Frontiers
in
Nanosciences

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Laboratory of Nanostructures at Surfaces
IPHYS

Fall 2024

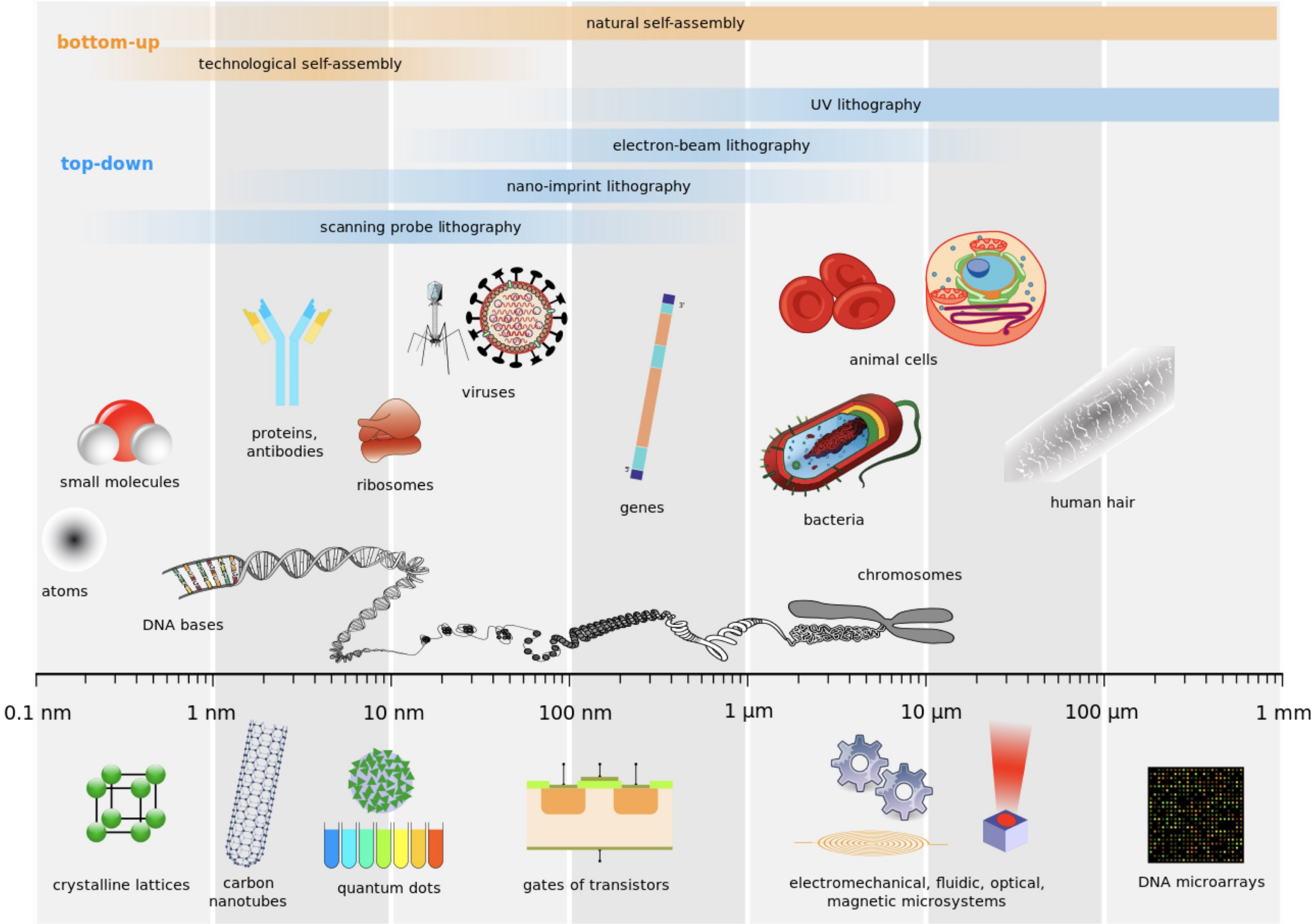
Frontiers in Nanosciences

Program

Introduction to the concepts of nanoscale science	week 1	
From atoms to bulk: electronic states	week 2	
Imaging and manipulation at the atomic scale: scanning probe techniques	weeks 3-4	
Magnetism at the nanoscale: magnetic data storage concepts (hard disk drive)	weeks 5-7	Rusponi
Spin transport: spin valve, GMR and TMR effects	week 8	Rusponi
Making the nanostructures: top-down and bottom-up approaches	...	
Electron transport in low-dimensional systems	...	
Characterization of structural and electronic properties, for example by TEM, XPS, XAS	...	
2D materials	...	

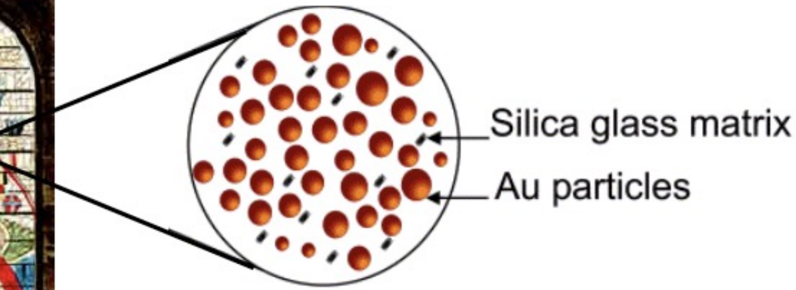
Files on Moodle may be updated shortly before the lecture

Nanoscale



courtesy of K. Kern

(Quantum) Size Effects



Westminster Abbey,
East-Window

Medieval Nanotechnology

Lycurgus Cup

Au and Ag particles, 70 nm

courtesy of K. Kern

Au nanoparticles

Michael Faraday discovered in **1851** that the colors of ruby gold were due to its finely divided state

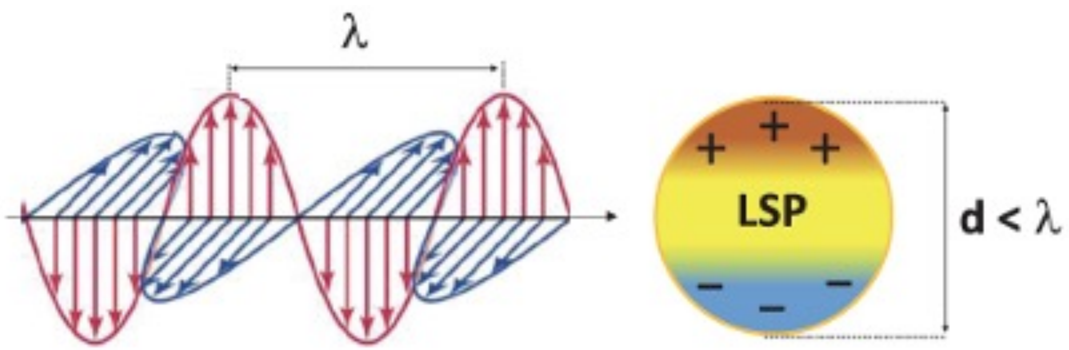
Original Au colloids still on display at the Royal Institution

Au nanoparticles

Plasmons: collective oscillations of free electrons in metals

Light: limited penetration depth (skin depth)
→ excitation of Surface Plasmon Resonances

Metallic nanoparticles (size comparable to the metal skin depth)
→ Localized Surface Plasmon Resonances



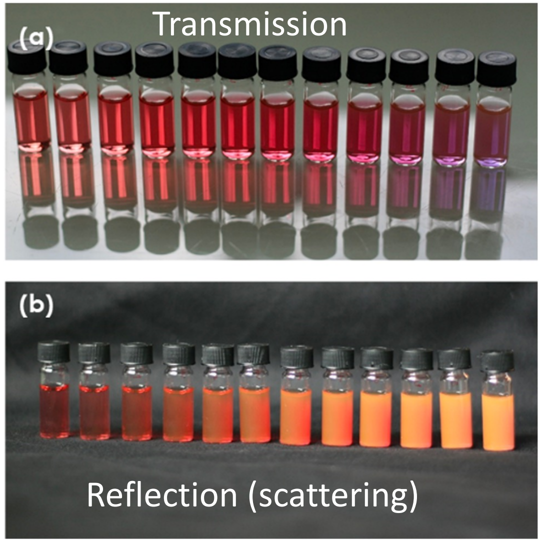
J. Phys.: Condens. Matter **29,** 203002 (2017)

Au nanoparticles, size   20 – 100 nm

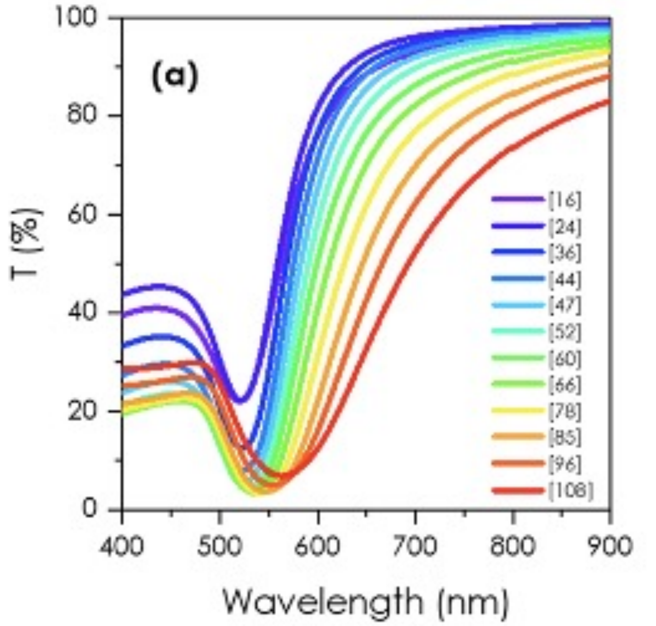
the plasmon resonance is in the 500 - 600 nm range (green) → they appear red / reddish in transmission

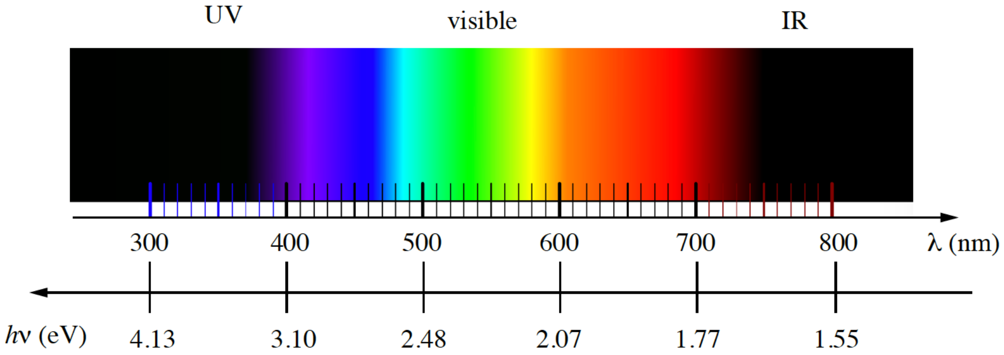
Au nanoparticles

A complete explanation of the plasmonic colours of gold nanoparticles and of the bichromatic effect, J. Mater. Chem. C **11**, 15824 (2023)



Au_{16} to Au_{108}



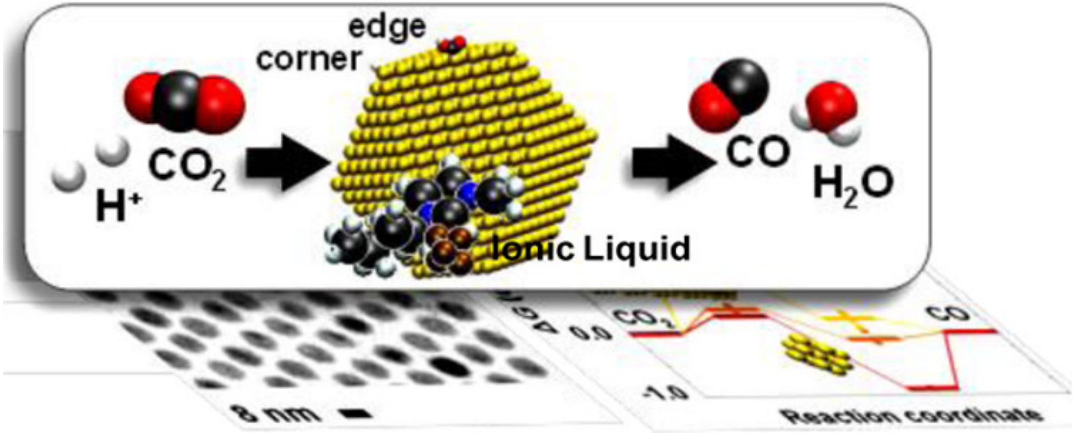


When scattering dominates the LSP resonance color is observed

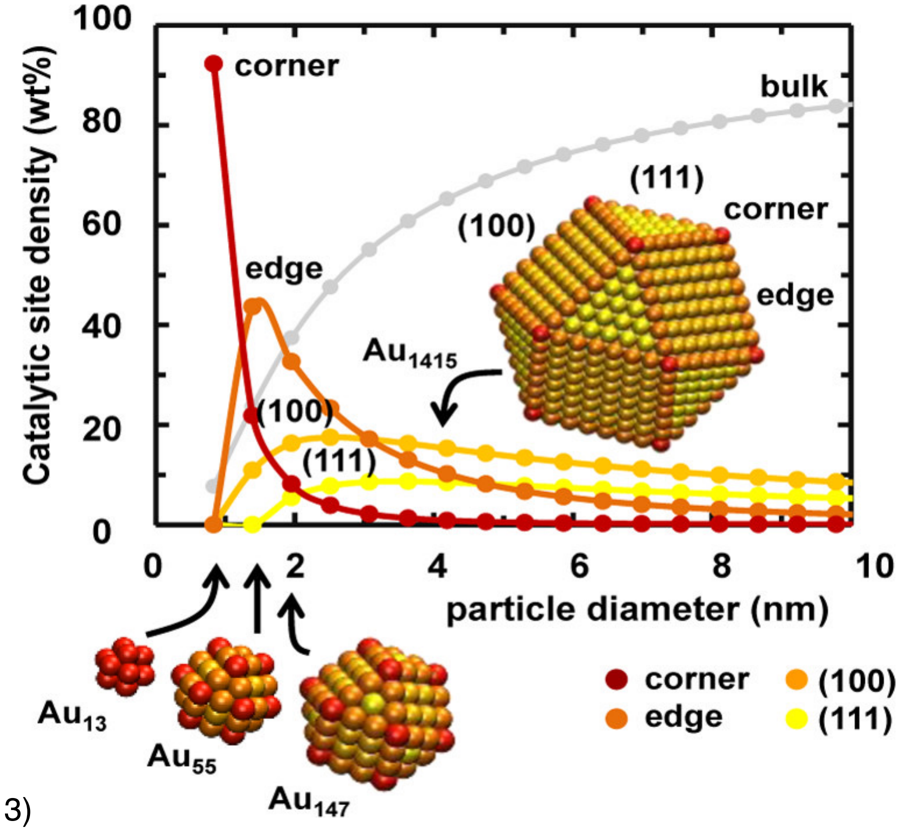
When absorption dominates, the complementary color is seen

Au nanoparticles

Modern applications:
organic photovoltaics
sensor probes
staining
therapeutic agents
drug delivery
electronic conductors
catalysis
...

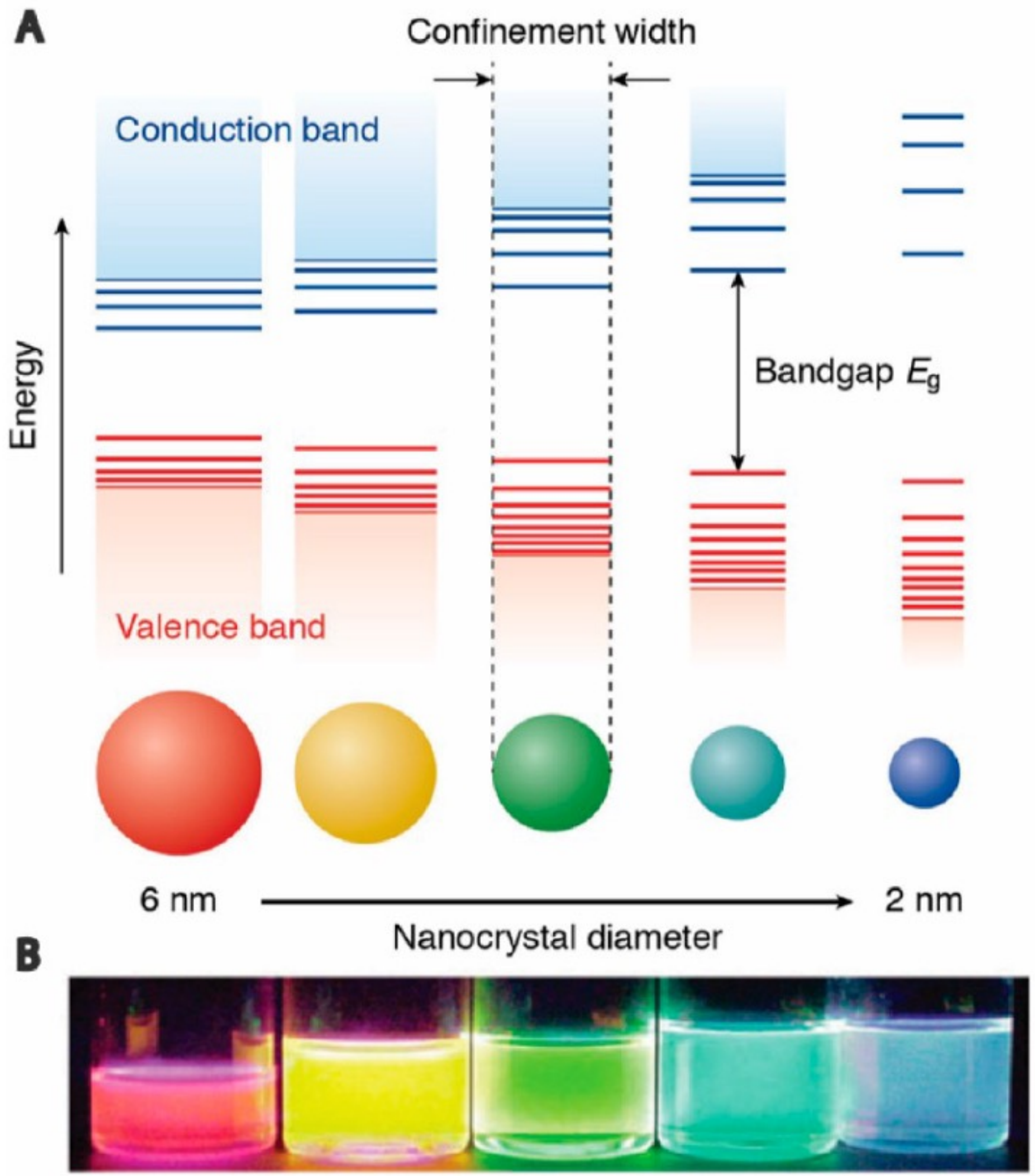


The optical and electronic properties of gold nanoparticles are tunable by changing the size, shape, surface chemistry, or aggregation state.



10.1021/ja409445p
J. Am. Chem. Soc. **135**, 16833 (2013)

Semiconductor quantum dots



CdSe Nanocrystals

10.1021/acs.jpclett.7b01640
J. Phys. Chem. Lett. **8**, 4077 (2017)

Nothing tends so much to the advancement of knowledge as the application of a new instrument

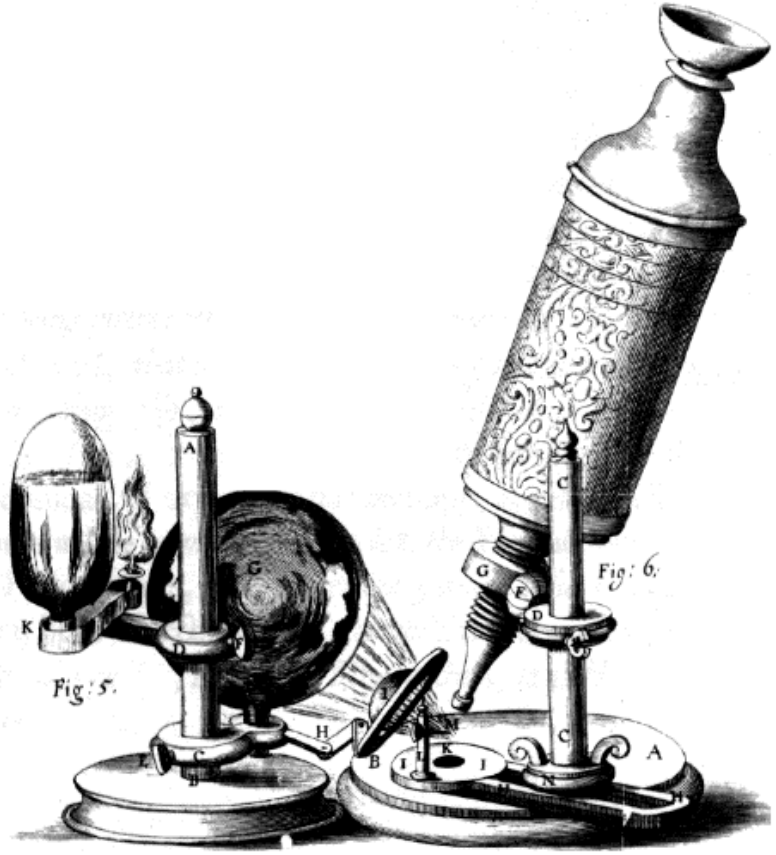
Sir Humphry Davy
(1778 – 1829)

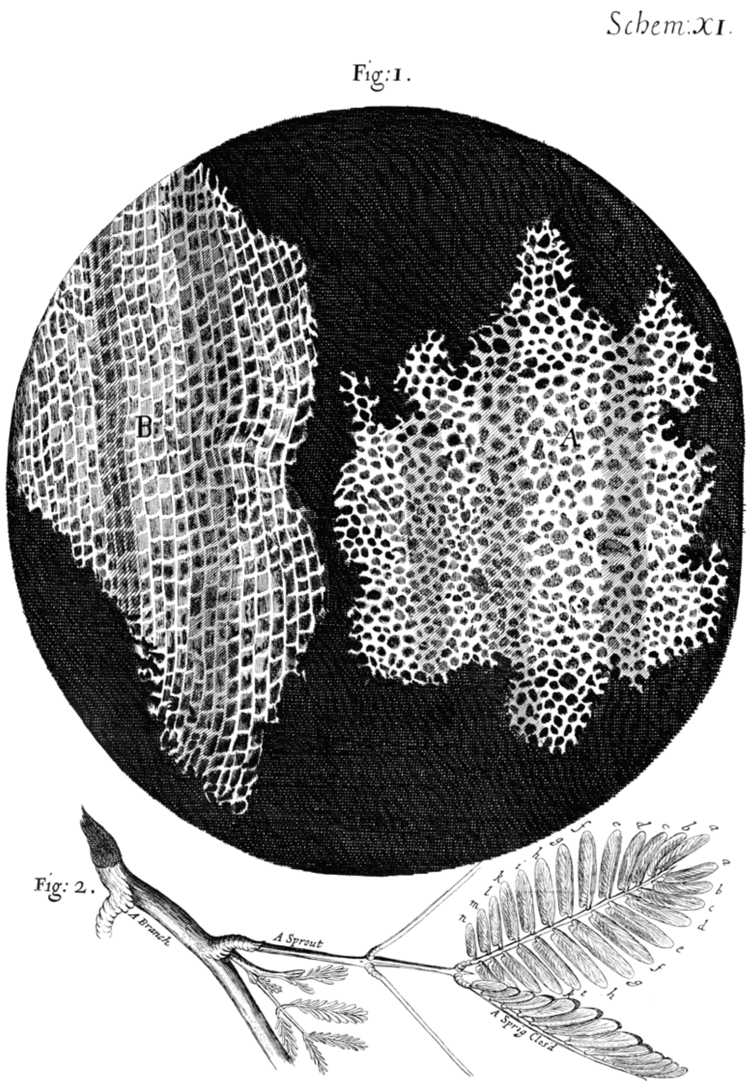
THEPALMER / Getty Images

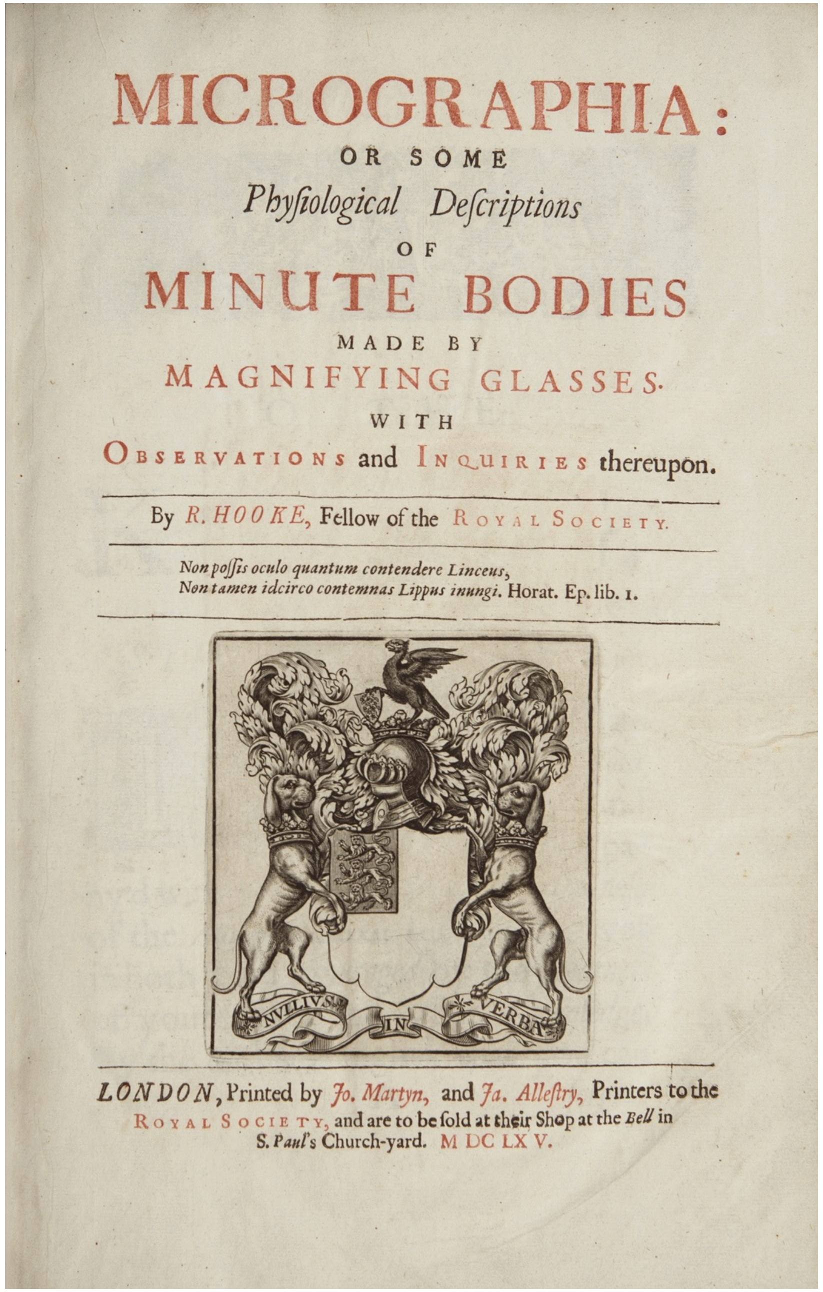
courtesy of K. Kern

A Very Short History of Microscopy

Optical microscopes






MICROGRAPHIA:
OR SOME
Phyſiological Deſcriptions
OF
MINUTE BODIES
MADE BY
MAGNIFYING GLASSES.
WITH
OBSERVATIONS and INQUIRIES thereupon.

By R. HOOKE, Fellow of the ROYAL SOCIETY.

Non poſſis oculo quantum contendere Linceus,
Non tamen idcirco contemnas Lippus inungi. Horat. Ep. lib. 1.

NVLLIVS IN VERBA

LONDON, Printed by *Jo. Martyn*, and *Ja. Alleſtry*, Printers to the ROYAL SOCIETY, and are to be ſold at their Shop at the *Bell* in S. *Paul's* Church-yard. M DC LX V.

discovery of cells
discovery of microorganisms

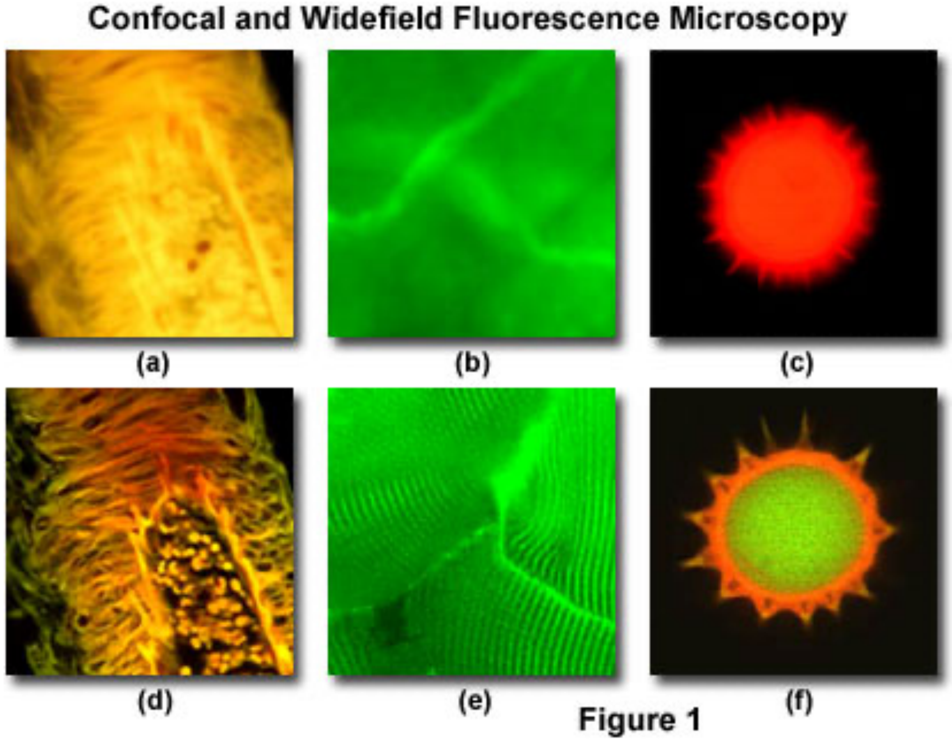
Robert Hooke (1635-1703) – compound microscopes, 30x
Antoni van Leeuwenhoek (1632-1723) – single-lens microscopes, 250x

Optical microscope

Zeiss 1914

Confocal microscope

Zeiss 2019



Excitation source: laser

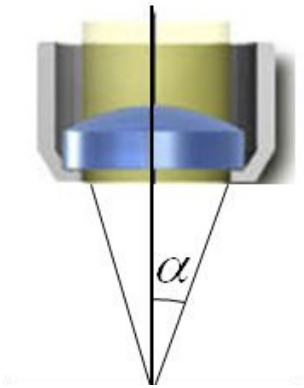
Advanced optical system that selects only the part of the sample that is on focus (field depth) + successive images (optical sections)

Fluorescence version (staining with fluorescent dyes)

Abbe's Diffraction Limit:

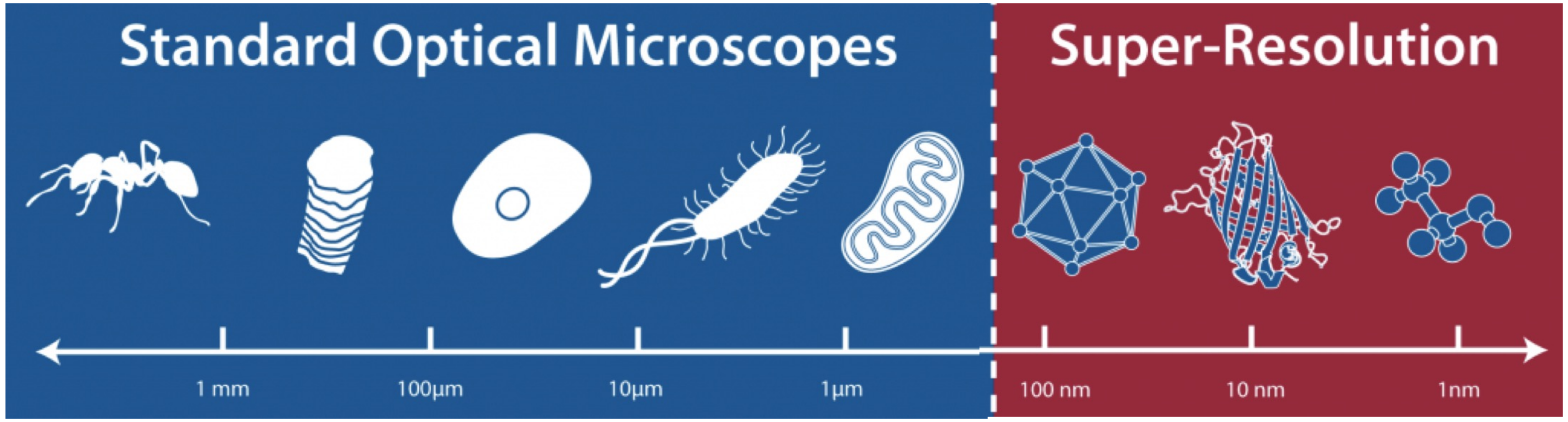
→ resolution limit

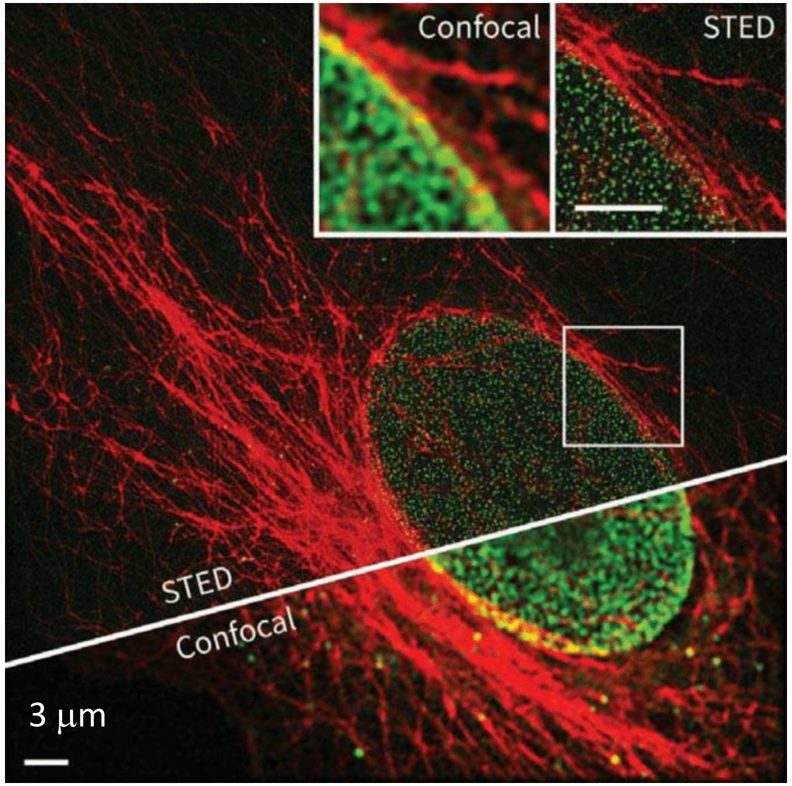
$$\Delta x \cong \frac{\lambda}{2n\sin\alpha}$$



Stefan Hell
STED

Eric Betzig
William E. Moerner
PALM





Abbe's Equation Modified for Fluorescence:

$$\Delta x \cong \frac{\lambda}{2n\sin\alpha\sqrt{1+\zeta}}$$

$\zeta \to 0$	Abbe Limit
$\zeta \to \infty$	$\Delta x \to 0$

Saturation Factor $\zeta = I(x)/I_{sat}$

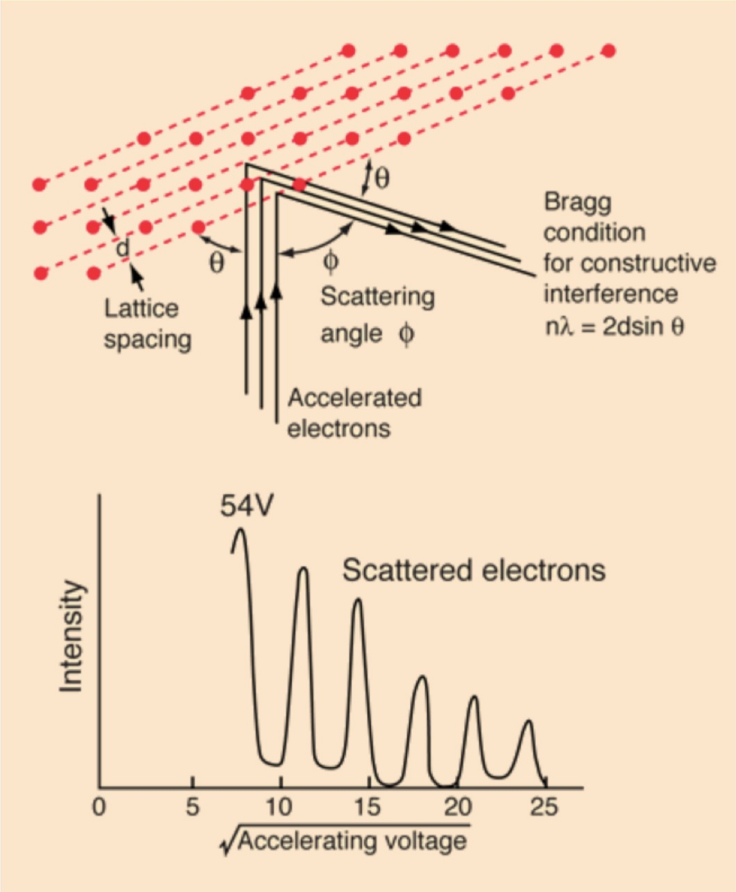
courtesy of K. Kern

Wave nature of electrons

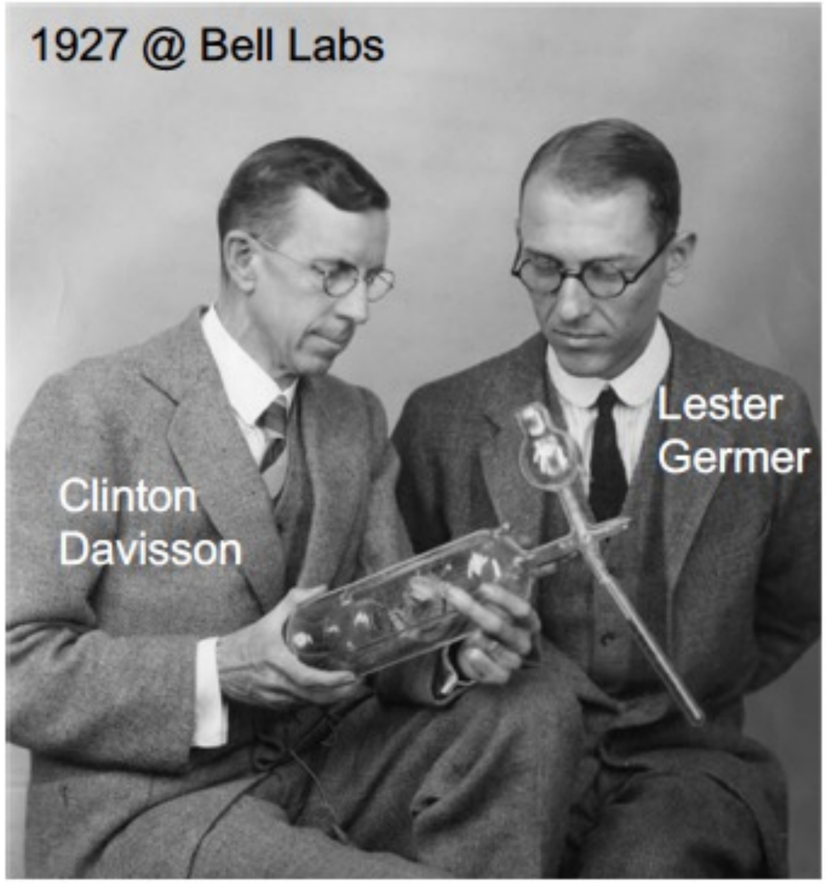
1929/1937

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}}$$

wave-particle duality
de Broglie wavelength
(1924)



Davisson, C. J., "Are Electrons Waves?," Franklin Institute Journal 205, 597 (1928)



diffraction peaks observed

E = 54 eV
λ = 0.17 nm

→ LEED (low energy electron diffraction), surface science tool

Transmission Electron Microscope (TEM)

1986

SONDERDRUCK AUS

KLINISCHE WOCHENSCHRIFT

ORGAN DER GESELLSCHAFT DEUTSCHER NATURFORSCHER UND ÄRZTE
VERLAG VON JULIUS SPRINGER, BERLIN, UND J. F. BERGMANN, MÜNCHEN

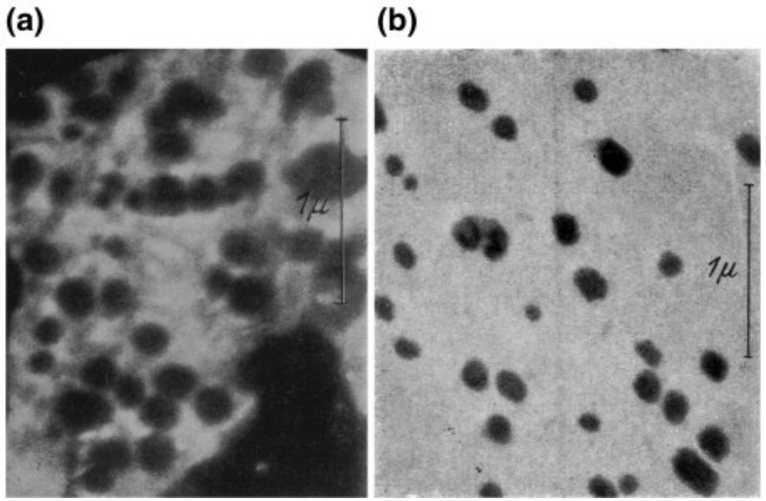
JAHRG. 17 2. JULI 1938 Nr. 27, S. 921/925

BAKTERIEN UND VIRUS IN ÜBERMIKROSKOPISCHER AUFNAHME
(mit einer Einführung in die Technik des Übermikroskops).

Von

B. VON BORRIES, E. RUSKA und H. RUSKA.*

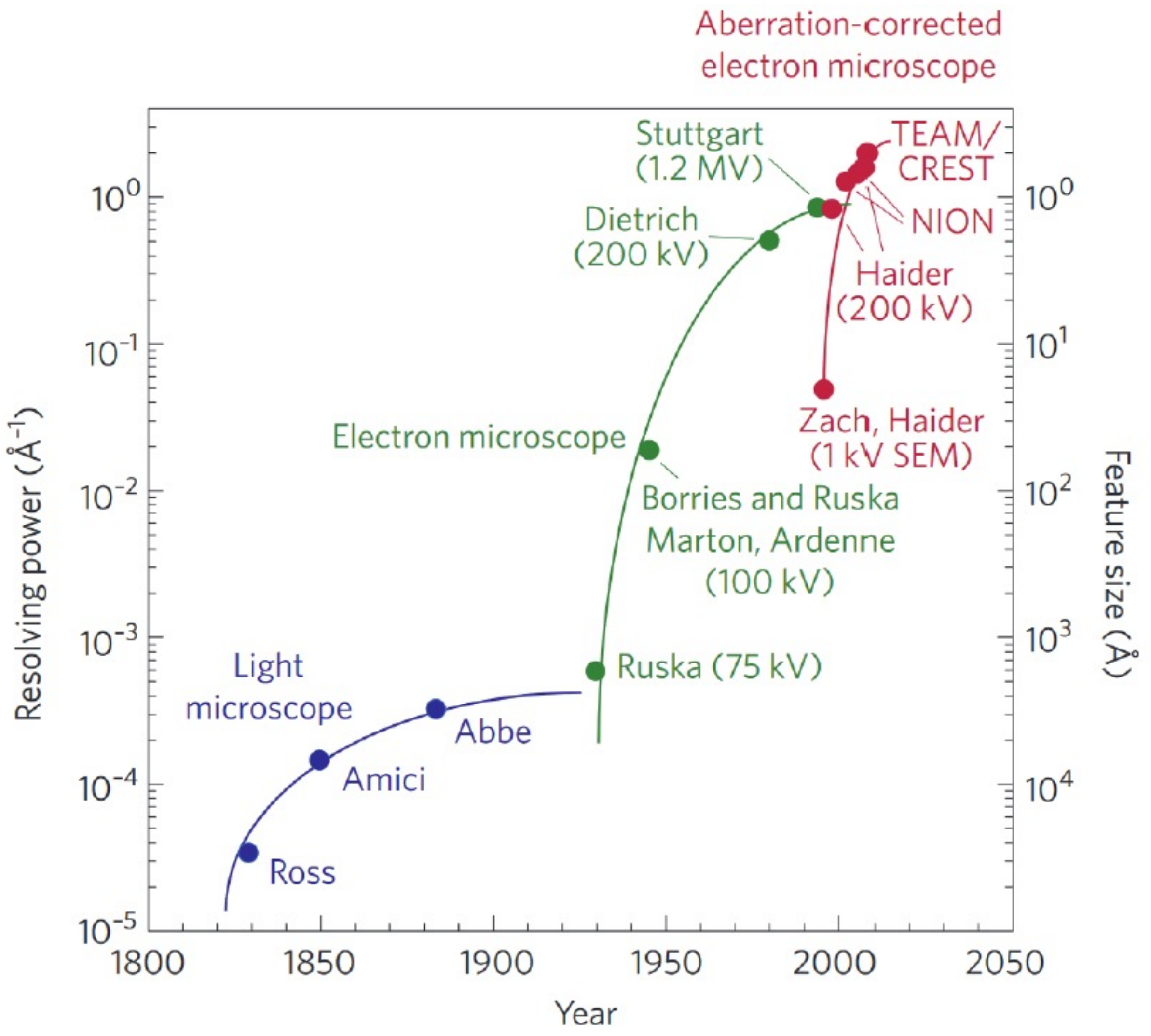
Aus dem Laboratorium für Elektronenoptik des Wernerwerks F der Siemens & Halske. Aktiengesellschaft und der I. Medizinischen Universitätsklinik der Charité.



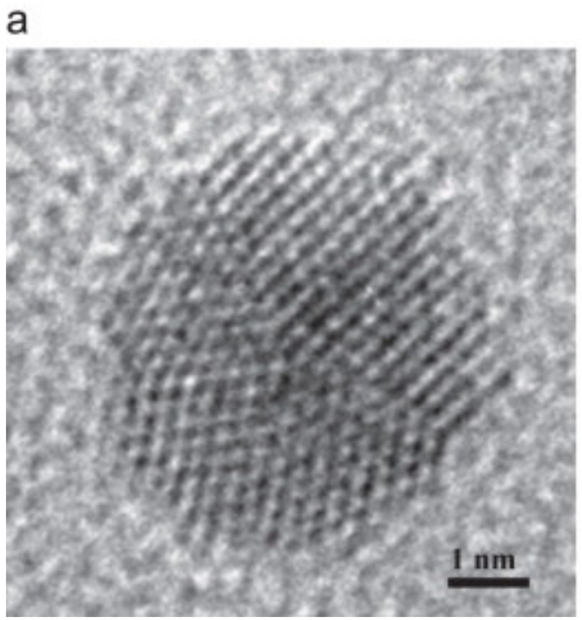
1933 Ernst Ruska

Transmission Electron Microscope (TEM)

energies in the range 50 keV to 400 keV



Nature Materials **8**, 263 (2009)



Au nanoparticle

Progr. Nat. Sci.: Mat. Inter. **23**, 222 (2013)

Cryo TEM

2017

Jacques Dubochet
Joachim Frank
Richard Henderson

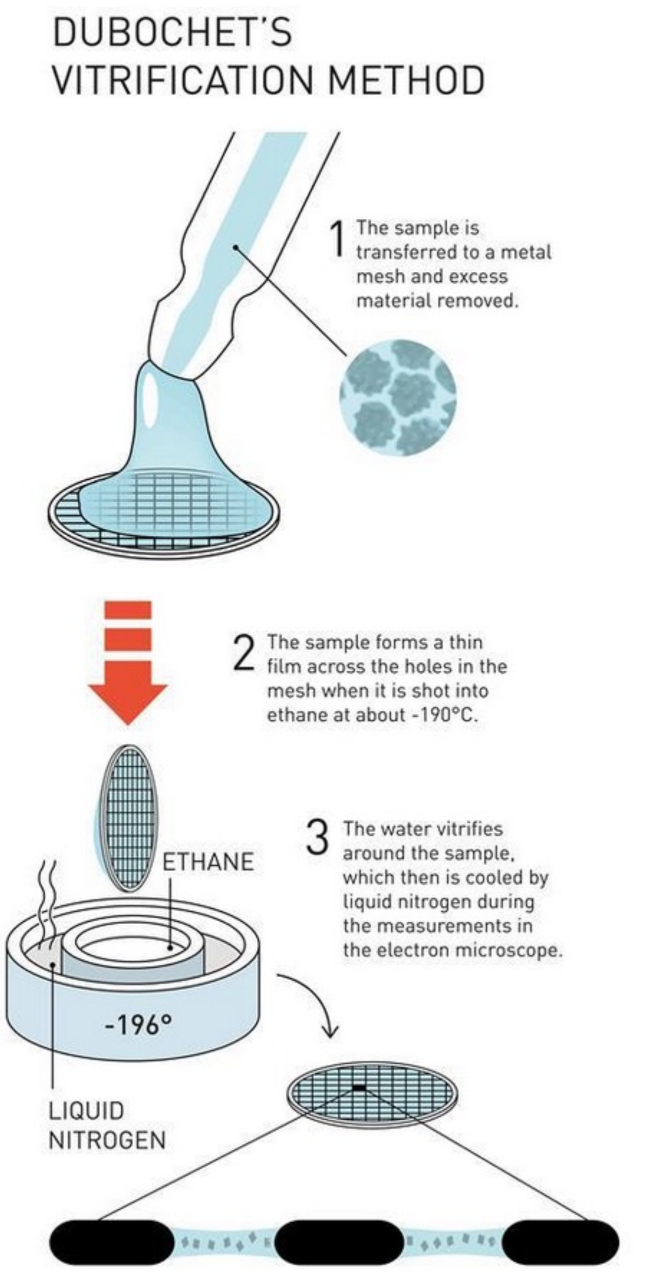
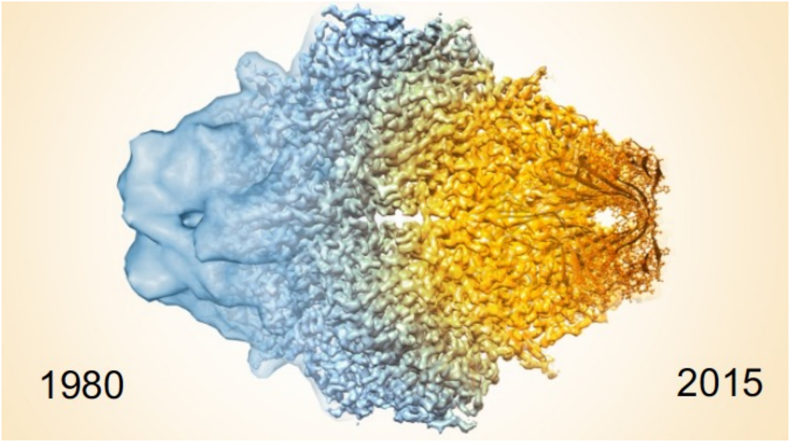


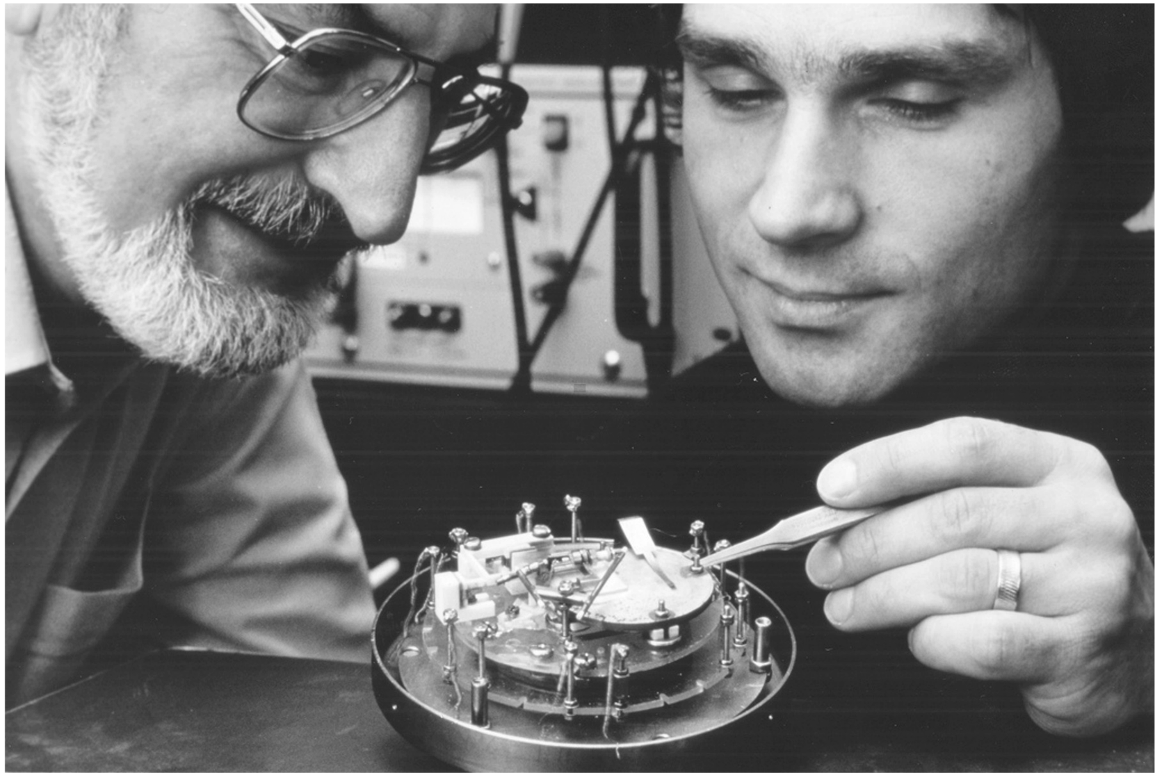
Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

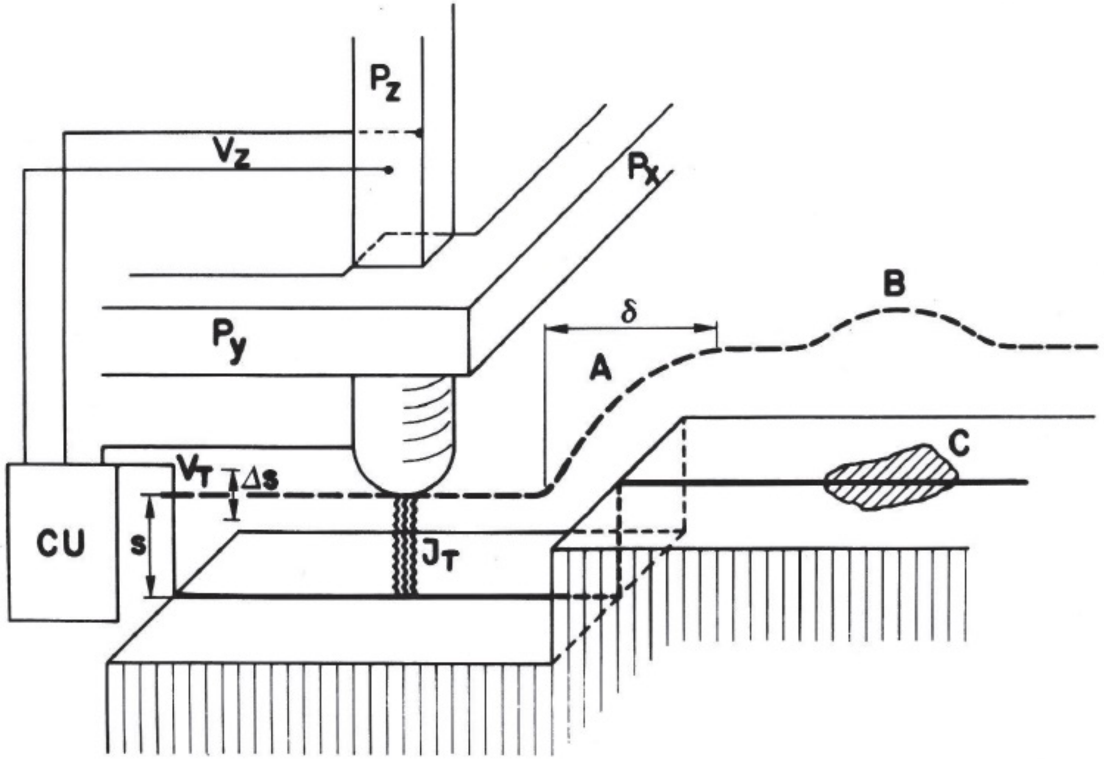
biological samples are not compatible with UHV: water desorbs and the sample is destroyed by the TEM e-beam

vitrification: rapid cooling of the sample, no water cristallization, but vitreus matrix that protects the biological samples



Scanning Tunneling Microscope (STM)





Heinrich Rohrer

Gerd Binnig

IBM Rüschlikon, 1981

based on quantum tunneling effect

typical currents: < 1 nA

Phys. Rev. Lett **50**, 120 (1983)

Helv. Phys. Acta **55**, 726 (1982)

Scanning Tunneling Microscope (STM)

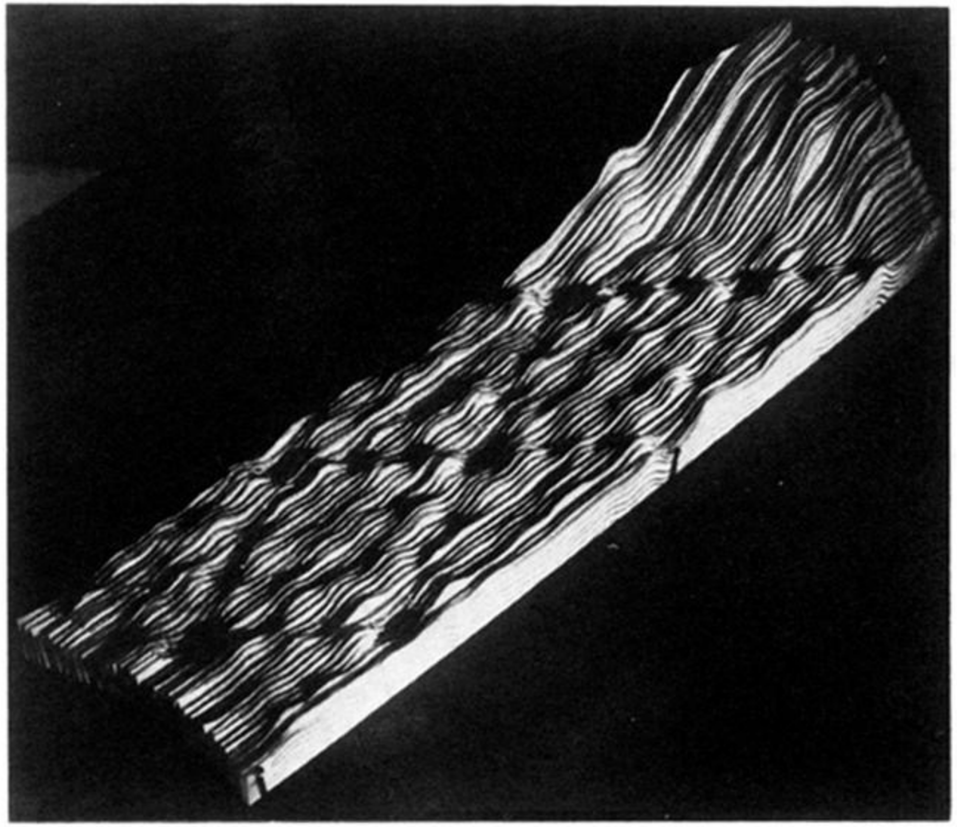
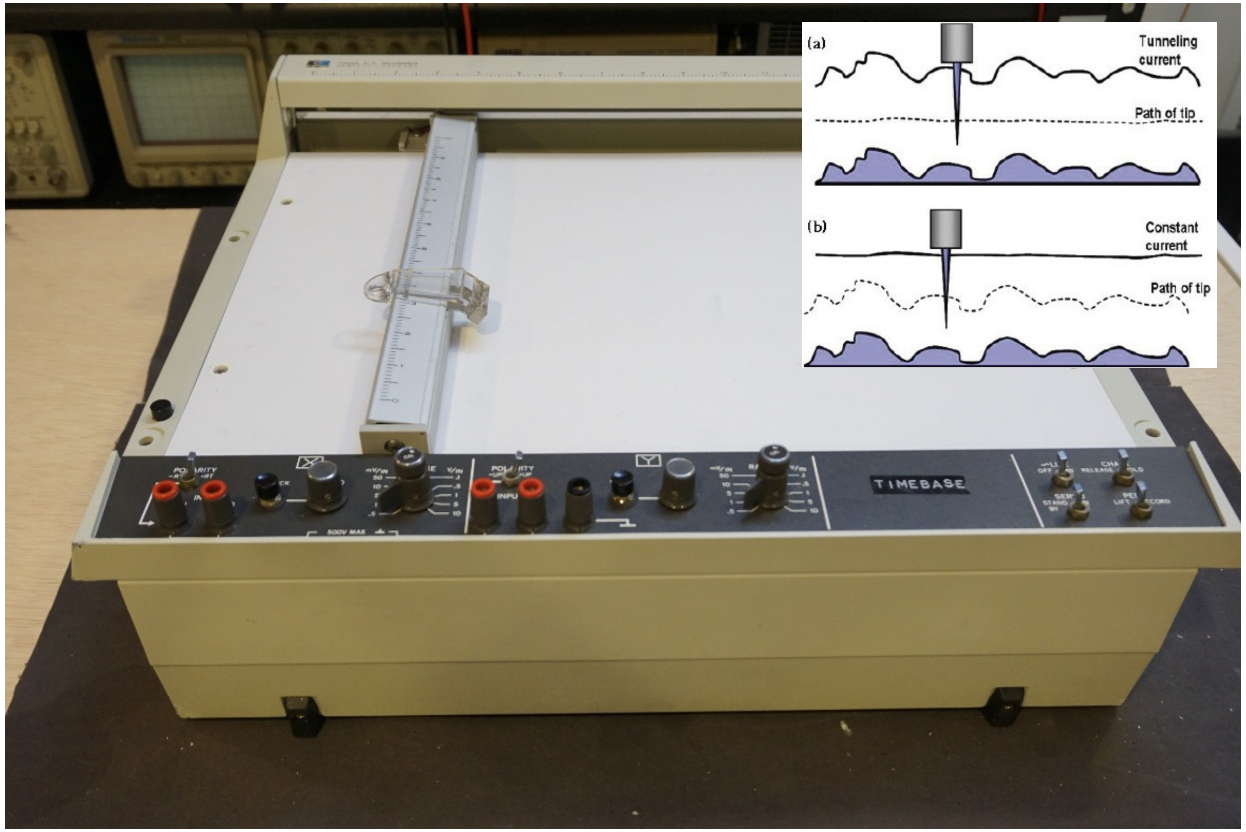
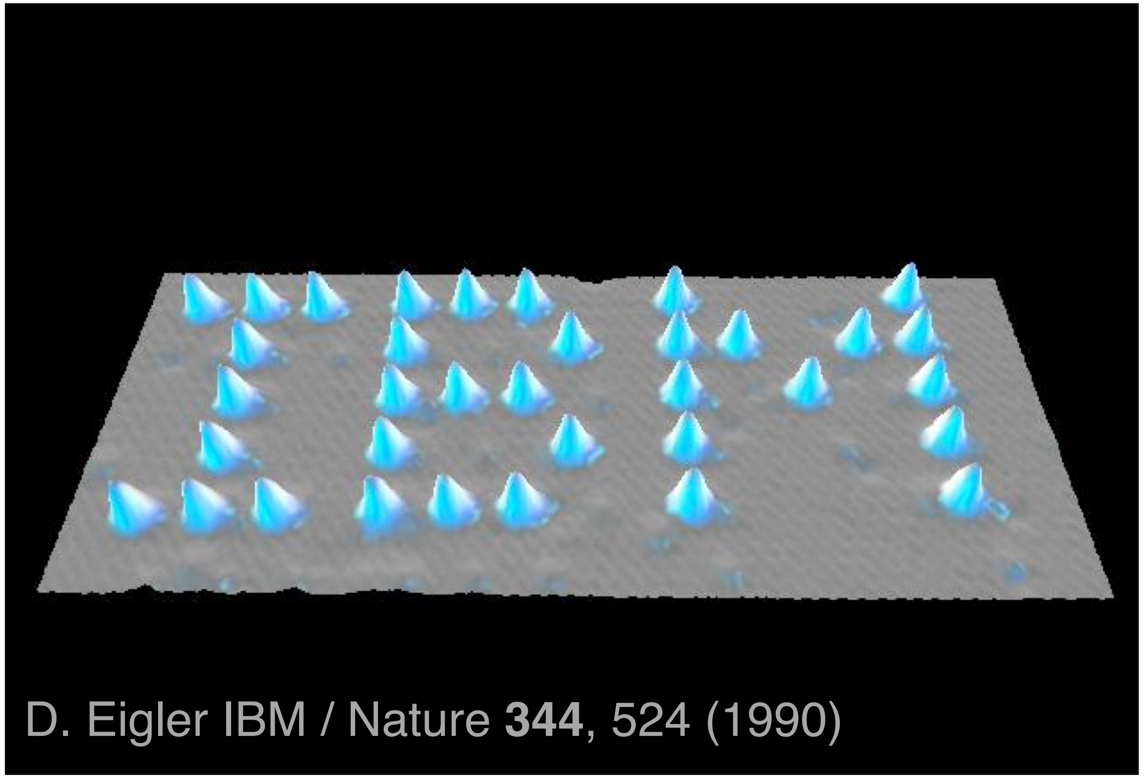


FIG. 1. Relief of two complete 7×7 unit cells, with nine minima and twelve maxima each, taken at 300 °C. Heights are enhanced by 55%; the hill at the right grows to a maximal height of 15 Å. The $[\bar{2}11]$ direction points from right to left, along the long diagonal.



Phys. Rev. Lett **50**, 120 (1983)

Scanning Tunneling Microscope (STM)



a powerful tool:

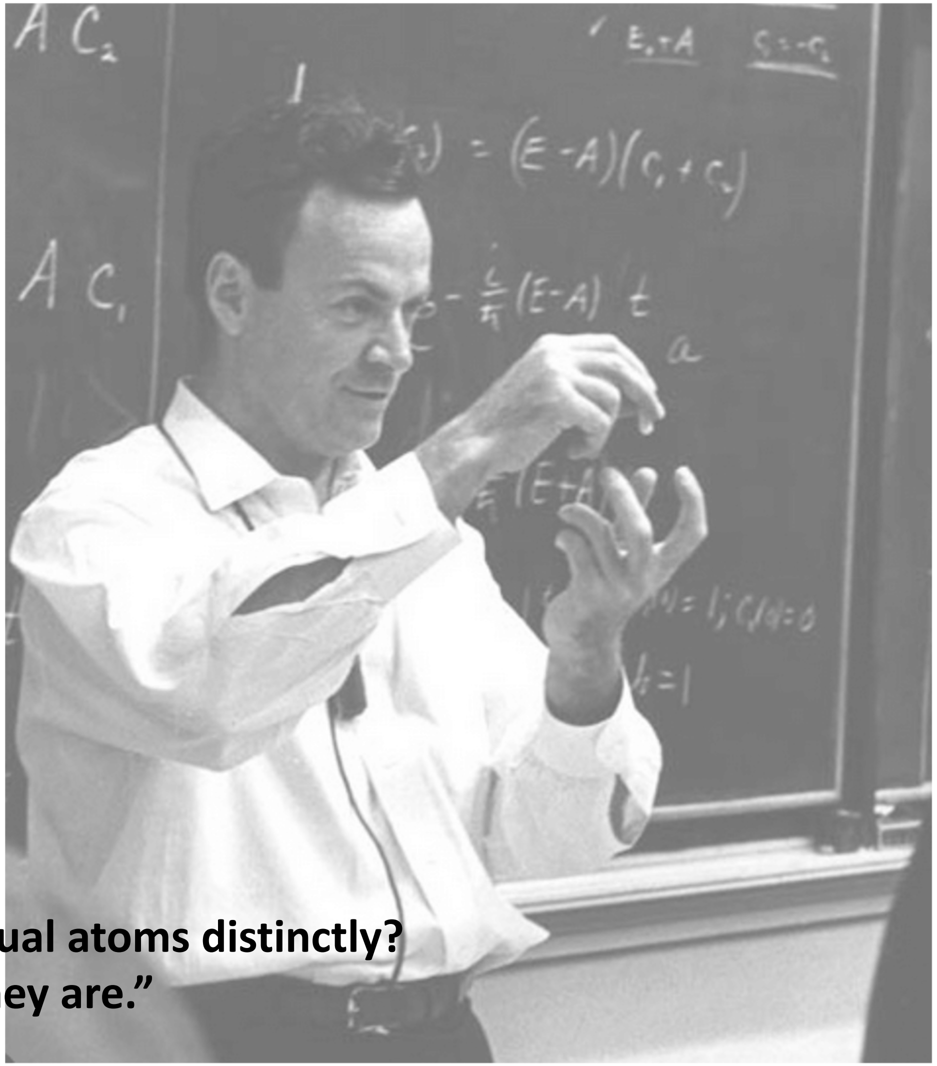
- imaging of surfaces and supported nanostructures
- manipulation at atomic level
- spectroscopy

for high-end applications, requirements:

- UHV
- low noise
- low vibrations
- low temperature

There’s plenty of room at the bottom (1959)

1965

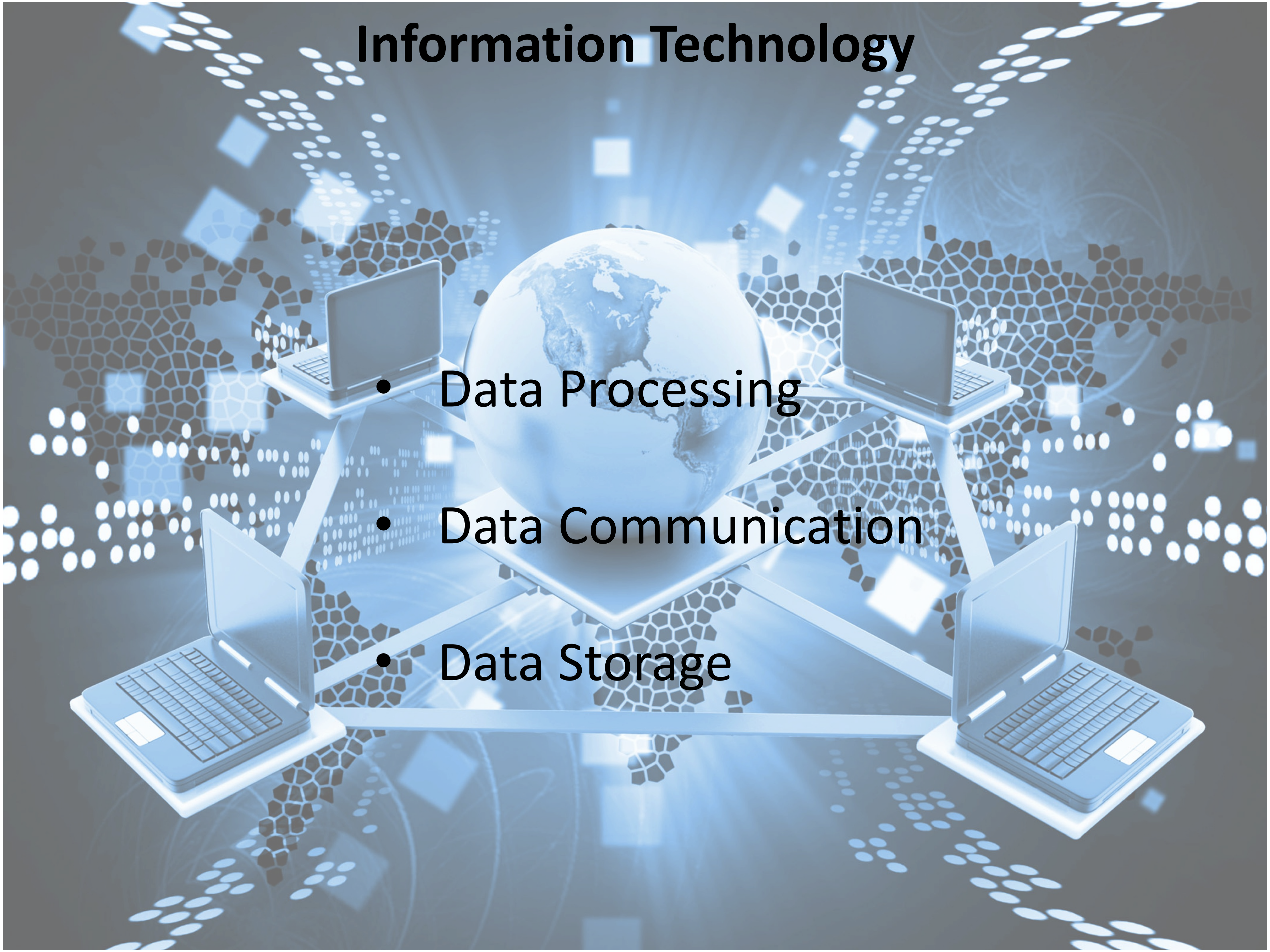


“What good would it be to see individual atoms distinctly?
…. look at the atoms and see where they are.”

“But I am not afraid to consider the final question as to whether, ultimately – in the great future – we can arrange the atoms the way we want; the very atoms, all the way down!”

Richard Feynman

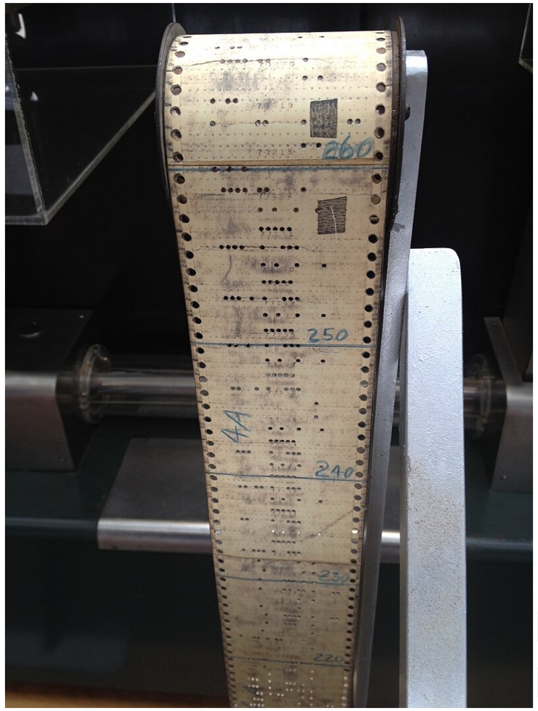
Information Technology



- Data Processing
- Data Communication
- Data Storage

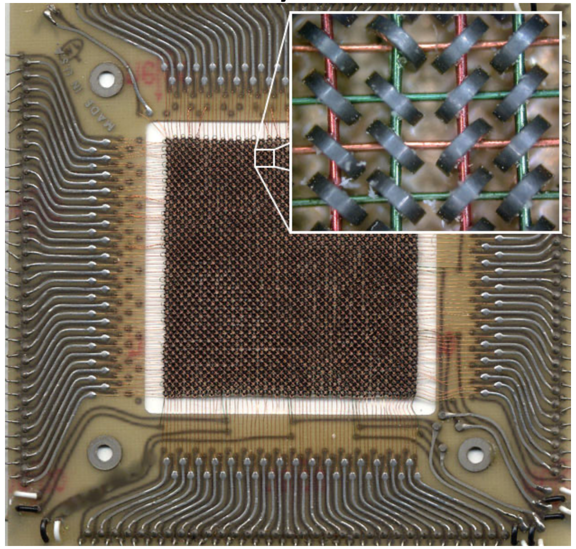
courtesy of K. Kern

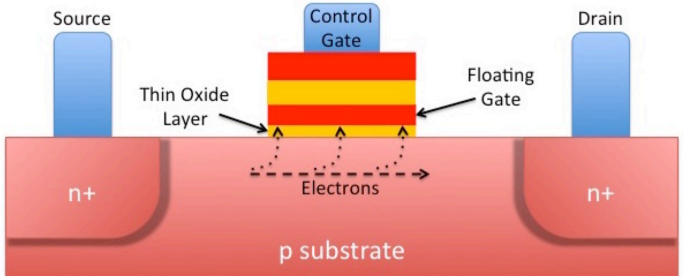
Data storage (historical, not exhaustive)

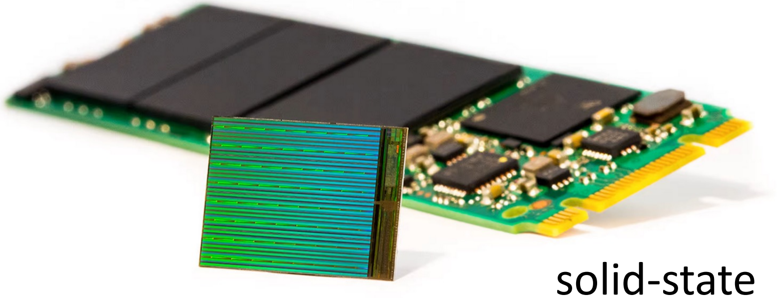


punched tapes
punched cards

magnetic-core memory







solid-state drive (SSD)

magnetic hard-disk drive (HDD)

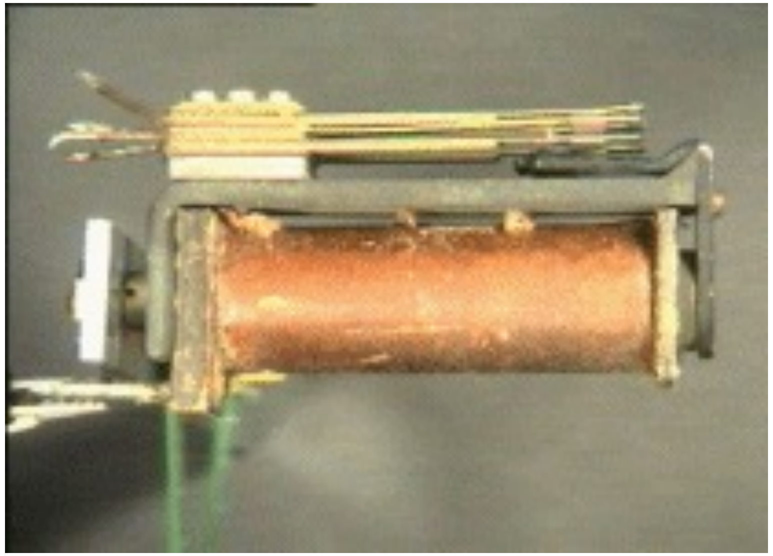
digital data
binary system

any number (or instruction)
can be represented
by a sequence of bits (binary digits)
which are in turn represented
by any mechanism capable of being
in two mutually exclusive states (1 and 0)

Data processing

binary systems - switches

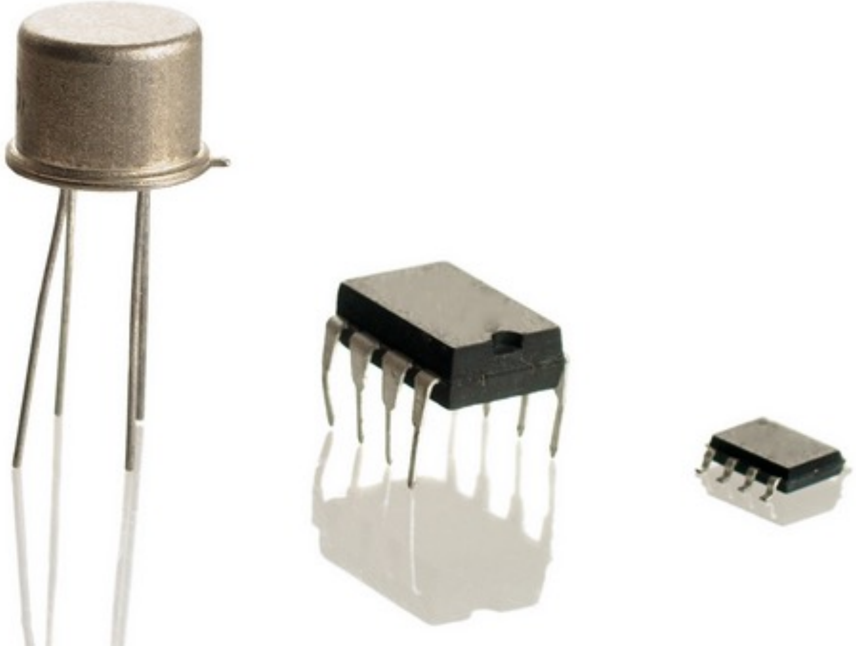
Boolean algebra
(logical operators, variables: true = 1, false =0)



http://zuse.zib.de/relay

electromechanical relays
1930-1950

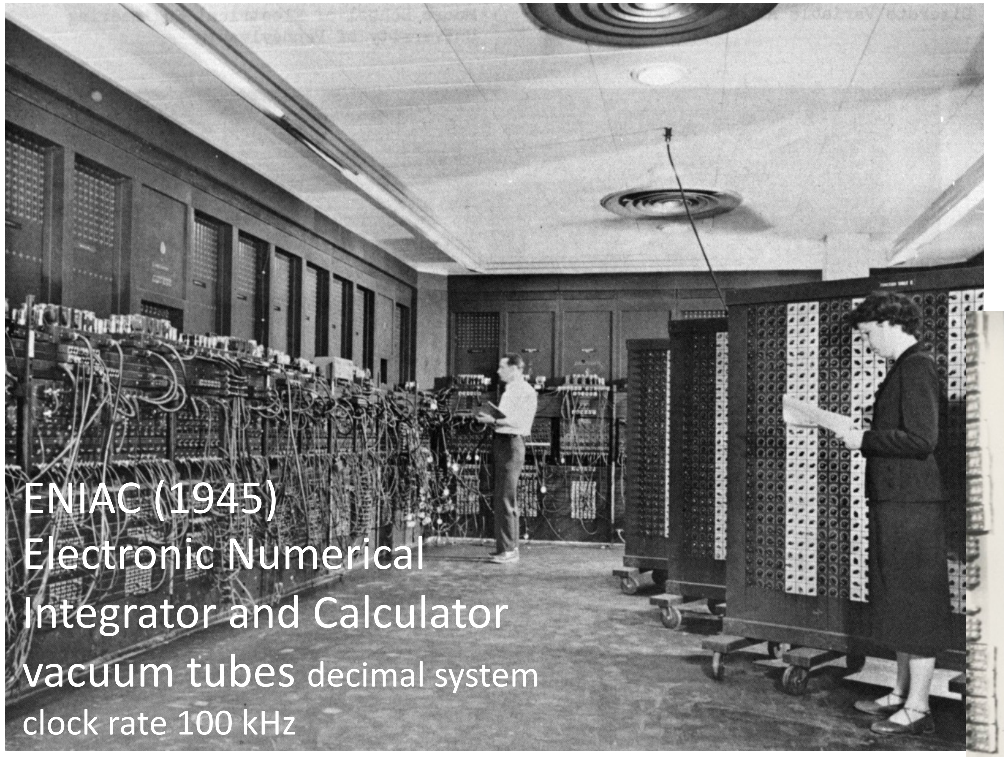
vacuum tubes – triodes
1940-1965



transistors
from 1960

Computers

Zuse Z3 (1941)
electromechanical relays
binary system



ENIAC (1945)
Electronic Numerical
Integrator and Calculator
vacuum tubes decimal system
clock rate 100 kHz

EDVAC (1949)
vacuum tubes binary

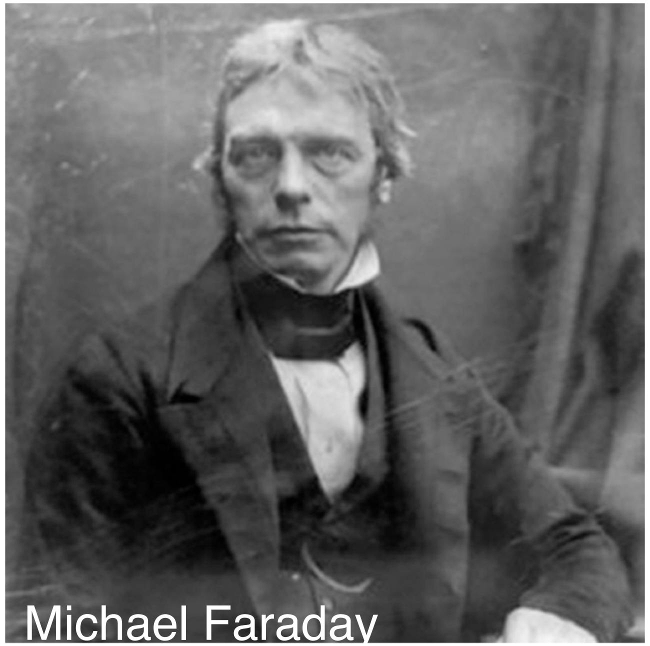
PDP-10 (1975)

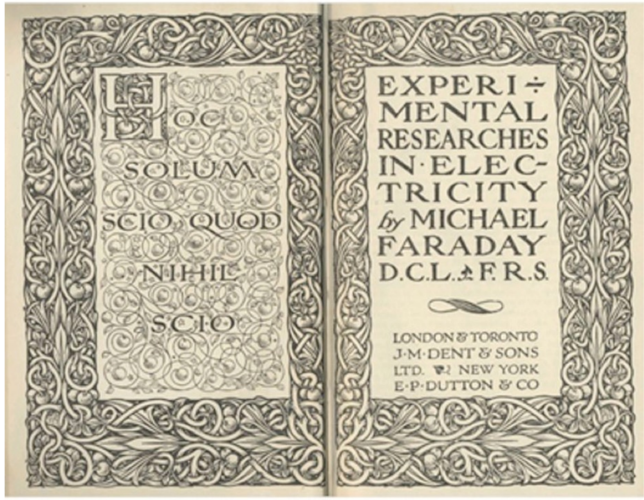
TX-0 (1955)
Transistorized Experimental computer zero

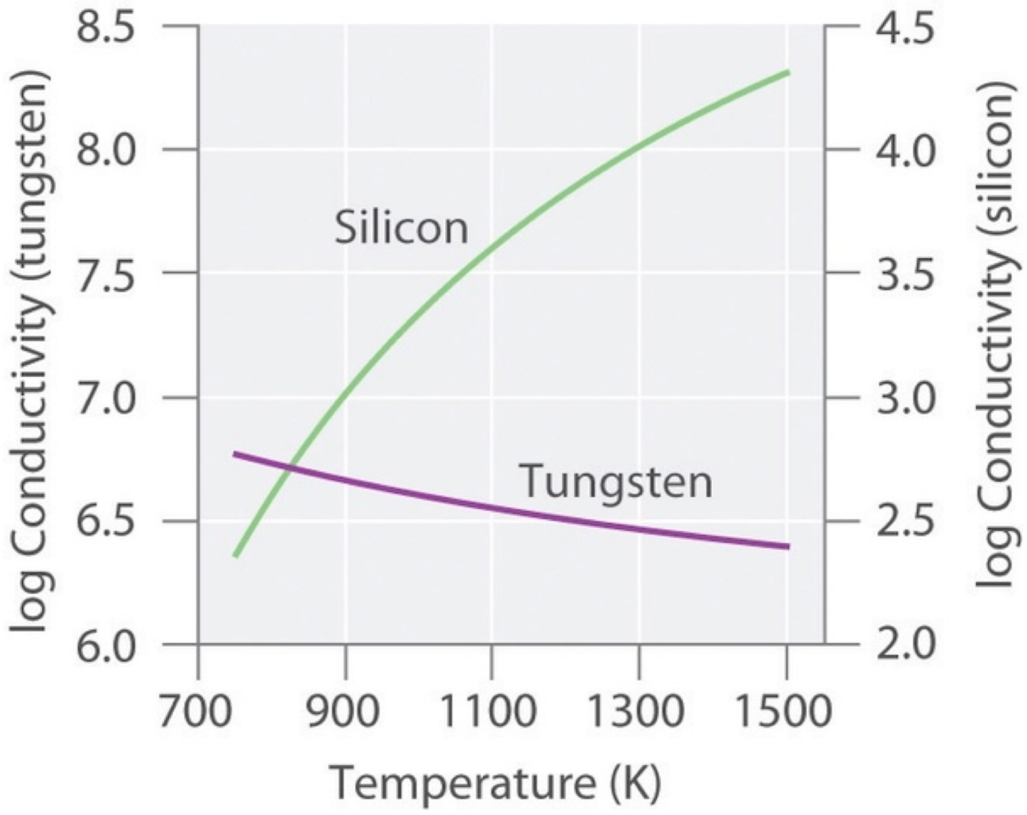
Smartphones: a Supercomputer in your Pocket

1984		2023
10^7 \$		10^3 \$
105 MHz	CPU clock rate	3.46 GHz

Semiconductors







discovery of semiconductors (1833)
(silver sulfide)

Semiconductors

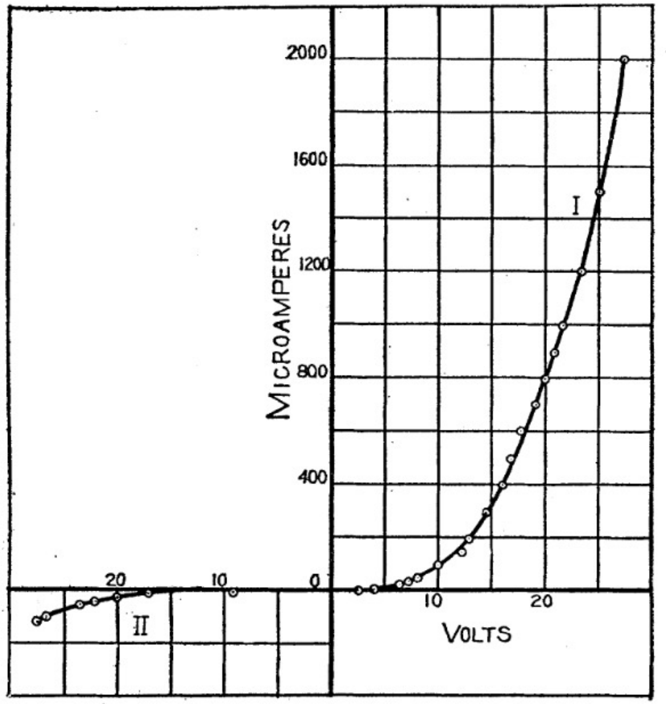
1909

Karl Ferdinand Braun

Ann. der Physik und Chemie (1874)
“Ueber die Stromleitung durch Schwefelmetalle”

lead sulfide (galena)
wire contact (cat whisker)

unilateral conduction →
crystal detector
point-contact diode

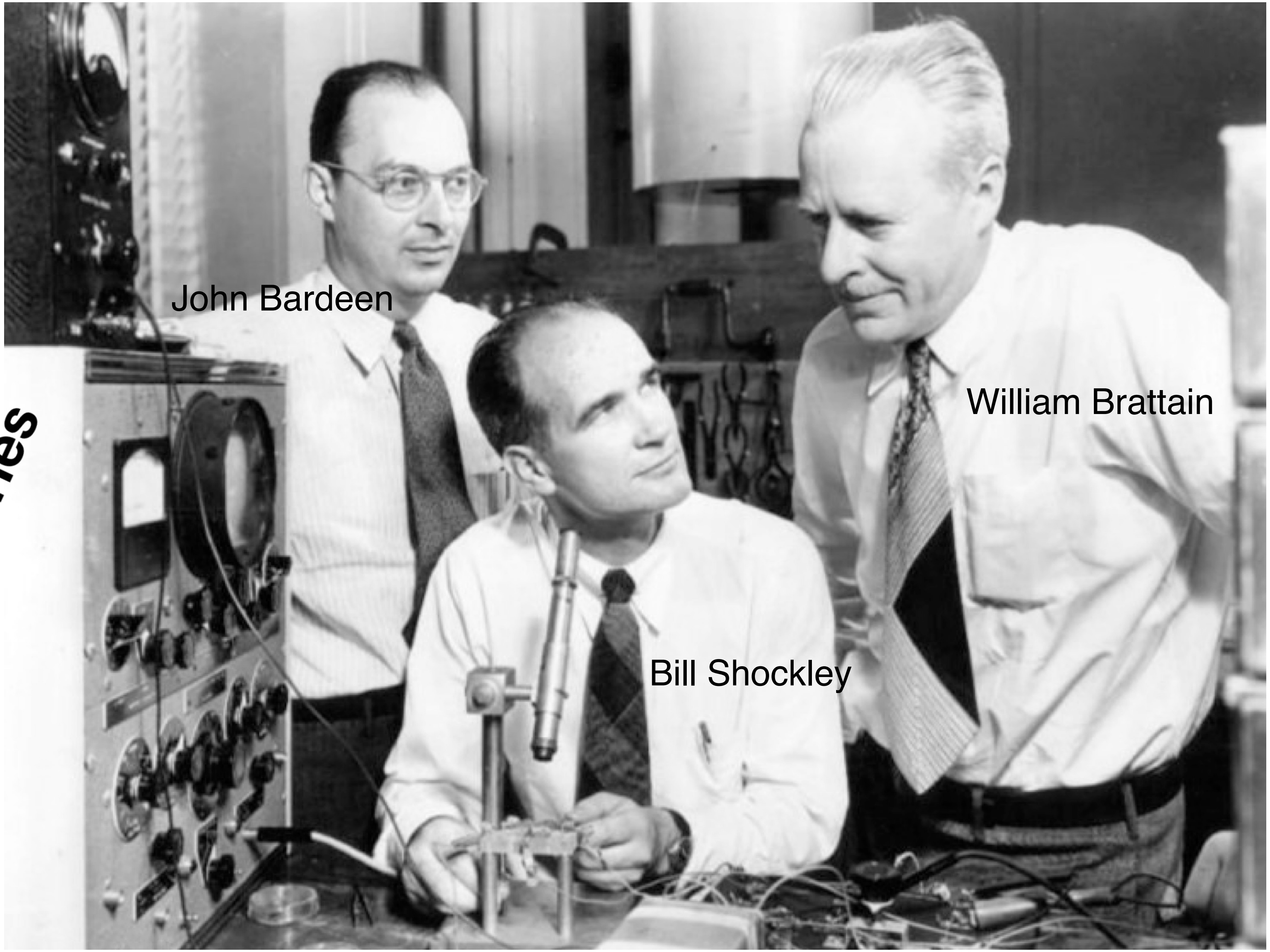


G.W. Pierce
Phys. Rev. **5**, 31 (1907)

carborundum

Transistor discovery (1947)

1956



Bell Laboratories

Transistor discovery (1947)

Phys. Rev. **74**, 230 (1948)

The Transistor, A Semi-Conductor Triode

J. BARDEEN AND W. H. BRATTAIN
Bell Telephone Laboratories, Murray Hill, New Jersey

June 25, 1948

A THREE-ELEMENT electronic device which utilizes a newly discovered principle involving a semi-conductor as the basic element is described. It may be employed as an amplifier, oscillator, and for other purposes for which vacuum tubes are ordinarily used. The device consists of three electrodes placed on a block of germanium[1] as shown schematically in Fig. 1. Two, called the emitter and collector, are of the point-contact rectifier type and are placed in close proximity (separation ~.005 to .025 cm) on the upper surface. The third is a large area low resistance contact on the base.

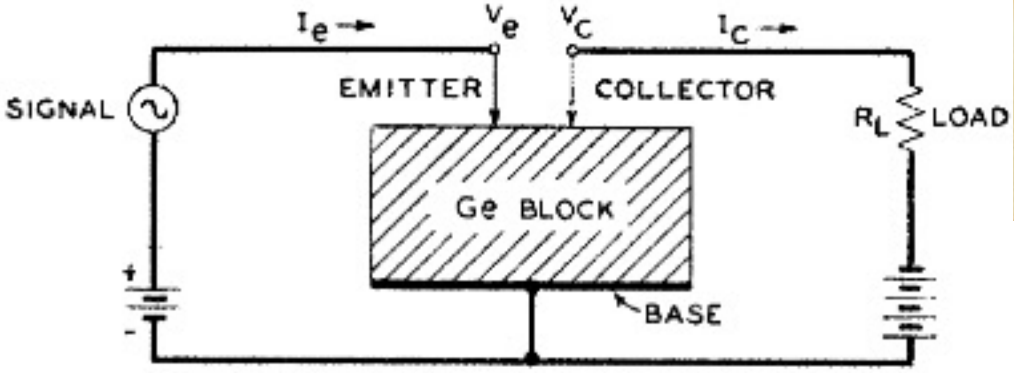
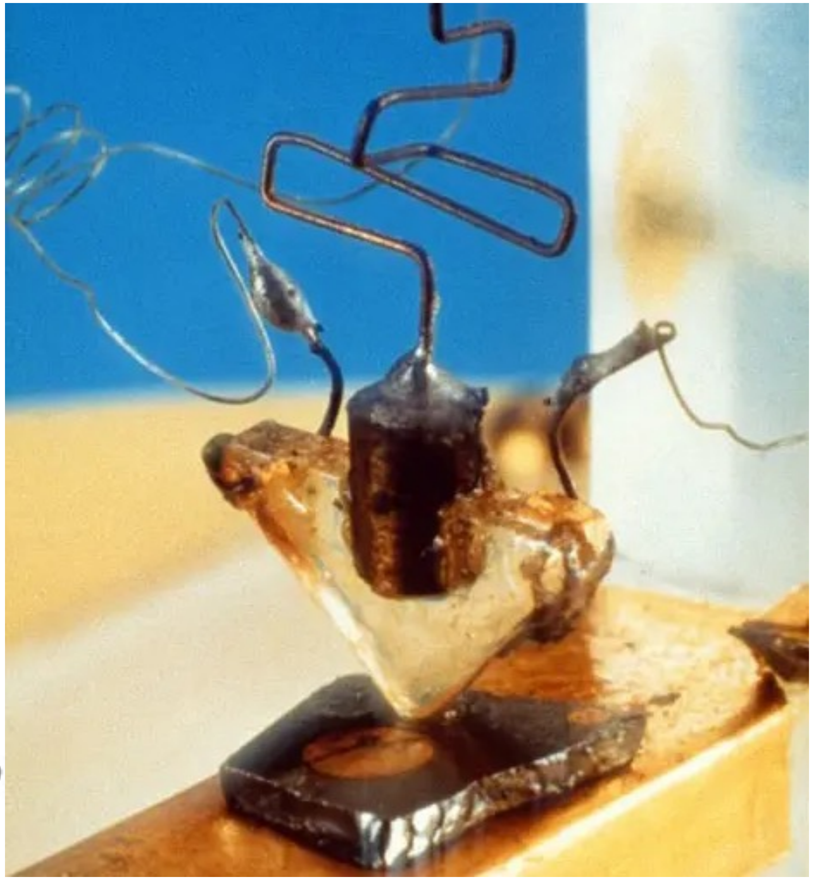
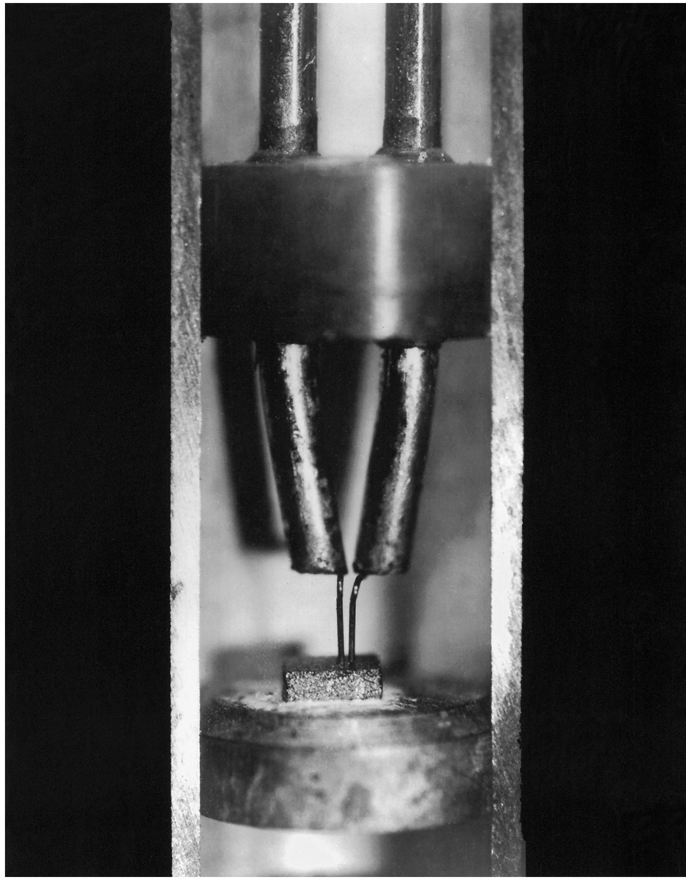


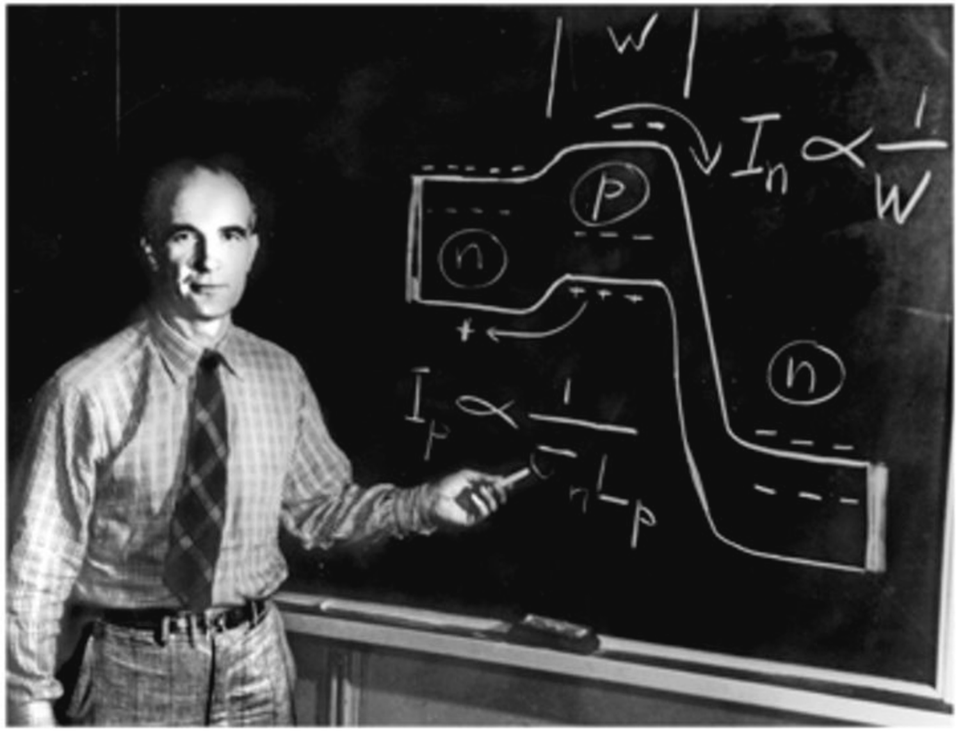
FIG. 1. Schematic of semi-conductor triode.



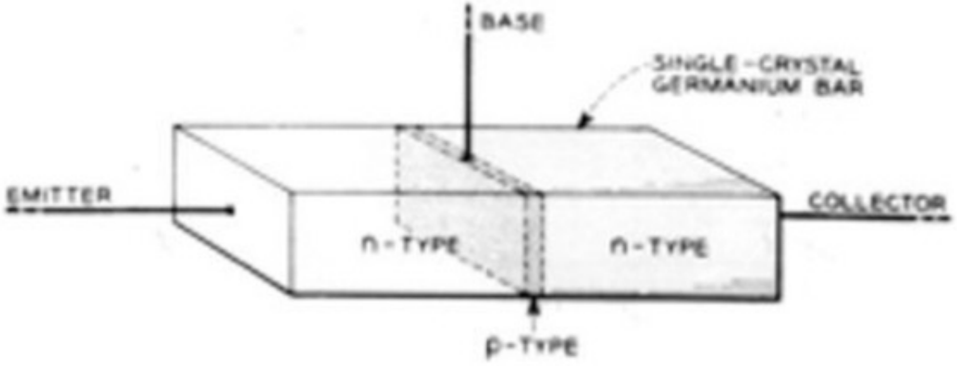


point contact transistor

Bipolar Junction Transistor (1948)

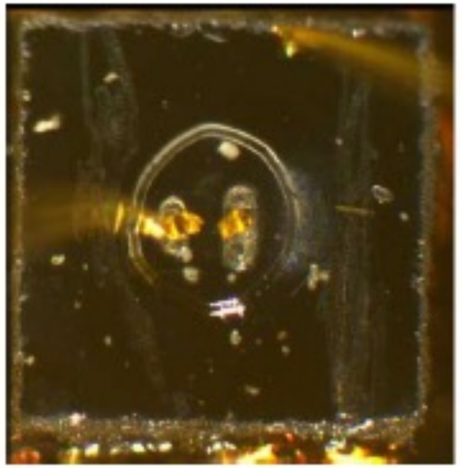


Bill Shockley



From germanium to silicon (mid 1950's)

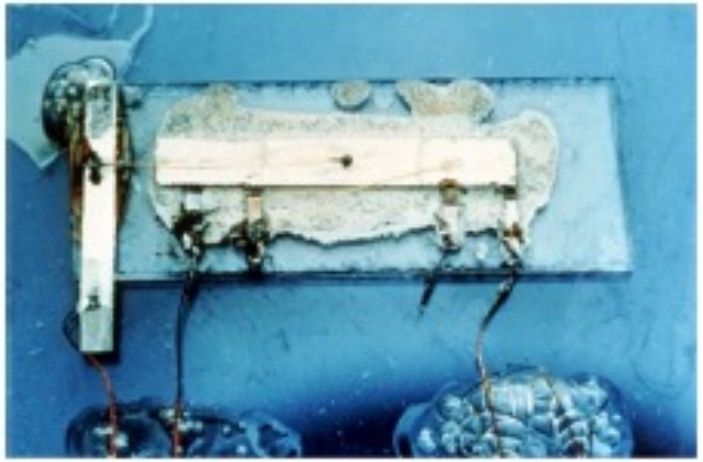
Morris Tanenbaum, Bell Labs, 1954/55

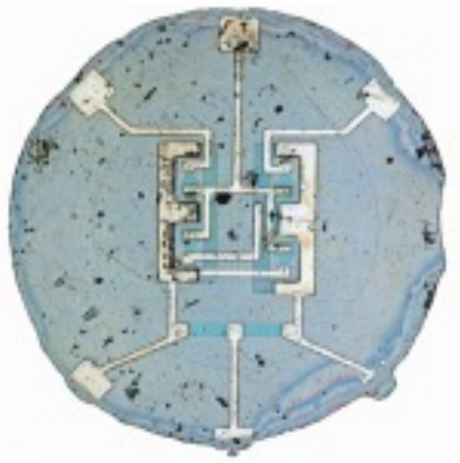


Shockley Semiconductor Lab (1955)

Fairchild Semiconductors (1957)

Going 2D





Jack Kilby
TI

first all
semiconductor
solid circuit

(1958)

Jean Hoerni
Fairchild

first planar
process

(1960)

Robert Noyce
Fairchild

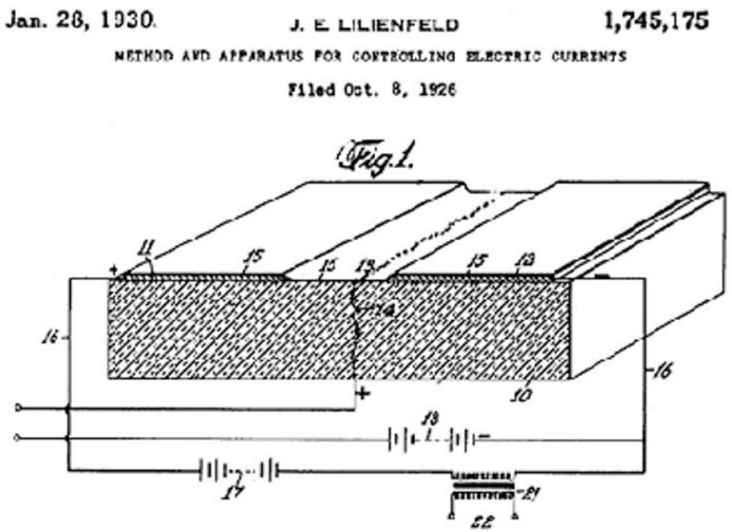
first planar
IC

(1960)

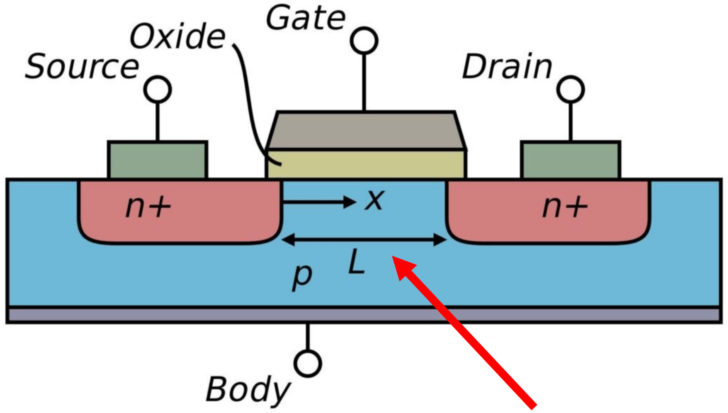
Field Effect Transistor

J.E. Lilienfeld, Bell Labs

US Patent (1926)
Semiconductor Field Effect Device

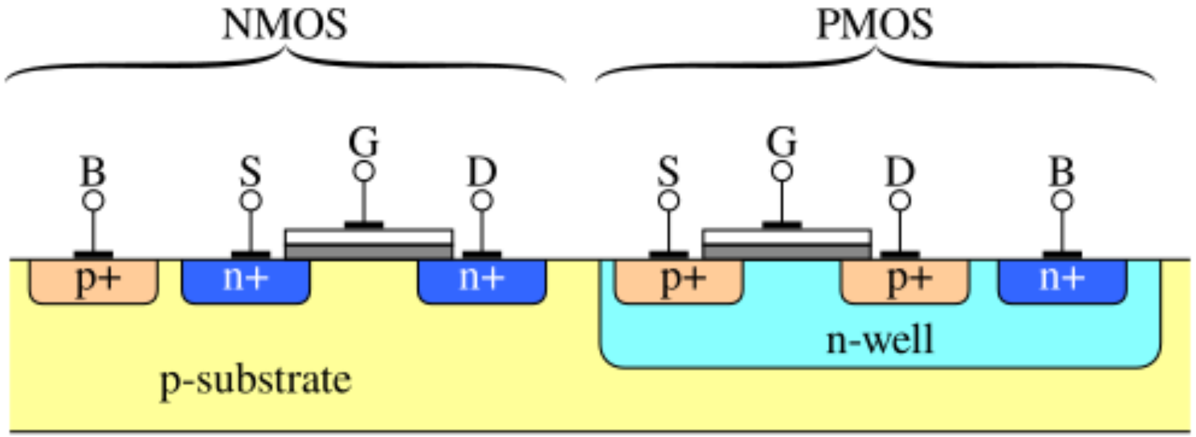


MOSFET (Metal-Oxide - Semiconductor FET)
Bell Labs (1959)



gate length =
channel lenght

CMOS (Complementary Metal-Oxide – Semiconductor)
combining p-type and n-type MOSFETs for logic functions
Fairchild Semiconductors (1963)



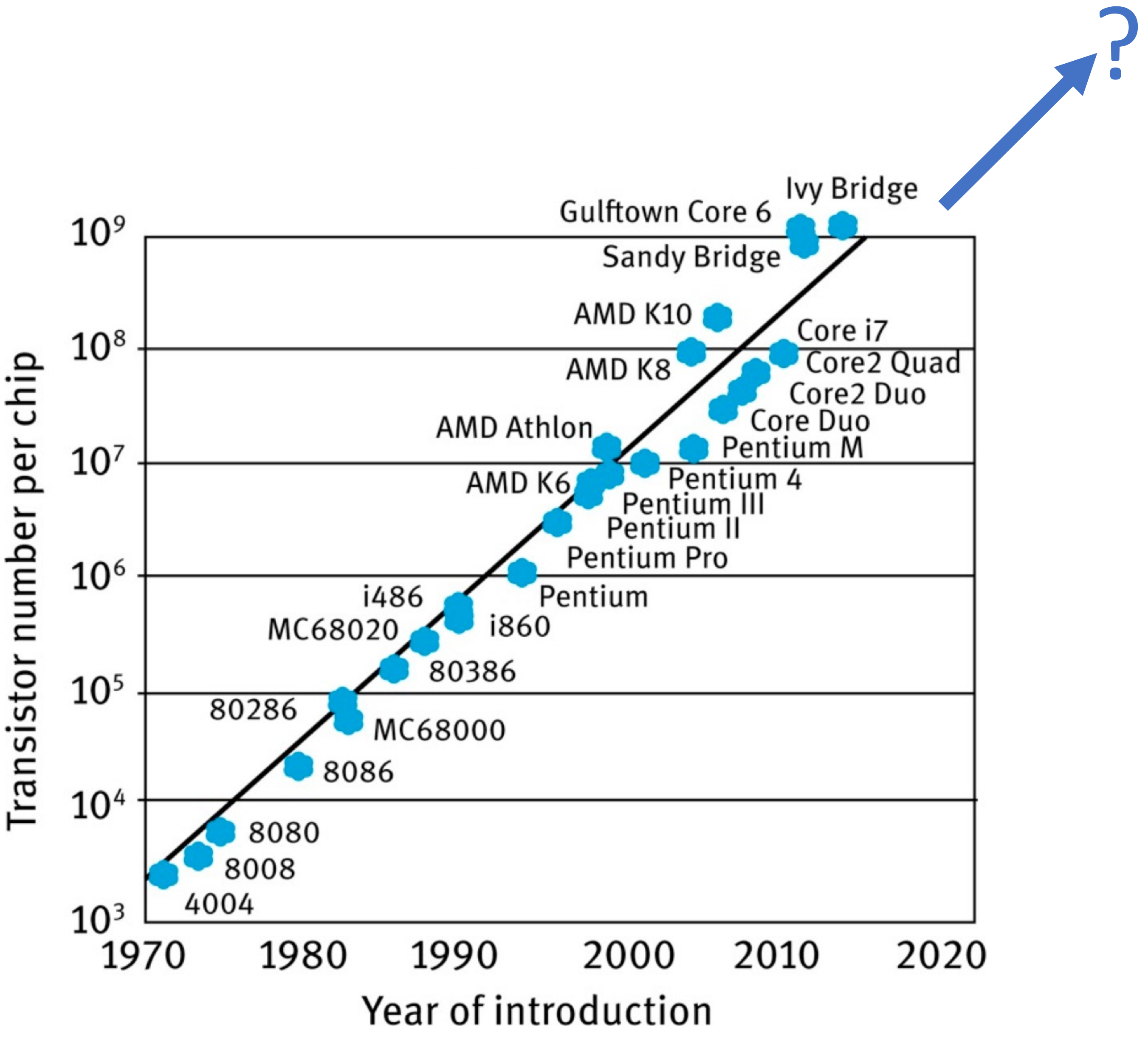
Miniaturization - Moore's law

Gordon E. Moore
Co-founder, Intel Corporation.

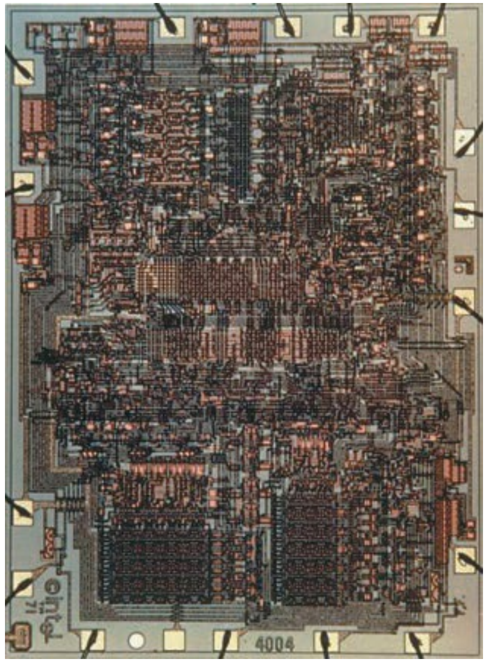
Electronics, Volume 38, Number 8 (1965)

"With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip."

"The number of transistors on a piece of silicon will double every couple of years."



Miniaturization

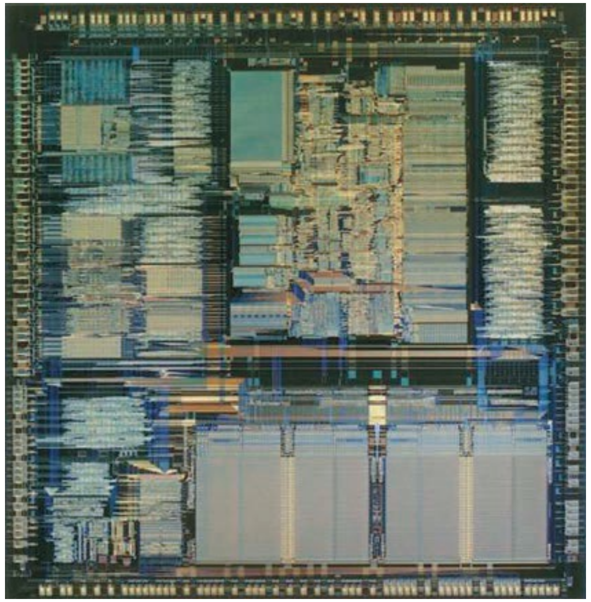


1971
Intel® 4004 processor

Initial clock speed:
108KHz

Transistors:
2,300

Manufacturing technology:
10 micron

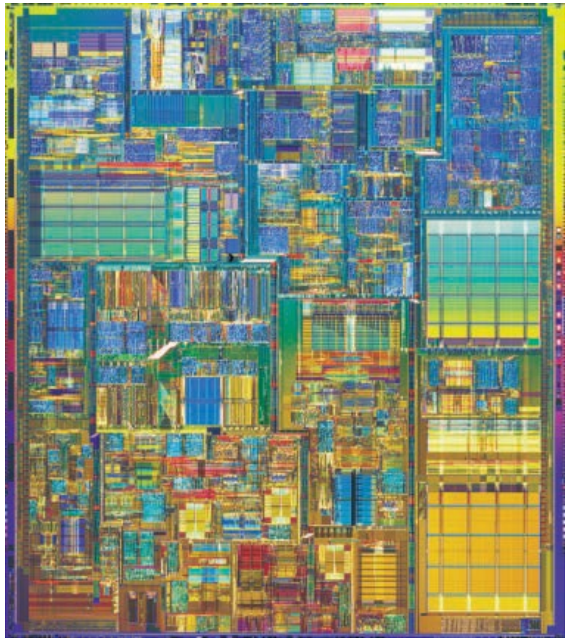


1985
Intel386™ processor

Initial clock speed:
16MHz

Transistors:
275,000

Manufacturing technology:
1.5 micron

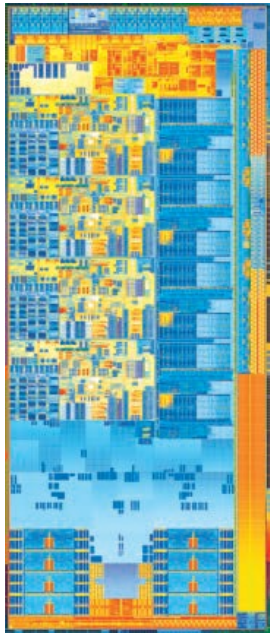


2000
Intel® Pentium® 4 processor

Initial clock speed:
1.5GHz

Transistors:
42 million

Manufacturing technology:
0.18 micron



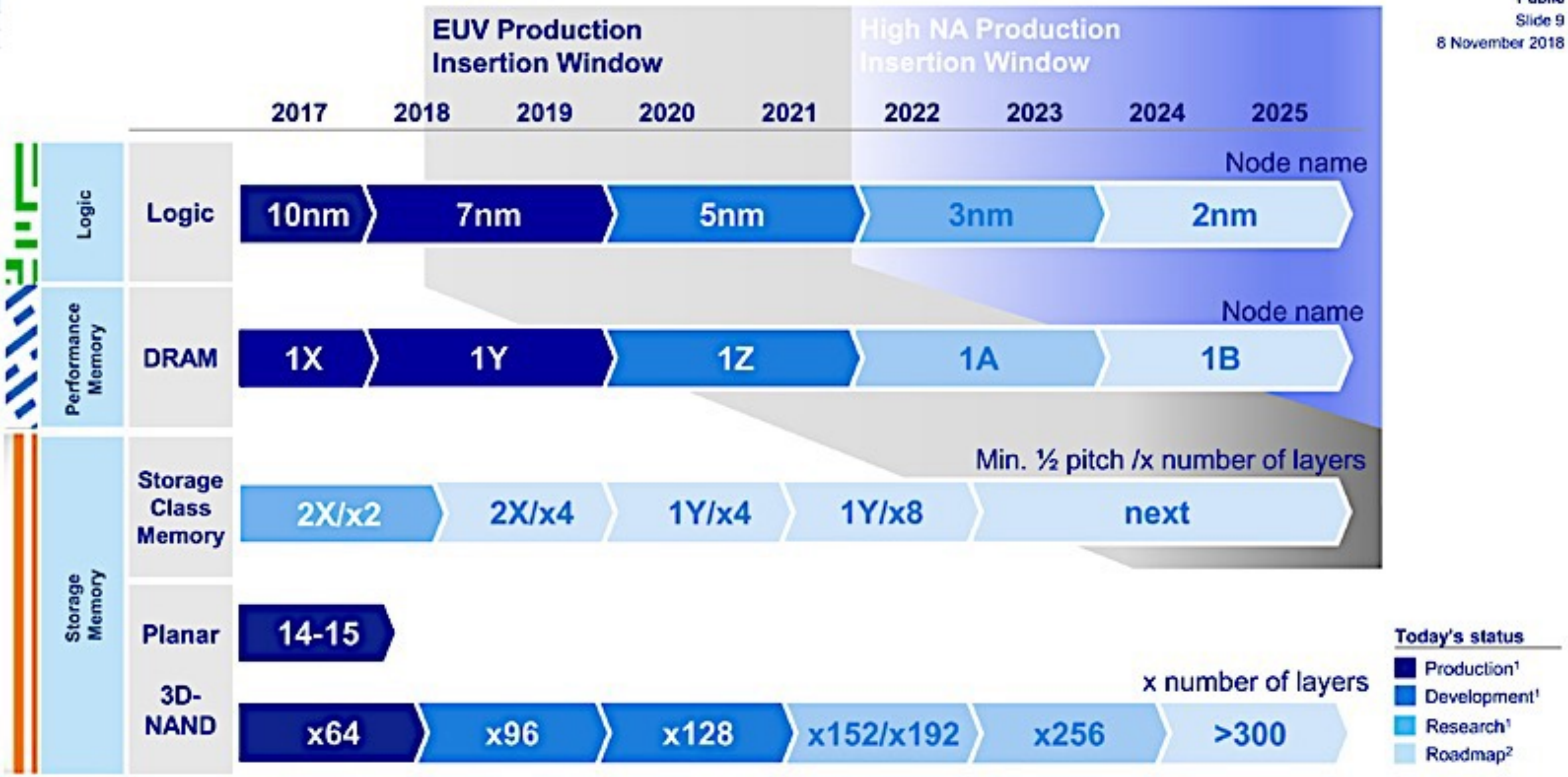
2012
3rd generation Intel® Core™ processor

Initial clock speed:
2.9GHz

Transistors:
1.4 billion

Manufacturing technology:
22nm

Customers’ scaling roadmaps continue



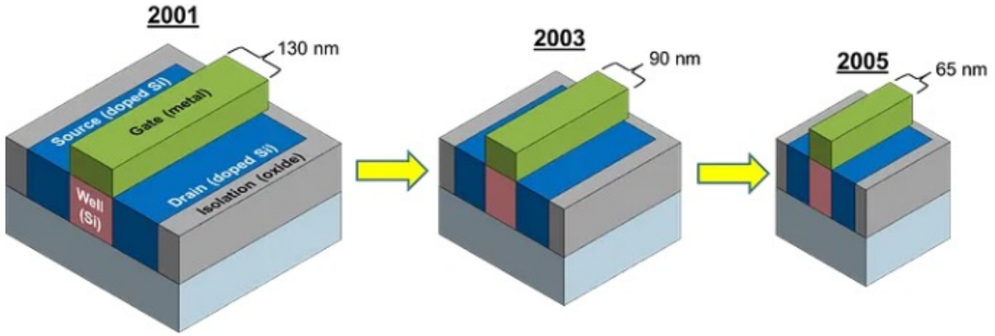
Source: [1] Customers public statements, IC Knowledge LLC; [2] ASML extrapolations

FET fabrication technology roadmaps - Nodes

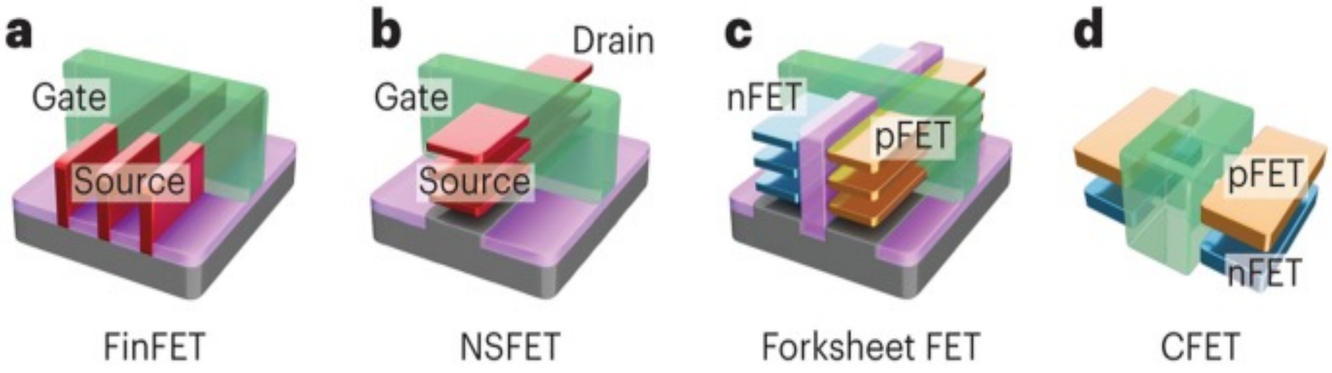
in early days until 2008
MOSFETs were purely planar, the node name (technology or process node) corresponds the size of the smalles feature on a processor, usually the **gate length**

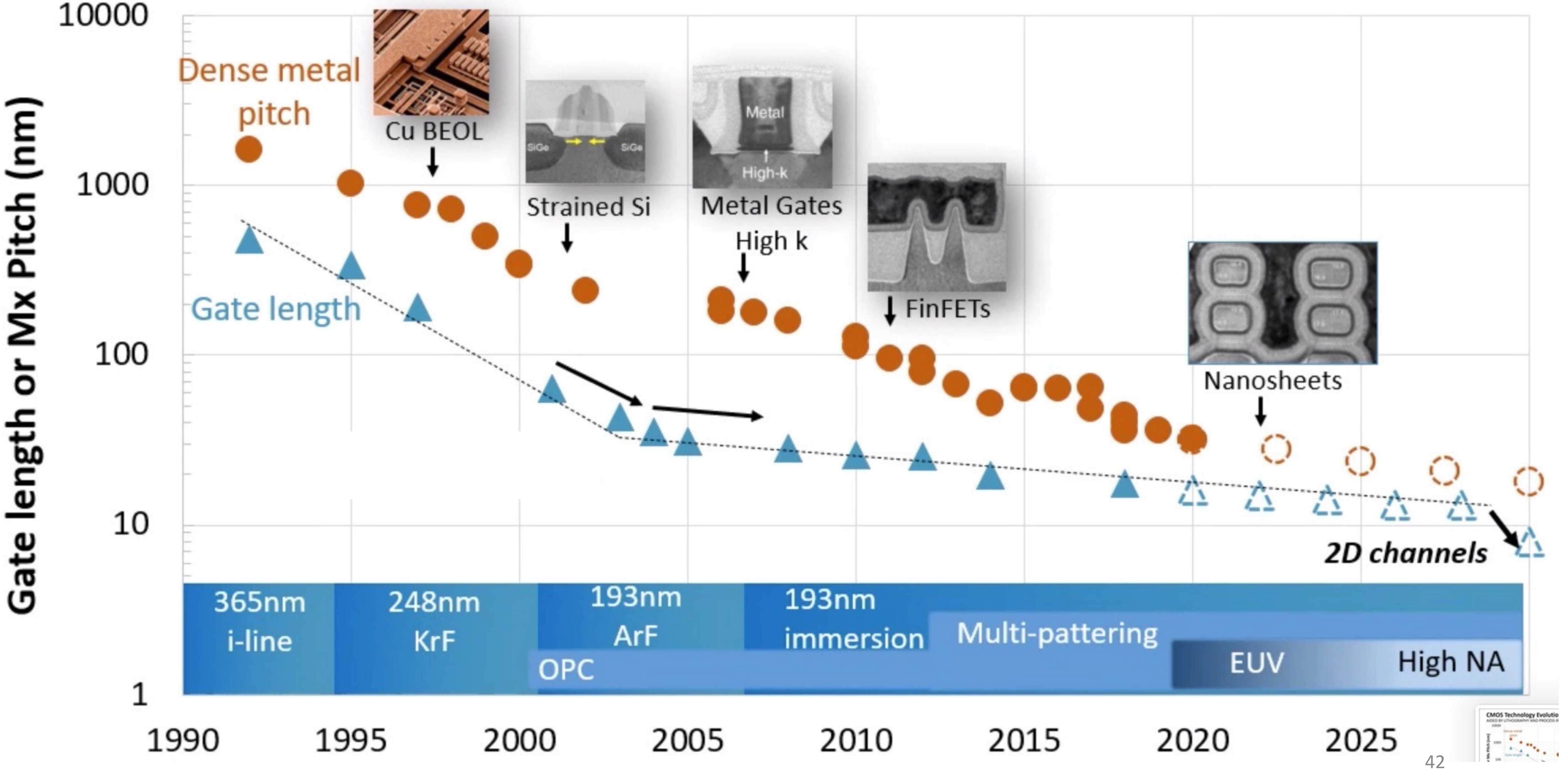
50 μm mid 1960's
1 μm late 1960's
350 nm late 1990's

130 nm 90 nm 65 nm



after 2008
transistors go in the third dimension;
the node name is not anymore related to feature sizes; it rather indicates the **transistor density**
other ways to optimize the density (packing, stacking in third dimension...)



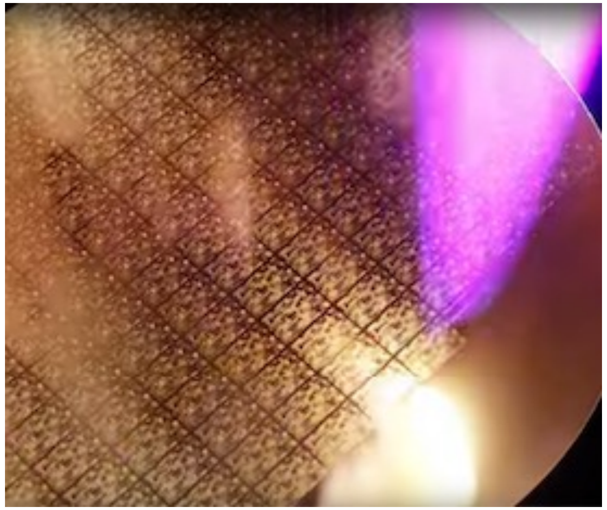

Dense metal pitch
Gate length
Gate length or Mx Pitch (nm)
10000
1000
100
10
1
Cu BEOL
Strained Si
SiGe
SiGe
Metal
High-k
Metal Gates
High k
FinFETs
Nanosheets
2D channels
365nm
i-line
248nm
KrF
193nm
ArF
OPC
193nm
immersion
Multi-pattering
EUV
High NA
1990
1995
2000
2005
2010
2015
2020
2025

Integrated Circuit Fabrication

thin film deposition
CVD, PVD, ALD

lithography
(today 13.5 nm Extreme UV litography)

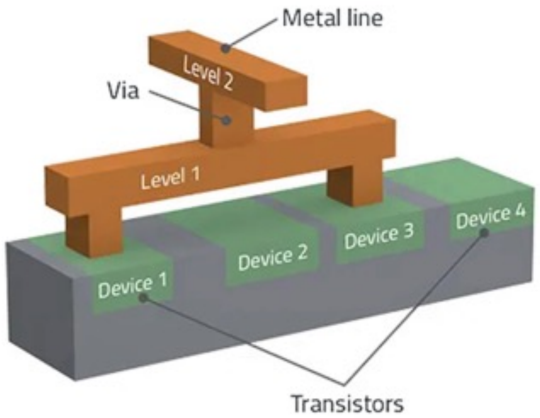
etching



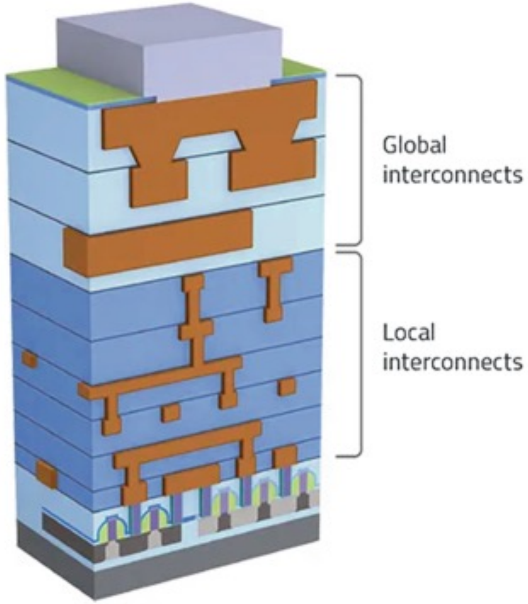
doping

cleaning

requires tens or even hundreds of successive steps



(a)

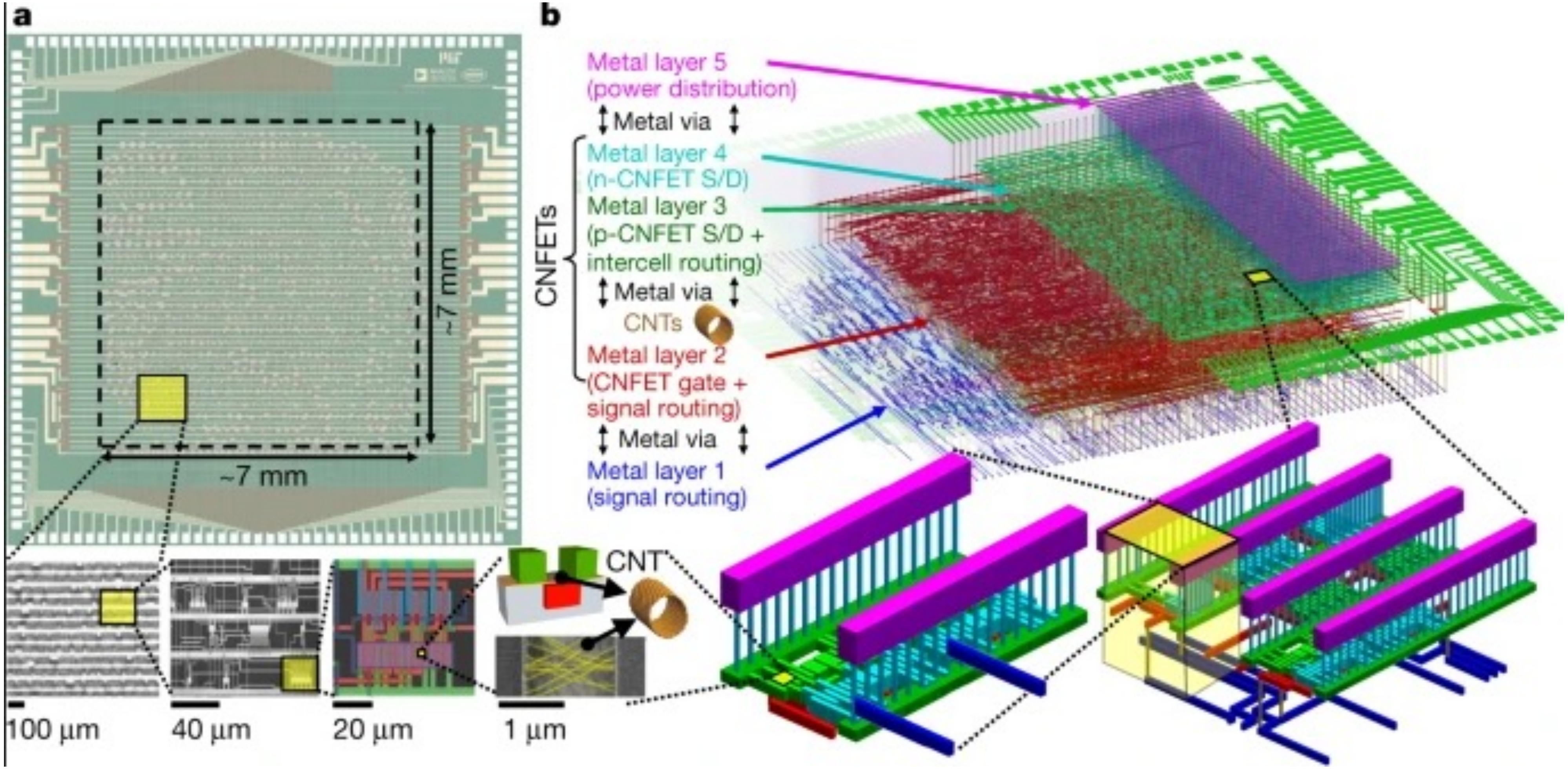


(b)

Carbon-based digital electronics

graphene or carbon nanotubes as channel materials

other 2D materials (MoS_2 , ...)



Modern microprocessor built from complementary carbon nanotube transistors, Nature **572**, 595 (2019)

14’000 transistor computer – Turing complete