Molecular and Cellular Computing

Lecture series at Universidad Politécnica de Madrid

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Day 1: Molecular Computing
1. Introduction, and Historical Motivation

Programme of lectures

- Day 1: Molecular Computing
  - Motivation behind molecular computing
  - Early experiments
- Day 2: From *in vitro* to *in vivo*
  - Molecular self-assembly and other advances
- Day 3: Biological Engineering
  - Synthetic biology and cellular computing

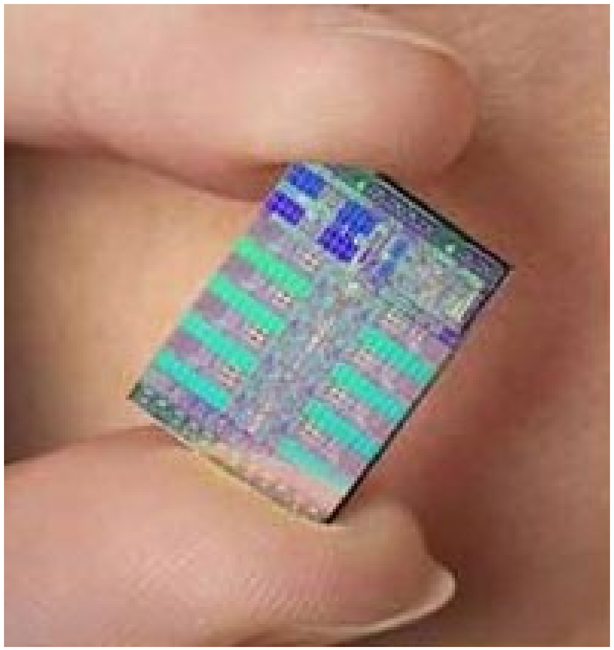
Motivation

- “In the future, computers may weigh less than 1 ½ tonnes…”
- Since then, we have achieved *massive* miniaturisation of computer components

Andrew Hamilton, Brains that Click, *Popular Mechanics* **91**, no. 3, March 1949, pp. 162-167, 256, 258

Development of computers

60 years



ENIAC (Electronic Numeric Integrator and Calculator), University of Pennsylvania, 1946

230 M^2, 3 “calculations” per second

Cell processor (PS3), Sony/Toshiba/IBM, c. 2006

25.6 gigaflops

History

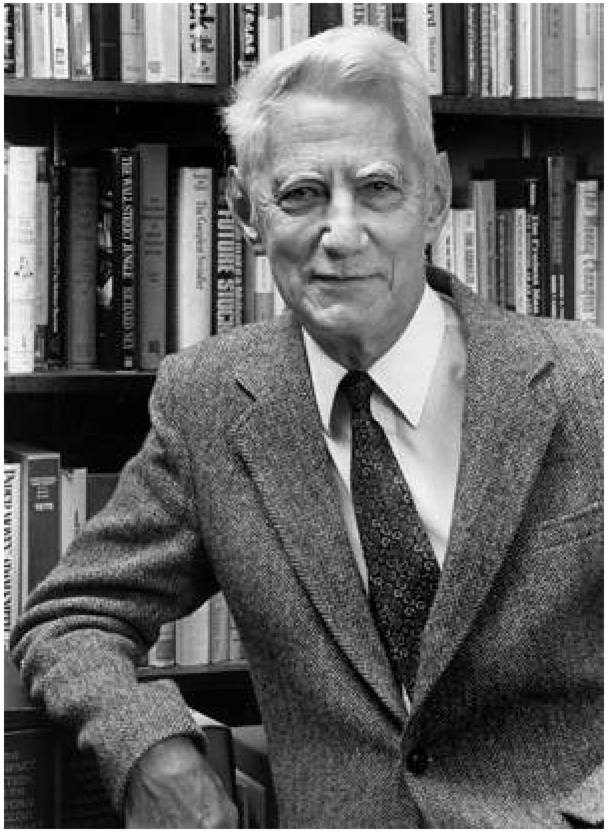
- Prior to World War 2, most people believed that the future lay with *analogue* computers
- Used real, continuous, *physical* quantities to represent data
- Spaghetti sort is a realisation of this idea
- Problem: constructed to solve a specific problem; difficult to generalise

Differential Analyzer

- Built by Vannevar Bush from 1927, later versions were used to design the “bouncing bomb”
- Gears, pulleys and rods to represent a set of differential equations

Shannon

- One of Bush's assistants, Claude Shannon, noted the fact that *relays* were used to turn various components of the DA on and off
- Made, for the first time, the connection with *Boolean logic*
- Realised that "on" and "off" could == "1" and "0"



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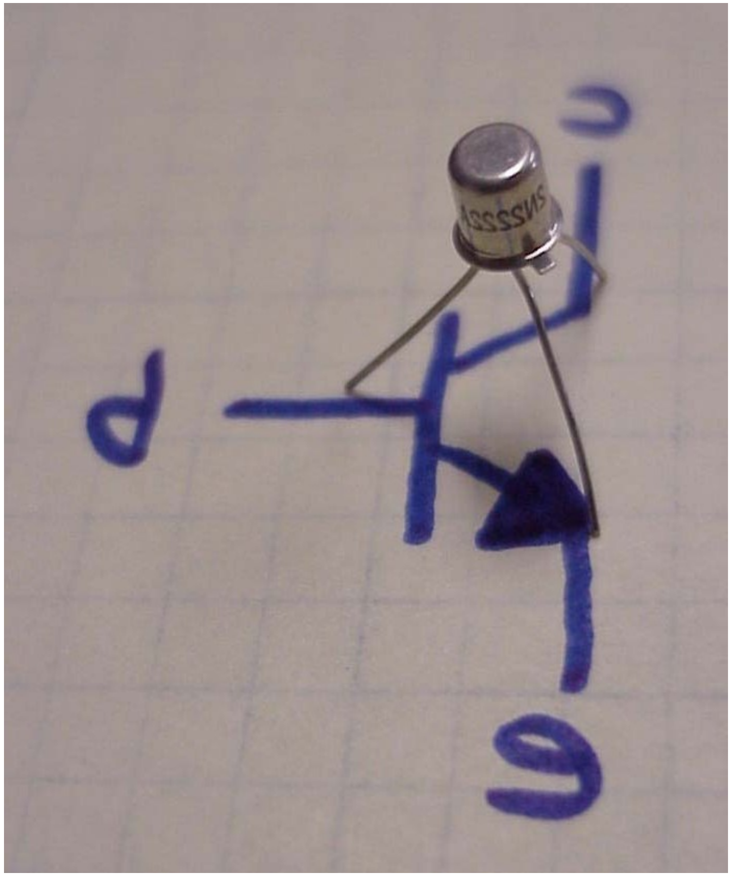
Boolean logic

- Using this insight, we can easily show how switches may be wired together to construct the familiar Boolean functions AND, OR, NOT and so on
- We might understand this in theoretical terms, but how does it physically work *in practice*?
- We jump forward to the invention of the *transistor*

Transistor

- Fundamental building block of modern computers
- Semiconductor device, used to amplify or switch electronic signals



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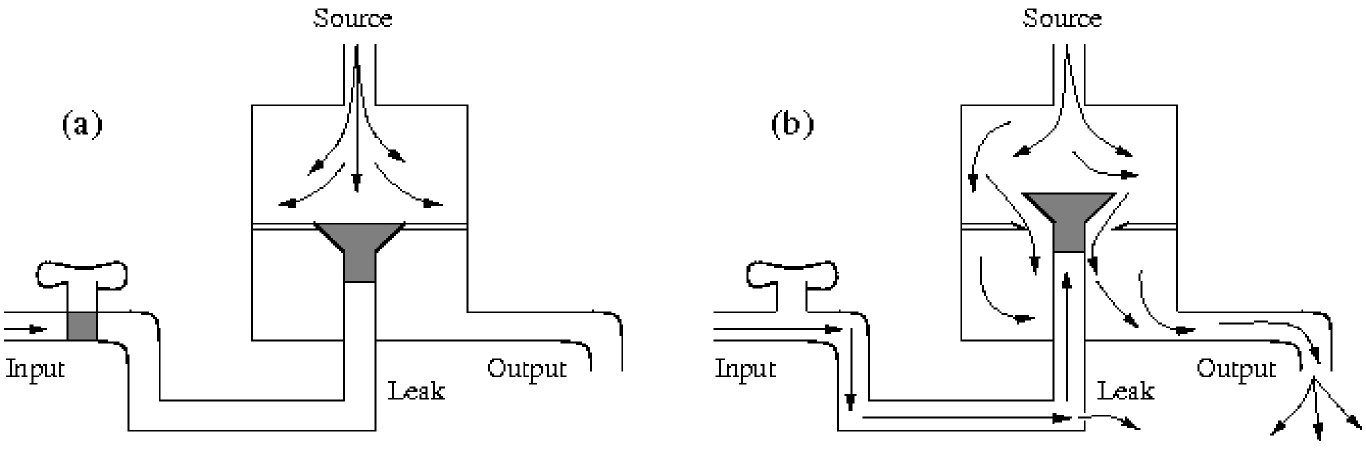
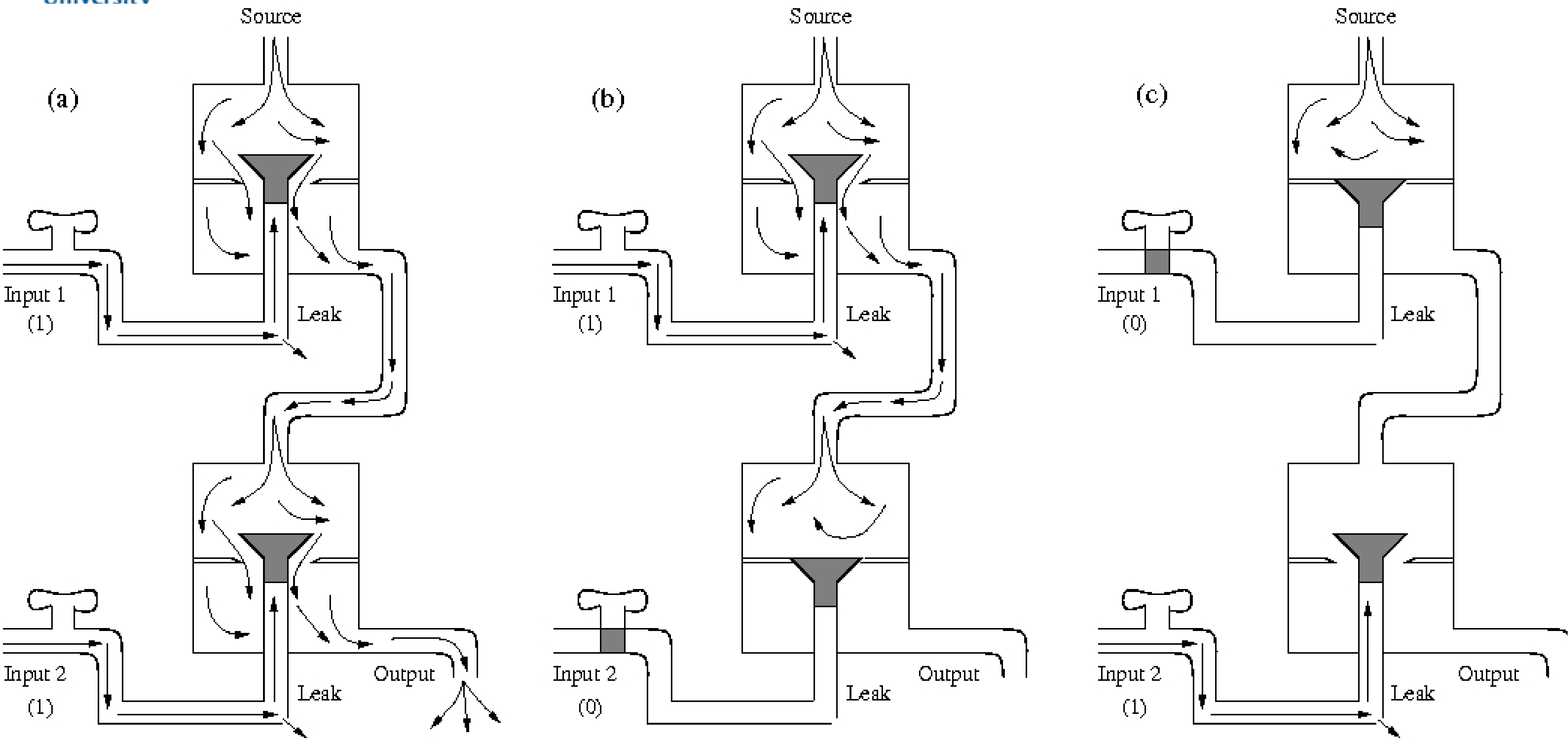
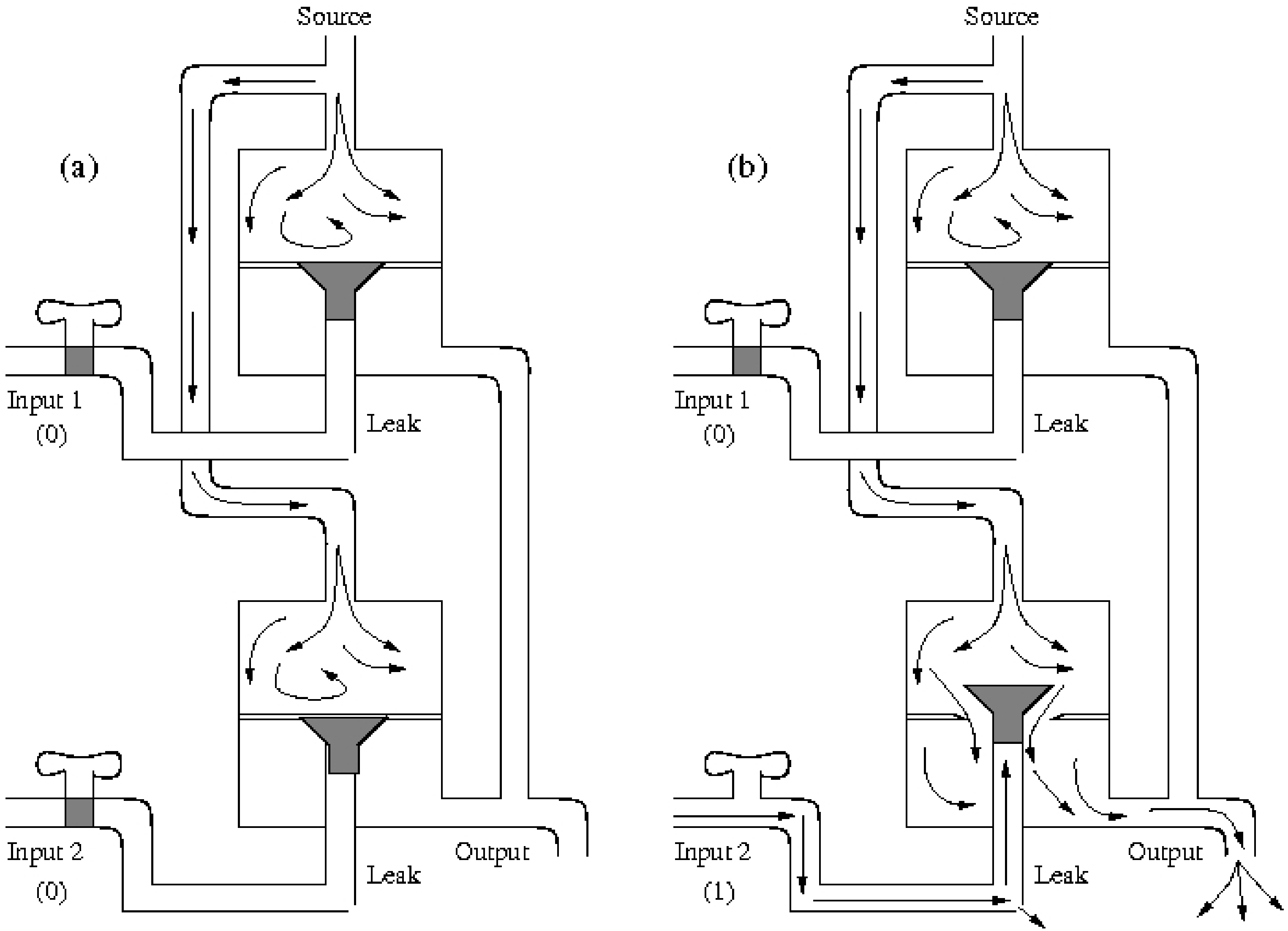
Transistor operation



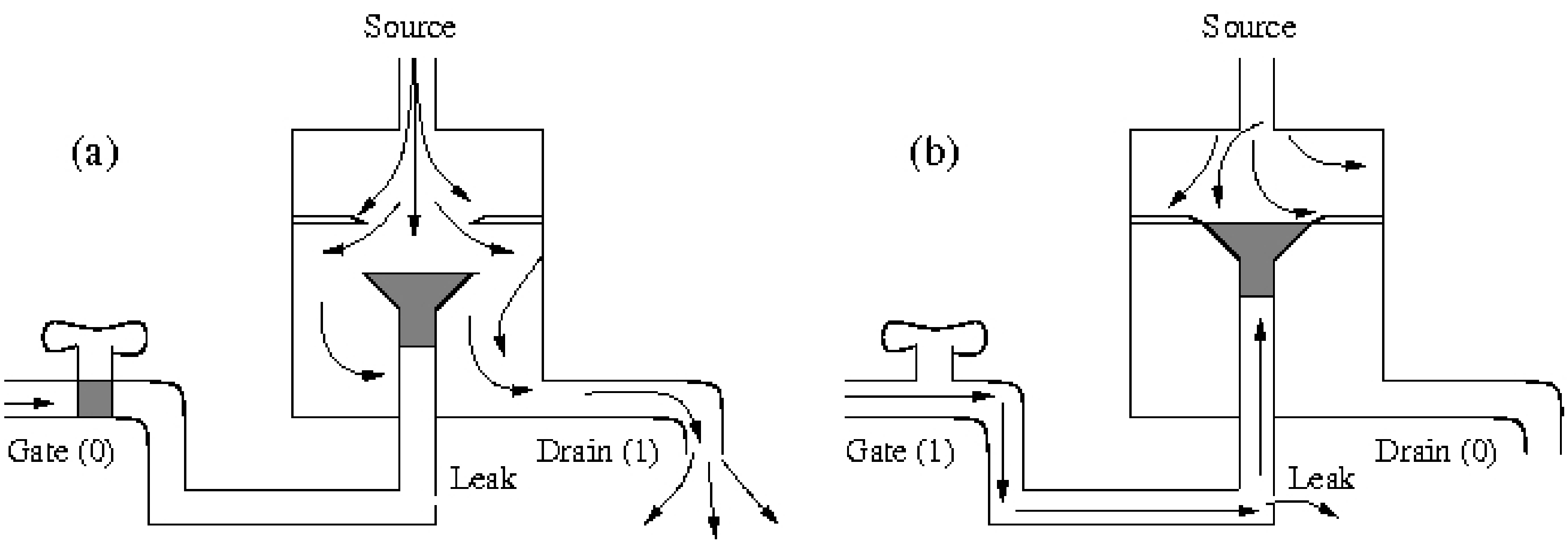
AND


Source
(a)
Input 1
(1)
Leak
Input 2
(1)
Leak
Output
Source
(b)
Input 1
(1)
Leak
Input 2
(0)
Leak
Output
Source
(c)
Input 1
(0)
Leak
Input 2
(1)
Leak
Output

OR


(a)
Source
Input 1
(0)
Leak
Input 2
(0)
Leak
Output
(b)
Source
Input 1
(0)
Leak
Input 2
(1)
Leak
Output

NOT



Implications

- We can see how a computation may be thought of in terms of a *flow* of information
- This may be made up of water, electricity, or something else; the important thing is that it carries *meaning*
- So what are the main motivations behind looking for new ways to perform computations?
  - *Miniaturisation*
  - *Machine model*

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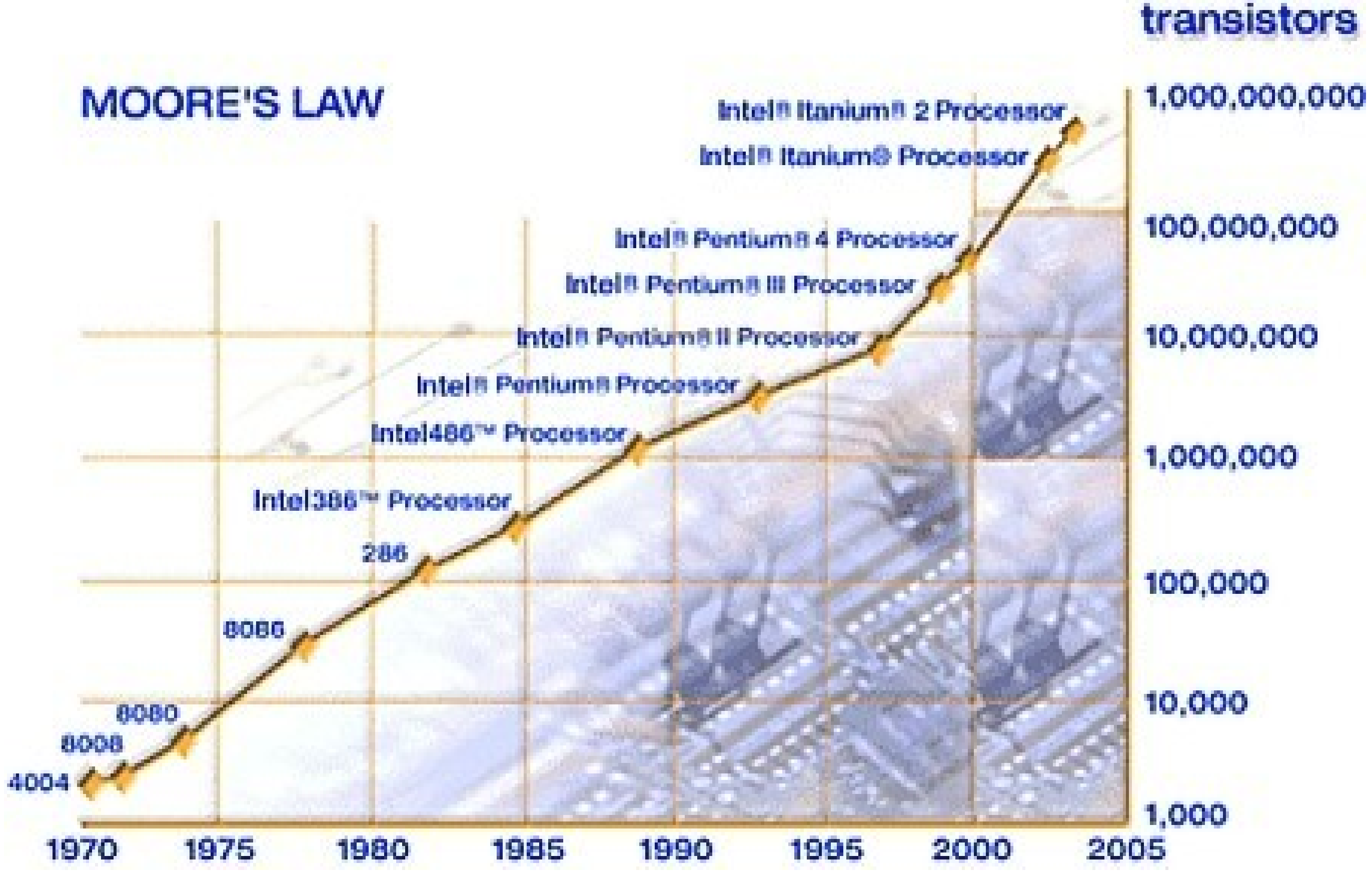

Intel

Miniaturisation

- "The computing power of processors doubles every 18 months" Gordon Moore, Intel
- How true is this, now that miniaturisation is approaching atomic resolutions?
- Eventually (10-15 years?), we will hit problems as far as *traditional* fabrication techniques are concerned
- Moore's *Wall*

Why?

- Transistors act as gates, channelling electrons around a circuit
- Their walls are thick enough to contain the electrons, and ensure that they “behave correctly”
- However, when the gates reach a critical width (c. 5nM), the electrons tunnel through the walls, causing interference

Why?

- Also, transistor leakage manifests itself as *heat*
- "...We find that we are rapidly approaching the point where compromises are forced between device density and switching speed due to thermal constraints." George Bourianoff, Intel affiliate, 2003.
- "This looks like a fundamental limit. From a total energy point of view, you are not fooling Mother Nature." Paolo Gargini, Intel Director Of Technology Strategy

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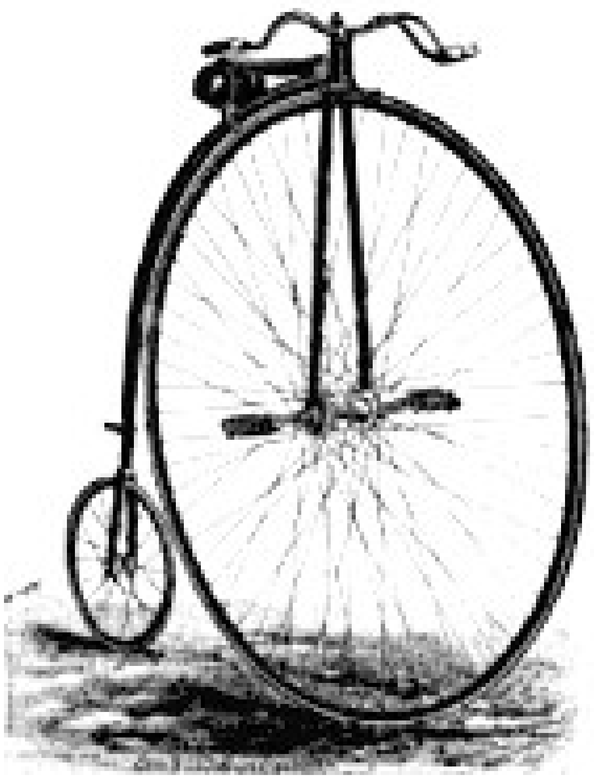
Machine model



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Von Neumann architecture

- Processor and memory
- Information passes between the two, along finite-width bus
- Places upper-bound on transfer rate
- The “von Neumann bottleneck”

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Solutions?

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Plenty of Room at the Bottom

Plenty of room at the bottom

- Richard Feynman - Nobel laureate in physics
- "*There's plenty of room at the bottom*" (1961)
- Essentially founded field of nanotechnology
- Key idea - *molecules* (or even *atoms*) as potential *machine* components

Richard P. Feynman, There's Plenty of Room at the Bottom, in *Miniaturisation*, D. Gilbert (Ed.), pp. 282-296, 1961