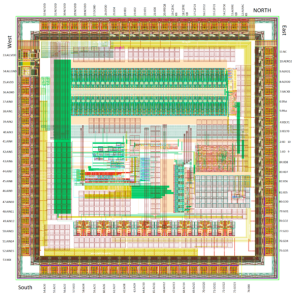

Neuromorphic Engineering I

21FS INI508

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Elisa Donati, Junren Chen, Zhe Su

Institute of Neuroinformatics
University of Zurich and ETH Zurich

Zurich, September 26, 2021

University of Zurich UZH

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Outline

Class details and links

- **Objectives** To learn to analyize neuromorphic electronic circuits intuitively and gain a deep understanding of the characteristics of neuromorphic circuit elements.
- **Lecture Room** Y44-H-05 Irchel Campus
- **Lecture times** Mondays 14:00 - 16:00
- **Exercises** Group lab sessions with hands-on experiments (dates/times TBD)
- **Credits** 6 ECTS credit points
- **Exam type** Oral 20-30 minutes, with mandatory at least 9 labs handed in.
- **Exam date** Monday, 24 May up to and including Friday, 18 June 2021 (TBD)
- **Online Management System** OLAT: https://lms.uzh.ch/url/RepositoryEntry/17073866265
- **Lecture recordings** ZOOM: https://ethz.zoom.us/j/69819395462
- **Study guide** Shared document: https://drive.google.com/file/d/1nOq3UbcEv_ik425VBYqcH9hAET7FyIeP/view?usp=sharing

Class exercises

- Exercises consist on experiments on full-custom class-chip interfaced to PC.
- Instructions and experiments are provided as Jupiter-Lab notebooks.
- Experiments can be carried out in teams of two for measurements and data collection.
- Each student has to hand in his/her individual Jupiter-Lab report with answers to the questions.
- Data plots can be shared among team members. Answers to questions should not be copied.
- Completed Jupiter-Lab notebooks should be exported to PDF.
- Both PDF and original source should be uploaded to the student's OLAT dropbox.
- Each lab-session should be completed and uploaded before the beginning of the next session.
- At least nine lab sessions have to be handed in (the first lab is mandatory).

Class schedule (OLAT)

Lecture	Date	Lecturer	Topic
	Mondays 14:15-16:00 (approx), Fall semester.		
1	27 Sept	GI	**Introduction to neuromorphic VLSI. Neuromorphic Systems** (slides / video) What the field is about. Introduction to device physics. Semiconductors, Fermi-Dirac distribution, energy bands, the contact potential, NP junctions, their characteristics (capacitance and current) under reverse and forward bias. Introduction to lab exercises with the class chip.
2	4 Oct	TD	**Transistor properties above threshold** (slides / video) linear/triode region, saturation region, velocity saturation Channel-length modulation: drain conductance and Early effect. Transconductance in weak and strong inversion. Threshold voltage and overdrive. Drain current saturation is the overdrive voltage. Transistor *specific current I_s*. Transistor intrinsic voltage gain, 2nd-order drain effects (DIBL and Impact Ionization).
3	11 Oct	GI	**Transistor properties below threshold** (slides / video) Device physics continued. MOS transistors. Subthreshold/Weak inversion operation. Triode/linear region, saturation region. Subthreshold Ids vs Vgs and Ids vs Vds equations.
4	18 Oct	GI	**Static analog circuits** (slides/video) Current mirrors, source-followers, differential pairs, bump circuits.
5	25 Oct	GI	**The transconductance amplifier** (slides / video) Five-transistor transconductance amplifier, saturation conditions, Wide output range transconductance amplifier. Voltage gain
	Sunday 31 October: Daylight savings time ends, clock falls back 1 hour		
6	1 Nov	TD	**Time & Freq. responses of 1st-order lowpass and highpass filters (Linear systems 1)** (slides / video) • Small signal analysis of first order RC & CR using s-plane and Heaviside's e^{st} method • Follower-integrator circuit • Follower-differentiator circuit • Large signal responses / slew rate limits

What is this really course about?

What is a transistor?

What is a neuron?

What is a synapse?

What is a current mirror?

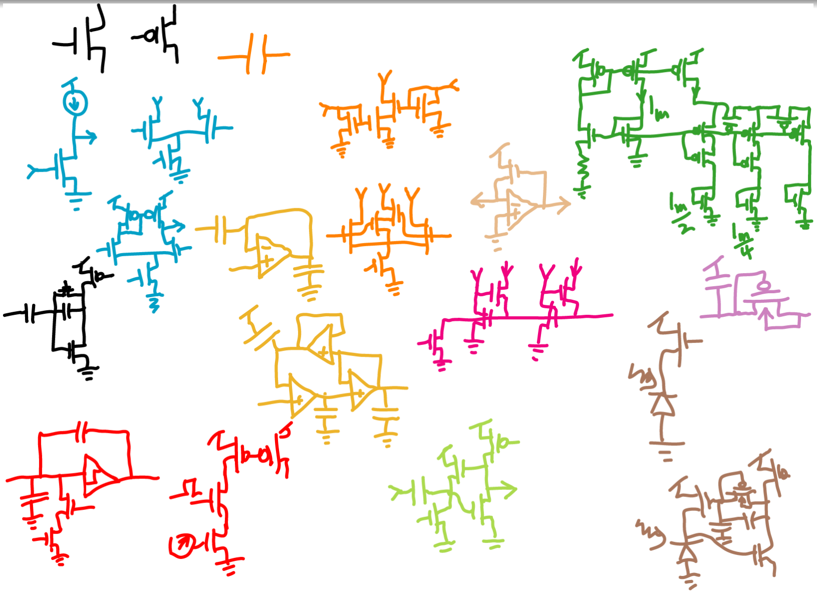
What is a semiconductor?

What is an Integrate-and-Fire model?

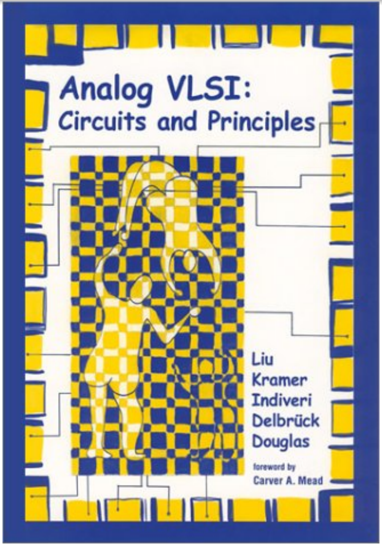
What can we do with these things?

What can we build?

Our building blocks



University of Zurich[UZH] | ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich



MIT Press

Materials

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Documentation	3 element(s)	9/20/21, 11:15 AM
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Session 03	3 element(s)	9/20/21, 11:15 AM
Session 04	3 element(s)	9/20/21, 11:15 AM
Session 05	1 element(s)	9/20/21, 11:15 AM
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Class handouts and zoom recordings

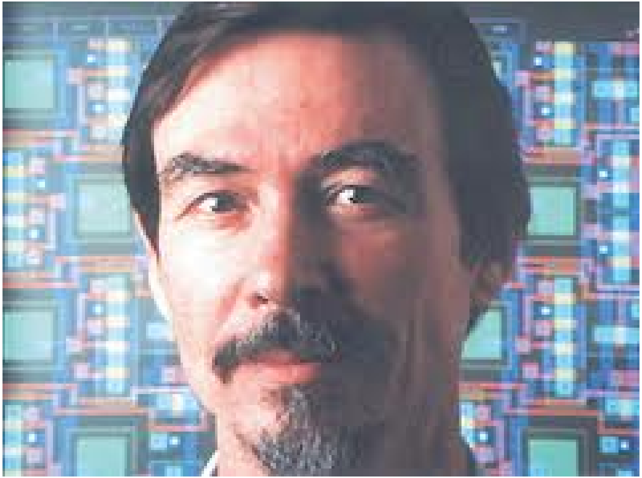
Outline

The brain of the worker honeybee occupies a volume of around 1mm^3 and weighs about 1mg.
The total number of neurons in the brain is estimated to be 950,000

- Flies acrobatically
- Recognizes patterns
- Navigates
- Forages
- Communicates

Energy consumption: 10^{-15} J/op.
At least 10^6 more efficient than digital silicon (20 W *vs.* 1 mW)

Carver Mead



The term *neuromorphic* was coined by Carver Mead, in the late 1980s to describe Very-Large-Scale Integration (VLSI) systems containing electronic circuits that emulate the bio-physics of neural systems using the physics of silicon.

http://youtu.be/jLDOnaq97ag

Neuromorphic Intelligence

One term, multiple communities

Neuromorphic Engineering

- Fundamental research
- *Emulation* of neural function
- Subthreshold analog
- Asynchronous digital

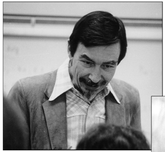
Neuromorphic Computing

- Application driven
- *Simulation* of neural networks
- Custom VLSI
- Conservative approach

Neuromorphic devices

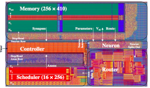
- Memristive devices
- New emerging memory technologies
- In-memory computing
- High density arrays

1980s

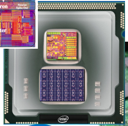


Carver Mead

Misha Mahowald

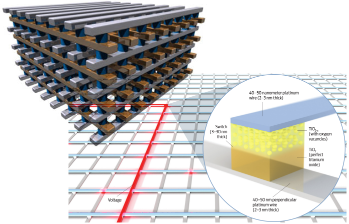


IBM

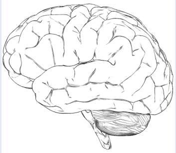


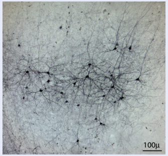
intel

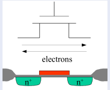
HP

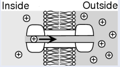


Methods



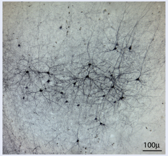


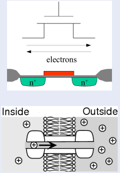




- Study fundamental neuroscience, principles of neuro-physiology, neuro-anatomy, theory of computation, electrical engineering,. . .
- Exploit the physics of silicon to reproduce the bio-physics of neural systems, using subthreshold analog VLSI circuits.
- Develop distributed multi-core spiking architectures using asynchronous digital VLSI circuits.
- Build real–time autonomous cognitive agents able to carry out behavioral tasks in complex environments.

Methods





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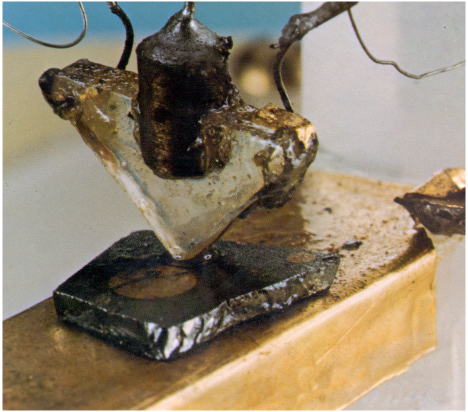
Outline

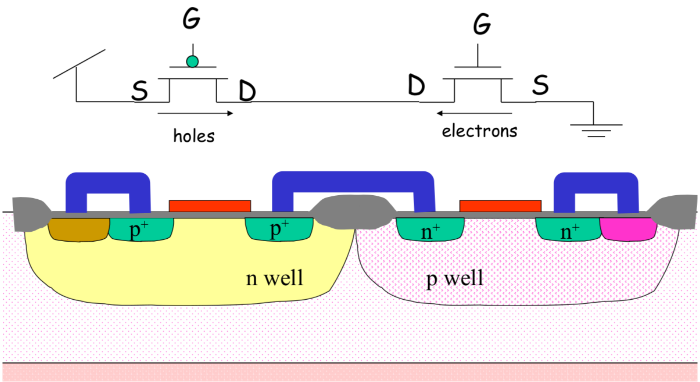
Transistors



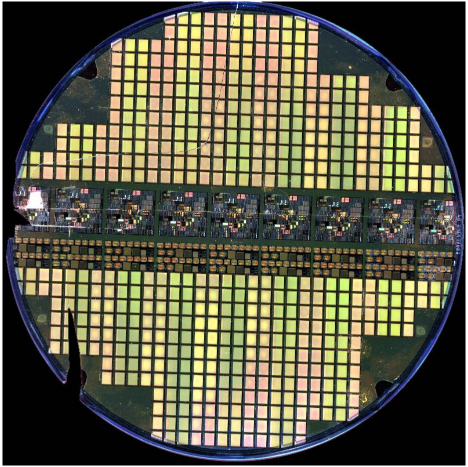
Bell Telephone Laboratories, Inc., 1947.

Walter H. Brattain and John A. Bardeen demonstrate a point-contact germanium transistor.

Walter H. Brattain, William Shockley, and John A. Bardeen are jointly awarded the 1956 Nobel Prize in Physics "for their researches on semiconductors and their discovery of the transistor effect."

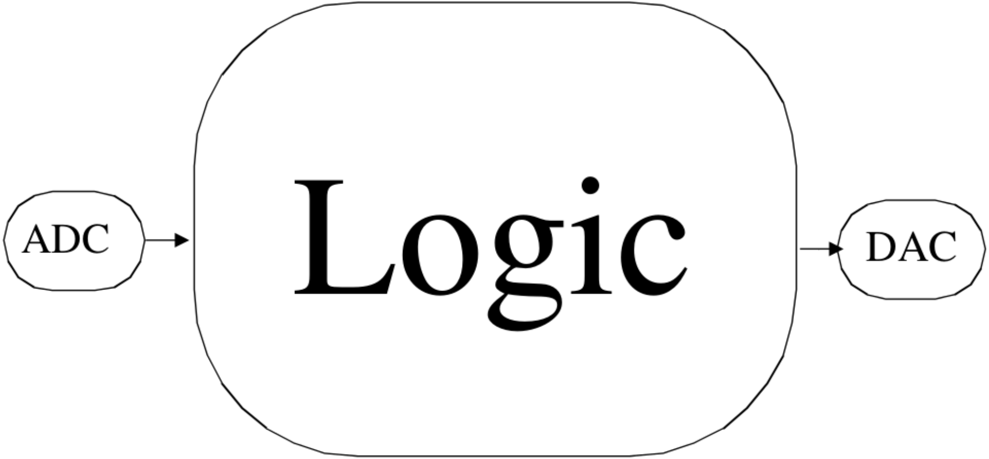


CMOS: Complementary Metal-Oxide Semiconductor
VLSI Very Large Scale Integration



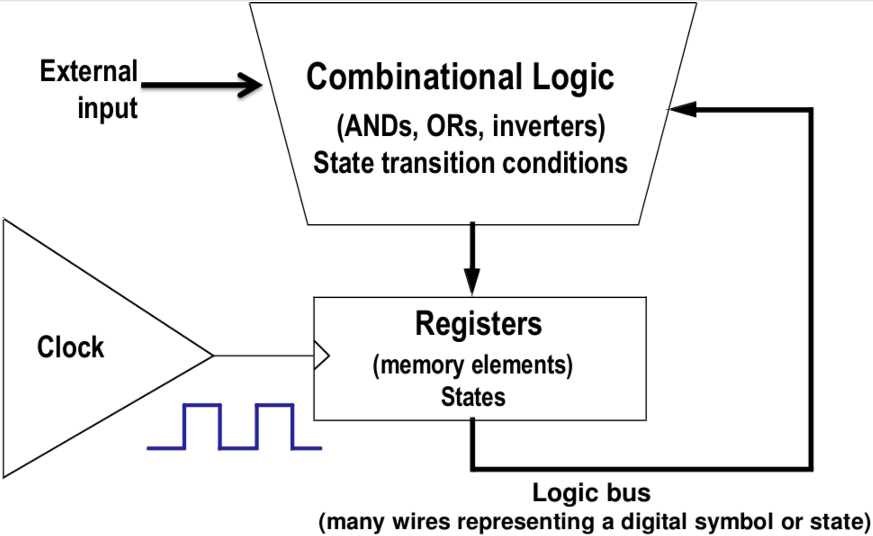
One of Tobi's wafers from his silicon-valley days, about 1996.

Today's latest Intel CPU, fabricated with a 10 nm process, has $\approx 6 \cdot 10^9$ transistors.



How industry thinks of analog

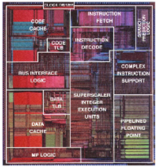
The conventional electronics industry



Computation and synchronous logic

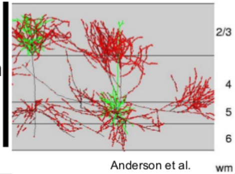
Computers versus the brain

Pentium 4



Cortex

1mm



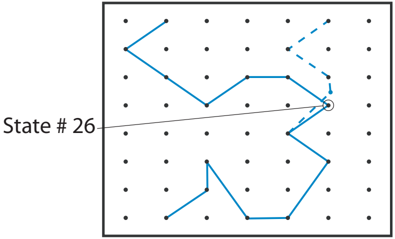
Anderson et al. 2003

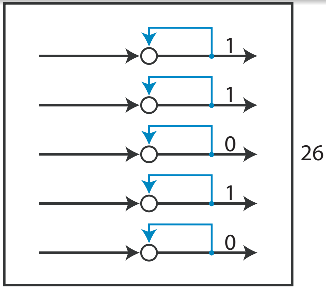
At the system level, brains are about 1 million times more power efficient than computers. Why?

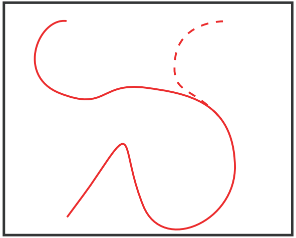
Cost of elementary operation (turning on transistor or activating synapse) is about the same. It's not some magic about physics.

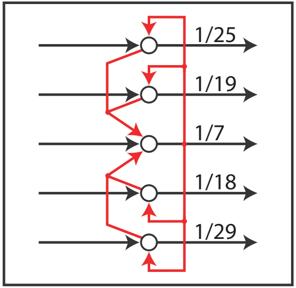
Computer	Brain
Fast global clock	Self-timed
Bit-perfect deterministic logical state	Synapses are stochastic! Computation dances: digital→analog→digital
Memory distant to computation	Memory at computation
Fast high precision power hungry ADCs	Low precision adaptive data-driven quantizers
Devices frozen on fabrication	Constant adaptation and self-modification

Digital versus neural signal restoration









The brain

The human brain has on the order on 10^{11} neurons and 10^{14} synapses. Its power dissipation is approximately 10^{-16}J per operation (total mean consumption < 10 Watts).

Computers

BlueGene (IBM): 10^{-9}J per operation, 131072 processors in parallel, needs one floor of an entire building AND one floor for cooling devices.

Analog circuits are a factor of 10^4 more power efficient than their digital counterparts, if operated in the *subthreshold* regime.

Applications for Neuromorphic Systems

Neuromorphic systems exploits similarities with neural systems at the physical level and implements on silicon the strategies adopted by neural systems.
The resulting devices are characterized by the following properties:

low-power	low precision
compact	low resolution
cheap	application specific

Single-chip devices with these properties are not optimal for precise measurement applications, high-resolution imaging, or pattern recognition tasks. Rather, they are best suited for implementing real-time models of perceptive systems.

Outline

1967-1972 The subterranean group

Biophysics of membrane channels

Carver Mead
(Caltech)

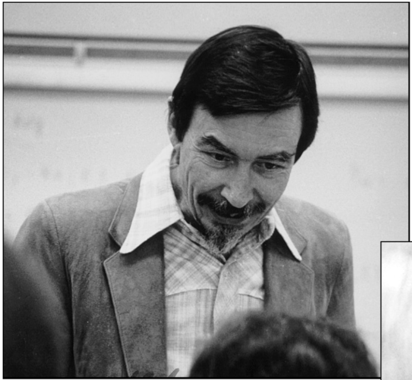
Max Delbruck
(Caltech)

Paul Mueller
(UPenn)

Moshe Eisenberg (from UPenn)
Jim Hall (recalled early from Vietnam)
Peter Leuger (Konstanz)
Fred Sigworth

Engineers and biologists

1980s



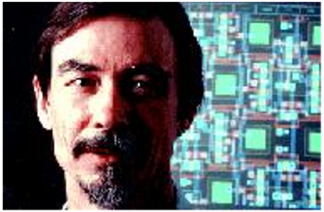
Carver Mead

Misha Mahowald

Physics of Computation Course

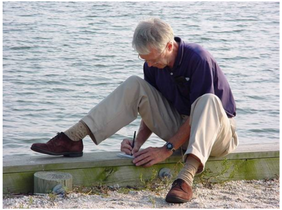
1982

1985

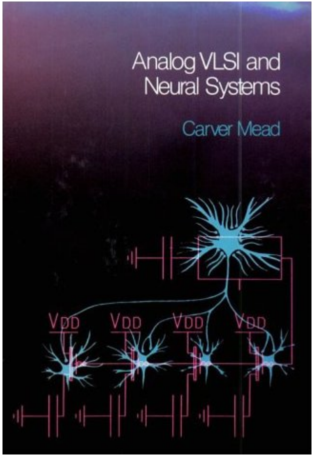


Carver Mead

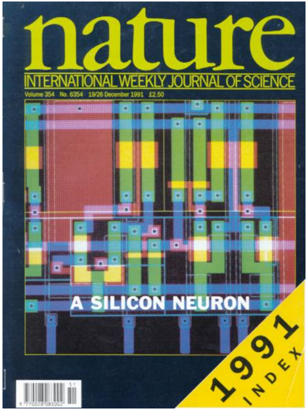
Dick Feynman



John Hopfield

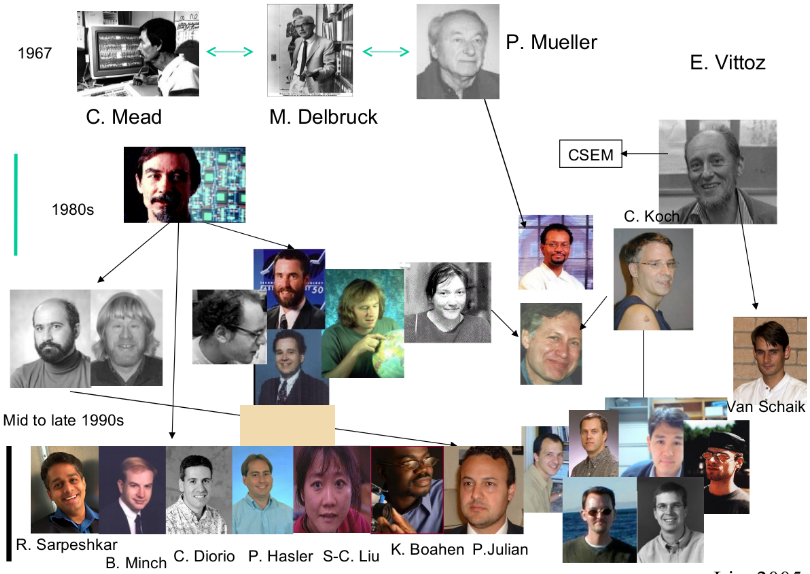


1989



In 1991 Misha Mahowald and Rodney Douglas proposed a conductance-based silicon neuron and showed that it had properties remarkably similar to those of real cortical neurons.

Neuromorphic Engineering Origins



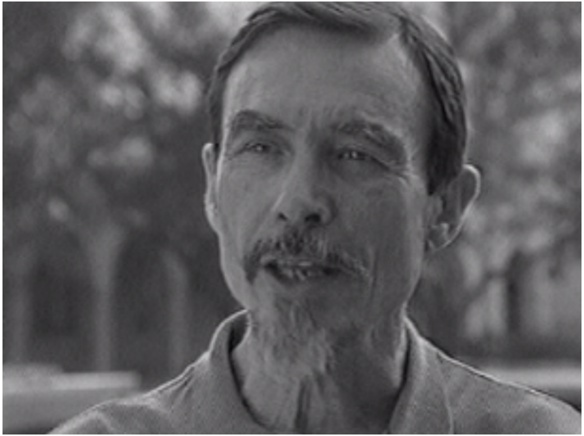
Liu, 2005

Neuromorphic Engineering today

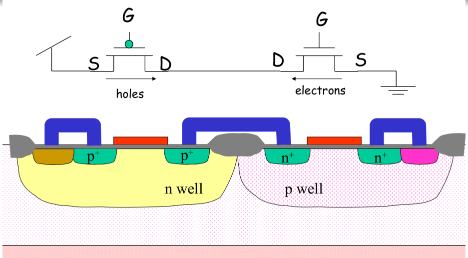
Limited by our understanding

> *"The fact that we can build devices that implement the same basic operations as those the nervous system uses leads to the inevitable conclusion that we should be able to build entire systems based on the organizing principles used by the nervous system."*

Carver Mead, Proc. IEEE, 1990



Outline



We need to understand enough about semiconductors and junctions to understand how MOS transistors work Insulators, conductors, semiconductors

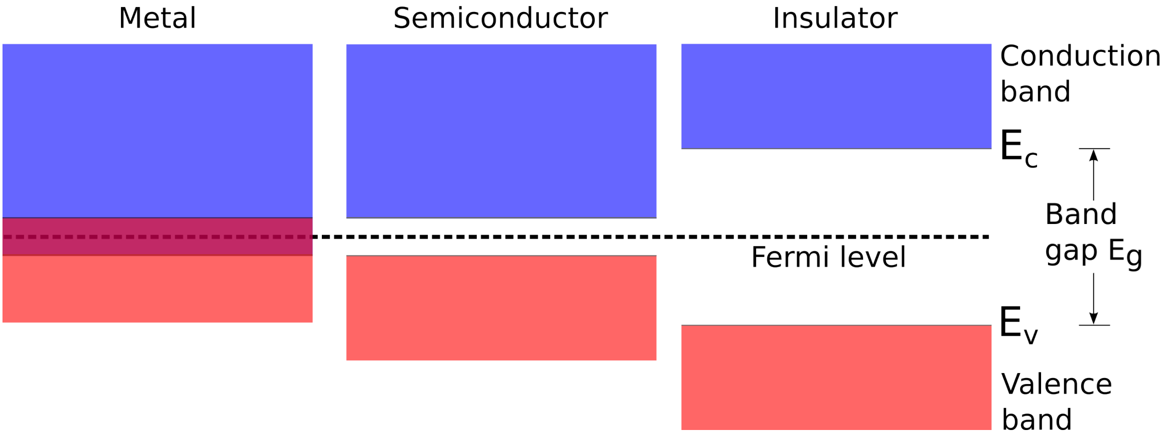
- Crystal structure of silicon
- Band structure (valence, conduction, and forbidden bands)
- Holes and electrons
- Mechanisms of charge transport (diffusion & drift)
- Doping with donors and acceptors
- Fermi-Dirac distribution
- Law of mass action (np=ni2)
- p-n junction
- Reverse biased junction and its capacitance

Donors and Acceptors

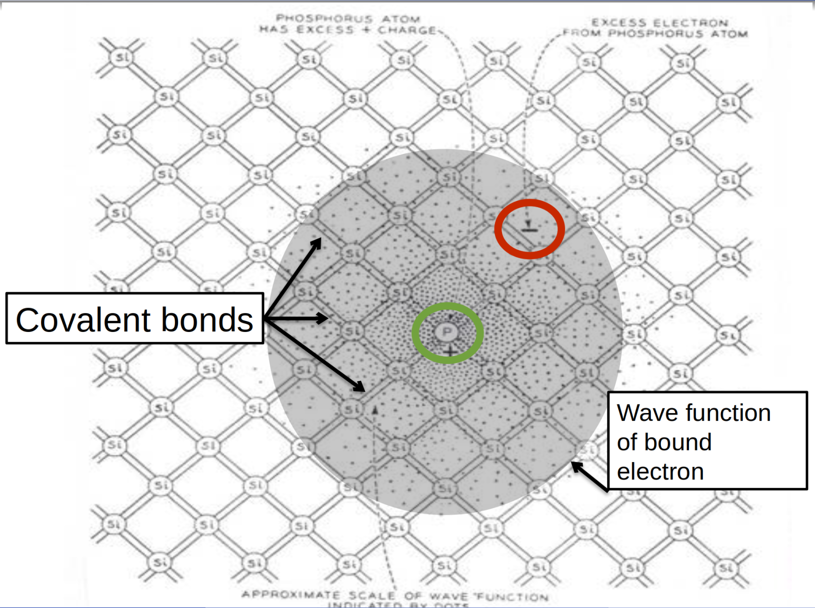
I	II	III	IV	V	VI	VII	Zero
H							He
Li	Be	B	C	N	O	F	Ne
Na	Mg	Al	Si	P	S	Cl	Ar
K	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Cd	In	Sn	Sb	Te	I	Xe

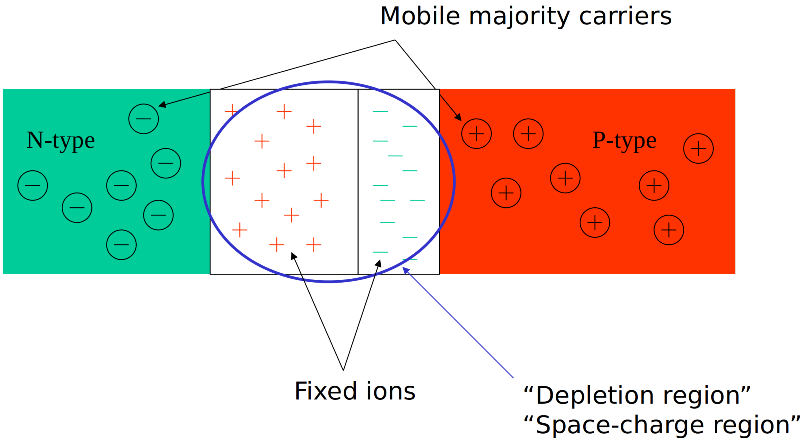
Acceptors | Donors

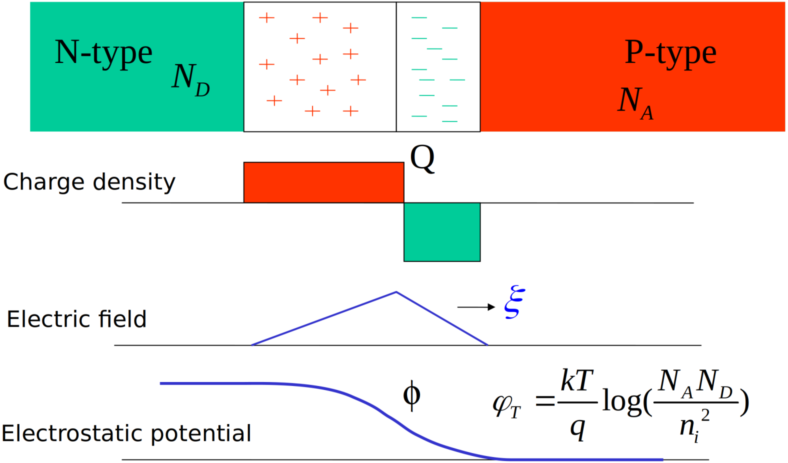
1 missing electron | 1 extra electron



Metal
Semiconductor
Insulator
Conduction band
E_c
Band gap E_g
Fermi level
E_v
Valence band


PHOSPHORUS ATOM HAS EXCESS + CHARGE
EXCESS ELECTRON FROM PHOSPHORUS ATOM
Covalent bonds
Wave function of bound electron
APPROXIMATE SCALE OF WAVE FUNCTION INDICATED BY DOTS

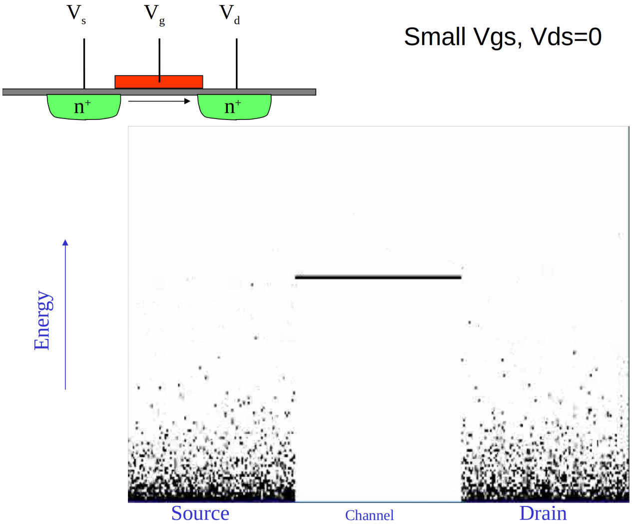

Mobile majority carriers
N-type
P-type
Fixed ions
"Depletion region"
"Space-charge region"



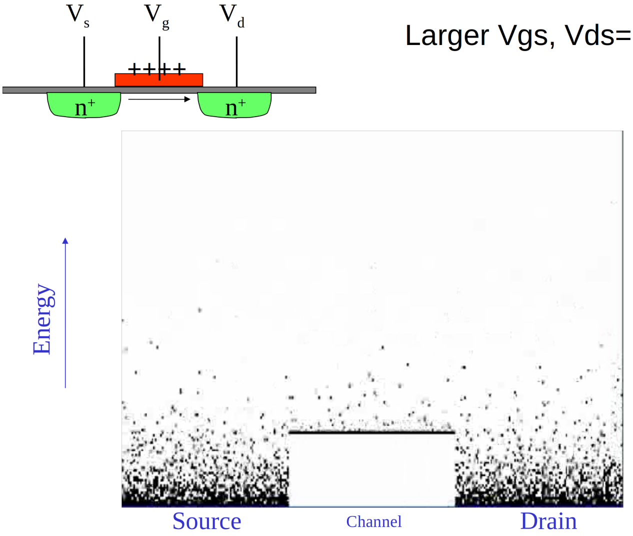
$$\varphi_T = \frac{kT}{q}\log\left(\frac{N_A N_D}{n_i^2}\right)$$

Typically, the *built-in voltage*, φ_T, is about 0.75V

Small Vgs, Vds=0

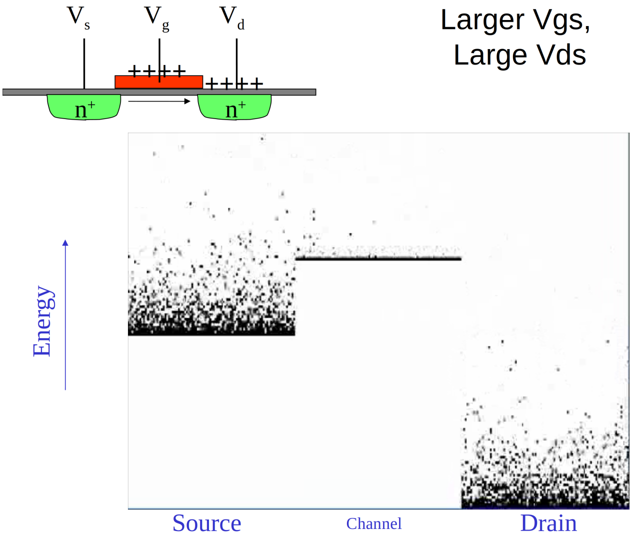


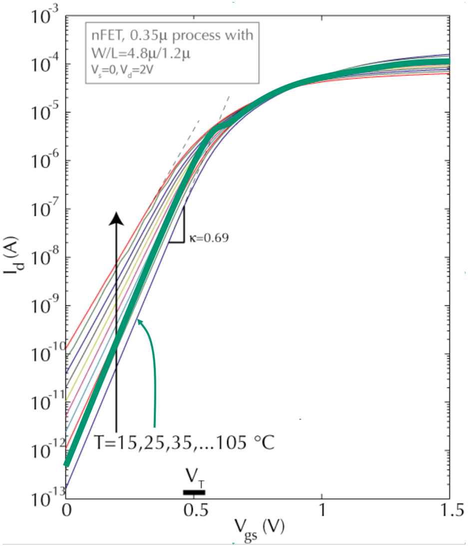
Larger Vgs, Vds=0



nFET operation

Larger Vgs,
Large Vds





Measured FET IV relationship demonstrates Boltzmann distribution

Increasing temperature increases current but decreases log slope