

# Thermodynamics in Quantum Systems

**Hyunggyu Park (KIAS)**

Talk at KIAS (Feb. 21, 2014)  
QUC Inaugural Conference : Quantum Challenge

**Quantum Challenge !!**

**Thermodynamics ?**

**Nonequilibrium processes**

# Thermodynamic 2<sup>nd</sup> Law

## Fluctuation Theorems

Entropy

Heat

Information

Work

**Open Quantum Systems**

**Environmental Reservoirs**

**Markovianization**

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Does Quantum Mechanics Flout the Laws of Thermodynamics?

By [Vlatko Vedral](#) | June 1, 2011 | (Nature)

- Landauer principle & **entanglement**
- Global & local erasing / negative entropy

The logo for Quanta Magazine. The word 'QUANTA' is written in a large, orange, sans-serif font. To its right, the words 'illuminating science' are written in a smaller, orange, sans-serif font. Below 'QUANTA' and 'MAGAZINE' is a thin orange horizontal line. The word 'MAGAZINE' is written in a large, black, sans-serif font.

QUANTA illuminating science  
MAGAZINE

## A New Physics Theory of Life

Jeremy England, a 31-year-old physicist at MIT, thinks he has found the underlying physics driving the origin and evolution of life.

- Replication dynamics sets a **higher** lower bound for the entropy production (dissipation energy or heat)
- Generalized 2nd laws

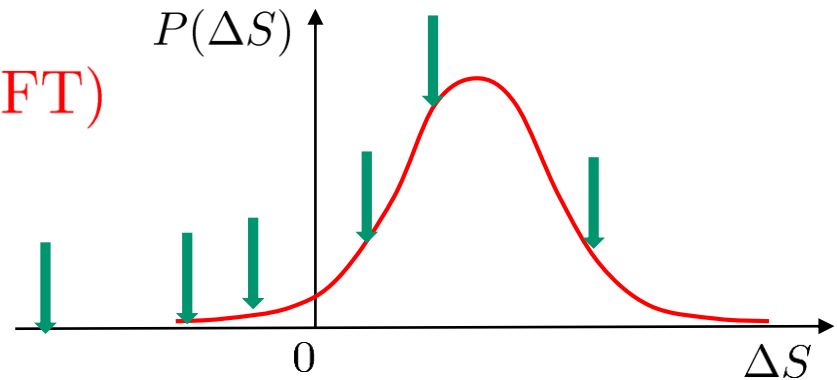
## Brief history of FT (I)

- Evans, Cohen, Morris (1993)  
observation of FT in molecular dynamics simulations on fluid systems
- Gallavotti and Cohen (1995)  
analytic derivation of FT in “deterministic” systems (NEQ steady state)

$$\frac{P(\Delta S)}{P(-\Delta S)} = e^{\Delta S}$$

(Detailed FT)

Gallavotti-Cohen symmetry



$$\langle e^{-\Delta S} \rangle = 1 = \int d(\Delta S) P(\Delta S) e^{-\Delta S} \quad (\text{Integral FT})$$

- ➔ Jensen's inequality ( $\langle e^x \rangle \geq e^{\langle x \rangle}$ ) leads to  $\langle \Delta S \rangle \geq 0$ .
  - Thermodynamic 2nd law is a consequence of (Gallavotti-Cohen symmetry (FT)).  
with  $y = x - \langle x \rangle$
- ★ Special NEQ processes, NEQ steady state

## Brief history of FT (II)

- Jarzynski (1997)

FT in Hamiltonian systems (work-free energy relation)

$$\langle e^{-\beta W} \rangle = e^{-\beta \Delta F}$$

- Kurchan (1998)

FT in Langevin equation approach for stochastic systems

- Lebowitz and Spohn (1999)

★ Bochkov/Kuzovlev (1977)

FT in master equation approach for stochastic systems ★ Kawasaki (1967)

- Crooks (1999)

DFT for stochastic systems

$$\frac{P_F(W)}{P_R(-W)} = e^{\beta W - \beta \Delta F}$$

- Hatano and Sasa (2001)

two independent FT

- Speck/Seifert/vdBroeck (2005)

$$\Delta S = \Delta S_{hk} + \Delta S_{ex}$$

- Speck/Seifert (2007)

non-Markovian, non-Gaussian

- Sagawa/.... (2008)

Information entropy

- **Our group**/Spinney/Ford (2012)

odd parity

- Experiments: Bustamante, Ciliberto (2002,2005), ...

## Brief history of FT (III)

### ★ Quantum FT

- Kurchan/Tasaki (2000)

DFT in quantum Hamiltonian systems (work-free energy relation)

- Jarzynski/Wojcieck (2004)
- Talkner, Lutz, Hänggi (2007)
- Talkner, Campisi, Hänggi (2009)

DFT for heat and work in Open quantum systems (weak coupling)

- Campisi, Talkner, Hänggi (2009)

DFT for work in Open quantum systems (strong coupling)

**Open quantum system ?**

**How to define Entropy or heat? Entanglement?**

**Irreversibility out of reversible dynamics ?**

**Stochastic quantum thermodynamics ?**