SURF Research Talk, June 16, 2015

Along for the Ride –

reflections on the past, present, and future of nanoelectronics

Mark Lundstrom
lundstro@purdue.edu
Electrical and Computer Engineering
Birck Nanotechnology Center
Purdue University, West Lafayette, Indiana USA

PURDUE UNIVERSITY

“If someone from the 1950’s suddenly appeared today, what would be the most difficult thing to explain to them about today?”

“I possess a device in my pocket that is capable of assessing the entirety of information known to humankind.”

“I use it to look at pictures of cats and get into arguments with strangers.”

Curious, by Ian Leslie, 2014.

transistors

The basic components of electronic systems.

>100 billion transistors

transistors

"The **transistor** was probably the most important invention of the 20th Century, and the story behind the invention is one of clashing egos and top secret research."

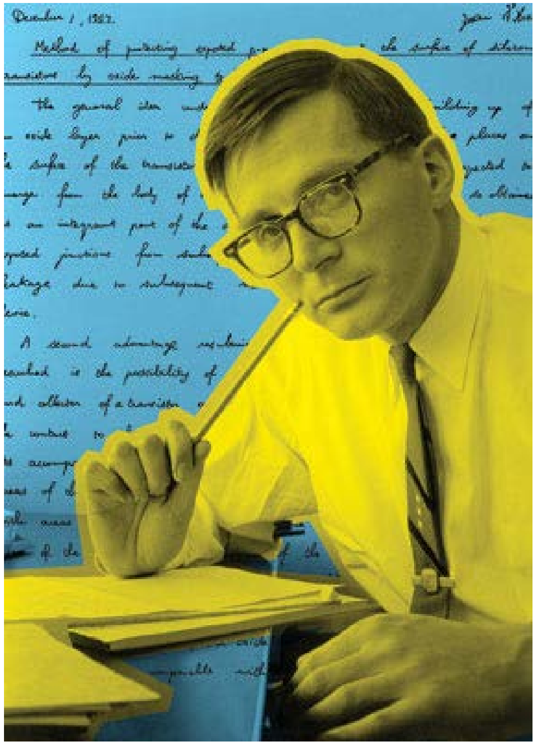
-- Ira Flatow, Transistorized!

http://www.pbs.org/transistor/

“The most important moment since mankind emerged as a life form.”

Isaac Asimov

(speaking about the “planar process” used to manufacture ICs -- invented by Jean Hoerni, Fairchild Semiconductor, 1959).



IEEE Spectrum Dec. 2007

Integrated circuits

"In 1957, decades before Steve Jobs dreamed up Apple or Mark Zuckerberg created Facebook, a group of eight brilliant young men defected from the Shockley Semiconductor Company in order to start their own transistor business…"

Silicon Valley:

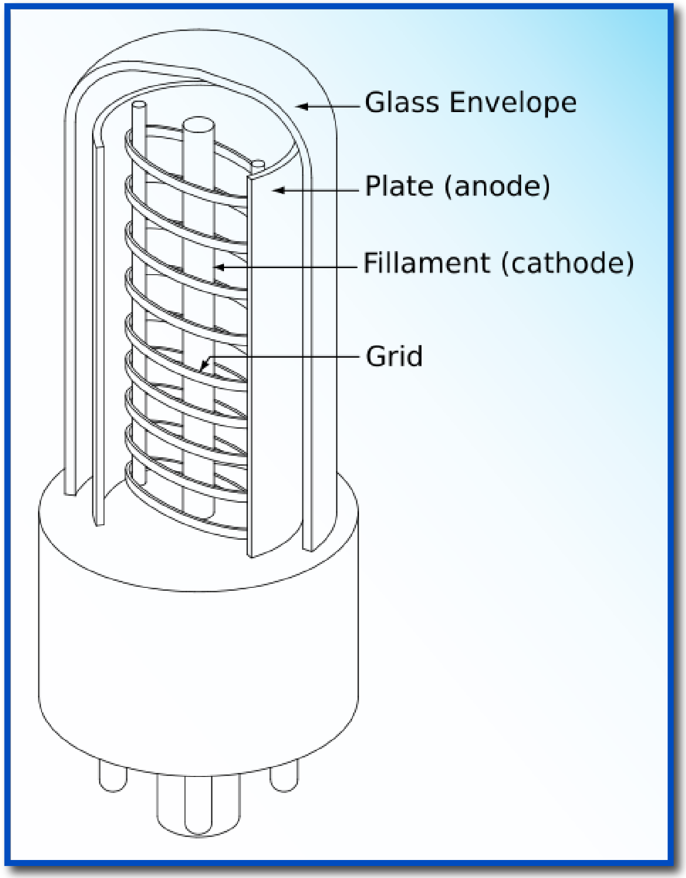
http://www.pbs.org/wgbh/americanexperience/films/silicon/

a brief history of electronic devices…

From the vacuum tubes until today.

vacuum tubes

Vacuum Tube



http://en.wikipedia.org/wiki/Vacuum_tube

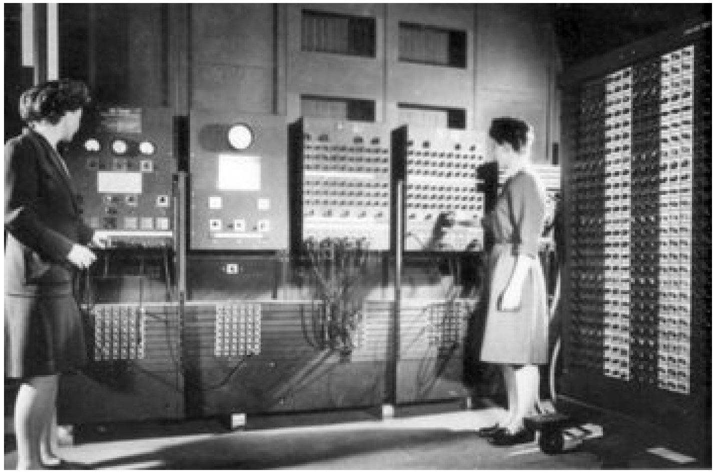
Edison effect (Edison, 1883)
cathode rays (Thompson, 1897)
diode (Fleming, 1904)
triode (De Forest, 1905)

vacuum tube electronics

Golden age of radio
1935 - 1950

http://history.sandiego.edu/GEN/recording/images5/radio11.jpg

ENIAC
(1945, Mauchly and Echkert, U Penn)



http://en.wikipedia.org

17,468 vacuum tubes
1000 sq. feet of floor space
30 tons
150 KW
~50 vacuum tubes / day

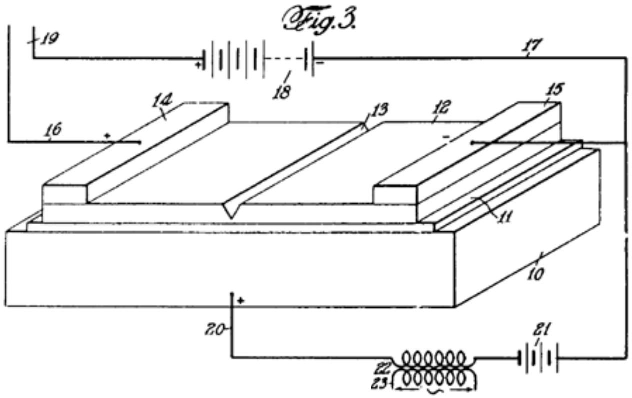
microelectronics

"Nature abhors the vacuum tube."

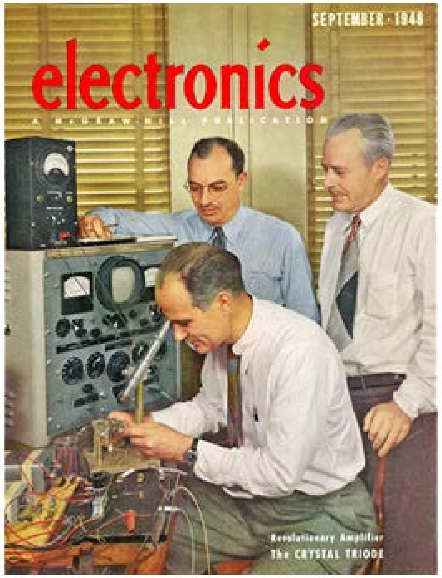
−J.R. Pierce, Bell Labs

invention of the transistor

Field-Effect Transistor
Lilienfeld, 1925
Heil, 1935

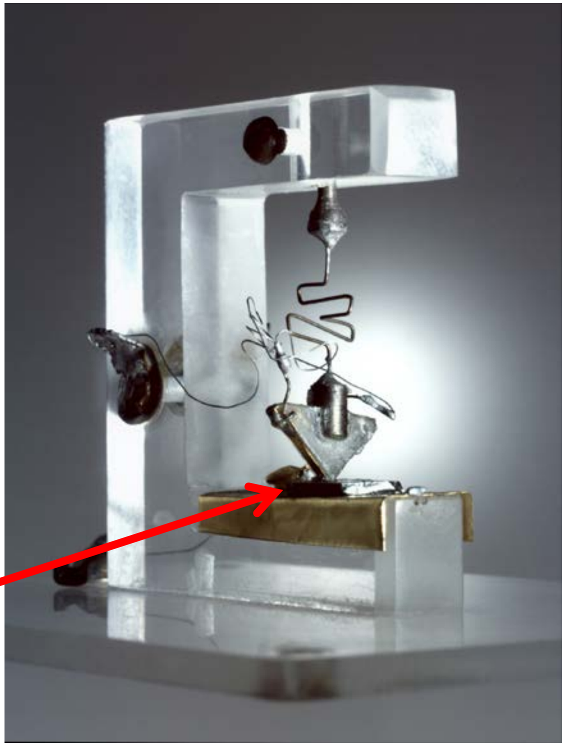


transistor



Bardeen, Brattain,
Shockley, 1947

the point contact transistor



Purdue
1930's – 1940's

Bell Labs 1947

Purdue's semiconductor history

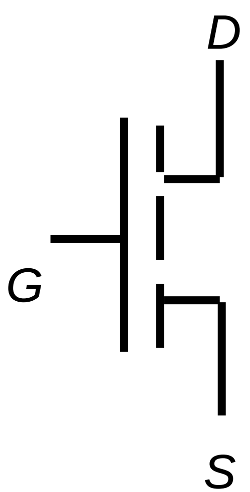
"Karl Lark-Horovitz is best known for turning the physics department of Purdue University, then a backwater school, into a research powerhouse. His personal research was in germanium and solid state science -- and if anyone had had a chance of inventing the transistor before Bell, it was Lark-Horovitz. As it was, the Purdue physics lab was probably only six to twelve months behind."

http://www.pbs.org/transistor/album1/addlbios/lark.html

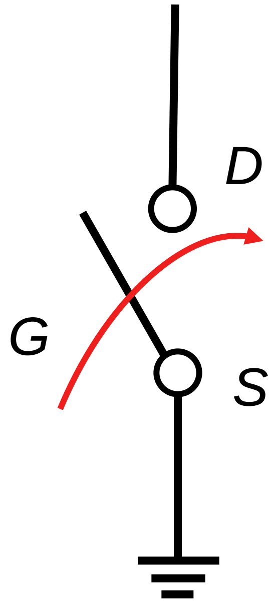
1941: WWII: Semiconductor diode rectifiers
http://www.computerhistory.org

transistors

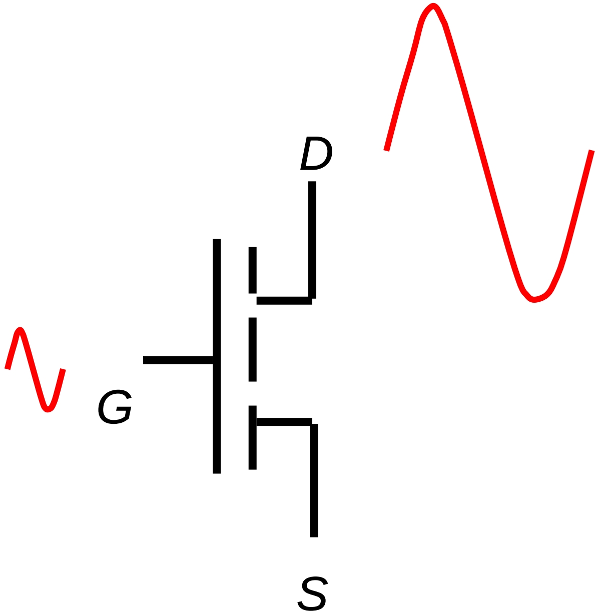
symbol



switch



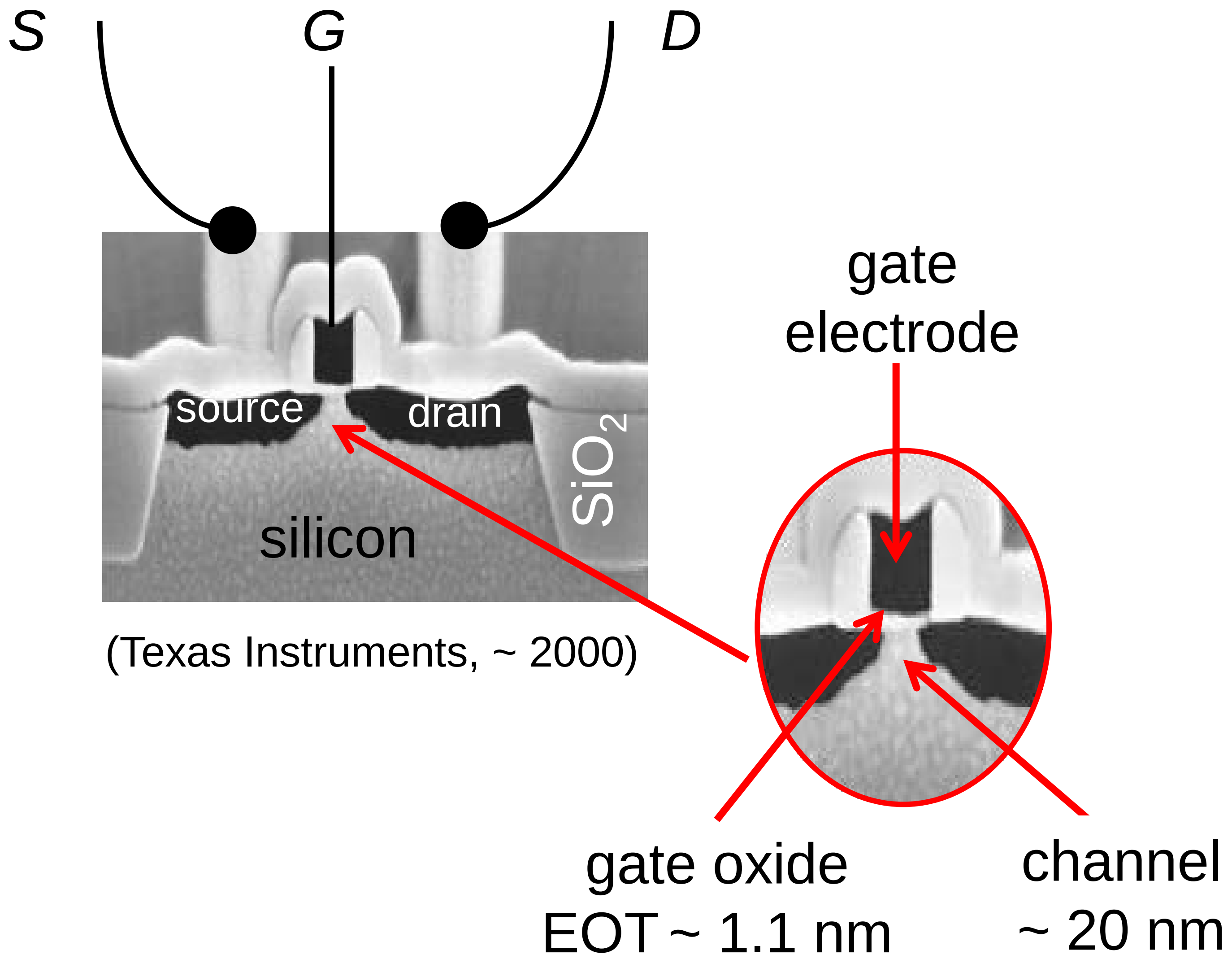
amplifier



digital electronics

analog electronics

nanotransistors

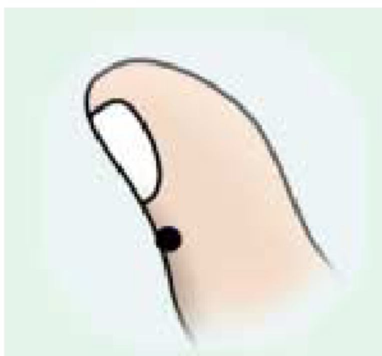


(Texas Instruments, ~ 2000)

What is nanotechnology?

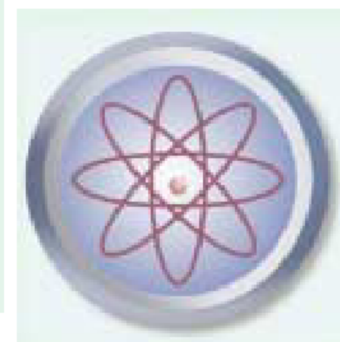
Billions of nanometers
A two meter tall male is two billion nanometers.

A million nanometers
The pinhead sized patch of this thumb is a million nanometers across.



Thousands of nanometers
Biological cells have diameters in the range of thousands of nanometers.

Nanometers
Ten shoulder-to-shoulder hydrogen atoms span 1 nanometer. DNA molecules are about 2.5 nanometers wide.

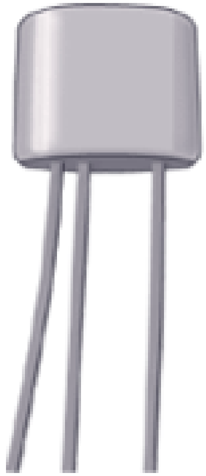


Less than a nanometers
Individual atoms are up to a few tenths of a nanometer, in diameter.

(from Prof. Mildred Dresselhaus, MIT)

Transistors get started….

transistors



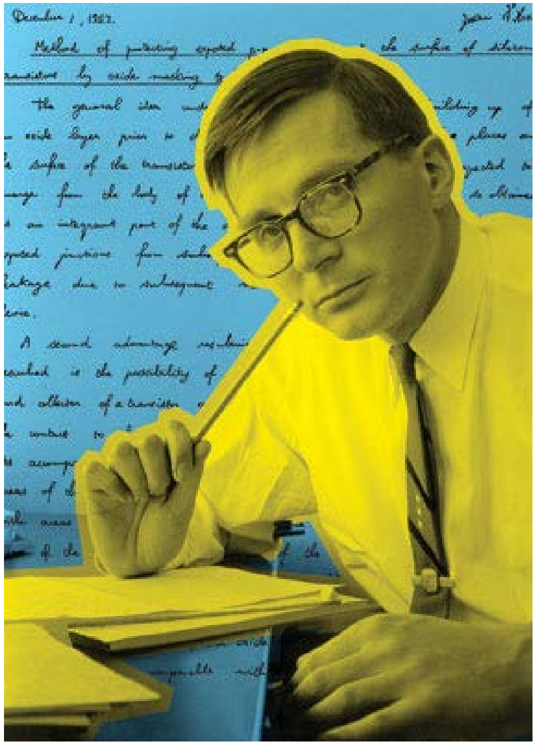
Sony TR-63
6-transistor
shirt pocket radio
1957

http://www.sony.net/Fun/SH/1-6/h2.html

“The most important moment since mankind emerged as a life form.”

Isaac Asimov

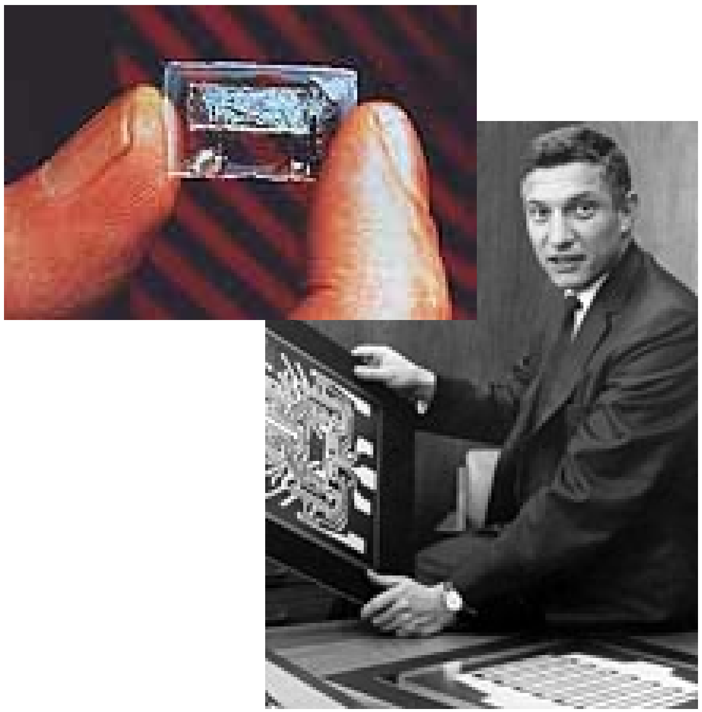
(speaking about the “planar process” used to manufacture ICs -- invented by Jean Hoerni, Fairchild Semiconductor, 1959).



IEEE Spectrum Dec. 2007

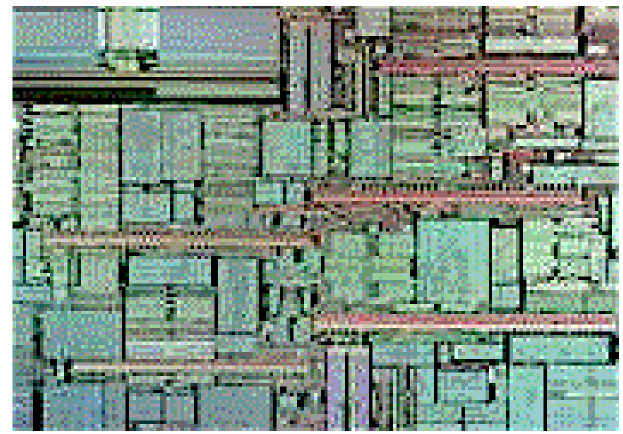
“microelectronics”

integrated circuit



Kilby /Noyce, 1958/59

Intel 4004



Hoff (1971)

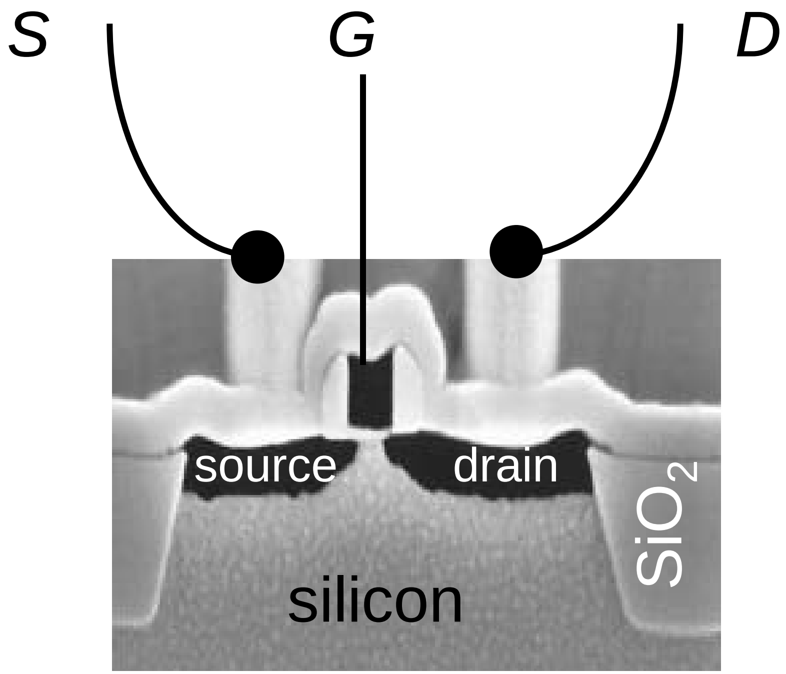
2300 transistors
L = 10 micrometers
L = 10,000 nanometers

Frederick Terman

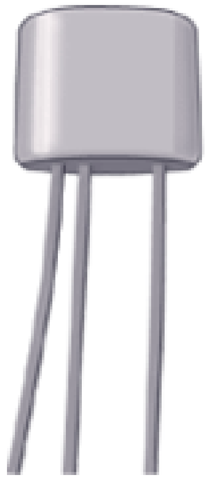
"This new electronics lives close to the frontiers of science, and requires a high level of technical competence. It grows by the development of new products. It is characterized by the transistor and other solid-state devices."

Frederick Emmons Terman, "Education – A Basic Component of the New Electronics – Including a Appraisal of Electronics in the Midwest," Delivered at the luncheon of the 16th National Electronics Conference, Chicago, IL, October 12, 1960.

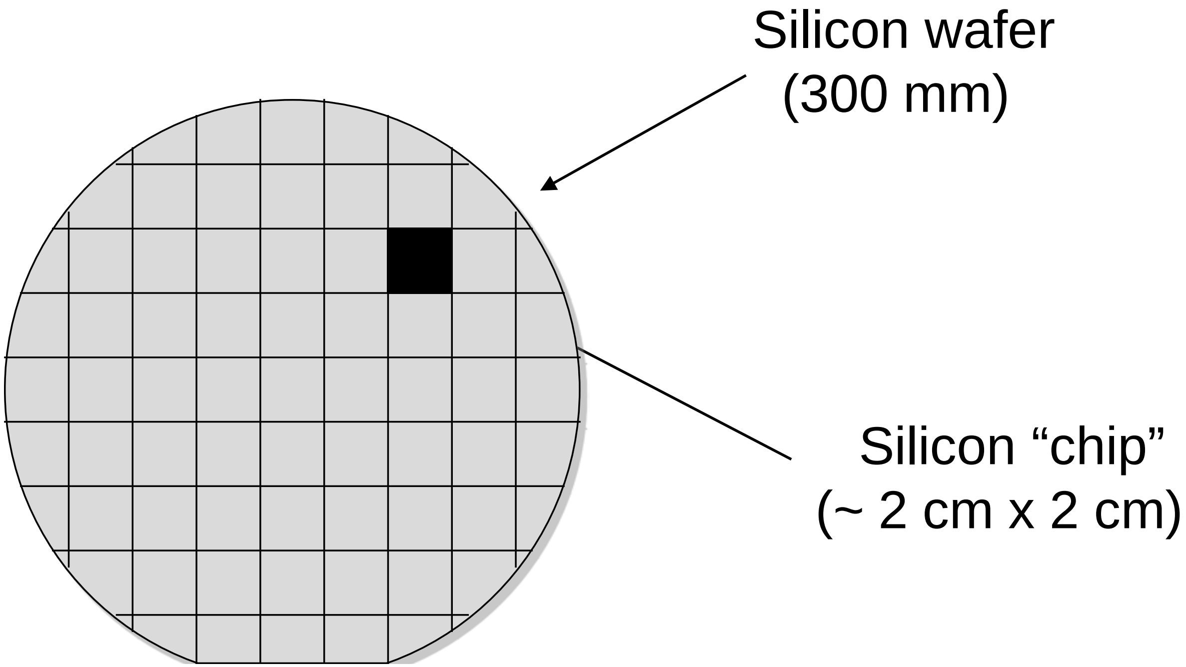
discrete transistors

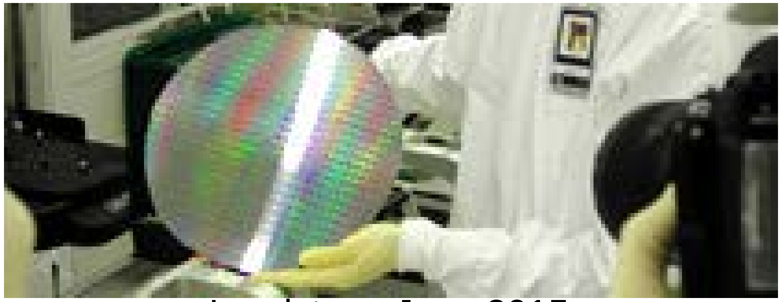


(Texas Instruments, ~ 2000)



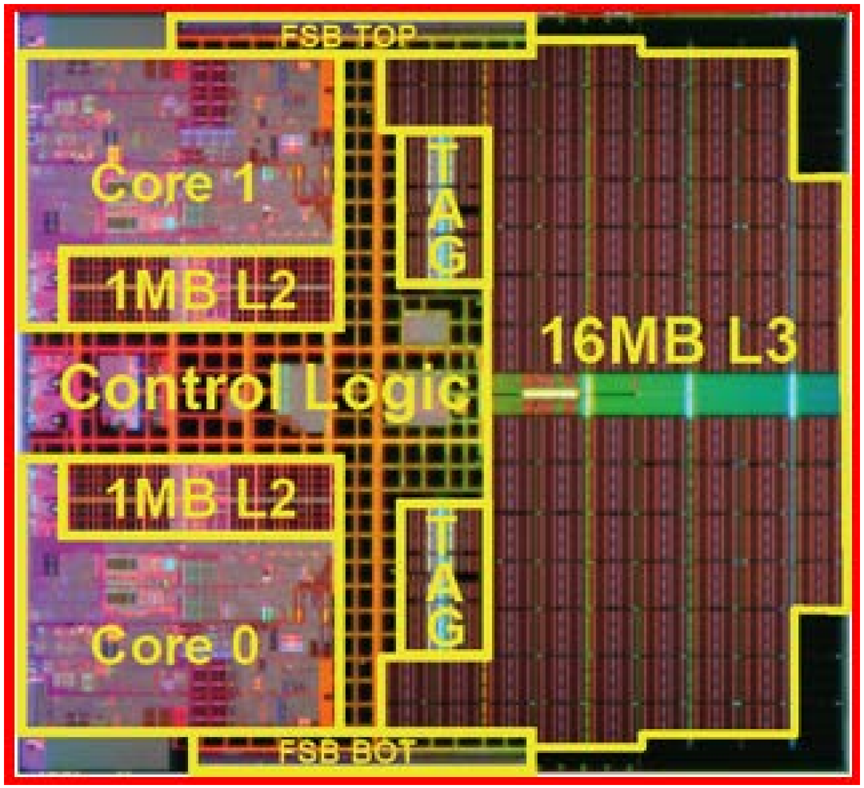
microelectronics





Intel

CMOS microprocessor (65 nm technology)



# of transistors:	1.328B
# in logic core:	121M per core
size of chip:	435mm^2
speed:	3.4 GHz
supply voltage:	1.25V
power dissipation:	150 W
amount of wire:	6000m (source: ITRS)

Rusu et. al. "A Dual-Core Multi-Threaded Xeon® Processor with 16MB L3 Cache", ISSCC, 2006

outline

Transistors

Integrated circuits

The planar process

Moore's Law

Today's challenges

The future

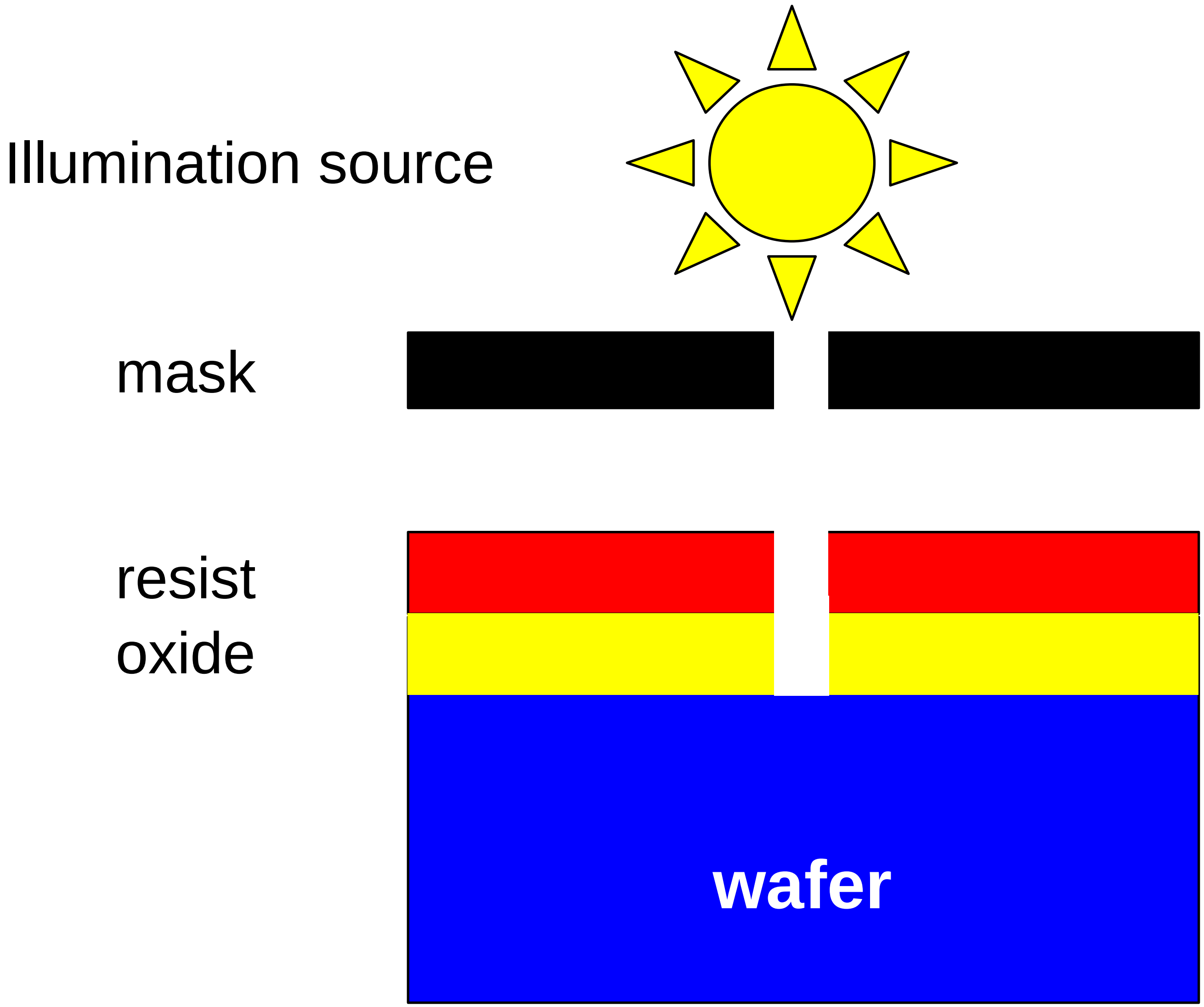
manufacturing integrated circuits:

How a CPU is Made

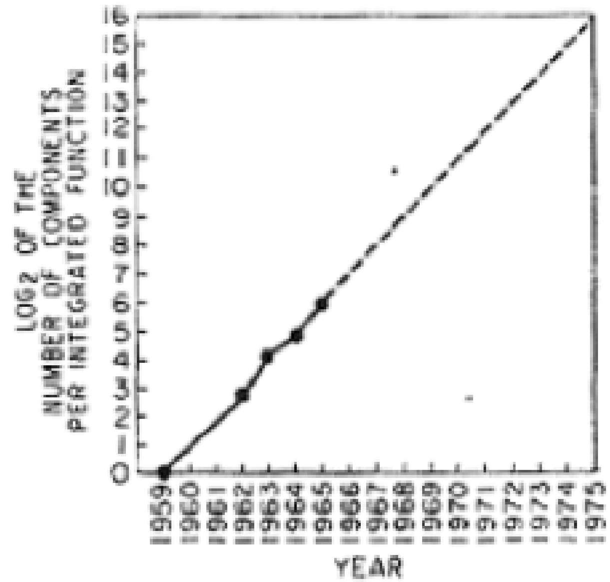
(Global Foundries)

https://www.youtube.com/watch?v=qm67wbB5GmI

optical lithography



Moore's Law

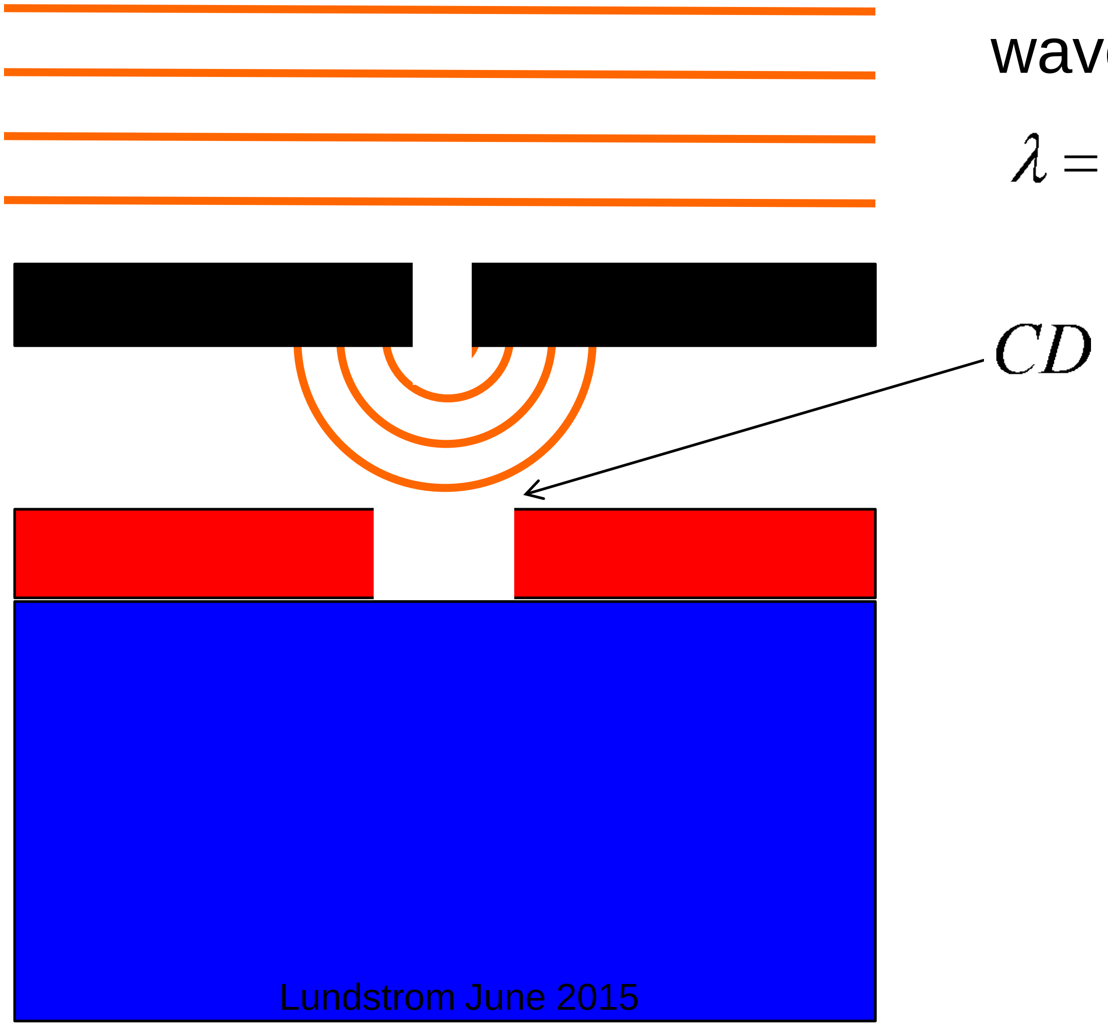


Electronics, vol. 38, April 19,1965

"The number of transistors incorporated in a chip will approximately double every 24 months."

-- Gordon Moore, Intel co-founder

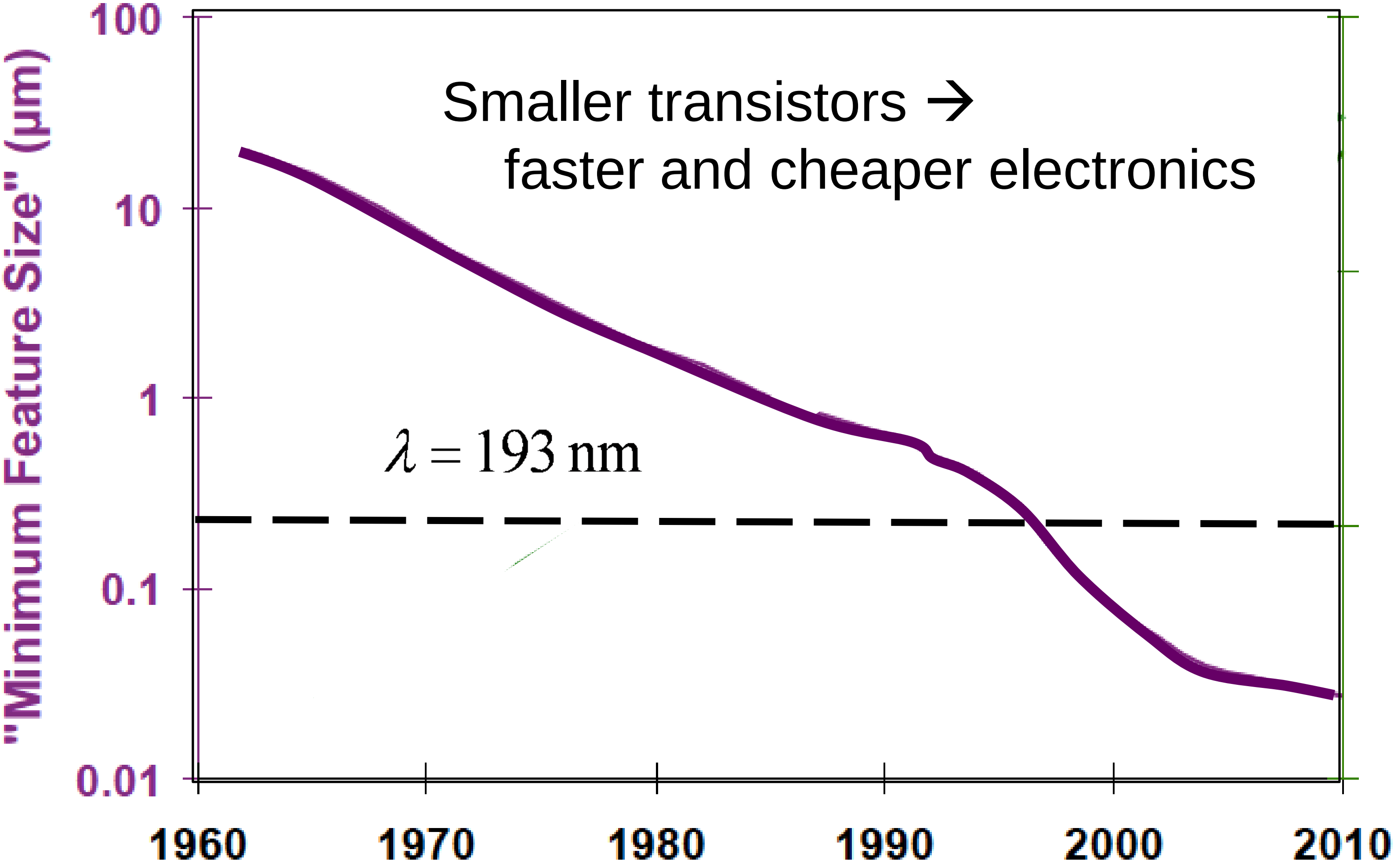
diffraction



wavelength

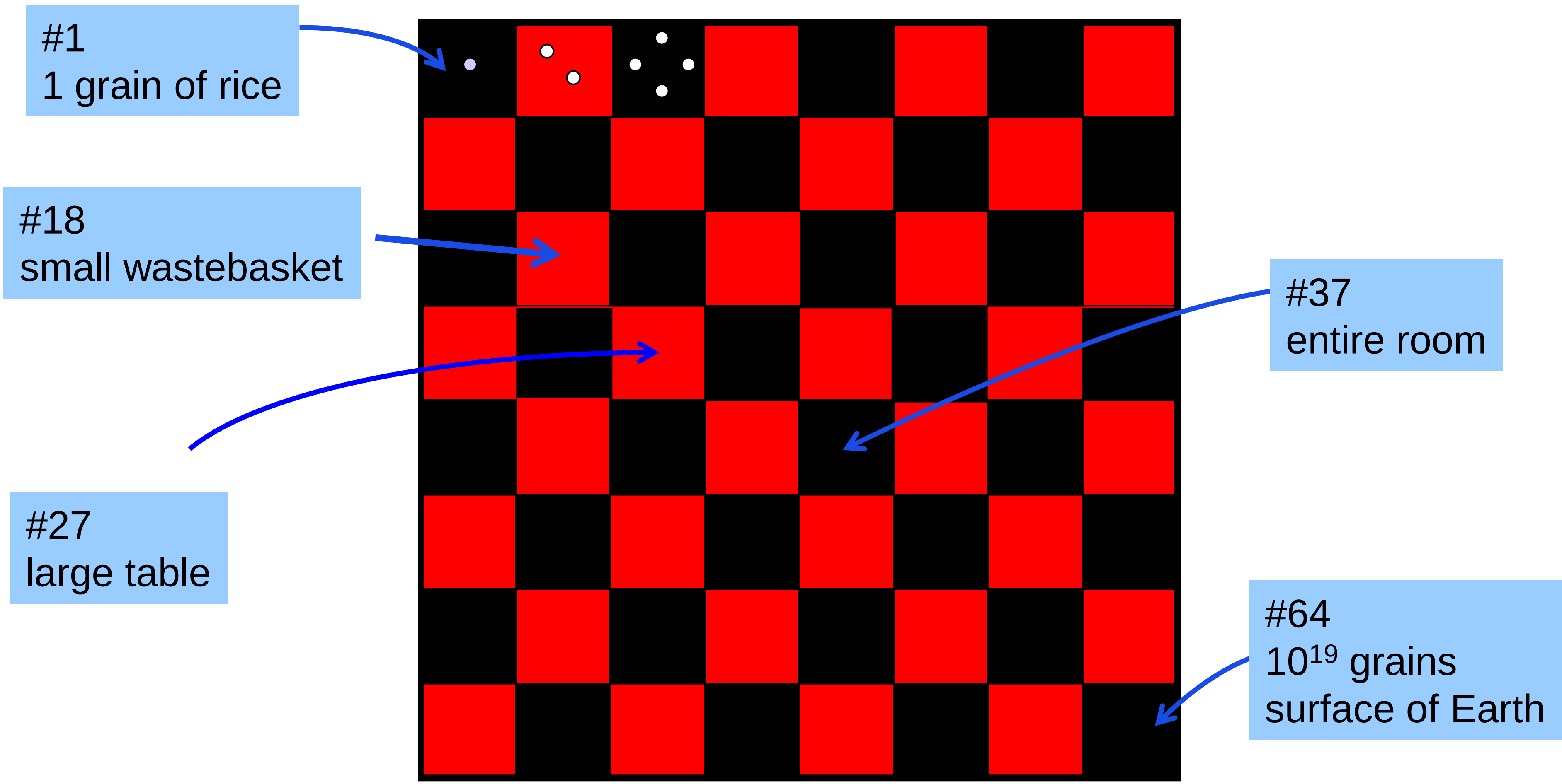
$\lambda = 193 \text{ nm}$

Challenges: scaling



Source: Semiconductor Industry Association (ITRS and WTSS)

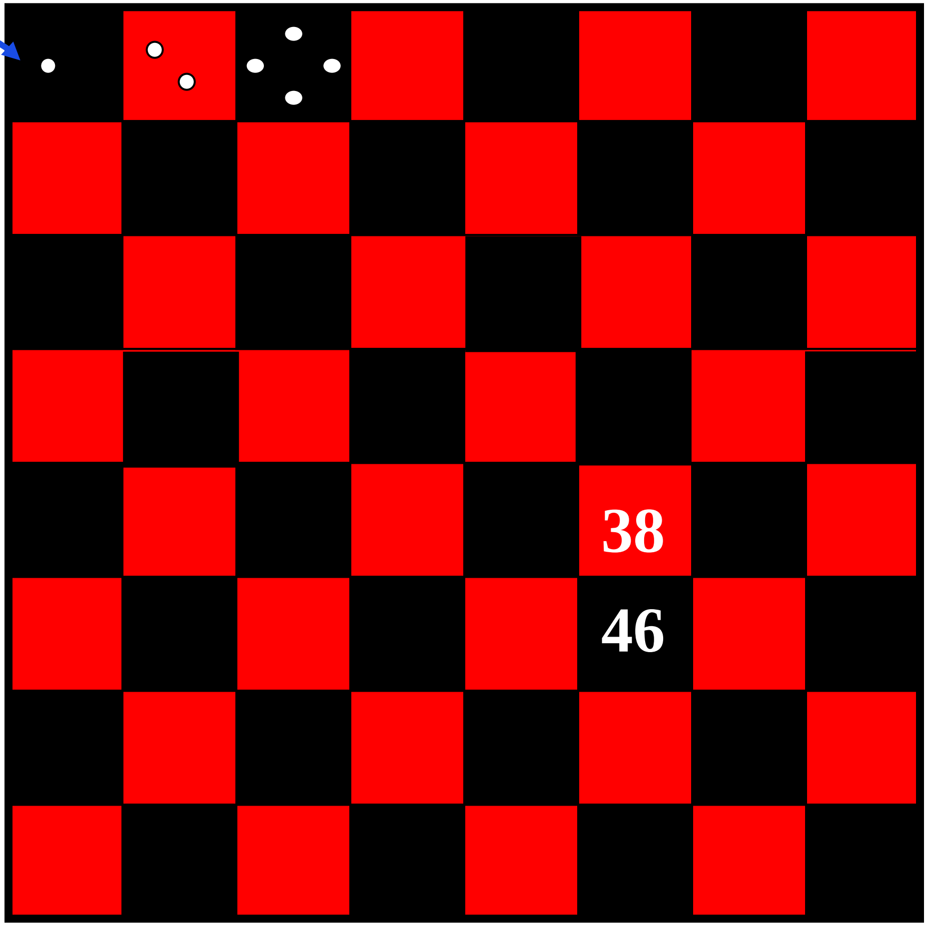
exponential growth



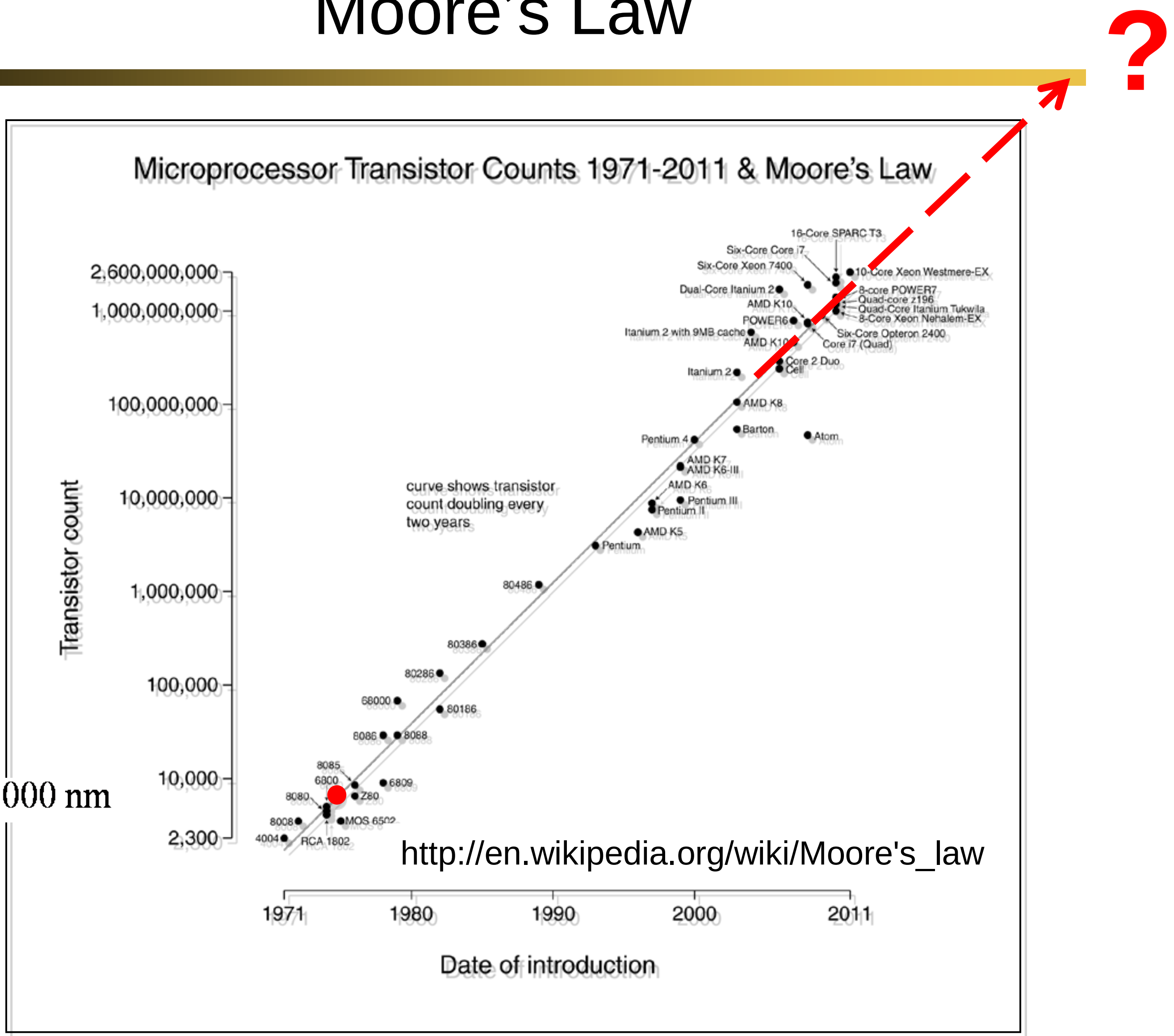
from “Digital Immortal,” by R.W. Lucky, *New Republic*, Nov. 8. 1999

exponential growth

#1
First transistor
(1947)



Moore's Law



$L = 5000\ \text{nm}$

the dawn of 21st Century electronics: 2007

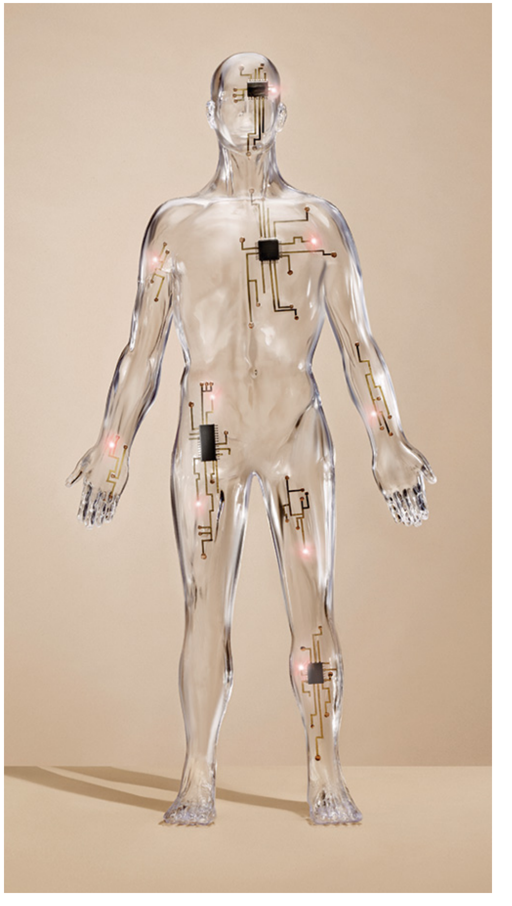
www.apple.com

CMOS transistors for logic
III-V transistors for RF
A/D and D/A convertors
Digital Signal processor
Microprocessor
ROM and FLASH memory

CMOS imager
Gyroscope
MEMS devices
Magnetometer
Microphone, speaker
LCD display and touch screen

a technological threshold?

- We Will End Disability by Becoming Cyborgs
- Robots Will Pave the Way to Mars
- Make Your Own World With Programmable Matter
- Digital Actors Go Beyond the Uncanny Valley
- The Rise of the Personal Power Plant
- Wearable Computers Will Transform Language
- Driverless Cars: Optional by 2024, Mandatory by 2044
- So, Where Are My Robot Servants?



"The Future We Deserve", *IEEE Spectrum, Jan. 2015.*

The World Is Fast

Recent Elections Missed the Biggest Challenge of All

NOV. 4, 2014

Thomas L. Friedman

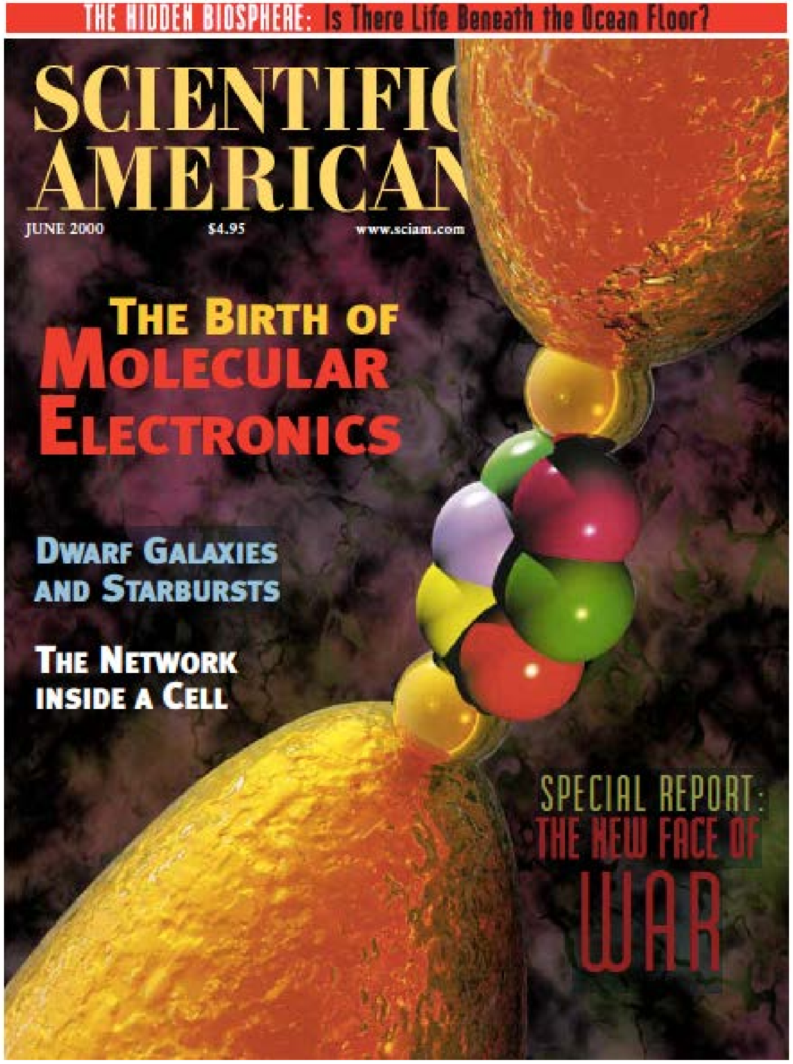
We've just had a nonsense midterm election. Never has more money been spent to think so little about a future so in flux. What would we have discussed if we'd had a serious election? How about the biggest challenge we're facing today: The resilience of our workers, environment and institutions.

The world is fast. The three biggest forces on the planet — the market, Mother Nature and Moore's Law — are all surging, really fast, at the same time.

globalization, is tying economies more tightly together than ever before, making our workers, investors and markets much more interdependent and exposed to global trends, without walls to protect them.

Moore's Law, the theory that the speed and power of microchips will double every two years, is, as Andrew McAfee and Erik Brynjolfsson posit in their book, "The Second Machine Age," so relentlessly increasing the power of software, computers and robots that they're now replacing many more traditional whi[illegible]s, while spinning off new ones — all of which require more skills.

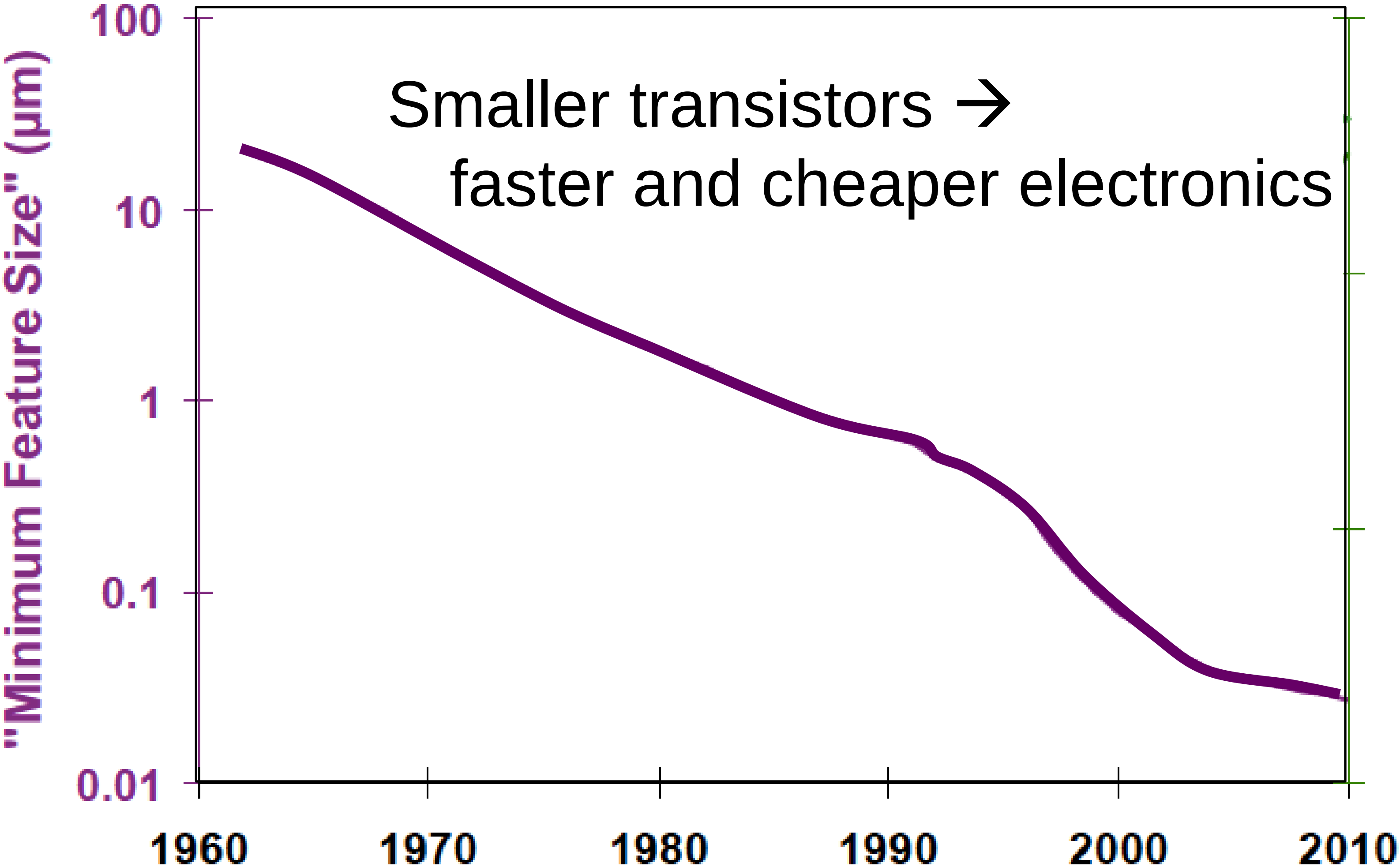
The end of Moore’s Law?



Molecular Electronics Will Change Everything
It's the dawn of a new technological revolution – and the death of silicon.”

(archive.wired.com)

Challenges: scaling



Lundstrom June 2015

Source: Semiconductor Industry Association (ITRS and WTSS)

Challenges: power

personal electronics

server farms

“Power, pollution, and the Internet,” NY Times, Sept. 22, 2012

Novel nanoelectronic devices

Carbon nanotubes

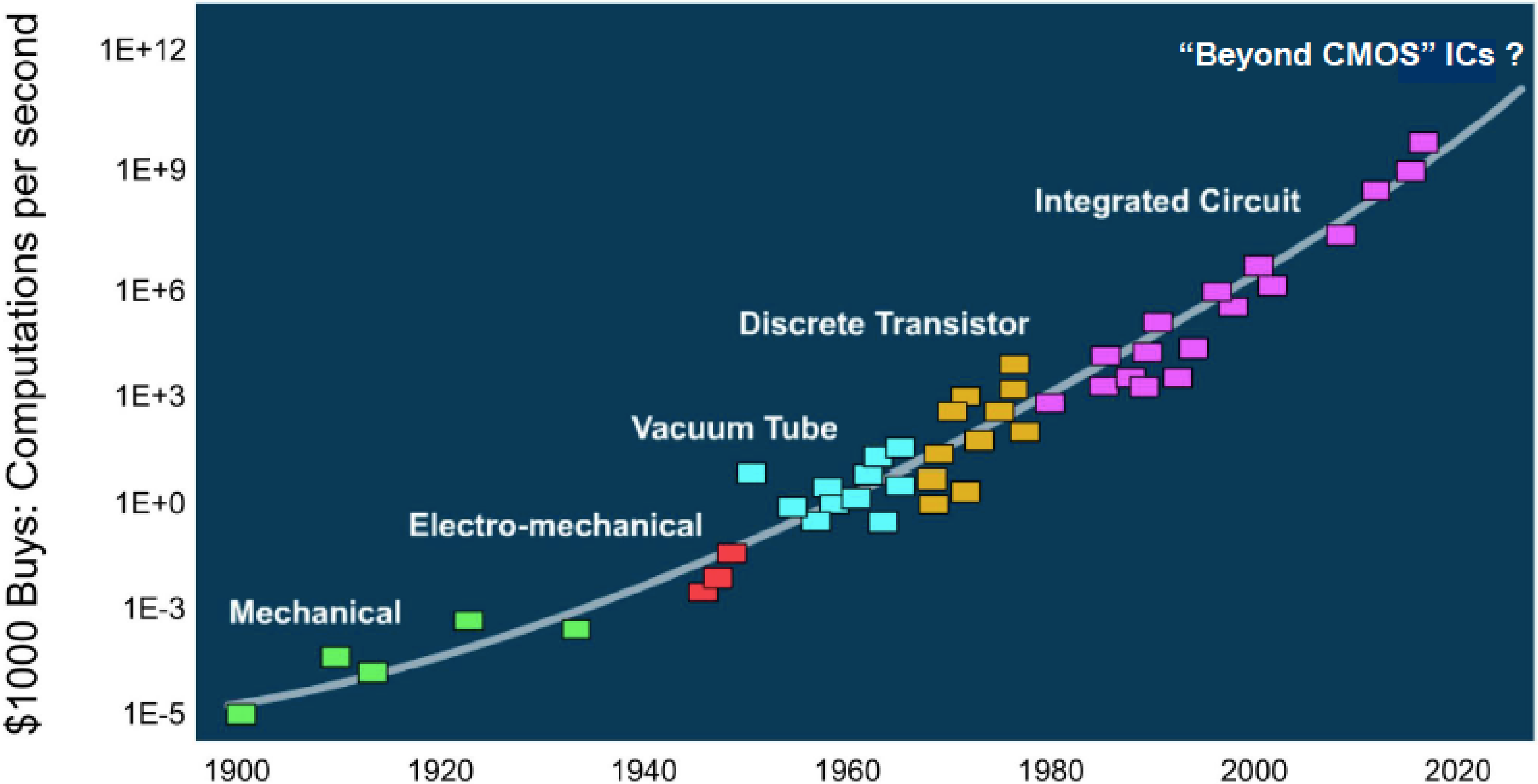
Graphene and 2D materials

Spintronics

Topological insulators

…

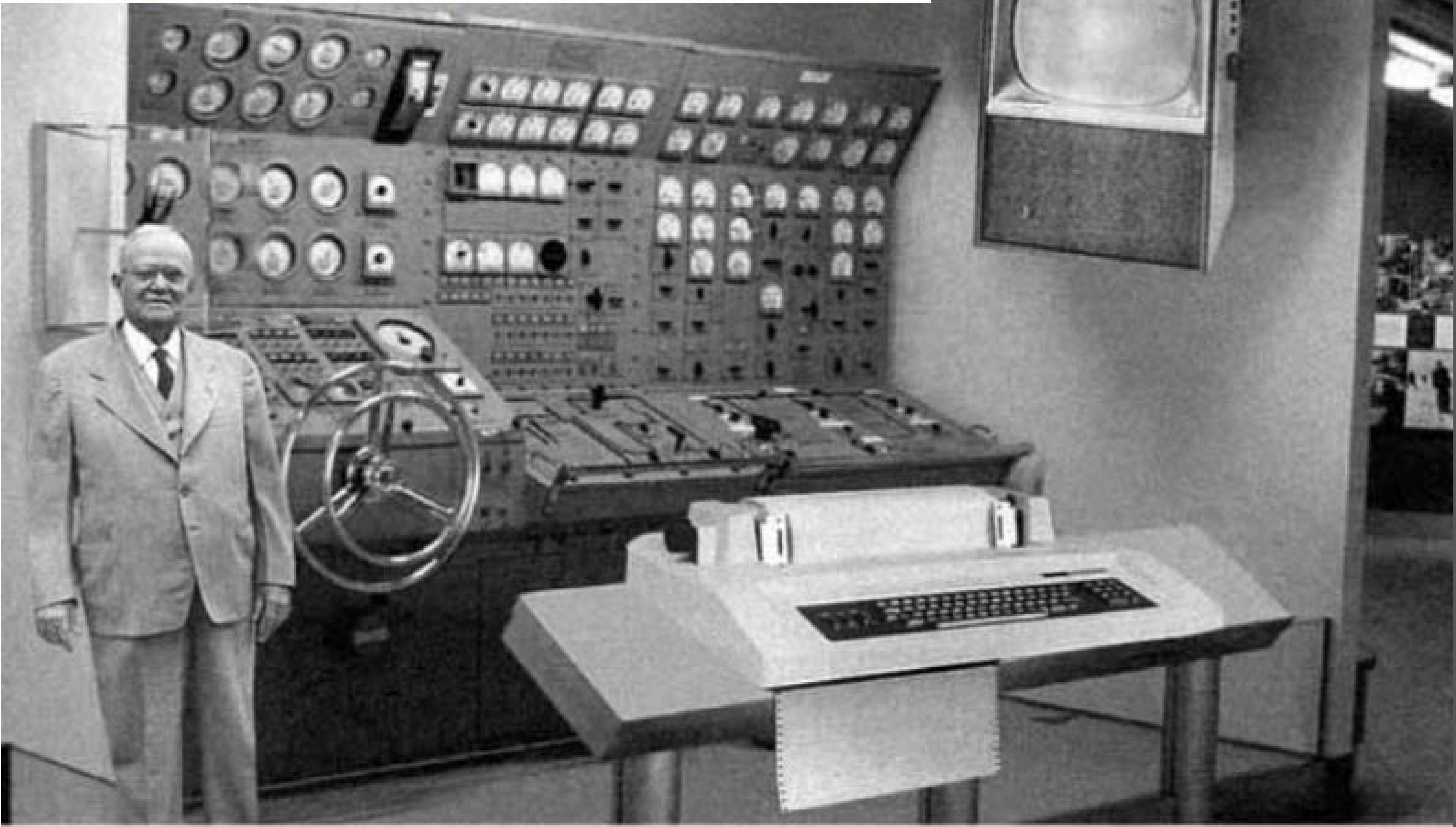
What will it mean?



Lundstrom June 2015

The future of electronics?

“Personal Computer without ICs”



Scientists from the RAND Corporation have created this model to illustrate how a "home computer" could look like in the year 2004. However the needed technology will not be economically feasible for the average home. Also the scientists readily admit that the computer will require not yet invented technology to actually work, but 50 years from now scientific progress is expected to solve these problems. With teletype interface and the Fortran language, the computer will be easy to use.

Source: Popular Mechanics, 1954

Predicting the Great Achievements of the 21st Century

Looking at the technologies of 1914 might give a hint to the future

By Robert W. Lucky
Posted 25 Dec 2014 | 16:00 GMT

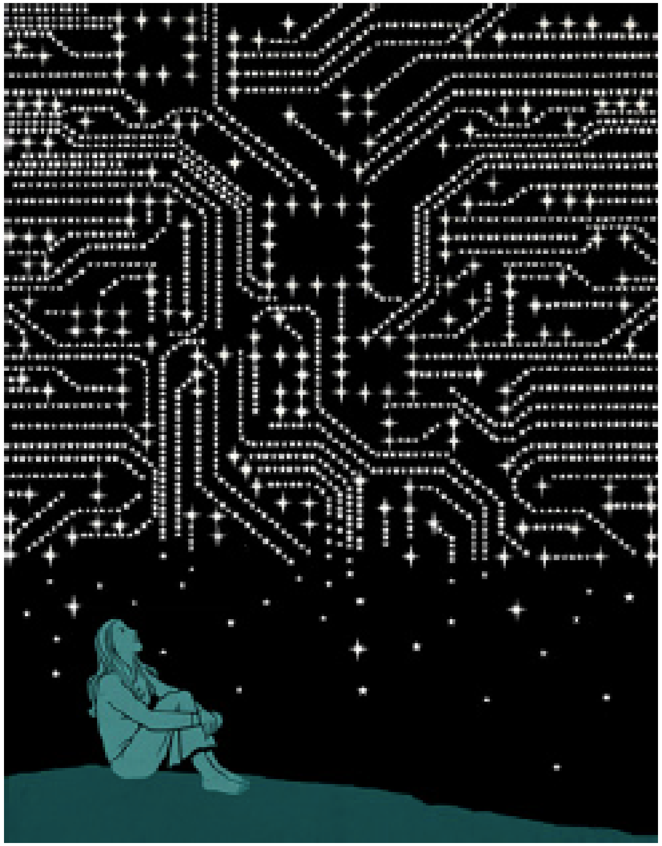


Illustration: Dan Page

"Think of what we knew in 1915 of the achievements that would come to be listed in 2000. It's actually quite a bit.

1) Things that have already happened or are well under way.

2) Things we can anticipate – or should have.

3) Things we can't possibly predict.

Wrap-up

Solid-state electronics (microelectronics / nanoelectronics) is one of the significant accomplishments in human history.

It transformed the 20^{th} Century.

It will have even greater impact in the 21^{st} Century.

But there are many hard, interesting, and important research challenges to address.