Quantum heat engine operating between thermal and spin reservoirs

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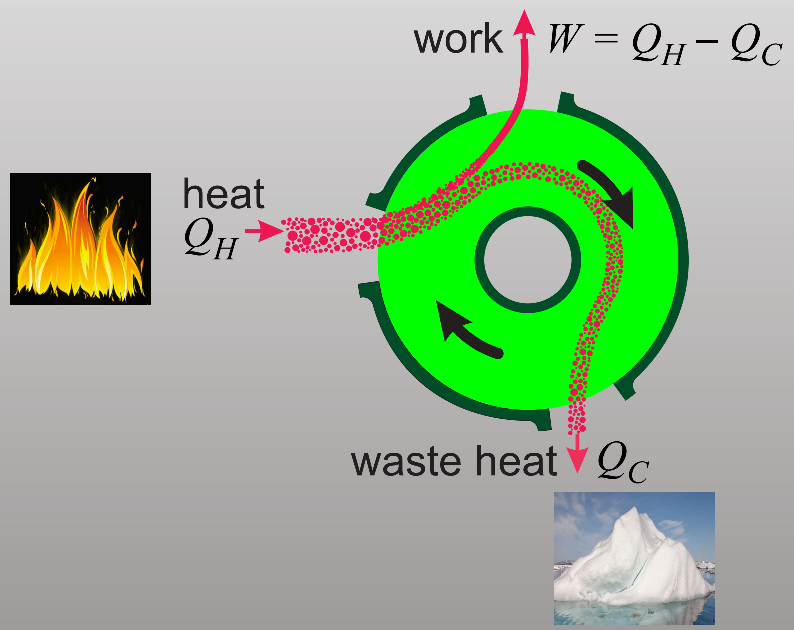
Overview

- Classical Heat Engines
- Maxwell's Demon, Landauer's erasure, and engines
- The spin heat engine (SHE)
- Proposal for quantum dot (QD) implementation*

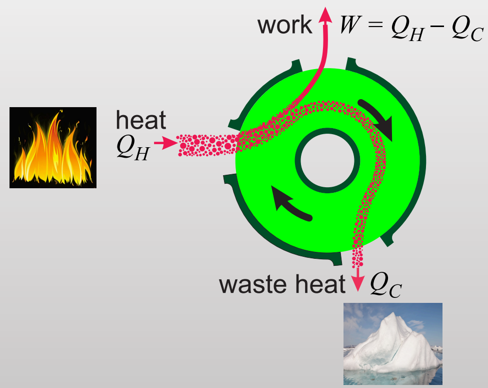
* J. S. S. T. Wright, T. Gould, A. R. R. Carvalho, S. Bedkihal, and J. A. Vaccaro
Phys. Rev. A 97, 052104 (2018)

Classical heat engine

Heat Engine

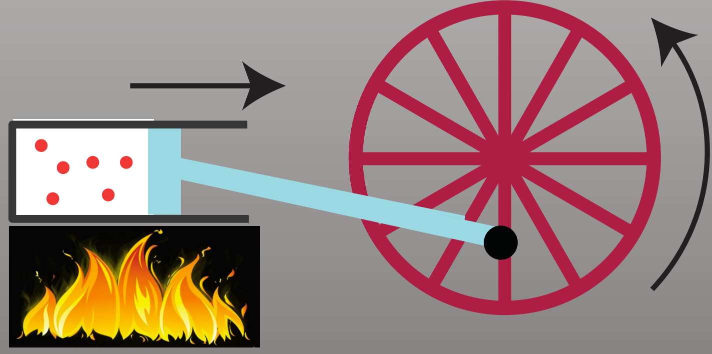


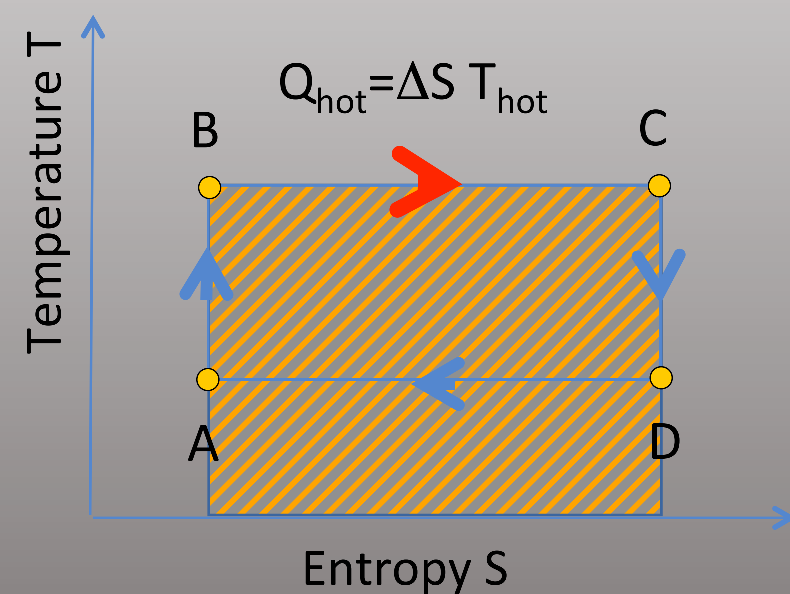
Classical Heat Engine



Carnot cycle:

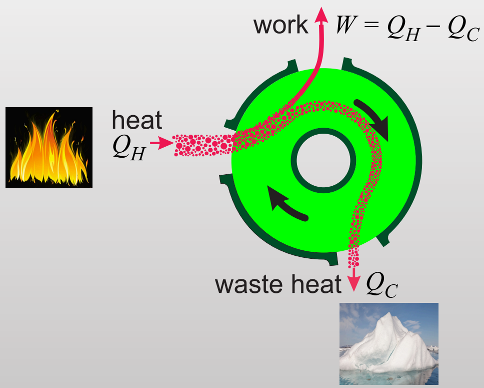
Isothermal Expansion
Heated gas does work on system





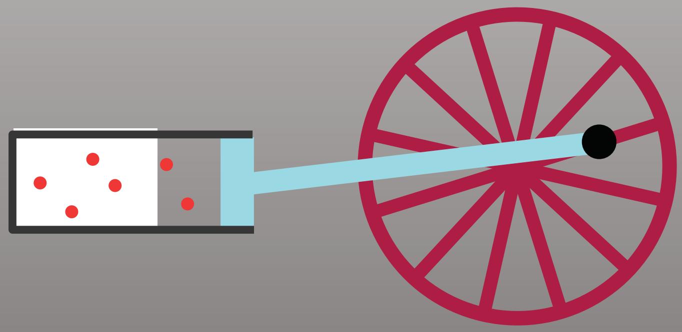
Isothermal- Heat Absorption

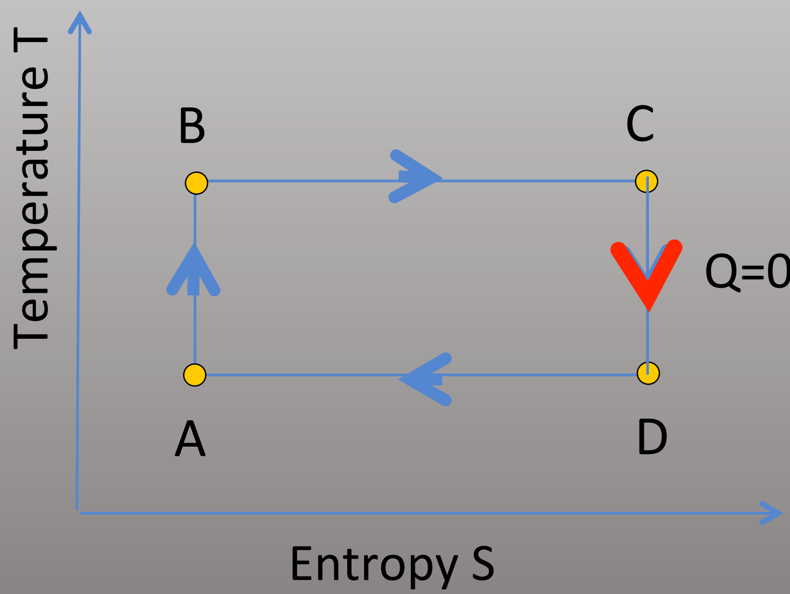
Classical Heat Engine



Carnot cycle:

Adiabatic Expansion
Expanding gas cools and does work





Adiabatic- Thermal Isolation

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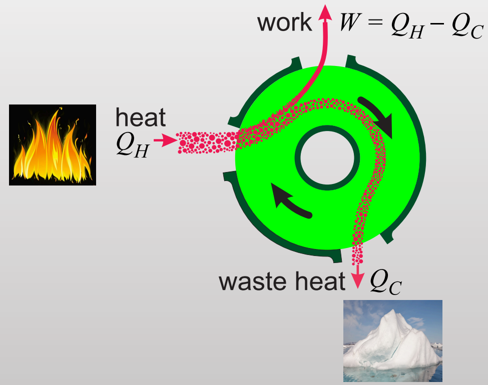
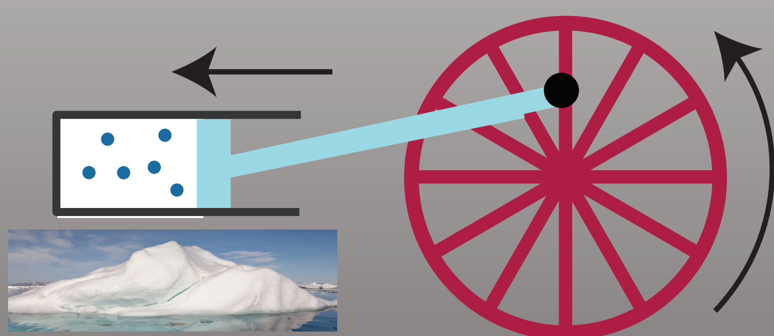
Classical Heat Engine

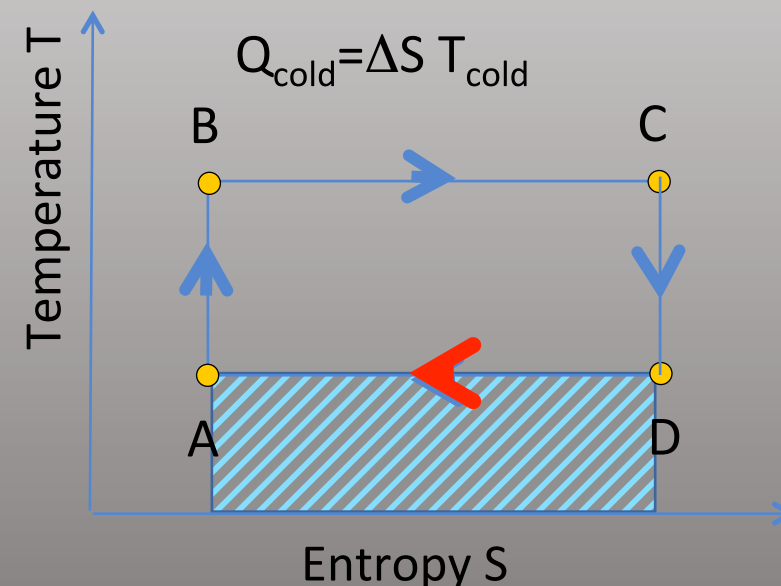


Carnot cycle:

Isothermal compression

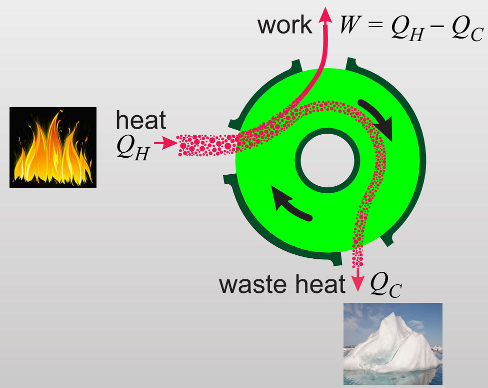
Work done on system, heat ejected





Isothermal – heat expulsion

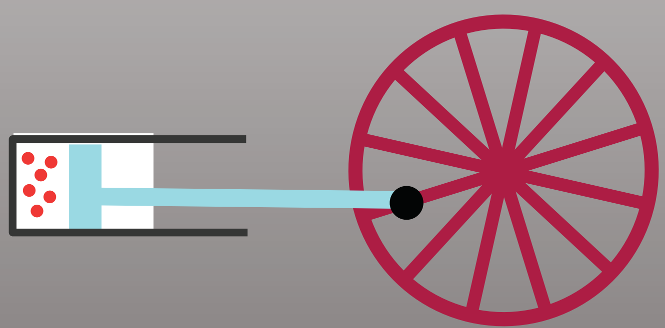
Classical Heat Engine

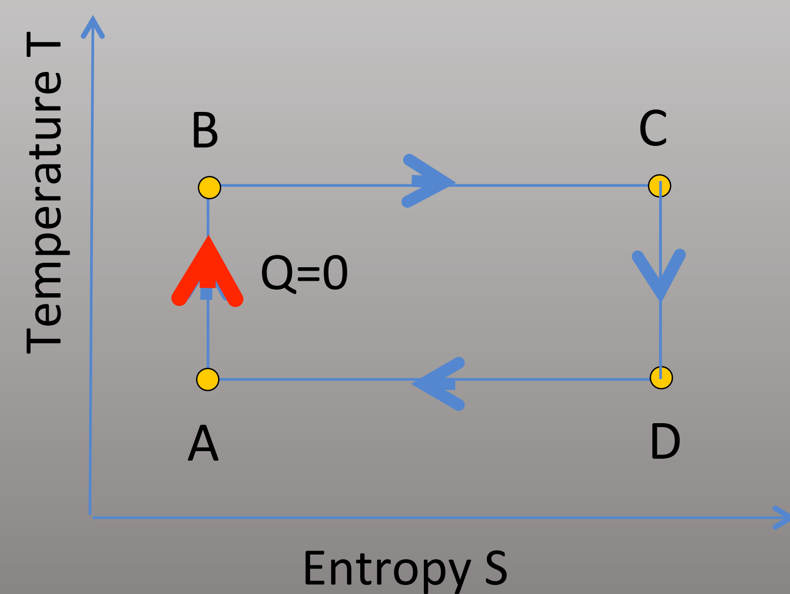


Carnot cycle:

Isothermal compression

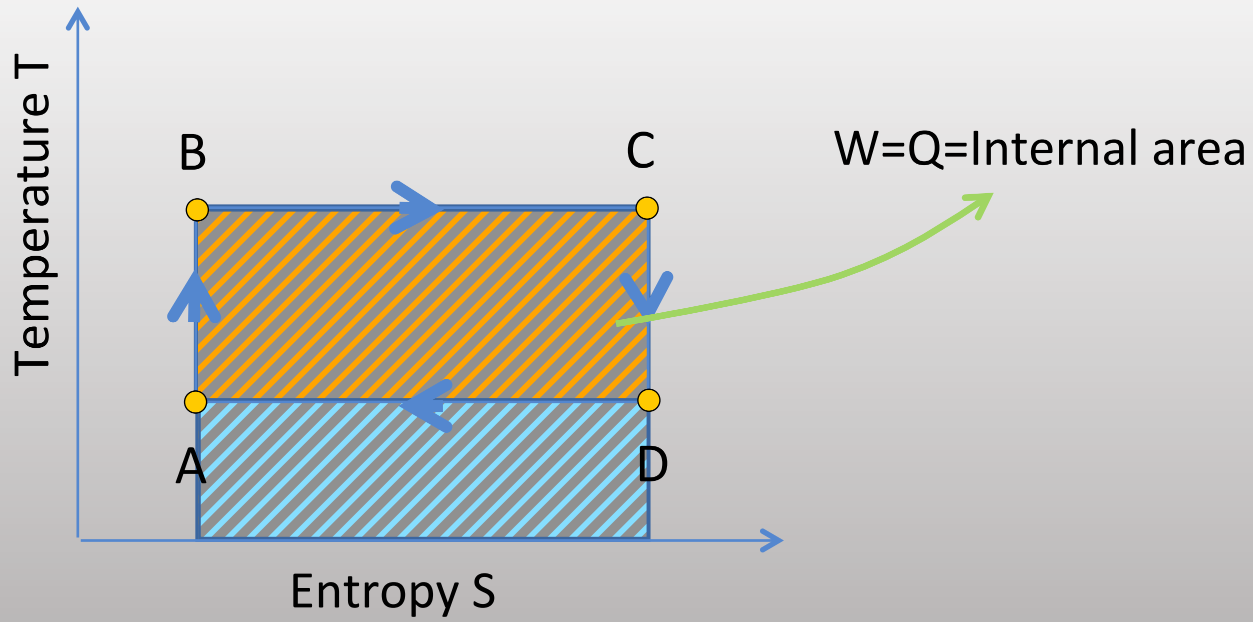
Work done on system, heat ejected





Adiabatic – thermal isolation

Carnot Cycle



Requires Hot and Cold Reservoirs

Max Efficiency η_{eff}=1- T_{cold}/T_{hot}

Want Hot side hotter, Cold side Colder

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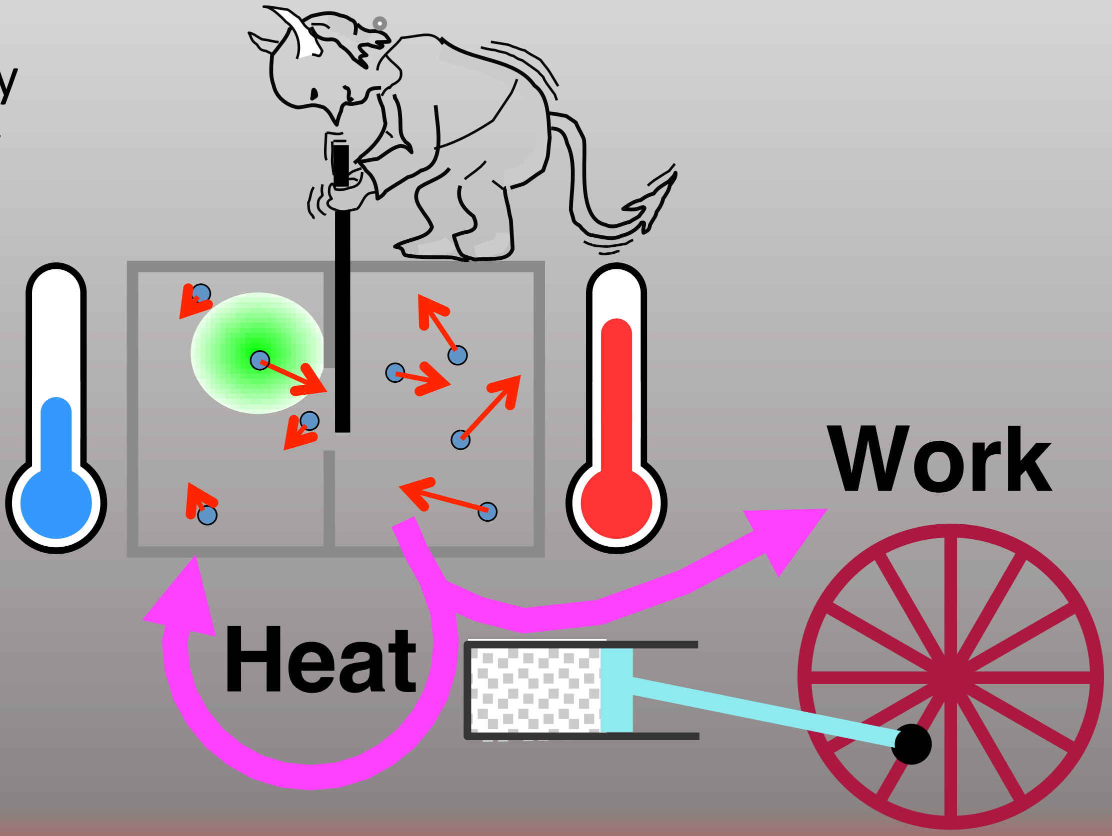
Enter the Demon…

Maxwell's Proposal (1871)
Collect Hot particles
Extracts ΔQ
Reduces Entropy
Violates 2nd Law



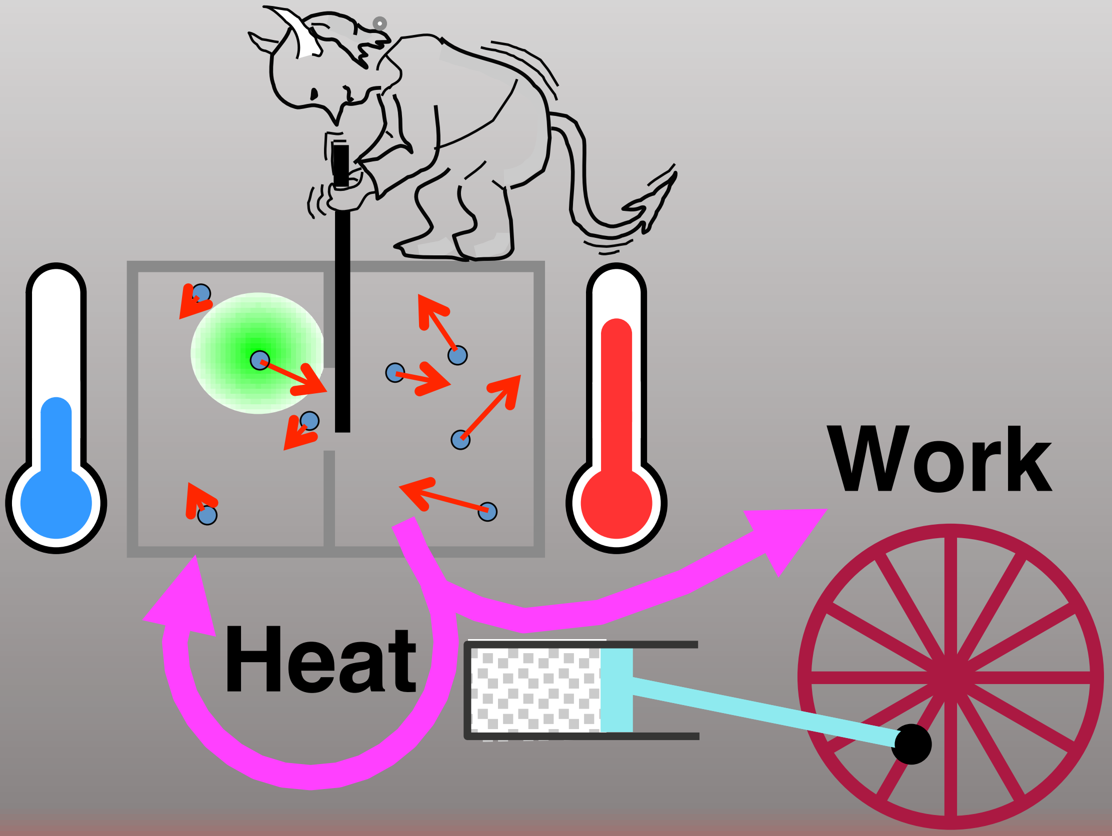
Exorcising the Demon…

Landauer Erasure (1961) – erasure of information requires energy expenditure

Bennett Proposal (1982)

Erasure cost > ΔQ

No violation ☺



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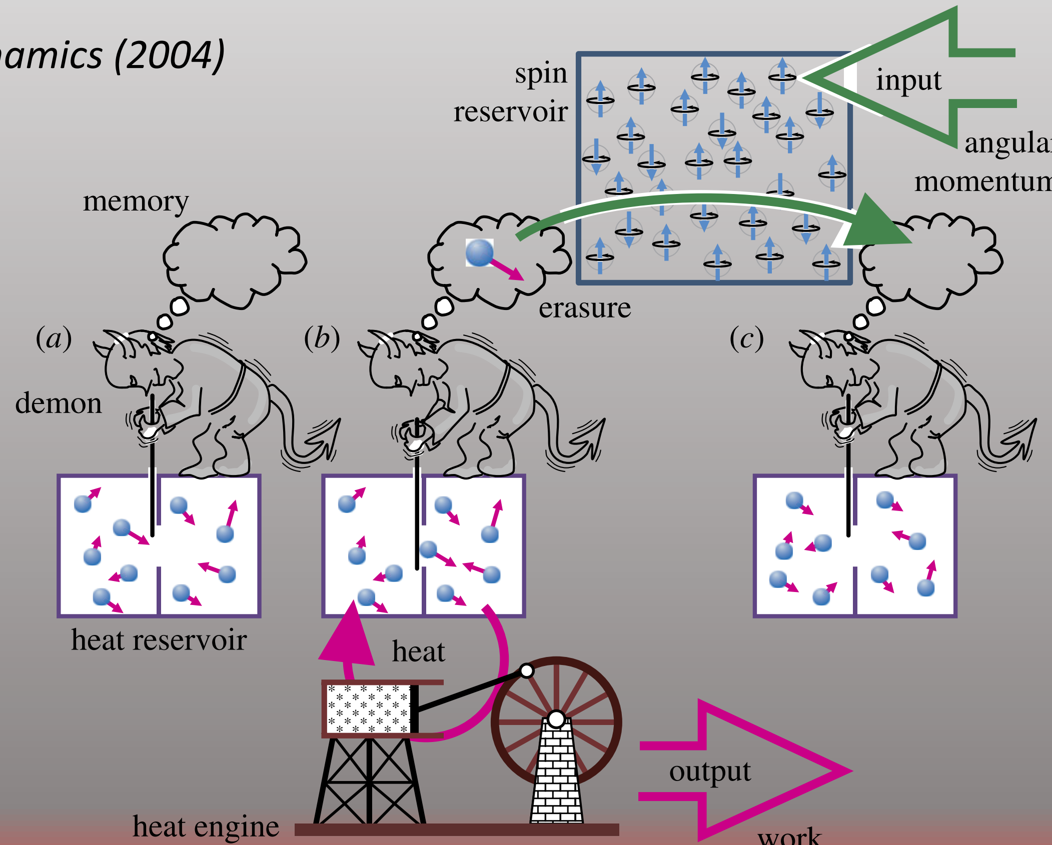
Taming the Demon…

Information erasure without an energy cost

Using quantum correlations
del Rio et al., Nature (2011)
Alicki et al., Open Systems & Information Dynamics (2004)
+…

Using other conserved quantities
J. A. Vaccaro and S. M. Barnett,
Asian Conference on
Quantum Information Science (2006)
J. Vaccaro & S. Barnett, Proc. Royal Soc. (2011)
N. Yunger Halpern et al., Nat Comm. (2016)
+…

Beware: blatant self promotion!
See also "Information Erasure"
*Chapter in "*Thermodynamics in the quantum Regime - Recent Progress and Outlook"



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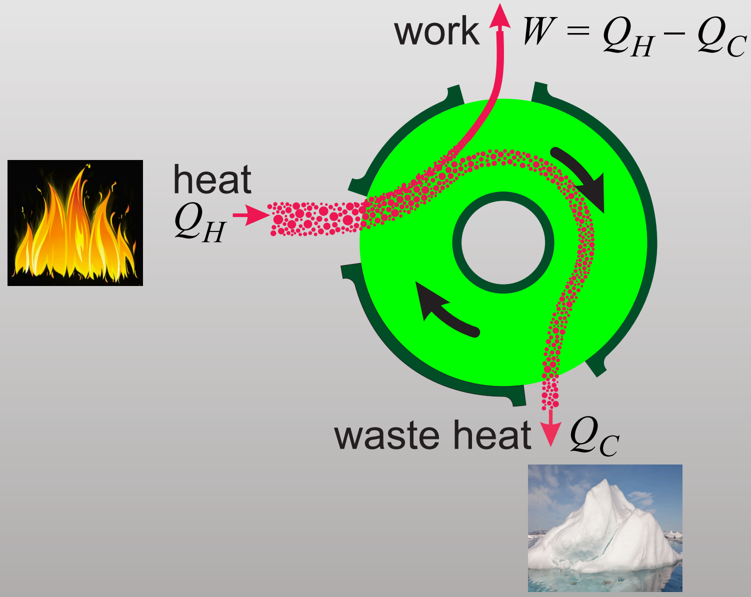
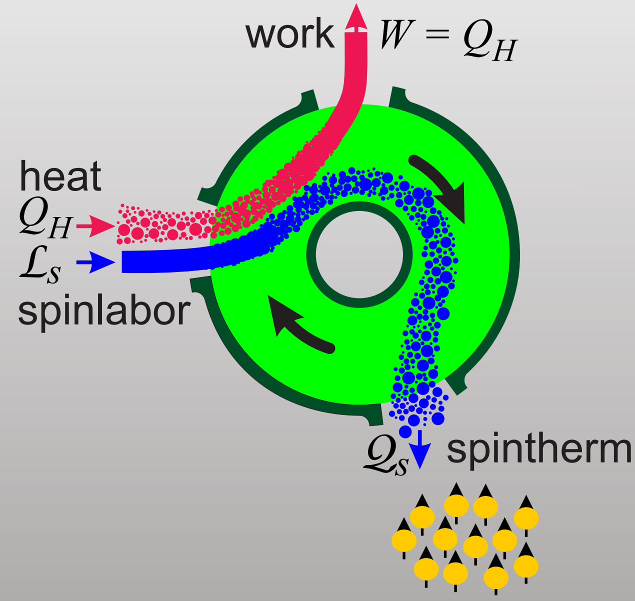
Spin heat engine (SHE) - conceptual model

Heat Engine



Spin Heat Engine



A heat engine based on a generalised statistical mechanics

PHYSICAL REVIEW VOLUME 106, NUMBER 4 MAY 15, 1957

Information Theory and Statistical Mechanics

E. T. Jaynes
Department of Physics, Stanford University, Stanford, California

(Received September 4, 1956; revised manuscript received March 4, 1957)

It is clear that any quantity which can be interchanged between two systems in such a way that the total amount is conserved, may be used in place of energy in arguments of the above type, and the fundamental symmetry of the theory with respect to such quantities is preserved. Thus, we may define a "volume bath," "particle bath," "momentum bath," etc., and the probability distribution which gives the most unbiased representation of our knowledge of the state of a system is obtained by the same mathematical procedure whether the available information consists of a measurement of $\langle f_k \rangle$ or its statistically conjugate quantity λ_k.

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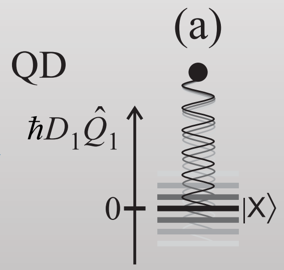
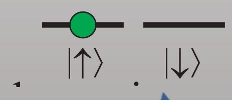
An optical SHE with quantum dots

Working fluid: electron in a quantum dot

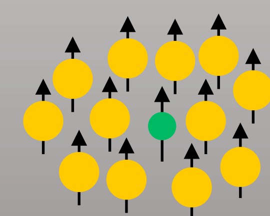
Thermal reservoir:
phonons



Exciton



Degenerate
ground state energies



Nuclei around the QD
work as the spin reservoir

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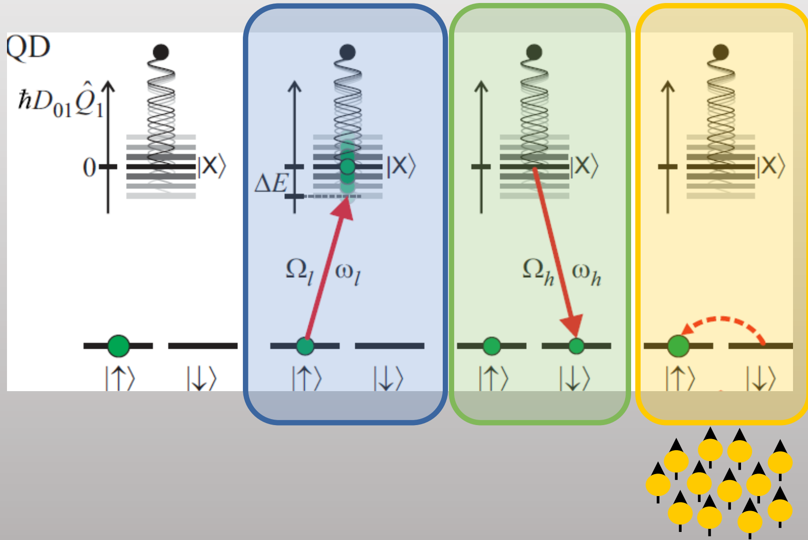
An optical SHE with quantum dots

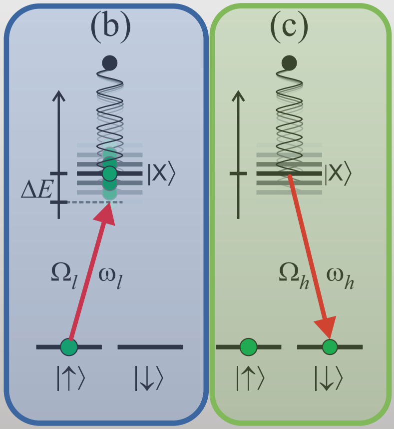


Reset (erasure) stage: Hyperfine interaction between electron and nuclei

Heat extraction (from thermal phonon energy)

Work output (in the form of coherent light)

Modelling laser interaction and phonon reservoir



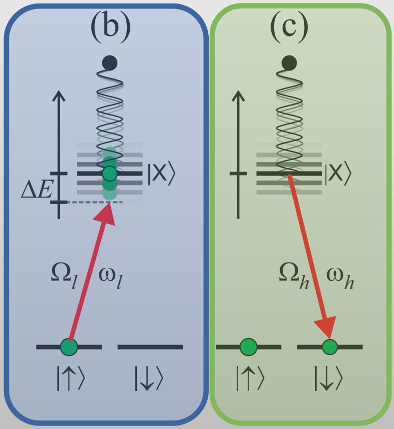
QD-phonon-laser interaction

$$\hat{H}_{\mathrm{ep}} = \hbar\Omega_\mu(\hat{\sigma}_\mu^+ + \hat{\sigma}_\mu^-) + |X\rangle\langle X| \left[\hbar\Delta_\mu + \sum_k \hbar\lambda_k(\hat{b}_k^\dagger + \hat{b}_k)\right] + \sum_k \hbar\omega_k \hat{b}_k^\dagger \hat{b}_k,$$

$$\sigma_\mu^+ = |X\rangle\langle\mu| = (\hat{\sigma}_\mu^-)^\dagger, \quad \mu = \uparrow \text{ or } \downarrow$$

$\Delta_\mu,\ \Omega_\mu$ Detuning and Rabi frequency

Modelling laser interaction and phonon reservoir



Effective mode description to deal with non-Markovian effects

$$\hat{Q}_1 = \frac{1}{D_1}\sum_k \lambda_k (b_k^\dagger + b_k)\ , \quad \hat{P}_1 = \frac{i\hbar}{2D_1}\sum_k \lambda_k (b_k^\dagger - b_k)$$

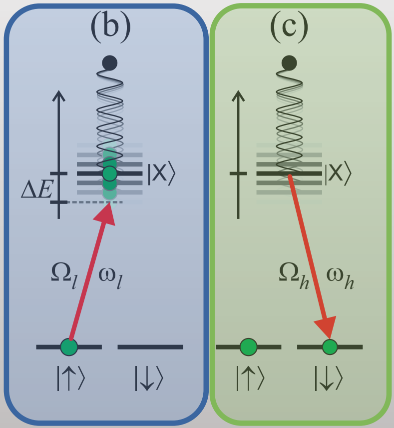
$$D_1^2 = \sum_k |\lambda_k|^2\ .$$

$$\hat{H}_{\text{ep}} = \hbar\Omega_\mu(\hat{\sigma}_\mu^+ + \hat{\sigma}_\mu^-) + |X\rangle\langle X|(\hbar\Delta_\mu + \hbar D_1 \hat{Q}_1) + \frac{1}{2}\sum_n [\hat{P}_n^2 + \widetilde{\omega}_n^2 \hat{Q}_n^2]\ ,$$

First mode couples to the exciton and the remaining are considered as Markovian reservoirs for the first mode

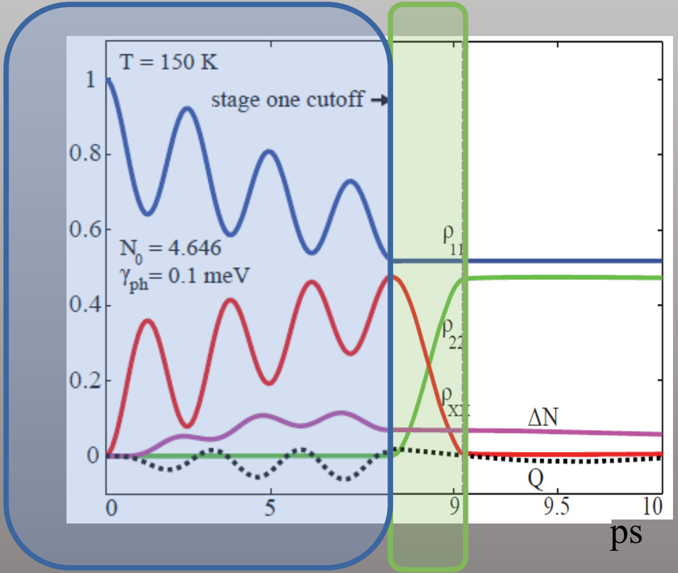
$$\frac{\partial \hat{\rho}}{\partial t} = \frac{1}{i\hbar}[\hat{H}_{\text{ep}}^{(1)}, \hat{\rho}] + \frac{\gamma_R}{2}\mathcal{L}(\hat{\sigma}_\uparrow^-) + \frac{\gamma_R}{2}\mathcal{L}(\hat{\sigma}_\downarrow^-) + \frac{\gamma_{\text{ph}}}{i\hbar}[\hat{Q}_1, [\hat{P}_1, \hat{\rho}(t)]_+] - \frac{2\gamma_{\text{ph}} E_{\text{th}}}{\hbar^2}[\hat{Q}_1, [\hat{Q}_1, \hat{\rho}(t)]],$$

Heat extraction and work output



Results from simulations of the master equation

$$\frac{\partial \hat{\rho}}{\partial t} = \frac{1}{i\hbar}[\hat{H}_{\mathrm{ep}}^{(1)}, \hat{\rho}] + \frac{\gamma_R}{2}\mathcal{L}(\hat{\sigma}_{\uparrow}^{-}) + \frac{\gamma_R}{2}\mathcal{L}(\hat{\sigma}_{\downarrow}^{-}) + \frac{\gamma_{\mathrm{ph}}}{i\hbar}[\hat{Q}_1, [\hat{P}_1, \hat{\rho}(t)]_+] - \frac{2\gamma_{\mathrm{ph}} E_{\mathrm{th}}}{\hbar^2}[\hat{Q}_1, [\hat{Q}_1, \hat{\rho}(t)]],$$



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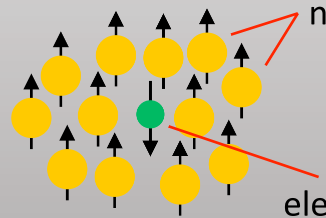
Closing the cycle: entropy resetting

Central spin problem

H =∑j↑▒g↑* μ↓B B↓z (j)I ↓z (j)+2a(j)S ↓z I ↓z (j)+a(j)(S ↓+ I ↓− (j

adjust B_z to cancel this

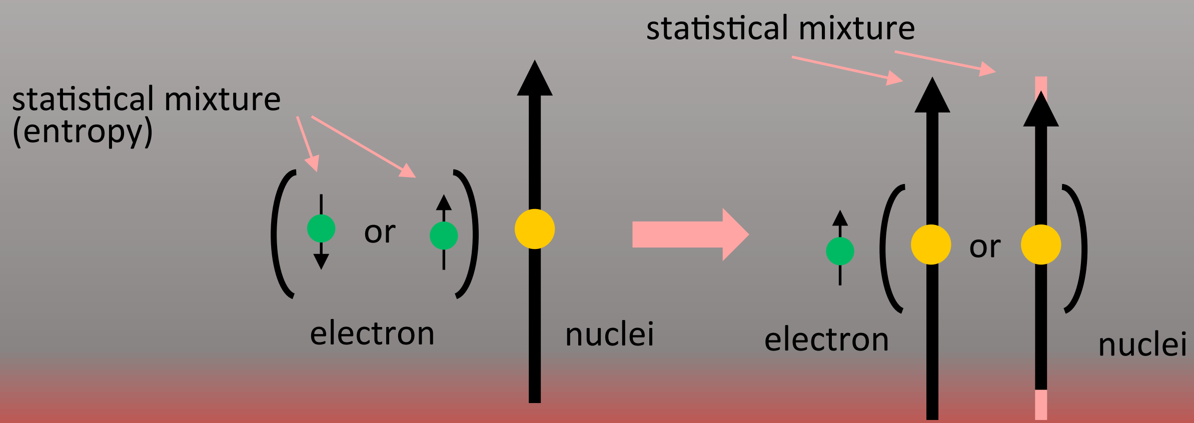
hyperfine interaction



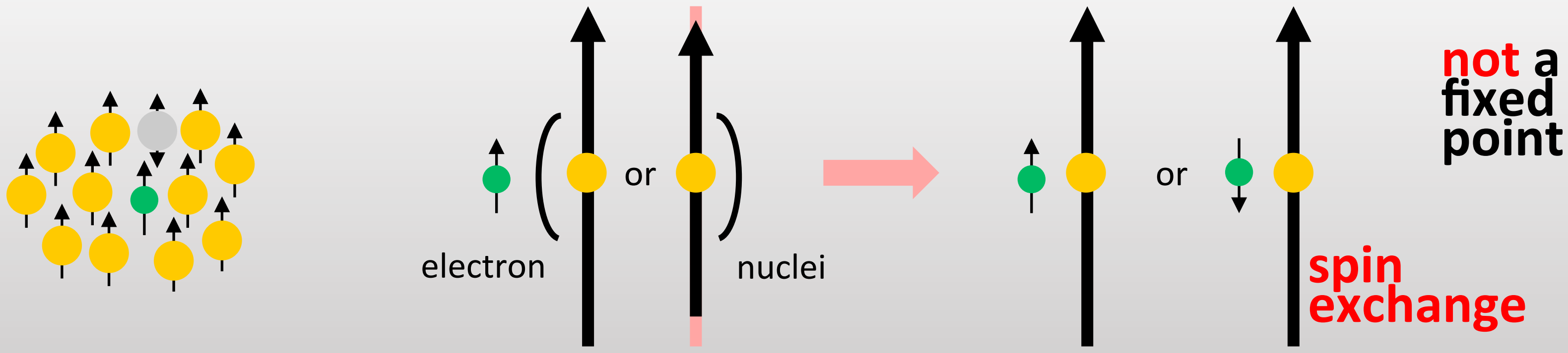
Erasure in the first cycle

$$|\uparrow, 0\rangle \mapsto |\uparrow, 0\rangle$$
$$|\downarrow, 0\rangle \mapsto -i\,|\uparrow, 1\rangle_0$$

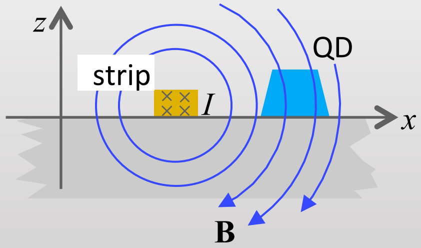
$$|0\rangle = |\uparrow\uparrow\uparrow\cdots\uparrow\rangle$$
$$|1\rangle_0 = \hat{\mathbb{I}}_-\,|0\rangle$$
$$\hat{\mathbb{I}}_- \equiv \frac{1}{\sqrt{\gamma}}\sum_j a_j \hat{I}_-^{(j)}$$
$$\gamma \equiv \sum_j a_j^2$$



Erasure fails in the second cycle!



Solution: spatially-varying magnetic field

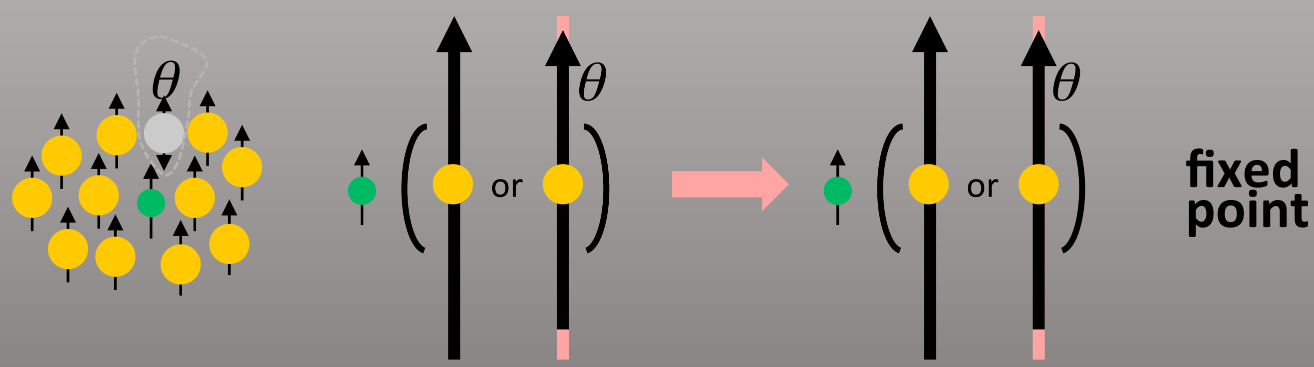


$$\hat{H}_{\mathrm{pls}} = g_n \mu_n \sum_j B_{\mathrm{pls}}(\mathbf{r}_j) \hat{I}_z^{(j)}$$

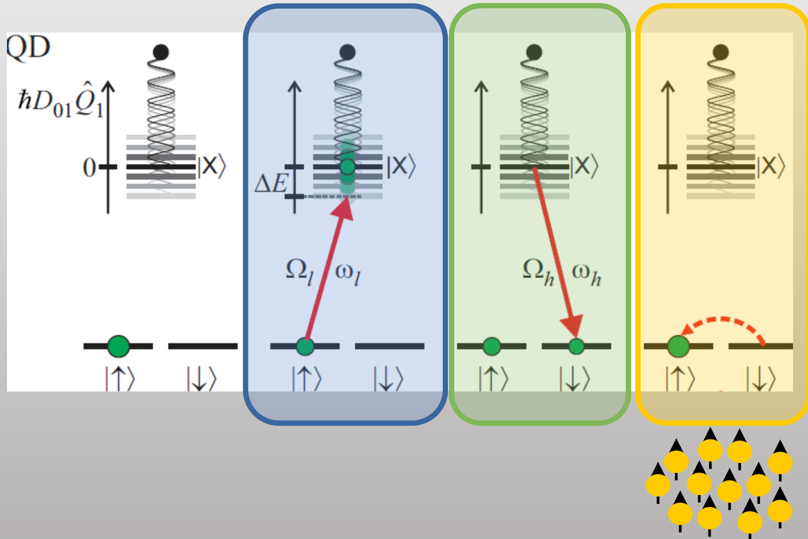
Induces a phase in the state that restores the fixed point properties

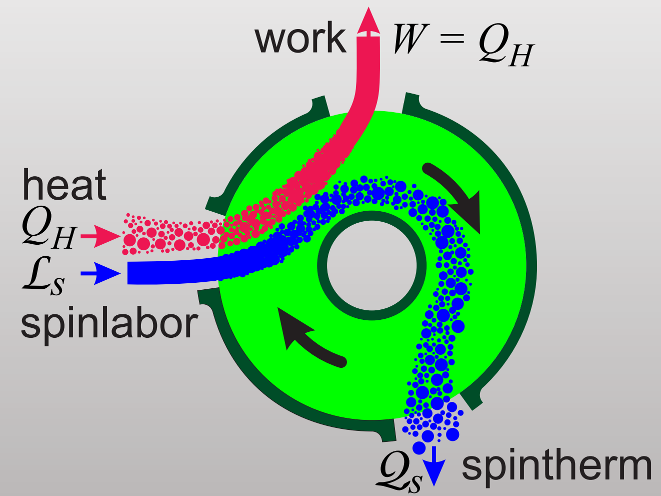
$$\hat{U}_{\mathrm{en}}^{(\mathrm{eff})}(t) \left|\uparrow, 1\right\rangle_\tau = \left|\uparrow, 1\right\rangle_\tau + e^{-i\Theta\tau} \frac{\tilde{\gamma}(\tau)}{\gamma} \times \left\{ \left[\cos(\sqrt{\gamma} t) - 1\right] \left|\uparrow, 1\right\rangle_0 - i \sin(\sqrt{\gamma} t) \left|\downarrow, 0\right\rangle \right\}$$

Need $\dfrac{\tilde{\gamma}(\tau)}{\gamma} \ll 1$ (tough experimentally)



Wrapping up





No free-lunch! (it is just paid in a different currency)

Conclusions and perspectives

- SHE: extracts work from a single thermal reservoir
- No magic and no violation of physical laws:

  Statistical mechanics doesn't care which

  currency you use, as long as you pay the bill!

- QD: proposal of a proof-of-principle demonstration

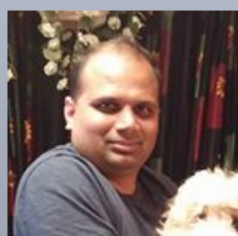
Our group

Joan Vaccaro

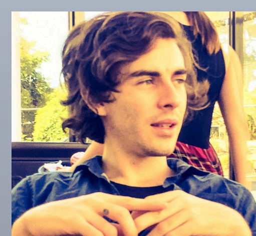
Tim Gould

Eric Cavalcanti

Erik Streed



Salil Bedkihal
(now in the UK)



Jackson Wright

Toshio Croucher

* J. S. S. T. Wright, T. Gould, A. R. R. Carvalho, S. Bedkihal, and J. A. Vaccaro
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Australian Government
Australian Research Council

LOCKHEED MARTIN

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PhD opportunities!

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