Unit 1.5. Electronic circuits and logic families

Digital Electronic Circuits
E.T.S.I. Informática
Universidad de Sevilla

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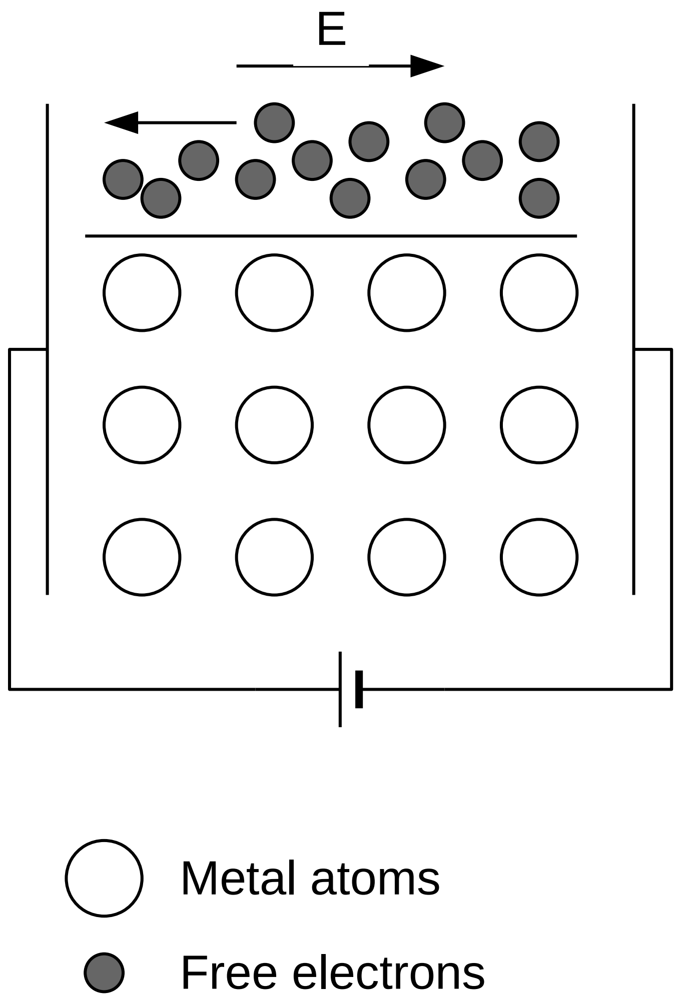
Contenidos

- Electronic circuits
  - Charge and conductors
  - Electronic devices
  - Electric circuits
  - Semiconductors
  - Technology: discrete and integrated devices
- Logic families
  - Digital circuits
  - Gates and logic operators
  - Logic families
  - Electrical and switching parameters

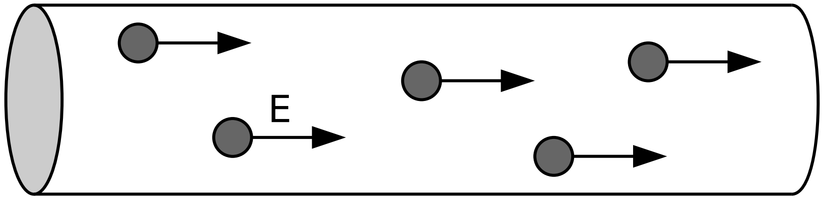
Conductors and charge carriers



- Conductors charge carriers can be positive (+) or negative (-)
- Most typical charge carriers are “free” electrons (-) in metals.
- When an electric field (E) is applied, electrons move accordingly.
- Electric fields exist whenever an electric potential difference (voltage) is applied.

Basic conductor properties

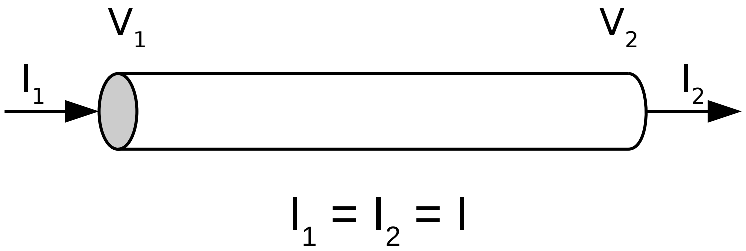
- Conductors in electrical circuits
  - Typically wire-shaped.
  - Charge (and electric field) is confined inside the conductors.
- Charge does not accumulate inside conductors: conductors remain neutral.



Electrical magnitudes

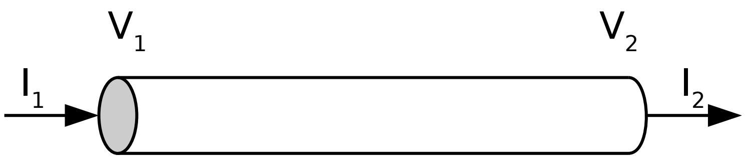
- Voltage: potential energy difference between two points in the circuit by unit of charge (Volts [V]).
  - Electric field (electric force) points from high to low voltage areas.
  - Positive charges move to lower voltage, negative charges to higher voltage (lower energy in both cases).
  - Absolute voltage values do no exist. An arbitrary point is selected as zero voltage (ground node or GND).
- Current: charge per unit time crossing the conductor's section (Amperes [A]).
  - Same current in all sections of a conductor. Why?

$$I = \frac{dQ}{dt}$$



Ohm's Law

- Ohms law
  - Resistance: relation between the voltage and current across the conductor.
  - Unit: Ohms [Ω]=[V]/[A]
- Ideal conductors (R=0)
  - Wires: metals used for connection in electronic circuits can be considered ideal conductors most of the time.
  - Consequence: same voltage across wires.

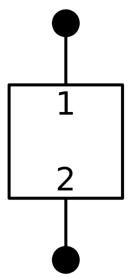


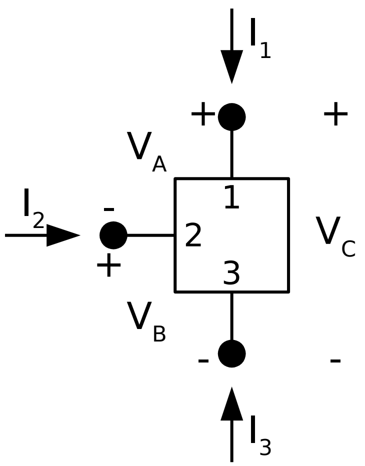
$I_1 = I_2 = I$

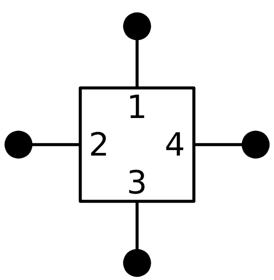
$$R=\frac{V_1-V_2}{I}$$

$$R=0\Rightarrow V_1=V_2$$

Electronic devices



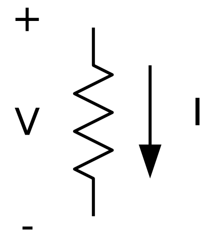




- Electronic elements with two or more terminals (connection points).
- Impose a relationship between the current and voltage across the terminals.
- All currents and voltages are signed numbers.
  - Current: arrow indicates positive current direction (going into the device by convention).
  - Voltage: when the voltage is positive, (+) voltage is higher than (-) voltage, and the other way around.
- Net charge is not accumulated inside the devices:
  - $I_1+I_2+I_3+... = 0$

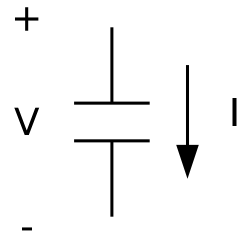
Basic electronic devices

Resistor
Ohm [Ω]



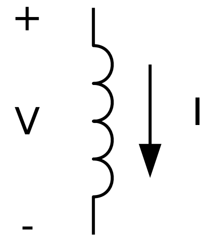
$$V = IR$$

Capacitor
Farad [F]



$$I = C\frac{dV}{dt}$$

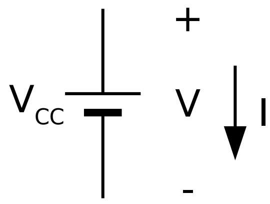
Inductor
Henry [H]



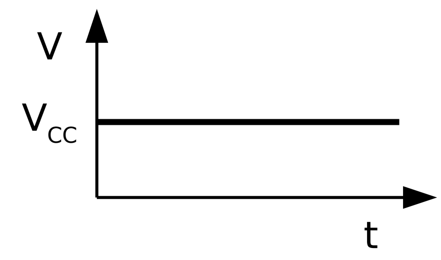
$$V = -L\frac{dI}{dt}$$

Basic electronic devices
Ideal sources

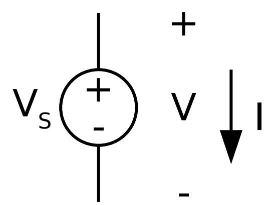
Constant voltage source (power supply) (battery)



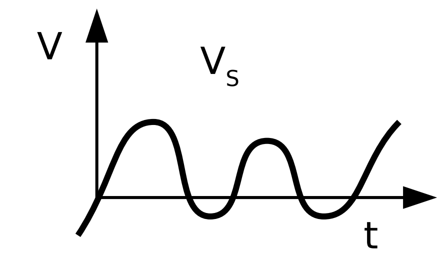
$$V = V_{CC}$$



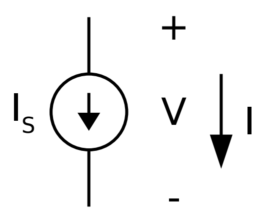
Variable voltage source



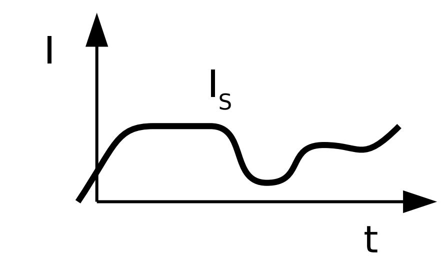
$$V = V_S(t)$$



Variable current source

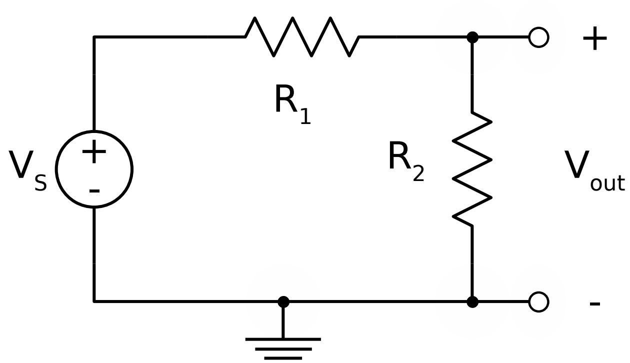


$$I = I_S(t)$$

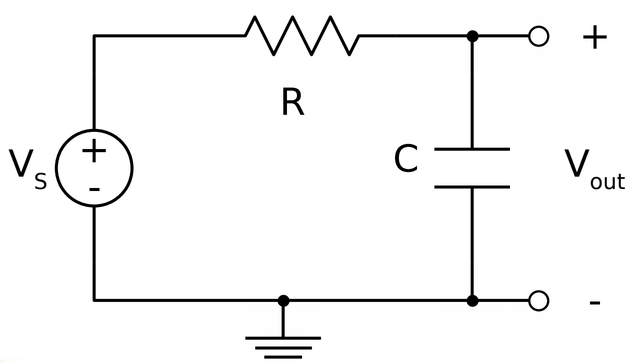


Electric circuits

- Connection of devices with wires to achieve some properties or functionality.
- Node: connection between two or more devices.
  - Same voltage alongside a single node (ideal wire)



Voltage divider



Low-pass filter

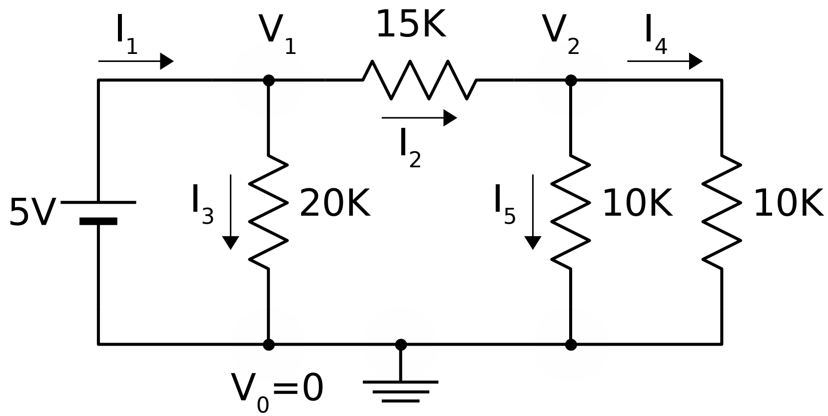
Circuit analysis

- Circuit analysis is based on:
  - Device equations
  - Topological Equations (Kirchhoff laws)
- Kirchhoff laws
  - Current: the sum of the currents entering a circuit node is zero (charge does not accumulate in circuit nodes)
  - The sum of voltage drops along any close path is zero.

Types of circuit analysis

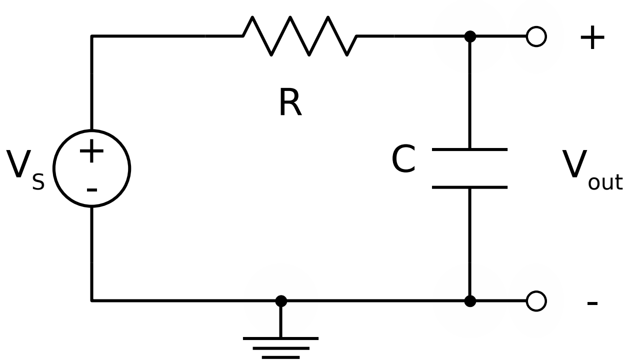
- Static analysis (DC):
  - All magnitudes and sources are constant.
  - The solution is derived from algebraic equations.
- Transient analysis
  - Considers variable sources and the evolution of circuit's magnitudes with time.
  - In general, the solution implies resolving differential equations :(
- Frequency analysis (AC)
  - Solves the circuit for sinusoidal signals.
  - Simplified resolution thanks to the use of specific mathematical tools (Laplace's Transform).
  - Obtains the circuit response as a function of the signal's frequency.

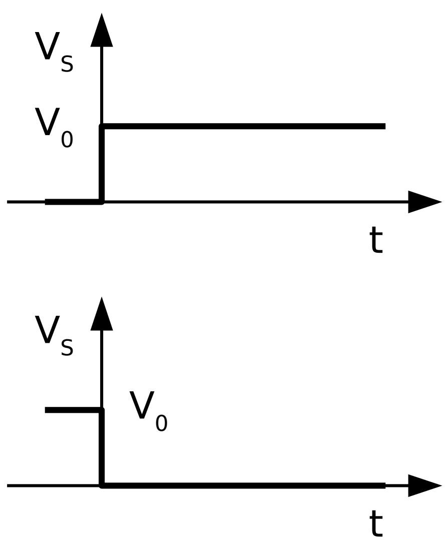
Circuit analysis. Example



Static analysis (DC)

Simulation

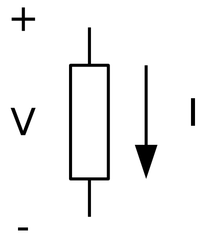




Transient analysis

Simulation

Power

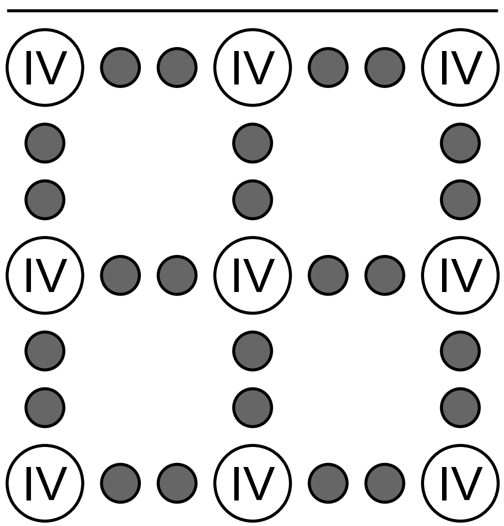


$$P = VI$$

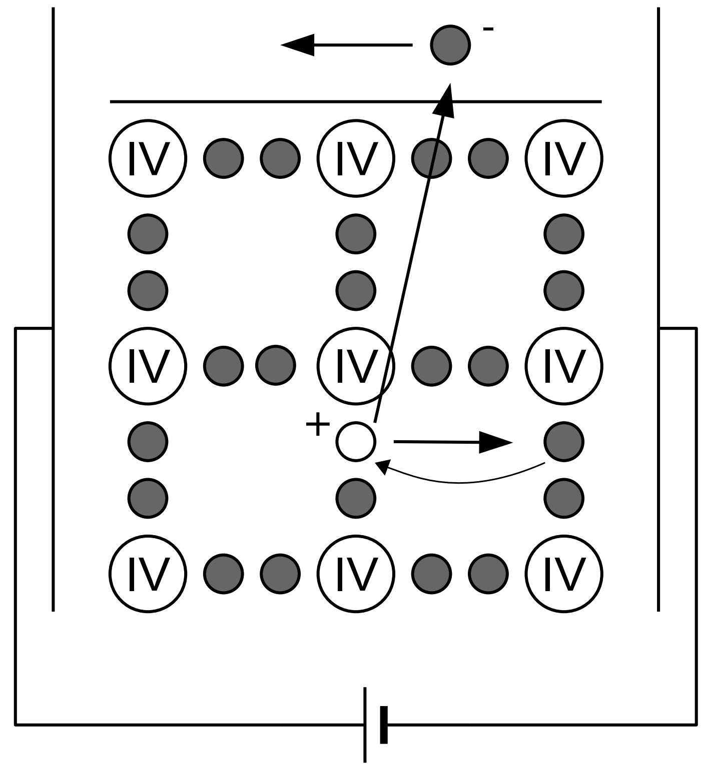
- Consumed energy per unit time.
- Power is a major concern in current electronics.
  - Portable devices (battery duration).
  - Dissipation (put a big fan!).
  - Environment (climate change).
- Power is consumed (dissipated) every time some current goes from a higher to a lower potential.
- Power can be negative
  - In this case, the device is "producing" power to be consumed in the circuit (e.g. a power supply)

Semiconductor devices (intrinsic)

T=0



T>0



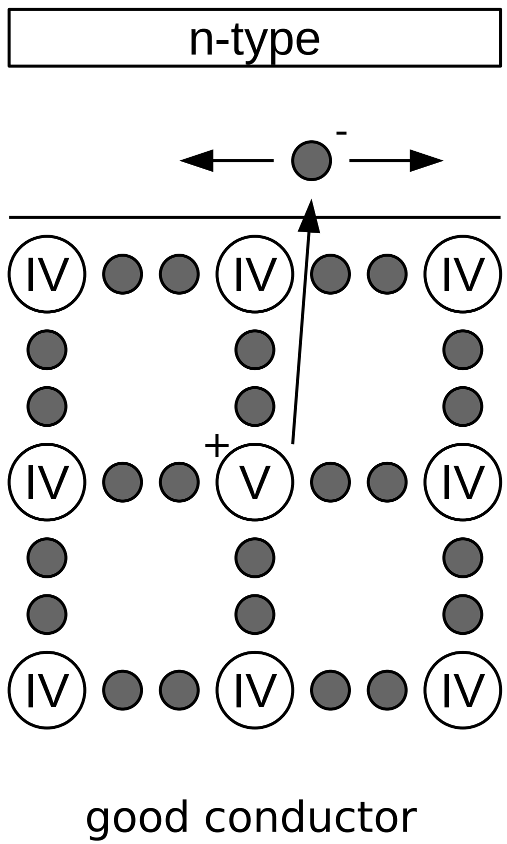
IV Group IV atom (Si)

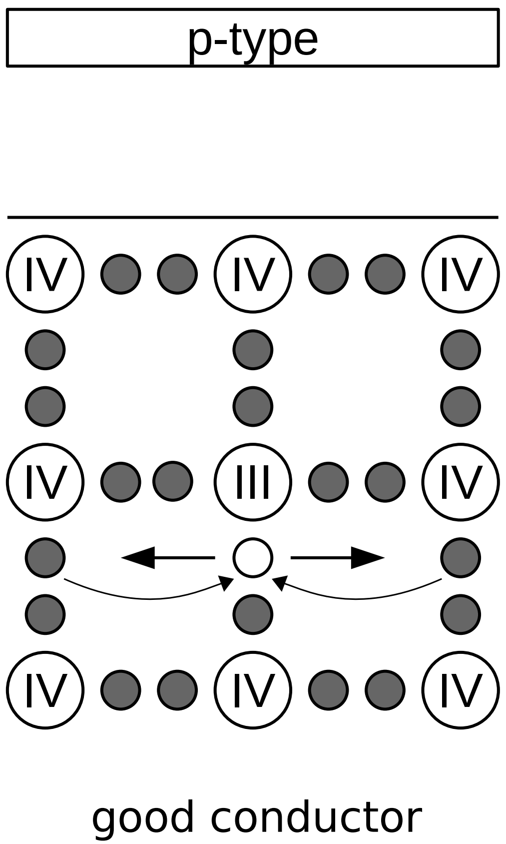
Electron (-)

Hole (+) (left by the electron)

bad conductor

Semiconductor devices (doped) (T=0)





Electron (-)

Hole (+) (left by the electron)

IV Group IV athom (Si)

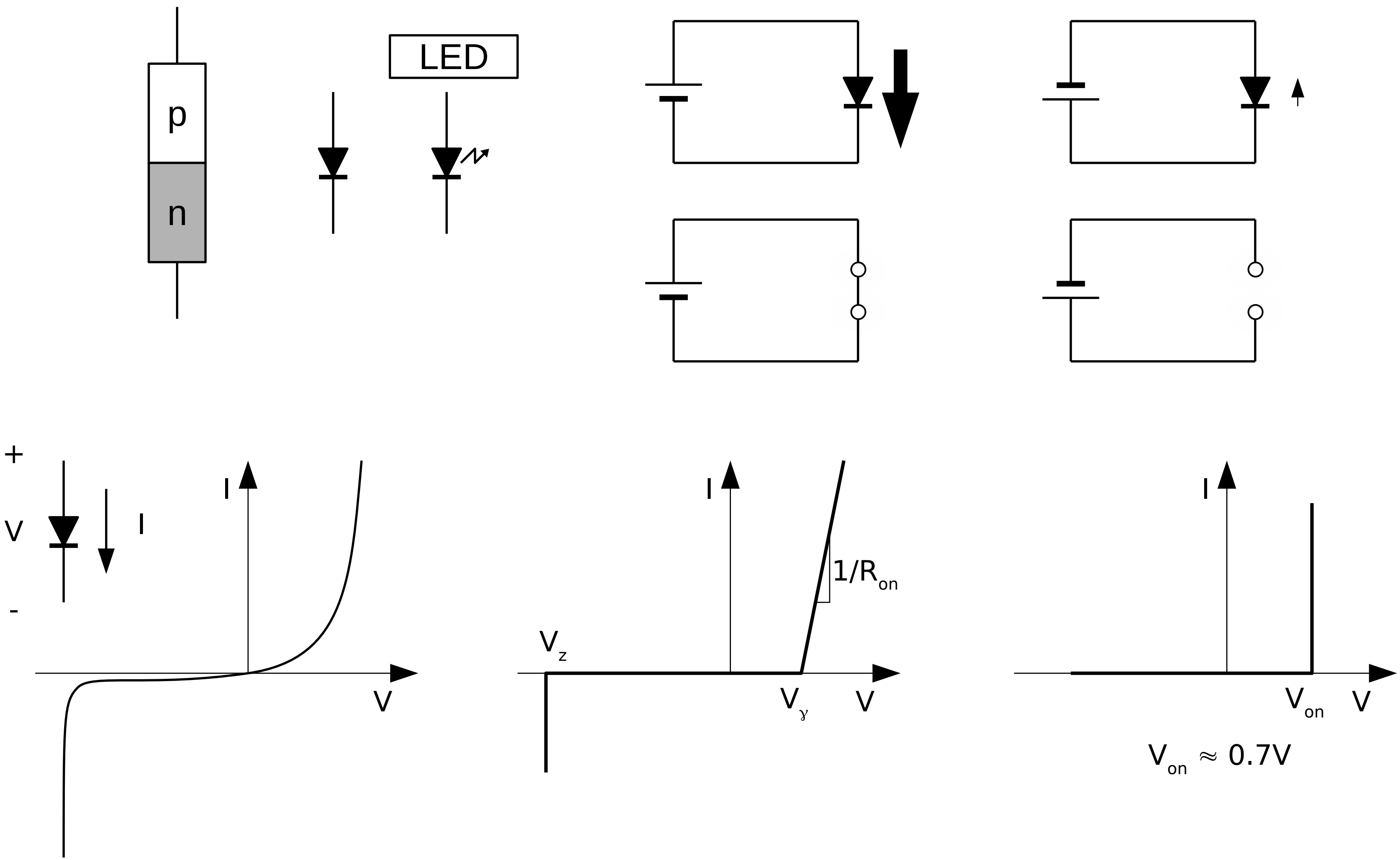
V Group V athom (P, As)

III Group III athom (B, Ga)

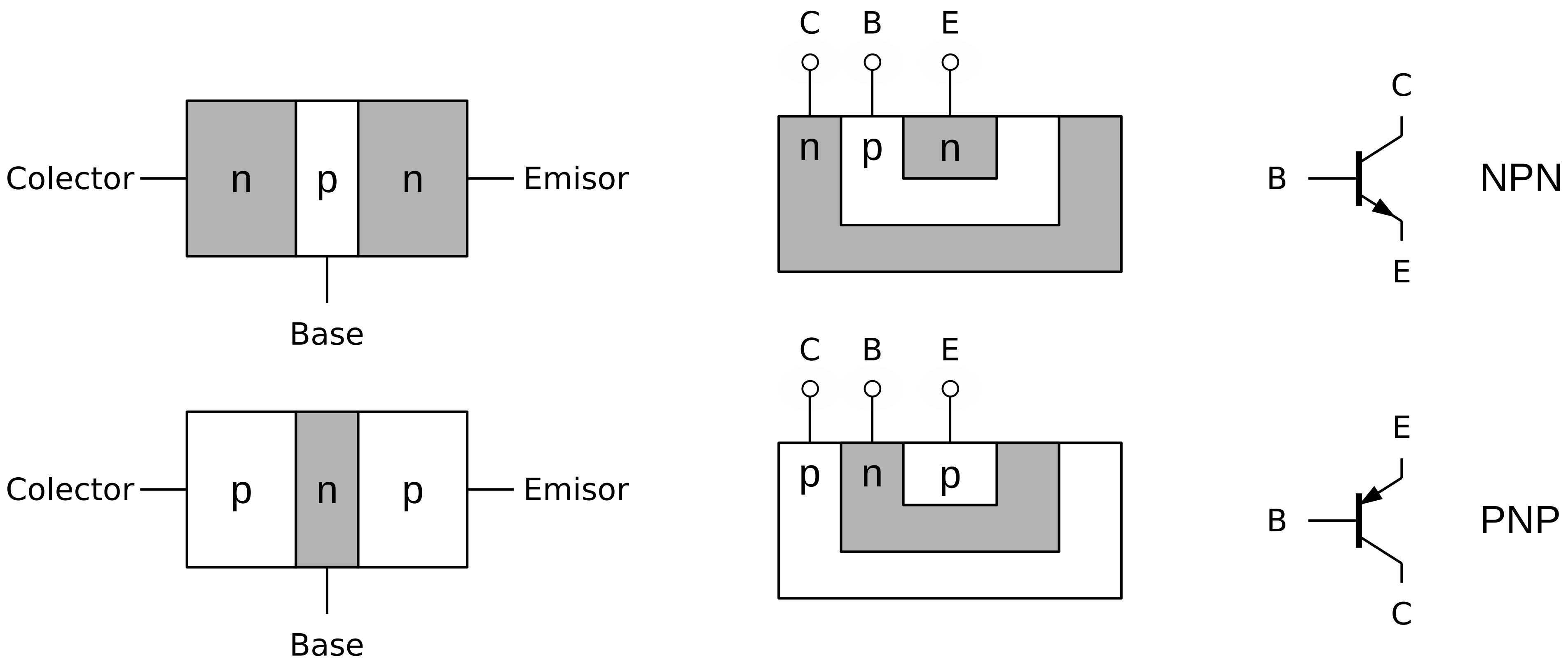
Semiconductors nice properties

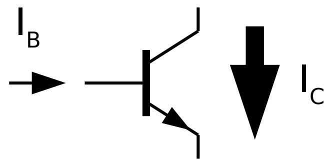
- Conductance depends on temperature, light, etc.
  - Temperature sensors
  - Light sensors
  - Solar cells
  - ...
- Conductance can be controlled by doping.
- Type of carrier (+ or -) can be controlled by doping (P or N).
- Nice devices can be created by combining different types of semiconductors (P+N).
  - Electrical: selective conductivity.
  - Optical: light emission.

Diodes and Light-Emitting Diodes (LED's)



Bipolar transistor



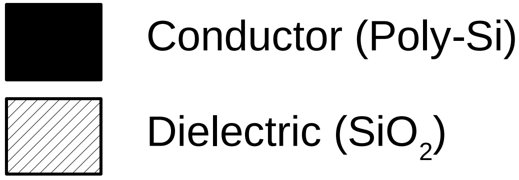


$$I_C = \beta\, I_B$$
$$\beta \approx 100$$

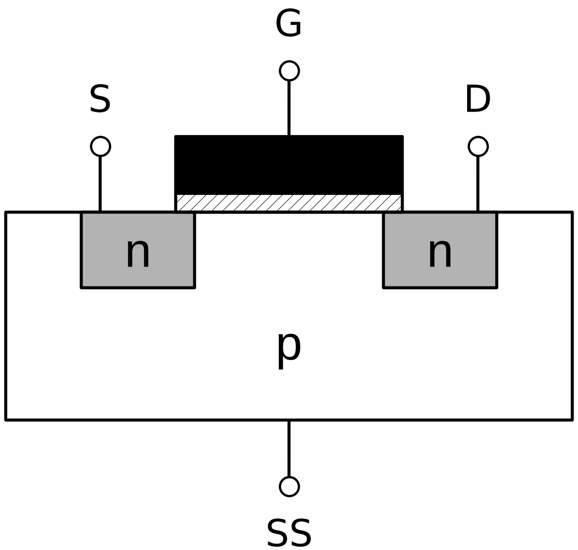
A small current through B-E allows a big current to flow through C-E.

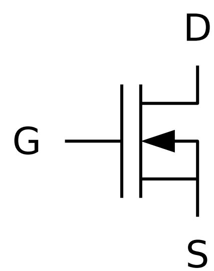
Direct use: amplifier.

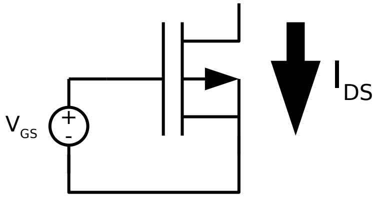
Field Effect Transistors (E.g.: MOSFET's)



nMOS

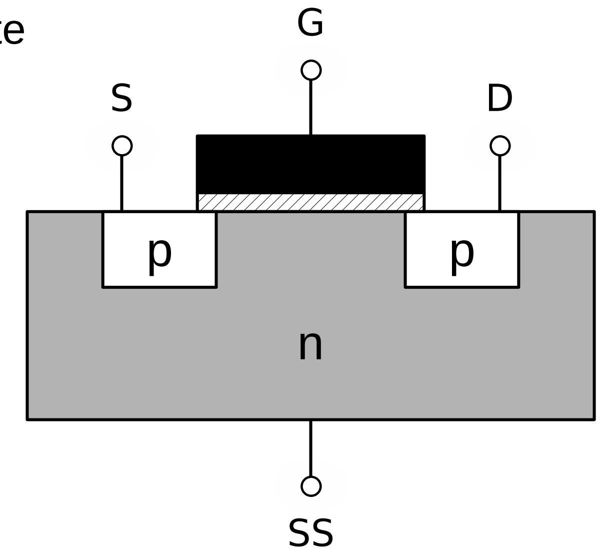


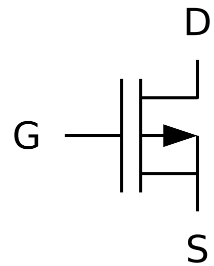




G: gate
S: source
D: drain
SS: substrate

pMOS





A small voltage between G and S allows a big current to flow from D to S.

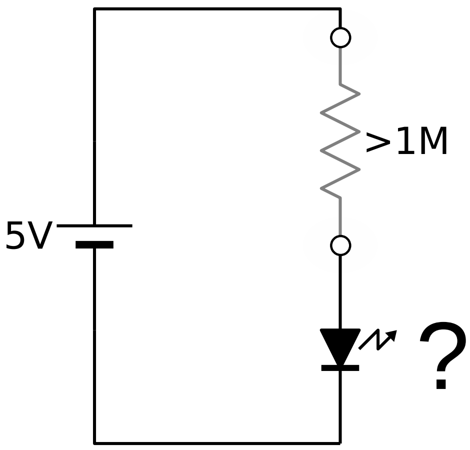
Applications: amplifier, sensors, power control, etc.

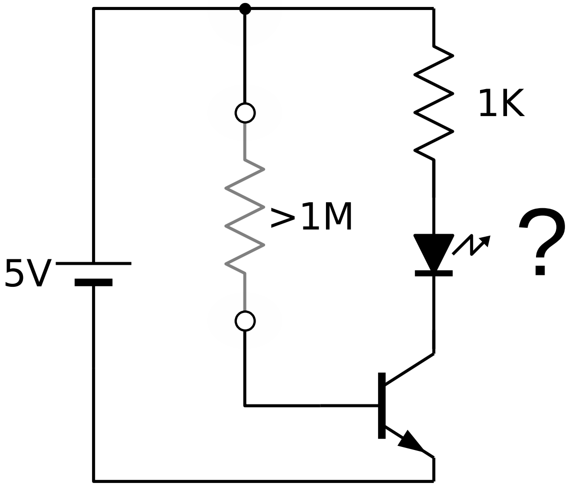
Transistors demo

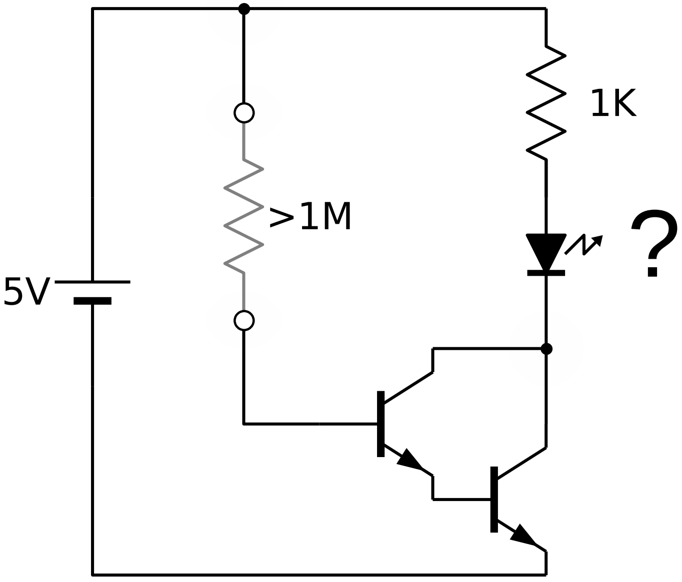
$V = IR$ $\quad I = \frac{V}{R}$

$I_C = \beta\, I_B$

$\beta \approx 100$







$I_D = I_R \approx 0$

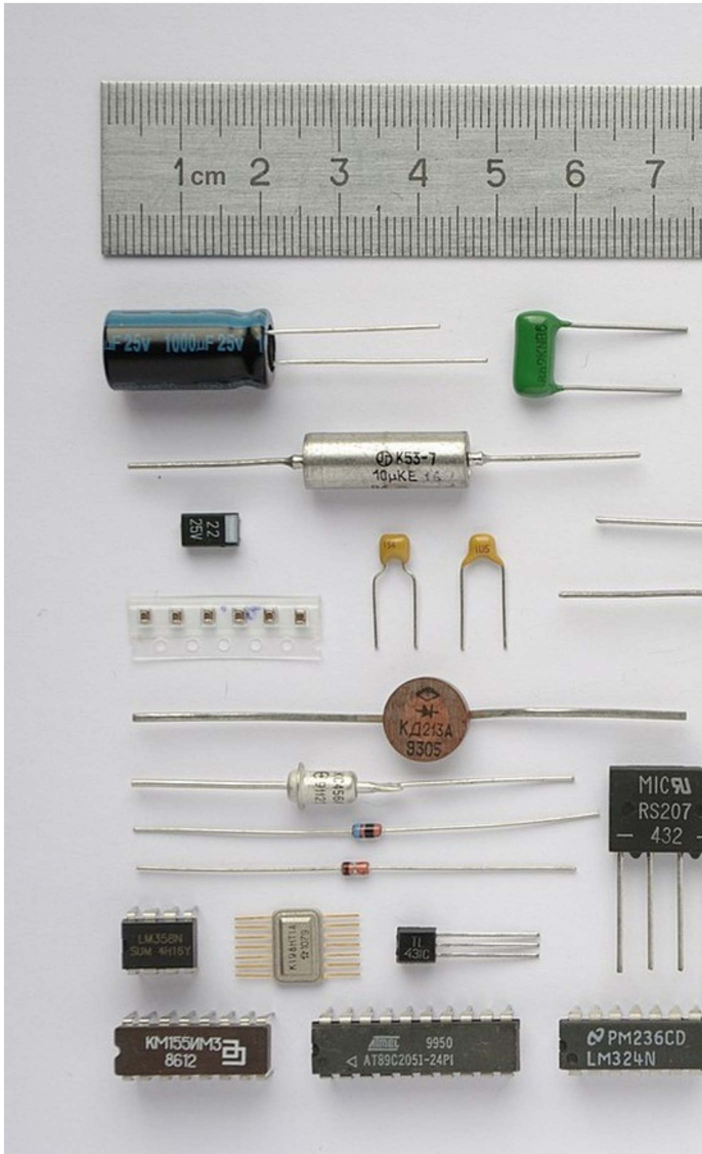
$I_D = I_C \approx 100\, I_R$

$I_D \approx 10000\, I_R$

Electronic technology

- Discrete components
  - Devices are fabricated one by one
  - Normally, they are soldered in printed circuit boards (PCB's)
- Integrated circuits (chips, IC's)
  - Several devices (mostly transistors) are fabricated at the same time over a common substrate.
  - Really big numbers: 10-500 million! devices in the same chip.
  - Most of today's electronics is done as IC's
- Types of IC's
  - Application specific (ASIC)
  - Programmable (E.g. FPGA)

Electronic devices



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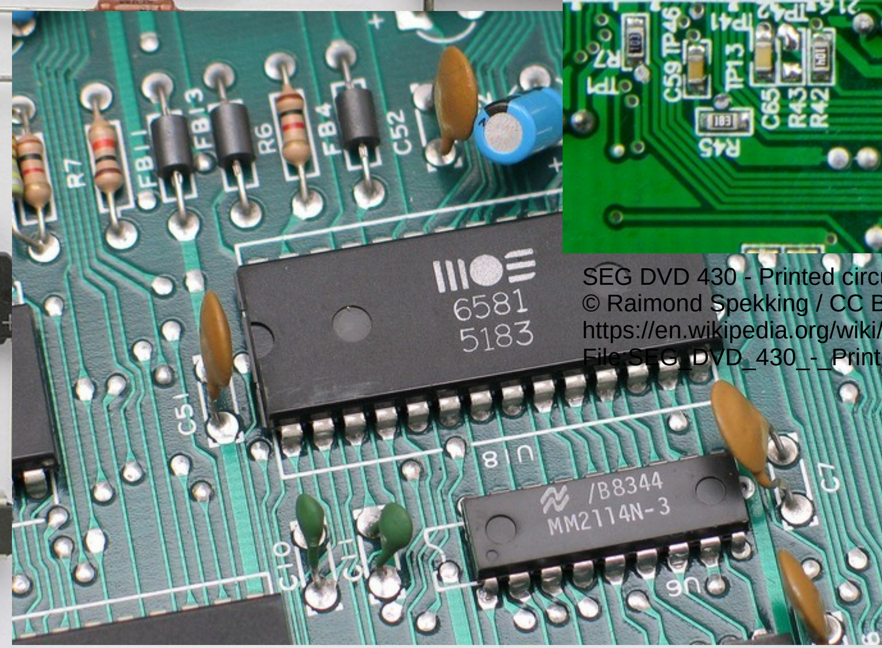

Commodore 64 PCB (1980)
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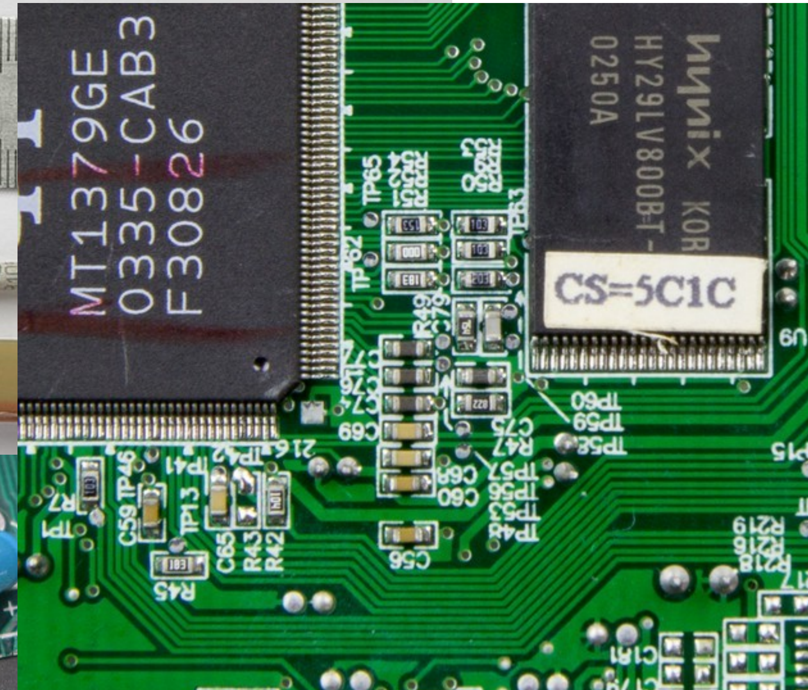

SEG DVD 430 - Printed circuit board (2003)
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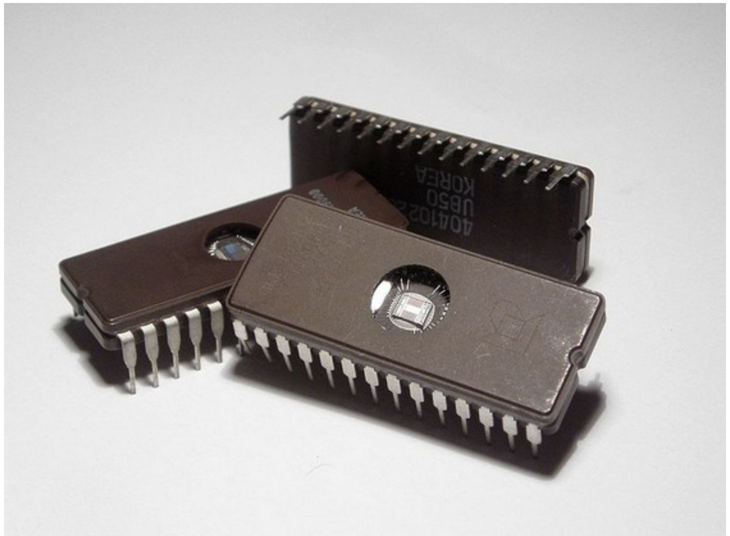
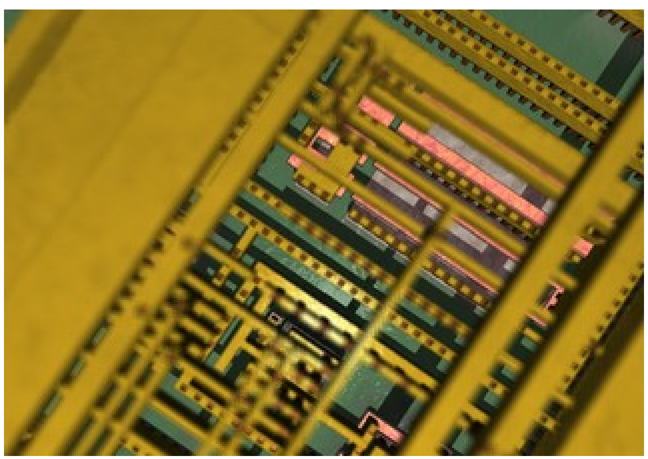
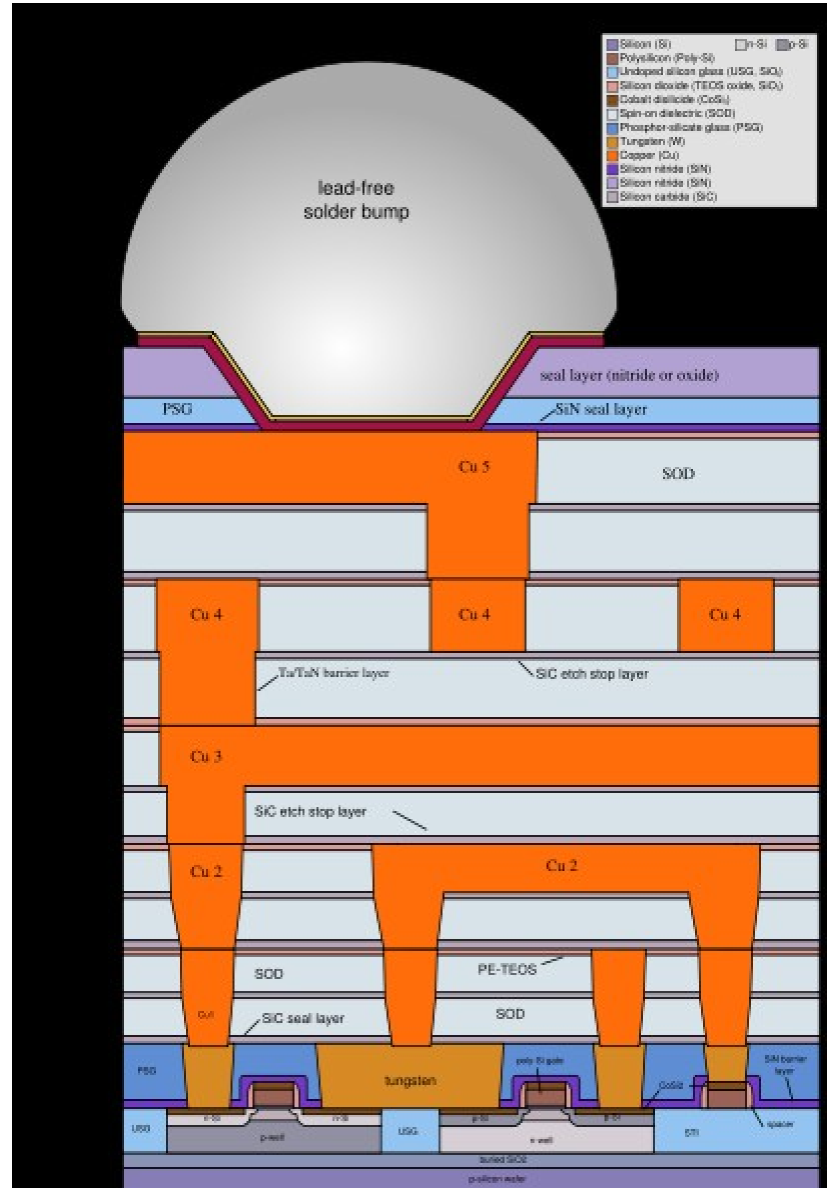
https://en.wikipedia.org/wiki/Printed_circuit_board#/media/
File:SEG_DVD_430_-_Printed_circuit_board-4276.jpg

Integrated circuits







http://en.wikipedia.org/wiki/Integrated_circuit

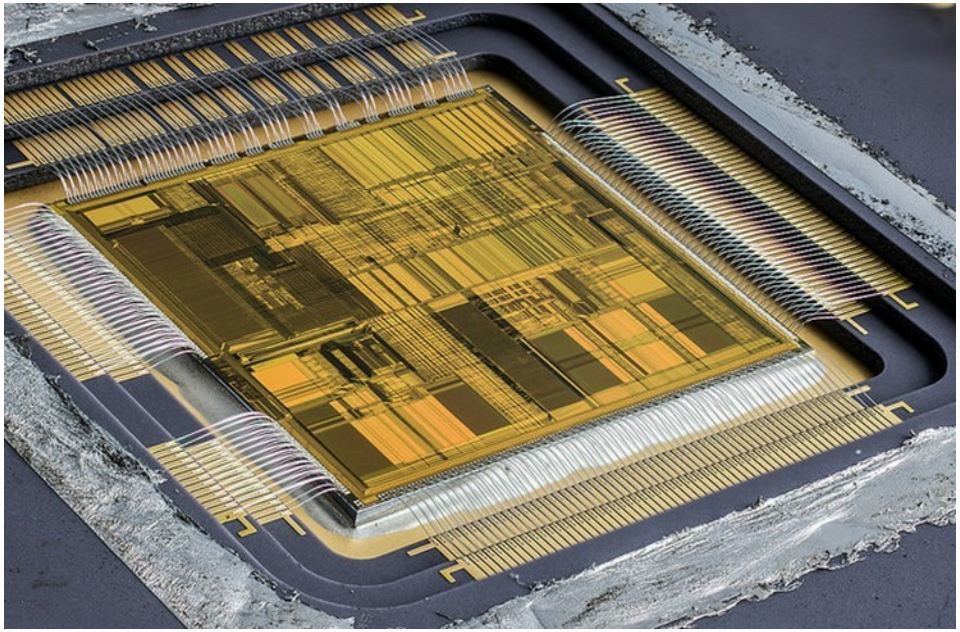
Integrated circuits. Types

Application Specific IC (ASIC)

Programmable (ej. FPGA)

Xilinx XC4010-6

Intel Pentium



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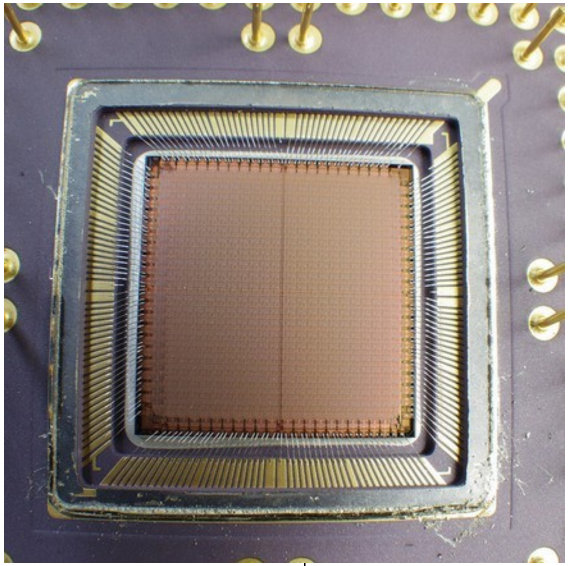

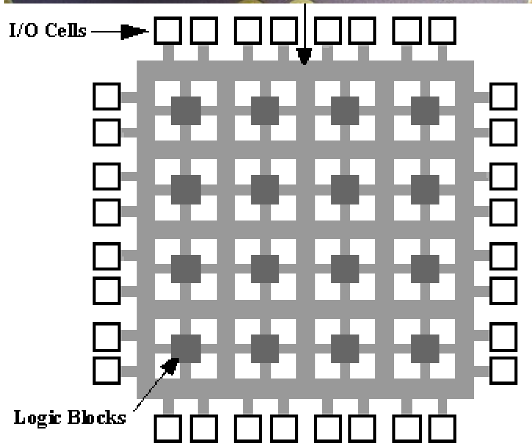

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Xilinx XC4010-6. Public domain.
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Integrated Circuits. Generations

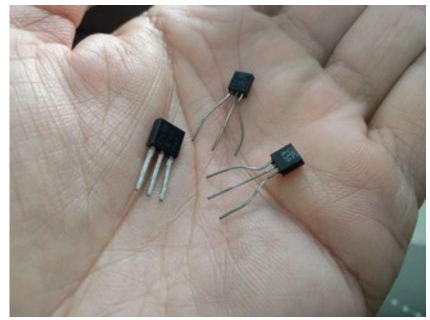
Name	Meaning	Year	No. tt	Comment
SSI	Small-scale integration	1964	1 a 10	Military and space applications
MSI	Medium-scale integration	1968	10 a 500	Consumer electronics
LSI	Large-scale integration	1971	500 a 20000	Microprocessors and integrated memories
VLSI	Very large-scale integration	1980	20000 a 1M	Advances microprocessors and memories. Need Design Automation (DA)
ULSI	Ultra-large-scale integration	1984	> 1M	System on Chip (SoC)

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

Evolution

Vacuum tube

Transistors



Integrated Circuit
Intel Pentium IV (~50Mtt)

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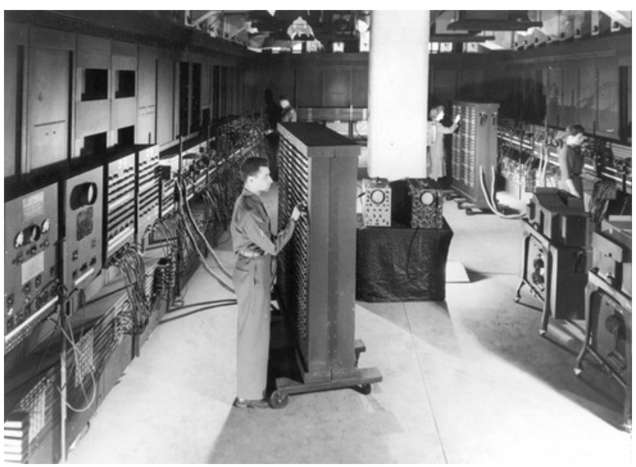
ENIAC (1946)



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IBM 360 Model 20 (1966)

By Ben Franske - DM IBM S360.jpg on en.wiki, CC BY 2.5
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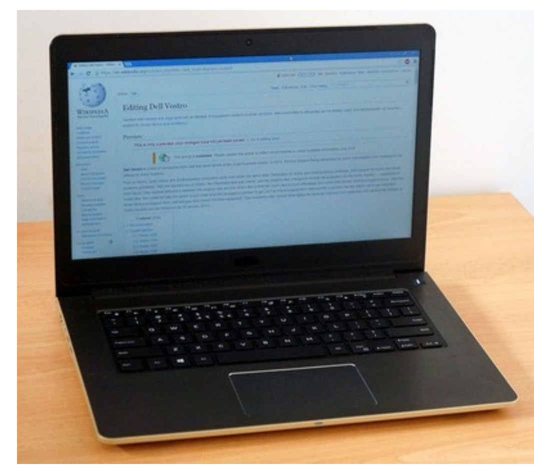
Laptop (2018)



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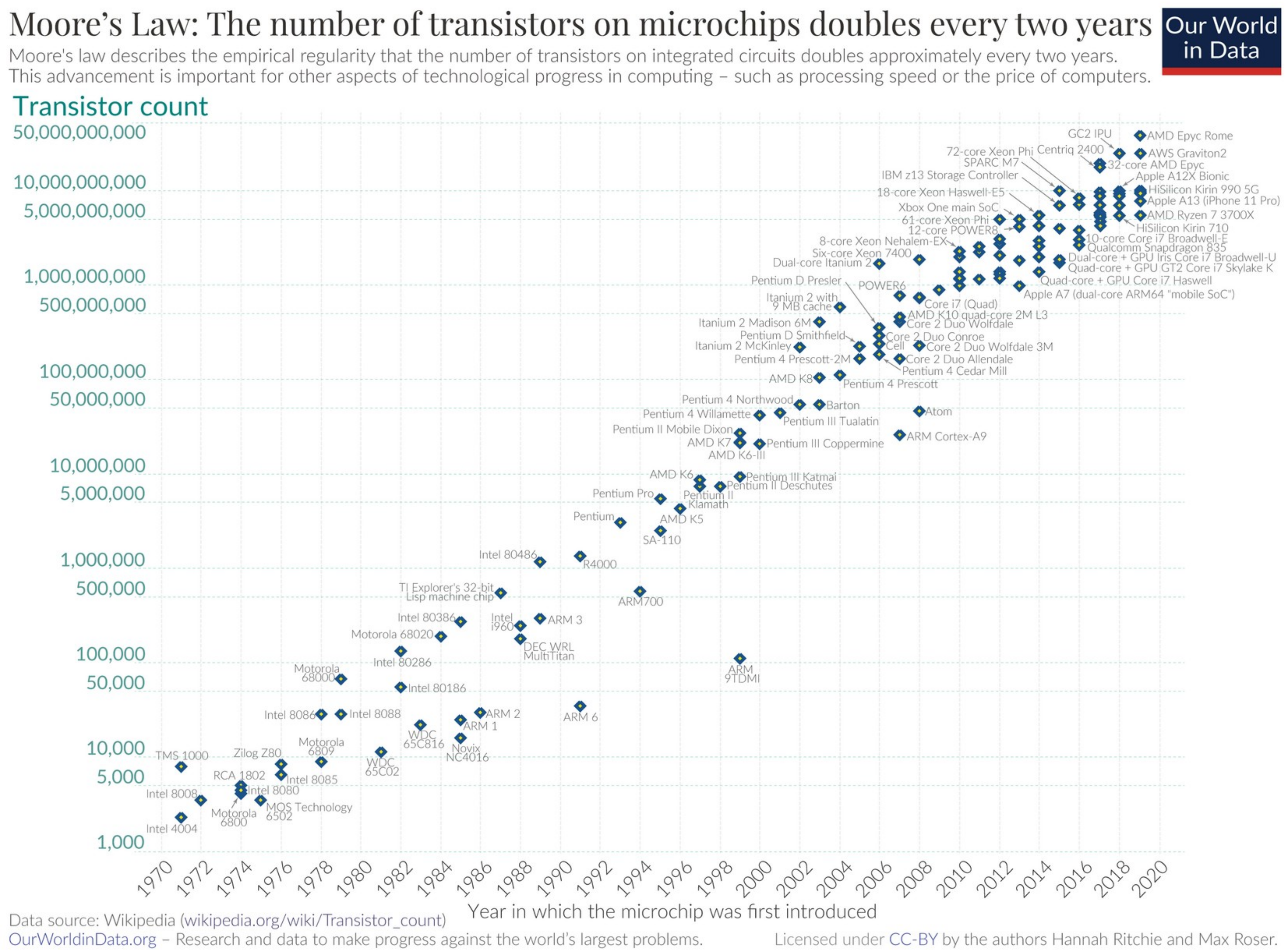
Moore's Law: The number of transistors on microchips doubles every two years
Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years.
This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.
Our World in Data
Transistor count
50,000,000,000
10,000,000,000
5,000,000,000
1,000,000,000
500,000,000
100,000,000
50,000,000
10,000,000
5,000,000
1,000,000
500,000
100,000
50,000
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2010
2012
2014
2016
2018
2020
Year in which the microchip was first introduced
GC2 IPU
AMD Epyc Rome
72-core Xeon Phi
Centriq 2400
AWS Graviton2
SPARC M7
32-core AMD Epyc
IBM z13 Storage Controller
Apple A12X Bionic
18-core Xeon Haswell-E5
HiSilicon Kirin 990 5G
Apple A13 (iPhone 11 Pro)
Xbox One main SoC
AMD Ryzen 7 3700X
61-core Xeon Phi
HiSilicon Kirin 710
12-core POWER8
8-core Xeon Nehalem-EX
10-core Core i7 Broadwell-E
Qualcomm Snapdragon 835
Six-core Xeon 7400
Dual-core + GPU Iris Core i7 Broadwell-U
Dual-core Itanium 2
Quad-core + GPU GT2 Core i7 Skylake K
Quad-core + GPU Core i7 Haswell
Pentium D Presler
POWER6
Apple A7 (dual-core ARM64 "mobile SoC")
Itanium 2 with 9 MB cache
Core i7 (Quad)
AMD K10 quad-core 2M L3
Itanium 2 Madison 6M
Core 2 Duo Wolfdale
Pentium D Smithfield
Core 2 Duo Conroe
Itanium 2 McKinley
Cell
Core 2 Duo Wolfdale 3M
Pentium 4 Prescott-2M
Core 2 Duo Allendale
Pentium 4 Cedar Mill
AMD K8
Pentium 4 Prescott
Pentium 4 Northwood
Barton
Pentium 4 Willamette
Atom
Pentium III Tualatin
Pentium II Mobile Dixon
ARM Cortex-A9
AMD K7
Pentium III Coppermine
AMD K6-III
AMD K6
Pentium III Katmai
Pentium II Deschutes
Pentium Pro
Pentium II Klamath
Pentium
AMD K5
SA-110
Intel 80486
R4000
TI Explorer's 32-bit Lisp machine chip
ARM700
Intel 80386
Intel i960
ARM 3
Motorola 68020
DEC WRL MultiTitan
Intel 80286
ARM 9TDMI
Motorola 68000
Intel 80186
Intel 8086
Intel 8088
ARM 2
ARM 1
ARM 6
WDC 65C816
Motorola 6809
Novix NC4016
TMS 1000
Zilog Z80
WDC 65C02
RCA 1802
Intel 8085
Intel 8008
Intel 8080
MOS Technology 6502
Motorola 6800
Intel 4004
Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)
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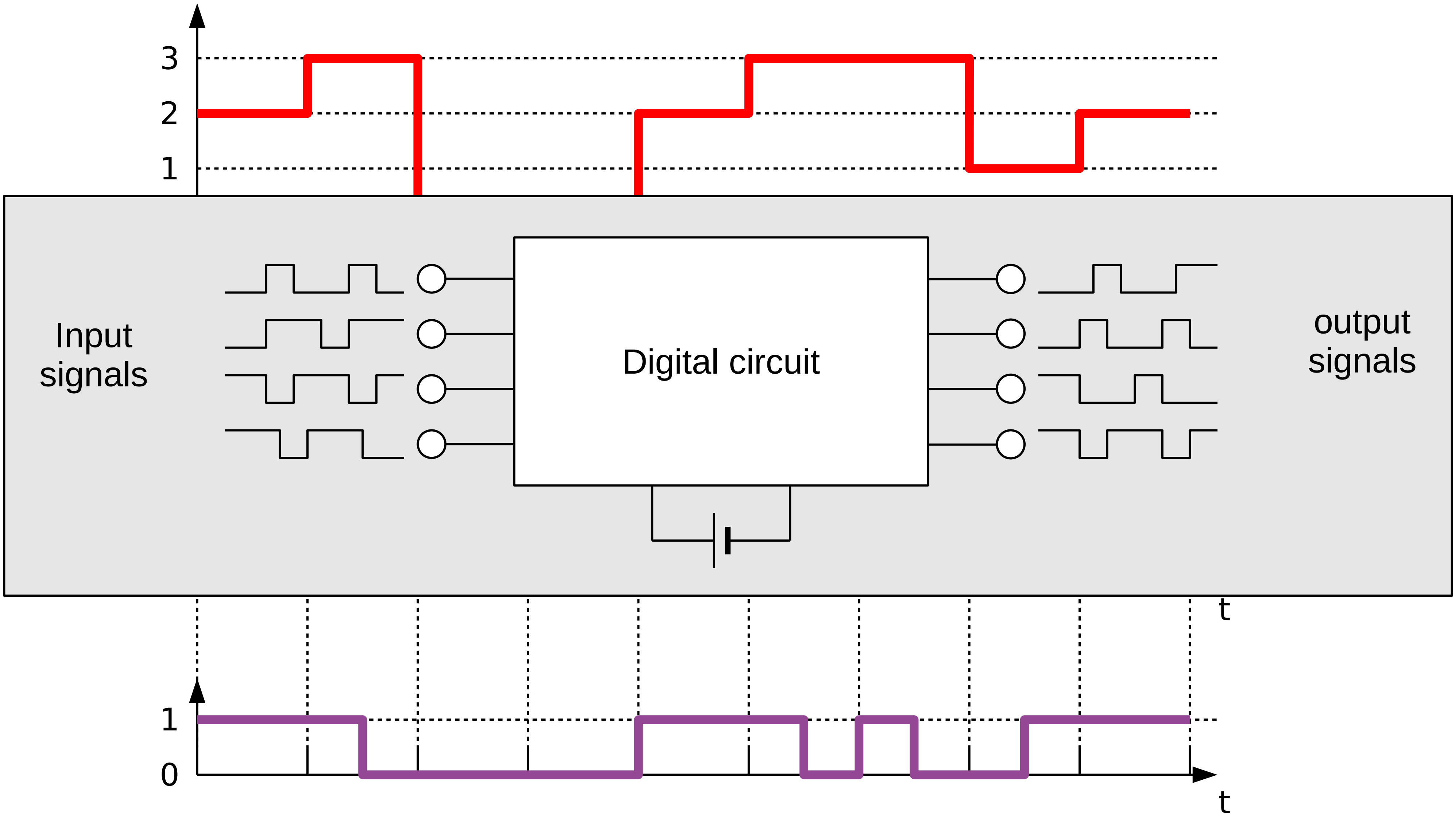
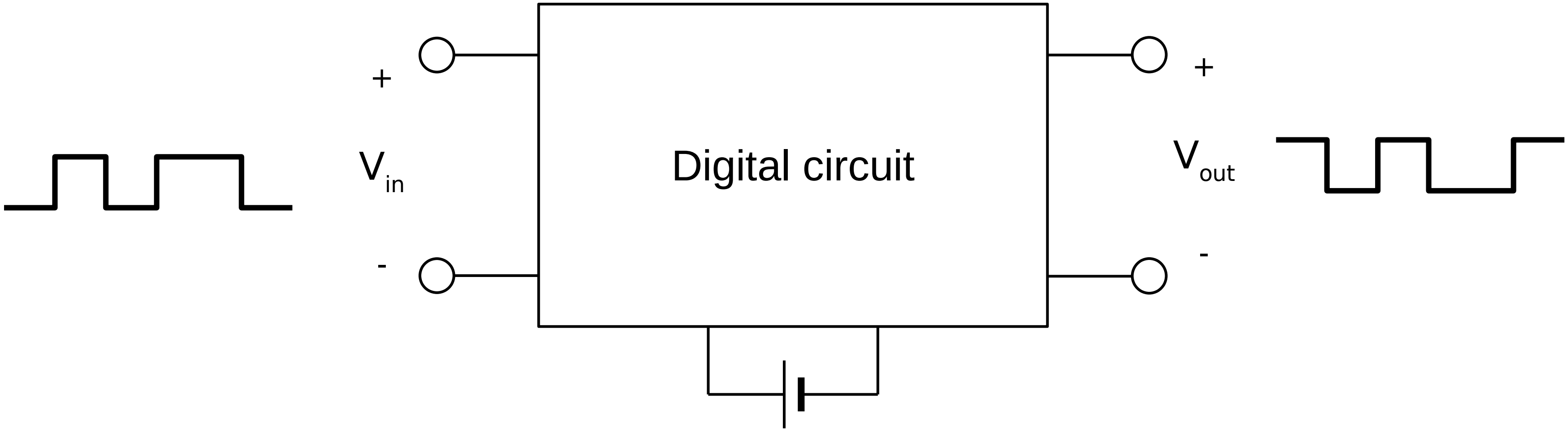
Digital circuits and logic families

- Digital circuits
- Logic gates and logic operators
- Logic families
- Electrical parameters
- Switching parameters

Digital circuits

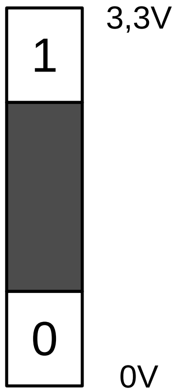


Digital circuits. Logic levels

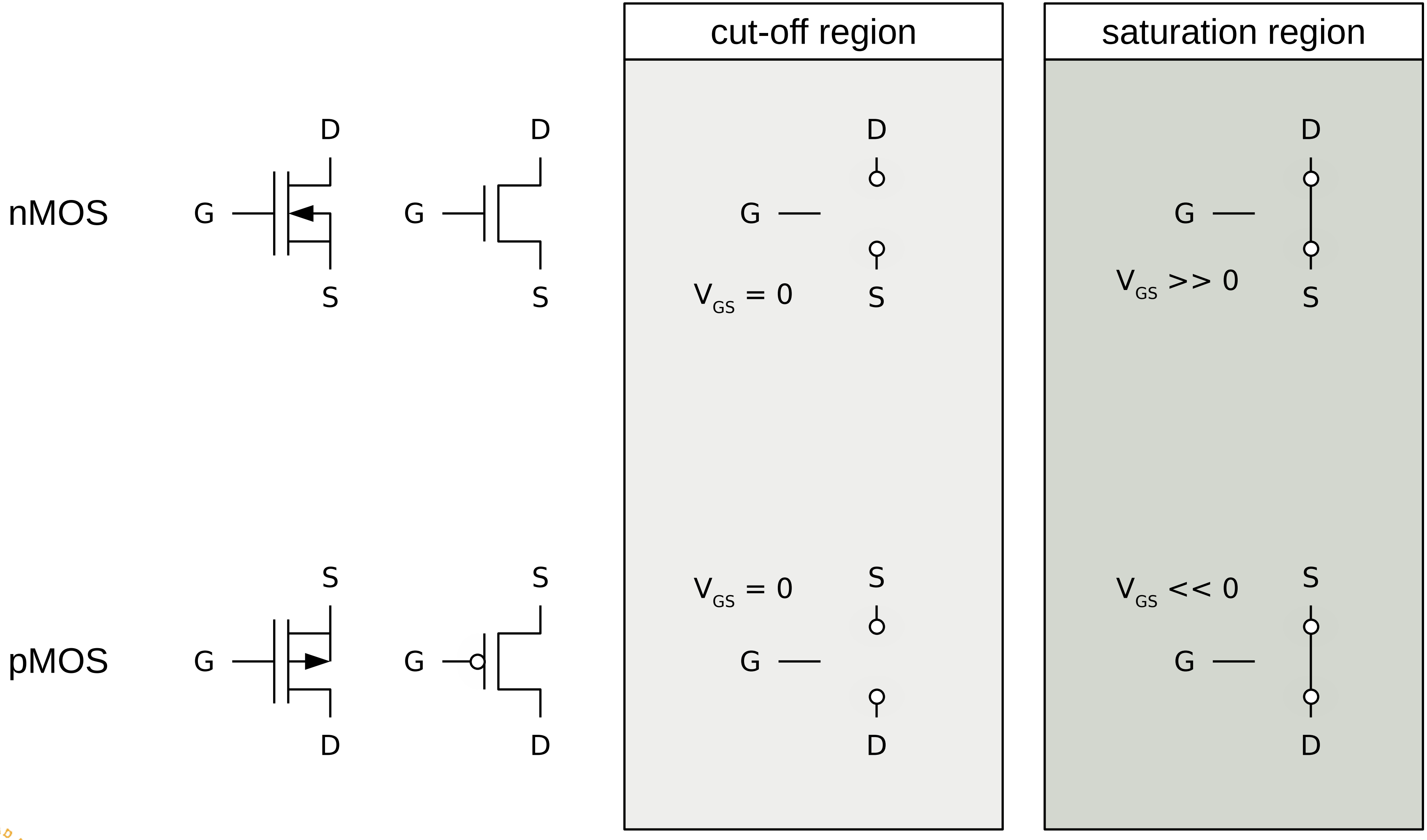


Electric value (V_X) vs. logic value (X)
Ejemplo: 3,3V

V_X	X
~0V	0
~3,3V	1

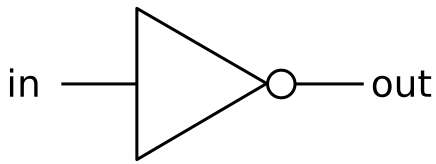


Transistors in switching mode (MOS example)

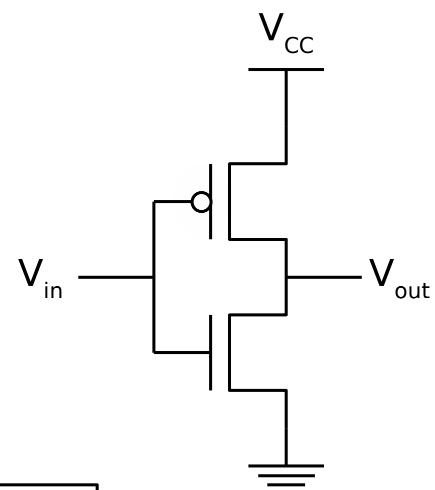


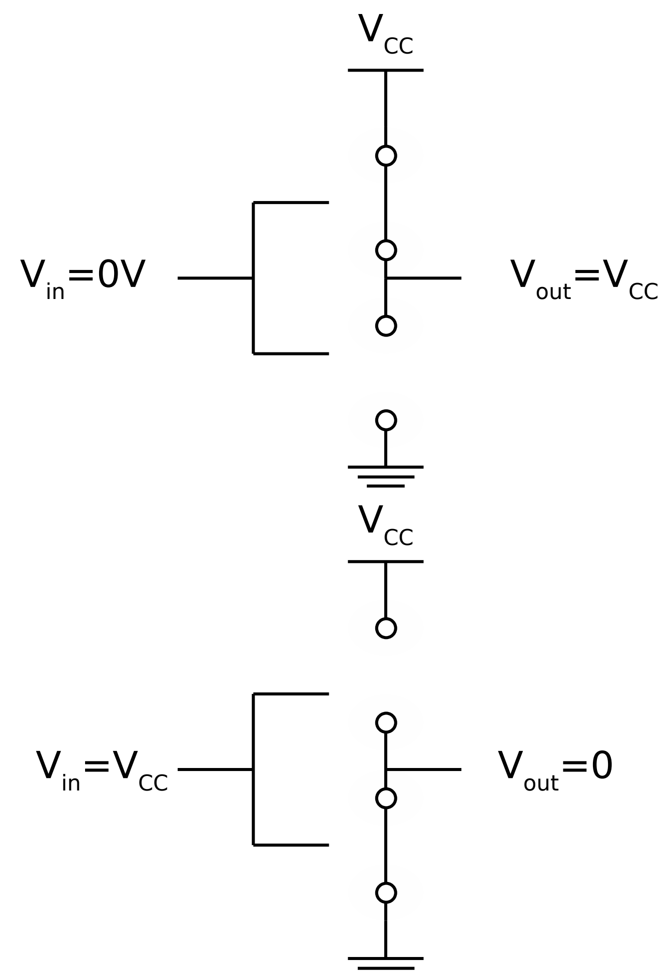
Logic gates. CMOS Inverter

- Logic gates perform simple operations on digital data.
- The simplest (non identical) operation is “inversion”, implemented by the inverter gate.



in	out
0	1
1	0

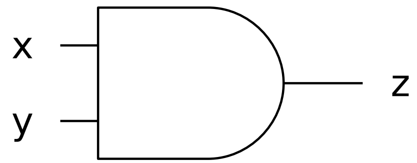




Simulación

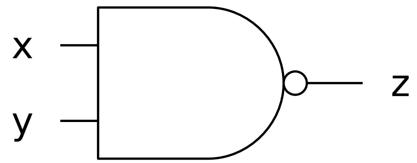
Logic gates and logic operators

AND



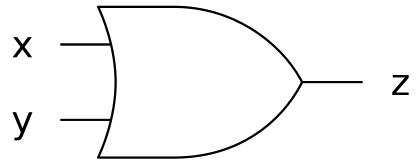
x y	z
0 0	0
0 1	0
1 0	0
1 1	1

NAND



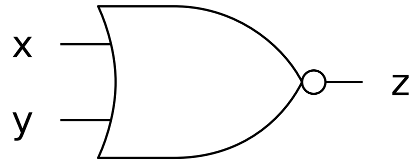
x y	z
0 0	1
0 1	1
1 0	1
1 1	0

OR



x y	z
0 0	0
0 1	1
1 0	1
1 1	1

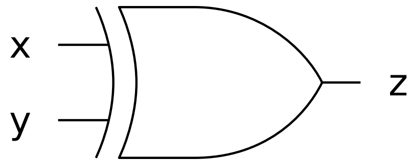
NOR



x y	z
0 0	1
0 1	0
1 0	0
1 1	0

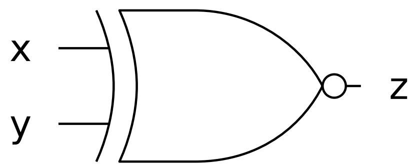
Logic gates and logic operators

XOR



x y	z
0 0	0
0 1	1
1 0	1
1 1	0

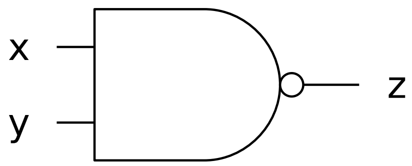
XNOR

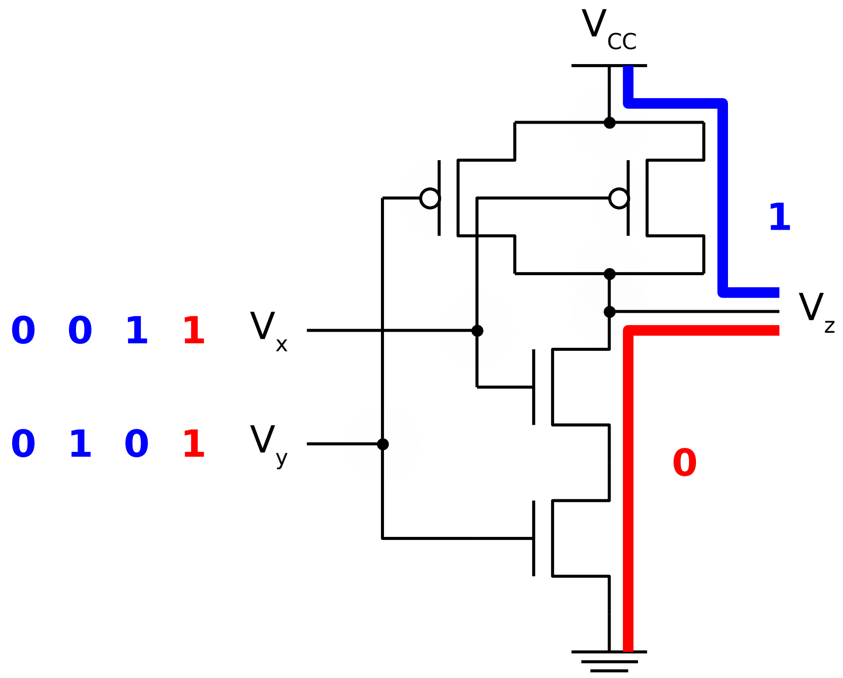


x y	z
0 0	1
0 1	0
1 0	0
1 1	1

CMOS gates are “naturally inverting”
(INV, NAND, NOR, ...)

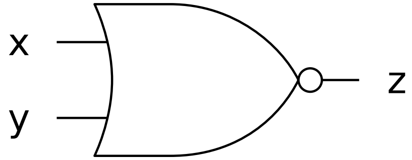
Logic gates. CMOS NAND

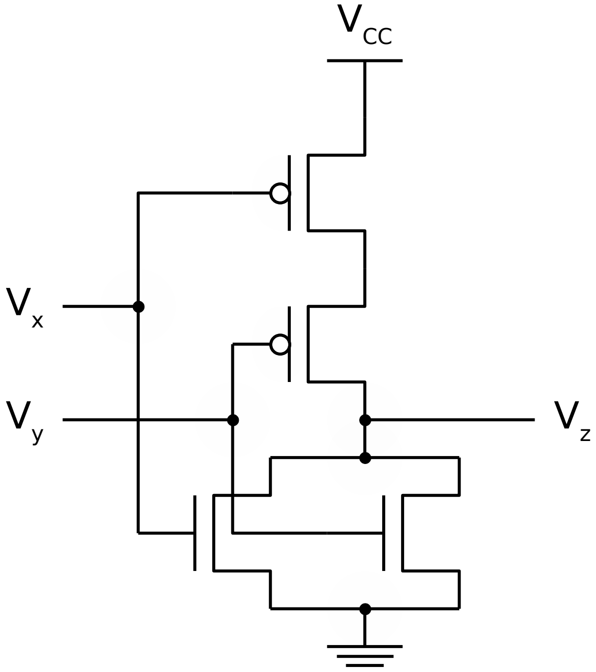




Simulation

Logic Gates. CMOS NOR



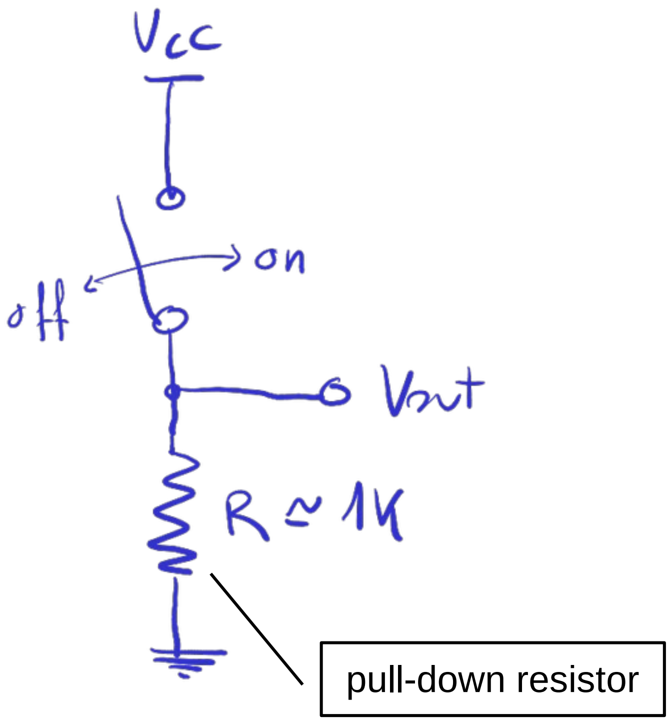


Simulation

Examples: digital interface

- Simple digital signal generation
  - Switch
  - Push button
  - Variable resistance sensor:
    - light, temperature, humidity, etc.
  - Sensor sensitivity adjustment
- Simple digital signal perception
  - LED + resistor
  - Buzzer
  - Etc.

Switch with pull-down resistor

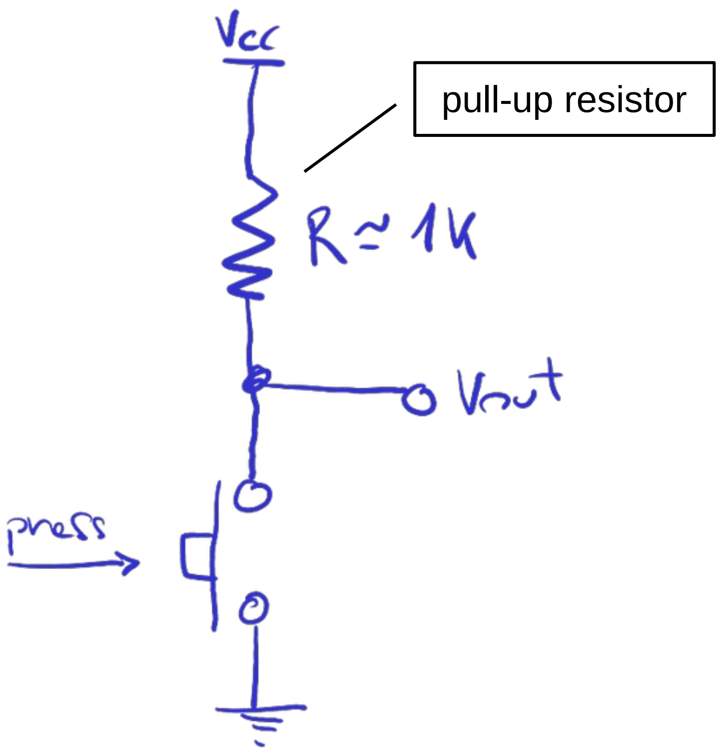


on: $V_{out} = V_{CC}$ (logic 1)
off: V_{out} = 0V (logic 0)

- Pull-down resistor:
  - Forces V_{out} low when the switch is off.
  - Prevents V_{out} node from being disconnected (floating).
  - The voltage in floating nodes may change without control: interferences, radiation, etc.

Simulation

Push button with pull-up resistor

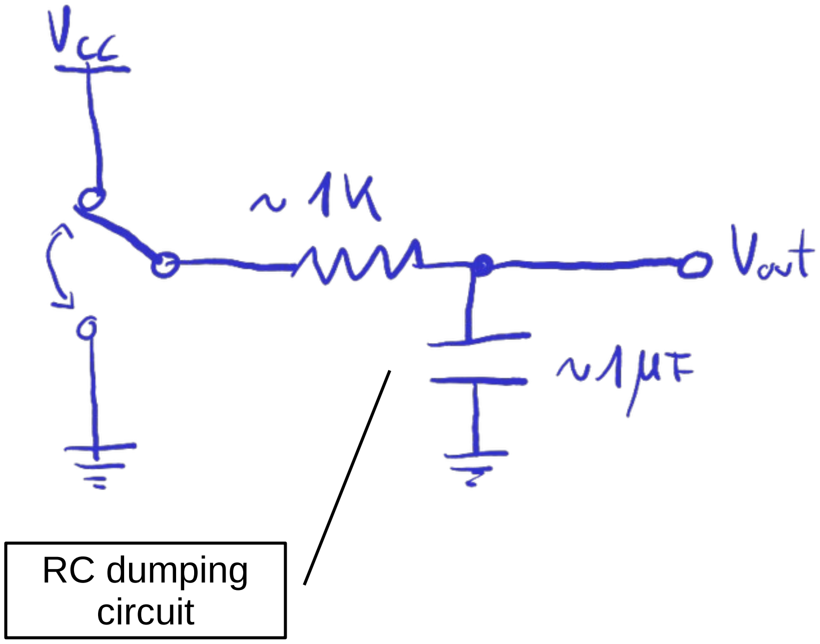


press: V_{out} = 0V (logic 0)
release: $V_{out} = V_{CC}$ (logic 1)

- Pull-up resistor:
  - Forces V_{out} high when the button is not pressed.
  - Prevents V_{out} node from being disconnected (floating).

Simulation

SPDT switch with RC dumping circuit



- Dumping circuit
  - Keeps the output voltage while the switch is changing.
  - Dump switch “bounces”.

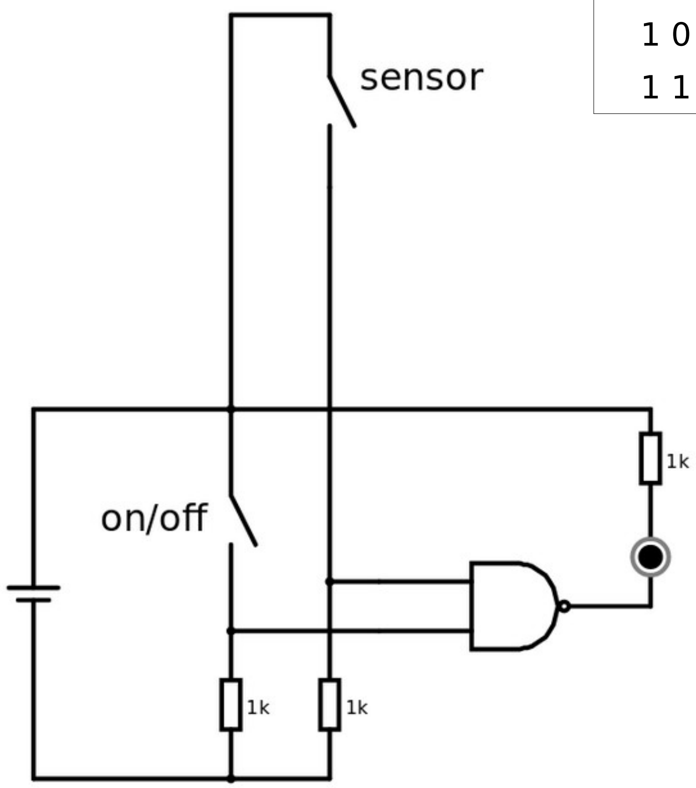
up: $V_{out} = V_{CC}$ (logic 1)
down: V_{out} = 0V (logic 0)

Simulation

Example

- Simple alarm system with a NAND gate
  - On/off switch
  - Contact sensor
  - Alarm indicator (LED, etc.)
- Modifications
  - Alarm when sensor is off
  - Activate something bigger
    - Relay
    - Light
    - Engine
    - ...

x y	NAND
0 0	1
0 1	1
1 0	1
1 1	0



Simulation

Logic families

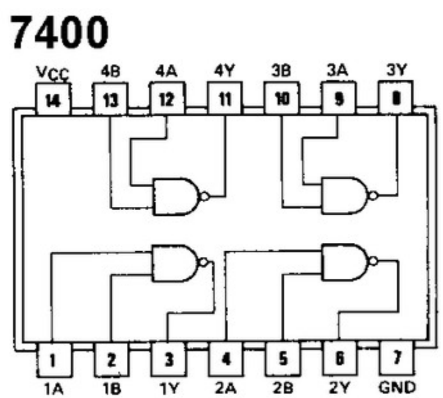
- Logic gates are fabricated using different technologies (Bipolar, CMOS, …) and different techniques.
- Logic family: set of gates sharing the same technology and similar design techniques
  - Gates in a family are compatible: will operate correctly when connected to each other.
  - Share similar electrical and dynamic parameters.
- Some logic families are compatible with others.
- Specially relevant when working with SSI and MSI devices (7400 series)

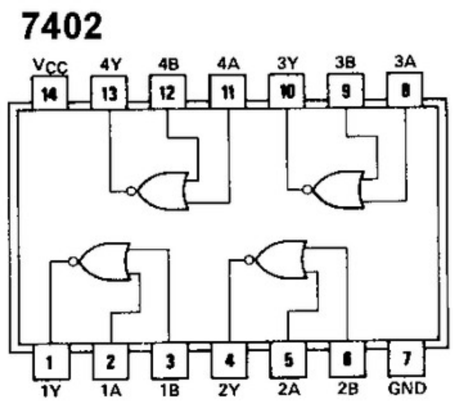
Logic families

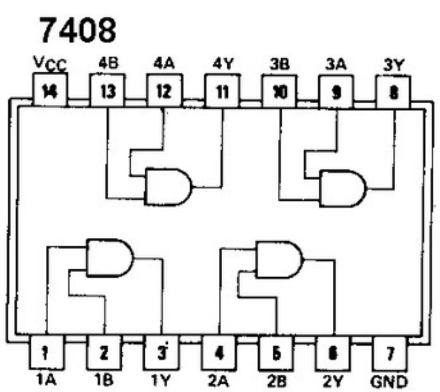
- Bipolar
  - ECL (Emitter-coupled-logic, 1962): first logic family available in integrated circuits.
  - DTL (Diode-Transistor-Logic, 1962).
  - RTL (Resistor-Transistor-Logic, 1963): used in the Apollo guidance computer (first CPU built from IC's).
  - TTL (Transistor-transistor logic): very popular. Many improvements since 1963. E.g. 74 series.
    - LS TTL: very popular low-power variant.
- CMOS
  - E.g. HC logic. Compatible with TTL. E.g. 74HC series.
  - Most extended technology nowadays in IC's.
  - Better noise margins, lower static consumption, cheaper, but slower.
- BiCMOS
  - Combines CMOS inputs with TTL drivers.
  - Includes various logic families.

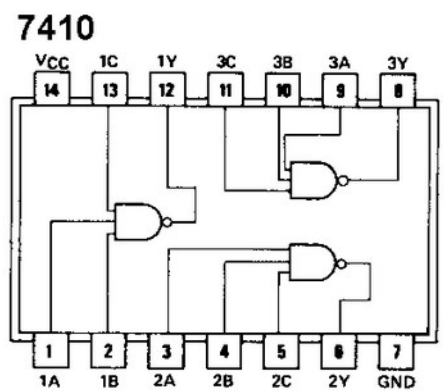
Logic families

- 7400 series
  - Very popular as SSI and MSI devices in education
  - Initially a TTL family, there exist various compatible logic families in various technologies.









Electrical parameters

- Supply voltage (V_{CC})
- Logic levels
  - High and low
  - Input and output
  - Allow noise margin calculations
- Maximum current
  - Input (I_{IL}, I_{IH}). Lower is better.
  - Output (I_{OL}, I_{OH}). Higher is better.
  - Allow *fan-out* calculations.
- Power consumption
  - Static: when signals do not change.
  - Dynamic: when signals change.

Electrical parameters

recommended operating conditions

		SN54AS04			SN74AS04			UNIT
		MIN	NOM	MAX	MIN	NOM	MAX	
V_{CC}	Supply voltage	4.5	5	5.5	4.5	5	5.5	V
V_{IH}	High-level input voltage	2			2			V
V_{IL}	Low-level input voltage			0.8			0.8	V
I_{OH}	High-level output current			−2			−2	mA
I_{OL}	Low-level output current			20			20	mA
T_A	Operating free-air temperature	−55		125	0		70	°C

electrical characteristics over recommended operating free-air temperature range (unless otherwise noted)

PARAMETER	TEST CONDITIONS		SN54AS04			SN74AS04			UNIT
			MIN	TYP§	MAX	MIN	TYP§	MAX	
V_{IK}	V_{CC} = 4.5 V,	I_I = −18 mA			−1.2			−1.2	V
V_{OH}	V_{CC} = 4.5 V to 5.5 V,	I_{OH} = −2 mA	V_{CC} −2			V_{CC} −2			V
V_{OL}	V_{CC} = 4.5 V,	I_{OL} = 20 mA		0.35	0.5		0.35	0.5	V
I_I	V_{CC} = 5.5 V,	V_I = 7 V			0.1			0.1	mA
I_{IH}	V_{CC} = 5.5 V,	V_I = 2.7 V			20			20	µA
I_{IL}	V_{CC} = 5.5 V,	V_I = 0.4 V			−0.5			−0.5	mA
I_O¶	V_{CC} = 5.5 V,	V_O = 2.25 V	−30		−112	−30		−112	mA
I_{CCH}	V_{CC} = 5.5 V,	V_I = 0		3	4.8		3	4.8	mA
I_{CCL}	V_{CC} = 5.5 V,	V_I = 4.5 V		14	26.3		14	26.3	mA

§ All typical values are at V_{CC} = 5 V, T_A = 25°C.
¶ The output conditions have been chosen to produce a current that closely approximates one half of the true short-circuit output current, I_{OS}.

Electrical parameters

recommended operating conditions (see Note 4)

		SN54LS00			SN74LS00			UNIT
		MIN	NOM	MAX	MIN	NOM	MAX	
V_{CC}	Supply voltage	4.5	5	5.5	4.75	5	5.25	V
V_{IH}	High-level input voltage	2			2			V
V_{IL}	Low-level input voltage			0.7			0.8	V
I_{OH}	High-level output current			–0.4			–0.4	mA
I_{OL}	Low-level output current			4			8	mA
T_A	Operating free-air temperature	–55		125	0		70	°C

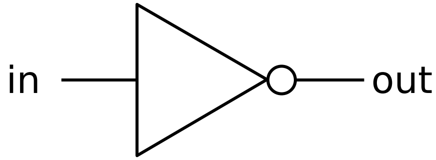
NOTE 4: All unused inputs of the device must be held at V_{CC} or GND to ensure proper device operation. Refer to the TI application report, *Implications of Slow or Floating CMOS Inputs*, literature number SCBA004.

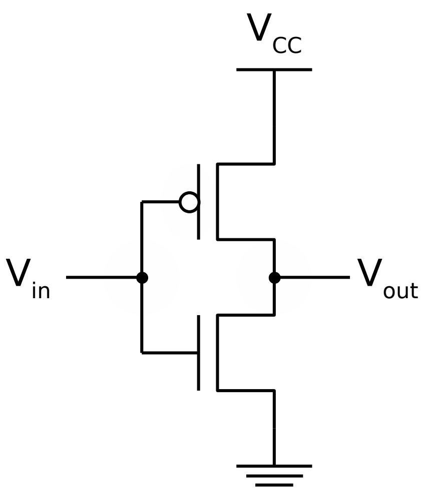
electrical characteristics over recommended operating free-air temperature range (unless otherwise noted)

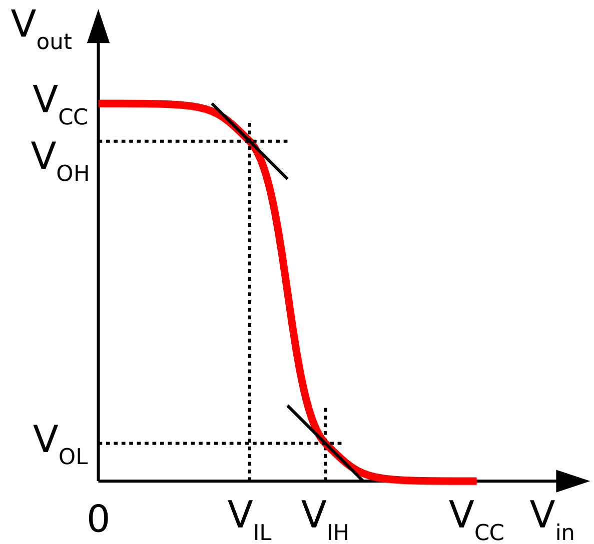
PARAMETER	TEST CONDITIONS†			SN54LS00			SN74LS00			UNIT
				MIN	TYP‡	MAX	MIN	TYP‡	MAX	
V_{IK}	V_{CC} = MIN,	I_I = –18 mA				–1.5			–1.5	V
V_{OH}	V_{CC} = MIN,	V_{IL} = MAX,	I_{OH} = –0.4 mA	2.5	3.4		2.7	3.4		V
V_{OL}	V_{CC} = MIN,	V_{IH} = 2 V	I_{OL} = 4 mA		0.25	0.4		0.25	0.4	V
			I_{OL} = 8mA					0.35	0.5	
I_I	V_{CC} = MAX,	V_I = 7 V				0.1			0.1	mA
I_{IH}	V_{CC} = MAX,	V_I = 2.7V				20			20	µA
I_{IL}	V_{CC} = MAX,	V_I = 0.4 V				–0.4			–0.4	mA
I_{OS}§	V_{CC} = MAX			–20		–100	–20		–100	mA
I_{CCH}	V_{CC} = MAX,	V_I = 0 V			0.8	1.6		0.8	1.6	mA
I_{CCL}	V_{CC} = MAX,	V_I = 4.5 V			2.4	4.4		2.4	4.4	mA

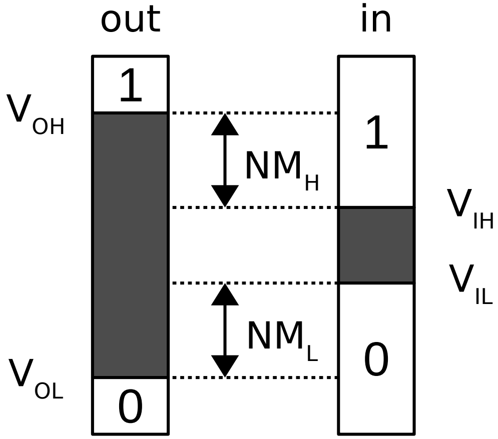
† For conditions shown as MIN or MAX, use the appropriate value specified under recommended operating conditions.
‡ All typical values are at V_{CC} = 5 V, T_A = 25°C.
§ Not more than one output should be shorted at a time.

Electrical parameters
Logic levels and noise margins





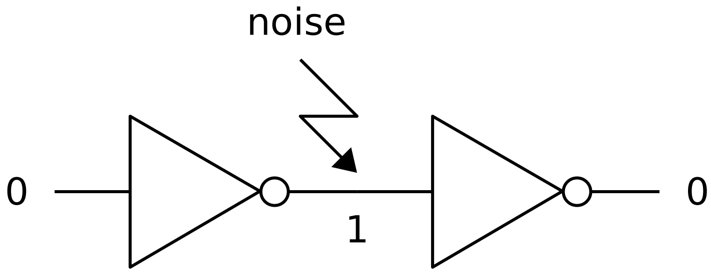




$NM_L = V_{IL} - V_{OL}$

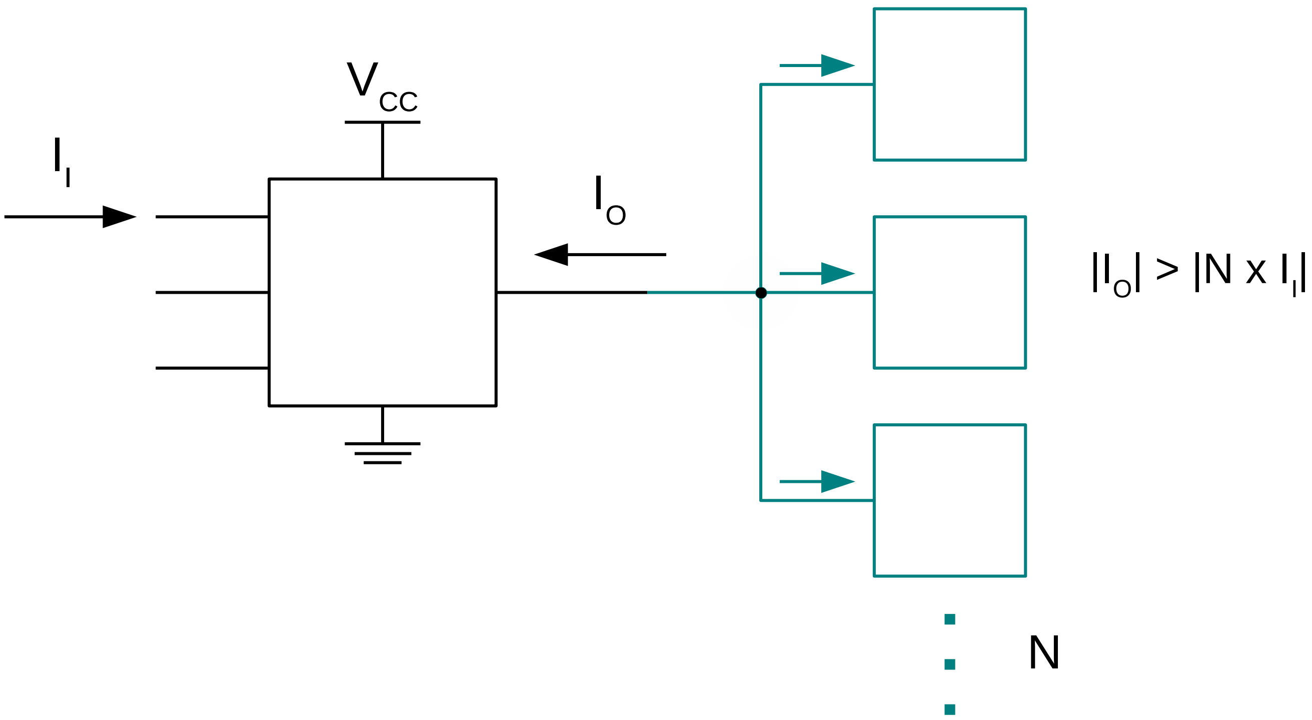
$NM_H = V_{OH} - V_{IH}$

$NM = \min(NM_L, NM_H)$



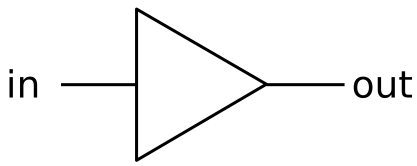
Simulation

Electrical parameters
Fan-out



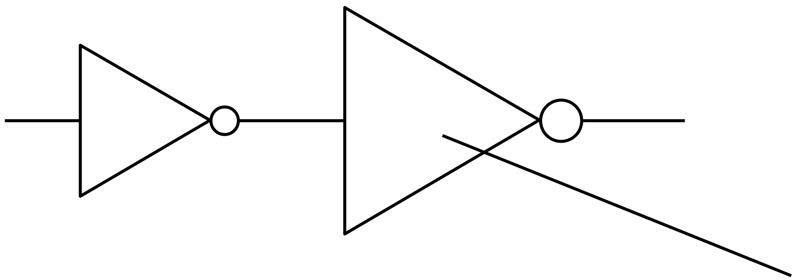
FAN-OUT
Maximum value of N so that $|I_O| > |N \times I_I|$ in both cases (high and low output levels)

The buffer



in	out
0	0
1	1

Sample implementation



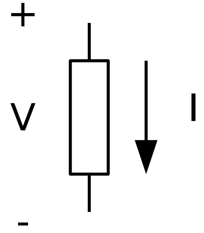
An inverter using bigger transistors

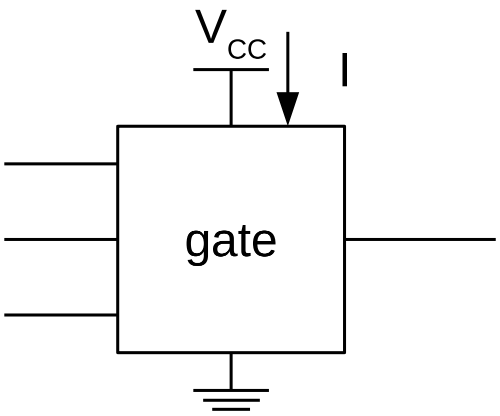
- Implements the “identity” logic operation.
- Used to generate an identical “logic” signal with better “electrical” characteristics:
  - Restoring logic levels.
  - Incrementing output current (and fan-out thereafter).
  - Filtering voltage picks (input buffer).
  - Amplifying voltage and providing more power (output buffer).

Electrical parameters
Power consumption

- Static
- Dynamic
  - Depends on the frequency

$$P = VI$$





$$P = V_{CC} I$$

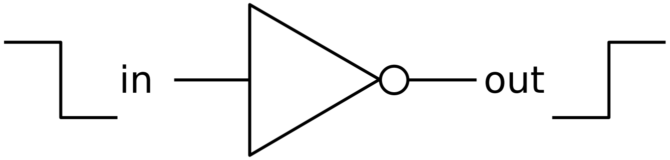
Switching parameters

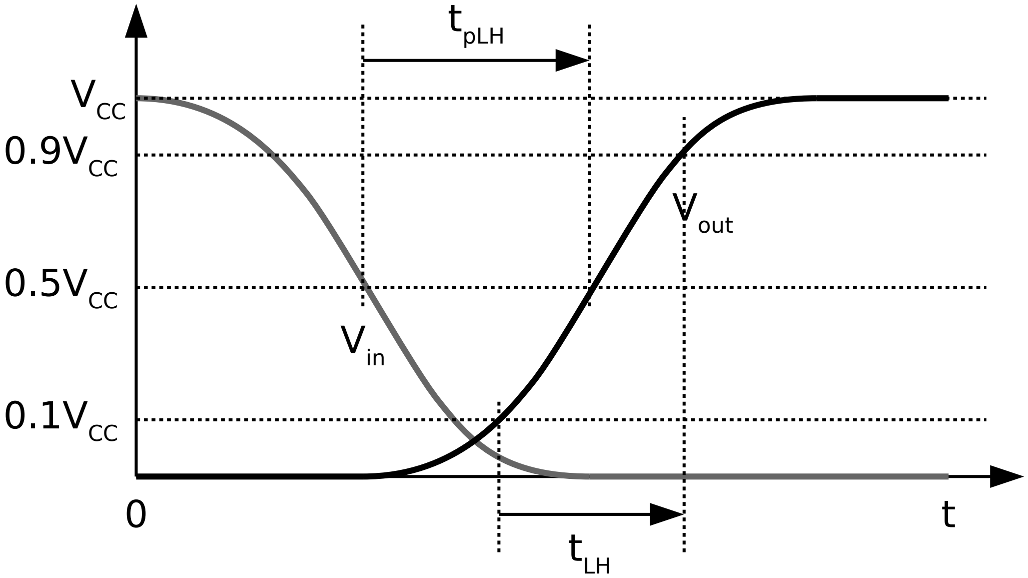
- Transition time: time for a transition to change from:
  - 10% V_{CC} to 90% V_{CC} (rising transition): t_{LH}
  - 90% V_{CC} to 10% V_{CC} (falling transition): t_{HL}
  - Depends on many factors, specially gate's strength and load.
- Propagation delay: time elapsed from the input transition to the output transition.
  - Two types: low-to-high (t_{pLH}) and high-to-low (t_{pHL}).
  - 50% V_{CC} as the reference for transitions.
  - Depends on many factors: gate design, output load (linear), etc.

switching characteristics, V_{CC} = 5 V, T_A = 25°C (see Figure 1)

PARAMETER	FROM (INPUT)	TO (OUTPUT)	TEST CONDITIONS	SN54LS00 SN74LS00			UNIT
				MIN	TYP	MAX	
t_{PLH}	A or B	Y	R_L = 2 kΩ, C_L = 15 pF		9	15	ns
t_{PHL}					10	15	

Switching parameters





Simulation

Larger propagation delays make digital systems (computers) to run slower (smaller clock frequency)