## *Fundamentals of Solid State Physics*

# Introduction

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# Goal of This Course

- Study the foundations of our world: solid materials
  - electronic, optical, magnetic, thermal, mechanical, ...

- Based on theories of physics
  - classical mechanics
  - electrodynamics
  - quantum mechanics
  - statistical mechanics
  - ...

- Emerging applications: semiconductors, lasers, ...

# Goal of This Course

- **Main Focus: Electrons**

**Department of Electronic Engineering**

**电子工程系**

- **Other topics: Photons, Phonons, Magnetics, ...**

# What is Unique?

- Programming (程序)
- Circuits (电路)
- Data and Algorithm (数据与算法)
- Signals and Systems (信号与系统)
- Probability (概率)
- Digital Logics (数字逻辑)
- Communications (通信)
- Media and Cognition (媒体与认知)
- Electromagnetism (电磁场)
- Solid State Physics (固体物理)

} 10 core courses in EE department

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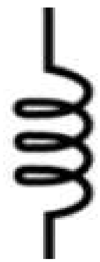
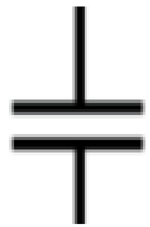
$$v = iR$$

$$v = L\frac{di}{dt}$$



$$i = C\frac{dv}{dt}$$



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- Solid State Physics (固体物理)

$$\nabla \cdot \mathbf{D} = \rho_V$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

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}

maths,
engineering,
application,
design,
model,
perfect,
...

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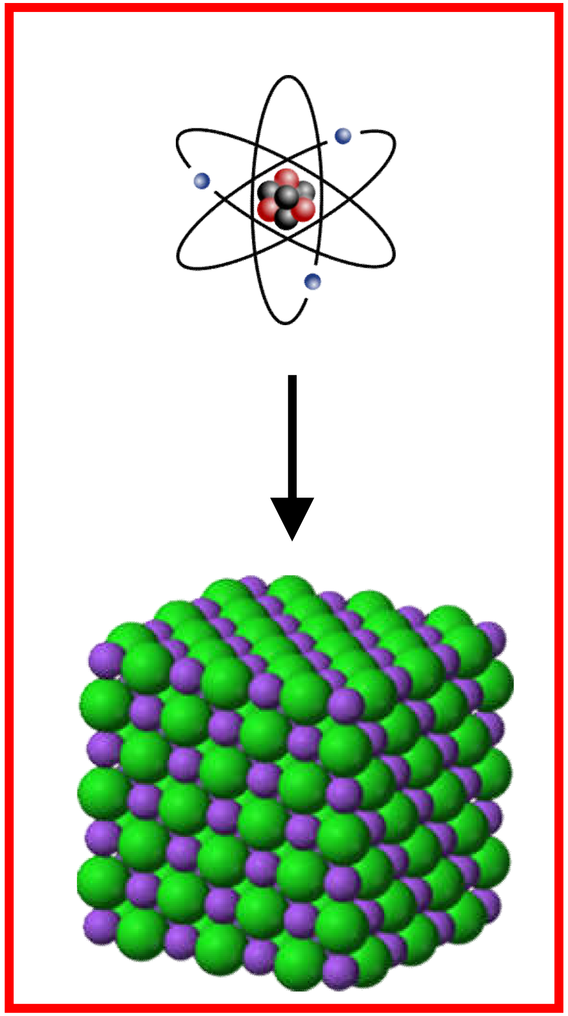
- **Solid State Physics (固体物理)**



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- Solid State Physics (固体物理)

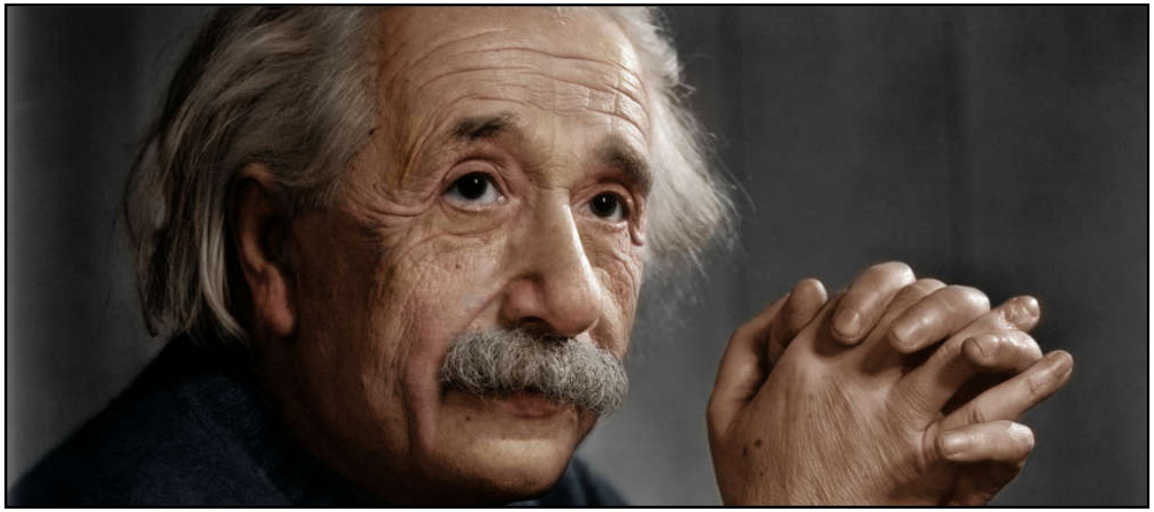
observation,
discovery,
understanding,
approximation,
assumption,
modified theory,
imperfection,
...

# Course Philosophy

***"The eternal mystery of the world is its comprehensibility. ... The fact that it is comprehensible is a miracle."***

**这个世界最不可理解之处在于它是可以理解的**

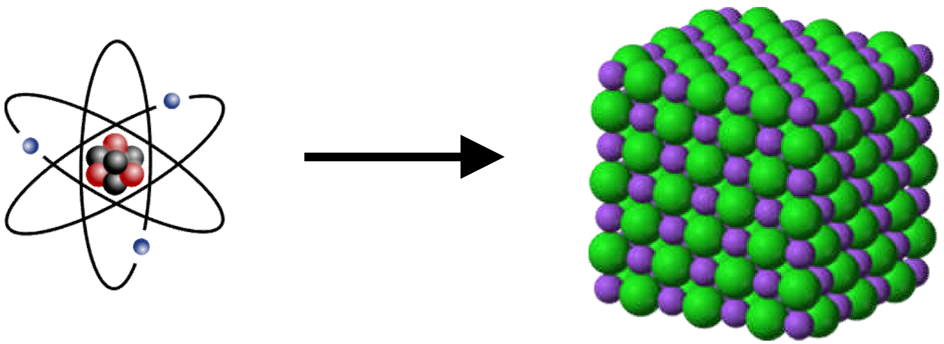
***---- Albert Einstein***



# Solid is very Complex

- **If we understand the basic physics of all the fundamental particles (electrons, photons, atoms, ...), can we understand everything?**

**No!**




ARTICLES

More Is Different

By P. W. Anderson

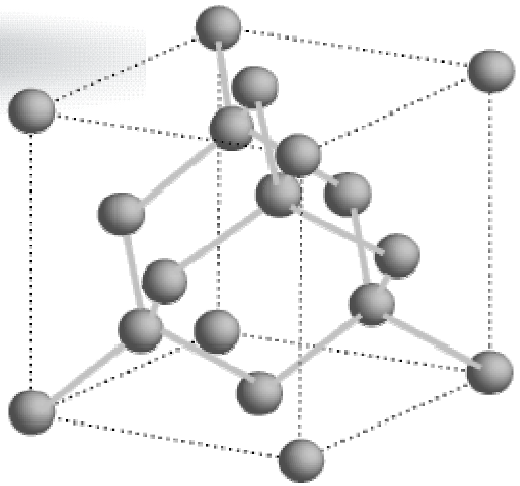
+ See all authors and affiliations

*Science* 04 Aug 1972:
Vol. 177, Issue 4047, pp. 393-396
DOI: 10.1126/science.177.4047.393

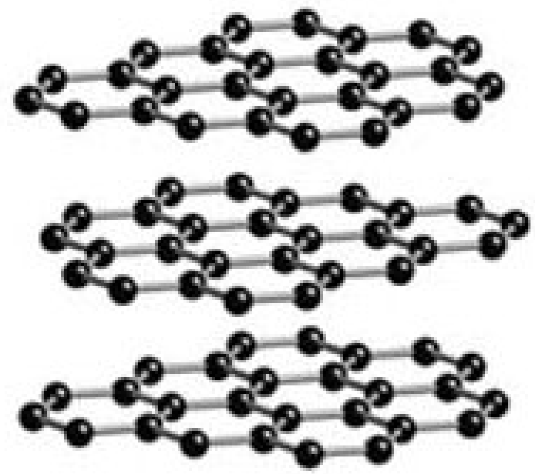
**Philip W. Anderson**
**1923–2020**

# Example: Carbon

- Diamond 金刚石
  - hard
  - insulating
  - transparent

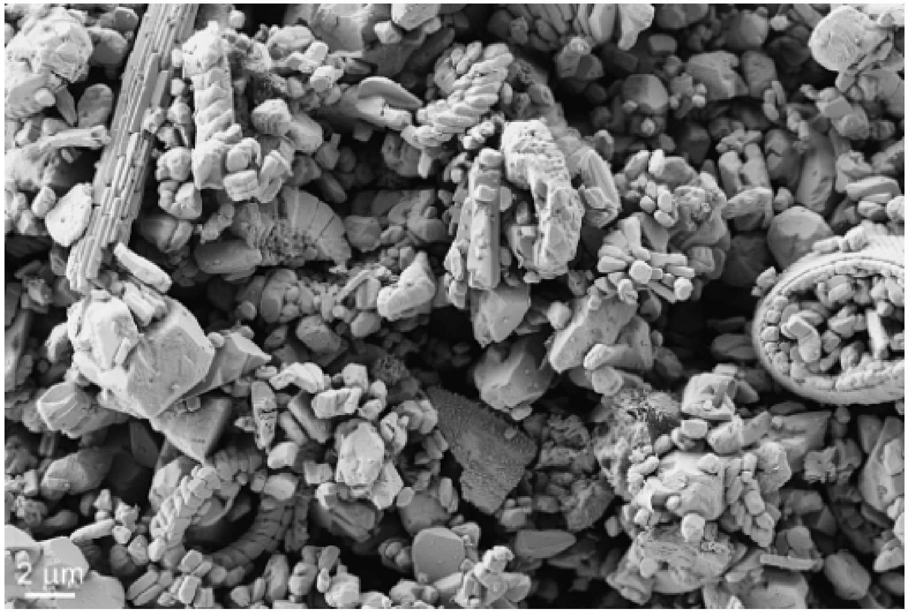


- Graphite 石墨
  - soft
  - conductive
  - black



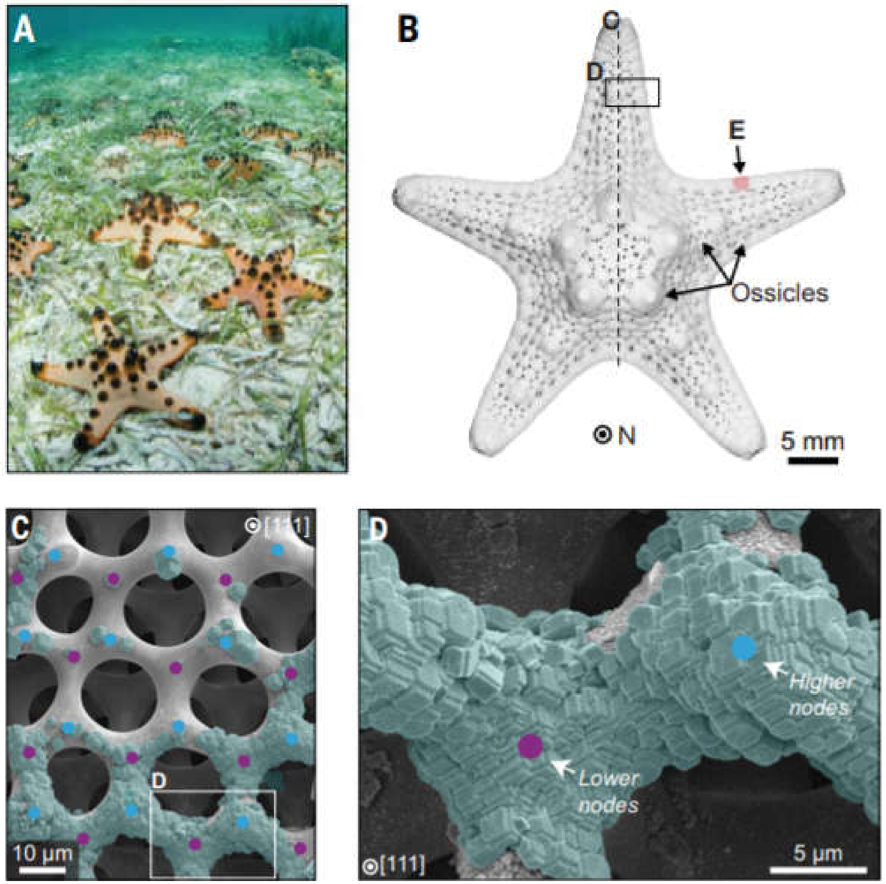
# Example: $CaCO_3$

- **Chalk 粉笔**
  - **brittle**




S. Strand, *et al.*, *Petro. Geosci.* **13,** 69 (2007)

- **Starfish 海星**
  - **robust**

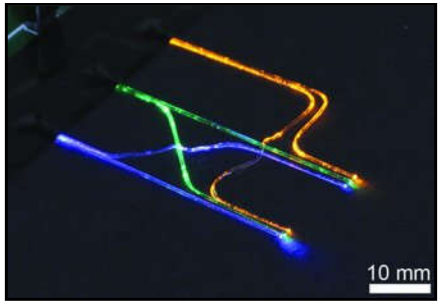



T. Yang, *et al.*, *Science* **375,** 647 (2022)

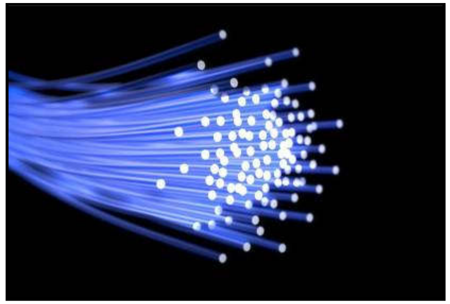
# Optical and Electronic Devices

LEDs

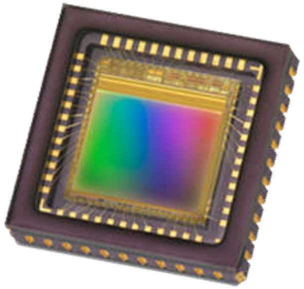
lasers




waveguides

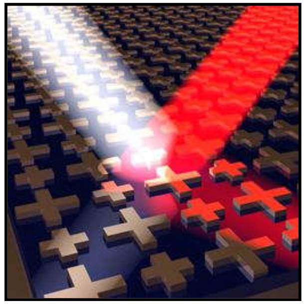


fibers

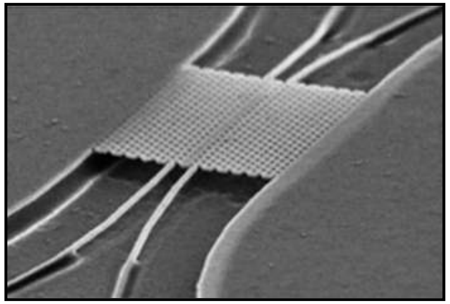


detectors

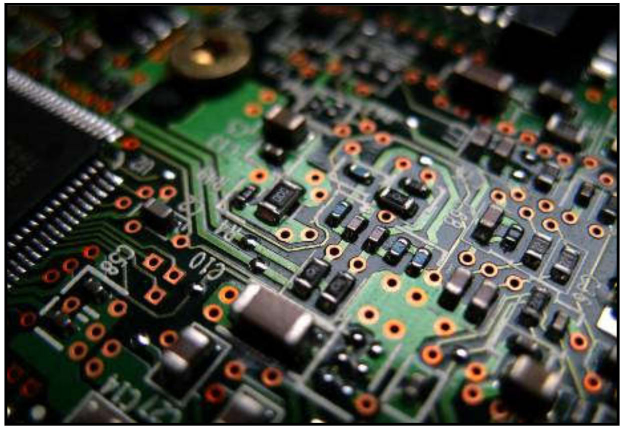
solar cells



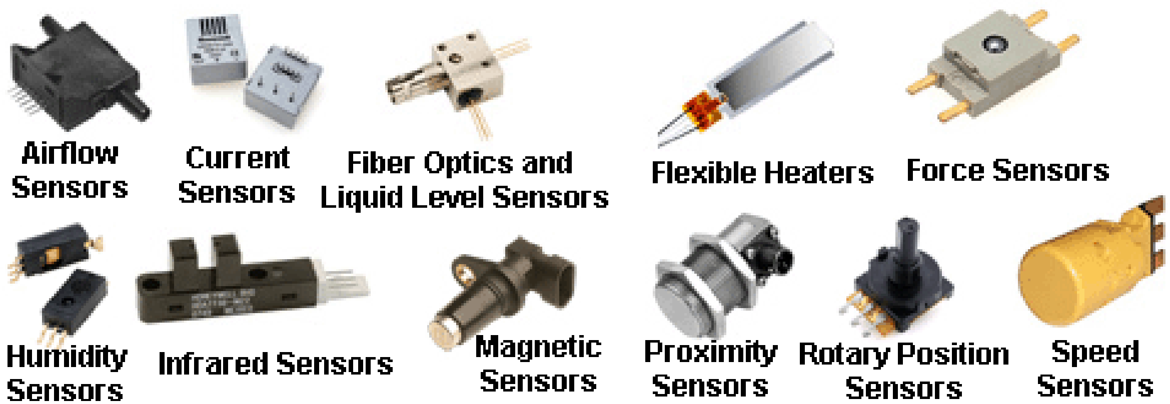
metamaterials



photonic crystals



integrated circuits



# Nobel Prizes in Solid-State Physics

- Before 1950s
  - atoms, materials, radiation, quantum mechanics, ...
- 1956 Semiconductor transistors
- 1991 Liquid crystals
- 2000 Integrated circuits
- 2009 CCD imaging sensors
- 2009 Optical fibers
- 2014 GaN based blue LEDs

# 'Disruptive' Technologies 颠覆性技术

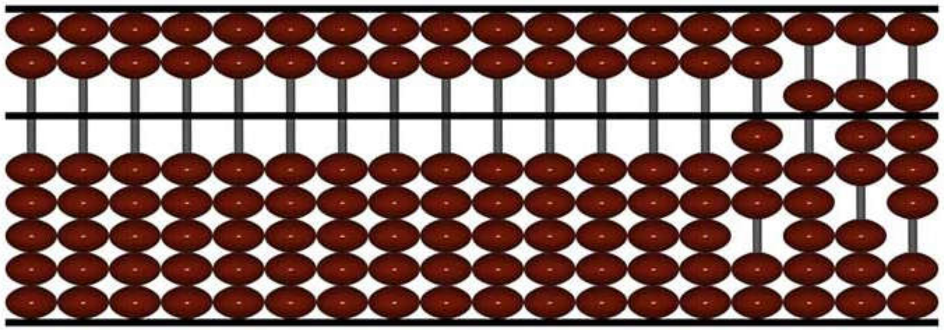
- Before 1950s
  - atoms, materials, radiation, quantum mechanics, ...

| | | | |
|---|---|---|---|
| 1956 | Semiconductor transistors | ← | vacuum tubes |
| 1991 | Liquid crystals | ← | CRT displays |
| 2000 | Integrated circuits | ← | Computation |
| 2009 | CCD imaging sensors | ← | film cameras |
| 2009 | Optical fibers | ← | copper cables |
| 2014 | GaN based blue LEDs | ← | incandescent light bulbs |

# Devices in a Smartphone

| | Nobel Prize |
|---|---|
| ▪ Transistors | 1956 |
| ▪ Liquid crystals | 1991 |
| ▪ Integrated circuits | 2000 |
| ▪ Semiconductor heterostructures | 2000 |
| ▪ CCD cameras | 2009 |
| ▪ GaN blue LEDs | 2014 |
| ▪ Li ion batteries | 2019 (Chemistry) |

# Computation

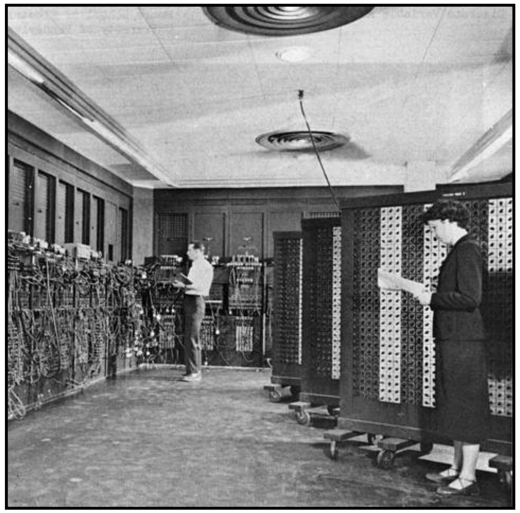


abacus


slide rule

- Ancient computers

- First 'electronic' computer
  - ENIAC, 1943
  - 30 tons, 200 kW
  - 18000 vacuum tubes
  - 5000 times/sec
  - cost $480,000



vacuum tube

# Transistors

***The first point contact transistor***
*William Shockley, John Bardeen, and Walter Brattain*
Bell Laboratories, Murray Hill, New Jersey (1947)

**Germanium**
**Bipolar Transistor**


**semiconductors**

*Bardeen* *Brattain*

*Shockley*

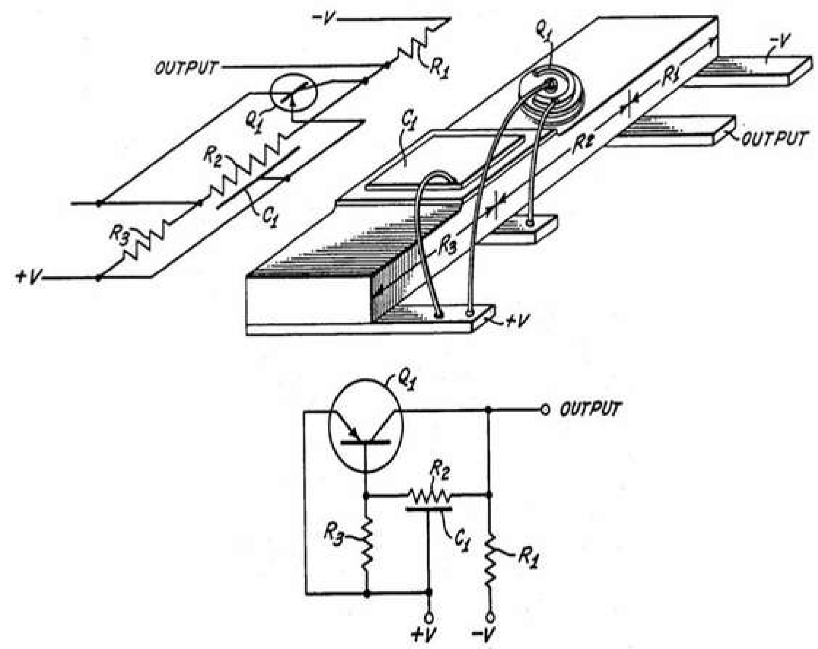
**1956 Nobel Prize in Physics**

# First Integrated Circuits

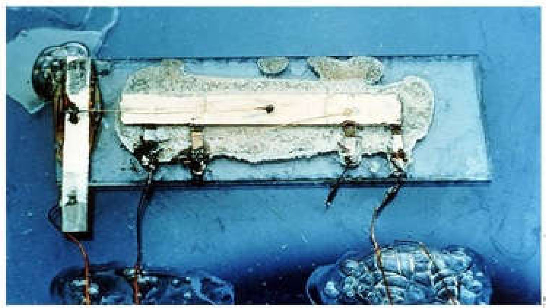
**The First (2D) Integrated Circuit**
**Jack Kilby, Texas Instruments, 1958**

- Transistor, Resistors and Capacitors on the same piece of semiconductor
- Interconnects between components not integrated

  → Low connectivity between components




**Germanium**

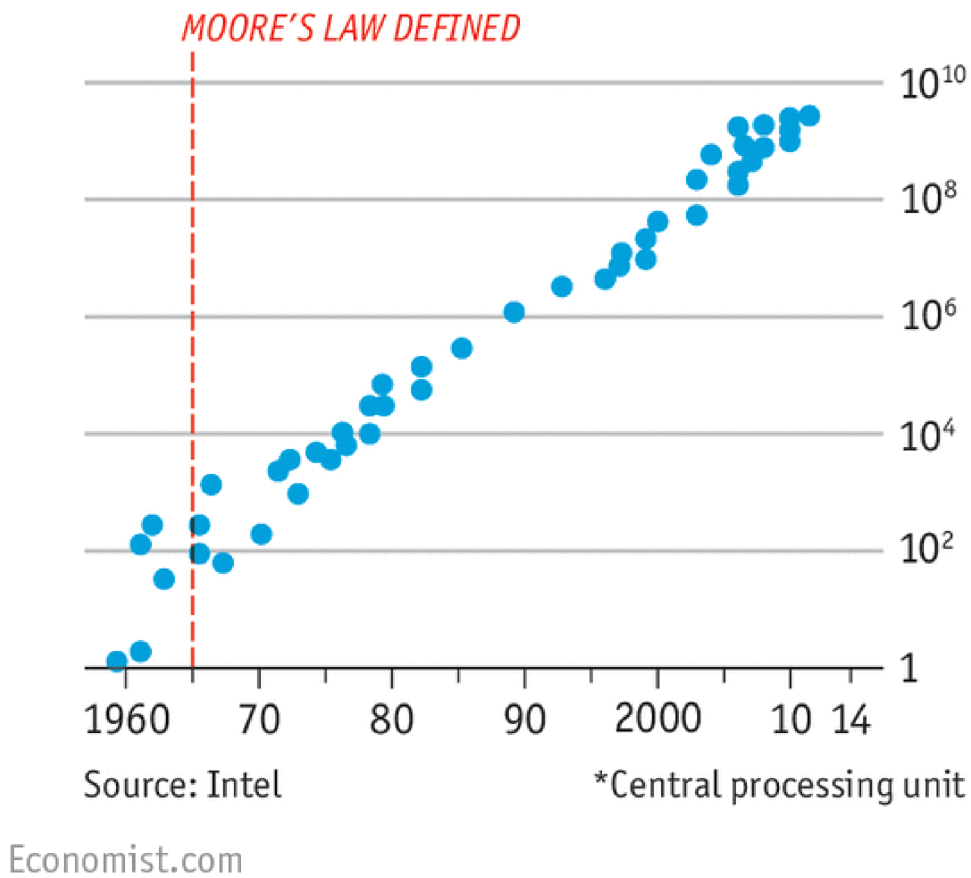


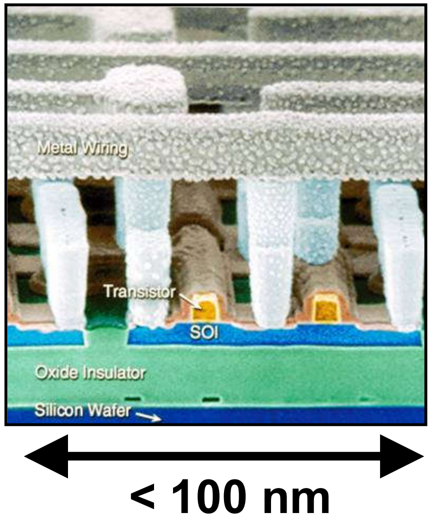
**J. Kilby**

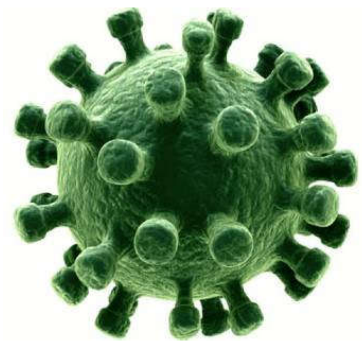
**2000 Nobel Prize in Physics**

# Modern Integrated Circuits

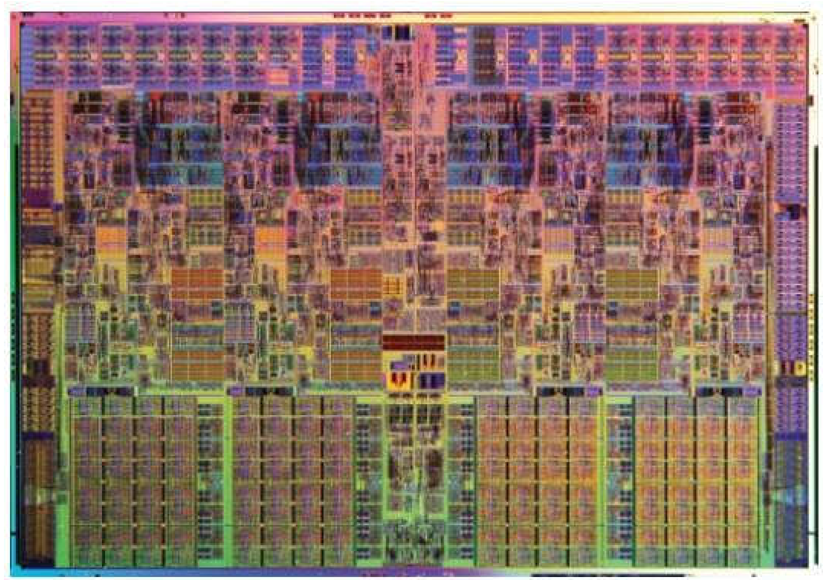
- **Moore's law, Fairchild, 1965**



coronavirus



***Modern Electronics is a real Nanotechnology***

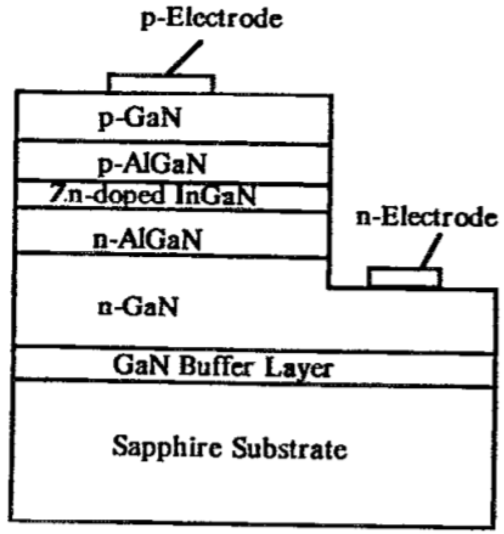
**Intel i7 CPU, ~ $10^9$ transistors**

# Lighting

**Incandescent bulb**

**Fluorescent lamp**

## GaN blue LEDs



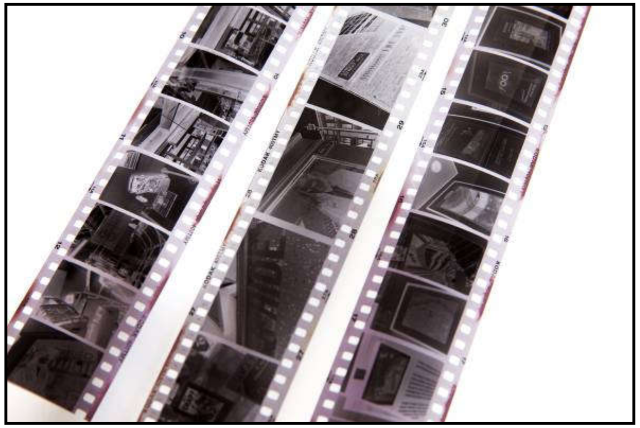

S. Nakamura, *et al.*, *Appl. Phys. Lett.* **64,** 1687 (1994)

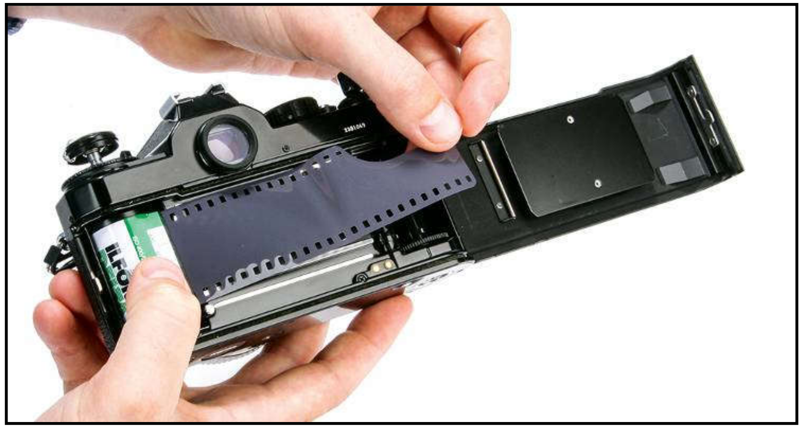
**I. Akasaki H. Amano S. Nakamura**

**2014 Nobel Prize in Physics**

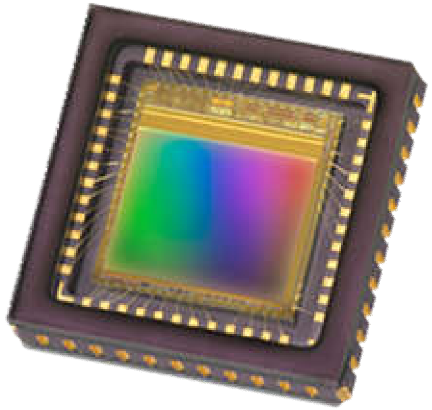
# Imaging

## CCD and CMOS cameras





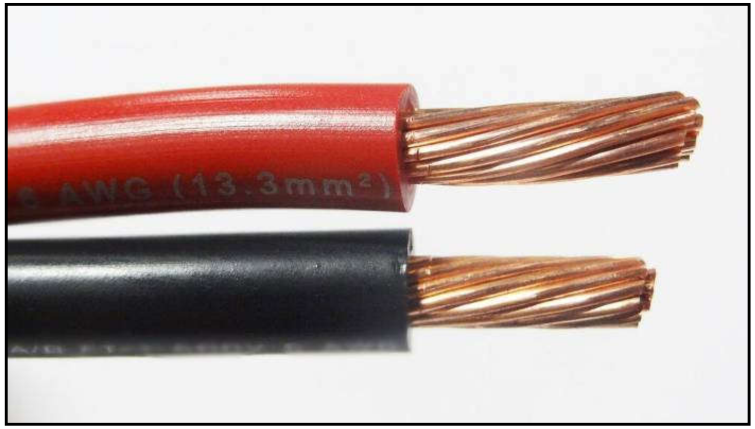
**films**



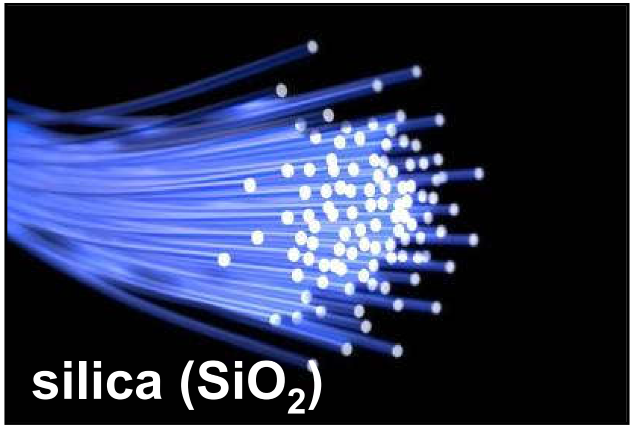
**W. Boyle and G. Smith**

**2009 Nobel Prize in Physics**

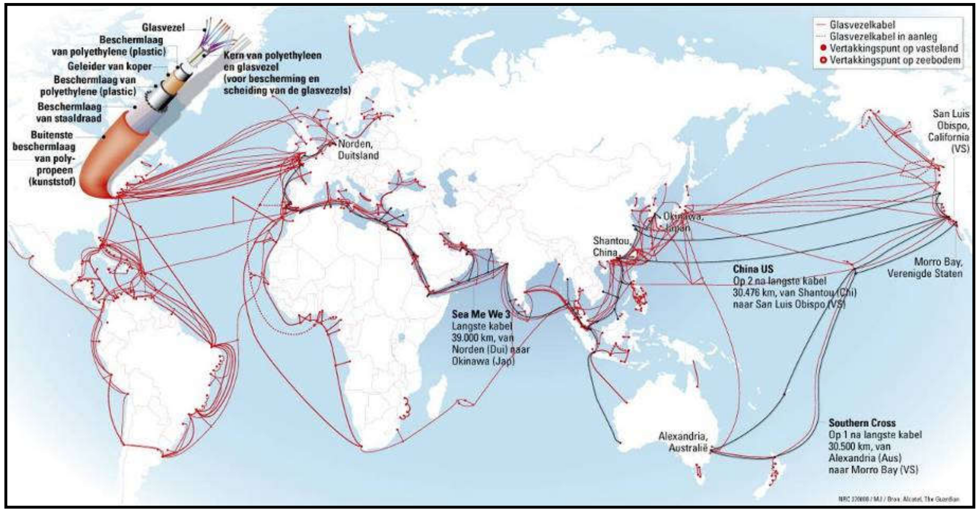
# Communication



copper cables




optical fibers

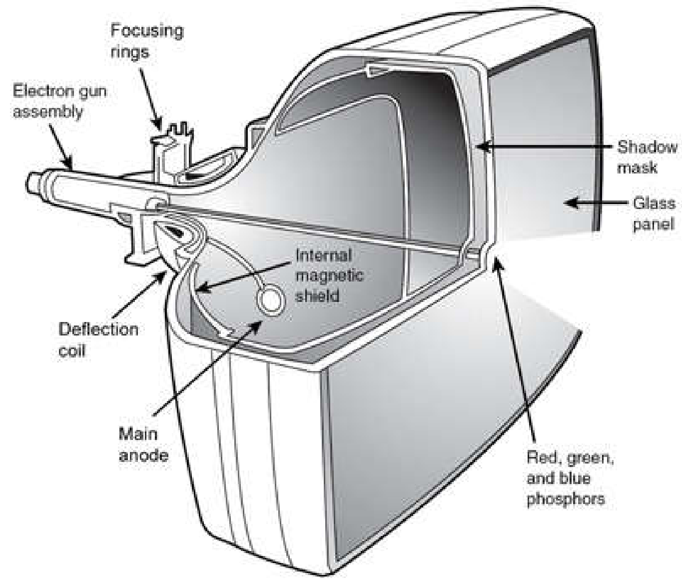



K. Kao (高锟)

2009 Nobel Prize in Physics

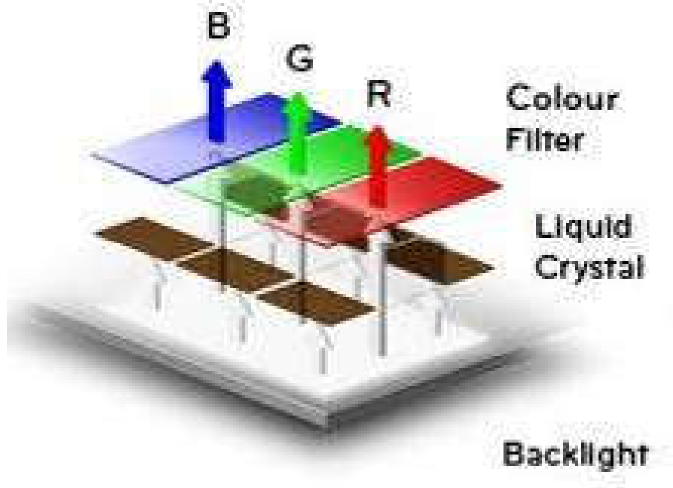
K. C. Kao, G. A. Hockham, *Proc. IEE* **113,** 1151 (1966)

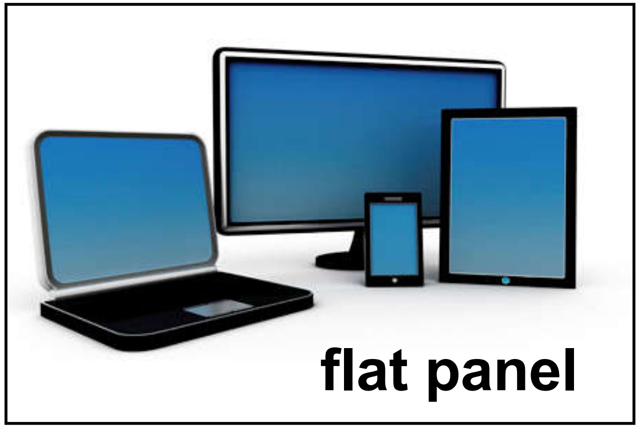
# Displays




Cathode Ray Tube (CRT)

**liquid crystal display (LCD)**




**de Gennes**
**1991 Nobel Prize in Physics**

# Syllabus

- Introduction (Week 1)
- Materials and Crystal Structures (Week 2–3)
- Electronic Properties (Week 4–12)
- Thermal Properties (Week 13)
- Optical Properties (Week 14)
- Magnetic Properties (Week 15)

# Syllabus

- **Introduction (Week 1)**
  - **Overview, history, applications**
  - **Preliminary knowledge**
- **Materials and Crystal Structures (Week 2–3)**
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- **Thermal Properties (Week 13)**
- **Optical Properties (Week 14)**
- **Magnetic Properties (Week 15)**

# Syllabus

- Introduction (Week 1)
- **Materials and Crystal Structures (Week 2–3)**
  - Bravais lattices, Crystal structures, Defects
  - Reciprocal space, Brillouin zones
  - Materials Characterization: Wave diffraction, the Bragg law
- Electronic Properties (Week 4–12)
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- Introduction (Week 1)
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- **Electronic Properties (Week 4–12)**
  - Free electrons (the Drude and Sommerfeld models)
  - Electrons in a periodic potential, Bloch's Theorem
  - The nearly free electron model, the tight-binding model
  - Electronic band diagram, band gaps, effective mass, holes
  - Metals, insulators, semiconductors
  - Devices: junctions, diodes, transistors
- Thermal Properties (Week 13)
- Optical Properties (Week 14)
- Magnetic Properties (Week 15)

# Syllabus

- Introduction (Week 1)
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- Electronic Properties (Week 4–12)
- **Thermal Properties (Week 13)**
  - Crystal vibration, phonon band
  - Thermal conductivity and capacity
- Optical Properties (Week 14)
- Magnetic Properties (Week 15)

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- Introduction (Week 1)
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- Electronic Properties (Week 4–12)
- Thermal Properties (Week 13)
- **Optical Properties (Week 14)**
  - **Origin of Dielectric constant ($\varepsilon$) and Refractive index ($n$)**
  - **Optical absorption, reflection, refraction, emission**
- Magnetic Properties (Week 15)

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- Introduction (Week 1)
- Materials and Crystal Structures (Week 2–3)
- Electronic Properties (Week 4–12)
- Thermal Properties (Week 13)
- Optical Properties (Week 14)
- **Magnetic Properties (Week 15)**
  - Origin of Magnetics
  - Diamagnetism, Paramagnetism, Ferromagnetism
  - Superconductivity

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***Thank you for your attention***