4IF EESN

A societic-historical perspective on digital hardware (from pebbles to integrated circuits)

en bon français: **du digital au numérique**

Florent de Dinechin

Outline

Transition: the war of the programming models

Prehistory: who controls numbers controls the world

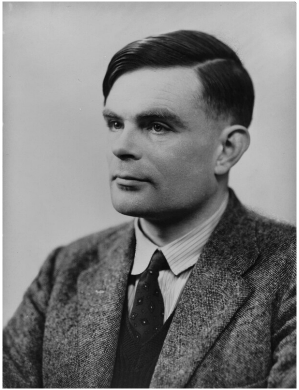
History: what kind of law is Moore's Law

Preparing for post-history

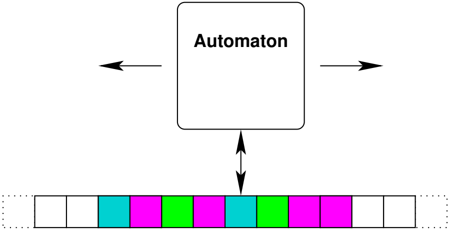
Transition: the war of the programming models

Alan Turing and John von Neumann

... *the twin gods of the computing pantheon* (A. C. Clarke in 2001: A Space Odyssey)



The Turing Machine: a good idea, but a commercial failure



- Defines universality
- Finite automaton infinite memory
- local access to the memory

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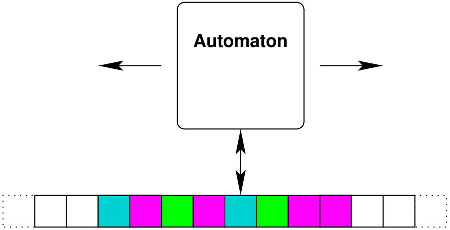

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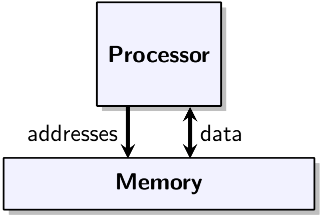
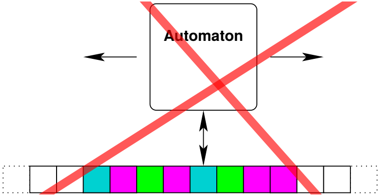
Kahan: the fast drives out the slow even if the fast is wrong

The von Neumann Machine that ruled





- Universal as well
- Same finite automaton (processor), same infinite[1] memory
- Turing-killer feature: random access to the memory

[1] From there on, infinite means: some power of two, e.g. 2^{32} so large that I can't count that far.

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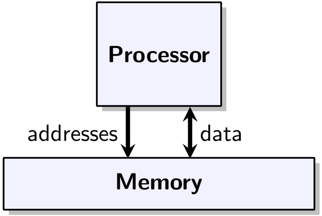

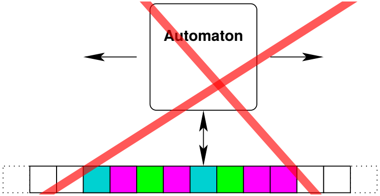

- Universal as well
- Same finite automaton (processor), same infinite[1] memory
- Turing-killer feature: random access to the memory
  - so much more efficient (no tape rewinding)
  - so much easier to exploit (program here, data there, etc)

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When reality kicks back

A law of nature

You can't move data
faster than the speed of light
If the memory is infinite,
some bits will be physically distant
and will therefore be accessed slowly.

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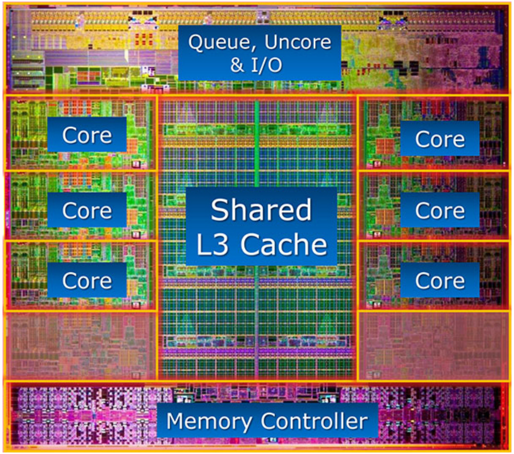
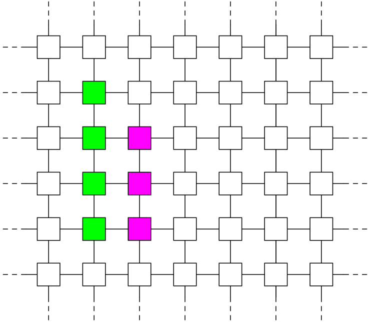


One half of your processor is there to keep this dream alive!

Meanwhile, von Neumann had a better idea

Cellular automaton: a spatial/parallel version of Turing machine.

(most famous instance: Conway's **Game of Life**)



- an infinite number of automata
- all working in parallel
- with next-neighbour (local) communications
- univeral all the same

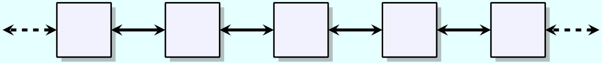
  (youtube "game of life in game of life")

Let us build this! (with a little help of Moore's law)

Yes but... next-neighbour communications suck!

The firing squad synchronization problem

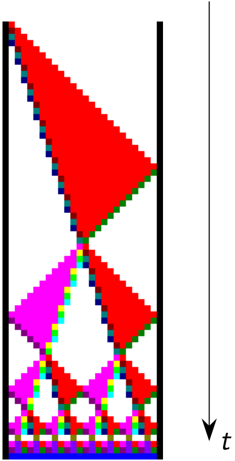
Synchronize n cells, using next-neighbour communication only



- right: $3n$ steps, using 15 states
- best known: $2n-2$ steps, 6 states

Jacques Mazoyer.
A six-state minimal time solution to the firing squad synchronization problem. *Theoretical Computer Science*, 50(2):183–238, 1987.

2D version: youtube "game of life in game of life"



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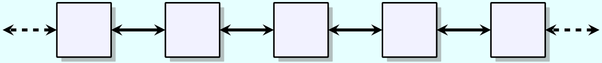

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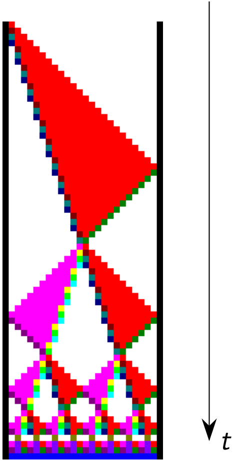
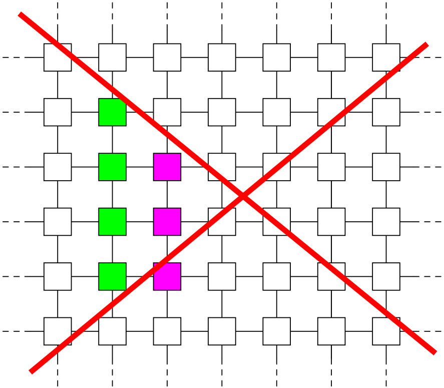
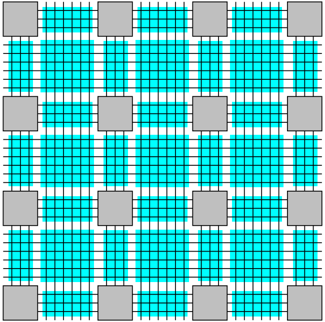


... in real life the captain simply shouts "Fire!" (a global communication)

Field-Programmable Gate Arrays

FPGAs are to 2D cellula automata what von Neuman machines are to Turing machines: **something useful in practice**.





Prehistory: who controls numbers controls the world

EESN pour Numérique: l'invention des nombres

Un survol approximatif et incompétent de l'histoire des nombres pour illustrer deux idées :

- des inventions motivées par des Enjeux Sociétaux™®;
- des inventions contraintes par les limitations de la technologie.

Neolithic

Joint invention of

- the unary representation of integers
- the non-volatile memory (*calculus* == pebble)
- the bijection / set idempotency

Enjeu sociétaux:

- compter les moutons

  (alors qu'on ne sait pas encore compter)
- du troc au commerce
  - premiers contrats:

    des cailloux enfermés dans une coquille de terre cuite

Antiquity

alphabetical systems
(Roma, Egypt, Greece, China)

position systems
(Babylonia, India, Maya)

Alphabetical systems

- unary, but several symbols/tokens.
  - coins and bills
  - Roman numerals
- addition and subtraction easy as in unary
  - low-tech addition device: your purse

Je me demande bien à quel enjeu sociétal cela répond ?

D'après un haut relief de Saqqara en Egypte. Bec dans le vent, les oiseaux indiquent l'ordre de lecture, ici de droite à gauche. Les autres hiéroglyphes comptent les tributs payés à Pharaon après une campagne victorieuse. Chaque signe vaut : un pour la barre, 10 pour le fer à cheval, 100 pour le serpent, 1000 pour le lotus, 10 000 pour l'obélisque et 100 000 pour la salamandre.

Jean Vuillemin, les langages numériques (dispo sur le web)

Position systems

Our decimal system is an example of position system:

- The *position* i of a digit gives its *weight* 10^i
- Example: $789 = 7 \cdot 10^2 + 8 \cdot 10^1 + 9 \cdot 10^0$
- With 3 decimal digits we represent numbers from 000 to 999 $= 10^3 - 1$
- In general, using n digits, we can represent integers in $[0..10^n - 1]$

First advantage of positions systems

A compact representation of arbitrarily large numbers with a fixed number of symbols.

Exponential economic growth can begin...
But also science.

The Babylonian system

A positional number system in radix 60

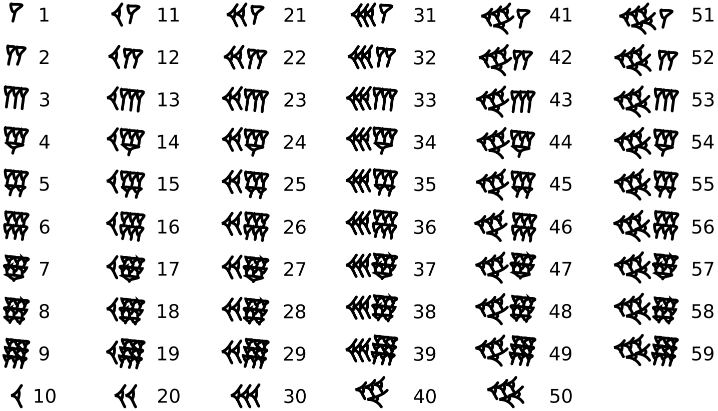
- Radix 60 needs to represent 60 different digits... 60 symbols?
- Each digits represented in a two-symbol alphabetical system:

𒁹 $= 1$,
𒌋 $= 10$

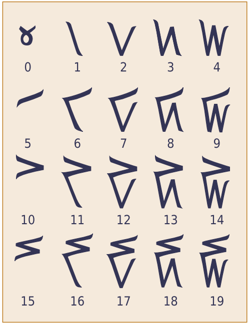
YBC7289 from `http://www.math.ubc.ca/~cass/euclid/ybc/ybc.html`

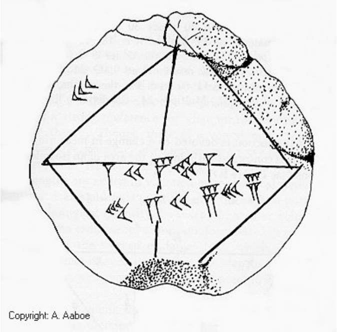
Code superpositions

Babyloniens de jadis



Eskimos de maintenant
(Kaktovik)





Une antisèche babylonienne donnant $\sqrt{2}$ et $1/\sqrt{2}$ en base 60.
(on lit 30, autrement dit 1/2, sur le côté du carré,
et sur la diagonale 1:24:51:10 et 42:25:35)

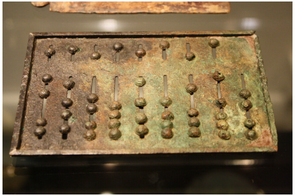
Notation scientifique à exposant implicite

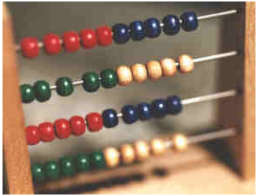
Si je vous dis que j'ai 𒐈 enfants, cela peut signifier 3/60 enfants, ou 3 enfants, ou 3x60 enfants, ou...
En général, le contexte aide à décider (merci la grande base)

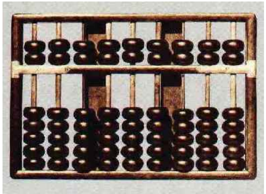
Taking into account the limitations of the technology

- Our brain is able to distinguish at a glance 3 pebbles from 4, but not 7 pebbles from 8...
- On the other hand, it is good at recognizing shapes
- For this reason, Babylonians fixed the shape of the digits

Also reflected in the evolution of the computing device:







Taking into account the limitations of the technology

Digital electronic technology is based on 2-value (Boolean) logic.

Positive integers in the binary position system

- Radix $\beta = 2$
- Two digits 0 and 1
- Bit for “binary digit”
- Larger radices possible by grouping bits :
  e.g. hexadecimal = radix 16, 4-bit digits

Conclusion: la nécessité du calcul

Interro pour voir qui a suivi

A votre avis, les nouveaux systèmes de numération répondaient à un besoin de :

- compter les bulletins de votes pour l'élection du Pharaon
- compter les trimestres ouvrant droit à la retraite pour les tailleurs de pierre
- compter les esclaves, les soldats, et les impôts
- faire avancer la science astronomique

Le numérique accompagne la construction de la civilisation

- Système unaire pour compter les moutons dans de petites communautés
- Systèmes alphabétiques pour compter
  - la richesse dans l'économie réelle
  - mais aussi les soldats (pelotons, compagnies, bataillons, régiments, brigades, divisions)
  - etc.
- Systèmes positionnels pour les calculs plus compliqués :
  - géométrie (un peu pour la science, beaucoup pour le cadastre donc les impôts)
  - lever des impôts
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Mais quand est-ce qu'il va nous parler d'ordinateurs ?

Ici bientôt construction d'une transition

Exercice: pour chacun de ces héros, retrouve à quel enjeu sociétal il répond.

- Claude Chappe invente la couverture réseau sans fil
- Ada Lovelace invente le langage de programmation et le multimedia
- Konrad Zuse invente l'ordinateur moderne
- Alan Turing et John von Neumann aussi
- Margaret Hamilton fonde la profession de hacker, puis pour se faire pardonner invente l'ingéniérie logicielle

Mais sautons tout de suite à l'ère moderne de l'informatique.

History: what kind of law is Moore's Law

Transition: the war of the programming models

Prehistory: who controls numbers controls the world

History: what kind of law is Moore's Law

Preparing for post-history

Moore's law

From observations in a 1965 paper by Gordon Moore (Intel)

The number of transistors
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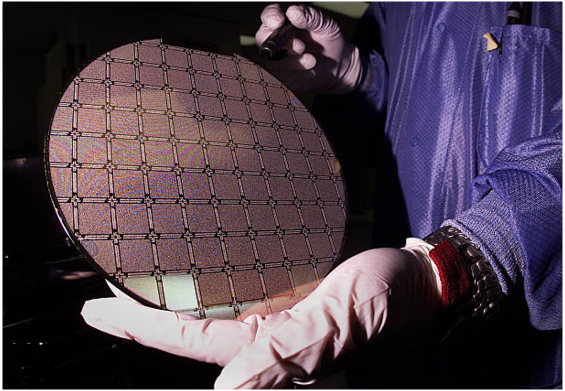
From 2004 on: more transistors produced in the world than grains of rice, and cheaper

Economically viable ?



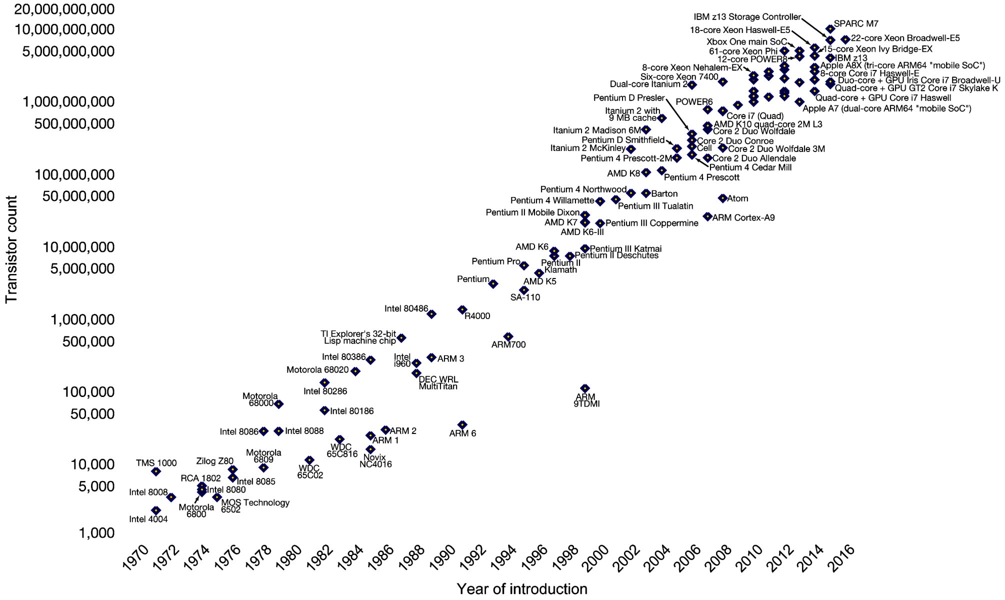
Very expensive and very clean factories

- The wafer size is fixed
  (30 cm since 2002)
- Despite the gloves and stuff,
  you will have about 10 defects per wafer

Yield

- 4 chips per wafer:
  very low chance that one works
- 20 chips per wafer: 50% should work
- 1000 chips per wafer: 99% should work

Gamerz GPU: about 5 cm^2 (about 100/wafer); notebook processor about $1cm^2$
Wafer-scale circuits possible if they are designed to be resilient to defects (Cerebras)



Transistor count
Year of introduction
20,000,000,000
10,000,000,000
5,000,000,000
1,000,000,000
500,000,000
100,000,000
50,000,000
10,000,000
5,000,000
1,000,000
500,000
100,000
50,000
10,000
5,000
1,000
1970 1972 1974 1976 1978 1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016
IBM z13 Storage Controller
SPARC M7
18-core Xeon Haswell-E5
22-core Xeon Broadwell-E5
Xbox One main SoC
15-core Xeon Ivy Bridge-EX
61-core Xeon Phi
12-core POWER8
IBM z13
Apple A8X (tri-core ARM64 "mobile SoC")
8-core Xeon Nehalem-EX
8-core Core i7 Haswell-E
Six-core Xeon 7400
Duo-core + GPU Iris Core i7 Broadwell-U
Dual-core Itanium 2
Quad-core + GPU GT2 Core i7 Skylake K
Pentium D Presler
POWER6
Quad-core + GPU Core i7 Haswell
Apple A7 (dual-core ARM64 "mobile SoC")
Itanium 2 with 9 MB cache
Core i7 (Quad)
AMD K10 quad-core 2M L3
Itanium 2 Madison 6M
Core 2 Duo Wolfdale
Pentium D Smithfield
Core 2 Duo Conroe
Itanium 2 McKinley
Cell
Core 2 Duo Wolfdale 3M
Pentium 4 Prescott-2M
Core 2 Duo Allendale
Pentium 4 Cedar Mill
AMD K8
Pentium 4 Prescott
Pentium 4 Northwood
Barton
Pentium 4 Willamette
Pentium III Tualatin
Atom
Pentium II Mobile Dixon
ARM Cortex-A9
AMD K7
Pentium III Coppermine
AMD K6-III
AMD K6
Pentium III Katmai
Pentium II Deschutes
Pentium Pro
Pentium II Klamath
Pentium
AMD K5
SA-110
Intel 80486
R4000
TI Explorer's 32-bit Lisp machine chip
ARM700
Intel 80386
Intel i960
ARM 3
Motorola 68020
DEC WRL MultiTitan
Intel 80286
ARM 9TDMI
Motorola 68000
Intel 80186
Intel 8086
Intel 8088
ARM 2
ARM 1
ARM 6
WDC 65C816
Novix NC4016
Motorola 6809
WDC 65C02
TMS 1000
Zilog Z80
RCA 1802
Intel 8085
Intel 8008
Intel 8080
MOS Technology 6502
Motorola 6800
Intel 4004

Dennard scaling

From a 1974 paper by Robert Dennard (IBM)

Smaller transistors

- run faster, and
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Dennard scaling stopped in 2004.

What happened to Dennard scaling?

Smaller transistors

- still could run faster, but
- no longer consume less

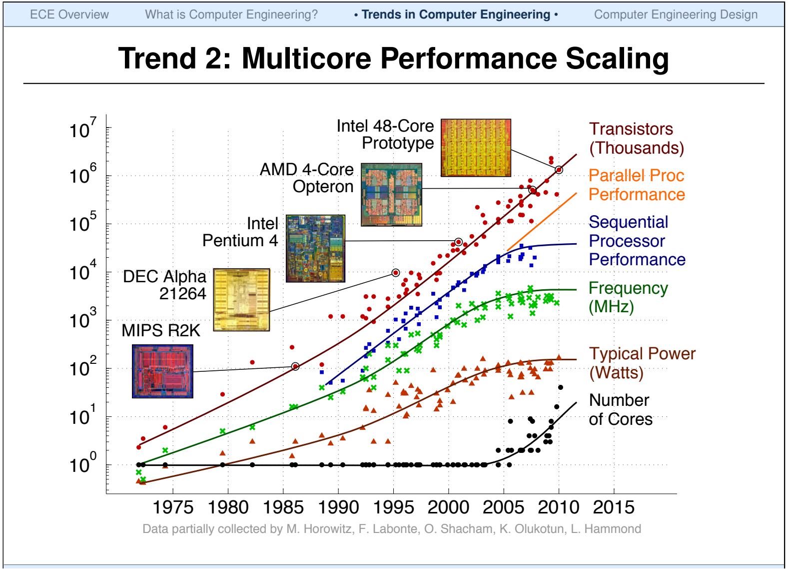
so more transistors (Moore) entails more power dissipation

The problem is to move the heat out

Practical power dissipation limit: $100W/cm^2$
10x your cooking pan, comparable to the rods of a nuclear power plant

Remark: 3D integration helps Moore, but annoys Dennard even more.

The current solution to the end of Dennard scaling



Nobody asked for multicores !

Life was simpler with single-core programming.

The great depression

- Edward Lee: The Problem With Threads, 2006
- David Patterson: The Trouble With Multicore, 2010

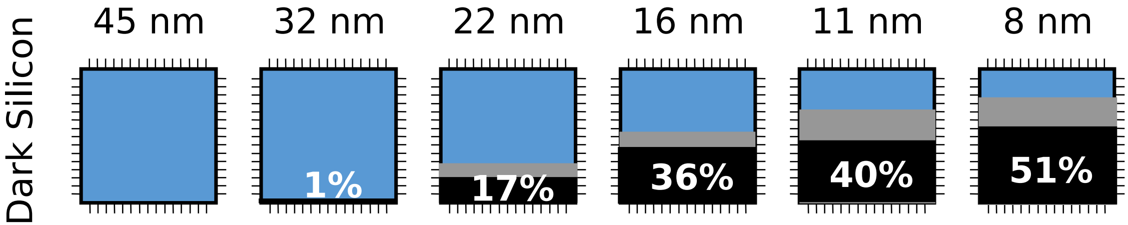
Homework: go read them.

The dark silicon apocalypse

Dark silicon?

In current tech, you can no longer
use 100% of the transistors 100% of the time
without destroying your chip.

"Dark silicon" is the percentage that must be off at a given time



(picture from a 2013 HiPEAC keynote by Doug Burger)

Pleasant times to be an architect

One way out the dark silicon apocalypse (M.B. Taylor, 2012)

Hardware implementations of rare (but useful) operations:

- when used, dramatically reduce the energy per operation (compared to a software implementation that would take many more cycles)
- when unused, serve as radiator for the used parts

Since they are rare, nobody bothered to study them before...

Reality shouldn't constraint our formalisms

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The end of Moore's law

- Size of an atom?
  The mesh size in silicon crystal is about 0.5nm (1nm=10^{-9}m).

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The end of Dennard scaling

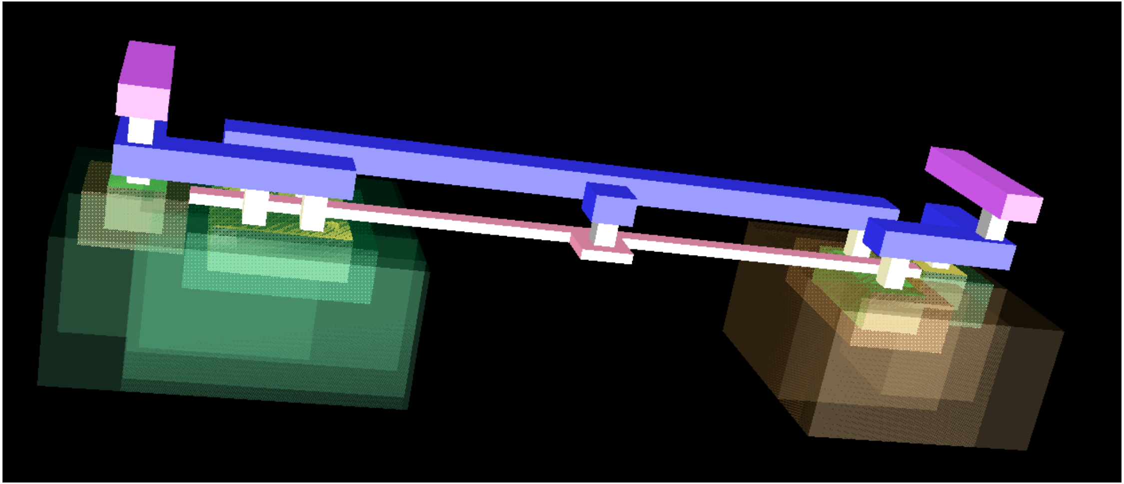
- Corresponding oxide layer is about two atoms high.
  $\longrightarrow$ quantum tunelling $\longrightarrow$ power waste
- Transistor threshold voltage got down from 5V to 1V, and won't go much lower

Remarks: these nanometers used to measure the width of a wire, but it got complicated and it is now pure marketing

Oxide layer?

The following picture is advertising for the Electric CAD software

`http://www.staticfreesoft.com/`



Reality shouldn't constraint our formalisms

Other limits

- Speed of light?

Reality shouldn't constraint our formalisms

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- Speed of light? $3 \cdot 10^8$ m/s.

Reality shouldn't constraint our formalisms

Other limits

- Speed of light? $3 \cdot 10^8$ m/s.
- At the speed of light, a 3GHz signal travels no further than 10 cm in a period
- Homework: cross this with atom size, and get a limit frequency

It's the economy, stupid

The economic cost of a self-fulfilling prophecy

Each new foundry is twice as expensive as the previous one
(or: the cost of a new foundry also follows Moore's law)

- Why?
  - Building billions of reliable objects, each 30 atoms wide requires a pretty good vacuum cleaner...
  - Lithographic process used light, then UV, now X rays...
- So foundries are merging to share the costs
  - In 2023, TSMC and Samsung control 70% of the market.
  - ... at some point there will be no competitor left to merge with.
  - (already the case for the manufacturers of foundry equipment, look up ASML)

Back to physics:

Computing consumes energy

- Each bit flipped entails a transfer of electrons from the ⊖ to the ⊕ through some resistors
- Currently, switching 1 bit costs $10^{-18} J$ (1 attoJoule)

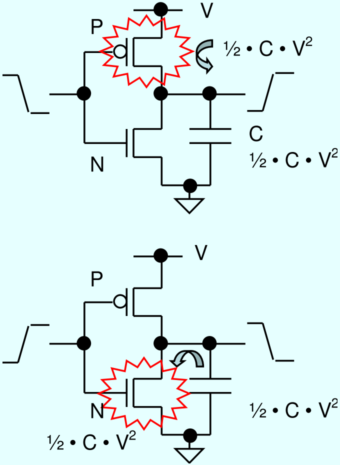

Figure from *Energy per Instruction Trends in Intel Microprocessors* by Grochowski and Annavaramx

It's the energy, stupid (2)

Moving bits consumes energy

- Switching 1 bit costs $10^{-18} J$,
- Moving 1 bit costs $10^{-12} J/cm$ $10^6\times$ more!

(Really the same drawing, but with a larger C)

Remark: there are several hundreds of km of wires inside your processor

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Doing nothing consumes energy

These days, roughly 1/3rd of power is leaked (quantum tunelling, etc).

It's the energy, stupid (3): the macro view

Approximate power in 28nm processor (adapted from Bill Dally)

- One 64-bit floating-point Fused Multiply-Add: **50 pJ**
  - This includes switching and moving around inside the FMA
- Access to a 1Kx256-bit on-chip SRAM: **50 pJ**

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- Some people will tell you that doing the same operation in the Cloud (10^4 times further away) saves energy.
  I have serious doubts.

Hence the current trends in VLSI circuits

Exposed here very well by Christopher Batten:

`https://web.csl.cornell.edu/engrg1060/handouts/engrg1060-ece-lecture.pdf`

Preparing for post-history

Transition: the war of the programming models

Prehistory: who controls numbers controls the world

History: what kind of law is Moore's Law

Preparing for post-history

Gordon Moore was also an engineer

... and engineers, unlike most economists, know one thing about exponentials:

Gordon Moore in 2005

"It can't continue forever. The nature of exponentials is that you push them out and eventually disaster happens."

(speaking of Moore's Law, but could apply as well to any economic growth of 5%/year).

Moore passed away last week

The International Technology Roadmap for Semiconductor

The ITRS was the consortium in charge of fulfilling the prophecy.

- hundreds of participants, including application people
- addressing gate and RAM technology, but also factory equipment (vacuum cleaners, UV lamps, etc.)

They self-dissolved in 2016, after publishing their final 5-year roadmap.

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- NVIDIA's CEO stated in september 2022 that Moore's law is dead.
- Intel's CEO replied one week later "même pas vrai". And indeed it still crawls a bit:
  - FinFET transistors
  - non-volatile RAMs around the corner, and memristors and ...
  - ... and some day the successor of the transistor

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Some of the industry is probably headed for disaster.

However, there will also be a (very similar, but more serious) *petrol* disaster,

and at least two other, actually serious, disasters: *climate* and *biodiversity*.

One example cut from the 2015 (and last) ITRS report

DRAM products are approaching fundamental limitations as scaling DRAM capacitors is becoming very difficult in 2D structures. It is expected that these limits will be reached by 2024 and after this year DRAM technology will saturate at the 32Gbit level unless some major breakthrough will occur.
Flash memory on the other hand ...

By the way I don't want to sound pessimistic

… Your jobs as computer engineers are not in danger (so focus on climate and biodiversity)

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- Current level of integration is here to stay. Maybe we won't get 2x better processors in two years, but we will still get current processors.
  (conversely, after peak oil, we get exponentially less petrol each day !
  This end-of-exponential will hurt much more.)

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  - digital sound quality improved drastically from square waves to stereo 16 bit @ 44KHz (reached in the 90s), and didn't progress since then.
  - digital video reached a similar plateau 10 years ago. Retina display etc.
  - we can still go real 3D, and then ?

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  or for 10 lines of text in Marmiton.
- There is space for better chips, better languages, better software... with the same transistors. This is what they do in the other departments of INSA, after all.

What disaster then ?

Disaster to those whose business model is based on Moore's law.

Shock, horror, PCs would become like fridges or dishwashers !

Old ones don't have more capacity or more performance than new ones.
We only buy a new one when the old one is broken.

- Some business models collapse (e.g. Microsoft doubling, from one Windows version to the next, the memory required to just do nothing)
  This is why they try to move to a subscription-based model.
- In general, move to data-oriented economy,
  with the admirable belief that data may grow exponentially forever.
- all this is not my speciality.

Pleasant times to be a computer engineer

- Admit it: all these years,
  software engineers have been parasites on the back of the electronic engineers.
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Maybe we can use the end of Moore's law to transition computing from More to Better.