Rantings on Landauer's principle and low-power electronic circuits

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Based mostly on others work

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Rantings on Landauer's principle and low-power electronic circuits

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Why?

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Computers are not abstract:

Information is inevitably physical.

[Landauer in *Feynman and Computations* (1999)]

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Every logical state of a device *must* correspond to a physical state of the device.

[Feynman in *Feynman Lectures on Computation* (1985)]

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[Feynman in *Feynman Lectures on Computation* (1985)]

Whenever a device changes between a logical 0 and 1, there is a corresponding change in the physical device (e.g. memory or a transistor in an AND gate).

Thermodynamics of computation

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Landauer's principle

Any computation involving loss of information must dissipate a minimum amount of energy as heat.

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- Actual amount of energy is correlated with signal representation.

  [Gershenfeld, 1996]

Landauer vs. Moore

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"You can spend a lot of time arguing about a sensible value but something like the following is not too unreasonable."

The Landauer switching limit at finite (GHz) clock speed:
Energy to switch 1 bit > $100 k_B T \ln(2)$

[Douglas J. Poul, url]

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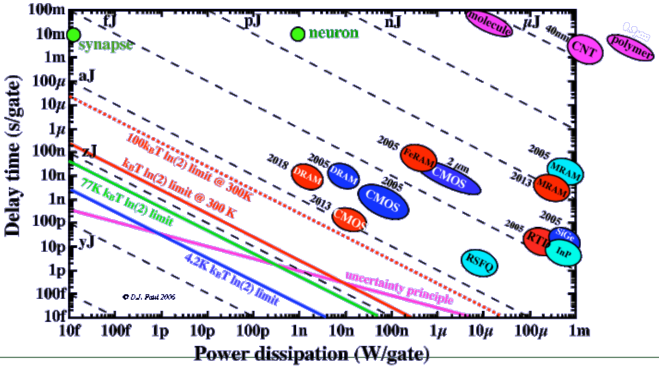

Transistor-based CMOS implementations I

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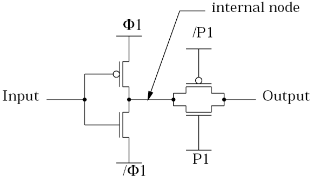
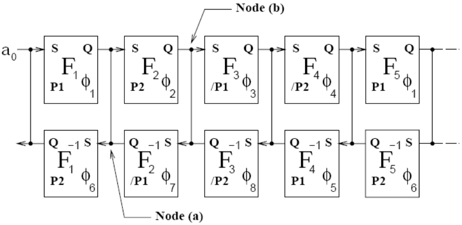
Switch-level charge-recovery logic

- Adiabatic switching
- Needs many clocks signal – hard to control
- Use compute-uncompute for energy restoration – not really reversible

[Younis and Knight, 1994]





Transistor-based CMOS implementations II

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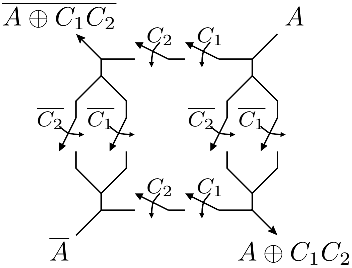
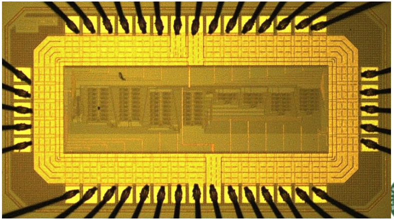
Complementary pass-transistor logic

- Adiabatic switching
- Degrading signals makes control of transistors hard over deep circuits
- Fully reversible implementation (dual-line ensures conservatism)

[De Vos and Van Rentergem, 2005, Burignat and De Vos, 2012]





Future Technologies - Materials and models

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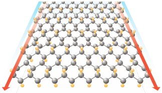
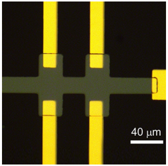
2D materials



The research community exploring 2D materials beyond graphene is rapidly expanding with new entrants from different fields such as materials science, physics, chemistry and electrical engineering. Encouraging work has already been intensively reported from different material systems such as nitrides (e.g., h-BN), dichalcogenides (e.g., MoS2), topological insulators (e.g., Bi2Se3 or Bi2Te3) and even oxides.

- Low energy consumption
- Low switching time

IBM: Liquid transistor

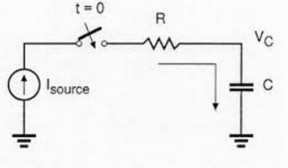


Gold electrical contacts surround a semiconducting material called vanadium oxide (brownish color). When a voltage is applied to ions in electrolyte (not seen) in contact with the material, it switches the material's state from insulating to conducting.

Future Technologies - Non-transistor models

Rantings on Landauer's principle and low-power electronic circuits

(Super) Capacitive Adiabatic Logic



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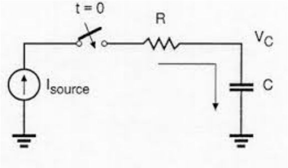

Micro-Electro-Mechanical Systems (MEMS)

Future Technologies - Non-transistor models

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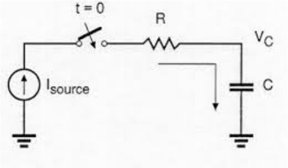
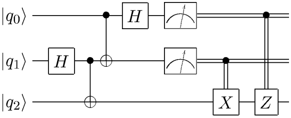
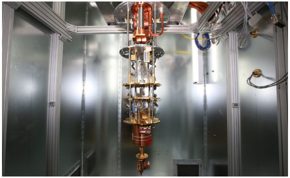


Micro-Electro-Mechanical Systems (MEMS)

Quantum Computing

- Related circuit model
- Step in synthesis of q-circuits





Thank you

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Bibliography I

Bérut, A., Arakelyan, A., Petrosyan, A., Ciliberto, S., Dillenschneider, R., and Lutz, E. (2012).
Experimental verification of Landauer's principle linking information and thermodynamics.
Nature, 483(7388):187–189.

Burignat, S. and De Vos, A. (2012).
A review on performances of reversible ripple-carry adders.
International Journal of Electronics and Telecommunications, 58(3):205–212.

De Vos, A. and Van Rentergem, Y. (2005).
Reversible computing: from mathematical group theory to electronical circuit experiment.
In *Proceedings of the Conference on Computing Frontiers*, pages 35–44. ACM Press.

Gershenfeld, N. (1996).
Signal entropy and the thermodynamics of computation.
IBM Systems Journal, 35(3.4):577–586.

Landauer, R. (1961).
Irreversibility and heat generation in the computing process.
IBM Journal of Research and Development, 5(3):183–191.

Orlov, A. O., Lent, C. S., Thorpe, C. C., Boechler, G. P., and Snider, G. L. (2012).
Experimental test of Landauer's principle at the sub-$k_{\mathrm{b}}t$ level.
Japanese Journal of Applied Physics, 51:06FE10.

Poul, D. J. (url).
The fundamental limits of computation.
`http://userweb.eng.gla.ac.uk/douglas.paul/SiGe/limits.html`.

Bibliography II

Younis, S. G. and Knight, J. T. F. (1994).
Asymptotically zero energy computing split-level charge recovery logic.
International Workshop on Low Power Design, pages 177–182.