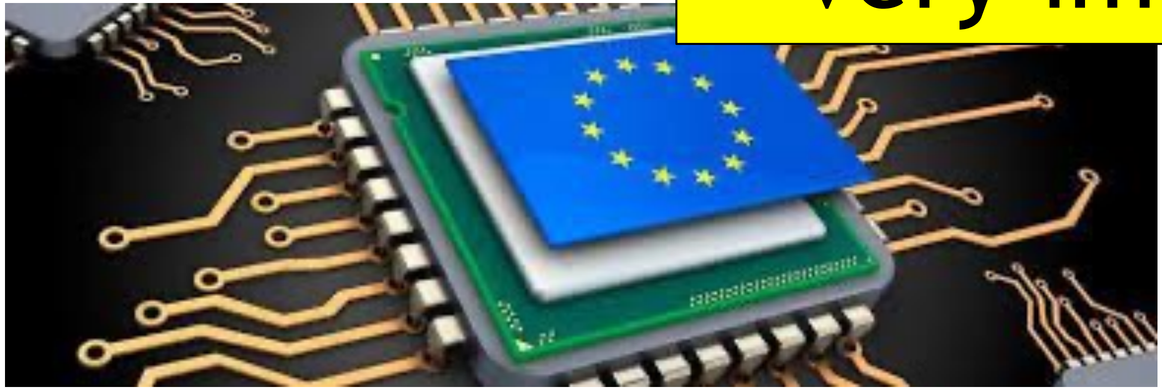
The Awesome World Enabled by the Transistor

Alvin Loke
San Diego, CA

Special Acknowledgment to
Alessandro Piovaccari

Semiconductors in the News

Must be globally very important



Silicon is the new oil!!!

Semiconductors in the News

The New York Times

America's Semiconductor Boom Faces a Challenge: Not Enough Workers

Strengthened by billions of federal dollars, semiconductor companies plan to create thousands of jobs. But officials say there might not be enough people to fill them.

America Faces Significant Shortage of Tech Workers in Semiconductor Industry and Throughout U.S. Economy

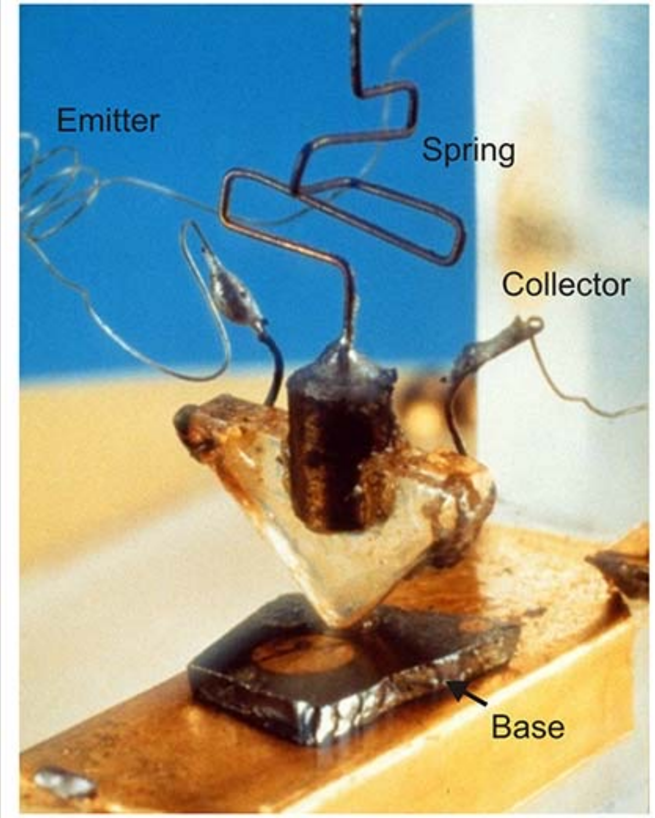
Tuesday, Jul 25, 2023, 5:00am
by **Semiconductor Industry Association**

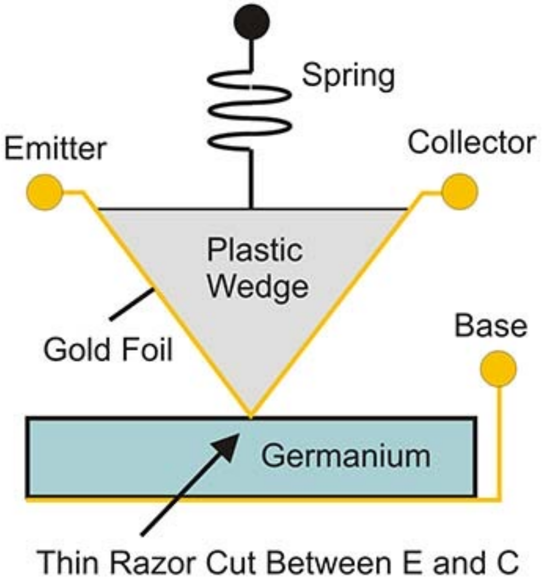
An estimated 67,000 jobs for technicians, computer scientists, engineers in semiconductor industry—and 1.4 million such jobs across the U.S. economy—risk going unfilled by 2030, according to new SIA/Oxford Economics study

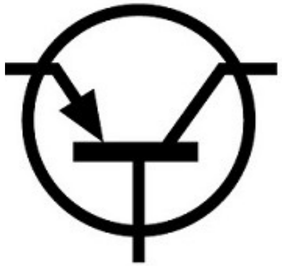
WASHINGTON—July 25, 2023—The Semiconductor Industry Association (SIA), in partnership with Oxford Economics, today released a study finding the United States faces a significant shortage of technicians, computer scientists, and engineers, with a projected shortfall of 67,000 of these workers in the semiconductor industry by 2030 and a gap of 1.4 million such workers throughout the broader U.S. economy. The report, titled "Chipping Away: Assessing and Addressing the Labor Market Gap Facing the U.S. Semiconductor Industry," also makes a set of policy recommendations to help close the talent gap and complement the workforce development initiatives that are already being carried out by semiconductor companies across the U.S.

A Humble Beginning 75 Years Ago

75TH ANNIVERSARY | TRANSISTOR







- First transistor was successfully demonstrated on December 23, 1947 at Bell Labs in Murray Hill, NJ (research arm of AT&T)
- Invented by John Bardeen, Walter Brattain & William Shockley

https://www.nutsvolts.com/magazine/article/the-story-of-the-transistor

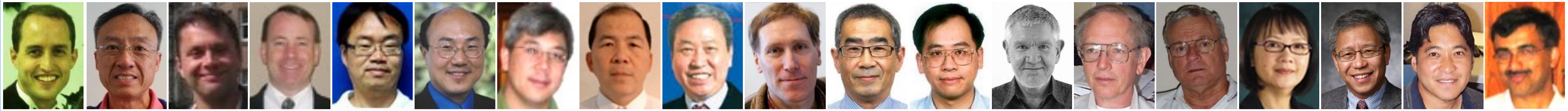
Me In a Nutshell

- Born in Malaysia, grew up in Vancouver (Canada), adult & family life in US
- Education: UBC BASc Engineering Physics, Stanford MS/PhD Electrical Eng.
  - Tinkered with electronics since 8th Grade
  - Intern for 6 summers (Texas Instruments, Motorola, Sumitomo Electric, …)
  - Fell in love with semiconductor physics in college junior year, still in love with it
- 25 years in industry (HP/Agilent, AMD, Qualcomm, TSMC, NXP)
  - Started in semiconductor technology development
  - Moved to analog design & technology/modeling interface
  - Now focused on design methodology & high-speed design
  - Worked on every CMOS node from 250nm down to 2nm (15 nodes)
  - Lived in Bay Area, Osaka, Singapore, Texas, Colorado, now San Diego
  - Active IEEE volunteer for 22+ years
- Wife Tin Tin is also circuit designer with semiconductor background
- Two kids – Theo (10th Grade) & Josephene (7th Grade)

My Mentors and Teachers

Matt Angyal | Larry Bair | Bob Bardsley | Bob Barnes | Suzanne Biganzoli | John Bravman | Mike Brunolli | Min Cao | Luigi Colombo | Tom Cynkar | Reinhold Dauskardt | Dick Dowell | Bruce Doyle | Pat Drennan | John Dyck | Emerson Fang | John Faricelli | Dennis Fischette | Phil Fisher

Dan Friedman | Doug Garrity | Lixin Ge | Mike Gilsdorf | Jung-Suk Goo | Bob Havemann | Rick Hernandez | Paul Holdaway | Tim Hollis | Mark Horowitz | Allen Hull | Reza Jalilizeinali | Philippe Jansen | Ted Kagetsu | Ron Kennedy | Takamaro Kikkawa | Xiaohua Kong | Greg Kovacs | Joachim Krücken



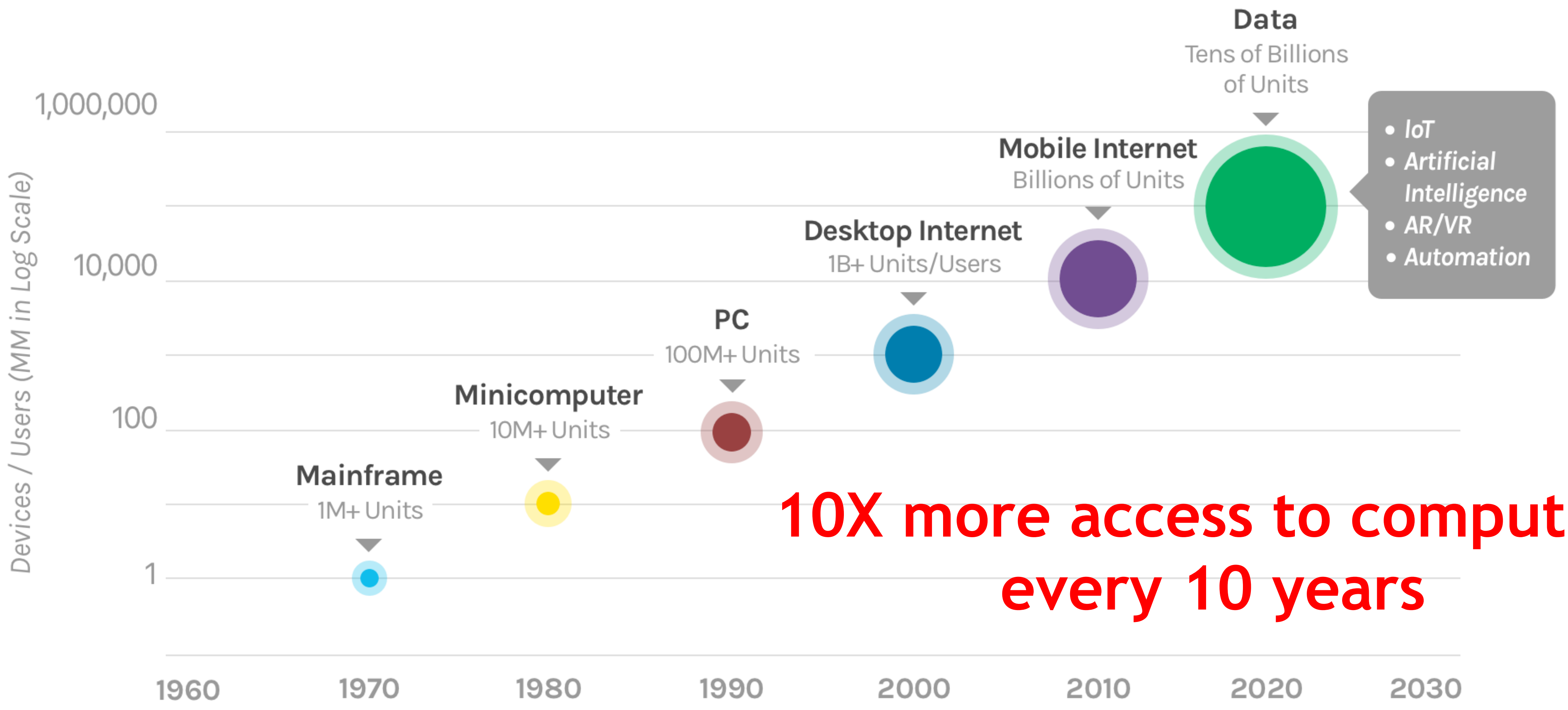
Steve Kuehne | Benny Lai | Ralph Lang | Mike Leary | C.K. Lee | Tom Lee | Justin Leung | Tom Lii | Rich Liu | John Long | Linus Lu | Shawming Ma | Colin McAndrew | Charles Moore | Don Morris | Bich-Yen Nguyen | Ken O | Michael Oshima | Chintamani Palsule

Marcel Pelgrom | Jim Pfiester | Alessandro Piovaccari | Jim Plummer | Dave Pulfrey | Gary Ray | Behzad Razavi | Jeff Rearick | Ken Rim | Paul Rissman | Changsup Ryu | Krishna Saraswat | Shawn Searles | Ray Stephany | David Sunderland | Gerry Talbot | Tom Tiedje | Paul Townsend | Jan van der Spiegel

Ram Venkatraman | Martin Wedepohl | Tin Tin Wee | Andy Wei | Jeff Wetzel | Daniel Weyl | Rick White | Philip Wong | Simon Wong | Bruce Wooley | Joanne Wu | Philippe Wyns | Guoqiang Xing | Joseph Yan | Geoffrey Yeap | Bo Yu | Patrick Yue | Carl-Mikael Zetterling

Barry Barnes
Maureen Brongo
Qi-Zhong Hong
Wei-Yung Hsu

Semiconductor Demand

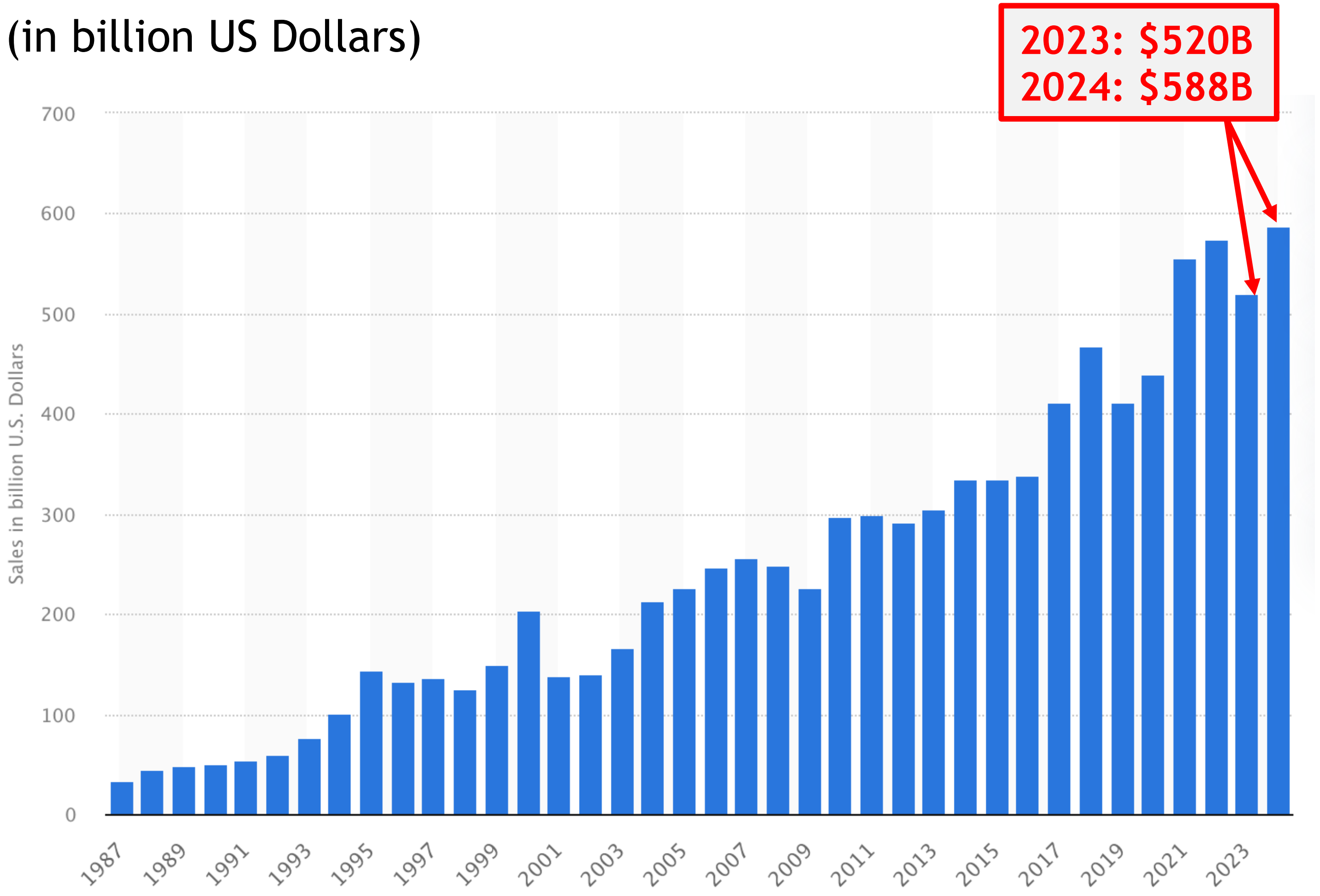


10X more access to computing every 10 years

Source: Morgan Stanley
(Courtesy Alessandro Piovaccari)

Worldwide Semiconductor Market Size

(in billion US Dollars)



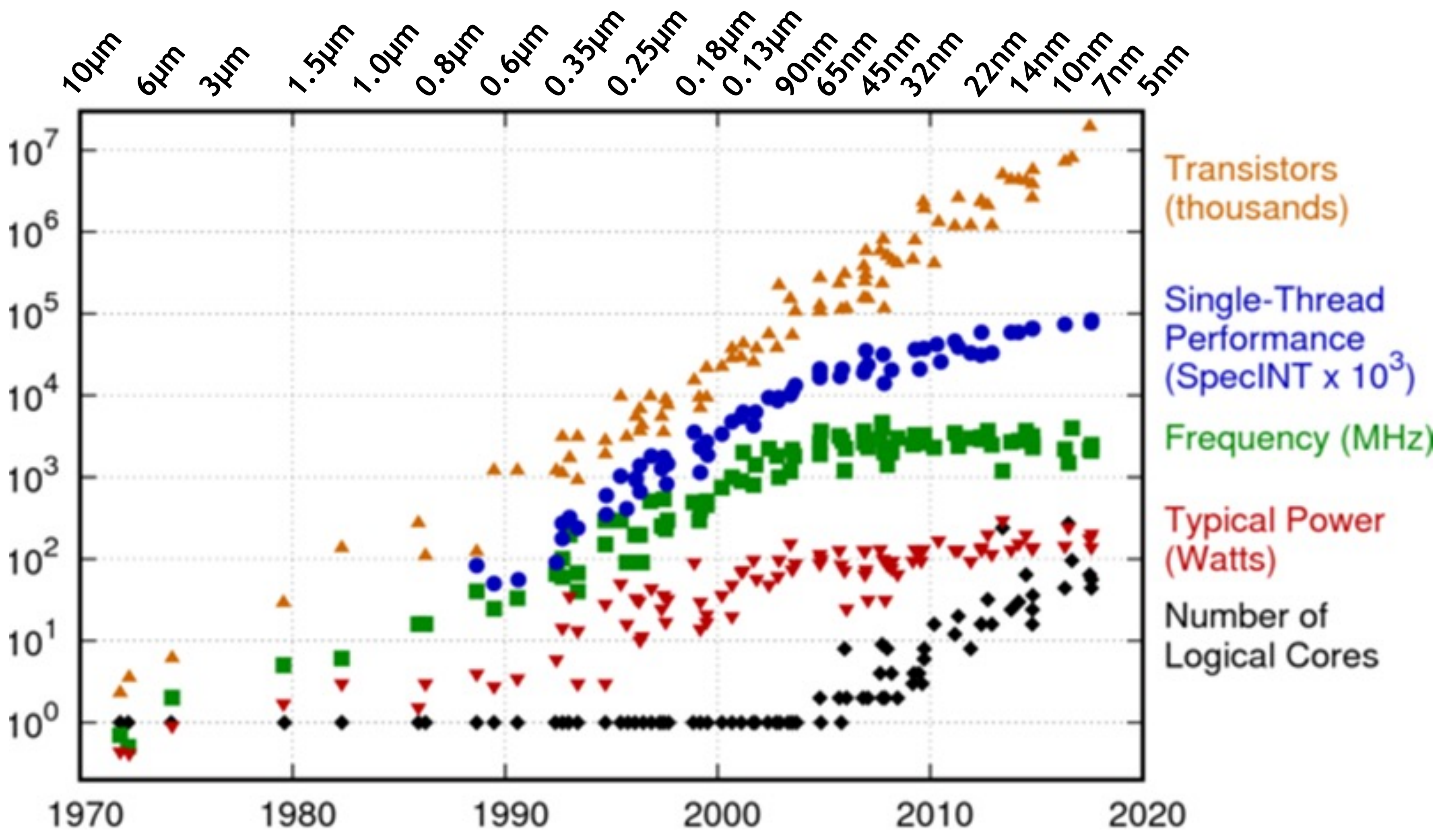
Let's put it in context…

→ Worldwide Markets (2021)

- Semiconductors: $553B
- GDP: $93,864B
- IT Data Centers: $228B
- IT Devices: $705B
- Car & Auto: $3,600B
- Home Appliances: $420B
- Semiconductor market expected to hit $1T in 2030

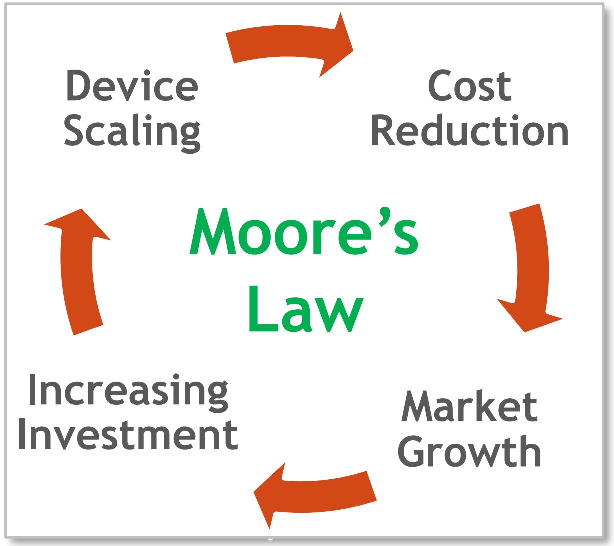
Sources: Statista, IBIS World, SIA
Reference: [SIA2021], [Gartner2021]
(Courtesy Alessandro Piovacarri)

What Makes This All Possible?



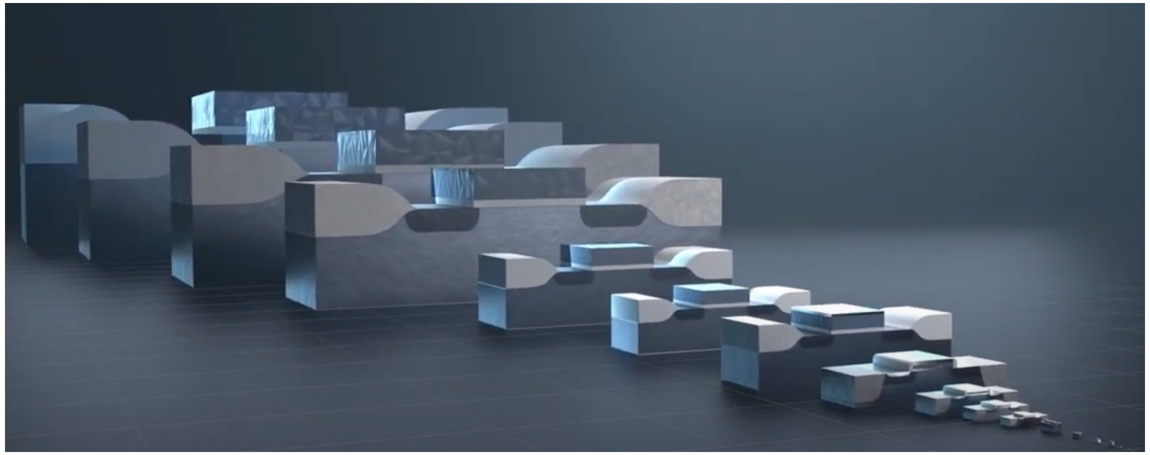
Source: https://www.karlrupp.net/2018/02/42-years-of-microprocessor-trend-data/

Miniaturizing (scaling) transistors makes them cheaper, faster, and more energy efficient



(Courtesy Alessandro Piovacarri)

What 50 Years of Moore's Law Has Enabled



(Source: intel.com)

- 1,000,000X smaller
- 3,500X greater performance
- 60,000X lower cost
- 90,000X more energy efficient

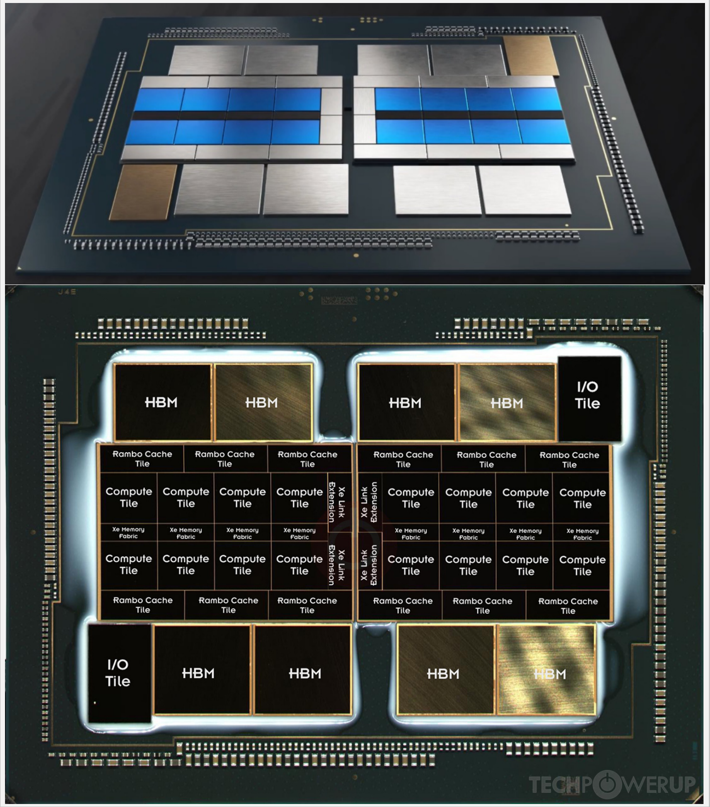
If car technology progressed at the same pace as semiconductors, the VW Beetle would:

- Go 300,000 mph
- Cost $0.04
- Get 2,000,000 miles per gallon of gas
- Last your entire life on one single tank of gas

(Courtesy Joe DiFilippo)

What's Possible After 50 Years

Intel Ponte Vecchio GPU (2023)
100B transistors
47 tiles in 5 process nodes
including TSMC 5nm + Intel 7nm
1.6GHz - 600W



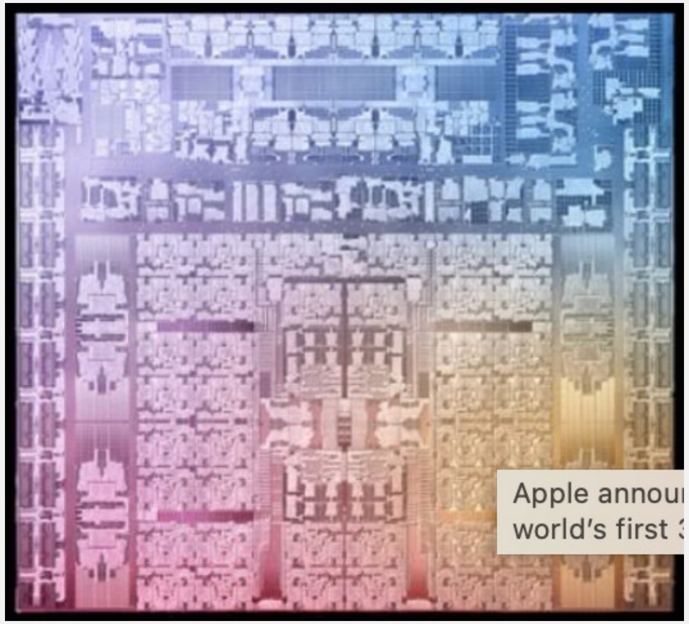
Source: intel.com

(Courtesy Alessandro Piovaccari)

Xilinx Virtex Ultrascale+ VU19P (2019)
35B transistors (total)
TSMC 16FF+ + CoWoS (4 dies)
16xA9 - 9M SLCs
2K I/Os - 4.5 Tbps BW

Source: AnandTech

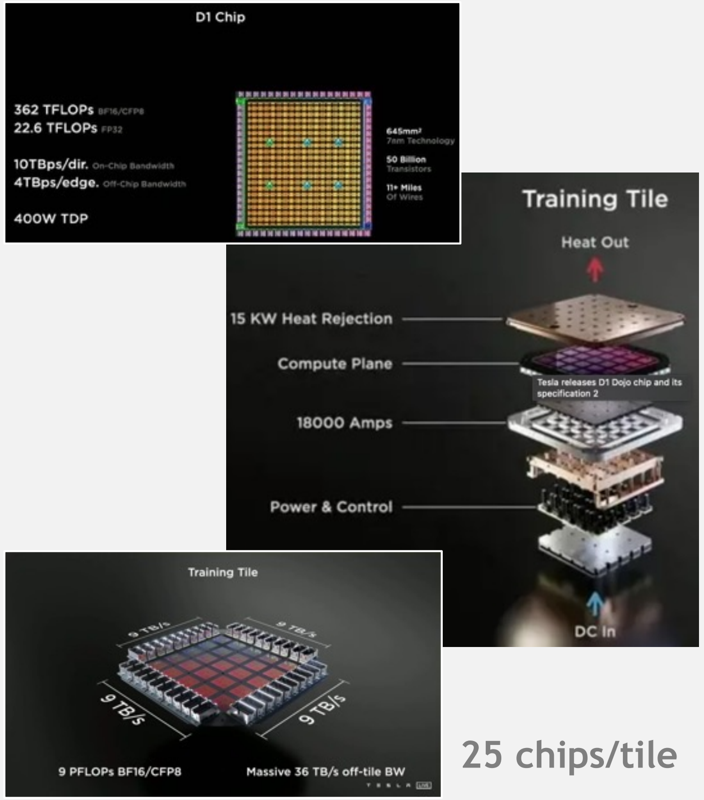
Apple M3 Max (2023)
92B transistors
TSMC 3nm (core)
16 CPU + 40 GPU
4.05 GHz - 78 W



Source: apple.com

More Amazing Possibilities

Tesla D1 (2021)
50B transistors (total)
TSMC 7nm
425MB cache - 16 Tbps BW
362 Tflop (BF16/CFP8) - 400W

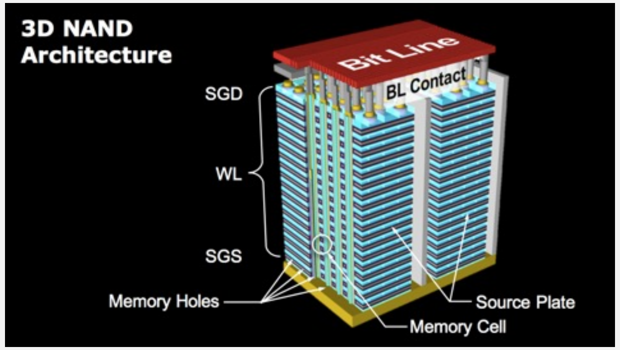


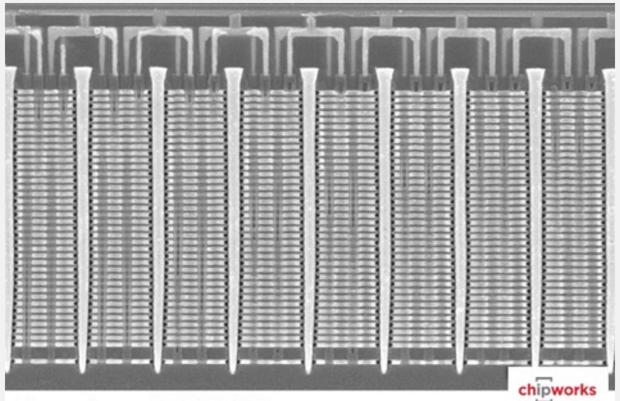
25 chips/tile

Source: teslanorth.com

(Courtesy Alessandro Piovaccari)

Samsung V-NAND Flash (2020)
2T transistors (3D stack)
Samsung V-NAND (100+ layers)
8x 256 Gb dies
1.4 Gbps

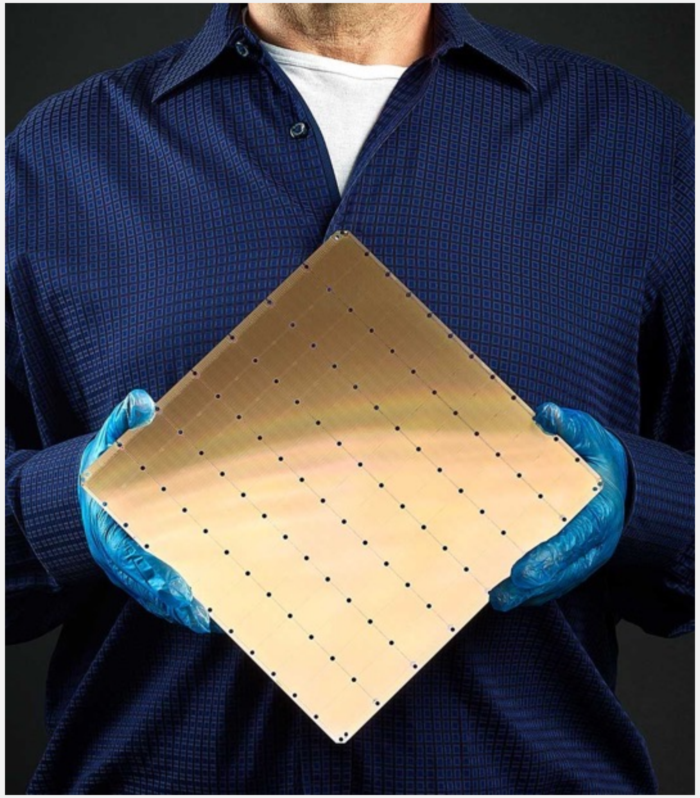




Close-up image of V-NAND flash array

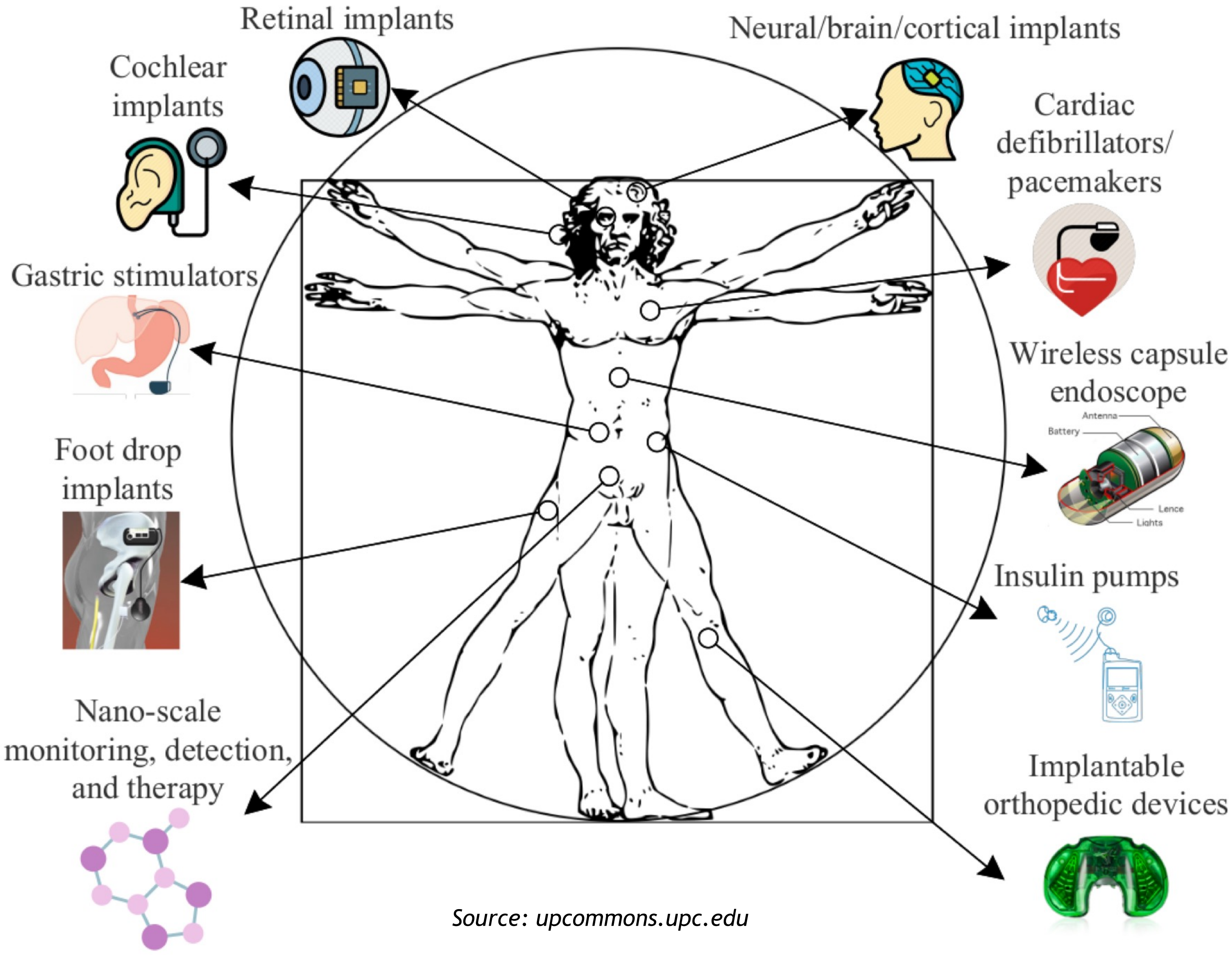
Source: Samsung, Chipworks

Cerebras WSE-2 (2019)
2.6T transistors
TSMC 7nm
850K cores - 40GB RAM
-



References: [Moore2021ISM]

Beyond Computing Applications



Source: upcommons.upc.edu

- Lots of amazing possibilities starting to emerge as other fields begin to understand how to apply semiconductor technology
- Science fiction turning into reality
- Lots more unexplored possibilities !!!

A Semiconductor Fab is Like a Book-Printing Plant That Happens To Be WAY More Expensive

Human Scale

Book Printing	Chip Fabrication
An author writes a book *They use a word processor*	 An engineer designs a chip *They use EDA Tools*
They contract with a publisher who sends text to the printing plant *It may print novels, tech manuals, histories, etc.*	 They select a Fab appropriate for their type of Chip *Memory, logic, RF, analog*
The plant buys raw materials *Paper, ink*	 The fab buys raw materials *Silicon, chemicals, gases*
The plant buys printing machinery *printing presses, binding, trimming*	 The fab buys wafer fab equipment *Etchers, deposition, lithography, testers, packaging*
The printing process - offset lithography *Filming, stripping, blueprints, plate making, printing, binding, trim*	 Chip manufacturing process - offset lithography *Etching, diffusion, lithography, assembly, testing, packaging*
The plant turns out millions of copies	 The plant turns out millions of copies

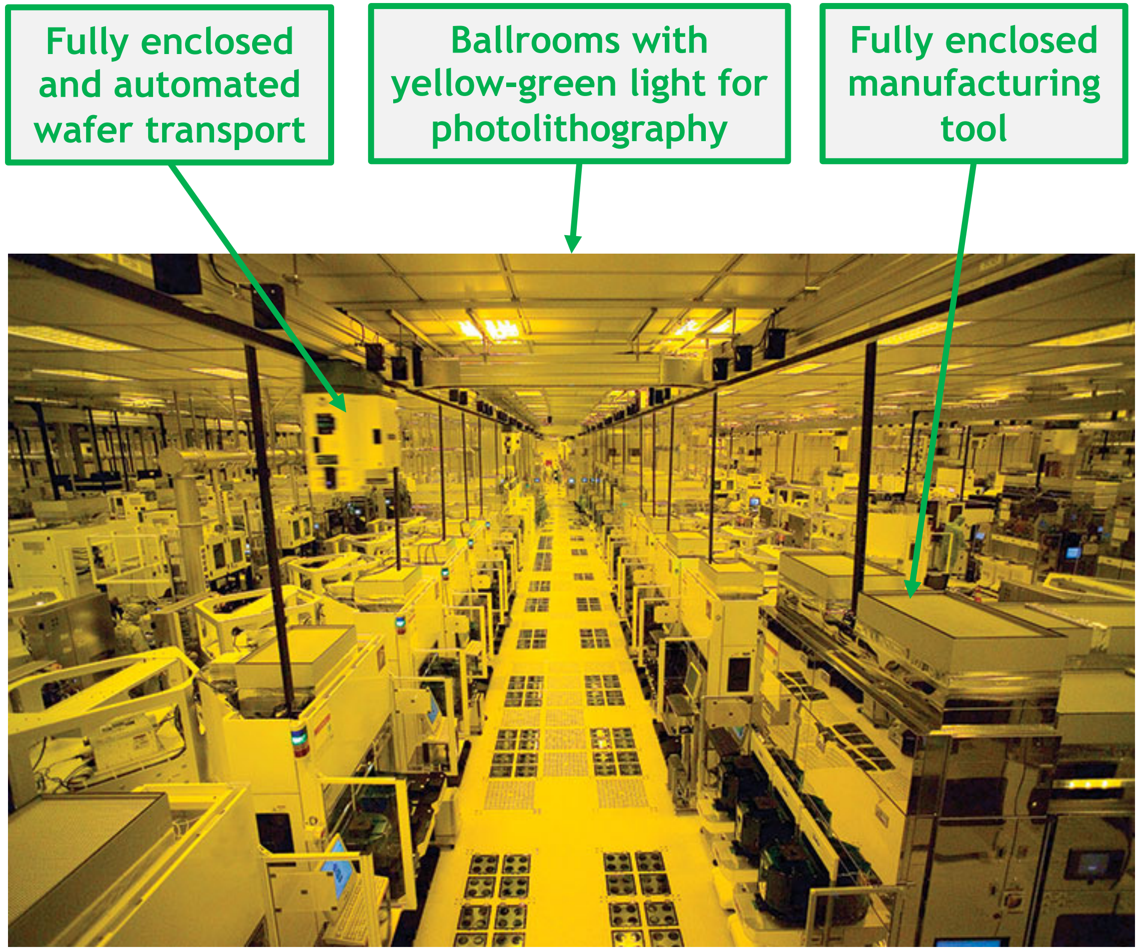
Atomic Scale

Source: SemiWiki

(Courtesy Alessandro Piovaccari)

A Modern Mega-Fab (Wafer Fabrication Plant)

- Typical price tag of $20B
- Throughput of 30-50k wafers per month
- Depreciates at $0.5M per hour

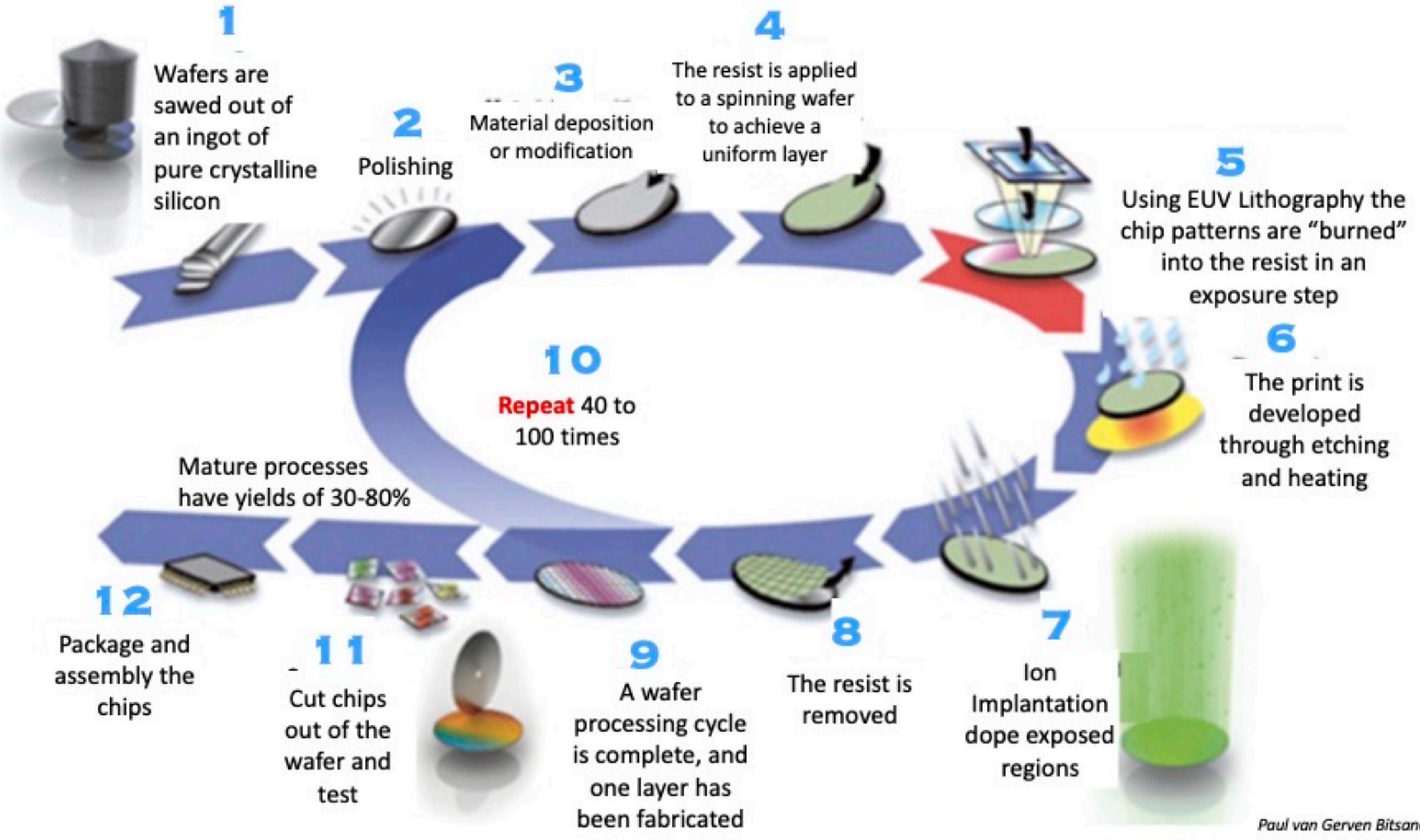


Source: WikiChip

(Courtesy Alessandro Piovaccari)

Chip Fabrication (Wafer Processing)

- All the action happens on the surface of a silicon wafer
- Sequentially deposit or remove/etch layer after layer of different materials
- Each deposited or etched layer is patterned using a different mask pattern
- Several thousand steps to complete a chip using 40 to 100 masks
- Chips are probably the most complicated products ever manufactured

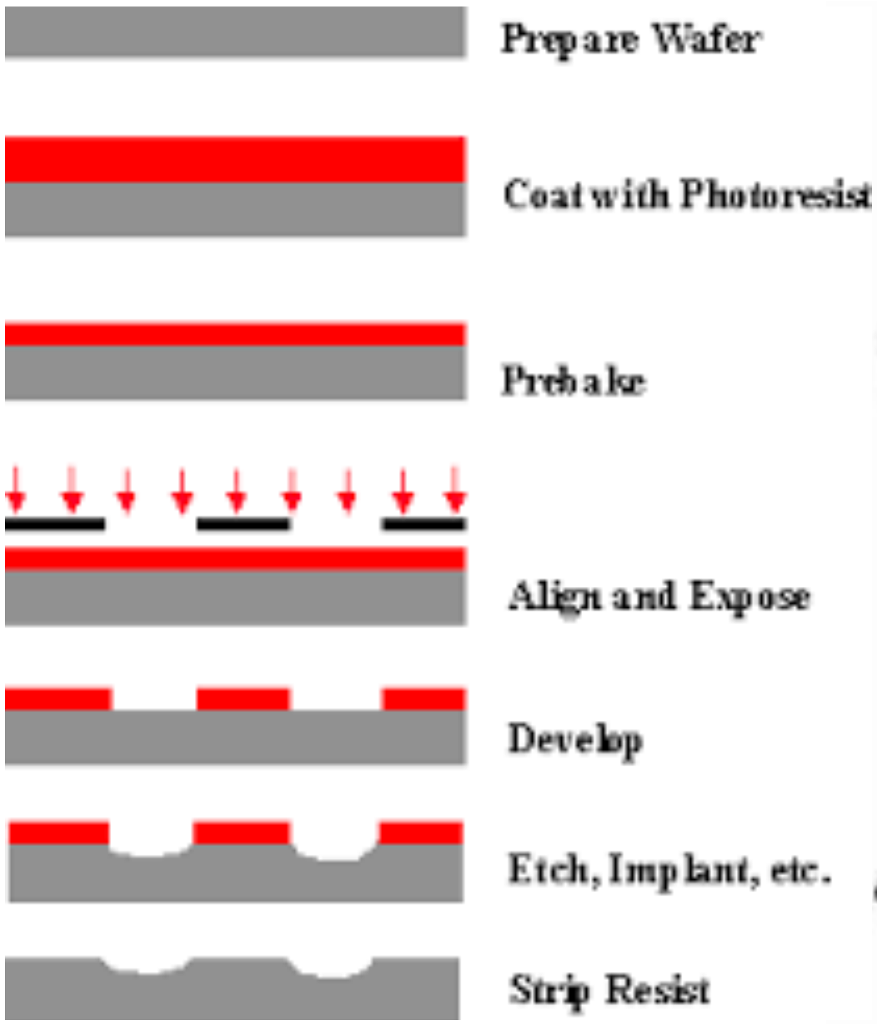


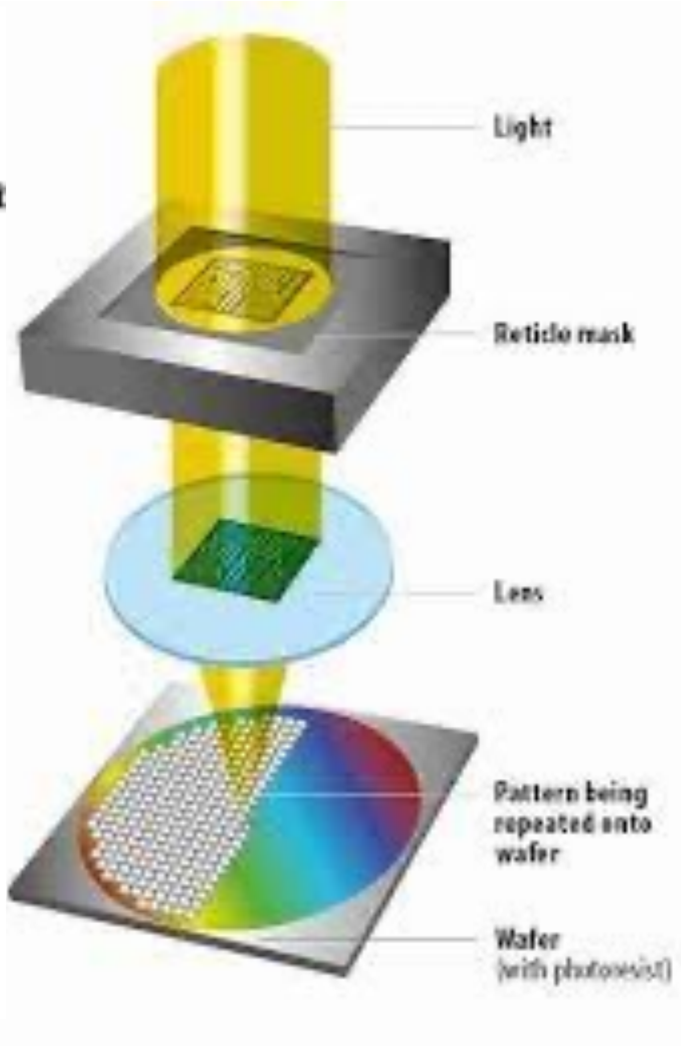
(Courtesy Alessandro Piovaccari)

Source: Bits & Chips

The Same Effort to Make 1 vs. 10B+ Transistors

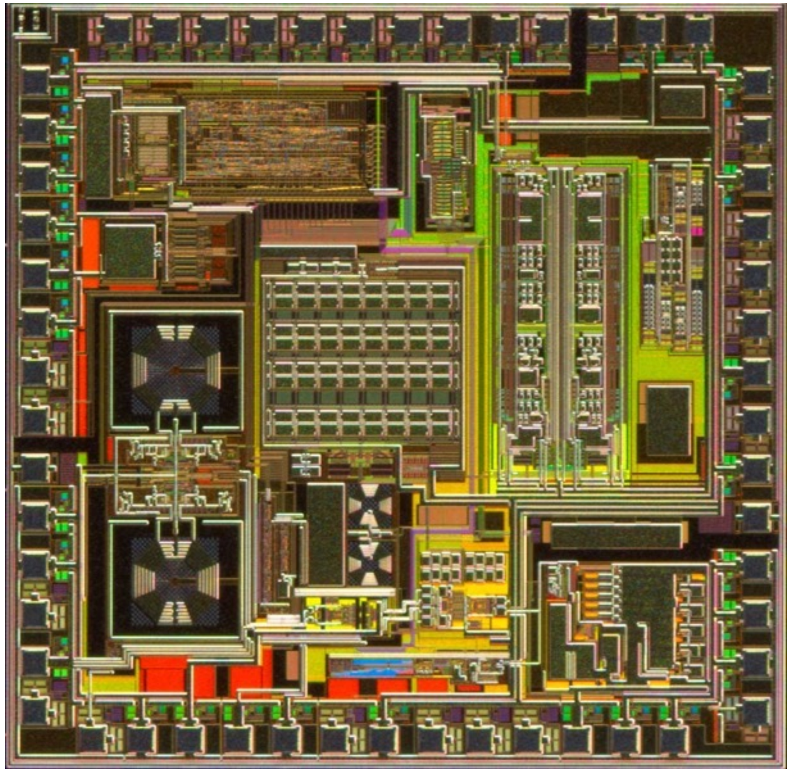
- Expose entire chip in one shot
- Pattern smaller features by using shorter wavelengths of light to expose photoresist (historically started at 436nm, now 13.5nm)
- Commonplace today to print nm-scale patterns
- Must be done in “clean room” free of dust particles that will destroy integrity of mask patterns





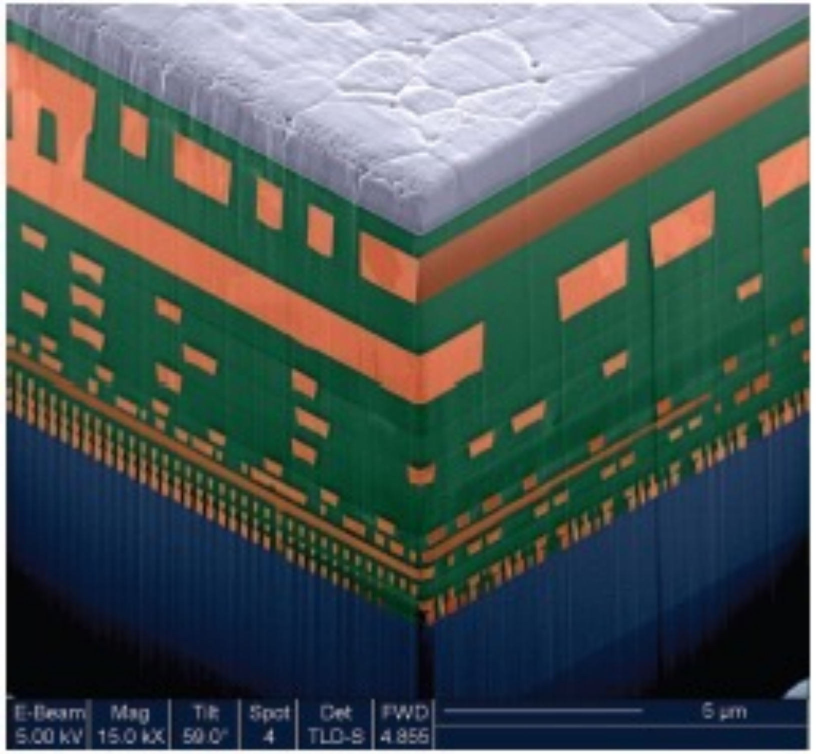
The Result

Top View of a Die



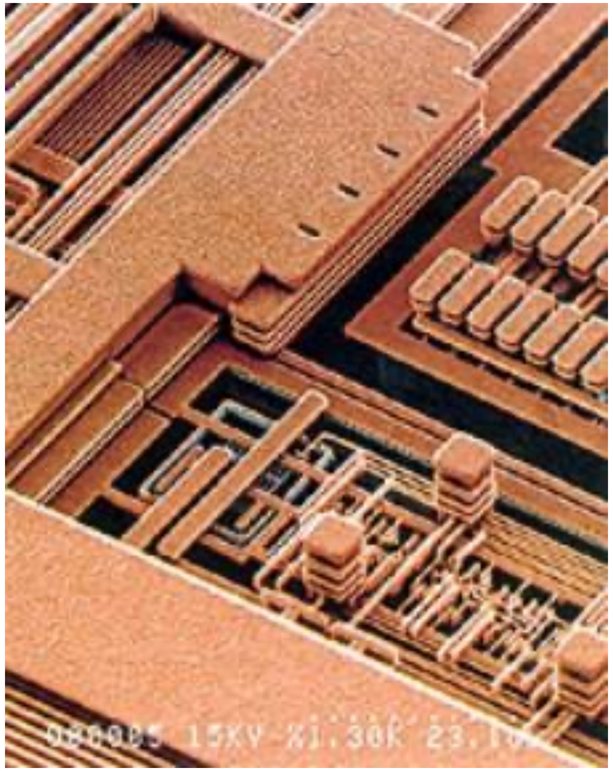
Source: IBM

Cross-section



Source: IBM

Metal layers

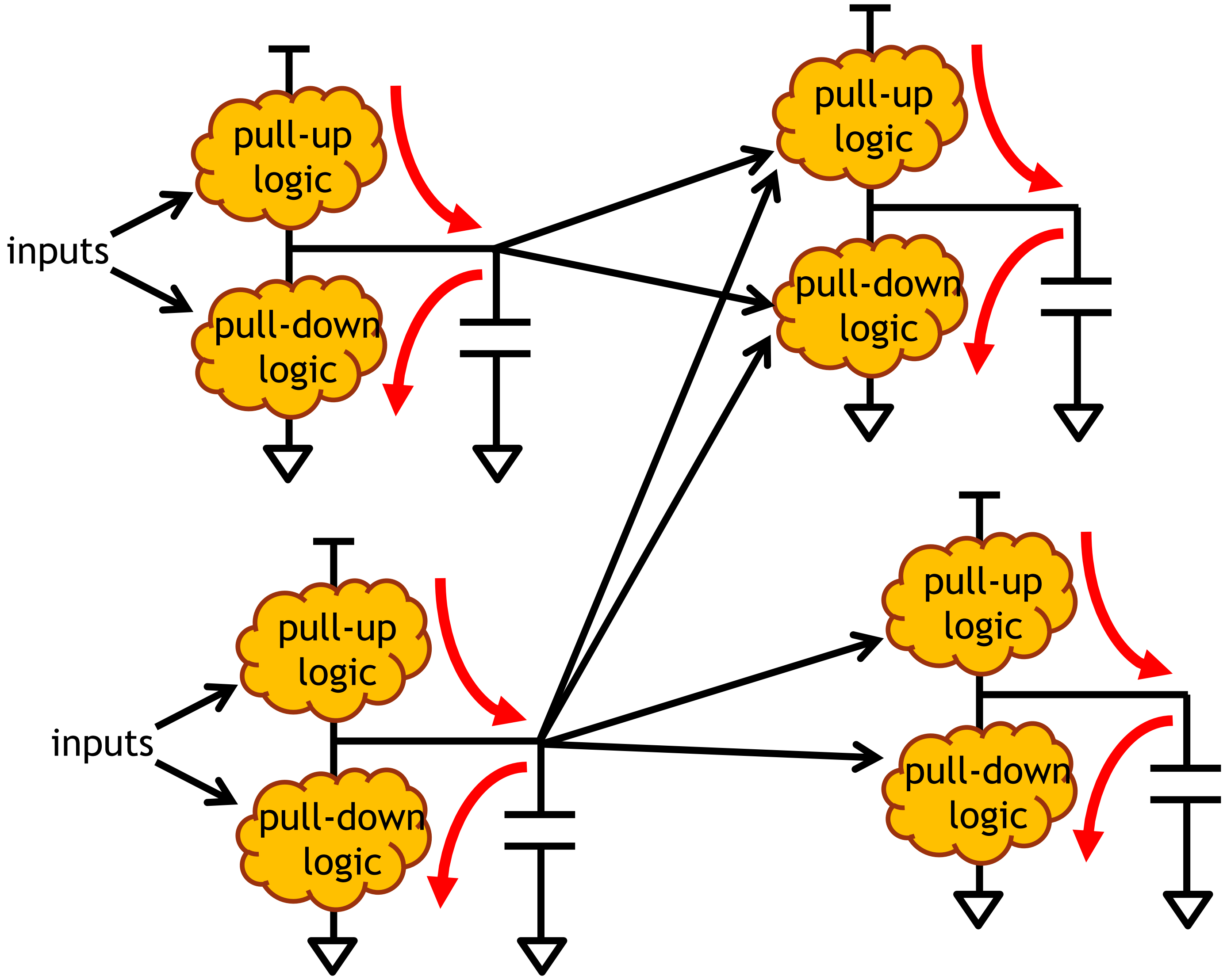


Source: IBM

(Courtesy Alessandro Piovaccari)

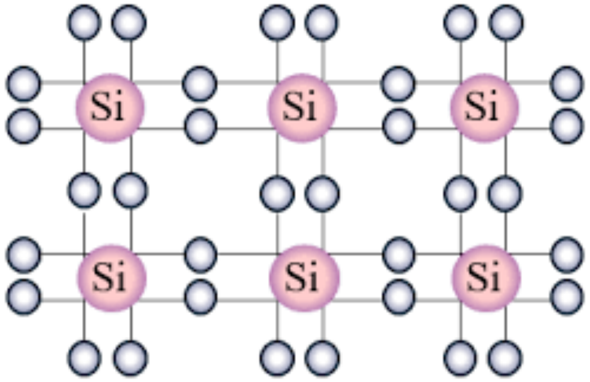
What's on a Chip?

- Billions of independent little capacitors – voltage of each represents a state or stored information (e.g., logic 0 or 1)
- Capacitors charge/discharge (pull-up to supply or pull-down to ground) depending on logical function of inputs
- Logic consists of switches implemented using transistors
- Clocks control when logical states get updated

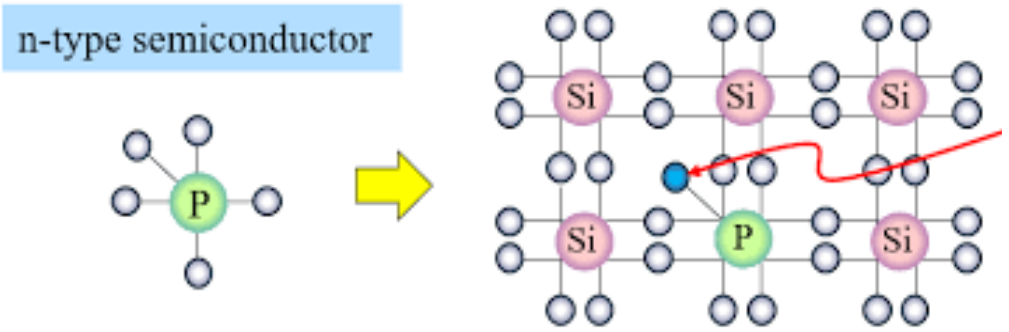


The Basics of Semiconductors

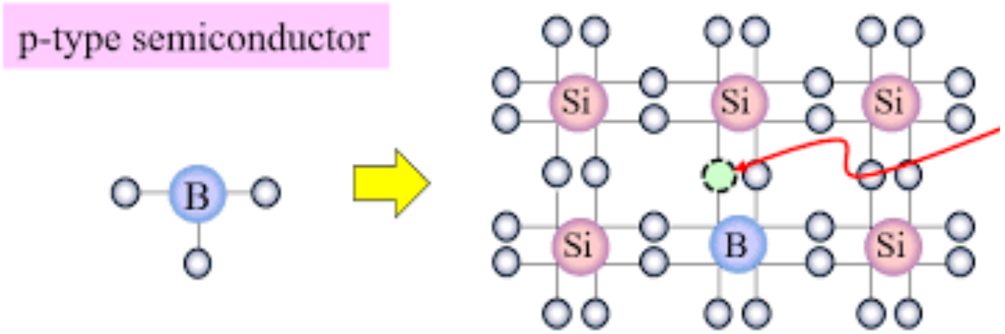
Pure semiconductor is an electrical insulator (not very interesting)



Replace occasional silicon atoms with impurity atoms (dopants) makes semiconductor an electrical conductor



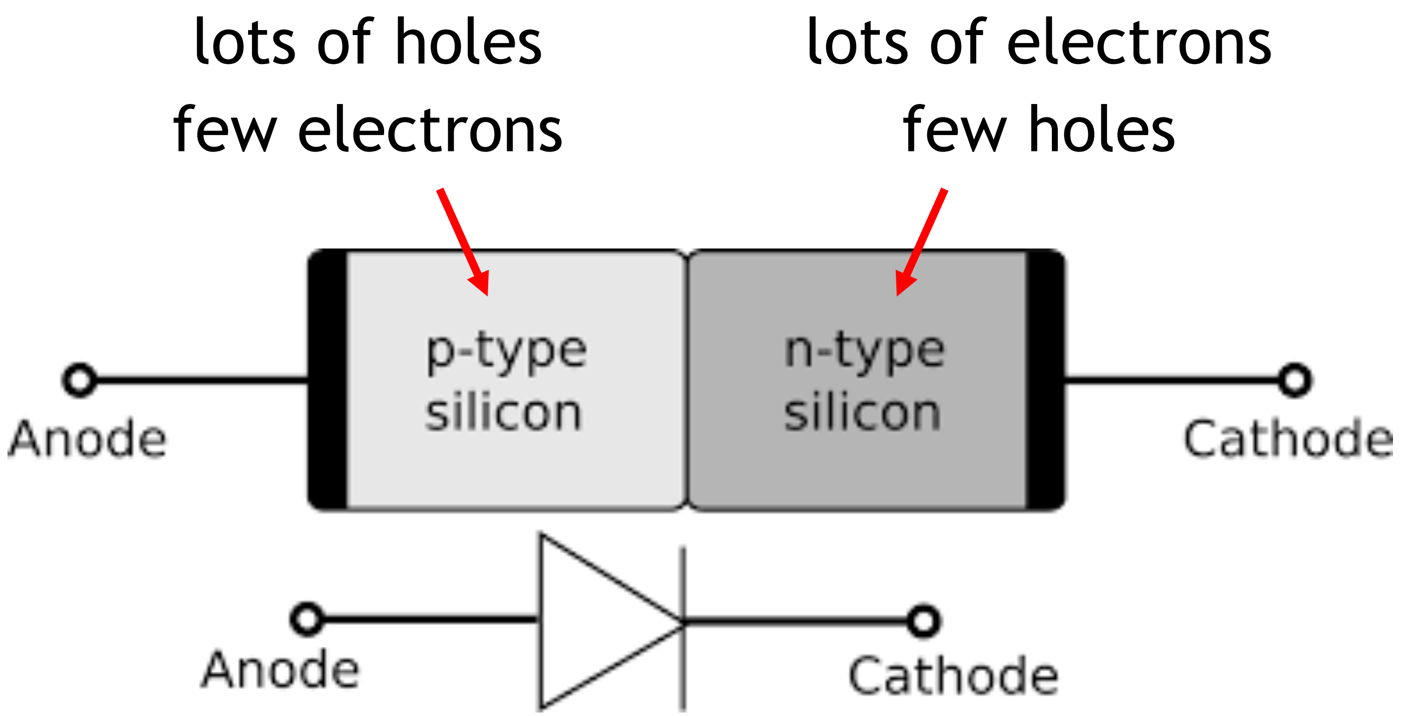
electrons can move around

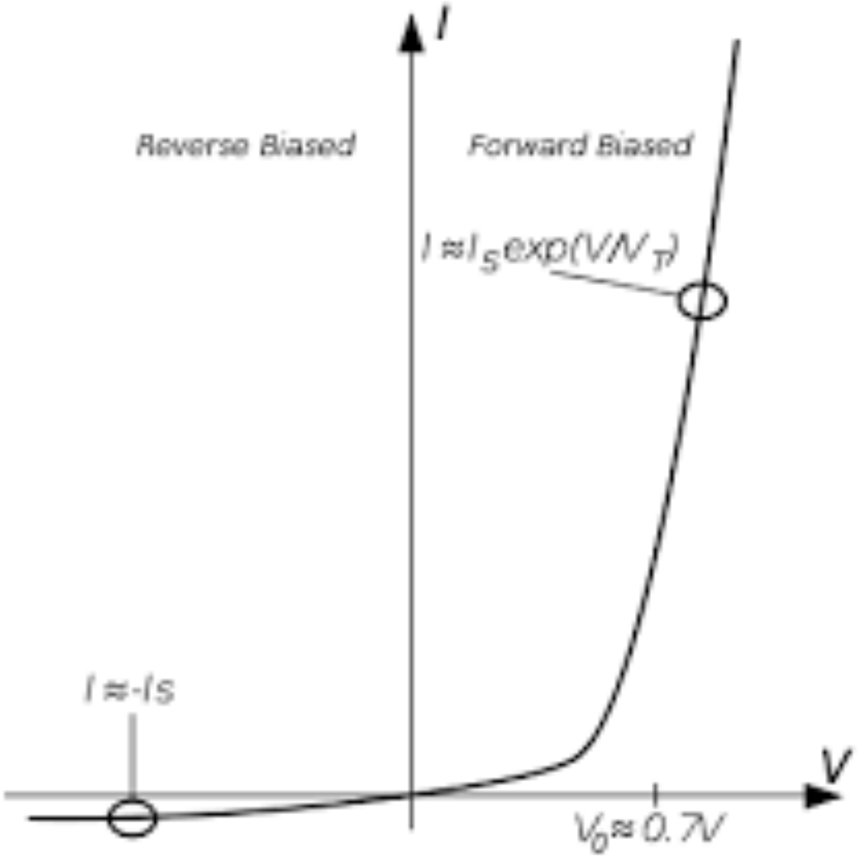


holes can move around

Source: shindengen.com

pn Junction (aka Diode)





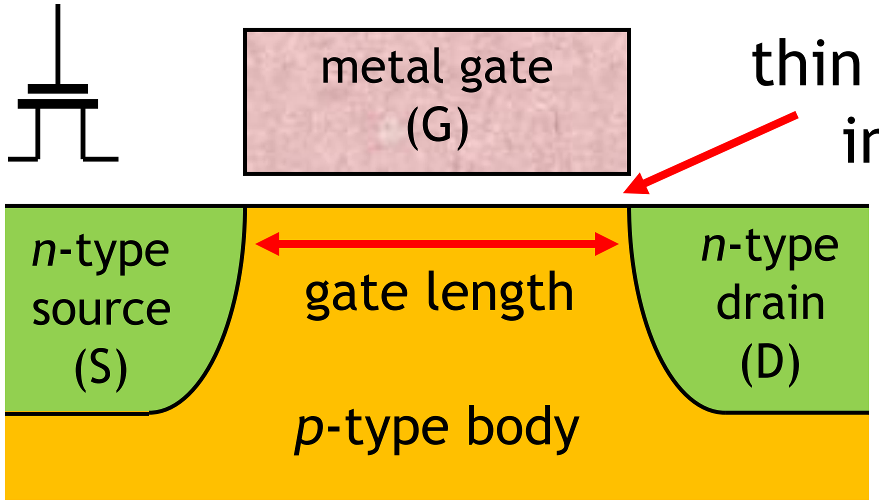
Allows current to flow in only one direction

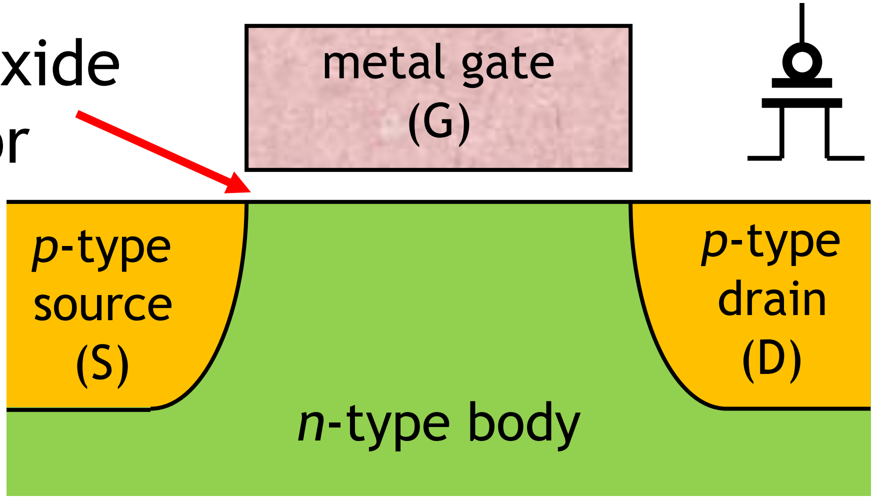
The MOSFET

- Metal-Oxide-Semiconductor Field Effect Transistor
- Patented in 1929, demonstrated in 1961
- Gate voltage controls current from source to drain
- Two flavors: N-MOSFET & P-MOSFET → Complementary MOS or CMOS
- Gate length is generally name of technology node (e.g., 32nm)

N-MOSFET (NMOS)

P-MOSFET (PMOS)

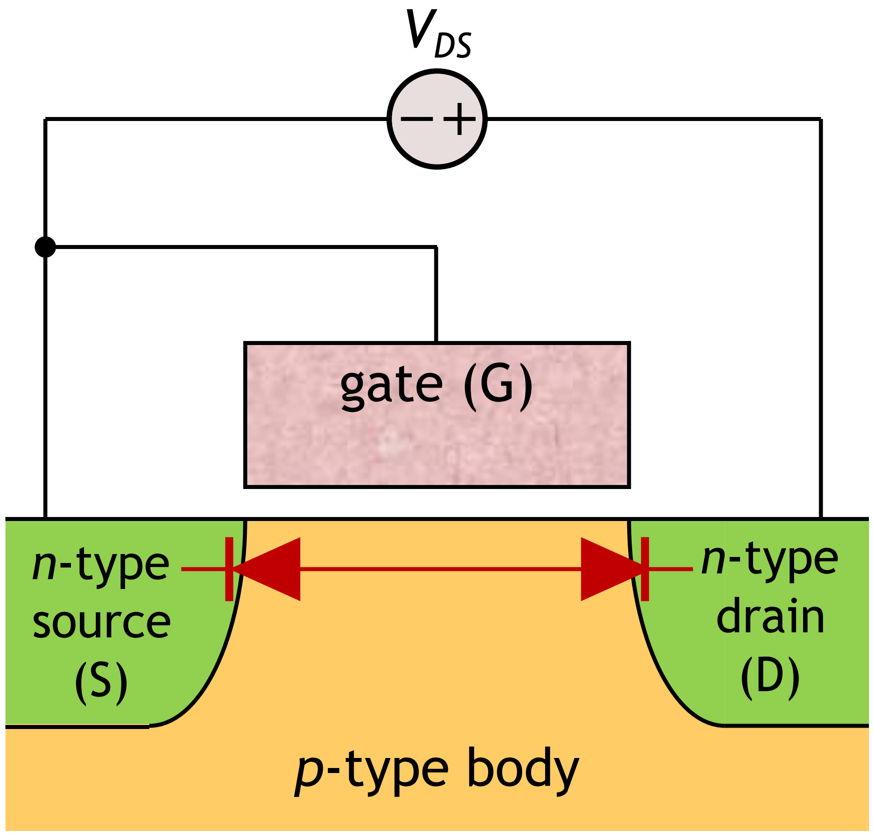




The N-MOSFET (NMOS)

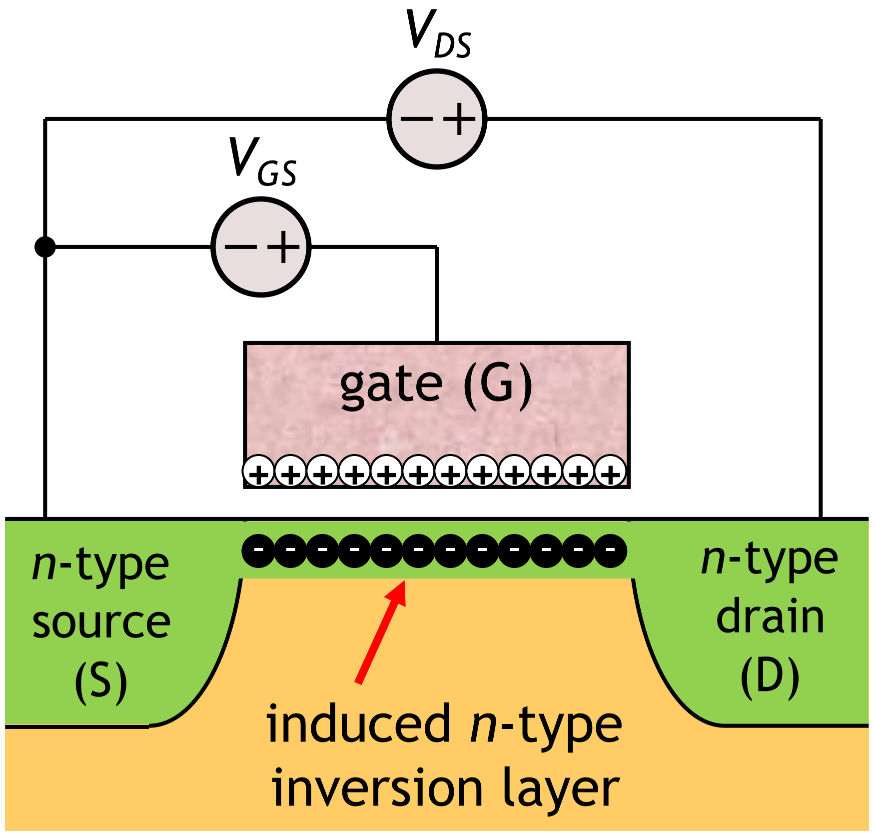
No gate voltage.

What happens when you apply voltage across source/drain?



Apply gate voltage to create *n*-type inversion layer of electrons

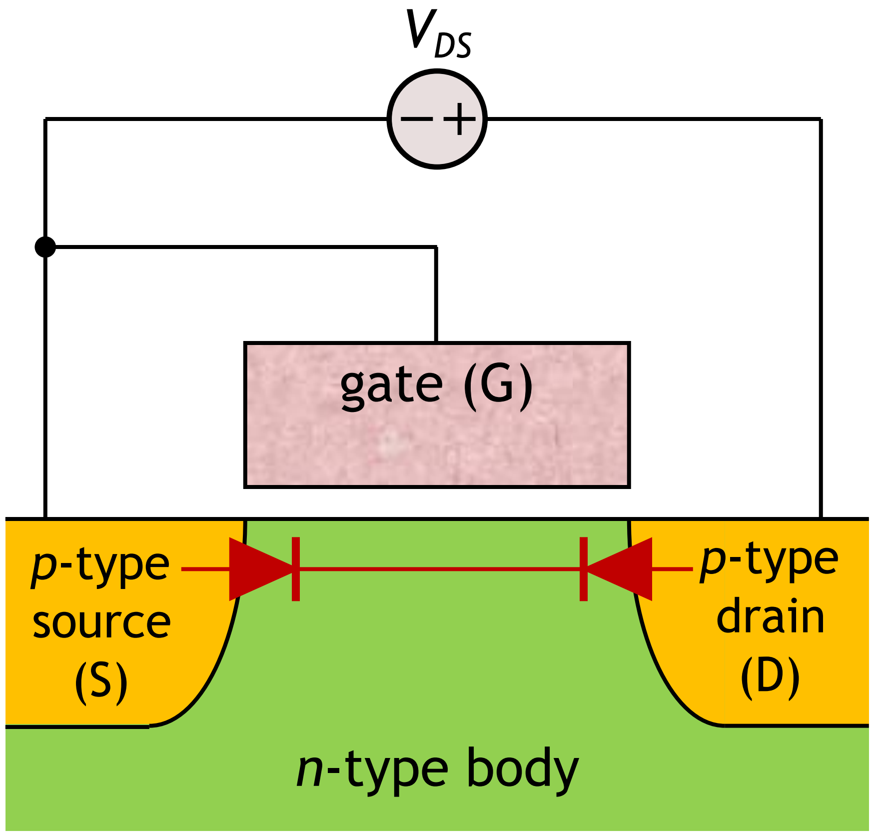
What happens now when you apply voltage across source/drain?



The P-MOSFET (PMOS)

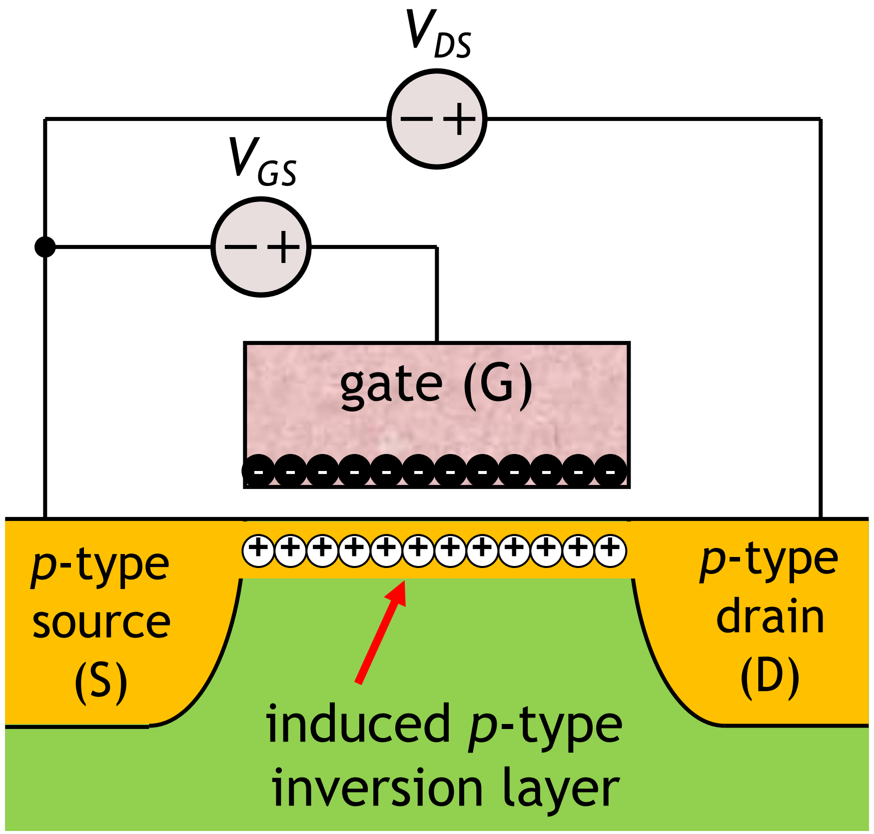
No gate voltage.

What happens when you apply voltage across source/drain?



Apply gate voltage to create *p*-type inversion layer of holes

What happens now when you apply voltage across source/drain?

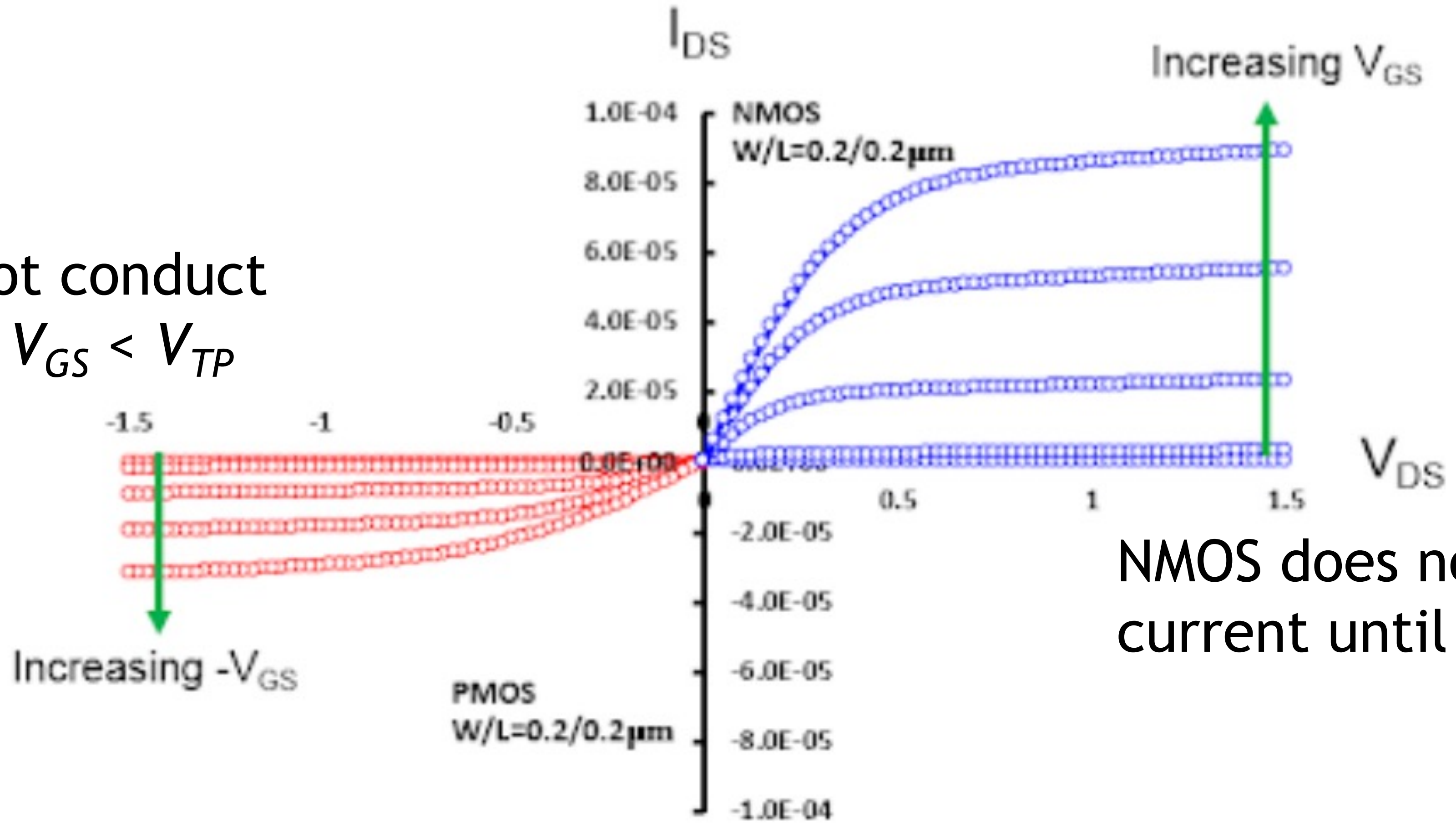


MOSFET I-V Characteristics

V_{TN} = NMOS threshold voltage (positive value)

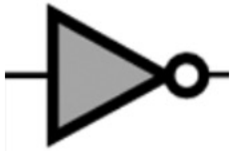
V_{TP} = PMOS threshold voltage (negative value)

PMOS does not conduct current until $V_{GS} < V_{TP}$

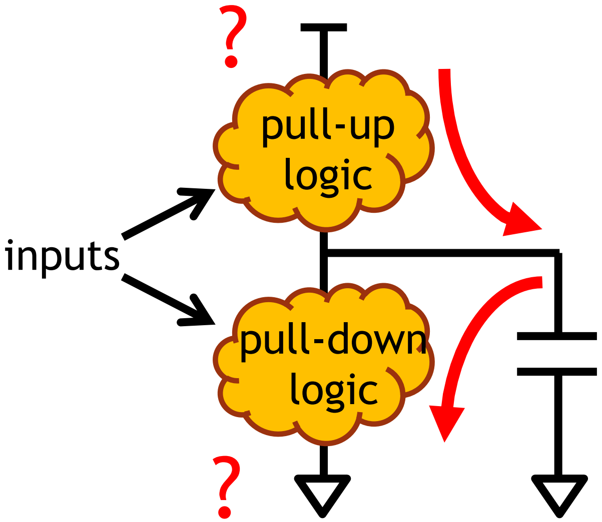


NMOS does not conduct current until $V_{GS} > V_{TN}$

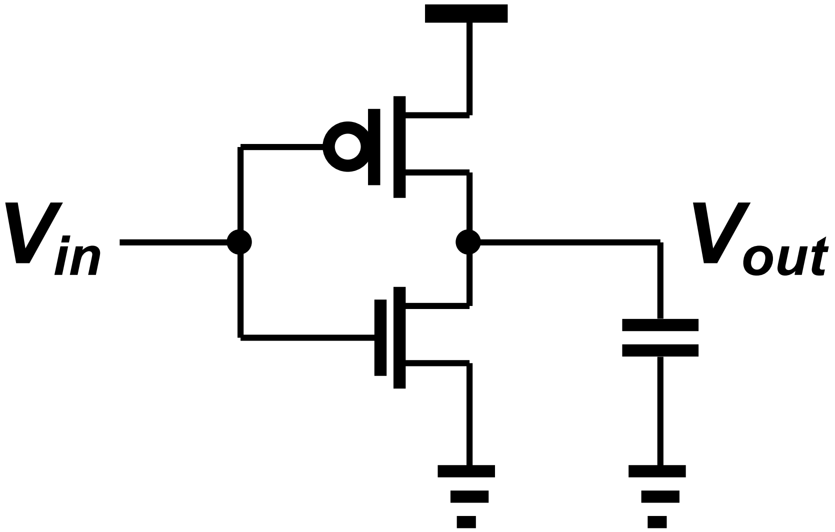
The CMOS Inverter - Simplest Logic Gate



V_{in}	V_{out}
0	1
1	0



The Solution



- V_{in}=0 → NMOS is off, PMOS is on → V_{out}=1
- V_{in}=1 → NMOS is on, PMOS is off → V_{out}=0
- No static current when input doesn't change → low power

Tiers Required to Build Today's IC Systems

- Natural language AI/ML
- Analytics machine learning
- Web application software
- Cloud infrastructure application software
- Edge applications software
- Operating systems & high-level networking software stacks
- Machine learning at the edge
- Low-level networking software stacks
- Real-time operating systems & device drivers
- Firmware & hardware-software co-design
- Architecture exploration & high-level synthesis
- Hardware verification
- Hardware description languages & design synthesis
- Device-level design, simulation, custom layout
- Device modeling & design enablement
- Device physics & foundry engineering
- Material science & nanotechnologies
- Solid-state physics & statistical mechanics
- Electromagnetics & quantum mechanics

Courtesy: Alessandro Piovaccari

Tiers Required to Build Today's IC Systems

- Natural language AI/ML
- Analytics machine learning
- Web application software
- Cloud infrastructure application software
- Edge applications softw
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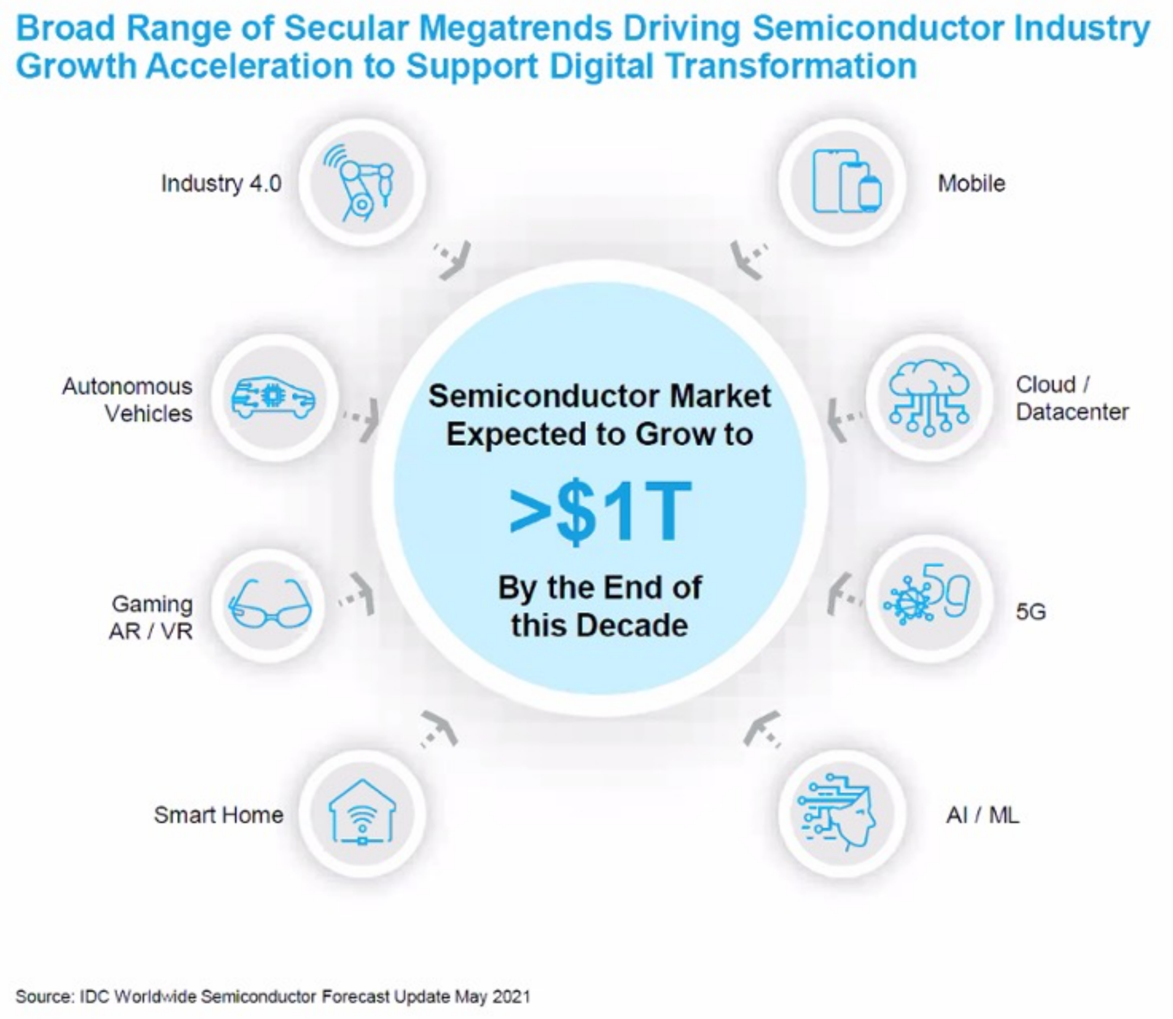
- Devic
- Device physics & foundry e
- Material science & nanotechnologies
- Solid-state physics & statistical mechanics
- Electromagnetics & quantum mechanics

- Takes an enormous village!
- It's complicated stuff!
- Expertise needed at every level.

Courtesy: Alessandro Piovaccari

Consider a Career in Semiconductors

The Opportunities

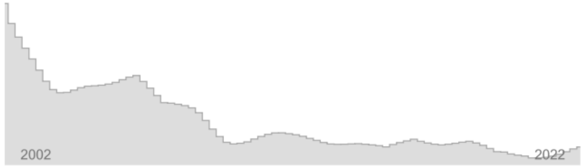


- Extremely multidisciplinary
  - Engineering (electrical, mechanical, materials, chemical, biomedical, systems, …)
  - Sciences (physics, chemistry, even biology)
  - Mathematics
  - Computer science (algorithms, AI)
- Very fast-paced, never a dull moment
- Change is normal
- Global – opportunities to travel
- Dress code is casual, otherwise I won’t be employable ☺
- Pays well too ☺

Don’t Take My Word for It

Semiconductor and Other Electronic Component Manufacturing
California – 2022Q4

EMPLOYMENT



85,102

Regional employment / **386,150** in the nation

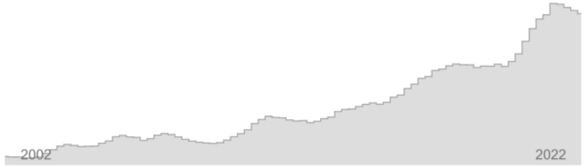
-0.5%

Avg Ann % Change Last 10 Years / **+0.0%** in the US

0.4%

% of Total Employment / **0.2%** in the US

WAGES



$222,530

Avg Wages per Worker / **$139,164** in the nation

7.0%

Avg Ann % Change Last 10 Years / **+4.6%** in the US

TOP OCCUPATION GROUPS

6-digit Occupation	Empl	Avg Ann Wages	Annual Demand
Electrical, Electronic, and Electromechanical Equipment Assemblers, Except Coil Winders, Tapers, and Finishers	12,283	$39,700	1,454
Semiconductor Processing Technicians	5,219	$48,800	622
Inspectors, Testers, Sorters, Samplers, and Weighers	3,887	$43,400	383
Electronics Engineers, Except Computer	3,621	$137,500	306
Electrical and Electronic Engineering Technologists and Technicians	3,378	$71,500	329
Software Developers	3,079	$155,000	272
Computer Hardware Engineers	2,912	$160,900	194
Team Assemblers	2,595	$35,500	242
Architectural and Engineering Managers	2,325	$194,800	172
Industrial Engineers	2,158	$111,400	181
Remaining Component Occupations	43,646	$82,900	4,258
Total	**85,101**		