EN2912C: Future Directions in Computing
Lecture 04: Fundamental Physical limits to Computing

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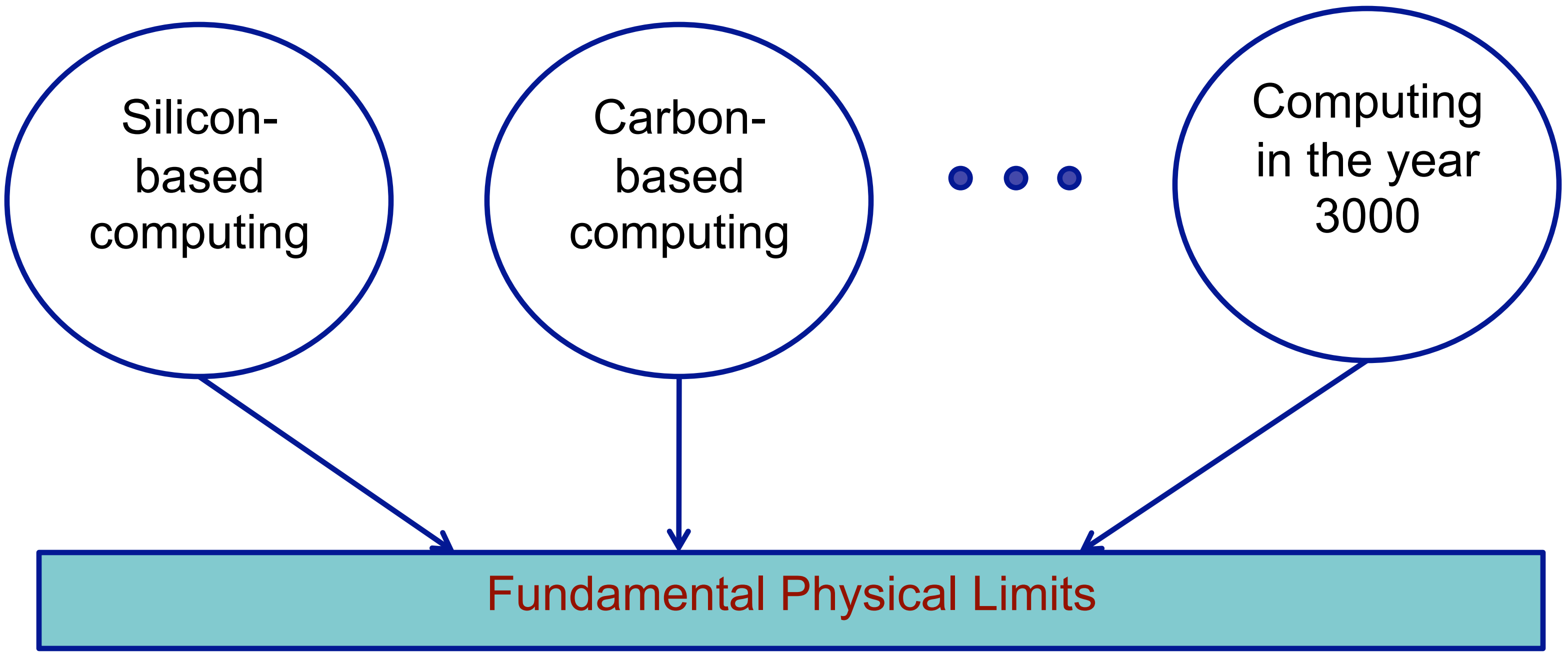
Limits to improving computing



A computer is an information processing engine that is ultimately constrained by the laws of physics

Physical limitations

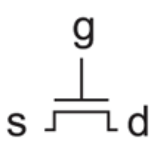
- Computers are physical systems. The laws of physics dictate their capabilities

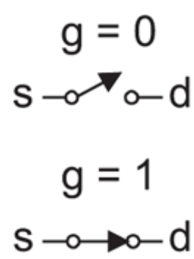
- The laws of physics determine the ultimate limits for these crucial metrics:

  1. Switching energy limitations (this lecture)
  2. Switching time limitations (this lecture)
  3. Size limitations (this lecture)
  4. Thermal limitations (part this lecture/next lecture)
  5. Noise limitations (next lectures)

Main two ingredients for digital computing

Switches





What is:

1. The minimum switching time?
2. The minimum switching energy?
3. The minimum device size?

irrespective of technology

interconnects

L

Minimum propagation delay

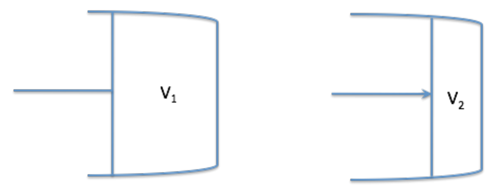
$$\tau \geq \frac{L}{c_0}$$

c_0 is the velocity of light in free space

1. Minimum energy required for a binary transition

If a force *F* moves through a small distance δx, the work done δW is:

$$\delta W = F\delta x$$



If the pressure of the gas is p, and the cross section of the piston is A then

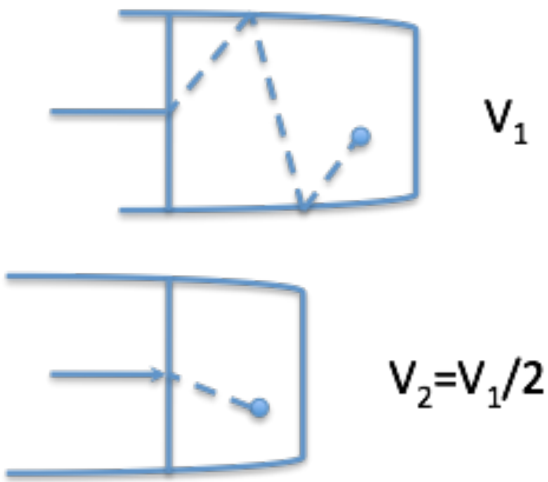
$$\delta W = P\delta V$$

From classical physics $pV = NkT$

where N is the number of particles in the gas and k is Boltzmann's constant

$$W = \int_{V_1}^{V_2} \frac{NkT}{V} dV = NkT \ln \frac{V_2}{V_1}$$

1. Minimum energy for irreversible switch



- Consider that we have one particle
- If the particle is in the left half of the “box” then the switch is in state 0 and if the particle in the right half then the switch in state 1.
- Therefore the *minimum energy per irreversible transition between two states* is equal to $E_{\min} = KT \ln 2$

1. Contrast to CMOS switching energy

- At 130 nm, $CV^2 = 0.17$ fJ
- At 22 nm, $CV^2 = 0.005$ fJ
- KTln2 = 3×10^{-21} J = 0.000003 fJ @ 300K

- We are still orders of magnitude above the theoretical KTln2 limit!!

Quantum-mechanical limits: Uncertainty principle

$$\Delta x \Delta p \geq \hbar/2$$

$$\Delta E \Delta t \geq \hbar/2$$

Lower bound on device size

"Heisenberg constraints" on minimum barrier width

A state which only exists for a short time cannot have a definite energy.

[Jeff Welser, IBM]

2. Fundamental limits on switching time

From Heisenberg uncertainty principle

$$\Delta E \Delta t \geq \frac{h}{2\pi}$$

Minimum transition time between two states

$$\Longrightarrow \Delta t_{\min} \geq \frac{h}{2\pi E_{\min}}$$

Maximum operation frequency

$$F_{\max} \leq \frac{2\pi E_{\min}}{h} \qquad E_{\min} = KT \ln 2$$

$$F_{max} \leq 25000GHz!$$

3. Minimum distance requirements

$$\Delta x \Delta p \geq \hbar$$

$$E_{\min} = KT \ln 2$$

$$x_{\min} = a = \frac{\hbar}{\sqrt{2mkT \ln 2}} = 1.5nm(300K)$$

Gate density

$$n = \frac{1}{x_{\min}^2} = 4.6 \times 10^{13} \frac{gate}{cm^2}$$

[Jeff Welser, IBM]

Putting it together

<u>Power consumption</u>

$$\begin{aligned} P &= nE_{\min}F_{\max} \\ &= 4.6 \cdot 10^{13} \cdot 3 \cdot 10^{-21} \cdot 2.5 \cdot 10^{12} \\ &= 4.74 \times 10^{6} W/cm^{2} \end{aligned}$$

The circuit would immediately vaporize once it is turned on

Circuit heat generation is the main limiting factor for scaling of device speed and switch circuit density

Paper discussions

- Limits on Silicon Nanotechnologies for Terascale integration. Meindl, Science, 2044-2049, 2001.