Theoretical Tools for Quantum Batteries:

Basic Concepts and Their Applications

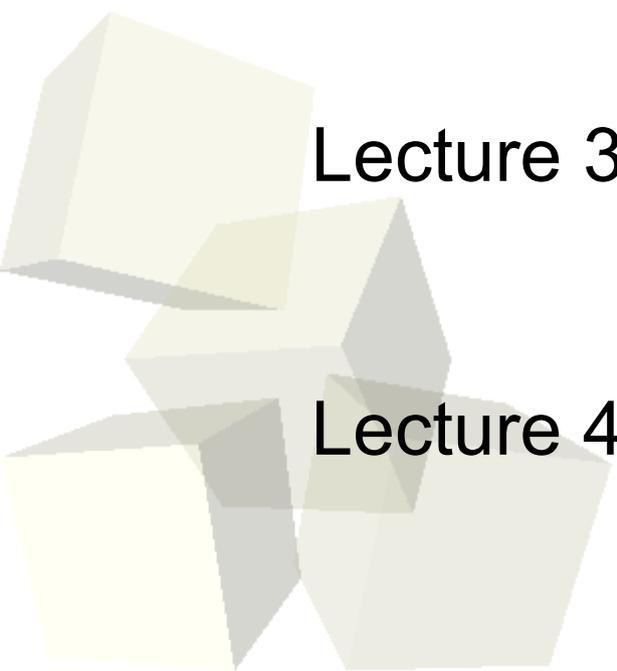# Lecture 0

Gentaro Watanabe

(Zhejiang University)

Lecture 0: Introduction to quantum batteries

Lecture 1: Theory of open quantum systems 101

Lecture 2: Ergotropy & coherence

Lecture 3: Dicke model: A workhorse of QB research

Lecture 4: Our recent results

Lecture 0: Introduction to quantum batteries
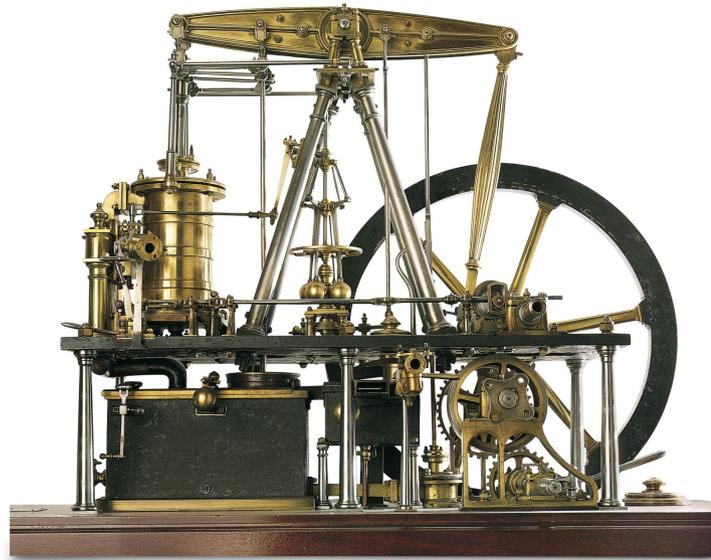
I. Quantum thermodynamics

II. What are quantum batteries?

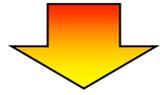III. Motivations & issues of quantum batteries

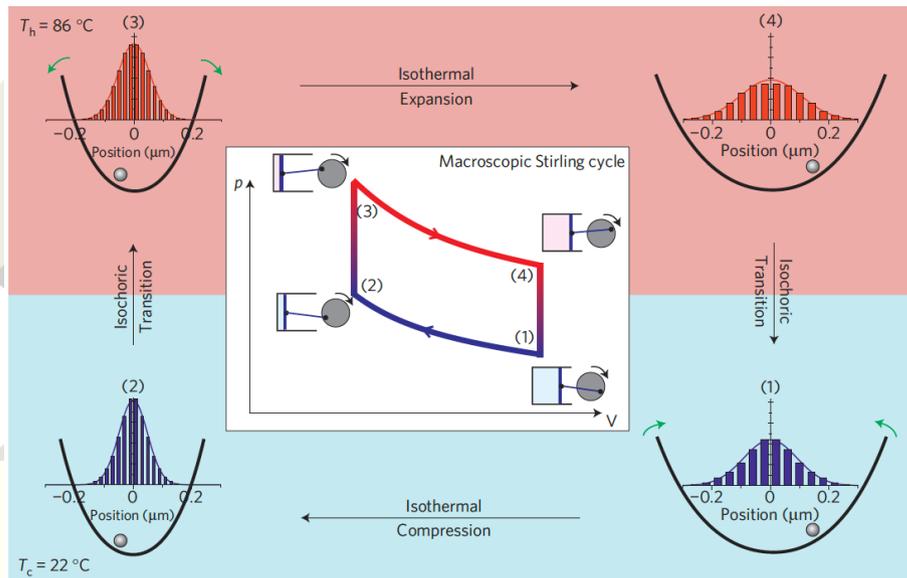Technological developments
allow us to downsize the heat engines.

A small system as a working substance.
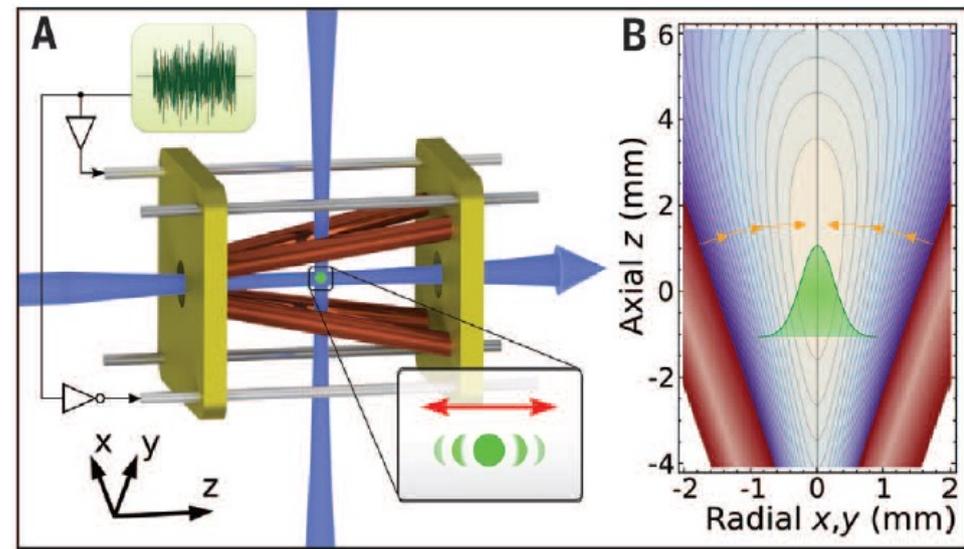
"small" : Number of DOF is small.

A colloidal particle in a trap

An ion in a trap

Blickle & Bechinger, Nat. Phys. **8**, 143 (2012)

Roßnagel *et al.*, Science **352**, 325 (2016)

Thermodynamics:

For macroscopic systems.

Mainly discuss mean values.

Classical physics not revised so far after quantum revolution.

Quantum thermodynamics:

Thermodynamics of small quantum systems.

Small: fluctuations (beyond mean values)

Quantum: coherence, entanglement, measurement, etc.

What is quantum origin of the laws of thermodynamics?

Batteries: energy storage & power supply to other machines

For remote (spatial and/or temporal) usage.

Ubiquitous device with a large variety in size and purpose.

For power plants

For daily-life gadgets

For microdevices

Quantum batteries: Quantum systems used to store energy.

Ex.: Two-level sys. (TLS), harmonic osc. etc.

Reviews: Bhattacharjee & Dutta, EPJ B **94**, 239 (2021)
Quach, Cerullo & Virgili, Joule **7**, 2195 (2023)
Campaioli *et al*., ROMP **96**, 031001 (2024)

Unlike classical battery, quantum batteries are usually non-electric.

"Work reservoir"

Incentive:

Improving the battery performance using quantum resources (quantum coherence, entanglement, etc.).

Alicki & Fannes, PRE **87**, 042123 (2013)
Hovhannisyan *et al*., PRL **111**, 240401 (2013)
Binder *et al*., NJP **17**, 075015 (2015)
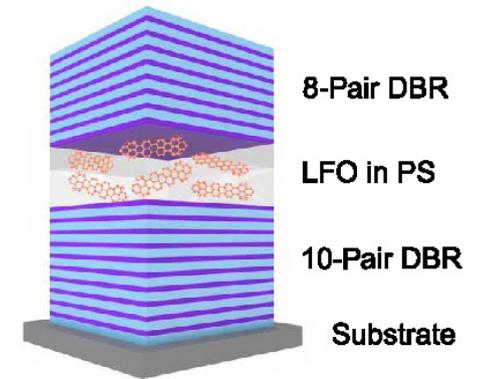Campaioli *et al*., PRL **118**, 150601 (2017)
Julia-Farre *et al*., PRR **2**, 023113 (2020)

Andolina, Polini *et al*.; Gyhm, Safranek & Rosa; Barra, …
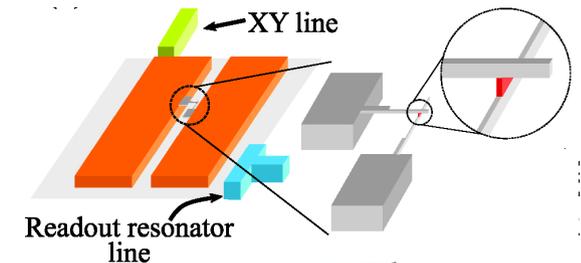
Gyhm & Fisher; Son, Talker, Thingna; Shaghaghi, Singh; …

1. Organic semiconductor microcavities
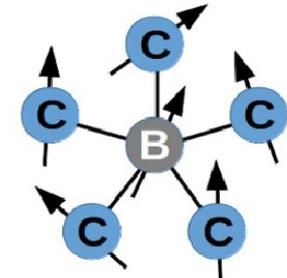
Quach *et al.*, Sci. Adv. **8** 3160 (2022)

8-Pair DBR

LFO in PS

10-Pair DBR

Substrate

2. Superconducting circuits

Hu *et al.*, Q. Sci. Tech. **7**, 045018 (2022)

XY line

Readout resonator line

3. NMR spins

Joshi & Maheshi, PRA **106**, 042601 (2022)

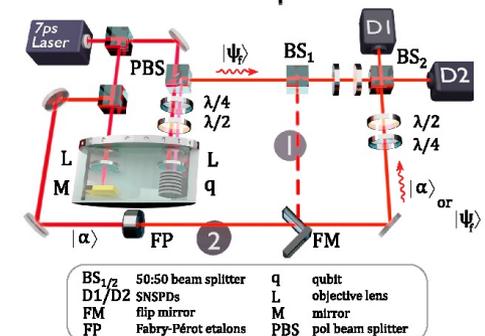**4. Quantum dots**

Wenniger *et al.*, PRL **131**, 260401 (2023)

5. Quantum computers

Gemme *et al.*, Batteries **8**, 43 (2022)

Diamond NV centers (potentially)

Song *et al.*, PRL **135**, 020405 (2025)

IBM**Q**

BS$_{1/2}$	50:50 beam splitter	q	qubit
D1/D2	SNSPDs	L	objective lens
FM	flip mirror	M	mirror
FP	Fabry-Pérot etalons	PBS	pol beam splitter

1. Practical side

Ronnie Kosloff

Miniaturization of refrigerators

Study on quantum thermal machines opens a way to miniaturize refrigerators.

(Ronnie Kosloff @ KIAS Workshop on Quantum Information and Thermodynamics, Nov. 2019)
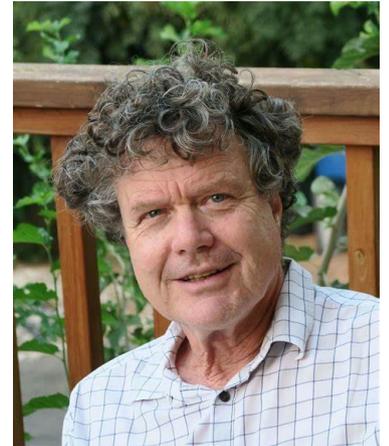
Power sources for future mechanical nanomachines

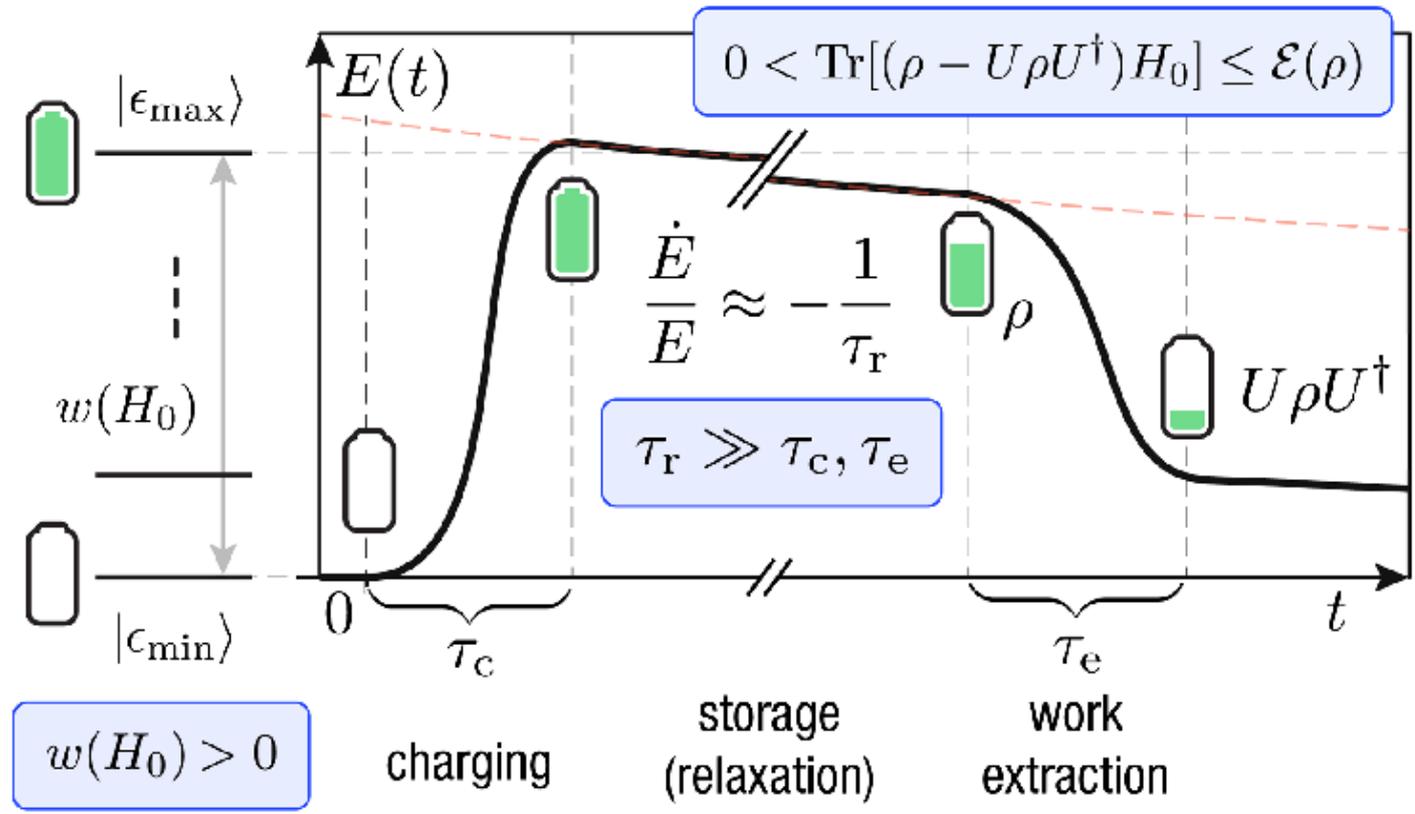Advance our understanding of energy storage.

2. Fundamental side

Understanding of quantum thermodynamics.

$$0 < \mathrm{Tr}[(\rho - U\rho U^\dagger)H_0] \leq \mathcal{E}(\rho)$$

$$\frac{\dot{E}}{E} \approx -\frac{1}{\tau_\mathrm{r}}$$

$$\tau_\mathrm{r} \gg \tau_\mathrm{c}, \tau_\mathrm{e}$$

$|\epsilon_\mathrm{max}\rangle$

$w(H_0)$

$|\epsilon_\mathrm{min}\rangle$

$E(t)$

ρ

$U\rho U^\dagger$

$w(H_0) > 0$

τ_c / charging

storage (relaxation)

τ_e / work extraction

t

Campaioli *et al.*, ROMP **96**, 031001 (2024)

1. Charging: Higher power, larger energy, smaller fluctuation

2. Storage: Smaller loss (leakage) for longer time

3. Discharging: Larger energy, higher/const. power, smaller fluct.

Important platform for quantum tech. & quantum thermodyn. research.

1. Fast charging:

Preparation of a target state in a short time
- Key agenda of quantum control
- Quantum speed limit, shortcut to adiabaticity

Efficient energy transfer from one quantum sys. to another
- Coherent energy transfer / superabsorption
- Many-body quantum correlation

2. Lossless storage:

Protecting energy, coherence, entanglement from env.
- Open system decoherence control

3. Maximal and stable/fast energy extraction:

Maximizing extractable work (ergotropy)
- Ergotropy and thermodynamic bounds

Stable & precise energy delivery
- Fluctuation suppression in work extraction
- Thermodynamic uncertainty relations

Various types of problems and their setups

$$
\begin{pmatrix} \text{charging} \\ \text{storage} \\ \text{discharging} \end{pmatrix} \otimes \begin{pmatrix} \text{closed} \\ \text{open} \end{pmatrix} \otimes \begin{pmatrix} \text{battery only} \\ \text{battery + charger} \end{pmatrix} \begin{cases} \text{driven charger} \\ \text{undriven charger} \end{cases}
$$

Earlier studies

Effects of entangling operations in discharging of N copies of QB.

Alicki & Fannes, PRE **87**, 042123 (2013)
Hovhannisyan *et al.*, PRL **111**, 240401 (2013)

(discharging) $\otimes$ (closed) $\otimes$ (battery only)

Super-extensive power of collective charging of QBs.

Binder *et al.*, NJP **17**, 075015 (2015)
Campaioli *et al.*, PRL **118**, 150601 (2017）

(charging) $\otimes$ (closed) $\otimes$ (battery+charger) $\otimes$ (undriven charger)
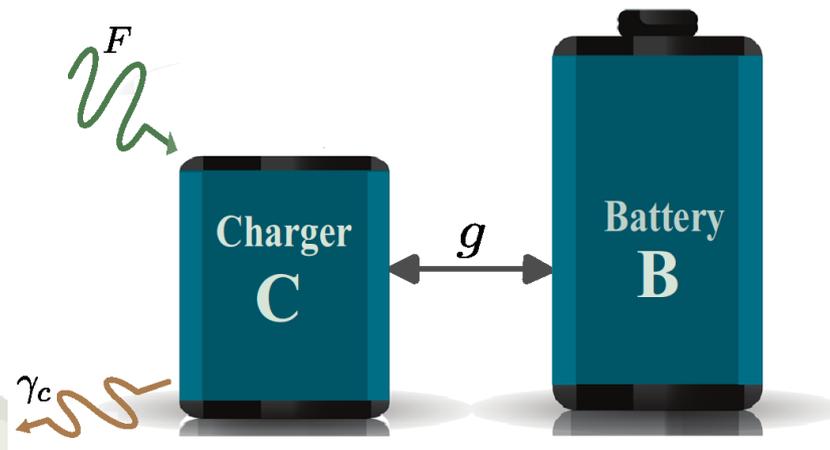
Various types of problems and their setups

$$
\begin{pmatrix} \text{charging} \\ \text{storage} \\ \text{discharging} \end{pmatrix} \otimes \begin{pmatrix} \text{closed} \\ \text{open} \end{pmatrix} \otimes \begin{pmatrix} \text{battery only} \\ \text{battery + charger} \end{pmatrix} \begin{cases} \text{driven charger} \\ \text{undriven charger} \end{cases}
$$

Our recent study

Decoherence for fast charging of QBs

Shastri, Jiang, Xu, Venkatesh & GW, npj Quantum Inf. **11**, 9 (2025)

(charging) $\otimes$ (open) $\otimes$ (battery+charger) $\otimes$ (driven charger)

13

Review articles

F. Campaioli *et al.*, ROMP **96**, 031001 (2024)

"Colloquium: Quantum batteries"

F. Campaioli, F. A. Pollock, and S. Vinjanampathy,

"Quantum batteries"

in *"Thermodynamics in the Quantum Regime: Fundamental Aspects and New Directions,"* (Springer, 2018)

S. Bhattacharjee and A. Dutta, EPJ B **94**, 239 (2021)

"Quantum thermal machines and batteries"

Short article

J. Q. Quach, G. Cerullo, and T. Virgili, Joule **7**, 2195 (2023)

"Quantum batteries: The future of energy storage?"