產業物理的典範：

半導體科技及其幾個關鍵與時機

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2019 – 11 - 12

什麼是產業物理？

Definition of Industrial Physics :

Industrial Physics is a synergistic combination of people, education, and scientific principles that catalyzes the technological products and services that drive today's economy.

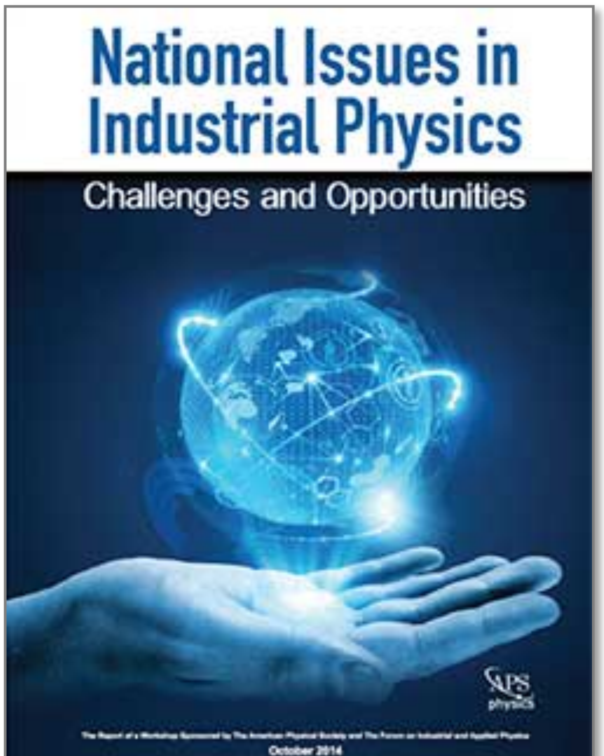
Industrial Physics involves application of physics knowledge and principles to the design and manufacture of products and services, practiced by more than just trained physicists.

Source: American Physical Society. The Impact of Industrial Physics on the U.S. Economy. Jan. 2019

美國物理學界已特別重視到此一問題

兩個重要的報告書：

- National Issues in Industrial Physics (Oct. 2014)
- The Impact of Industrial Physics on the U.S. Economy (Jan. 2019)

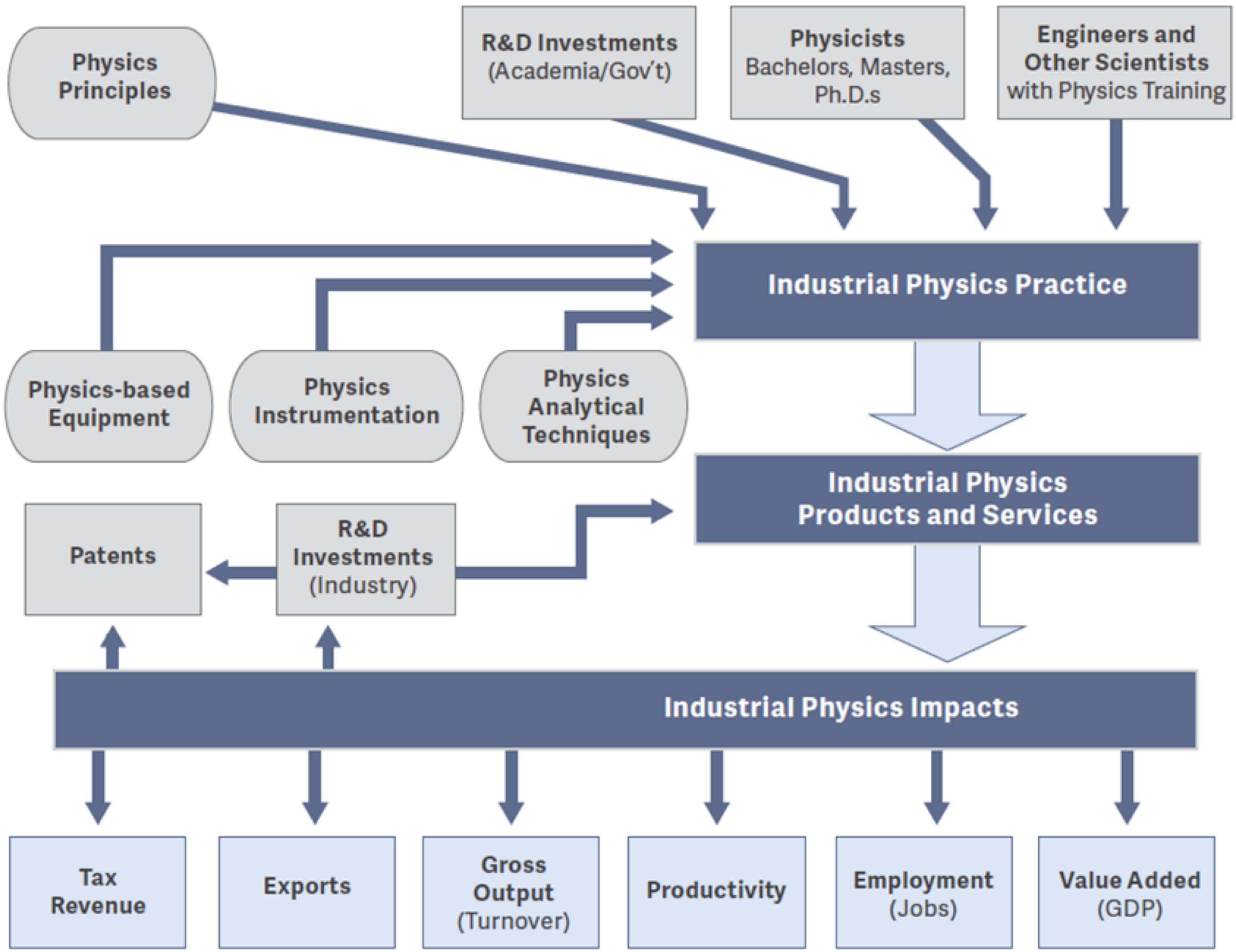


產業物理如何影響美國經濟？

- Direct hire of college-trained physicists of all degrees
- Physics as an essential element in the training of people who work in industry
- Use physical principles in the technology that creates products and services
- The emergence of new physics that drives disruptive changes to the economy

Source: American Physical Society. The Impact of Industrial Physics on the U.S. Economy. Jan. 2019

產業物理如何影響美國經濟？



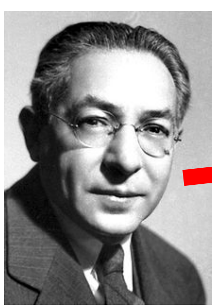
Source: American Physical Society. The Impact of Industrial Physics on the U.S. Economy. Jan. 2019

Thanks GPS…

from fundamental physics work to huge impact on the economy

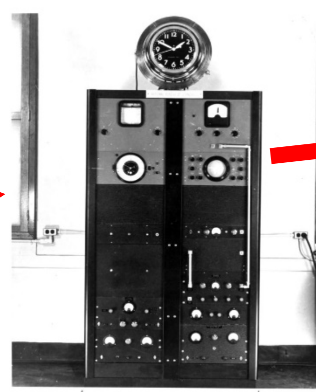
GPS Application Category	Benefits in U.S. 2013 ($B)
Consumer Location-based Service	14.6 - 37.7
Precision agriculture – grain	10.0 - 17.7
Surveying	9.8 - 13.4
Fleet Vehicle Telematics	7.6 - 16.3
Machine guidance in construction	2.2 - 7.7
….	
Total	**37 - 74**

Nuclear Magnetic Resonance (1938)



Isidor Rabi

1st Atomic Clock (1949)



1st commercial GPS device (1989)

Gary Burrell & MingKao

15 to 20 times impact on the U.S. economy

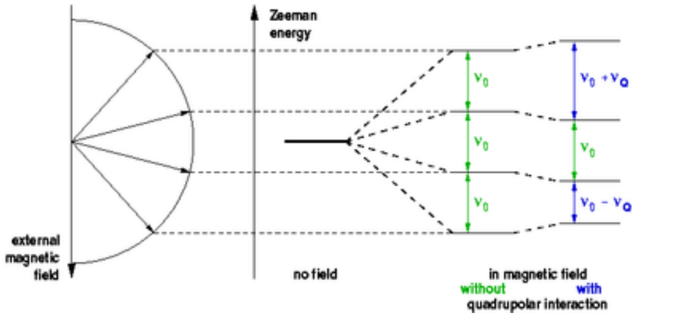
產業物理對美國經濟的影響

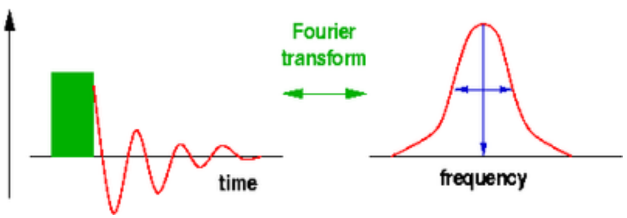
Industries are the direct result of the physics discoveries being transformed into products and services. The impact is even larger in the future.

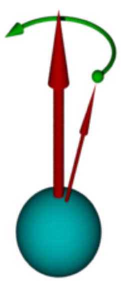
- Directly produced **12.6%** (2016) of the GDP, or **$2.3 trillion**. Including indirect and induced contributions, contributed **30%**, or **$5.5 trillion**
- Exports **20%** (or **$1.1 trillion**) of total physics-based GDP (2016)
- GDP in physics-based sectors grew **22 times** compared to overall growth of 4 times (1966-2016)
- Directly employment **6%** (2016) of total employment, or **11,500,000 people**. Adding in indirect and induced employment, contribute **23.6%** of the U.S. workforce
- **70,000** degreed physicists joined industry (2003-2016)
- **340,000** physics patents granted to companies (2010-2016)
- **$150 billion** internal R&D investments (2015) made by physics-based companies

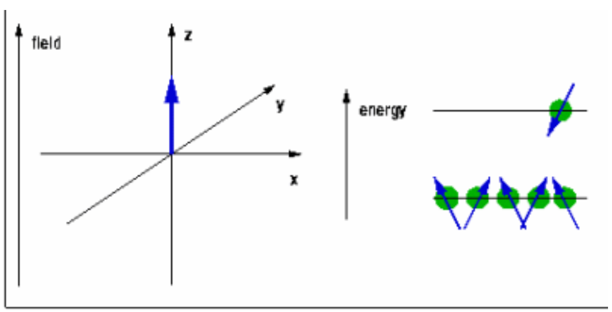
Source: American Physical Society. The Impact of Industrial Physics on the U.S. Economy. Jan. 2019

核磁共振－腦部斷層掃描

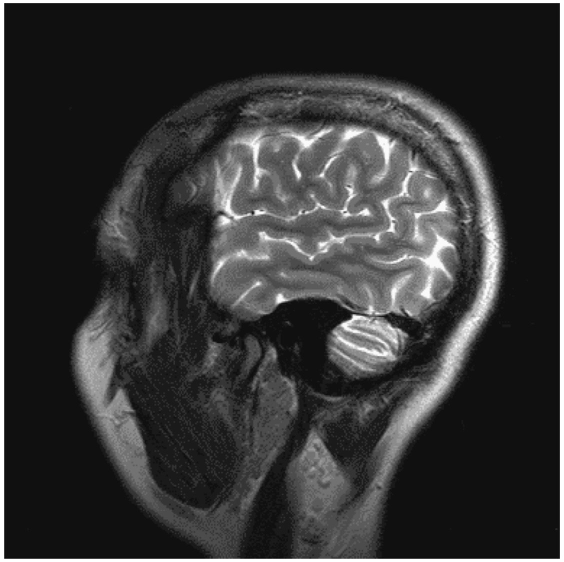








外在磁場改變氫原子的旋轉方向。氫原子核會吸收與釋放能量。能量激發後送出電磁波信號，經由線圈與電腦分析訊號組合成磁振造影影像

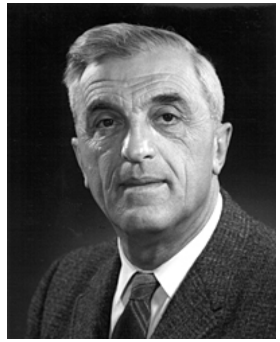


格物

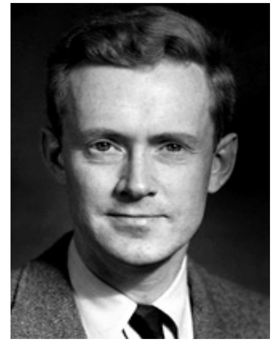
1944 Nobel Prize in Physics

Isidor Rabi

"for his resonance method for recording the magnetic properties of atomic nuclei"



Felix Bloch



Edward Mills Purcell

致知

1952 Nobel Prize in Physics

"for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith"

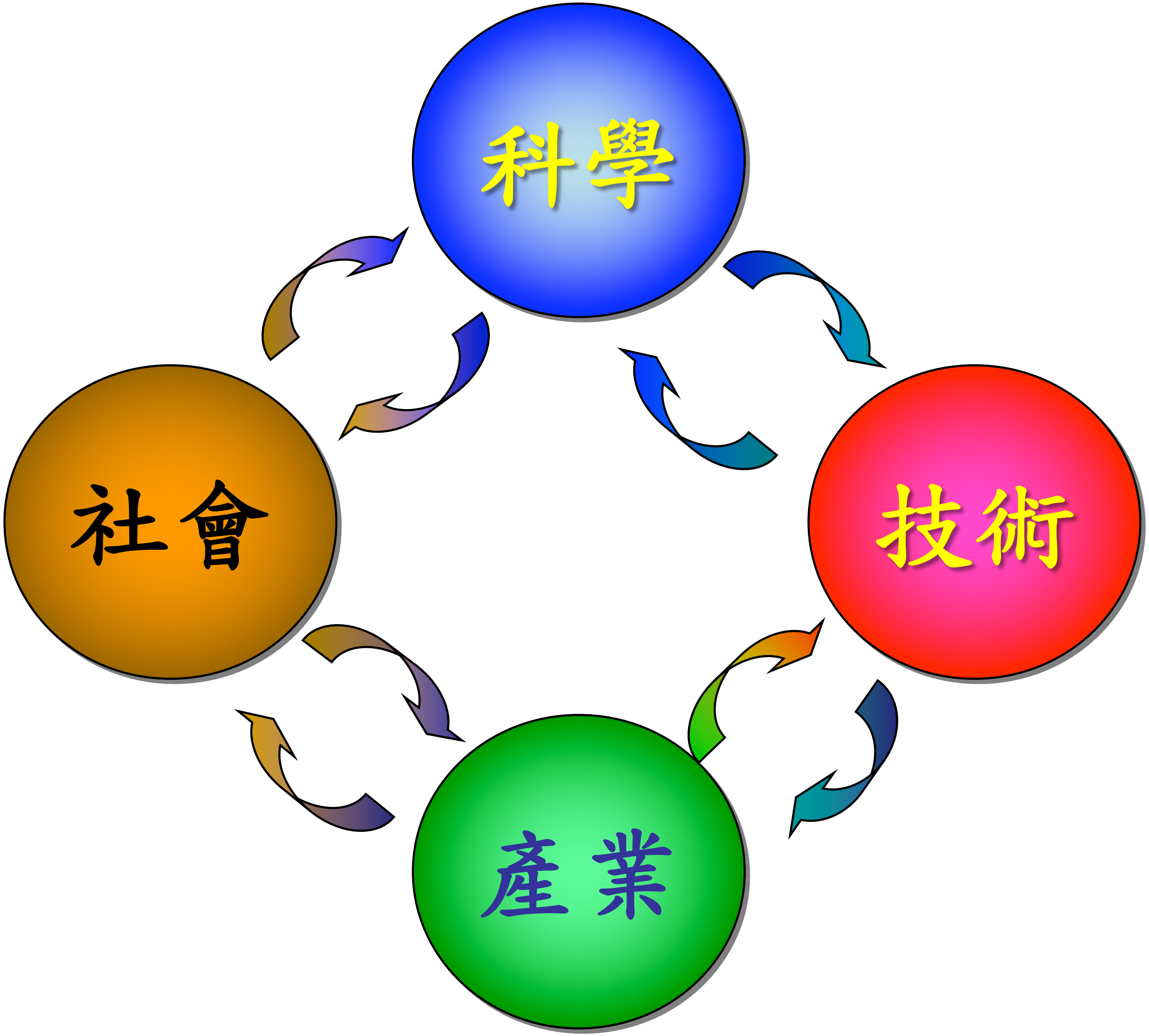
Paul C. Lauterbur

Peter Mansfield

經世濟人

2003 Nobel Prize in Medicine

"for their discoveries concerning magnetic resonance imaging"

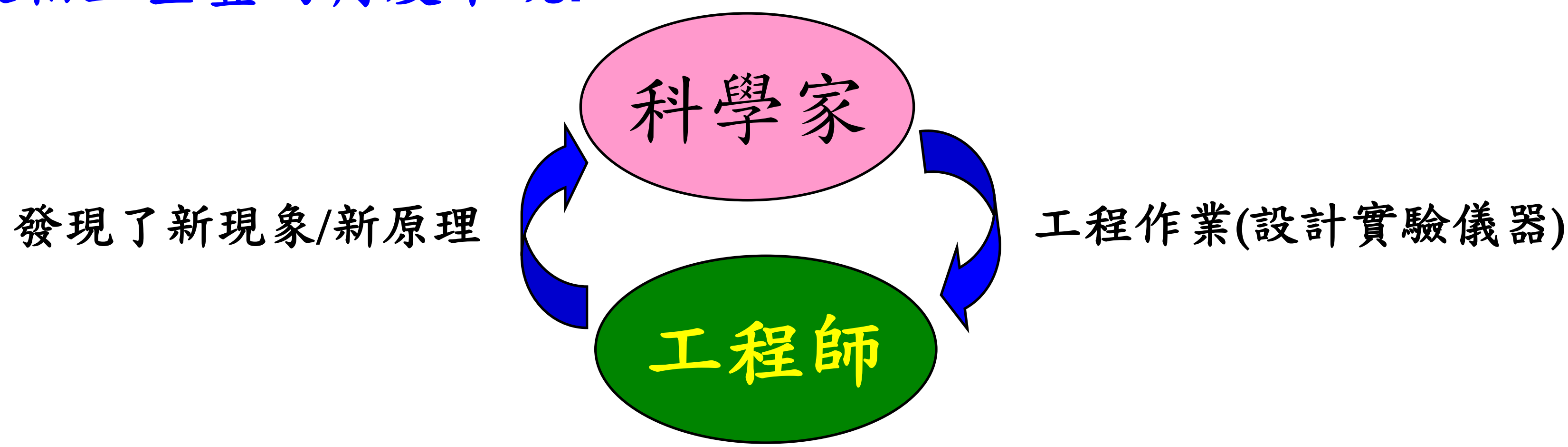

科學
技術
產業
社會

Scientist vs Engineer (科學家對工程師)

"Scientists study the world as it is; engineers create the world that has never been." <u>*Theodore von Karman*</u>

- 科學家問『為什麼』, Why？ 重視 Discovery
- 工程師問『怎麼作』, How？ 在乎 Invention

從相互重疊的角度來說:



Scientist vs Engineer (科學家對工程師)

- 從目的之先後順序而言：科學家為了學習而製造，工程師為了製造而學習
- 工程師和科學家都要作艱難的研究而皓首窮經，但也有不同之處：

	領域特徵	研究結論
科學家	對該領域基本學理尚未有了解	簡潔的公式或定理
工程師	基本理論成熟，但是難以精確解決	尋求出近似快捷方案

工程還涉及：經濟，安全，環保，倫理，專利。

Engineers make idea to be reality !!

純物理轉化為工程課題

在純物理學問中，常以 1st Principle 為基礎作出發點，作抽象的歸納與典雅的推理，以導出相當全備但十分難解的方程式。

如何能作“嚴謹的轉化”，而能在各適用範疇內做成易懂、簡約、易解，且又能在可掌握誤差下的工程命題與解式 (雖然可能要作更細節、更繁瑣的計算與解題)。

這就是「科學」經由「應用」邁向「工程」的典範起步。

產業物理的典範：

半導體科技及產業

An Industrial View for Quantum Computer

-- Disruptive and Revolutionary Technology

Outline

– Brief Review and Prospect of Silicon Semiconductor and ICT Industry

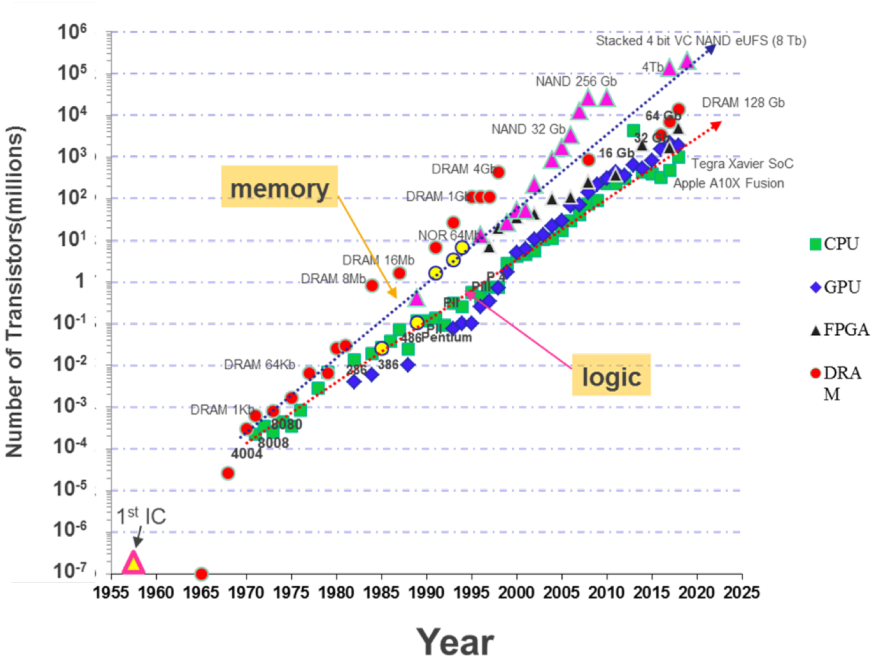
– A Totally Disruptive and Revolutionary Challenge is Appearing on the Horizon

– From a Viable Technology to Become an Industry

Brief Review and Prospect of Silicon Semiconductor and ICT Industry

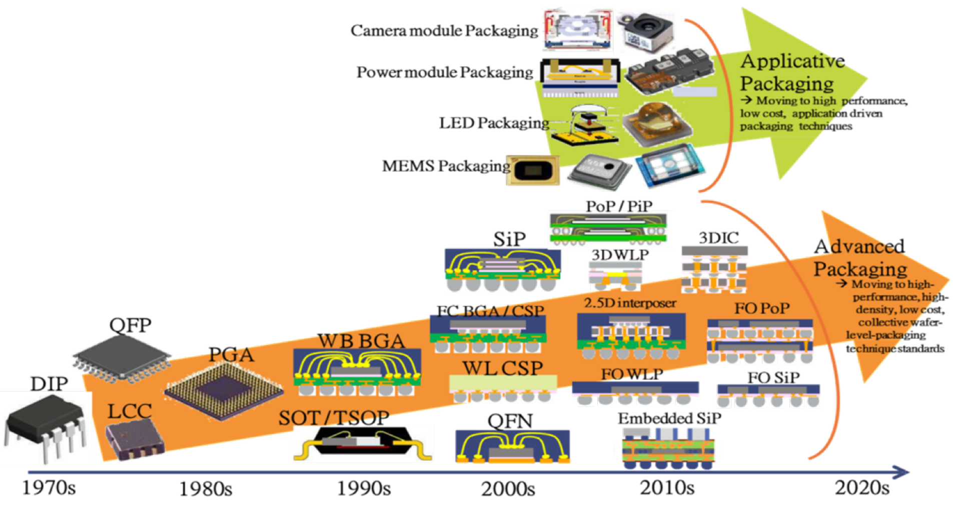
Semiconductor Industry Status and Technology Outlook

Moore's Law



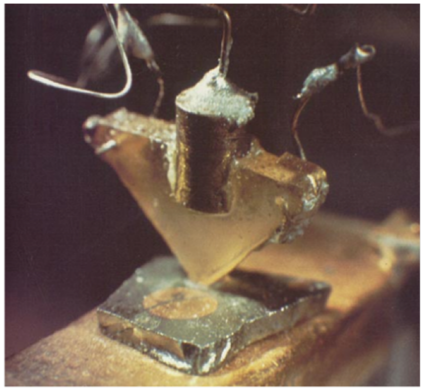
Data source: https://en.wikipedia.org/wiki/Transistor_count

Package Technology

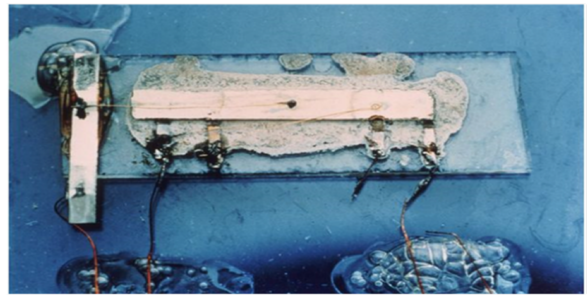


Yole Développement (2018)

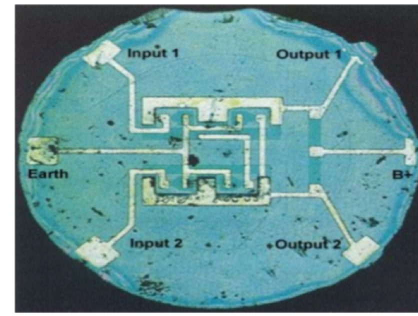
Big Step: Transistor → IC



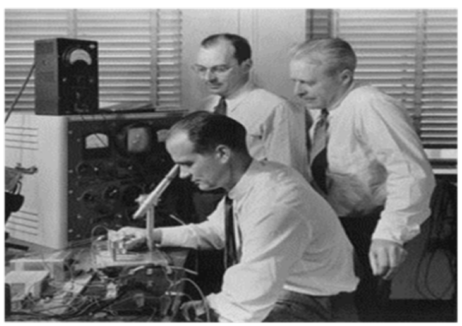
The 1st Transistor -1947



The 1st IC -1958



The 1st planar IC - 1961



William Shockley, John Bardeen, Walter Brattain

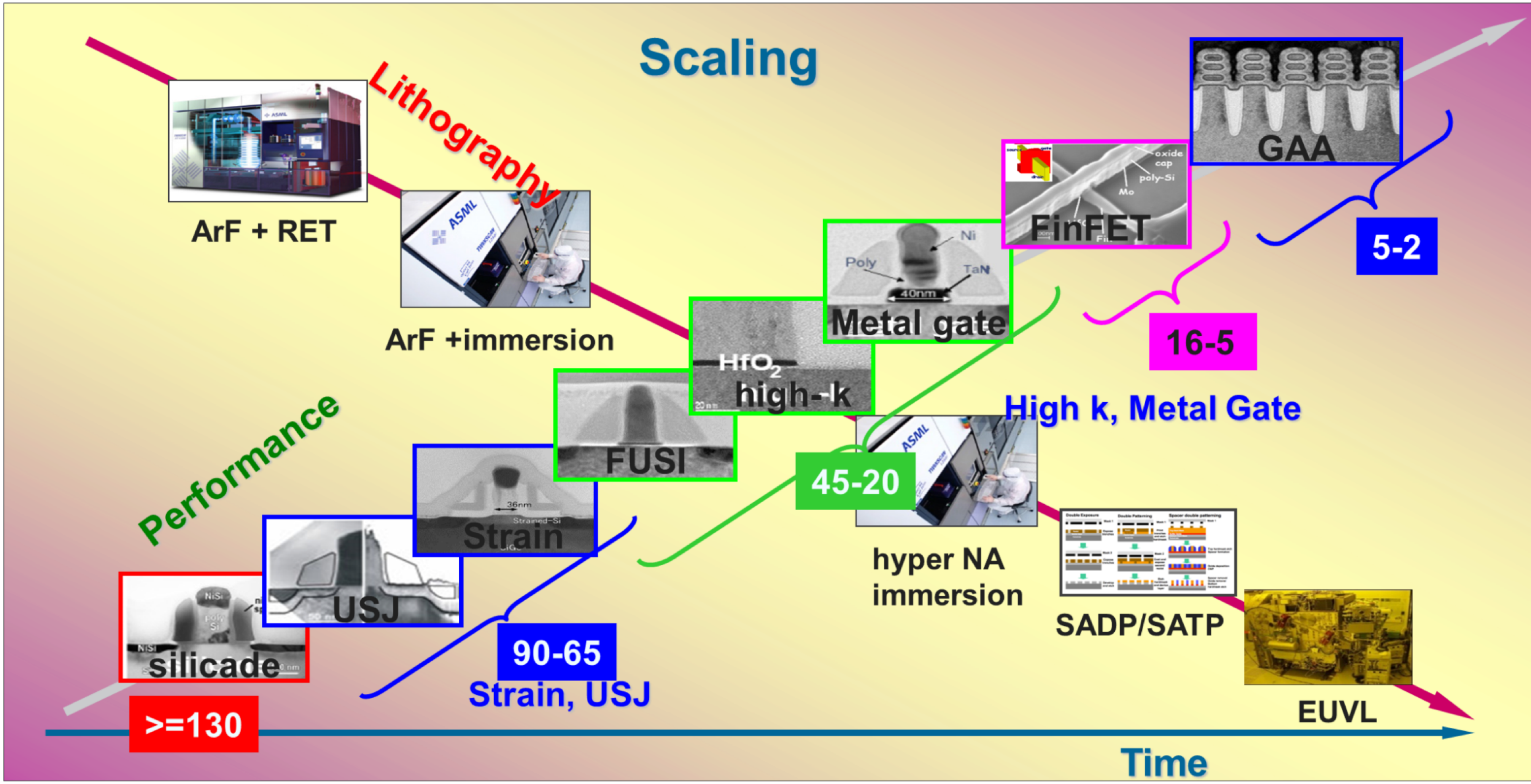
Nobel Prize Winner, 1956

Jack Kilby

Nobel Prize Winner, 2000

Robert Noyce

Transistor Scaling

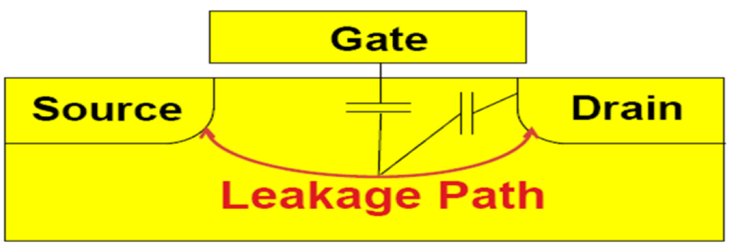


Source: Roger De Keersmaecker, IMEC Updated by Macronix

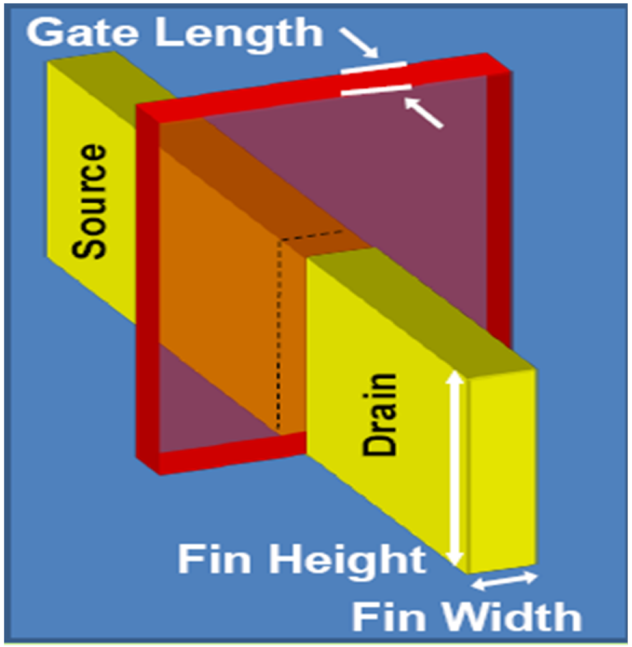
Logic: FinFET (Better Gate Control)

2D -------> 3D

Old scenario

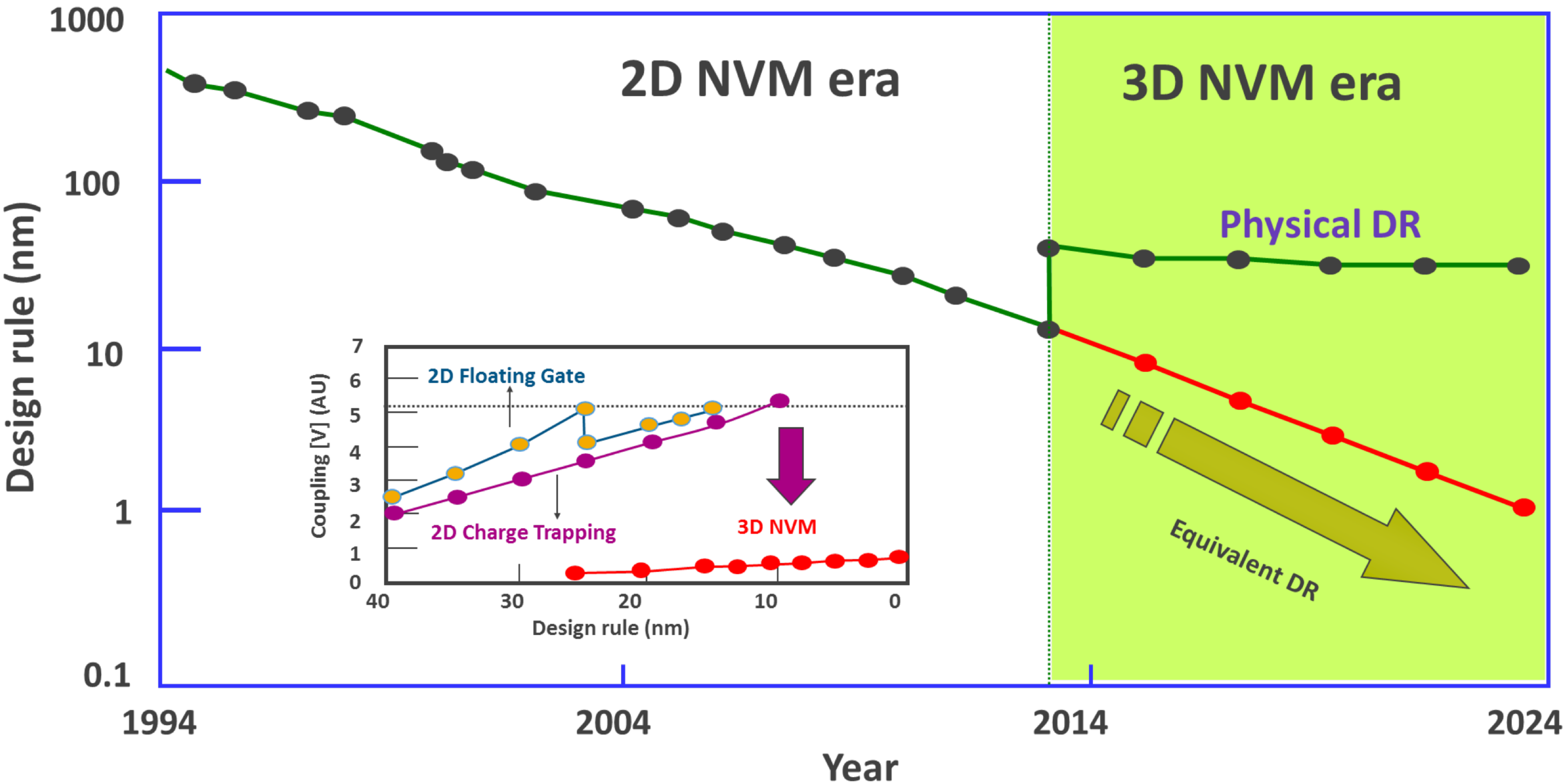


Gate cannot control the leakage current paths that are far from the gate.



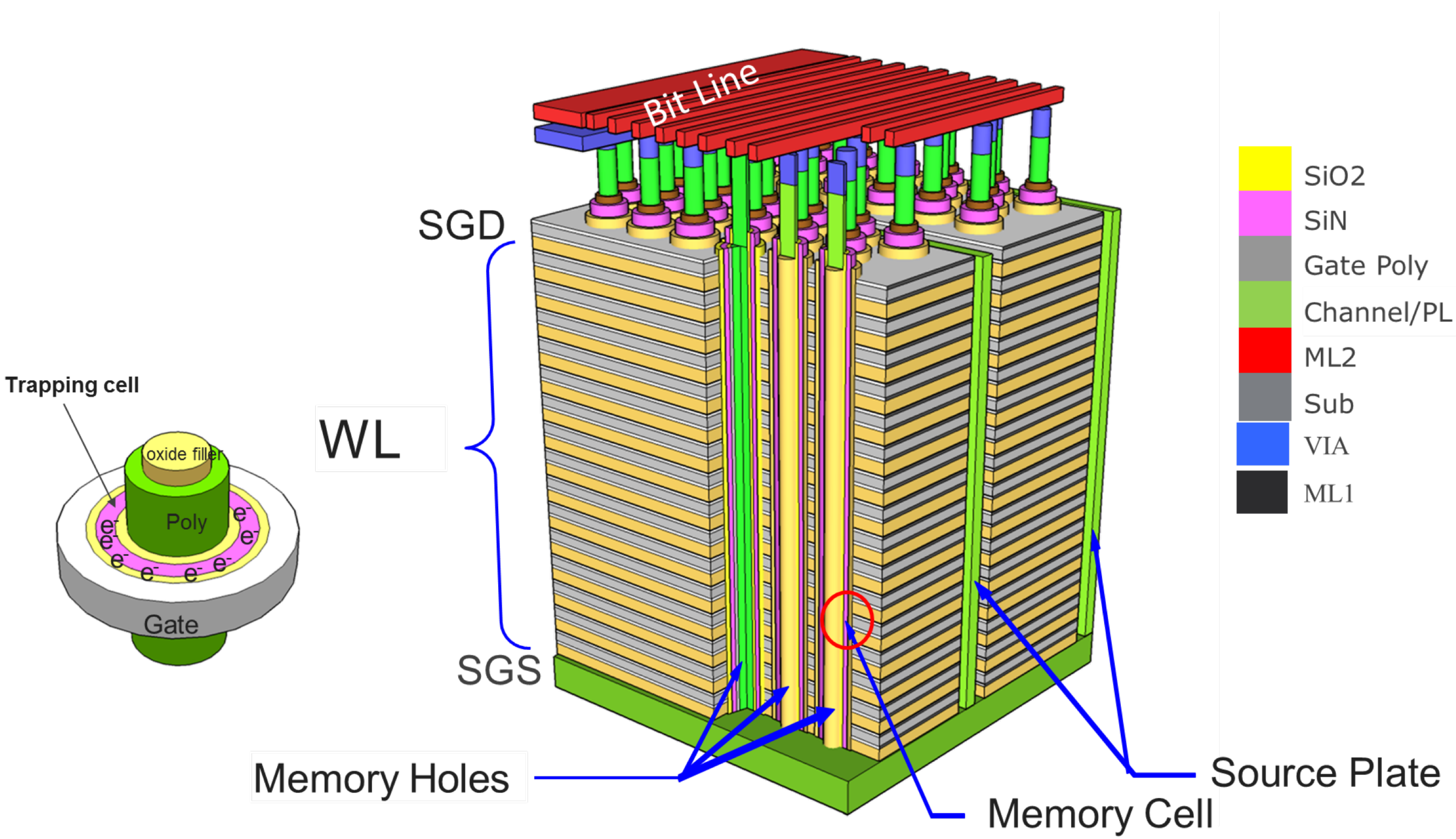
Trigate: triple side control

Memory: Trend of NAND Flash Development

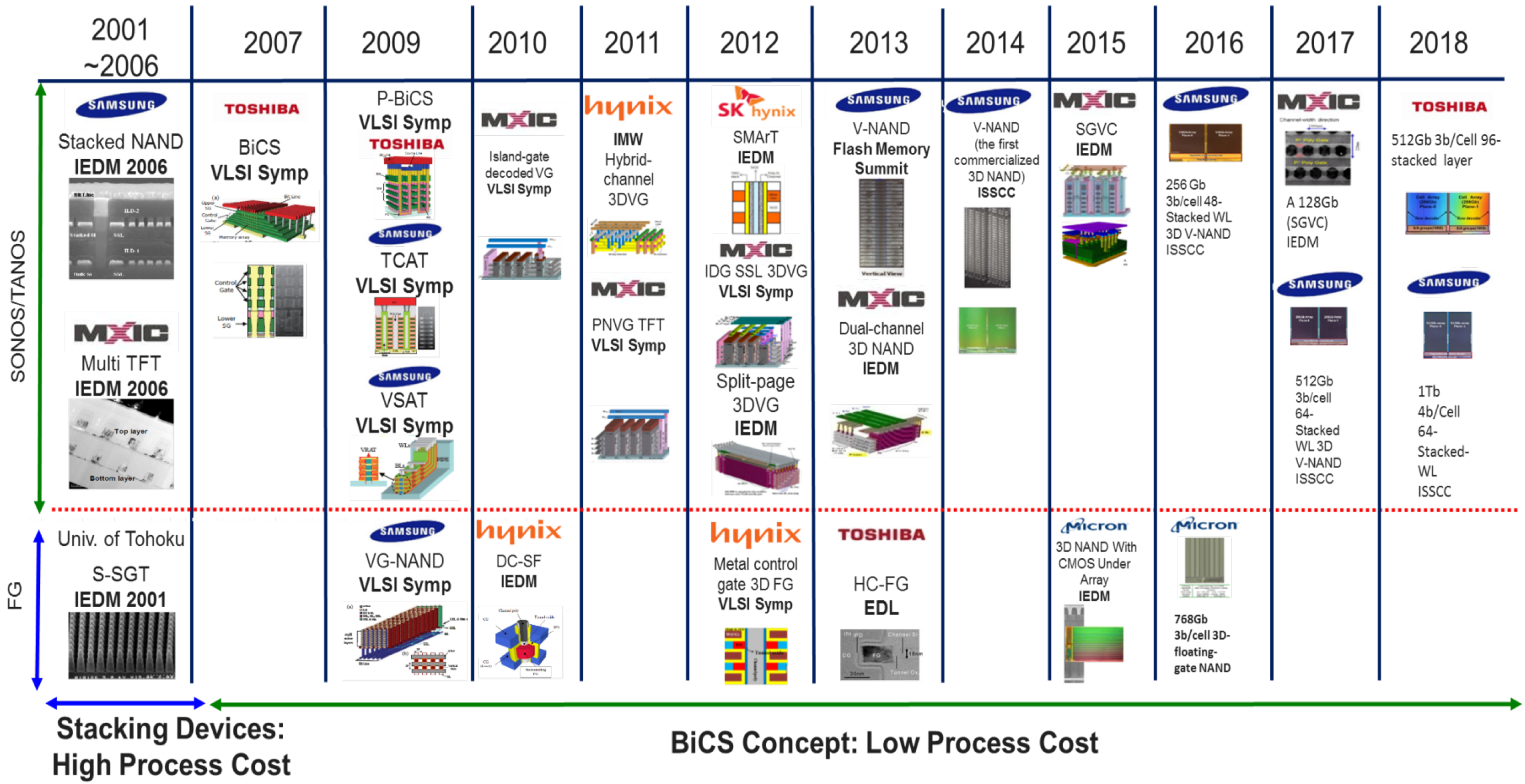


2011 VLSI , J. Choi and K. S. Seol

3D VC NAND Architecture



3D NAND Flash Structure/Density Landscape



How to keep Scaling Effects without X-Y Scaling

Go for Z direction!

Keep on Doubling Storage Density

Keep on Reduction in Cost/bit

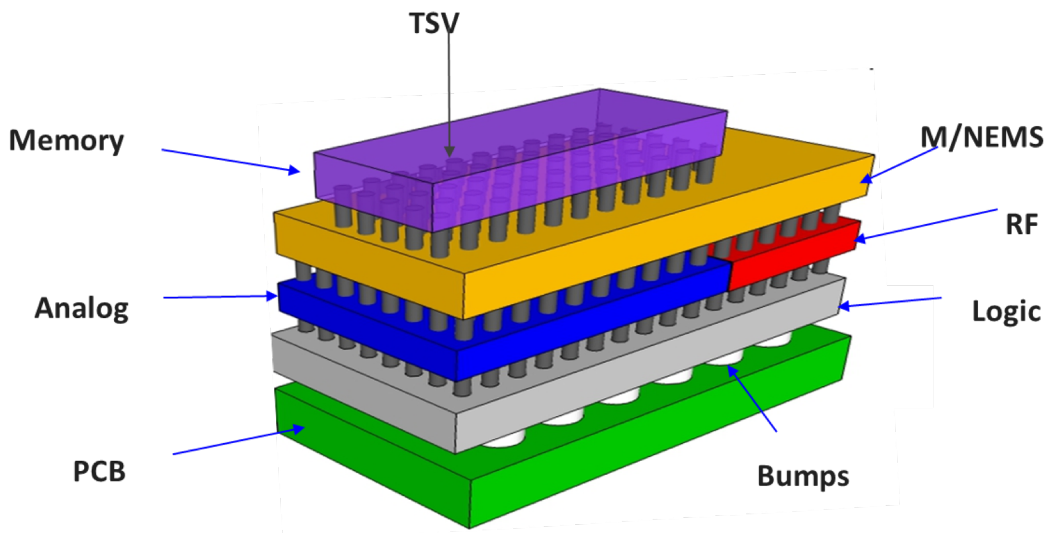
Keep Moore's Law On per Generation every Two Years

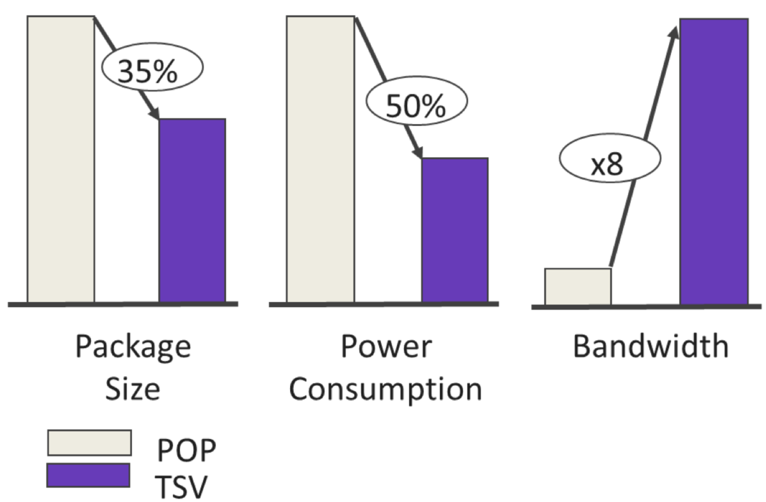
3D Memory

- **Assembly Stacking**
  - 2.5D, 3D ……
- **Monolithic Structure**
  - 96L/192L ……3D NAND
- **Homogeneous**
  - HBM
- **Heterogeneous**

  ……….

Heterogeneous 3D IC





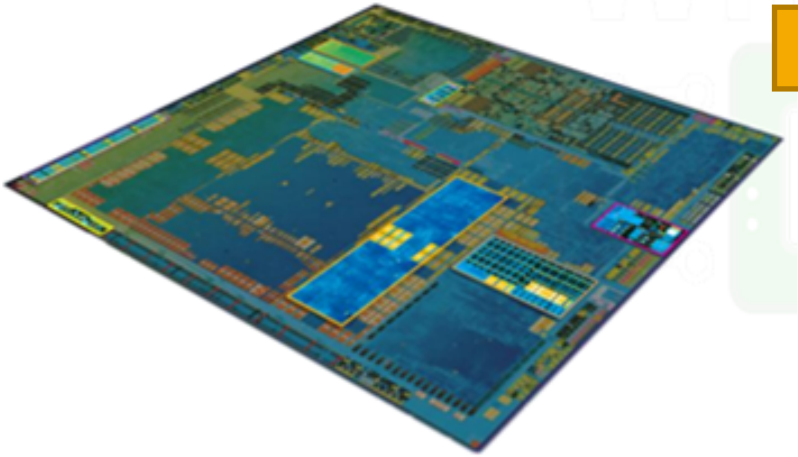
From Samsung

- **Reduced power consumption & Improved performance/bandwidth**
- **Small form factor**
- **New functionality**

Chips Approach

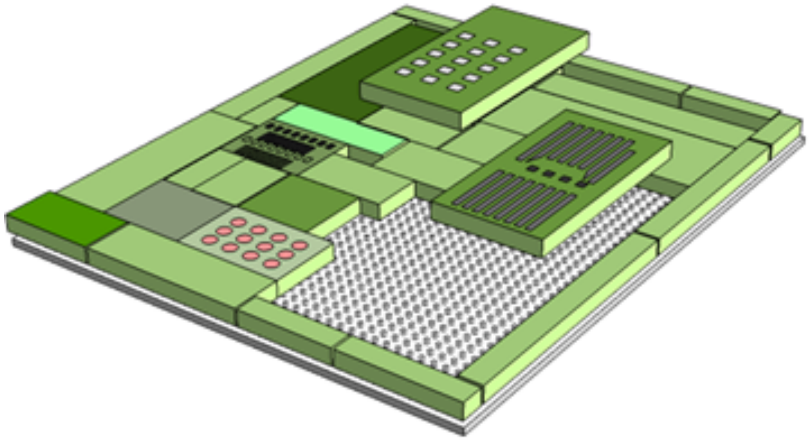
Today – Monolithic

Chip
(Chip of Single Process)



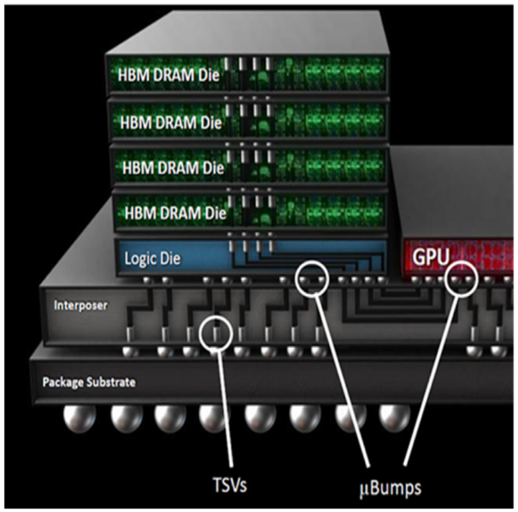
Tomorrow – Modular

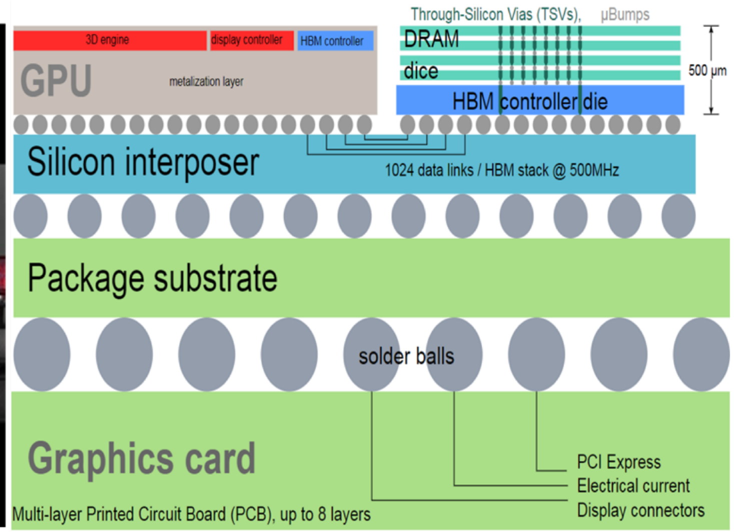
Chiplet
(Chips of Various Processes)

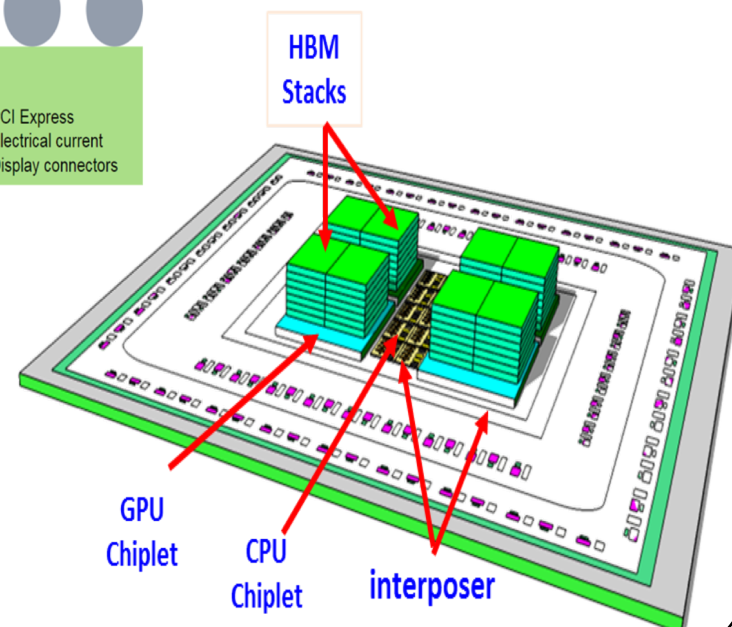


Source: David Schor, https://fuse.wikichip.org/news/1520/intel-opens-aib-for-darpas-chips-program-as-a-royalty-free-interconnect-standard-for-chiplet-architectures/

High Bandwidth Memory (HBM) on Chiplet System



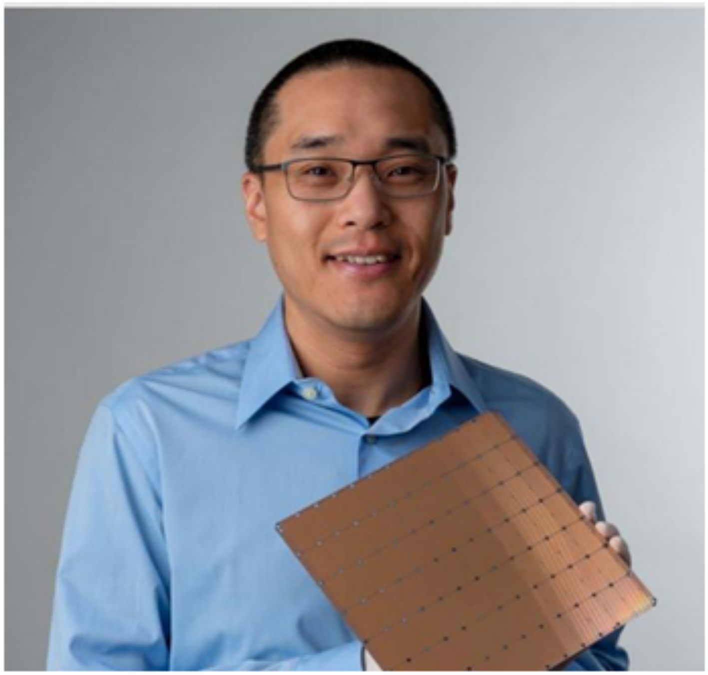


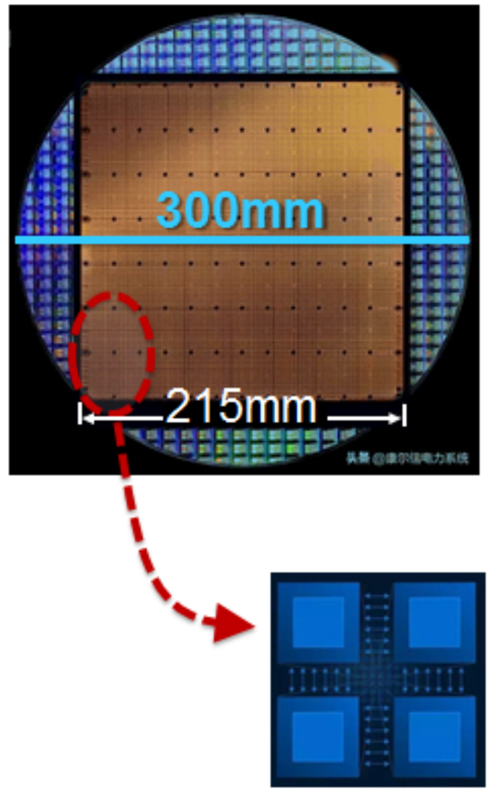


https://en.wikipedia.org/wiki/High_Bandwidth_Memory

Largest Chip Ever Built

- Cerebras Systems' new deep-learning chip



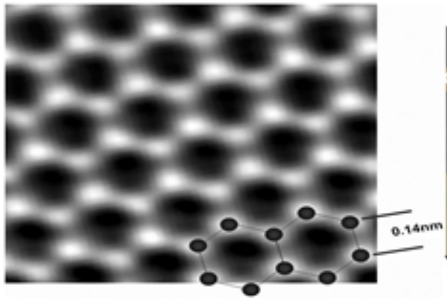


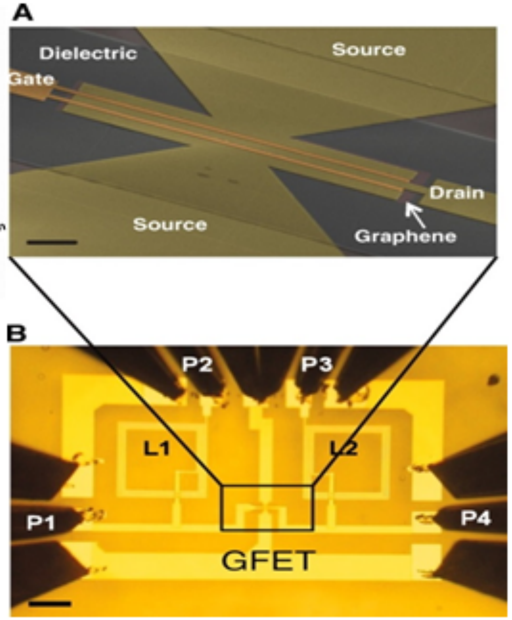
- 46,225 mm^2 silicon
- 1.2 trillion transistors
- 400,000 AI optimized cores
- 18 Gigabytes of On-chip Memory
- 9 PByte/s memory bandwidth
- 100 Pbit/s fabric bandwidth
- 84 processing tiles
- TSMC 16nm process

https://www.pcworld.com/article/3432977/cerebras-systems-new-deep-learning-chip-is-as-big-as-your-keyboard-and-the-largest-ever.html

Beyond Silicon

Graphene Materials





- High Young's modulus . 200 times stronger than Steel
- High carrier mobility (15,000 $cm^2V^{-1}s^{-1}$), 133 times faster than Si [1]
- High current density (6 order times larger than copper) [2]
- High thermal conductivity (~5000$Wm^{-1}K^{-1}$) , 10 times higher than that of Silver [2]

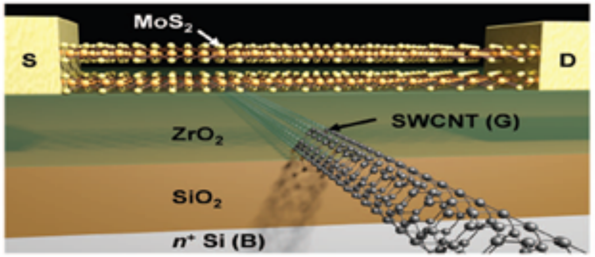
Y Lin et al. Science 2011;332:1294-1297

[1] Source: http://en.wikipedia.org/wiki/Graphene

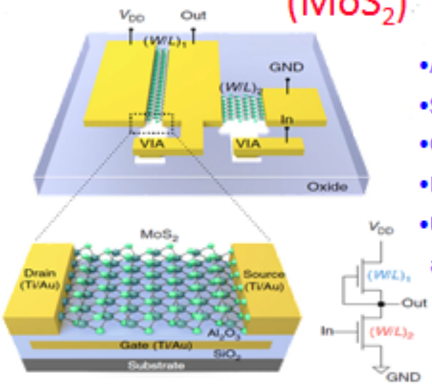
[2] A.K. Geim, "Graphene: Status and Prospects", Science, Vol. 324, pp. 1530-1534, 2009

Two-dimensional transistors

TMDC (Transition Metal Dichalcogenides)



(MoS_2)

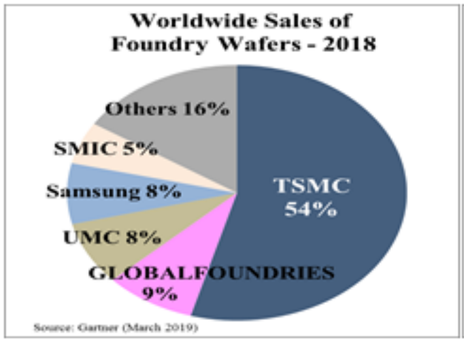


- Atomically thin channel
- Superior gate controllability
- Greatly suppressed OFF-state current
- Free of surface dangling bonds
- Ultimate transistor scaling to single atomic body thickness

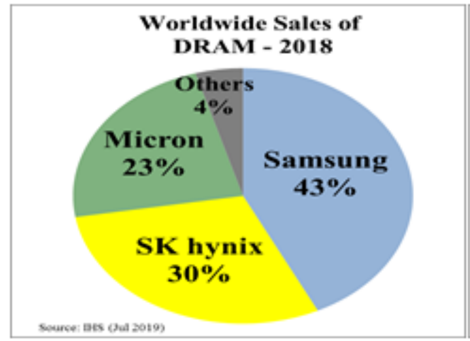
Stefan Wachter et al, Nature Communication.8, 14948(2017)

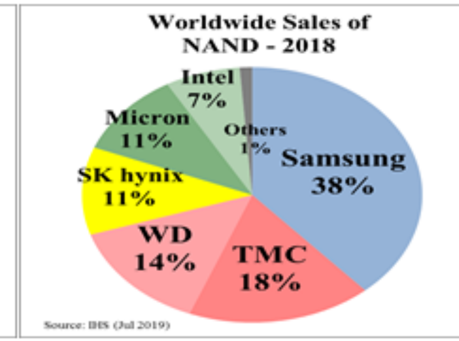
Present Semiconductor Industry

Advance Logic



Advance memory





Only TSMC, Intel, Samsung can go beyond 14nm....

Only Samsung, SK Hynix, Micron, Kioxia (TMC + WD)

Consolidation With possible emergent players → **China?**

Q: Why Semiconductor/IC Industry Progress so Rapidly in the Past 60 Years?

Ans: Scaling (Monolithic 2D planar Scaling Law)

→ Exponential Scaling Power

“ 2^n ” → **Moore’s Law**

(70% shrinkage for every 2 Years period = x2)

In fact, all those further scalings such as 2D → 2.5D → 3D … etc. and new material and new device structure evaluation are struggling extension of Moore's Law, plus "More than Moore" development.

→ Make semiconductor/IC industry well and survival for at least another 15-25 years.

A Totally Disruptive and Revolutionary Challenge is Appearing on the Horizon

Quantum Computing →

The 2nd Major Impact for Solid-State Electronic Devices by Quantum Physics

Qubit ....

→ " 2^n " again

- Quantum Superposition State
- Quantum Entanglement

Quantum entanglement and quantum interference are two major quantum physics mechanisms that distinguish a quantum computer from a classical electronic computer.

Quantum Supremacy

- Representing all the states of a 30-qubit quantum computer ($2^{30(\text{qubit})}$),

  you need a ⇨  Notebook

- Representing all the states of a 40-qubit quantum computer ($2^{40(\text{qubit})}$),

  you need a ⇨  supercomputer Summit: IBM

- Representing all the states of a 80-qubit quantum computer ($2^{80(\text{qubit})}$),

  you need ⇨ all the classical computers on earth 

- Representing all the states of a 160-qubit quantum computer ($2^{160(\text{qubit})}$),

  you need ⇨ more than all the silicon atoms on earth

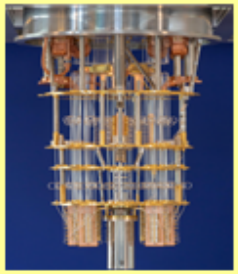
Source: Lecture materials from Dr. Jackson Hu presented at NCTU/NTU (2019)

Quantum Supremacy

5~20 qubit quantum computer can deal the tremendous task that required by top classical supercomputers

Quantum computer

IBM Q: IBM
5~20 qubits



Classical supercomputer

Summit: IBM
> 10^{15} bit

https://codecasters.wordpress.com/2017/10/17/what-is-quantum-computing-and-will-it-replace-the-classical-computers-in-future/

Moore's Law Is Replaced by Neven's Law for Quantum Computing

https://community.hitachivantara.com/community/innovation-center/hus-place/blog/2019/06/25/moore-s-law-is-replaced-by-nevens-law-for-quantum-computing

Quantum Computing Power Relative to Classical Computing Power

n	2^n	$2^{(2^n)}$	
* 1	2	2^2	4
* 2	4	2^4	16
* 3	8	2^8	256
* 4	16	2^{16}	65,536
* 5	32	2^{32}	4,294,967,296
⋮	⋮	⋮	⋮
* 9	512	2^{512}	1.340780792994259709957402499826e+154
* 10	1024	2^{1024}	1.797693134862315907729305190789e+308

enabled by Moore's law/quantum computing

enabled by Google's quantum processor

The Disruptive Revolution of Computing Technology

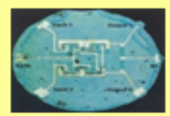
Vacuum tube

ENIAC (U Penn)
(Electronic Numerical Integrator And Calculator)
1946

1st QM manifestation
(Energy Band)

The 1st Transistor -1947

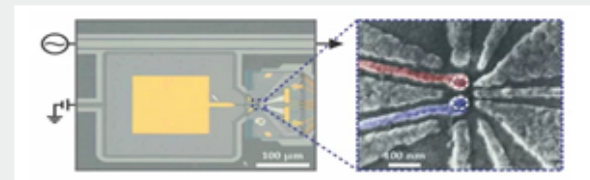
The 1st IC -1958
TI



The 1st planar IC – 1961
Fairchild

Super Computer
Summit (IBM)
2018

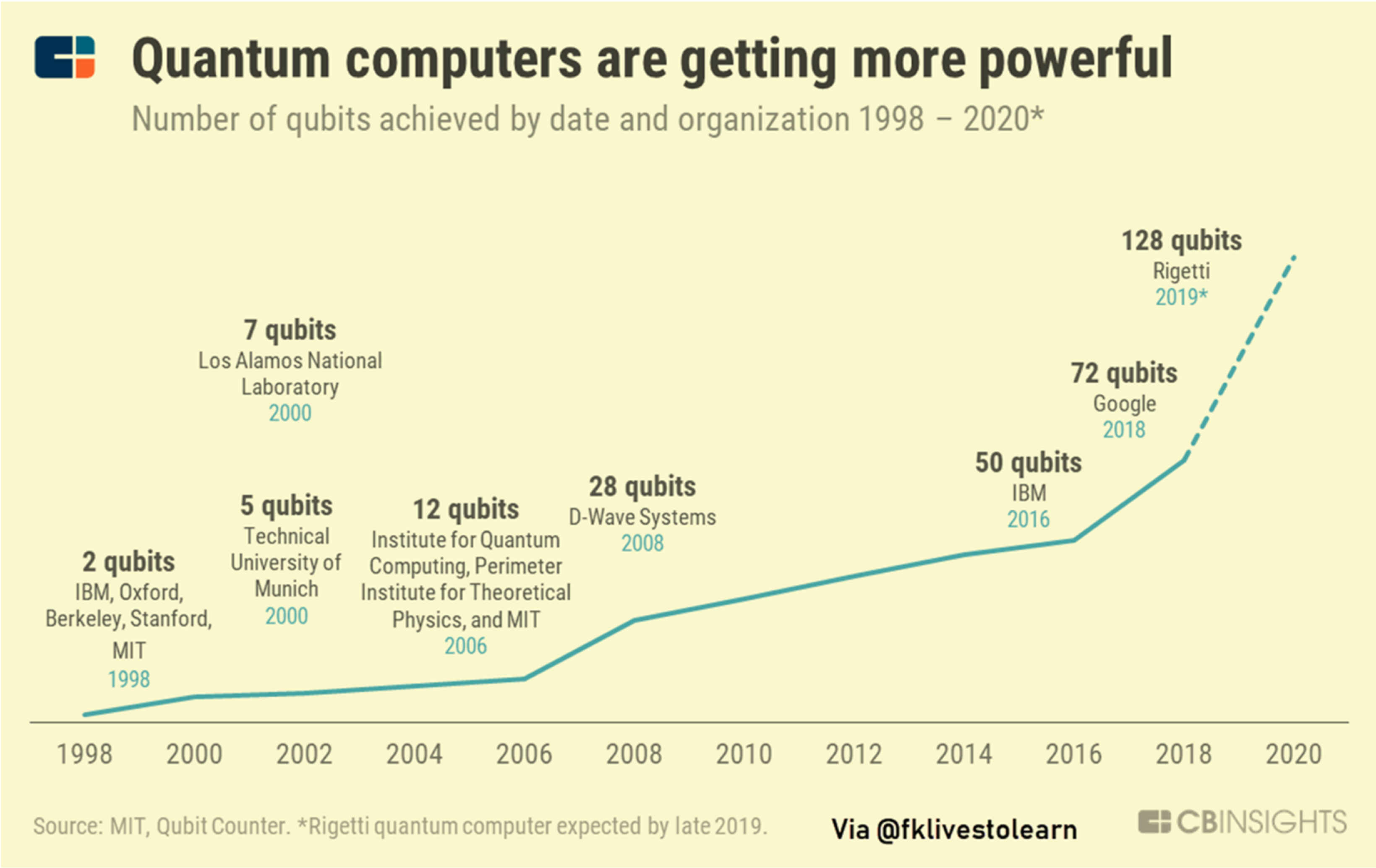
2nd QM manifestation
(Superposition/Entanglement)



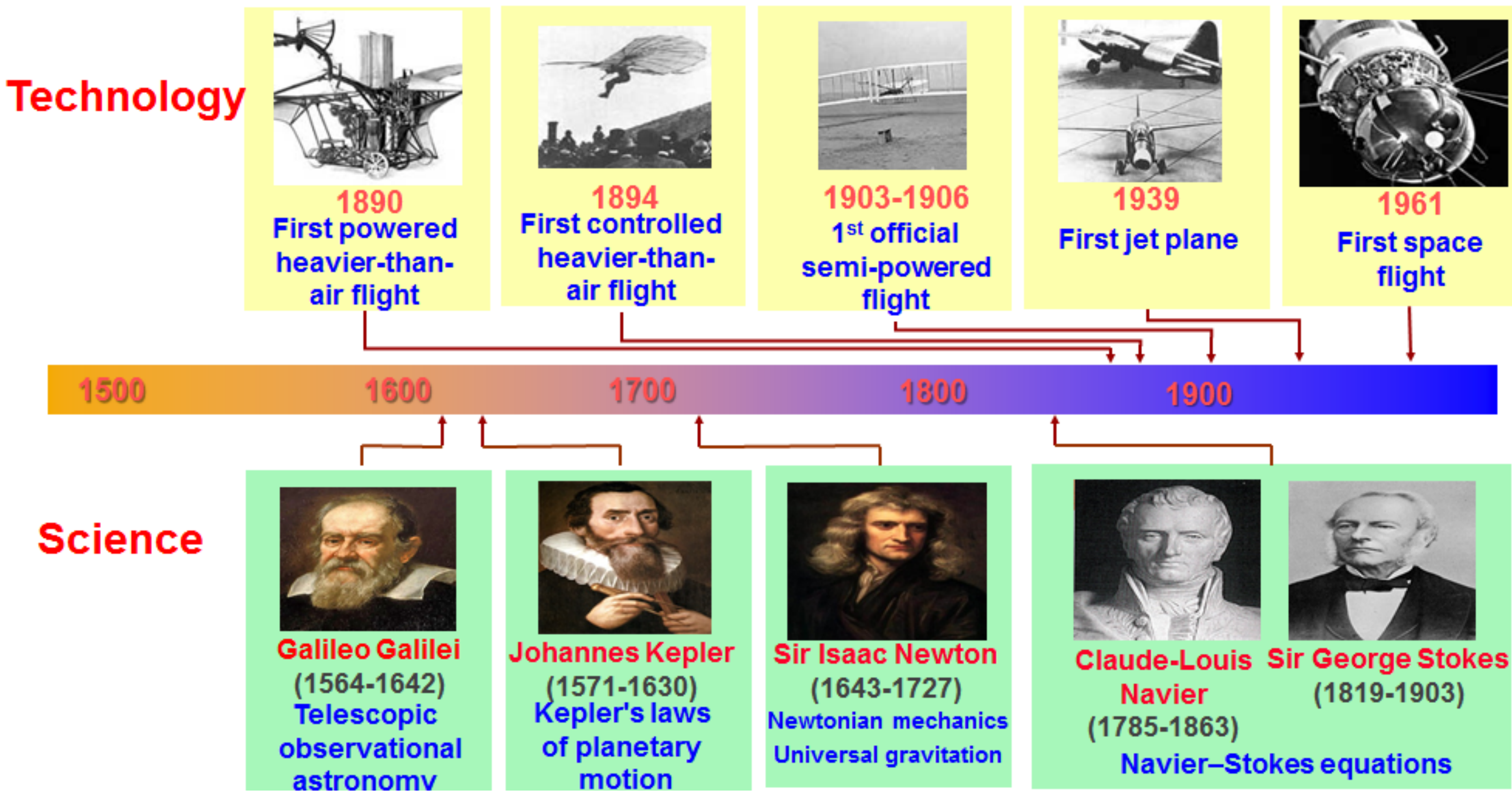
two-qubit quantum processor
(Si quantum dot)
Intel/ Delft University of Technology
https://www.fastcompany.com/90242006/old-school-silicon-could-bring-quantum-computers-to-the-masses

The IBM Q Computation Center at
IBM T J Watson Research Center
2019

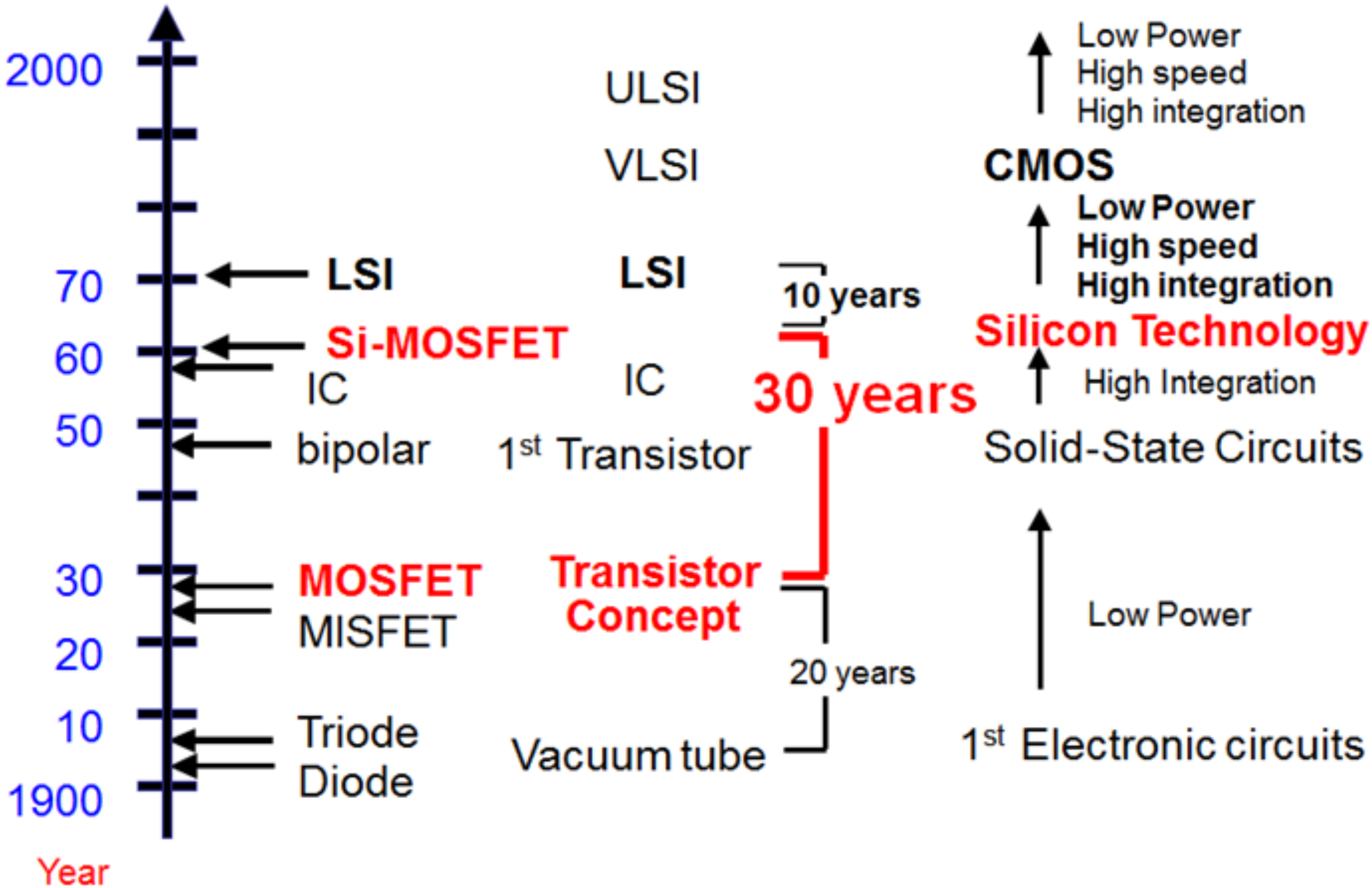
Quantum Moore's Law



From a Viable Technology to Become an Industry


Technology
1890
First powered heavier-than-air flight
1894
First controlled heavier-than-air flight
1903-1906
1st official semi-powered flight
1939
First jet plane
1961
First space flight
1500
1600
1700
1800
1900
Science
Galileo Galilei
(1564-1642)
Telescopic observational astronomy
Johannes Kepler
(1571-1630)
Kepler's laws of planetary motion
Sir Isaac Newton
(1643-1727)
Newtonian mechanics
Universal gravitation
Claude-Louis Navier
(1785-1863)
Sir George Stokes
(1819-1903)
Navier–Stokes equations

History of Electronic Devices

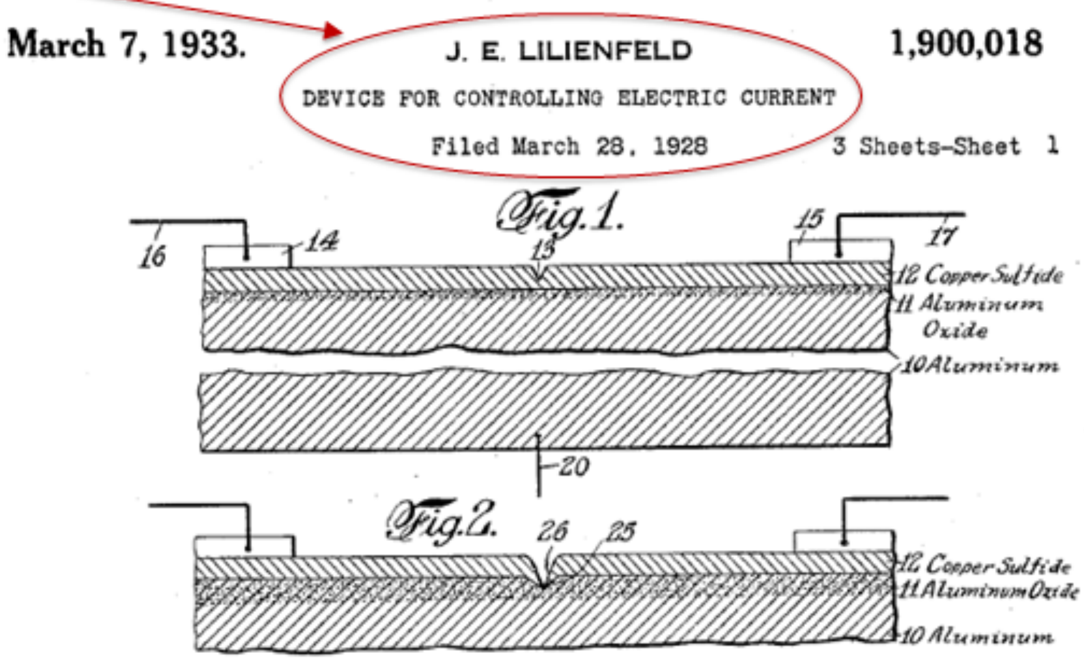


Device for Controlling Electric Current

J. E. LILIENFELD

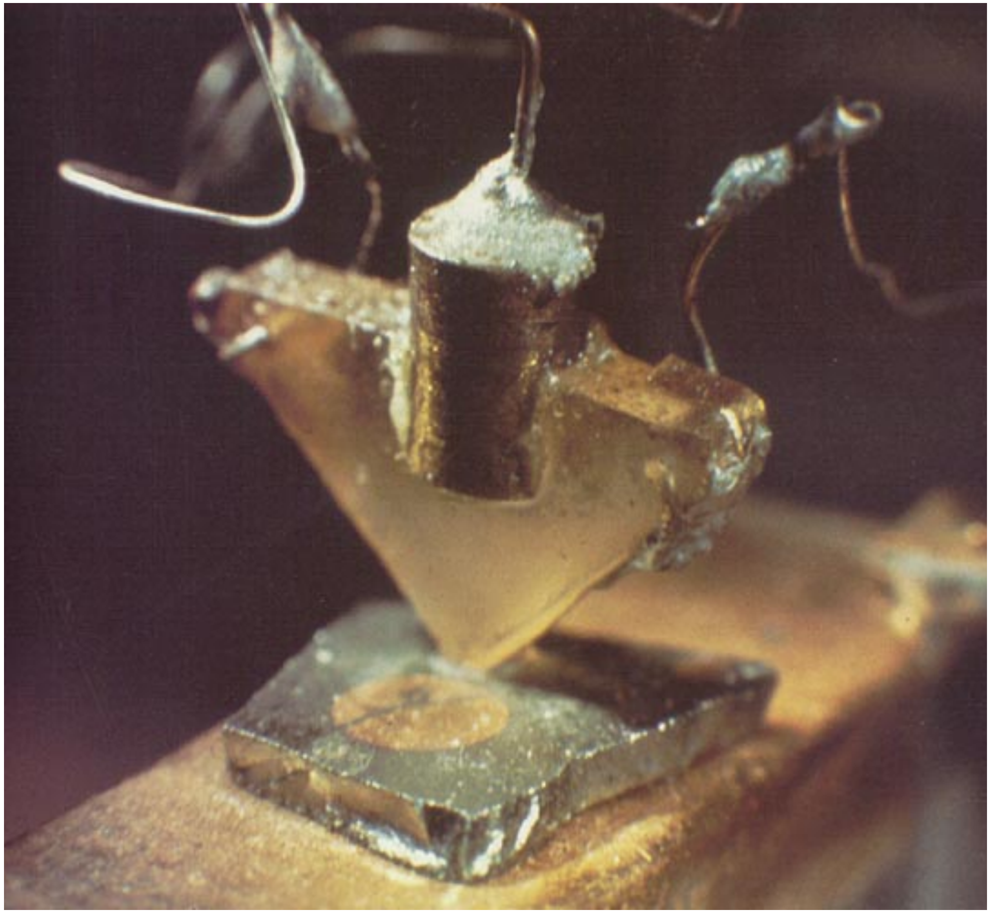
DEVICE FOR CONTROLLING ELECTRIC CURRENT

Filed March 28, 1928



J. E. Lilienfeld (1882-1963)

Bipolar Transistor Action Realized



The 1st Transistor -1947

Conceptualization of the Integrated Circuit

Geoffrey Dummer

(1909 – 2002)

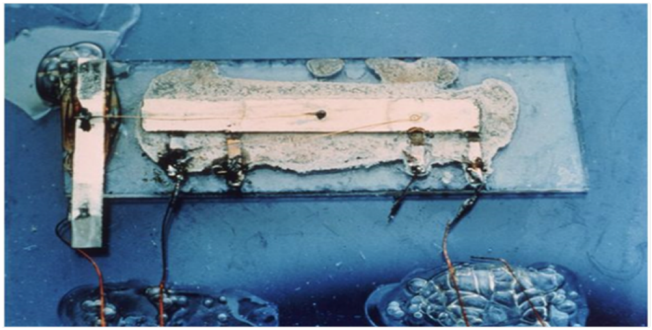
- An English electronics engineer and consultant who passed the first radar trainers and became a pioneer of reliability engineering at the Telecommunications Research Establishment in Malvern in the 1940s.
- Credited as being the first person to conceptualize and build a prototype of the integrated circuit, who has been called "**the prophet of the integrated circuit**".

" With the advent of the transistor and the work on semi-conductors generally, it now seems possible to envisage electronic equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying and amplifying materials, the electronic functions being connected directly by cutting out areas of the various layers ".

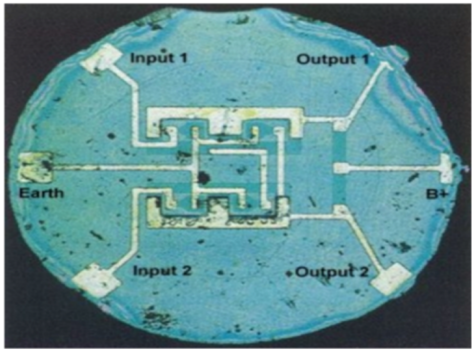
Symposium on Progress in Quality Electronic Components, Washington, D.C. 1952.

https://en.wikipedia.org/wiki/Geoffrey_Dummer

1st Practical Integrated Circuit



The 1st IC -1958

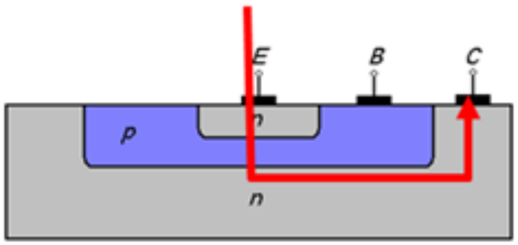


The 1st planar IC - 1961

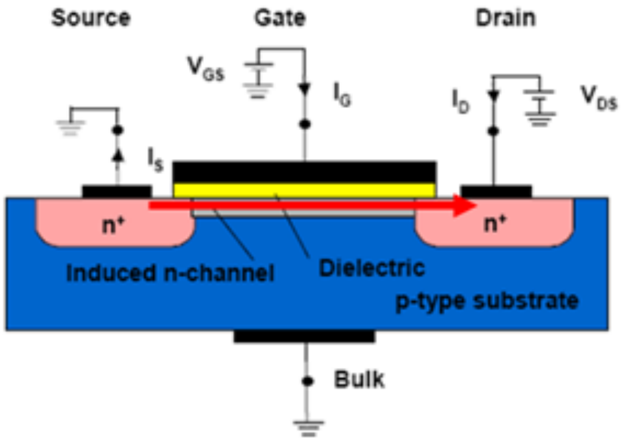
Jack Kilby
Nobel Prize Winner, 2000

Robert Noyce

Technology Choice by Material Controllability and Availability



Bipolar Junction Transistor



Field-Effect Transistor

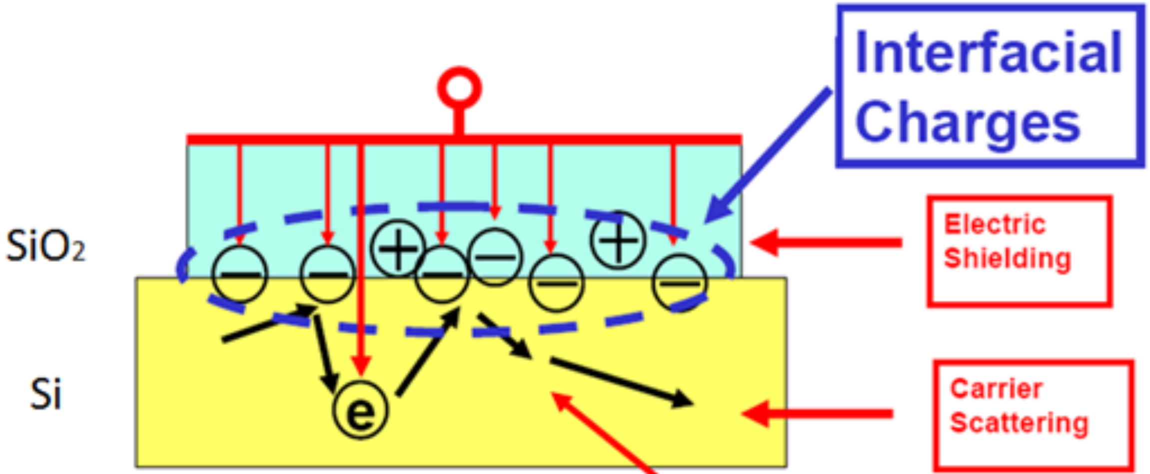
	BJT	FET
Control mode	Current-control	Voltage-control
Action region	bulk	surface
'ON' Resistance	low	high
Operation frequency	high	low
Power consumption	high	low

The 1st functional transistor and early industrial devices were bipolar, not field-effect due to hard to control of surface properties.

Key Material Breakthrough

-- Impurity Control and Interface Defect Improvement

Ions, Oxide traps ,Oxide fixed charges interface charges



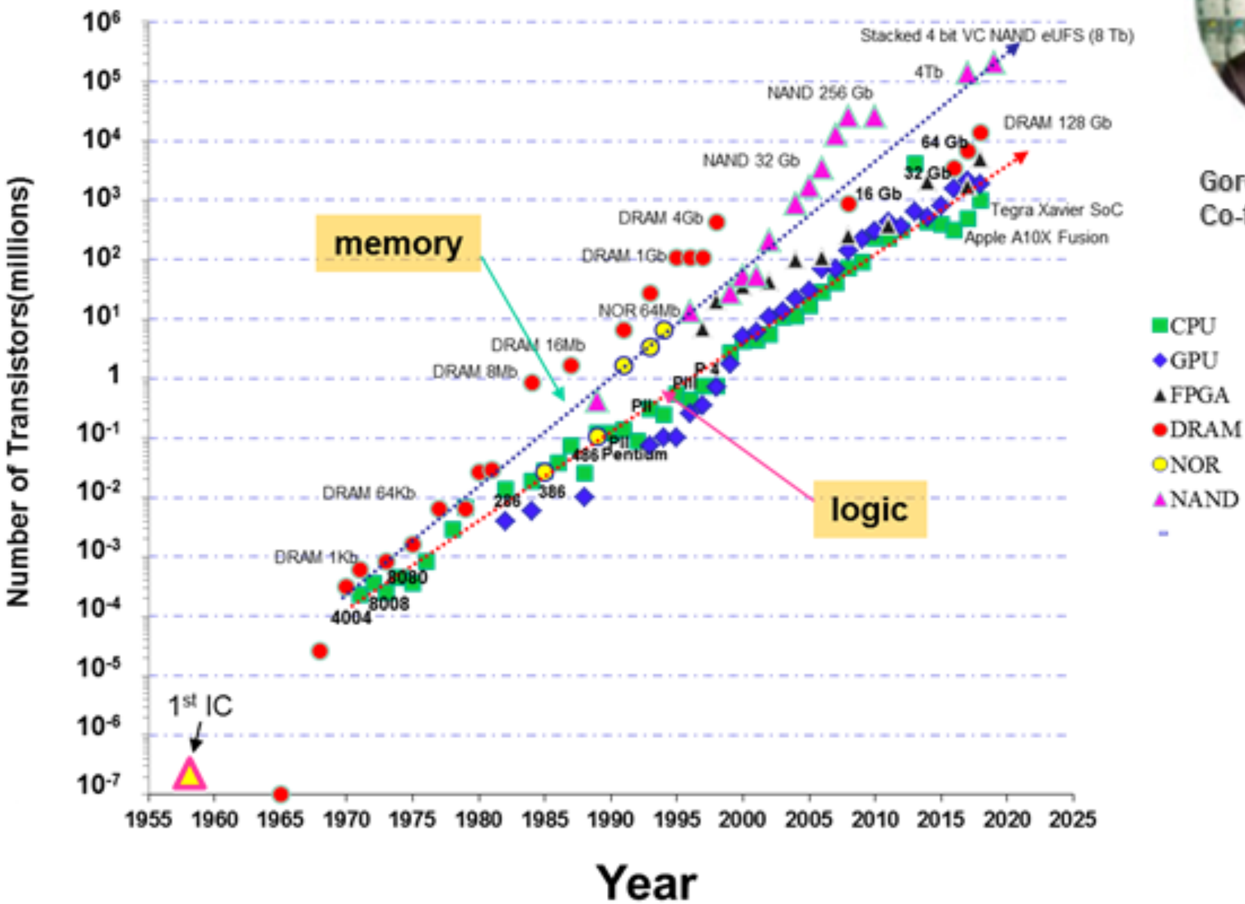
$$V_T = V_{FB} + 2\Psi_B + \frac{\sqrt{2\varepsilon_S q N_A (2\Psi_B)}}{C_{ox}}$$

$$= \left(\phi_{ms} - \frac{Q_d + Q_{ion} + Q_{oxide\,trap} + Q_{oxide\,fixed} + Q_{it} \cdots}{C_{ox}}\right) + 2\Psi_B + \frac{\sqrt{4\varepsilon_S q N_A \Psi_B}}{C_{ox}}$$

Un-controllable interface property between the semiconductor and gate insulator dominated.
No one knew how to make a functional controllable MOSFET until '60s, even Shockley!

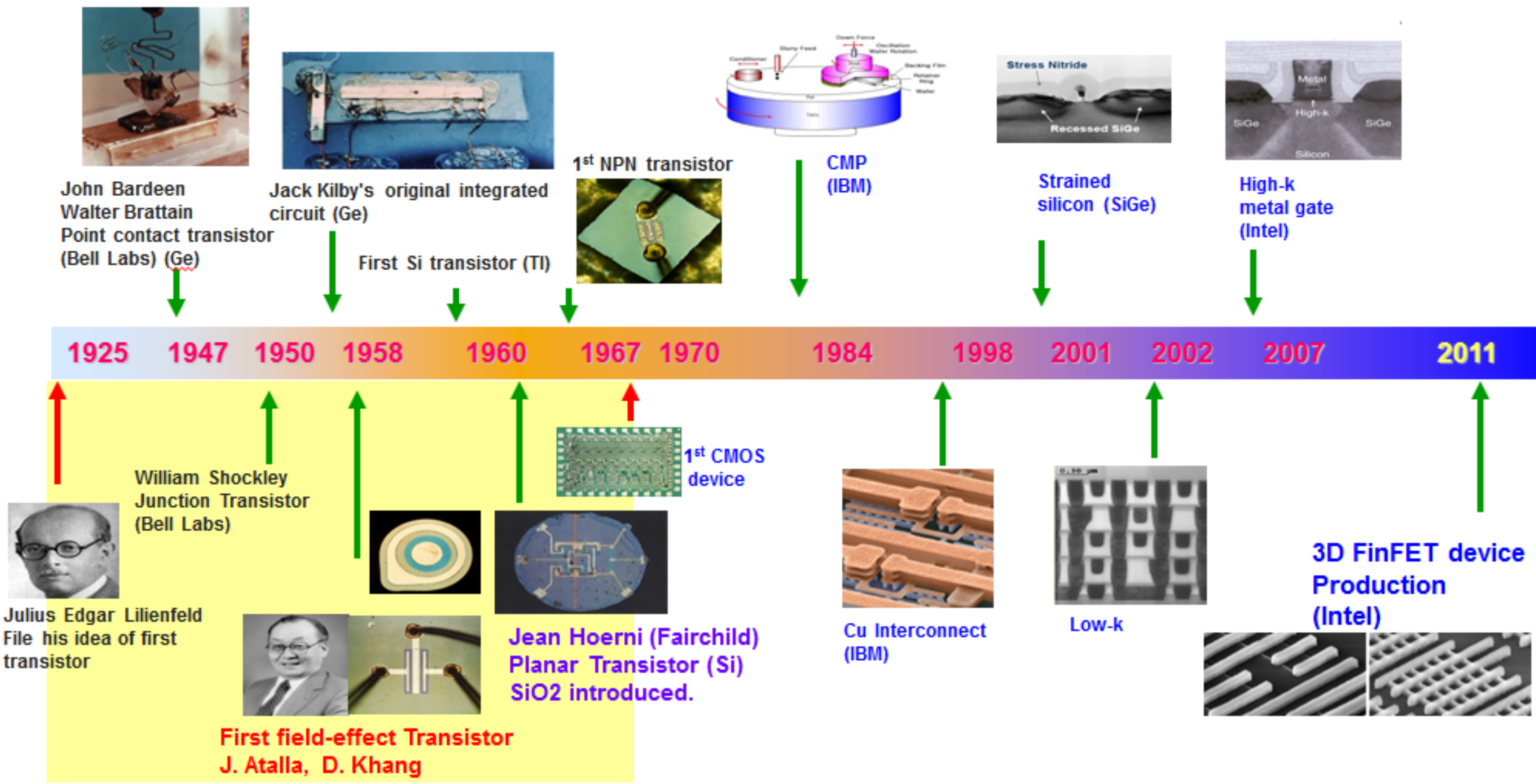
Moore's Law

The number of transistors per square-inch doubles each 18-24 months



Gordon Moore
Co-founder of Intel 1965

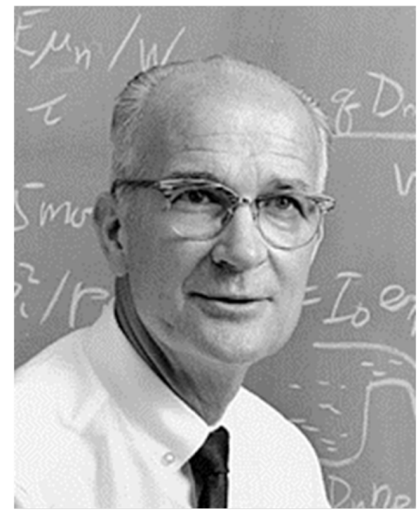
History of the IC Technology



Nobel Prize Laureates (1956) for 1st Transistor in Realization

John Bardeen
(1908-1991)

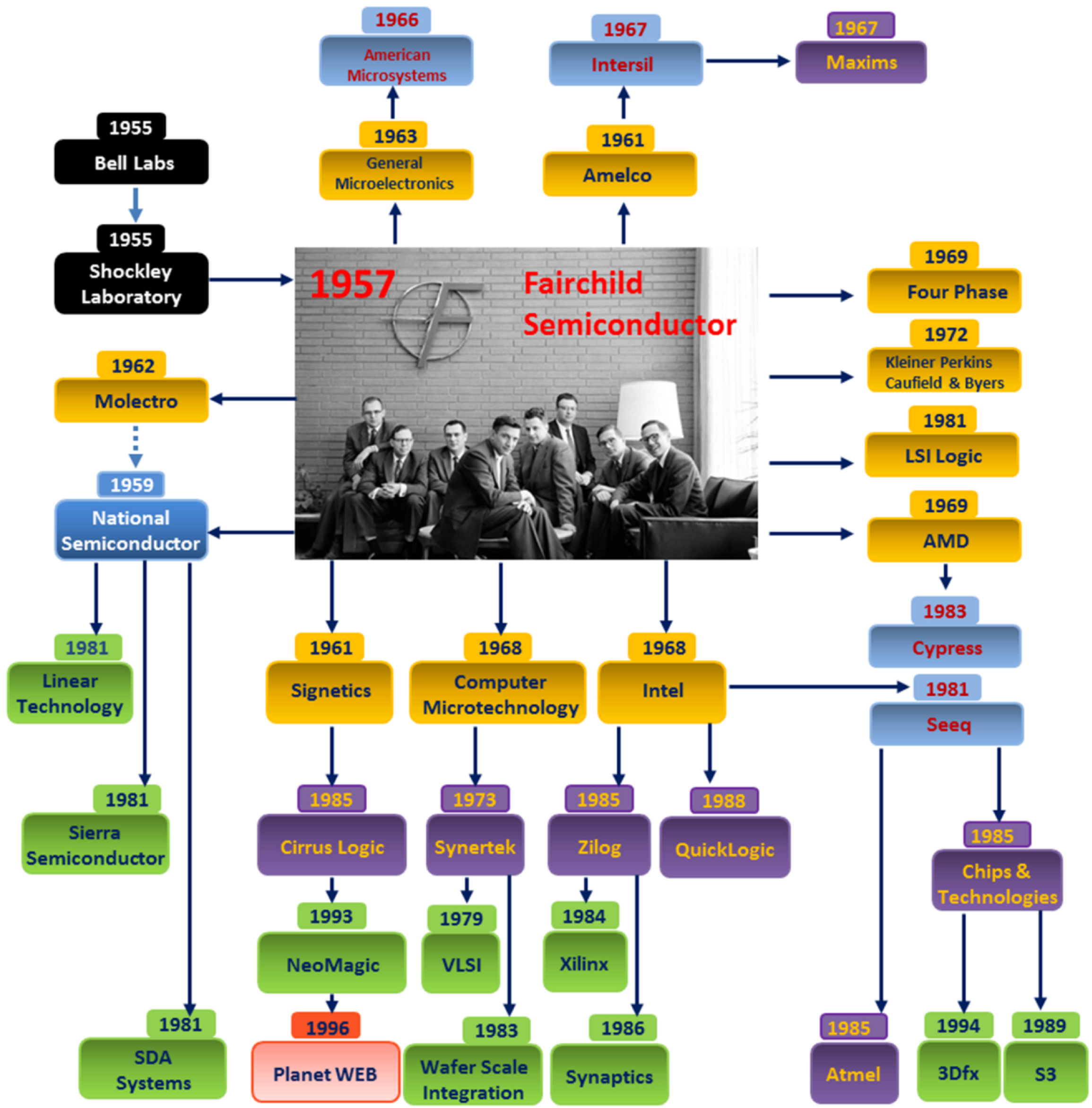
Walter Houser Brattain
(1902-1987)



William Shockley
(1910-1989)

Only Shockley has the vision of this discovery will open a totally new world (Era). So, Shockley acted as the Moses –The Exodus– to Silicon Valley.

Spin-off Companies from Fairchild



What Needed for a Disruptive Technology to be Successful

1. Need to have a valid and rigorous effective theory for Quantum Phenomena → Classical format method → Enable manageable engineering calculation

2. Need to develop supporting material and equipment for this new Industry → Usually will be self-propellant

3. Most Important of All → Need to find a set of key applications most fit with Quantum Computer

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Motion of Electrons and Holes in Perturbed Periodic Fields

PHYSICAL REVIEW VOLUME 97, NUMBER 4 FEBRUARY 15, 1955

Motion of Electrons and Holes in Perturbed Periodic Fields

J. M. LUTTINGER* AND W. KOHN†
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received October 13, 1954)

A new method of developing an "effective-mass" equation for electrons moving in a perturbed periodic structure is discussed. This method is particularly adapted to such problems as arise in connection with impurity states and cyclotron resonance in semiconductors such as Si and Ge. The resulting theory generalizes the usual effective-mass treatment to the case where a band minimum is not at the center of the Brillouin zone, and also to the case where the band is degenerate. The latter is particularly striking, the usual Wannier equation being replaced by a set of coupled differential equations.

I. INTRODUCTION

IN recent years, there has been a renewed interest in the problem of motion of charge carriers in perturbed periodic fields. The principle tool has been the so-called "effective mass" theory, which replaces the effect of the periodic field by a mass tensor, the elements of which are determined by the unperturbed band structure.[1] The rigorous theory has so far been limited almost entirely to the case where the relevant band is simple and has its lowest point at the center of the first Brillouin zone. In this form it is not directly applicable to the treatment of semiconductors such as Si and Ge. For these substances, recent "cyclotron" resonance experiments[2] indicate that both the conduction band and the valence band are not of this simple form. The conduction band for Si does not have its minimum at $\mathbf{k}=0$, but has six equivalent minima along the (100) directions of the first Brillouin zone. Similarly the conduction band in Ge consists of eight equivalent minima along (111) directions. In both these cases the principal curvatures —which determine the effective mass tensor—are known with some accuracy. For the valence band, the situation is rather more complex. The top of the valence band is at $\mathbf{k}=0$, but this is also a degeneracy point, i.e., there are several eigenfunctions with the same energy at this point. The theory of band structure in the neighborhood of such a degeneracy is due to Shockley.[3] There is in addition the complication that for such degenerate functions the spin-orbit coupling must be taken into account.[4]

We have investigated the form of the effective mass theory for these more complicated situations. For clarity, we begin with a new treatment of the case of a simple band with its lowest point at $\mathbf{k}=0$. This treatment, we believe, expresses the results of the effective mass theory in particularly compact form, and also has the advantage of being easily generalized to more complicated cases. (An alternative derivation more closely related to the work of Adams[1] is described in Appendix A. This derivation is perhaps simpler for impurity states in nondegenerate bands but is not as easily generalized for the cases of cyclotron resonance and degenerate bands.) In Sec. II, this theory will be developed for the discussion of impurity centers and "cyclotron" resonance. In Sec. III, the changes necessary for the "many-valley" case (i.e., the conduction band of Si or Ge) will be discussed. Section IV then extends the treatment to degenerate bands without spin-orbit coupling, and finally in Sec. V the modifications brought about by spin-orbit coupling are introduced.

* Permanent address: University of Michigan, Ann Arbor, Michigan.
† Permanent address: Carnegie Institute of Technology, Pittsburgh, Pennsylvania.
[1] R. Peierls, Z. Physik **80**, 763 (1933); **81**, 186 (1933); G. H. Wannier, Phys. Rev. **52**, 191 (1937); J. C. Slater, Phys. Rev. **76**, 1592 (1949); J. M. Luttinger, Phys. Rev. **84**, 814 (1951); E. N. Adams II, Phys. Rev. **85**, 41 (1952); P. Feuer, Phys. Rev. **88**, 92 (1952); E. N. Adams II, J. Chem. Phys. **21**, 2013 (1953).
[2] Dresselhaus, Kip, and Kittel, Phys. Rev. **92**, 827 (1953); **95**, 568 (1954); Lax, Zeiger, Dexter, and Rosenblum, Phys. Rev. **93**, 1418 (1954); Dexter, Zeiger, and Lax, Phys. Rev. **95**, 557 (1954); B. Lax (n-type Si) (private communication).
[3] W. Shockley, Phys. Rev. **78**, 173 (1950).
[4] R. J. Elliot, Phys. Rev. **96**, 266, 280 (1954).

II. SIMPLE BANDS

(A) Impurity Centers

We begin by considering an impurity center in a substance with a simple band, the minimum of which is at $\mathbf{k}=0$. Let H_0 be the Hamiltonian of the electron in the periodic potential, and let U be the additional potential due to the impurity. We shall assume in what follows that the fractional change of U over a unit cell is small, since it is only in this case that an effective mass theory might be expected to hold. The eigenfunctions of H_0 (the Bloch functions) will be denoted by $\psi_{n\mathbf{k}}$ and the corresponding eigenvalues by $\epsilon_n(\mathbf{k})$, n labelling the band and $\mathbf{k}$ wandering through the first Brillouin zone of the crystal. Thus

$$H_0\psi_{n\mathbf{k}}=\epsilon_n(\mathbf{k})\psi_{n\mathbf{k}}. \quad \text{(II.1)}$$

To find the impurity state wave function ψ we must solve the Schrödinger equation

$$(H_0+U)\psi=\epsilon\psi. \quad \text{(II.2)}$$

In order to proceed further, it is necessary to choose some complete set of functions in which to expand ψ. Rather than taking the Bloch functions or Wannier functions corresponding to H_0, as has been done previously,[1] we choose a set as follows. Write the Bloch functions as

$$\psi_{n\mathbf{k}}=e^{i\mathbf{k}\cdot\mathbf{r}}u_{n\mathbf{k}}, \quad \text{(II.3)}$$

where $u_{n\mathbf{k}}$ is a function of $\mathbf{r}$ with the lattice periodicity. The $\psi_{n\mathbf{k}}$ form, of course, a complete set of functions, in which any wave function may be expanded. Consider now the set of functions

$$\chi_{n\mathbf{k}}=e^{i\mathbf{k}\cdot\mathbf{r}}u_{n0}. \quad \text{(II.4)}$$

We assert that these form a complete orthonormal set if the $\psi_{n\mathbf{k}}$ do. Imagine any function $f(\mathbf{r})$ expanded in the $\psi_{n\mathbf{k}}$:

$$f(\mathbf{r})=\sum_n\int d\mathbf{k}\,g_n(\mathbf{k})\psi_{n\mathbf{k}}=\sum_n\int d\mathbf{k}\,g_n(\mathbf{k})e^{i\mathbf{k}\cdot\mathbf{r}}u_{n\mathbf{k}}. \quad \text{(II.5)}$$

On the other hand, any periodic function can be expressed in terms of the Bloch functions at the bottom of the band, which are complete with respect to periodic functions. Therefore

$$u_{n\mathbf{k}}=\sum_{n'}b_{nn'}(\mathbf{k})u_{n'0}, \quad \text{(II.6)}$$

which yields, when substituted in (II.5), the result

$$f(\mathbf{r})=\sum_n\int d\mathbf{k}\,\bar{g}_n(\mathbf{k})\chi_{n\mathbf{k}},$$

with

$$\bar{g}_n(\mathbf{k})=\sum_{n'}g_{n'}(\mathbf{k})b_{n'n}(\mathbf{k}).$$

The orthonormality is also easily established. For the Bloch waves this means

$$(\psi_{n\mathbf{k}},\psi_{n'\mathbf{k}'})=\int_{\substack{\text{entire}\\ \text{crystal}}}\psi_{n\mathbf{k}}^*\psi_{n'\mathbf{k}'}d\mathbf{r}=\delta_{nn'}\delta(\mathbf{k}-\mathbf{k}'). \quad \text{(II.7)}$$

The corresponding quantity for the $\chi_{n\mathbf{k}}$ is

$$(\chi_{n\mathbf{k}},\chi_{n'\mathbf{k}'})=\int e^{i(\mathbf{k}'-\mathbf{k})\cdot\mathbf{r}}u_{n0}^*u_{n'0}d\mathbf{r}. \quad \text{(II.8)}$$

Since $u_{n0}^*u_{n'0}$ has the lattice periodicity, we may expand it in a Fourier series, say

$$u_{n0}^*u_{n'0}=\sum_m B_m^{nn'}e^{-i\mathbf{K}_m\cdot\mathbf{r}}, \quad \text{(II.9)}$$

where the $B_m^{nn'}$ are just numerical coefficients, and the $\mathbf{K}_m$ are the reciprocal lattice vectors. Inserting (II.9) in (II.8), we obtain

$$(\chi_{n\mathbf{k}},\chi_{n'\mathbf{k}'})=(2\pi)^3\sum_m B_m^{nn'}\delta(\mathbf{k}'-\mathbf{k}-\mathbf{K}_m). \quad \text{(II.10)}$$

However, since $\mathbf{k}'$ and $\mathbf{k}$ are both in the first Brillouin zone, $\mathbf{k}'-\mathbf{k}-\mathbf{K}_m$ is only possible if $m=0$. Thus

$$(\chi_{n\mathbf{k}},\chi_{n\mathbf{k}'})=\delta(\mathbf{k}'-\mathbf{k})B_0^{nn'}(2\pi)^3. \quad \text{(II.11)}$$

Using Fourier's theorem (with Ω the volume of the unit cell) the $B_m^{nn'}$ are given by

$$B_m^{nn'}=\frac{1}{\Omega}\int_{\text{cell}}e^{i\mathbf{K}_m\cdot\mathbf{r}}u_{n0}^*u_{n'0}d\mathbf{r},$$

$$B_0^{nn'}=\frac{1}{\Omega}\int_{\text{cell}}u_{n0}^*u_{n'0}d\mathbf{r}=\frac{1}{(2\pi)^3}\delta_{nn'}$$

from (II.7). Finally, then,

$$(\chi_{n\mathbf{k}},\chi_{n'\mathbf{k}'})=\delta(\mathbf{k}'-\mathbf{k})\delta_{nn'}, \quad \text{(II.12)}$$

which is the required orthonormality.

We now make in (II.2) the Ansatz

$$\psi=\sum_{n'}\int d\mathbf{k}'A_{n'}(\mathbf{k}')\chi_{n'\mathbf{k}'}, \quad \text{(II.13)}$$

which gives the equation

$$\sum_{n'}\int d\mathbf{k}'(n\mathbf{k}|H_0+U|n'\mathbf{k}')A_{n'}(\mathbf{k}')=\epsilon A_n(\mathbf{k}). \quad \text{(II.14)}$$

The notation $(n\mathbf{k}|H_0+U|n'\mathbf{k}')$ means matrix elements with respect to the $\chi_{n\mathbf{k}}$. These may be evaluated in the

Semiconductor Basics

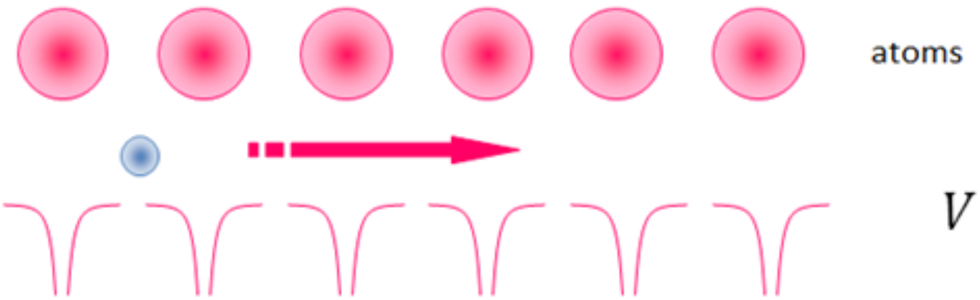
Schrödinger Equation

$$\left[-\frac{\hbar^2}{2m_o}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)+V(\vec{r})\right]\Psi(\vec{r}) = E\Psi(\vec{r})$$

Electron moves in free space

$$V(\vec{r}) = 0 \quad E = \frac{\hbar^2 k^2}{2m_0}$$

Electron moves in a periodic crystal

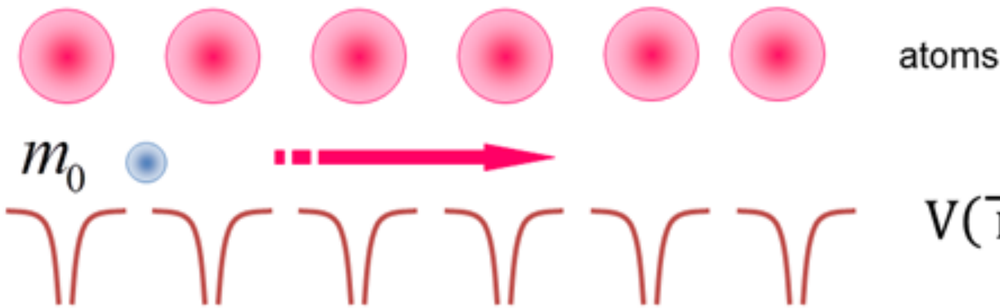


$$V(\vec{r}) = V_0 e^{-ikr}$$

Effective Mass

$$F_{total} = F_{external} + F_{crystal} = m_0 \frac{dv}{dt}$$

$$F_{external} = m_0 \frac{dv}{dt} - F_{crystal} = m^* \frac{dv}{dt}$$

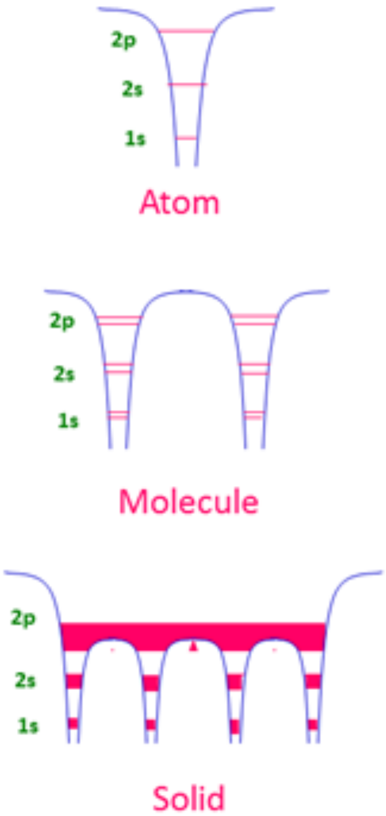


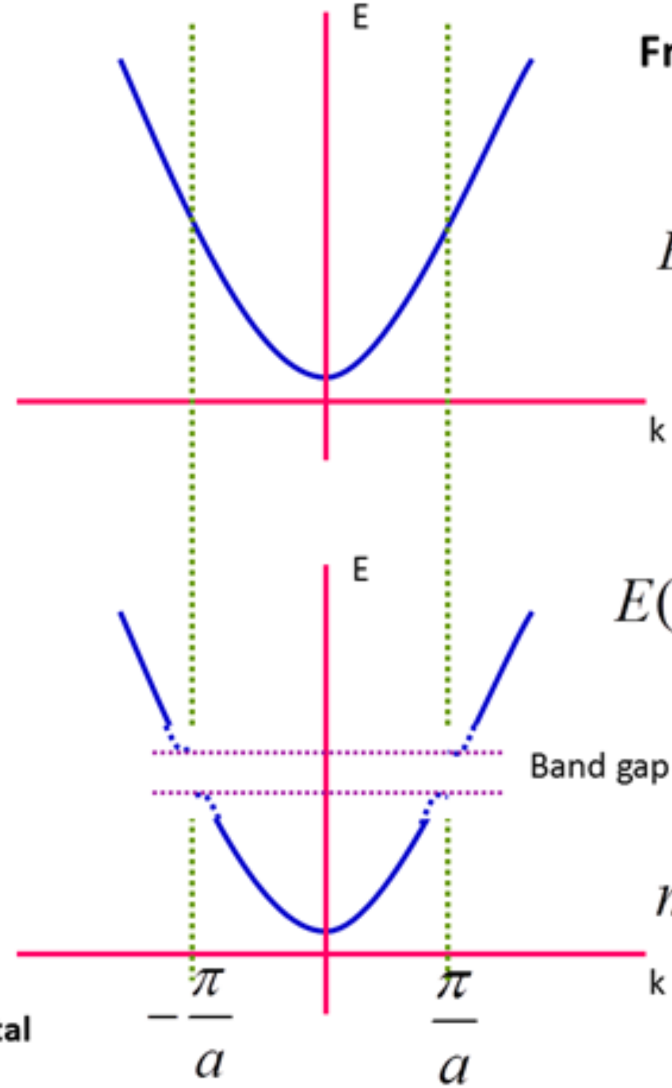
$$V(\vec{r}) = V_o e^{-ikr}$$

$m^*_{effective} = 0.2\ m_0$ (for Carbon)

$$V(\vec{r}) \simeq 0$$

Band Theory





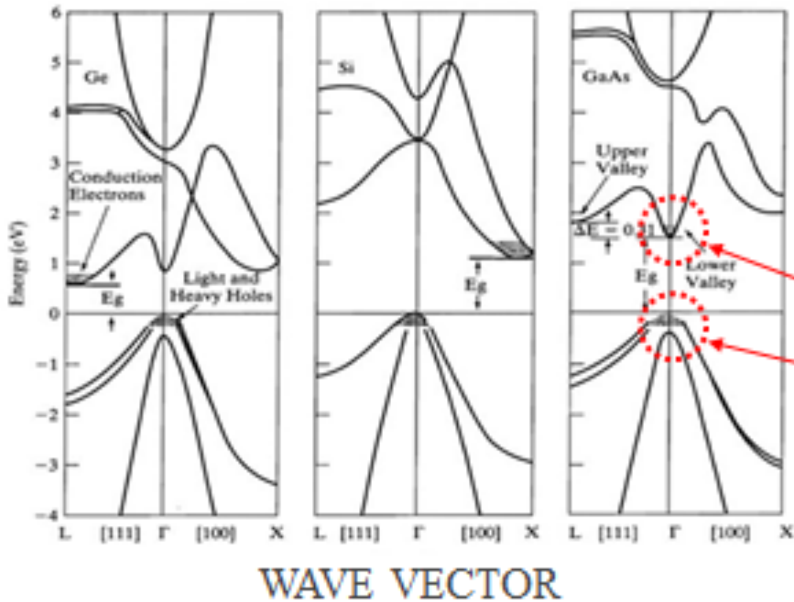
Free Electron

$$E_{free} = \frac{\hbar^2 k^2}{2m_o}$$

$$E(k)_{crystal} = \frac{\hbar^2 k^2}{2m^*_{effective}}$$

$$m^*_{effective} = \frac{\hbar^2}{d^2E(k)/dk^2}$$

Electron in crystal

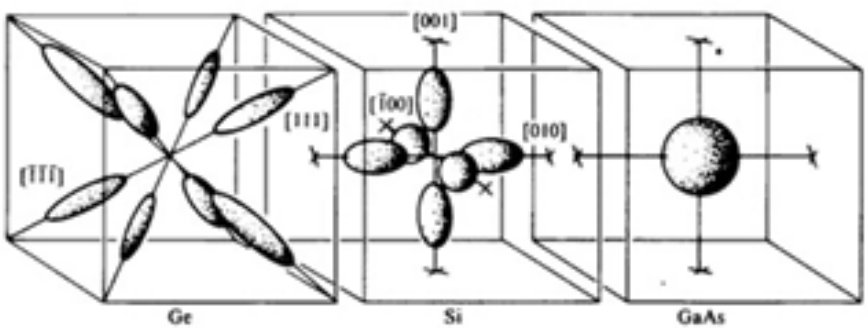


Energy band structures of Ge, Si and GaAs

electron

hole

The Tensorial Effective Mass: $m^*_{effective} = \dfrac{\hbar^2}{d^2E(k)/dk^2}$



Shape of constant energy surfaces in Ge, Si, and GaAs

Ge: eight half-ellipsoids of revolution along the <111> axes

Si: six ellipsoids along the <110> axes

GaAs: sphere constant energy surface

Properties of Important Semiconductor

Semiconductor			Crystal Struct.	Lattice Const. at 300K (Å)	Bandgap (eV) 300K	Bandgap (eV) 0 K	Band	Mobility at 300 K ($cm^2/V-s$) μ_n	Mobility at 300 K ($cm^2/V-s$) μ_p	Effective Mass m_n^*/m_o	Effective Mass m_p^*/m_o	$\varepsilon_s/\varepsilon_o$
	C	Carbon (diamond)	D	3.56683	5.47	5.48	I	1,800	1,200	0.2	0.25	5.7
	Ge	Germanium	D	5.64613	0.66	0.74	I	3,900	1,900	$1.64^{l}, 0.082^{t}$	$0.04^{lh}, 0.28^{hh}$	16.0
	Si	Silicon	D	5.43102	1.12	1.17	I	1,450	500	$0.98^{l}, 0.19^{t}$	$0.16^{lh}, 0.49^{hh}$	11.9
IV-IV	SiC	Silicon carbide	W	a=3.086,c=15.117	2.996	3.03	I	400	50	0.60	1.00	9.66
III-V	AlAs	Aluminum arsenide	Z	5.6605	2.36	2.23	I	180		0.11	0.22	10.1
	AlP	Aluminum phosphide	Z	5.4635	2.42	2.51	I	60	450	0.212	0.145	9.8
	AlSb	Aluminum antimonide	Z	6.1355	1.58	1.68	I	200	420	0.12	0.98	14.4
	BN	Boron nitride	Z	3.6157	6.4		I	200	500	0.26	0.36	7.1
	"	"	W	a=2.55,c=4.17	5.8		D			0.24	0.88	6.85
	BP	Boron phosphide	Z	4.5383	2.0		I	40	500	0.67	0.042	11
	GaAs	Gallium arsenide	Z	5.6533	1.42	1.52	D	8,000	400	0.063	$0.76^{lh}, 0.5^{hh}$	12.9
	GaN	Gallium nitride	W	a=3.189,c=5.182	3.44	3.50	D	400	10	0.27	0.8	10.4
	GaP	Gallium phosphide	Z	5.4512	2.26	2.34	I	110	75	0.82	0.60	11.1
	GaSb	Gallium antimonide	Z	6.0959	0.72	0.81	D	5,000	850	0.042	0.40	15.7
	InAs	Indium arsenide	Z	6.0584	0.36	0.42	D	33,000	460	0.023	0.40	15.1
	Inp	Indium phosphide	Z	5.8686	1.35	1.42	D	4,600	150	0.077	0.64	12.6
	InSb	Indium antimonide	Z	6.4794	0.17	0.23	D	80,000	1,250	0.0145	0.40	16.8
II-VI	CdS	Cadmium sulfide	Z	5.825	2.5		D			0.14	0.51	5.4
	"	"	W	a=4.136,c=6.714	2.49		D	350	40	0.20	0.7	9.1
	CdSe	Cadmium selenide	Z	6.050	1.70	1.85	D	800		0.13	0.45	10.0
	CdTe	Cadmium telluride	Z	6.482	1.56		D	1,050	100			10.2
	ZnO	Zinc oxide	R	4.580	3.35	3.42	D	200	180	0.27		9.0
	ZnS	Zinc sulfide	Z	5.410	3.66	3.84	D	600		0.39	0.23	8.4
	"	"	W	a=3.822,c=6.26	3.78		D	280	800	0.287	0.49	9.6
IV-VI	PbS	Lead sulfide	R	5.9362	0.41	0.286	I	600	700	0.25	0.25	17.0
	PbTe	Lead telluride	R	6.4620	0.31	0.19	I	6,000	4,000	0.17	0.20	30.0

D=Diamond, W=Wurtzite, Z=Zincblende, R=Rock salt. I, D=Indirect, direct bandgap.
***l,t,lh,hh*=Longitudinal,transverse,light-hole,heavy-hole effective mass.**

What Needed for a Disruptive Technology to be Successful

1. Need to have a valid and rigorous effective theory for Quantum Phenomena → Classical format method → Enable manageable engineering calculation

2. Need to develop supporting material and equipment for this new Industry → Usually will be self-propellant

3. Most Important of All → Need to find a set of key applications most fit with Quantum Computer

Intel's "cryoprober" for Qubit Testing could Get Quantum Computers Here Faster

MIT Technology Review, Feb 28, 2019

What Needed for a Disruptive Technology to be Successful

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Find a set of Key Applications Most Fit with Quantum Computer

IBM Research – Tokyo
Director Norishige (Noly) Morimoto

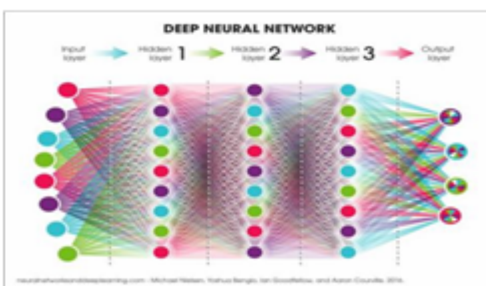
- Quantum Computer is not to replace the Classical Computer.
- Right now Quantum Computer is in pre-commercial stage. Need to find out the key application.

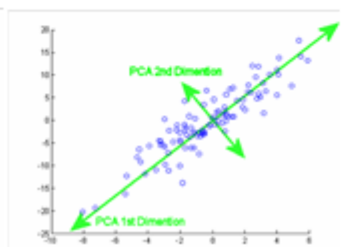
https://www.bnext.com.tw/article/53957/ibm-noly-san-talk-about-quantum-computer

Quantum Computing Application

Field：Hi-Tech

Case	Corporate
• Machine learning and artificial intelligence, such as neural networks • Search • Bidding strategies for advertisements • Cybersecurity • Online and product marketing • Software verification and validation	• Alibaba • Baidu • Google • IBM • Microsoft • Samsung • Telstra • Fujitsu





The most common categories of use:
- Optimization
- Machine learning/AI

Source：The Next Decade in Quantum Computing—and How to Play, BCG (Nov, 2018)

Quantum Computing Application

Field：Industry

Case	Corporate
• Logistics: scheduling, planning, product distribution, routing • Automotive: traffic simulation, e-charging station and parking search, autonomous driving • Semiconductors: manufacturing, such as chip layout optimization • Aerospace: R&D and manufacturing, such as fault-analysis, stronger polymers for airplanes • Material science: effective catalytic converters for cars, battery cell research, more-efficient materials for solar cells, and property engineering uses such as OLEDS	• Airbus • BMW • Bosch • Daimler • Grumman • Honeywell • Lockheed Martin • NASA • Northrop • Raytheon • Volkswagen

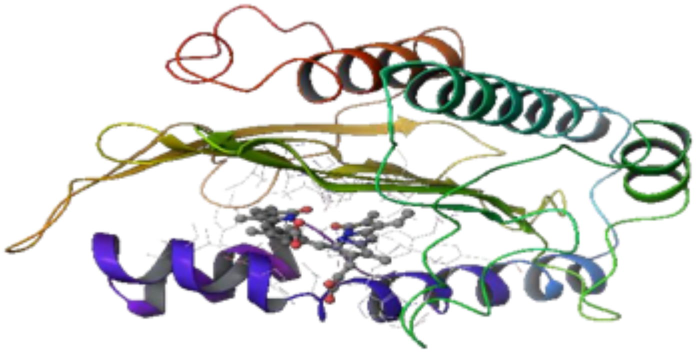
The most common categories of use:
- Simulation
- Optimization

Source：The Next Decade in Quantum Computing—and How to Play, BCG (Nov, 2018)

Quantum Computing Application

Field：Chemistry / Medical

Case	Corporate
• Catalyst and enzyme design, such as nitrogenase • Pharmaceuticals R&D, such as faster drug discovery • Bioinformatics, such as genomics • Patient diagnostics for health care, such as improved diagnostic capability for MRI	• Amgen • BASF • Biogen • Dow Chemical • DuPont • JSR



The most common categories of use:

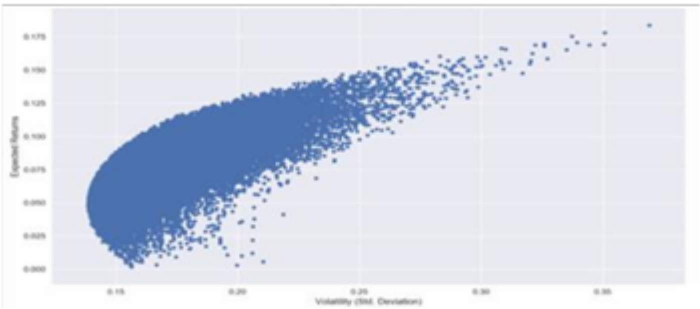
- Simulation
- Machine learning/AI

Source：The Next Decade in Quantum Computing—and How to Play, BCG (Nov, 2018)

Quantum Computing Application

Field：Finance

Case	Corporate
• Trading strategies • Portfolio optimization • Asset pricing • Risk analysis • Fraud detection • Market simulation	• Barclays • Commonwealth Bank • Goldman Sachs • J.P. Morgan • NatWest • Nomura



The most common categories of use:
- Optimization
- Machine learning/AI

Source：The Next Decade in Quantum Computing—and How to Play, BCG (Nov, 2018)

Quantum Computing Application

Field：Energy

Case	Corporate
• Network design • Power grid optimization • Energy distribution • Oil well optimization	• BP • Dubai Electricity & Water Authority • ExxonMobil

The most common categories of use:
- Optimization
- Machine learning/AI

Source：The Next Decade in Quantum Computing—and How to Play, BCG (Nov, 2018)

Lemma of New Technology

" The principal applications of any sufficiently new and innovative technology always have been - and will continue to be - applications created by that technology "

- **Herbert Kroemer , Nobel Prize Laureate (2000)**

Examples

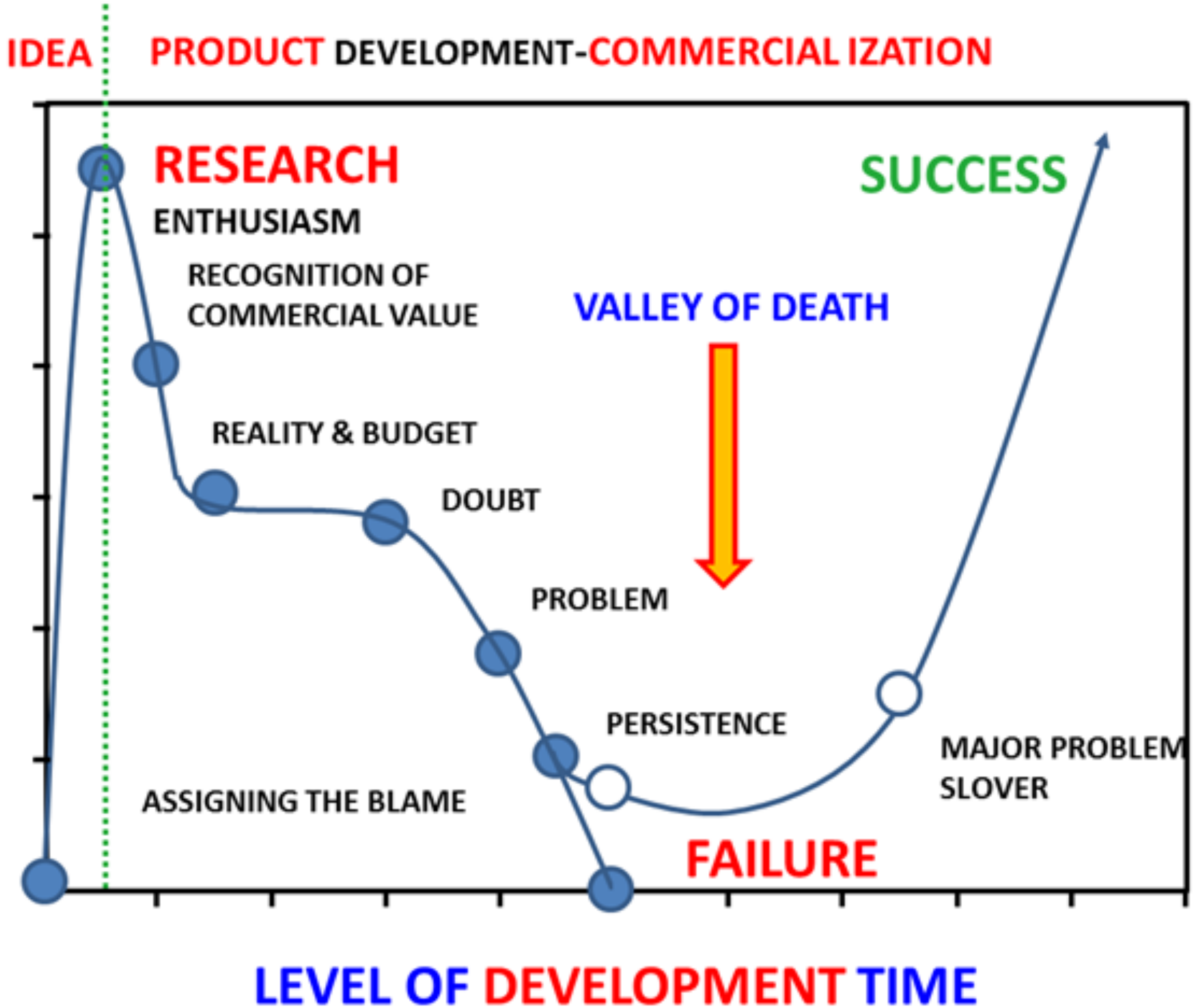
- The Transistor (1947), then IC (1958) was not just a replacement for vacuum tubes, it **Created** the modern computer and new industrial revolution.

- The Laser (1953/58), then Hetero-junction Laser (1963) has revolutionized the optoelectronics technology, it **Created** optical fiber communication, CD, DVD.

Even more critical are …

- for Individual Company or Institute
- for Country and Industry

The Success & Failure Principle



Gartner Hype Cycle for Emerging Technologies, 2019

蔡鴻青 專欄

（本專欄隔期刊出）

Column

藍色巨人戴紅帽的台灣啟示

蔡鴻青／台灣董事學會發起人
常從長期股東價值角度，觀察全球資本市場重大交易與策略剖析點

藍色巨人IBM最近幫自己添購了一頂台幣一兆元的「紅帽」，以每股現金一九〇美元收購軟體公司紅帽（Red Hat），總交易金額高達三四〇億美元。七月十日完成，這是公司創立一〇八年以來最大的收購案，也創下美國科技史前三大交易。

紅帽是全球最大的 Linux 開源系統（open source）公司，營收約IBM的三十分之一，收購紅帽對價約為該年本益比的一三七倍，而且是全現金交易！

IBM從打孔機起家，一九八〇年在系統主機領域壟斷稱王為「藍色巨人」後，錯失英特爾三八六發展，九三年大虧八十三億美元。十年轉型成功讓「大象跳舞」後，二〇〇一年逆轉為獲利七十三億美元！〇二年後併購超過六十件，收購蓮花軟體等，再收購PWC普華管理諮詢業務，從一個賣硬體的公司，變成軟體加硬體的整合方案，轉型成IT（資訊科技）服務諮詢集團。

同時，IBM也將低利的PC部門用一七．五億美元低價賣給聯想、把虧損連連的半導體倒貼十五億美元賣給格羅方德半導體，IBM的轉型史可說是資訊科技行業近代發展的縮影。

雲端業務前四名亞馬遜、微軟、谷歌及阿里巴巴都來自不同領域。IBM執行長羅睿蘭說，希望藉紅帽讓IBM轉型成為全球首屈一指的混合雲端供應商，行業龍頭亞馬遜（AWS）目前市占達三四%。

這種轉型場景很難出現在台灣。買自己看不懂的新領域，難！付高額溢價買未來，很難！倒貼主動賣資產，更難！台灣企業只想做加法買設備廠房，但因為面子與感情包袱不做減法處分事業。

最後只能留下舊東西或是破東西。企業轉型最後就是變成口號，發展幾個新技術與降低成本了事。轉型，就要做減法壯士斷腕，就要做加法進入新行業。資源有限，沒有先做減法就做不了加法。世界是平的，新競爭者隨時都會加入現有賽局，轉型向外找機會才有未來。

未來沒保證，但不轉型在原地打轉，保證連討論未來的機會都沒有。Ⓦ

Thanks !

藍色巨人戴紅帽的台灣啟示

藍色巨人IBM最近幫自己添購了一頂台幣一兆元的「紅帽」，以每股現金190美元收購軟體公司紅帽（Red Hat），總交易金額高達340億美元。7月10日完成，這是公司創立108年以來最大的收購案，也創下美國科技史前三大交易。

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IBM從打孔機起家，1980年在系統主機領域壟斷稱王為「藍色巨人」後，錯失英特爾386發展，1993年大虧83億美元。10年轉型成功讓「大象跳舞」後，2001年逆轉為獲利73億美元！2002年後併購超過60件，收購蓮花軟體等，再收購PWC普華管理諮詢業務，從一個賣硬體的公司，變成軟體加硬體的整合方案，轉型成IT（資訊科技）服務諮詢集團。

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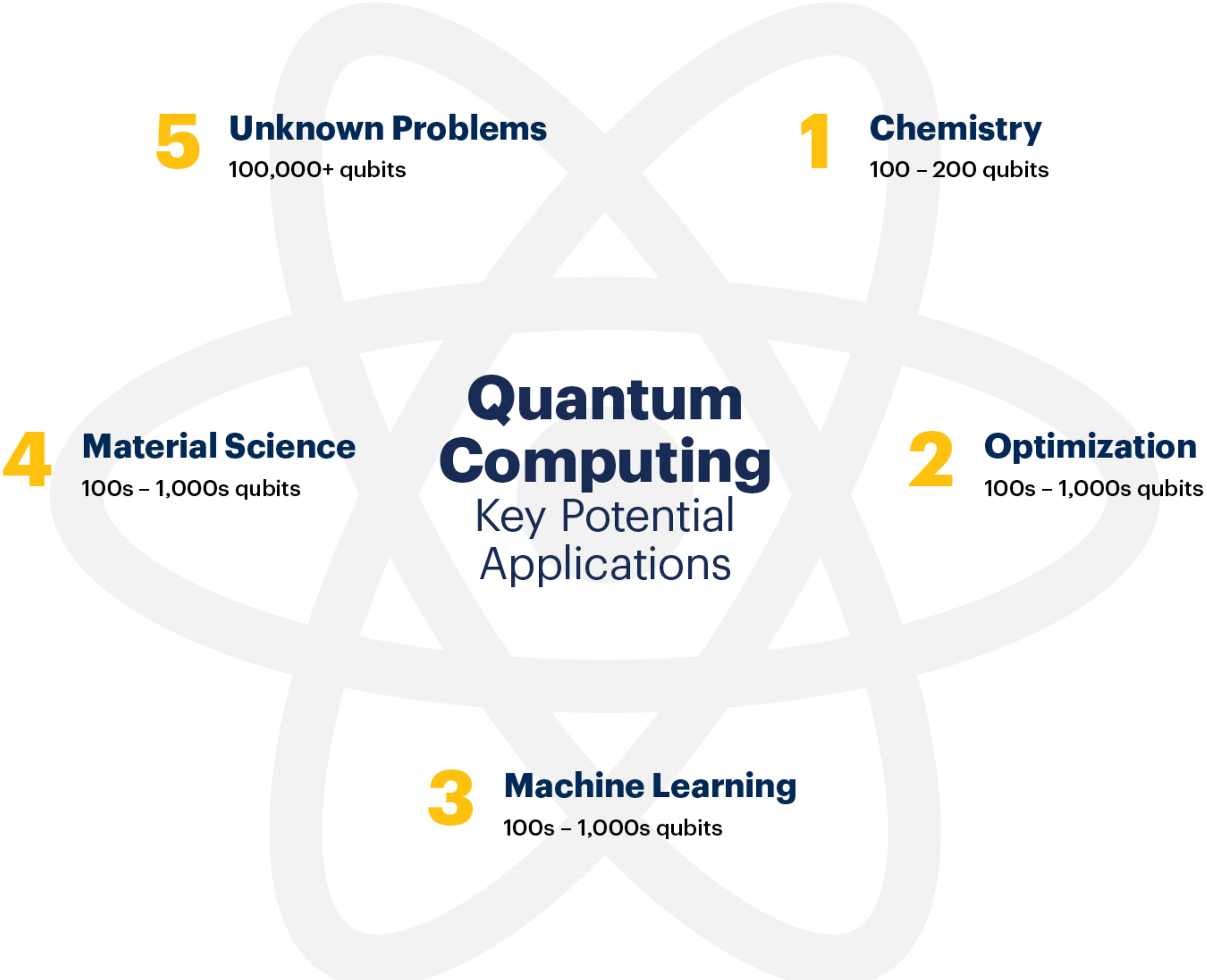
產業物理的典範：

半導體科技及其幾個關鍵與時機

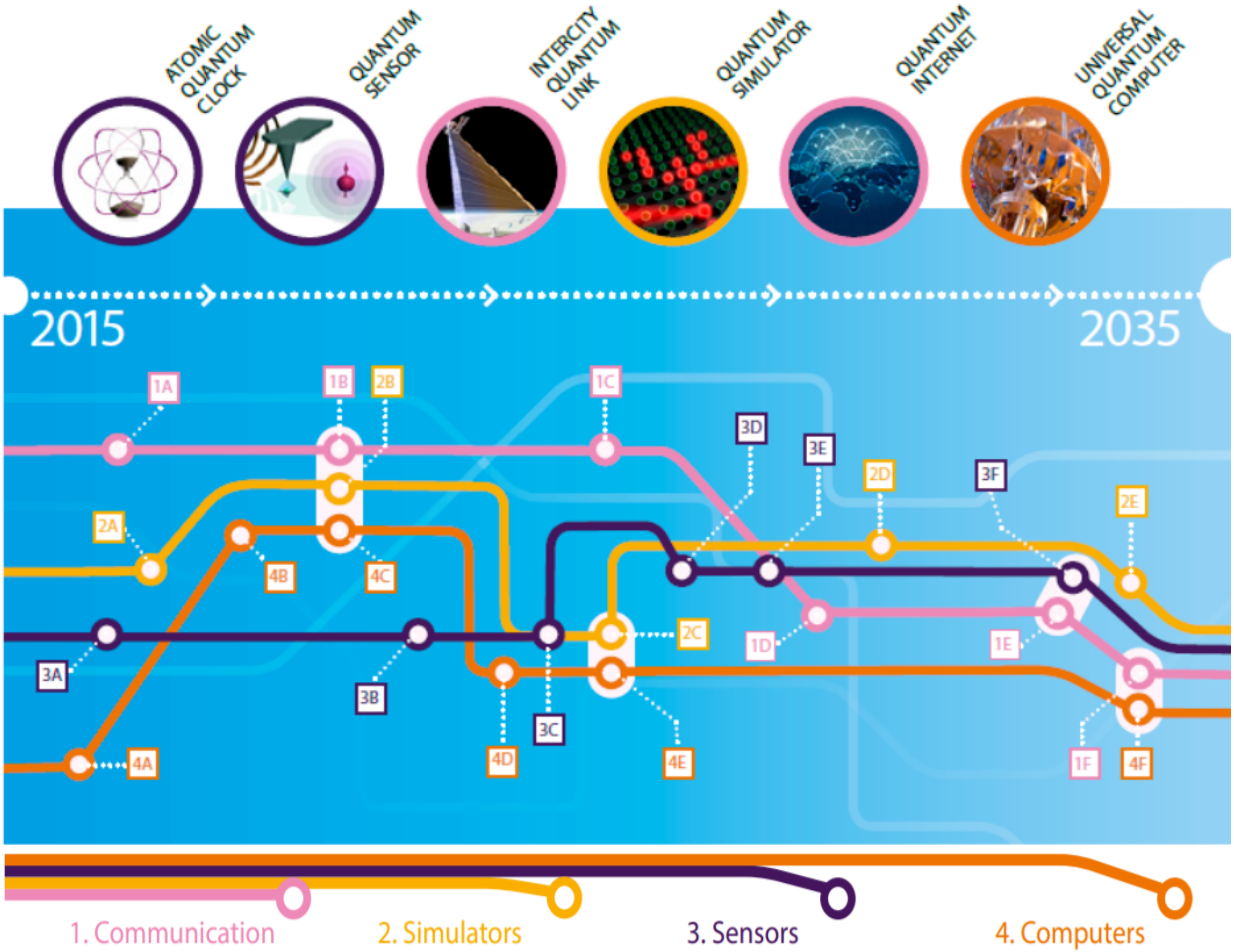
Appendix: Quantum Technology

Applications of Quantum Computing



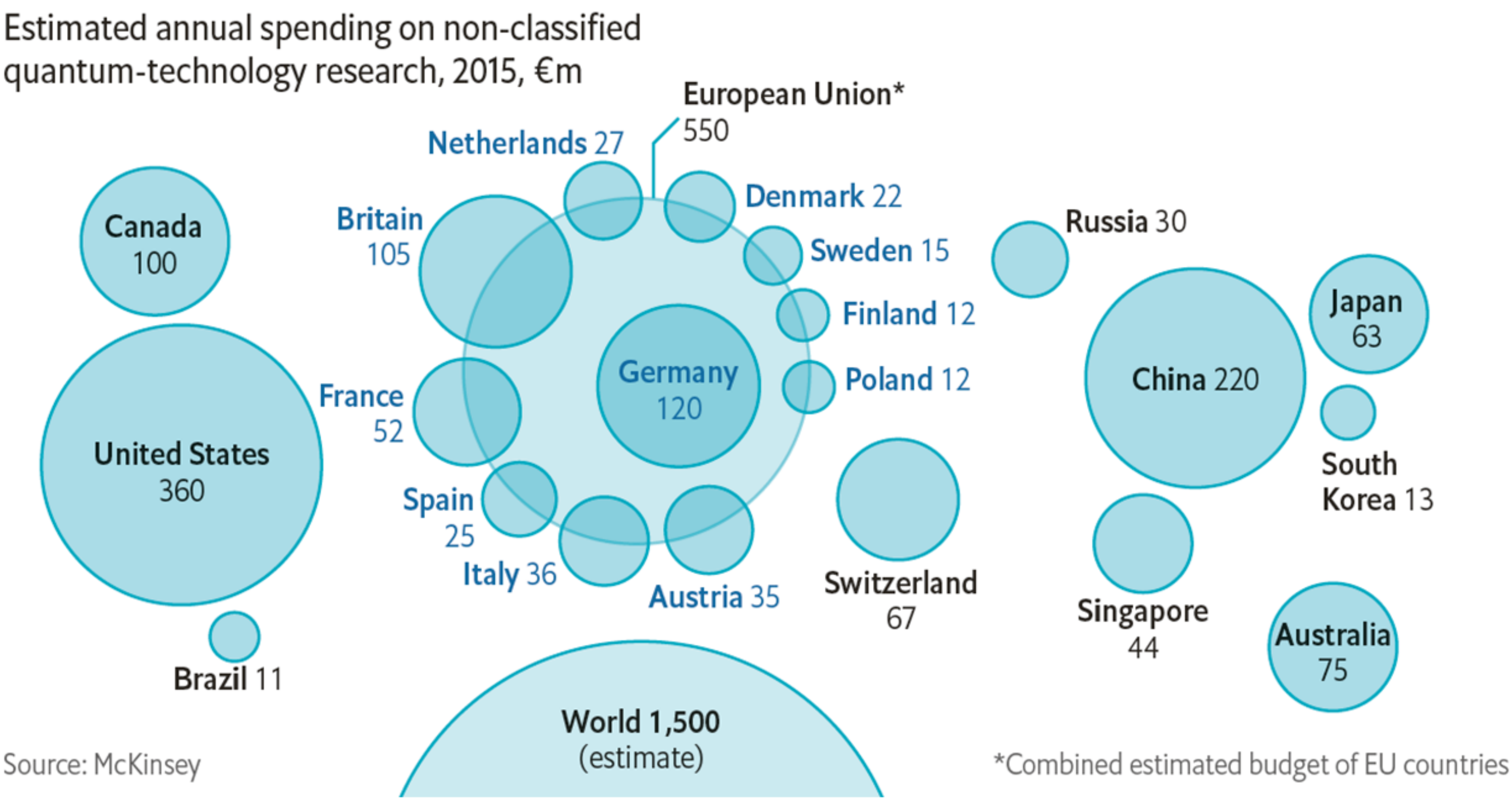
https://www.gartner.com/smarterwithgartner/the-cios-guide-to-quantum-computing/

Quantum Technologies Timeline



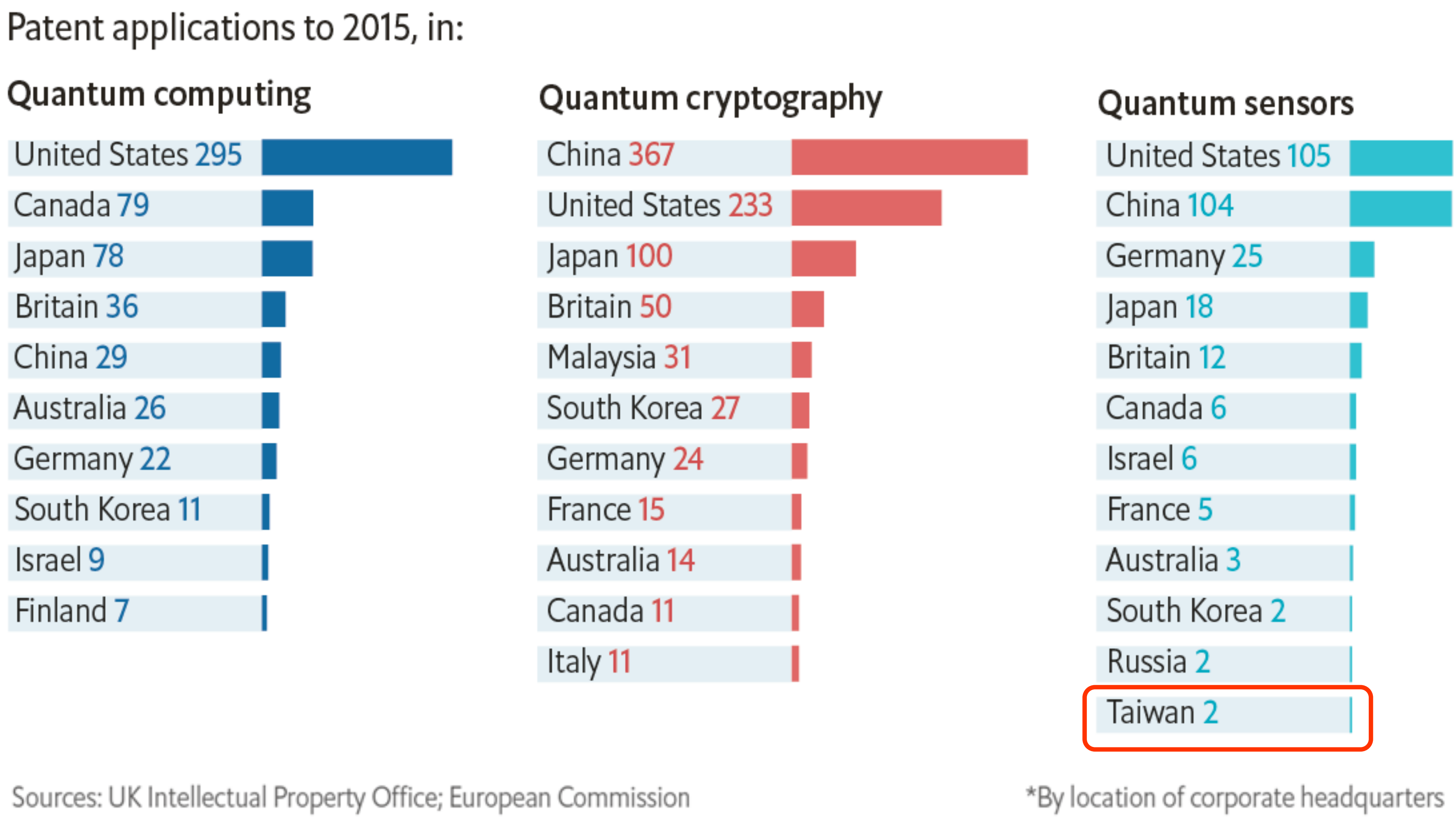
http://qurope.eu/system/files/u7/93056_Quantum%20Manifesto_WEB.pdf

Global Race on "Quantum Supremacy"



https://www.economist.com/news/essays/21717782-quantum-technology-beginning-come-its-own

Global Race on "Quantum Supremacy"



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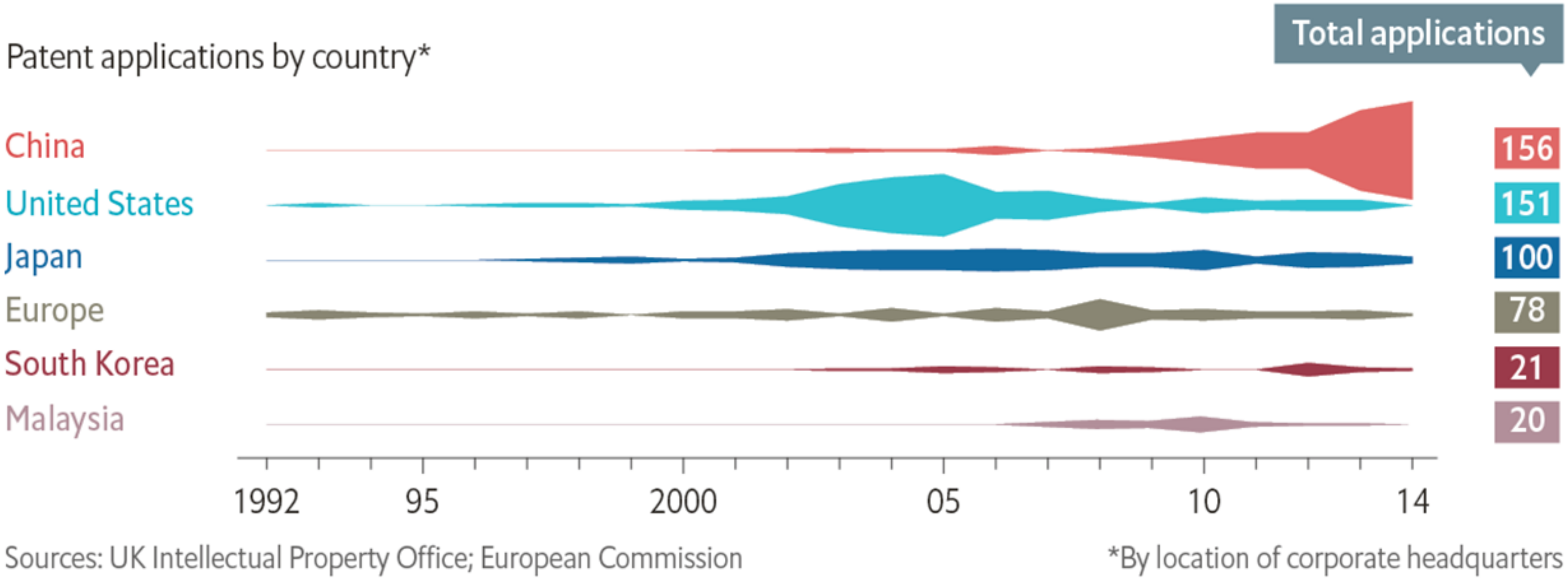


https://www.economist.com/news/essays/21717782-quantum-technology-beginning-come-its-own

產業物理的典範：

半導體科技及其幾個關鍵與時機

Appendix

Discovery, Idea, Invention, Innovation

- Discovery 發現
- Idea 發想
- Invention 發明
- Innovation 創新 (商業化)

原 理 性 的「發現」

開 創 性 的「發明」

與

具 商 業 爆 發 力 的「創新」

Patent (專利? 特許?) 之精義

「創新」與「創業」必須

要理解之精神

Patent

A **patent** is a set of exclusive rights granted by a state (national government) to an inventor or their assignee for a limited period of time in exchange for a public disclosure of an invention.

The word ***patent*** originates from the Latin ***patere***, which means ”to lay open” (i.e., to make available for public inspection), and more directly as a shortened version of the term ***letters patent***, which originally denoted an open for public reading royal decree granting exclusive rights to a person.

Source: Wikipedia

營業秘密

《營業秘密法》第 2 條

本法所稱營業秘密，係指方法、技術、製程、配方、程式、設計或其他可用於生產、銷售或經營之資訊，而符合下列要件者：

一、非一般涉及該類資訊之人所知者。

二、因其秘密性而具有實際或潛在之經濟價值者。

三、所有人已採取合理之保密措施者。

專利 v.s. 營業秘密

專利與營業秘密最大的不同是什麼？

➔ 專利說明書中需載明技術內容，等於讓競爭者可以合法地學習。

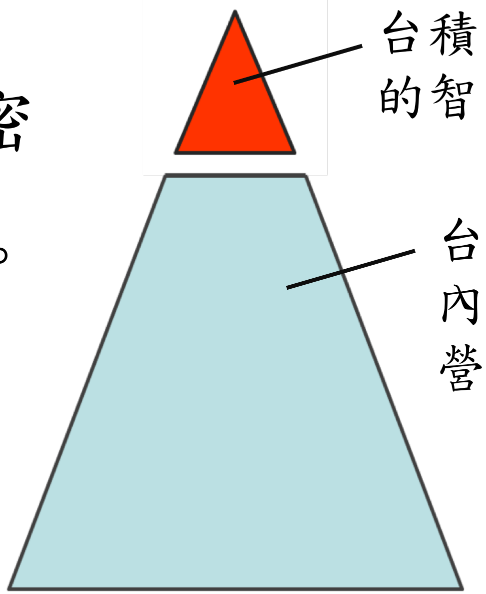
而營業秘密因採適當的保密措施，保障資訊內容不被競爭者知悉，進而保護公司機密資訊不外流。

來源：108年「竹科廉能誠信」座談會

專利 v.s. 營業秘密

專利及營業秘密，孰輕孰重？

➔ 欲確保公司的技術不外流，比起申請專利，以營業秘密的方式保護更能達到目的。



來源：108年「竹科廉能誠信」座談會

專利 v.s. 營業秘密

侵害專利與竊取營業秘密，何者之「道德可歸責性」較高？

➔ 專利侵權可能是制度問題導致侵權行為，就算是獨立研發的技術也可能會侵害他人的專利。而竊取營業秘密就明顯是偷竊行為。

在行為主觀評價上，竊取營業秘密具行為惡意，更具道德可歸責性。

來源：108年「竹科廉能誠信」座談會

如何防範營業秘密外洩

- 與員工或第三方簽署保密契約
- 與特定員工簽署競業禁止契約
- 門禁管制
- Need-to-know 的管理資訊揭露
- 錄音、錄影及照相功能之智慧型攜帶裝置管制
- 電子郵件管控
- 文件列印、影印管控與安檢

來源：108年「竹科廉能誠信」座談會

營業秘密案件處理

遇到營業秘密案件，第一時間該如何處理？

1. 組成專案小組，釐清人、事、時、地、物等事實

2. 找專門處理之律師協助內部調查

3. 向警察機關報案(刑事警察局、偵查隊或調查局)

來源：108年「竹科廉能誠信」座談會

營業秘密案件訴訟

營業秘密案件訴訟階段應注意什麼？

➔ 讓法官、檢察官能夠「理解」為何被竊取之標的是公司之營業秘密。

在不揭露過多公司機敏資訊的前提下，讓司法人員了解被竊取之標的內容與公司運作，以利案件調查及審判。

來源：108年「竹科廉能誠信」座談會