maximal entropy: $\mathbb{1}_{\Omega_E}/d_{\Omega_E}$
- $\rho_S = G_S(T(E))$

Why thermal states?

$$G(T) = \frac{1}{Z} e^{-\frac{H}{kT}}$$

Typicality of thermalization[5]

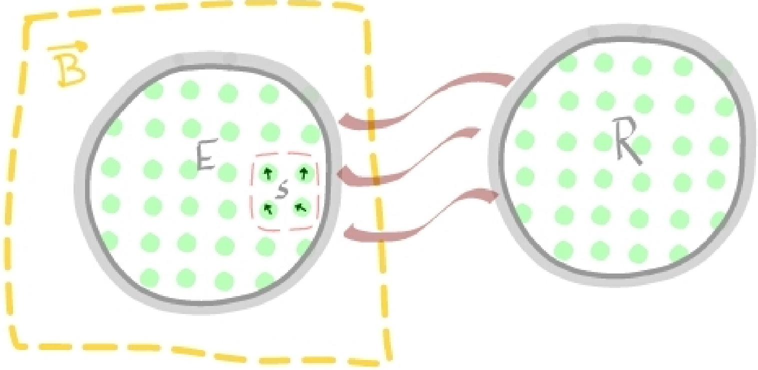
- $d_S \ll d_\Omega$
- Static thermalization: for most global states and most subsystems,
$$\rho_S \approx \mathrm{Tr}_E(\mathbb{1}_\Omega / d_\Omega) = G_S(T)$$
- Decoupling (also with side quantum information).
- Also if S corresponds to observable.

[5] Review: [Gogolin & Eisert 2016]

Why thermal states?

$$G(T) = \frac{1}{Z} e^{-\frac{H}{kT}}$$

Typicality of thermalization[5]



[5] Review: [Gogolin & Eisert 2016]

Why thermal states?

$$G(T) = \frac{1}{Z} e^{-\frac{H}{kT}}$$

Typicality of thermalization[5]

- Evolution towards thermal state: if H is rich, $\rho_S(t) \approx G_S(T)$ for most times t and initial states.
- Time scales: under study

[5] Review: [Gogolin & Eisert 2016]

Why thermal states?

$$G(T) = \frac{1}{Z} e^{-\frac{H}{kT}}$$

Complete passivity

Intuition: only free state that does not trivialize the resource theory

- Allowed operations: unitaries
- Allowed many copies of a state
- Cannot extract energy $\implies G(T)^{\otimes n}$

Why thermal states?

$$G(T) = \frac{1}{Z} e^{-\frac{H}{kT}}$$

Complete passivity

Intuition: only free state that does not trivialize the resource theory

- Allowed operations: unitaries
- Allowed many copies of a state
- Cannot extract energy $\implies G(T)^{\otimes n}$

Still a spherical cow...

Insights: noisy operations

Case $H = 0$

- Pre-order: majorization[6] $\rho \to \sigma \iff \rho \prec \sigma$,

$$\rho \prec \sigma \iff \sum_{i=1}^{k} \lambda_i(\rho) \geq \sum_{i=1}^{k} \lambda_i(\sigma)$$

[6] Review: [Gour et al (2013)]

Insights: noisy operations

Case $H = 0$

- Pre-order: majorization[6] $\rho \to \sigma \iff \rho \prec \sigma$,

$$\rho \prec \sigma \iff \sum_{i=1}^{k} \lambda_i(\rho) \geq \sum_{i=1}^{k} \lambda_i(\sigma)$$

- Monotones: Schur-convex functions, e.g.

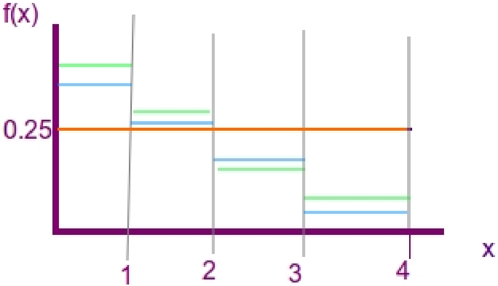
$$D^{\alpha}(\rho_S || \mathbb{1}_S / d_S),$$

entropies $H(\rho), H_{\alpha}(\rho), \ldots$

- Classically: $D^{\alpha}(\rho||\sigma) = \frac{\text{sgn } \alpha}{\alpha - 1} \log \sum_i p_i^{\alpha} q_i^{1-\alpha}$

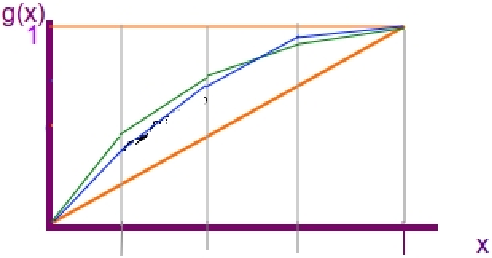
[6] Review: [Gour et al (2013)]

Lorenz curves



1. Sort eigenvalues of ρ: $p_1 \geq p_2 \geq \cdots \geq p_d$
2. Build step function: $f_\rho(x) = p_i(\rho) \quad \text{for } i-1 \leq x < i$

Lorenz curves



1. Integrate to get Lorenz curve:

$$g_\rho(x) = \int_0^{d\ x} f_\rho(x')\ dx'$$

2. Pre-order: $\rho \to \sigma \iff g_\rho(x) \geq g_\sigma(x),\ \forall\ x \in [0, 1[$

Insights: thermal operations

General Hamiltonian

- Pre-order: thermo-majorization (for block-diagonal states!)
- Monotones: e.g. relative entropy to thermal state

$$D^{\alpha}(\rho||G(T)),$$

  free energies...
- Rescaled Lorenz curves[7]

[7] [Renes] [Horodecki & Oppenheim]

Insights: thermal operations

Rescaled Lorenz curves

For block-diagonal states,

1. Rescale eigenvalues: $r_i = p_i \ e^{\beta E_i}$ and sort them.
2. Build step function:

$$f_\rho(x) = r_i \quad \text{for} \sum_{k<i} e^{-\beta E_k} \leq x < \sum_{k\leq i} e^{-\beta E_k}$$

3. Integrate to get Lorenz curve:

$$g_\rho(x) = \int_0^{x} f_\rho(x') \ dx'$$

4. Pre-order: $\rho \to \sigma \iff g_\rho(x) \geq g_\sigma(x), \ \forall \ x \in [0, 1)$

Recovering the second law

Free energies as monotones

- $\rho \to \sigma \implies F^{\alpha}(\rho, T) \geq F^{\alpha}(\sigma, T), \; \forall \, \alpha,$ where[8]

$$F^{\alpha}(\rho, T) = kT \; [D^{\alpha}(\rho || G(T)) - \log Z]$$

[8] [Brandao *et al* 2014]

Recovering the second law

Free energies as monotones

- $\rho \to \sigma \implies F^\alpha(\rho, T) \geq F^\alpha(\sigma, T), \ \forall\, \alpha$, where[8]

$$F^\alpha(\rho, T) = kT\ [D^\alpha(\rho || G(T)) - \log Z]$$

- $\Leftarrow$ for classical states

[8] [Brandao *et al* 2014]

Recovering the second law

Free energies as monotones

- $\rho \to \sigma \implies F^{\alpha}(\rho, T) \geq F^{\alpha}(\sigma, T), \ \forall\, \alpha$, where[8]

$$F^{\alpha}(\rho, T) = kT\ [D^{\alpha}(\rho||G(T)) - \log Z]$$

- $\Leftarrow$ for classical states
- In particular

$$F^{1}(\rho, T) = \mathrm{Tr}(H\ \rho) - kTS(\rho).$$

[8] [Brandao *et al* 2014]

Recovering the second law

Free energies as monotones

- $\rho \to \sigma \implies F^{\alpha}(\rho, T) \geq F^{\alpha}(\sigma, T), \; \forall\, \alpha$, where[8]

$$F^{\alpha}(\rho, T) = kT\; [D^{\alpha}(\rho || G(T)) - \log Z]$$

- $\Leftarrow$ for classical states
- In particular

$$F^{1}(\rho, T) = \mathrm{Tr}(H\;\rho) - kTS(\rho).$$

- Free energies: rescaling of $D^{\alpha}(\rho || G(T))$ such that

$$F^{1}(\;|E\rangle\langle E|\;, T) = E$$

[8] [Brandao *et al* 2014]

Recovering thermodynamics

Third law

Cannot cool to ground state with finite resources.[9]

[9] [Masanes & Openheim 2014] [Janzing] [Wilming *(in prep.)*]
[10] [LdR *et al* 2011]
[11] [Reeb & Wolf 2013] [Woods *et al* 2015]

Recovering thermodynamics

Third law

Cannot cool to ground state with finite resources.[9]

Landauer's principle

- Work cost of erasing S in the presence of M costs [10]

$$W \approx kT\ H(S|M)_\rho$$

- Single-shot: H^ε, finite-size effects[11] limit efficiency

[9] [Masanes & Openheim 2014] [Janzing] [Wilming *(in prep.)*]
[10] [LdR *et al* 2011]
[11] [Reeb & Wolf 2013] [Woods *et al* 2015]

Recovering thermodynamics

Fluctuation theorems

- Crooks' and Jarzinsky's relations: prob. violation exponentially surpressed
- Beyond two-measurement setting for coherent processes,[12] e.g. $|+\rangle \rightarrow |0\rangle$

[12] [Elouard et al 2015] [Åberg 2016] [Perarnau-Llobet, et al (2016)]

Multiple conserved quantities

- Multiple[13] conserved quantities $A_1, A_2, \ldots$
- Allowed operations: $U : [U, A_i] = 0, \ \forall i$

[13] [Vaccaro and Barnett 2011] [Lostaglio et al 2015] [Guryanova et al 2015] [Yunger Halpern et al 2015] [Perarnau-Llobet et al 2015]

Multiple conserved quantities

- Multiple[13] conserved quantities $A_1, A_2, \dots$
- Allowed operations: $U : [U, A_i] = 0,\ \forall i$
- Generalized Gibbs state

$$G(\beta_1, \beta_2, \dots) = e^{\beta_1 A_1 + \beta_2 A_2 + \dots}$$

- Typical thermalization and passivity results hold

[13] [Vaccaro and Barnett 2011] [Lostaglio et al 2015] [Guryanova et al 2015] [Yunger Halpern et al 2015] [Perarnau-Llobet et al 2015]

Multiple conserved quantities

- Multiple[13] conserved quantities $A_1, A_2, \ldots$
- Allowed operations: $U : [U, A_i] = 0, \ \forall i$
- Generalized Gibbs state

$$G(\beta_1, \beta_2, \ldots) = e^{\beta_1 A_1 + \beta_2 A_2 + \ldots}$$

- Typical thermalization and passivity results hold
- Monotones: $D^\alpha(\rho || G(\beta_1, \beta_2, \ldots))$
- First protocols for conversion between $A_1, A_2, \ldots$

[13] [Vaccaro and Barnett 2011] [Lostaglio et al 2015] [Guryanova et al 2015] [Yunger Halpern et al 2015] [Perarnau-Llobet et al 2015]

Coherence: quantum-quantum thermodynamics?

Needed to implement unitaries (laser).

[14] [Åberg 2014]
[15] [Korzekwa et al 2016]

Coherence: quantum-quantum thermodynamics?

Needed to implement unitaries (laser).

Catalytic coherence?

- Relevant properties of coherence reservoir ρ: (Δ_ρ, M_ρ)
  - $\Delta_\rho = \mathrm{Tr}(\frac{1}{2}(\Delta + \Delta^\dagger)\rho)$ coherence: $\Delta = \sum_n |n+1\rangle\langle n|$
  - M : lowest occupied energy level

[14] [Åberg 2014]
[15] [Korzekwa et al 2016]

Coherence: quantum-quantum thermodynamics?

Needed to implement unitaries (laser).

Catalytic coherence?

- Relevant properties of coherence reservoir ρ: (Δ_ρ, M_ρ)
  - $\Delta_\rho = \mathrm{Tr}(\frac{1}{2}(\Delta + \Delta^\dagger)\rho)$ coherence: $\Delta = \sum_n |n+1\rangle\langle n|$
  - M : lowest occupied energy level
- Unbounded coherence reservoir:[14]
  - back-action of implementing operations: stretching of ρ
  - no degradation of Δ
  - can always pump up M with energy

[14] [Åberg 2014]

[15] [Korzekwa et al 2016]

Coherence: quantum-quantum thermodynamics?

Needed to implement unitaries (laser).

Catalytic coherence?

- Relevant properties of coherence reservoir ρ: (Δ_ρ, M_ρ)
  - $\Delta_\rho = \mathrm{Tr}(\frac{1}{2}(\Delta + \Delta^\dagger)\rho)$ coherence: $\Delta = \sum_n |n+1\rangle\langle n|$
  - M : lowest occupied energy level
- Unbounded coherence reservoir:[14]
  - back-action of implementing operations: stretching of ρ
  - no degradation of Δ
  - can always pump up M with energy
- More realistic reservoirs:[15]
  - protocol for work extraction from coherent states
  - operationally restoring reservoir: $(\Delta_\rho, M_\rho) = (\Delta_{\rho'}, M_{\rho'})$

[14] [Åberg 2014]
[15] [Korzekwa et al 2016]

Clocks and control

$$[U, H_0] = 0, \quad U = e^{-i\,t\,H_U}$$

- $H_U(t) \implies$ control
- Effort of building and keeping control systems
- Clocks and controls are out of equilibrium systems
- Fairer book-keeping: give agents little control, explicit clocks

[16] [Brandao et al (2011)] [Malabarba et al 2014]
[17] [Wilming et al 2014]
[18] [Woods et al 2016]

Clocks and control

$$[U, H_0] = 0, \quad U = e^{-i\,t\,H_U}$$

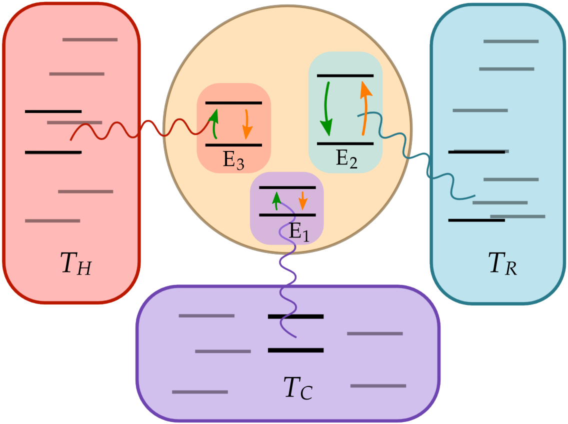
- $H_U(t) \implies$ control
- Effort of building and keeping control systems
- Clocks and controls are out of equilibrium systems
- Fairer book-keeping: give agents little control, explicit clocks

First steps

- Ideal clock (particle in a line) $\implies$ catalytic, perfect U [16]
- Thermal contact[17]
- Dimension bounds and clock degradation[18]

[16] [Brandao et al (2011)] [Malabarba et al 2014]
[17] [Wilming et al 2014]
[18] [Woods et al 2016]

Autonomous thermal engines



Carnot efficiency[19] (fine-tuned gaps)

[19] [Skrzypczyk et al (various)]

Open questions

Clocks and control

- Designs for efficient clocks (theory and experiment)
- Combine with insights from reference frames
- Further restrictions (no fine-tuning of baths, Hamiltonians)
- Clean framework (how much control to give the agent?)
- Relation to coherence (again!)
- Relation to time in foundations

Open questions

Realistic resource theories

- Operational notions of temperature: baths beyond Gibbs [20]
- Finite-size effects [21]
- Beyond weak coupling
- Realistic resource descriptions for experimentalists [22]
- Towards operational resource theories[23]

[20] [Farshi et al (in prep)]
[21] [Reeb et al (2013)], [Woods et al (2015)]
[22] [LdR et al (2015)], [Krämer & LdR (2016)]
[23] [Yunger Halpern (2015)]

Open questions

Generalized probability theories

- GPTs: apply von Neumann's operational approach to entropy [24]
- Relate thermodynamics on different physical theories

AdS/CFT

- Notions of thermalization
- Black hole entropy & information paradox

[24] [Barnum et al 2015]

Thank you for your attention!

Reviews

- Goold, Huber, Riera, LdR & Skrzypczyk, The role of quantum information in thermodynamics — a topical review, J. Phys. A, **49**, 14 (2016).
- Gour, Müller, Narasimhachar, Spekkens, Yunger Halpern, The resource theory of informational nonequilibrium in thermodynamics , Phys. Rev. Lett. 111, 250404 (2013).
- Gogolin, Eisert, Equilibration, thermalisation, and the emergence of statistical mechanics in closed quantum systems, Rep. Prog. Phys. 79, 056001 (2016).

Thermo QIP 2017

Talks

- Monday 3pm Carlo Sparaciari
- Wednesday 9am Jonathan Oppenheim
- Friday 2pm Michael Kastoryano, then Kohtaro Kato

Posters

Monday

- 35 A sufficient set of gates for thermodynamics
- 36 Fundamental energy cost for quantum measurement
- 38 Thermal Operations under Partial Information - An operational derivation of Jaynes Principle
- 39 Thermalization and Return to Equilibrium on Finite Quantum Lattice Systems

Tuesday

- 52 Autonomous quantum machines and finite sized clocks