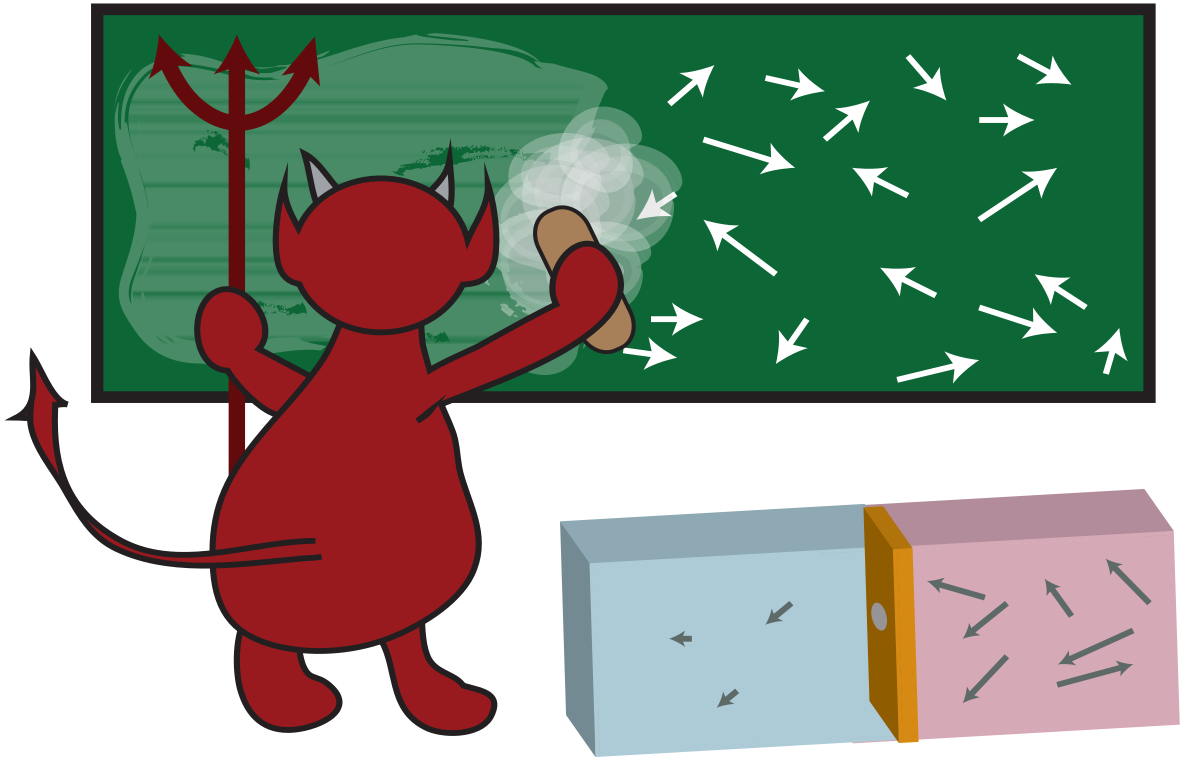
fundamental limits of heat dissipation in computation



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HPC User Forum

must computers always heat up?

what's the ultimate work cost of computations?

2007 (review by Bourianoff, Gargini, Nikonov @ Intel)

Commercial: 60nm , 2500 eV 10^5 kT

Lab: 10nm , 1.7 eV 75 kT

Landauer's principle

Landauer 1961 1-bit irreversible computation costs kT ln 2

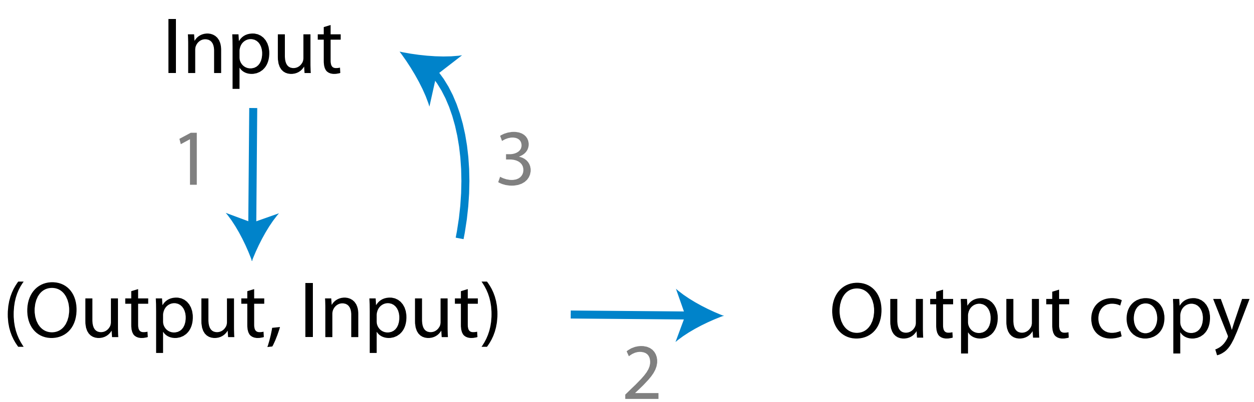
2030 ? 7.8 meV

Bennett 1973

irreversible operations $3 + 1 \longrightarrow 4$ 2+2 ? 1+3 ?

= reversible operations $3 + 1 \longrightarrow 4\ (3, 1)$

+ erasure $4\ \sout{(3, 1)}$

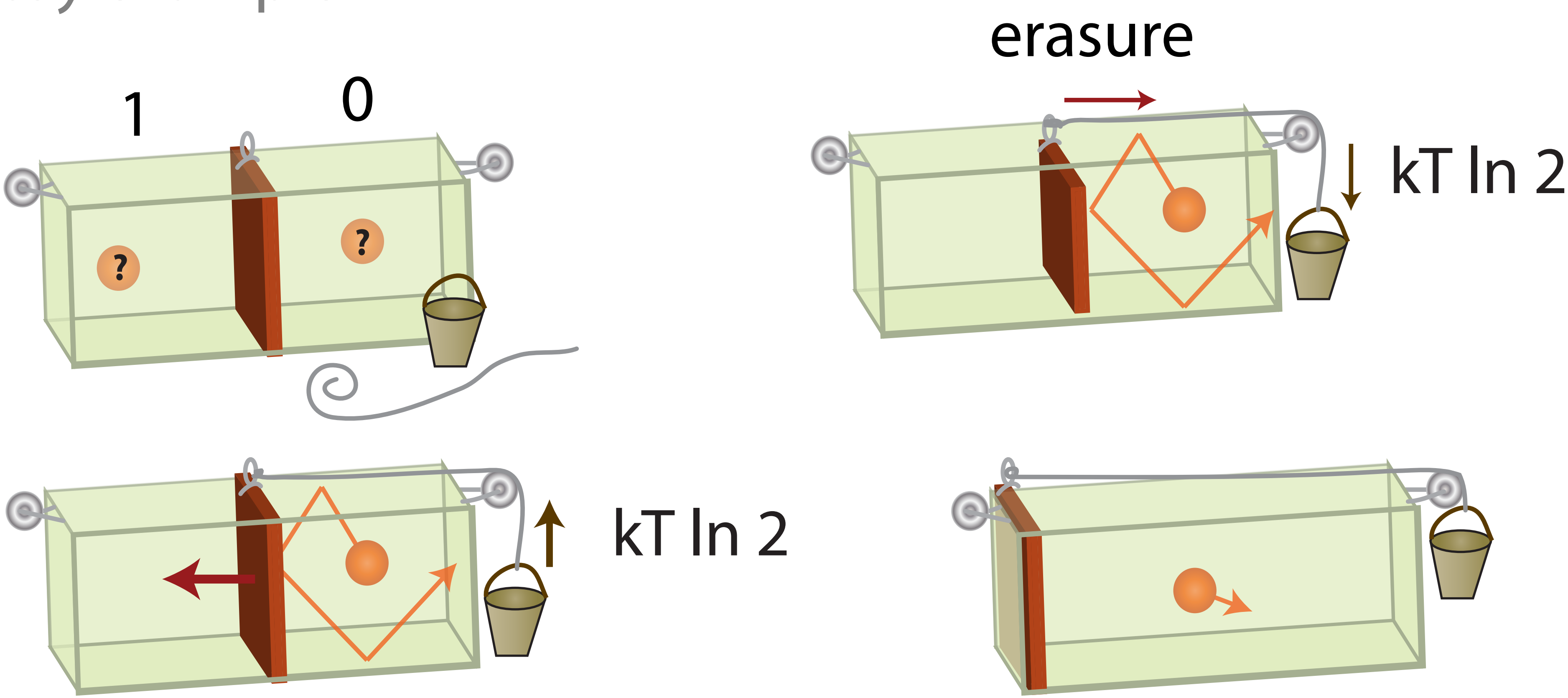


erasure

100?11???0?101?1 → 0000000000000000

(partial information) (known standard state)

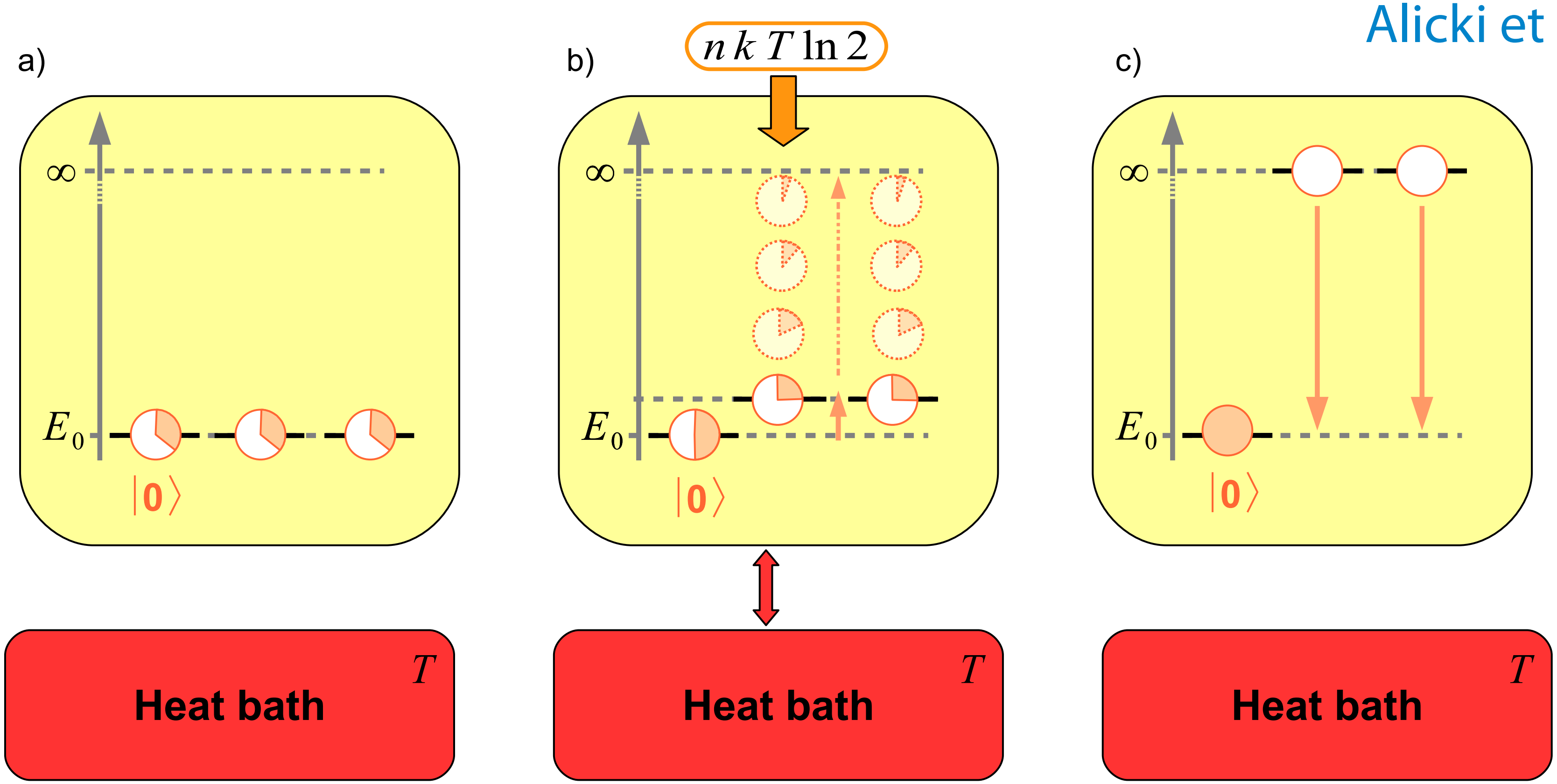
toy example

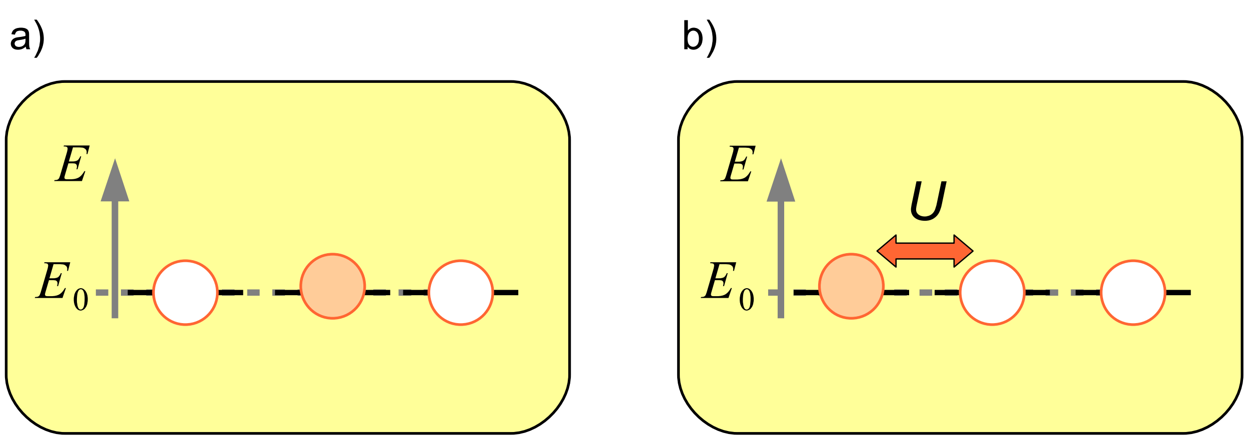


reversible operations free!

general quantum system

Piechocinska 2000
Alicki et al. 2004





reversible
operations free!

cost of erasure depends on our information about the initial state of the system

0 → 0 Free

1 → 0 Free

? → 0 k T ln 2

$$W(S|M) = H(S|M)\, k\, T \ln 2$$

entropy (eg. Shannon, von Neumann, smooth entropy) quantifies our ignorance about S given memory M

$$W(S|M) = H(S|M)\, k\, T \ln 2$$

entropy

$H(S|M)$ positive if M, S classical

$H(S|M)$ can be negative if M and S quantum

(S and M are entangled)

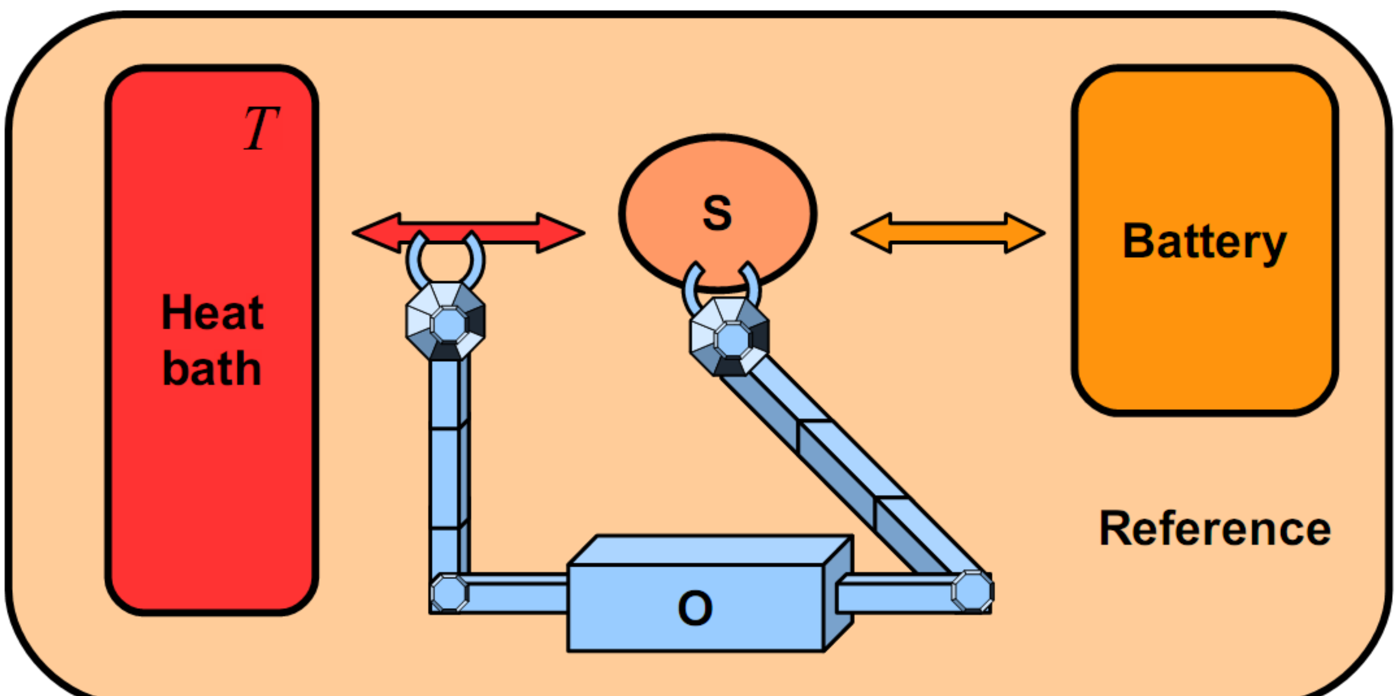
global state of S and M known,
but local states unknown

energy gain in erasure of S
(but now M needs erasing)

pre-requisites (for now)

extremely precise control of systems:

- Hamiltonian (energy levels)
- arbitrary reversible operations (on quantum systems)
- contact with environment
- storage of quantum states
- track energy costs



applications: “energy-efficient” quantum algorithms

probabilistic algorithms

simulation of quantum systems

state estimation

Lídia del Rio, Johan Aberg, Renato Renner, Oscar Dahlsten, Vlatko Vedral
The thermodynamic meaning of negative entropy
Nature 474, 61-63 (2011)