Unit 1.5. Electronic circuits and logic families

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

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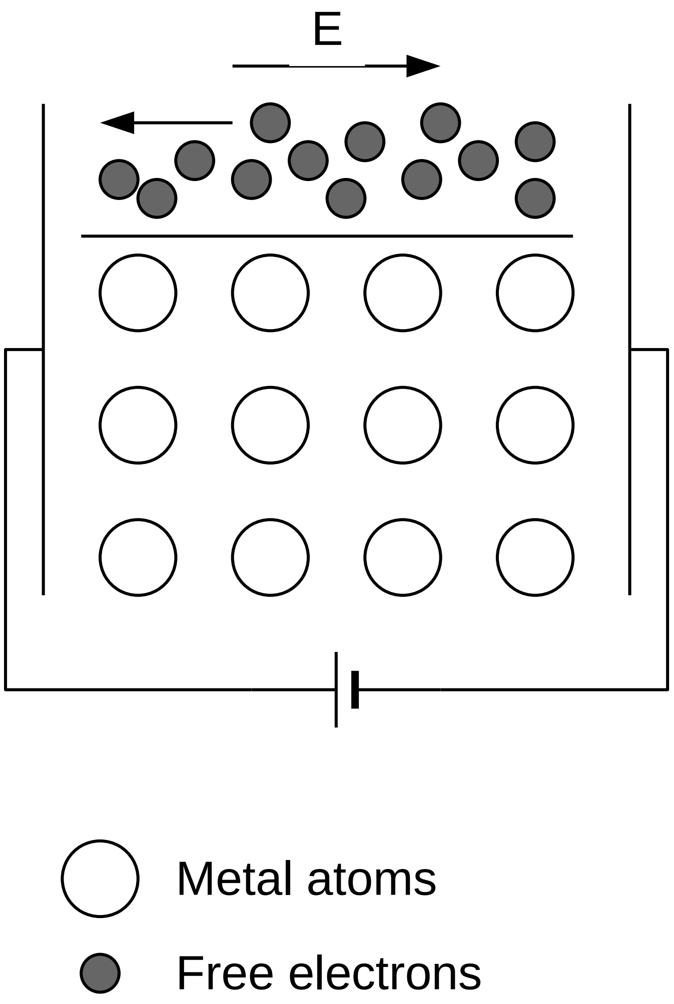
Contenidos

- 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

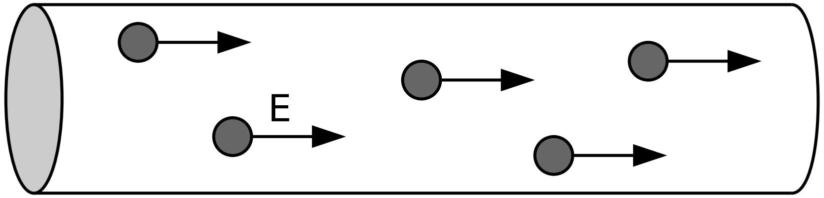
Conductors and charge carriers



- 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

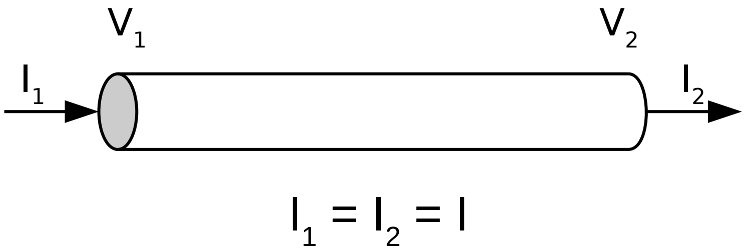
- Conductors in electrical circuits
  - Typically wire-shaped
  - Charge (and electric field) is confined inside the conductors
- Charge does not accumulate inside conductors: conductors remain neutral.



Electrical magnitudes

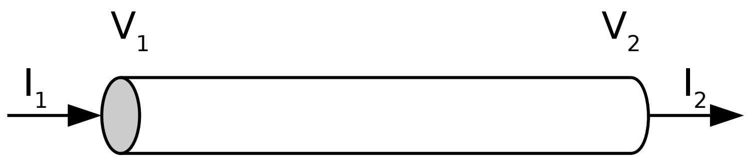
- Voltage: potential difference between two points in the circuit (Volts [V]).
  - Electric field (electric force) points from high to low voltage areas.
  - Positive charges move to lower voltage, negative charges to higher voltage (lower energy in both cases).
  - Current: charge per unit time crossing the conductor's section
  - 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.

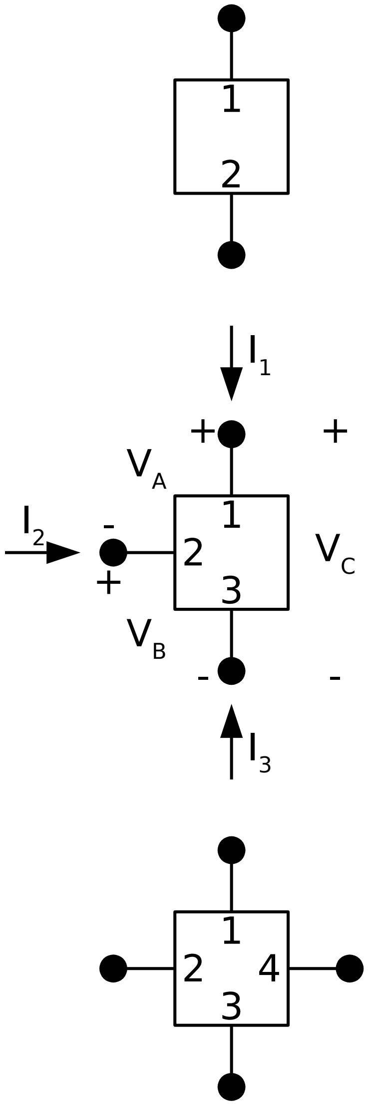


$I_1 = I_2 = I$

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

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

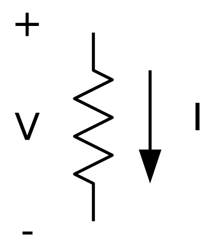
Electronic devices



- Electronic elements with two or more terminals (connection points)
- Impose a relationship between the current and voltage across the terminals
- Net charge is not accumulated inside the devices:
  - $I_1+I_2+I_3+... = 0$

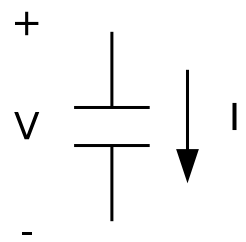
Basic electronic devices

Resistor
Ohm [Ω]



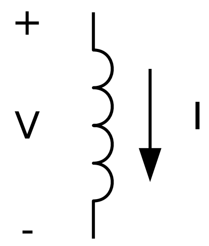
$$V = IR$$

Capacitor
Farad [F]



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

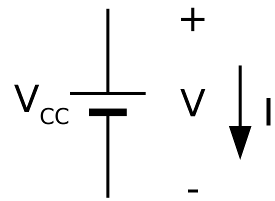
Inductor
Henry [H]



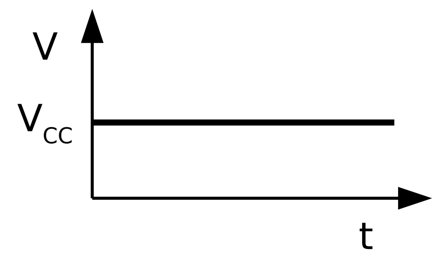
$$V = -L\frac{dI}{dt}$$

Dispositivos básicos: fuentes ideales

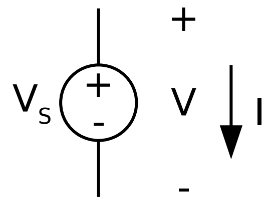
Constant voltage source
(power supply)
(battery)



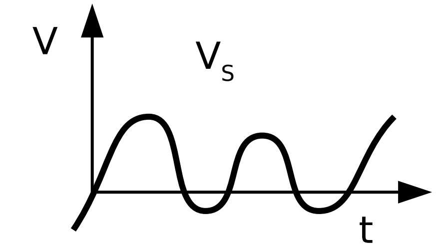
$$V = V_{CC}$$



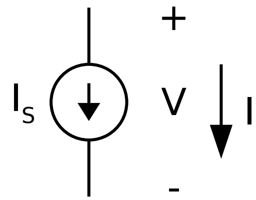
Variable voltage source



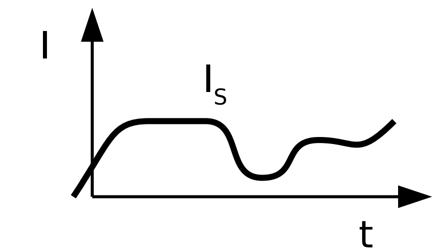
$$V = V_S(t)$$



Variable current source

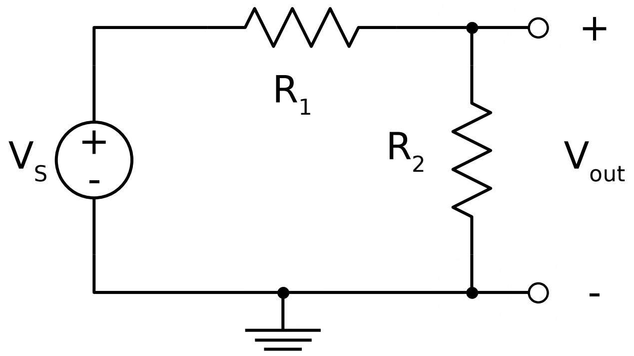


$$I = I_S(t)$$

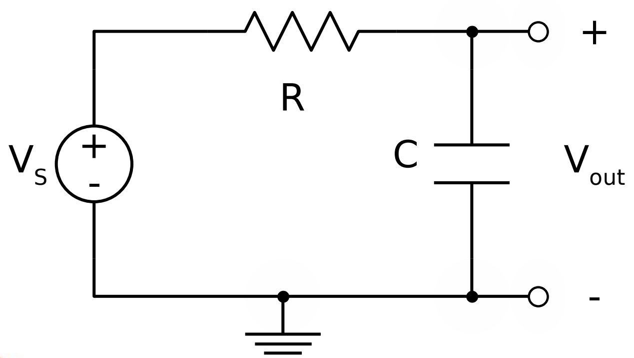


Electric circuits

- 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

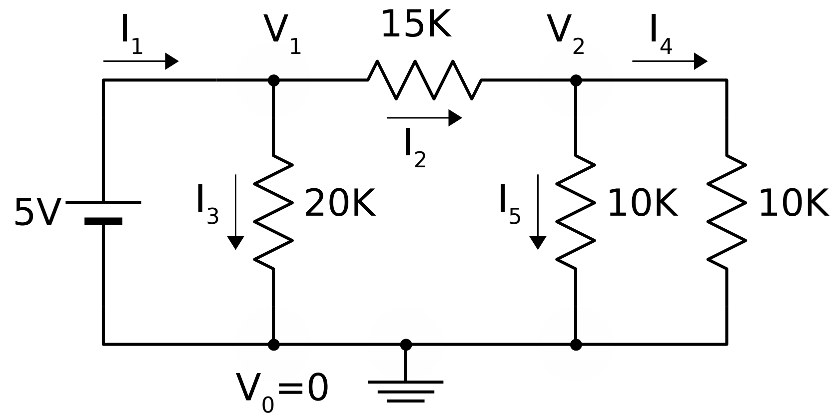
Circuit analysis

- 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

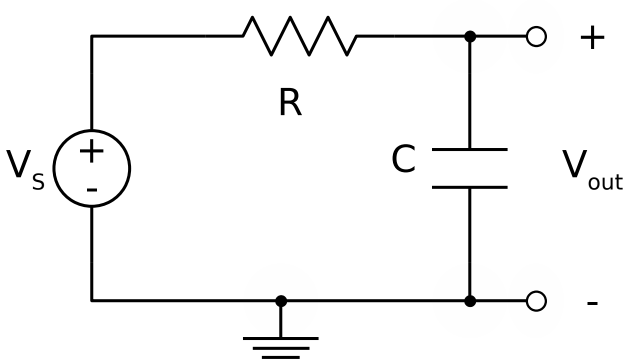
- Static analysis (DC):
  - All magnitudes and sources are constant.
  - The solution is derived from algebraic equations.
- Transient analysis
  - Considers variable sources and the evolution of circuit's magnitudes with time.
  - In general, the solution implies resolving differential equations :(
- 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.

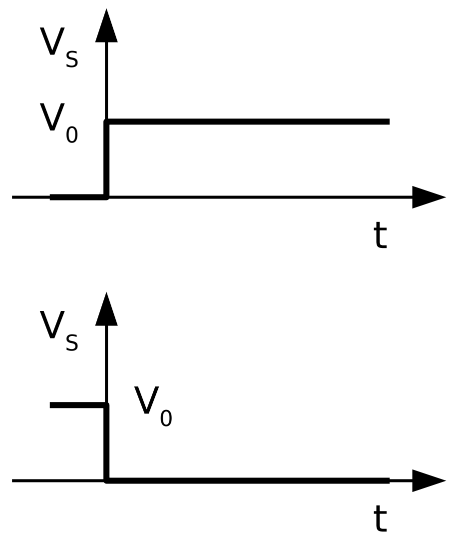
Circuit analysis. Example



Static analysis (DC)

Simulation

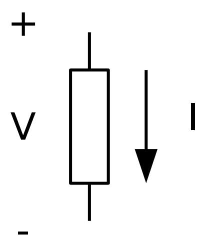




Transient analysis

Simulation

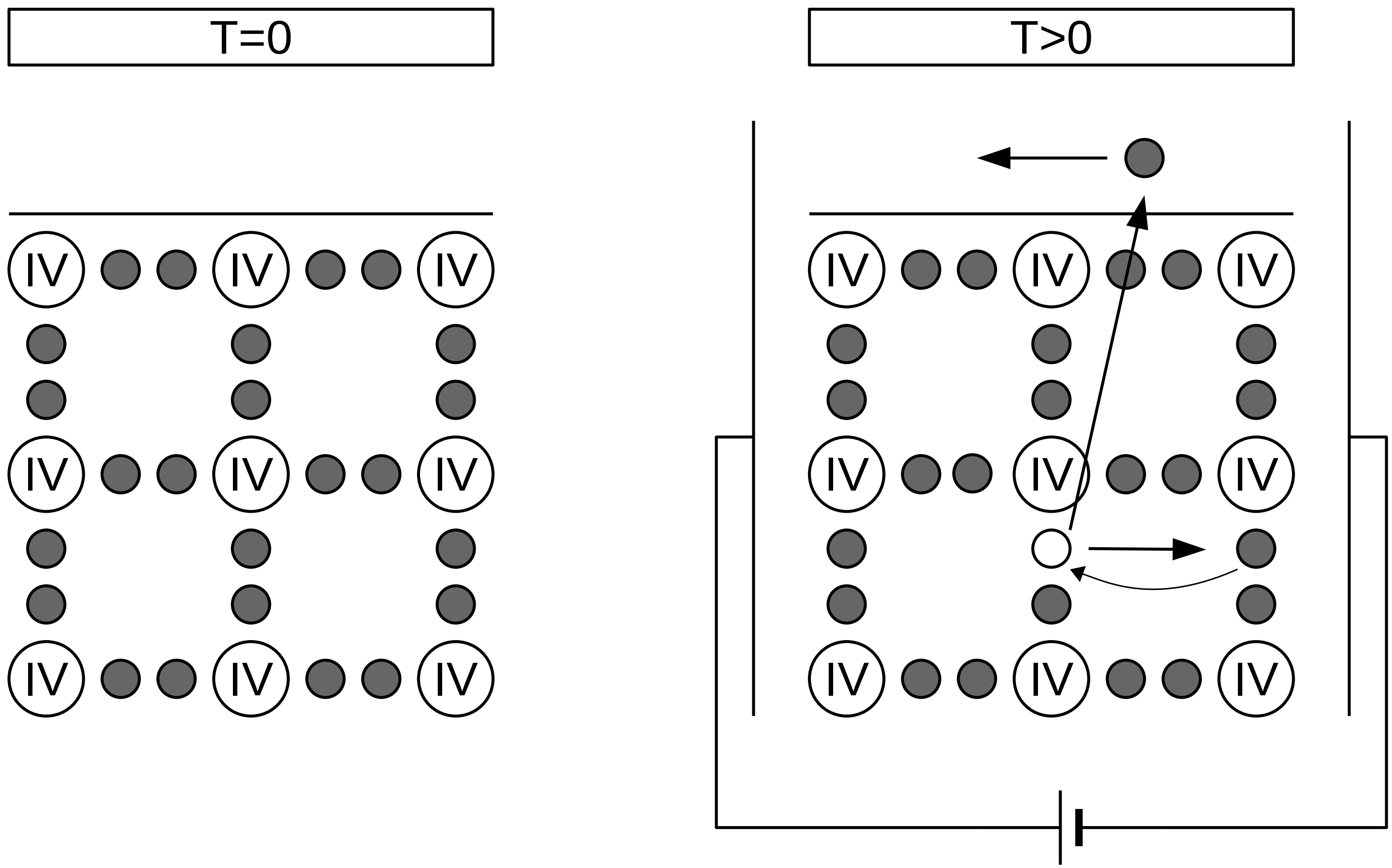
Power

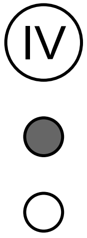


$$P = VI$$

- Consumed energy per unit time
- Power is a key point in current electronics.
  - Portable devices (batter 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. power supply)

Semiconductor devices (intrinsic)





Group IV atom (Si)

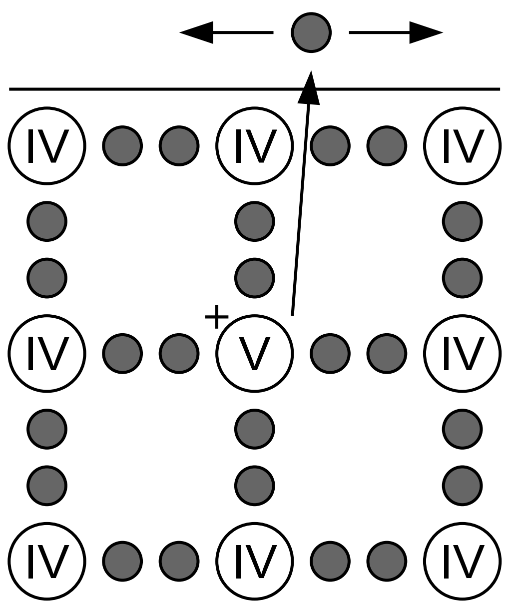
Electron (-)

Hole (+) (left by the electron)

bad conductor

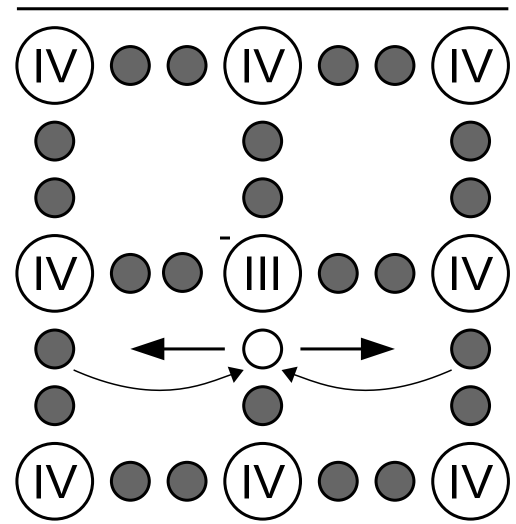
Semiconductor devices (doped) (T=0)

n-type



good conductor

p-type



good conductor

Electron (-)

Hole (+) (left by the electron)

IV Group IV athom (Si)

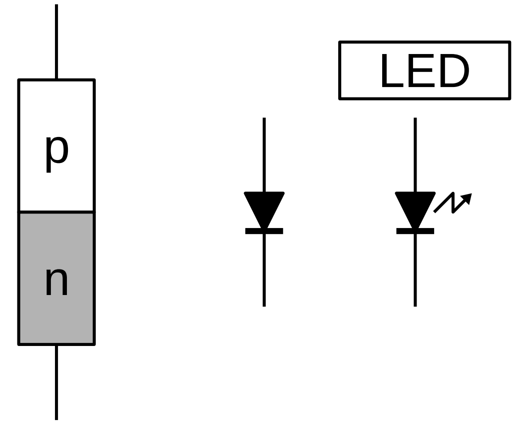
V Group V athom (P, As)

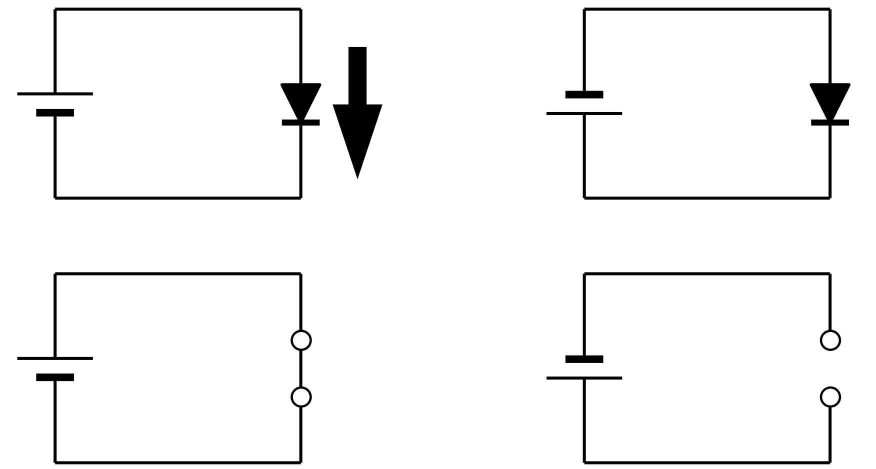
III Group III athom (B, Ga)

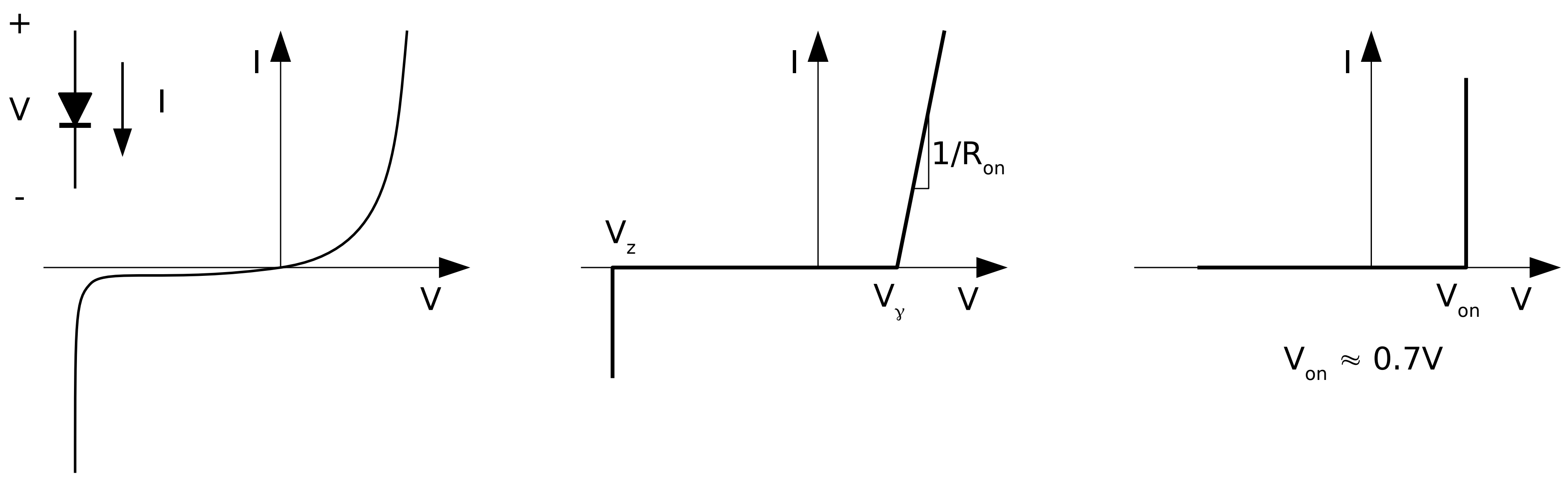
Semiconductors nice properties

- 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.

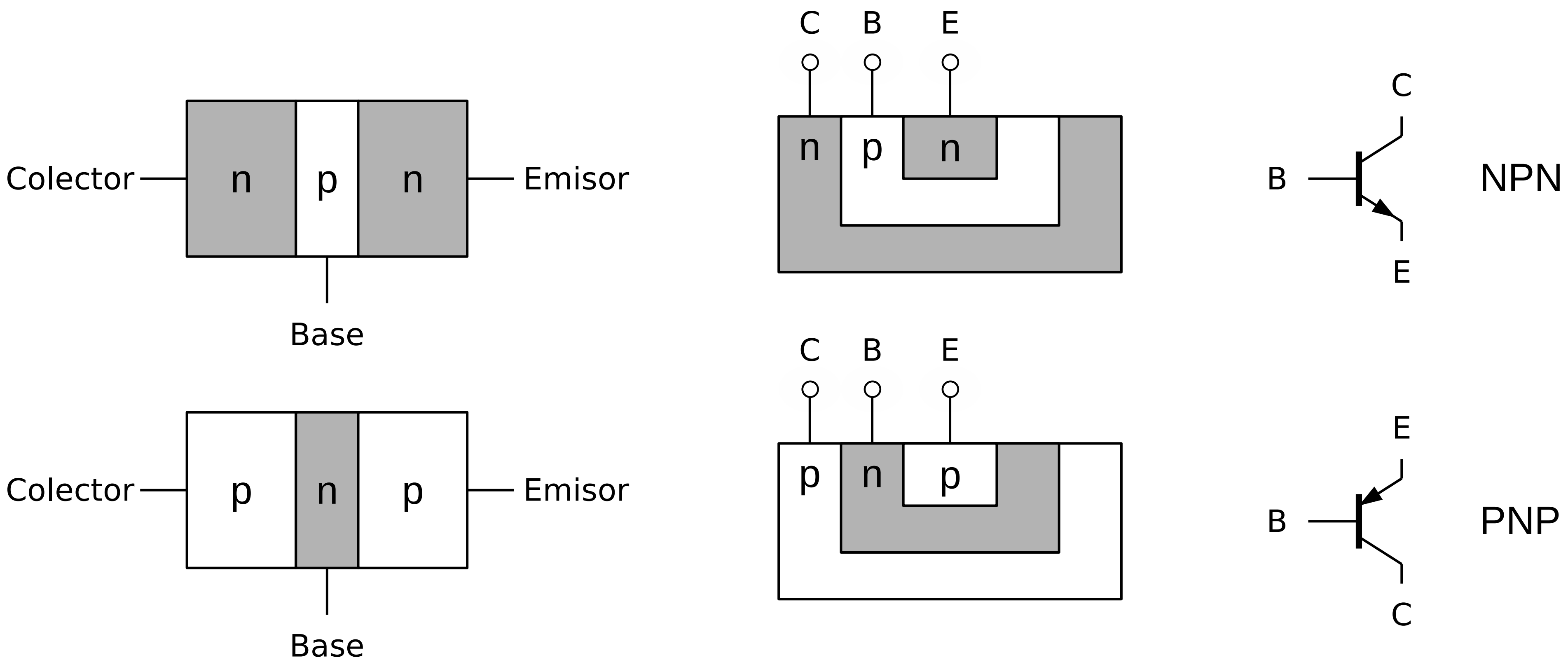
Diodes and Light-Emitting Diodes (LED's)

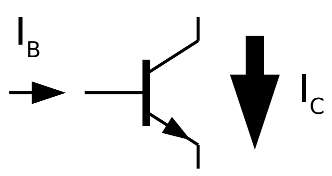






Bipolar transistor





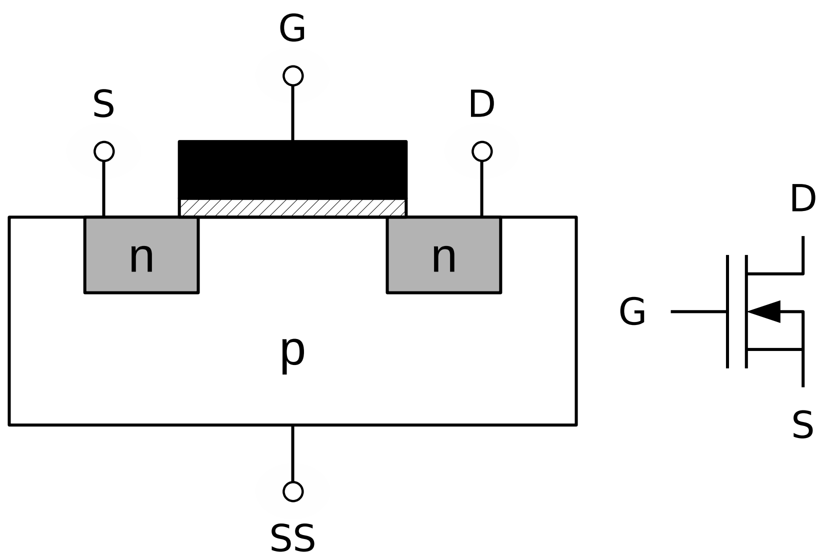
$$I_C = \beta\, I_B$$
$$\beta \approx 100$$

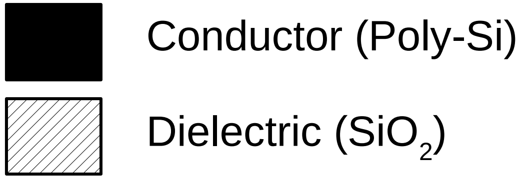
A small current through B-E allows a big current to flow through C-E.

Direct use: amplifier.

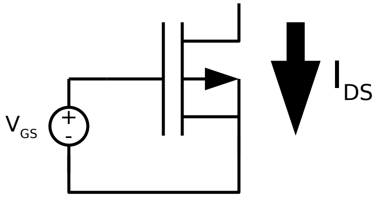
Field Effect Transistors (E.g.: MOSFET's)

nMOS

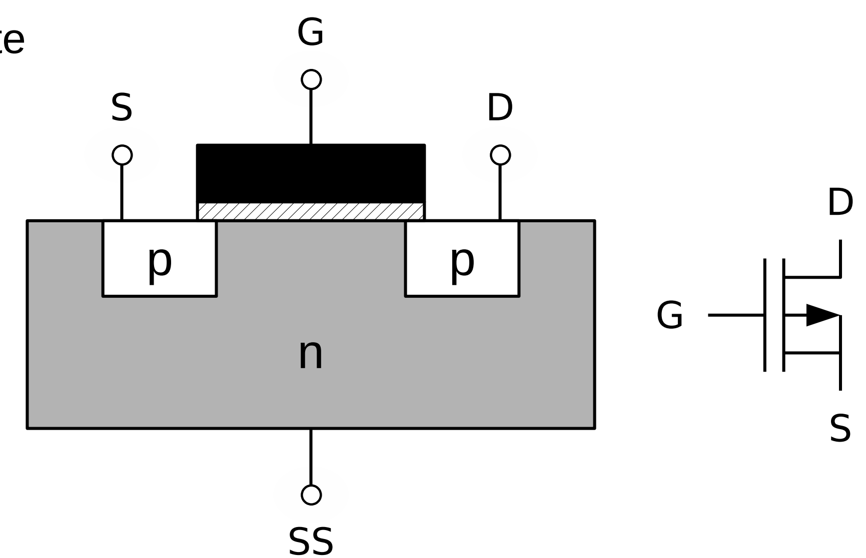




G: gate
S: source
D: drain
SS: substrate



pMOS



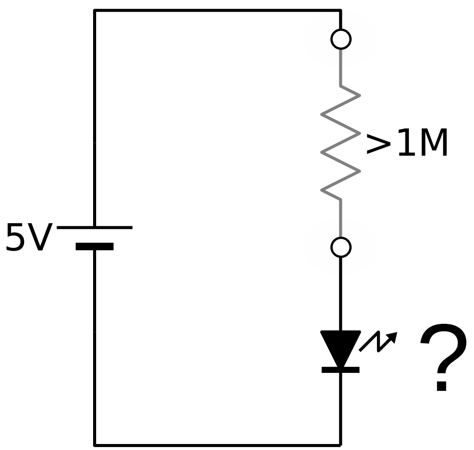
A small voltage between G and S allows a big current to flow from D to S.

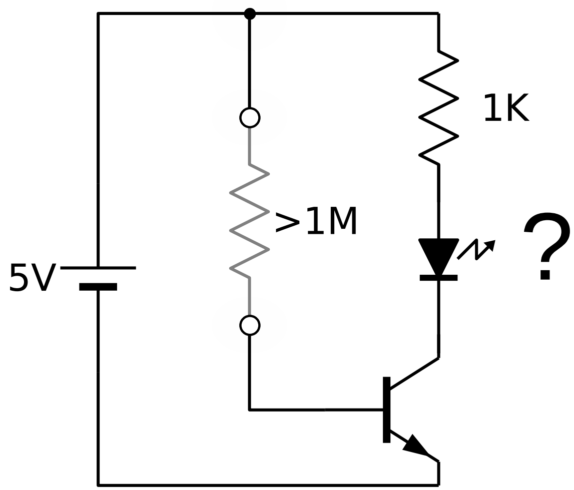
Applications: amplifier, sensors, power control, etc.

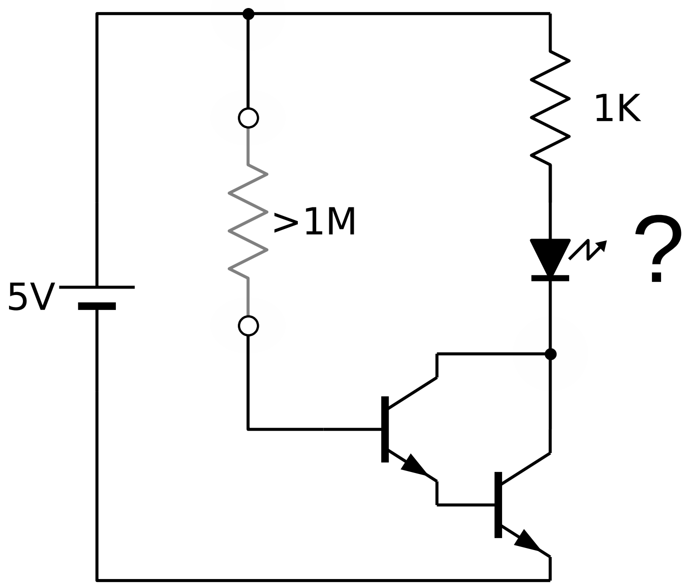
Transistors demo

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

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







$$I_D = I_R \approx 0$$

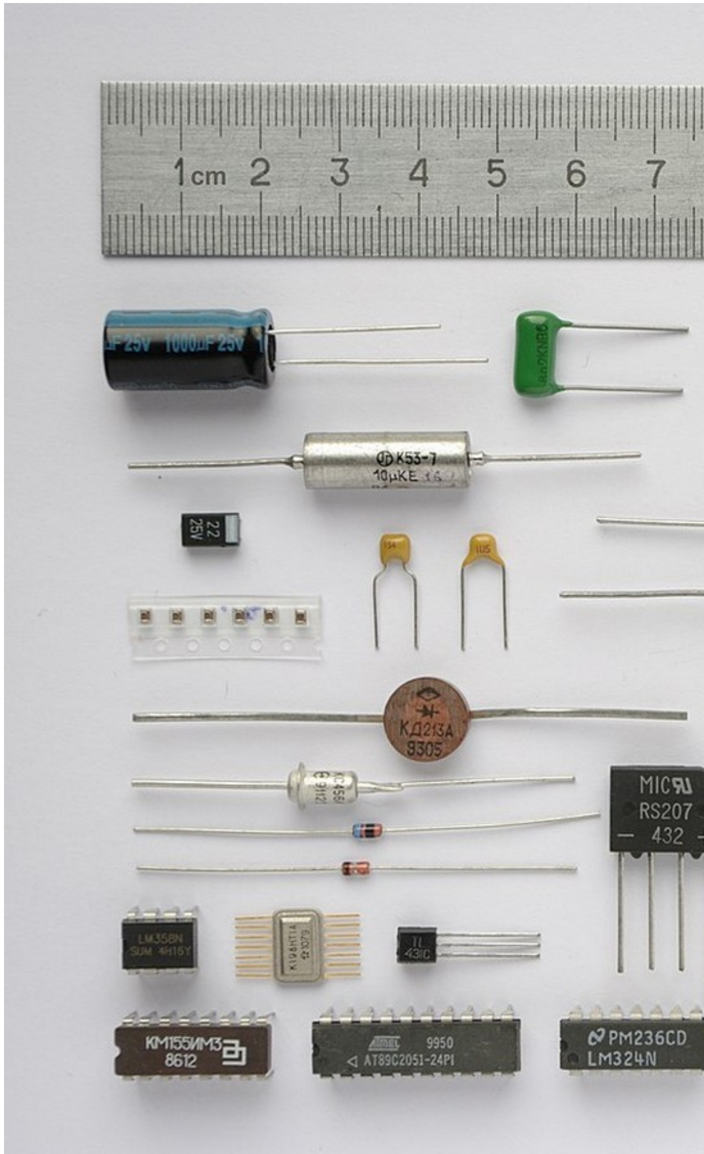
$$I_D = I_C \approx 100\, I_R$$

$$I_D \approx 10000\, I_R$$

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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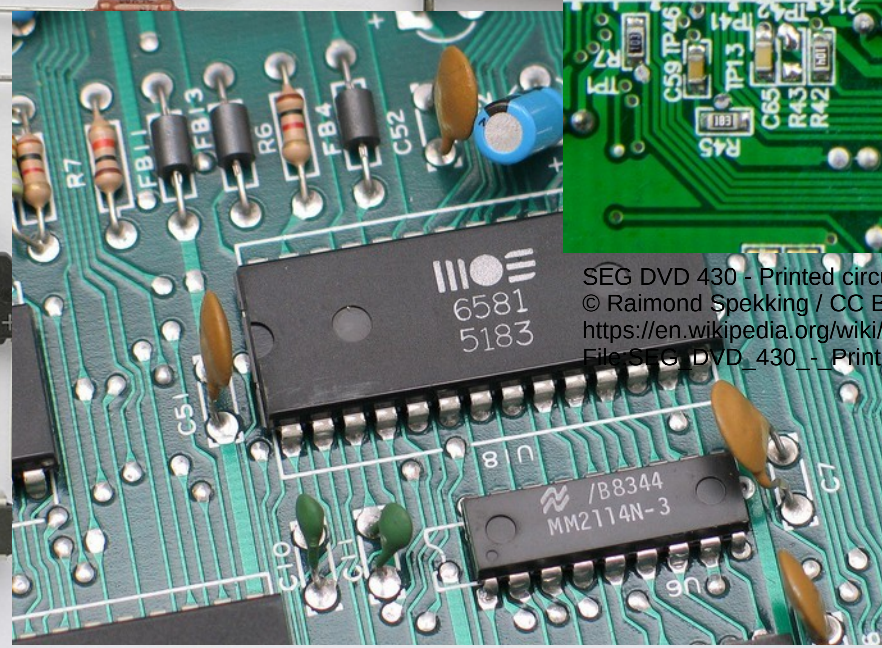

Commodore 64 PCB (1980)
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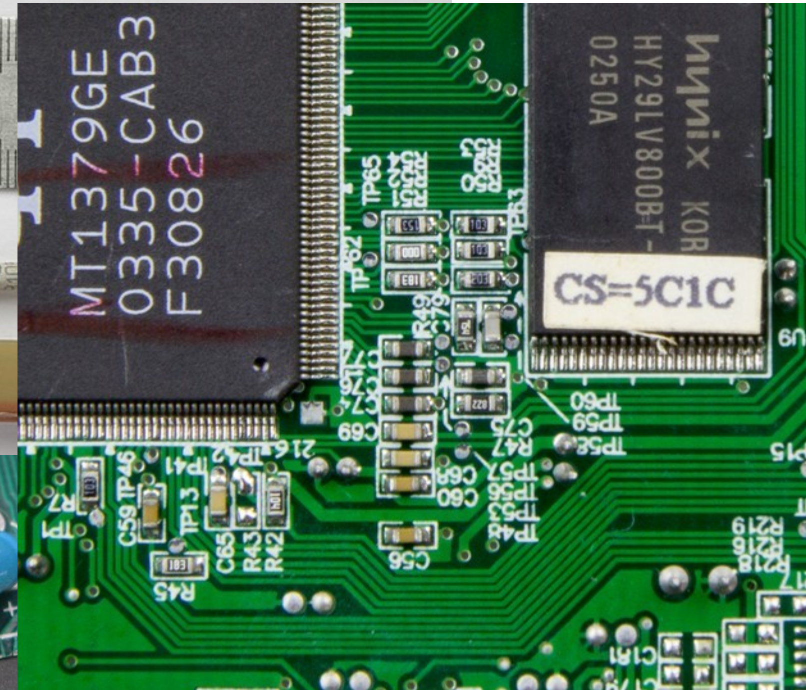

SEG DVD 430 - Printed circuit board (2003)
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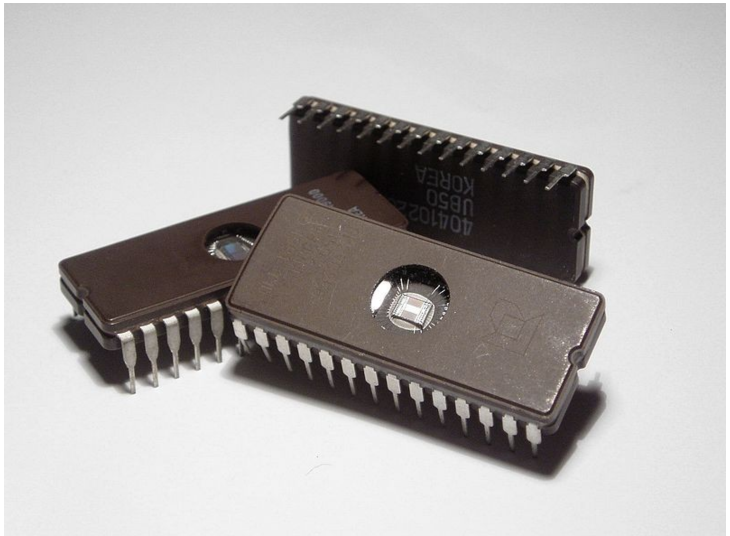
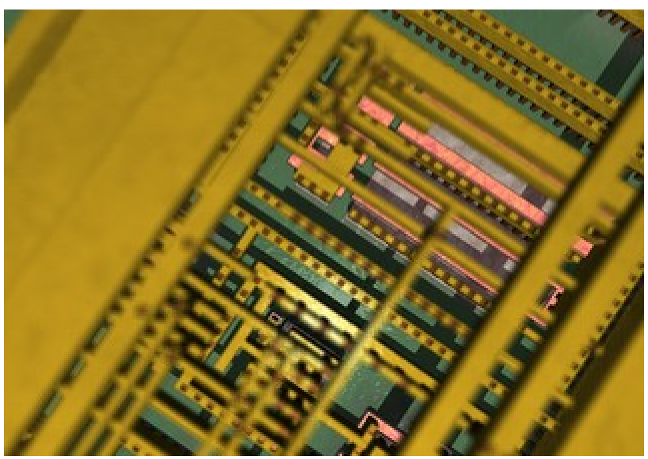
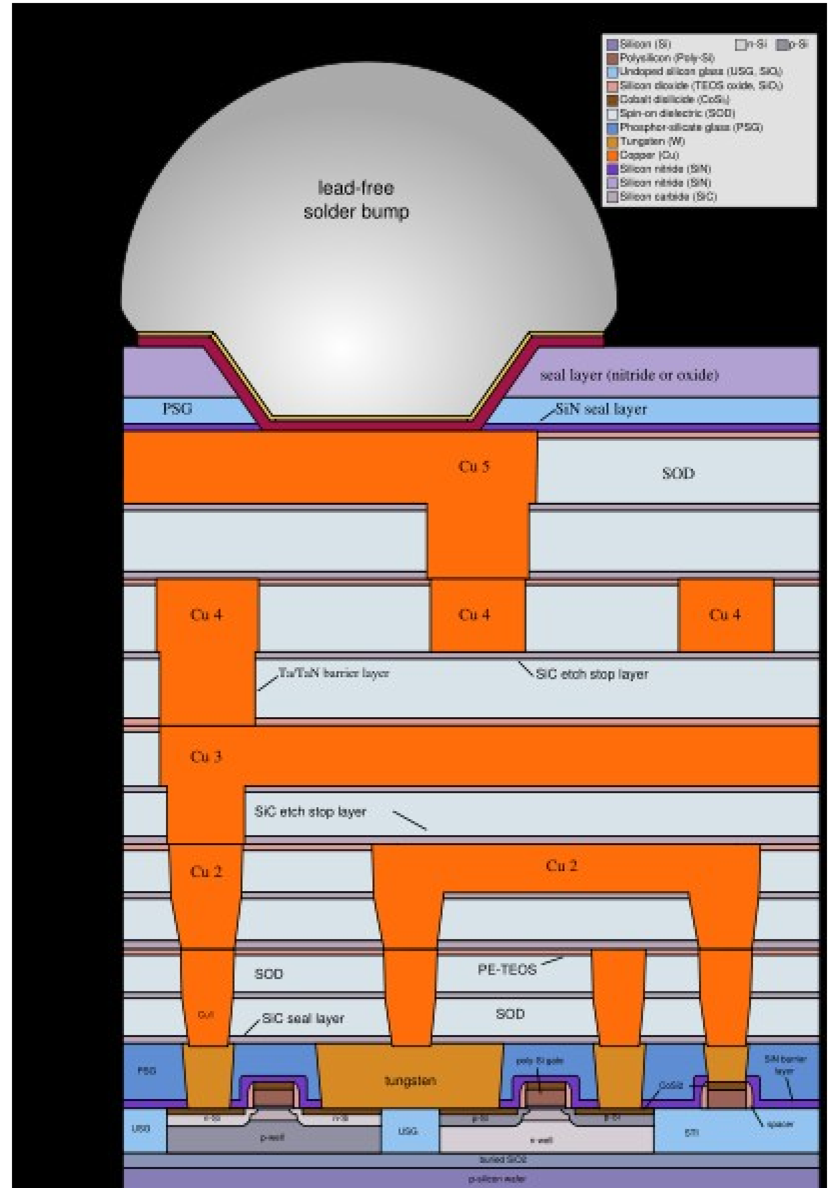
https://en.wikipedia.org/wiki/Printed_circuit_board#/media/File:SEG_DVD_430_-_Printed_circuit_board-4276.jpg

Integrated circuits





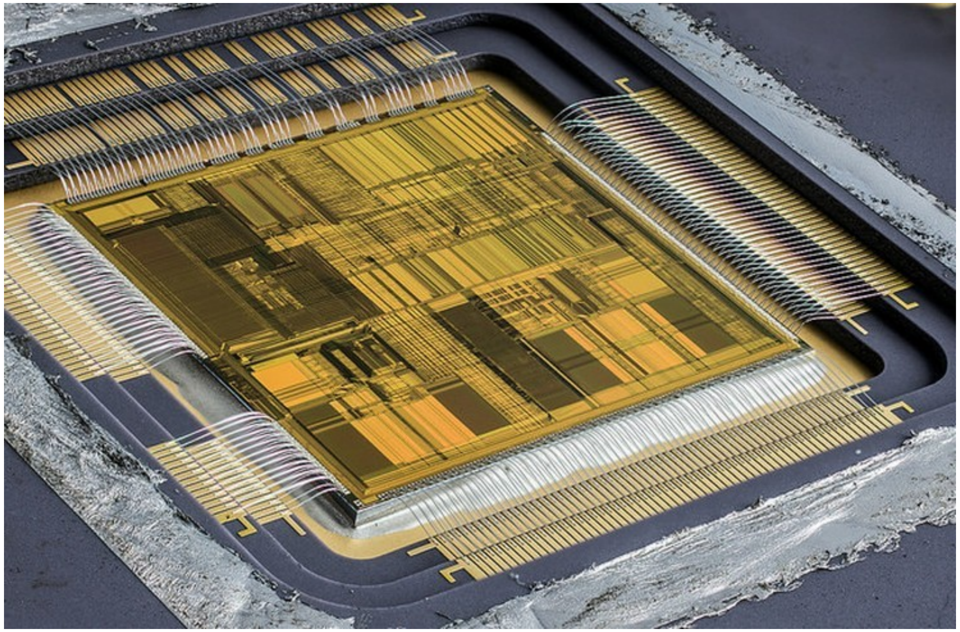


http://en.wikipedia.org/wiki/Integrated_circuit

Integrated circuits. Types

Application Specific IC (ASIC)

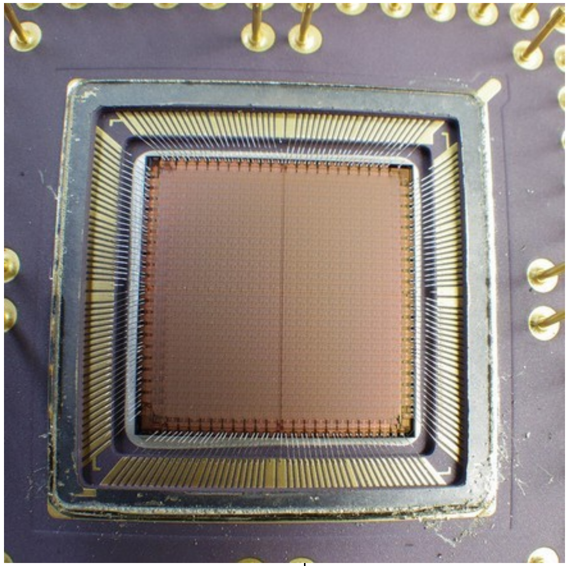
Intel Pentium

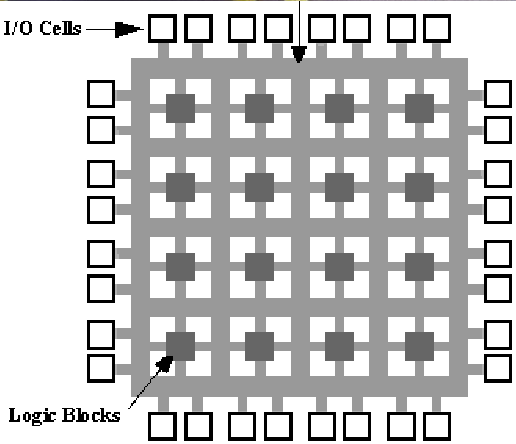


Dominio Público
https://www.flickr.com/photos/130561288@N04/16637740870

Programmable (ej. FPGA)

Xilinx XC4010-6





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Xilinx XC4010-6. Dominio Público
https://www.flickr.com/photos/34923408@N07/22054207552/

Integrated Circuits. Generations

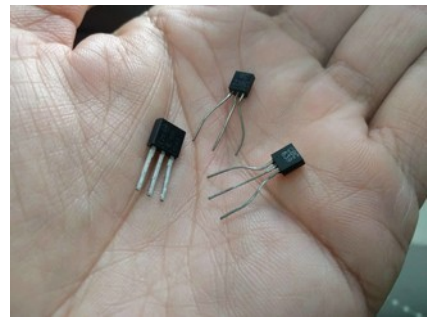
Name	Meaning	Year	No. tt	Comment
SSI	Small-scale integration	1964	1 a 10	Military and space applications
MSI	Medium-scale integration	1968	10 a 500	Consumer electronics
LSI	Large-scale integration	1971	500 a 20000	Microprocessors and integrated memories
VLSI	Very large-scale integration	1980	20000 a 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

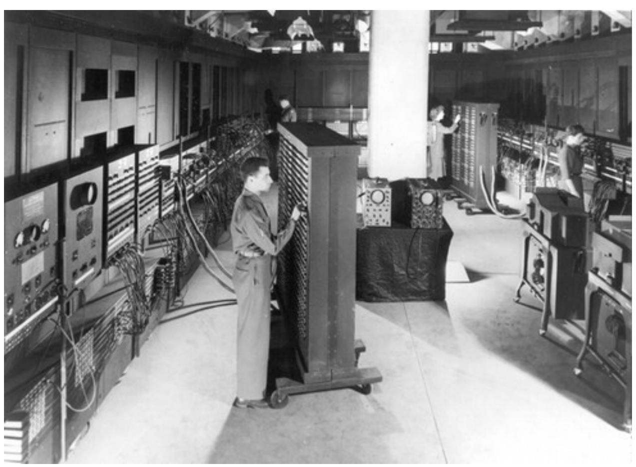
Vacuum tube

Transistors



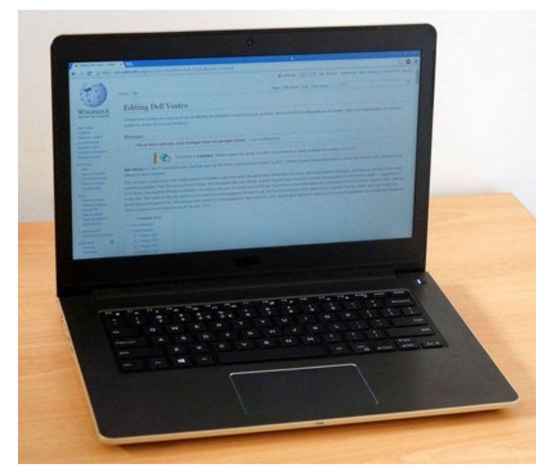
Integrated Circuit
Intel Pentium IV (~50Mtt)

ENIAC (1946)



IBM 360 Model 20 (1966)

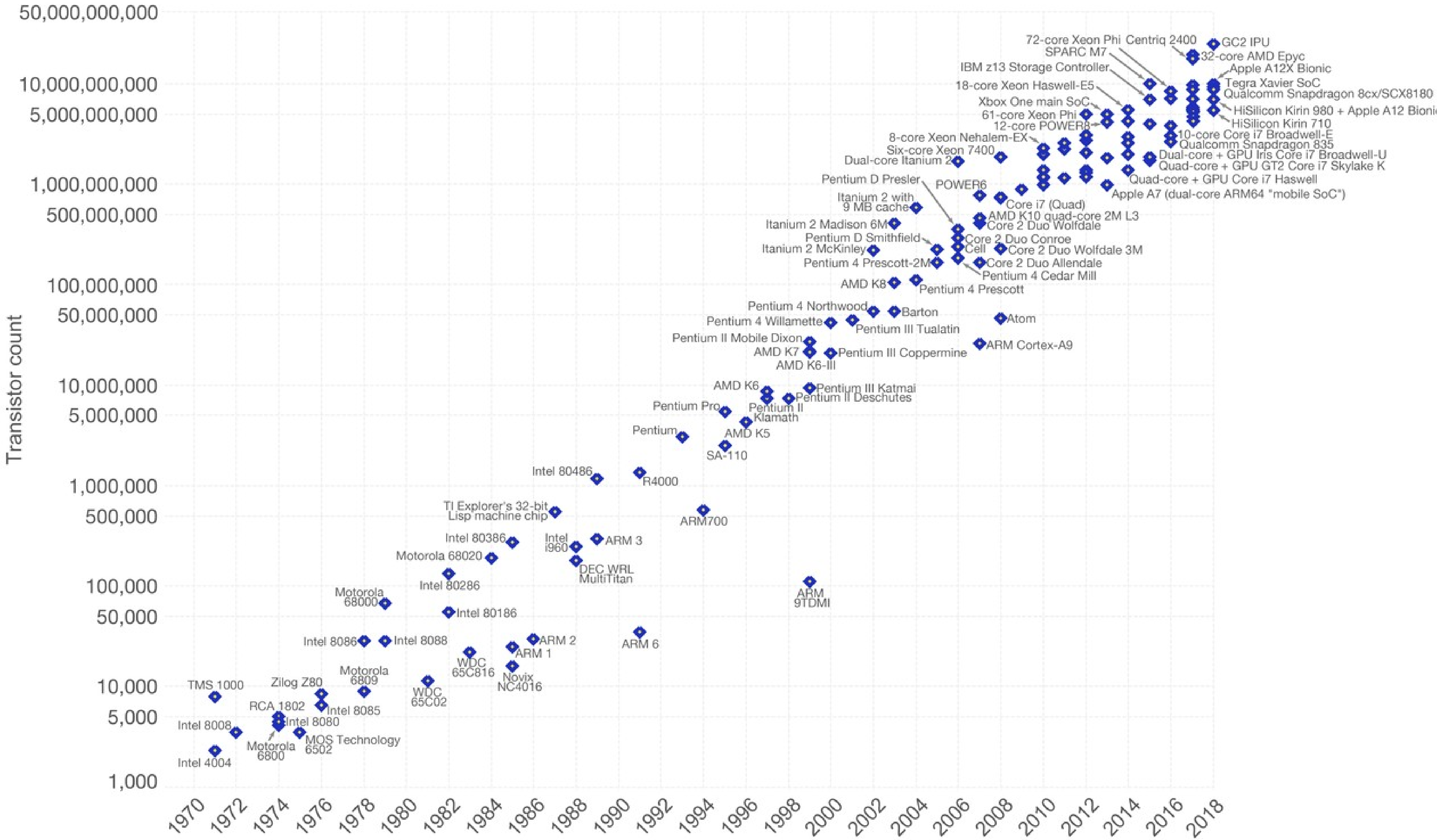
Laptop (2018)



Moore's Law – The number of transistors on integrated circuit chips (1971-2018)

Our World in Data

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.

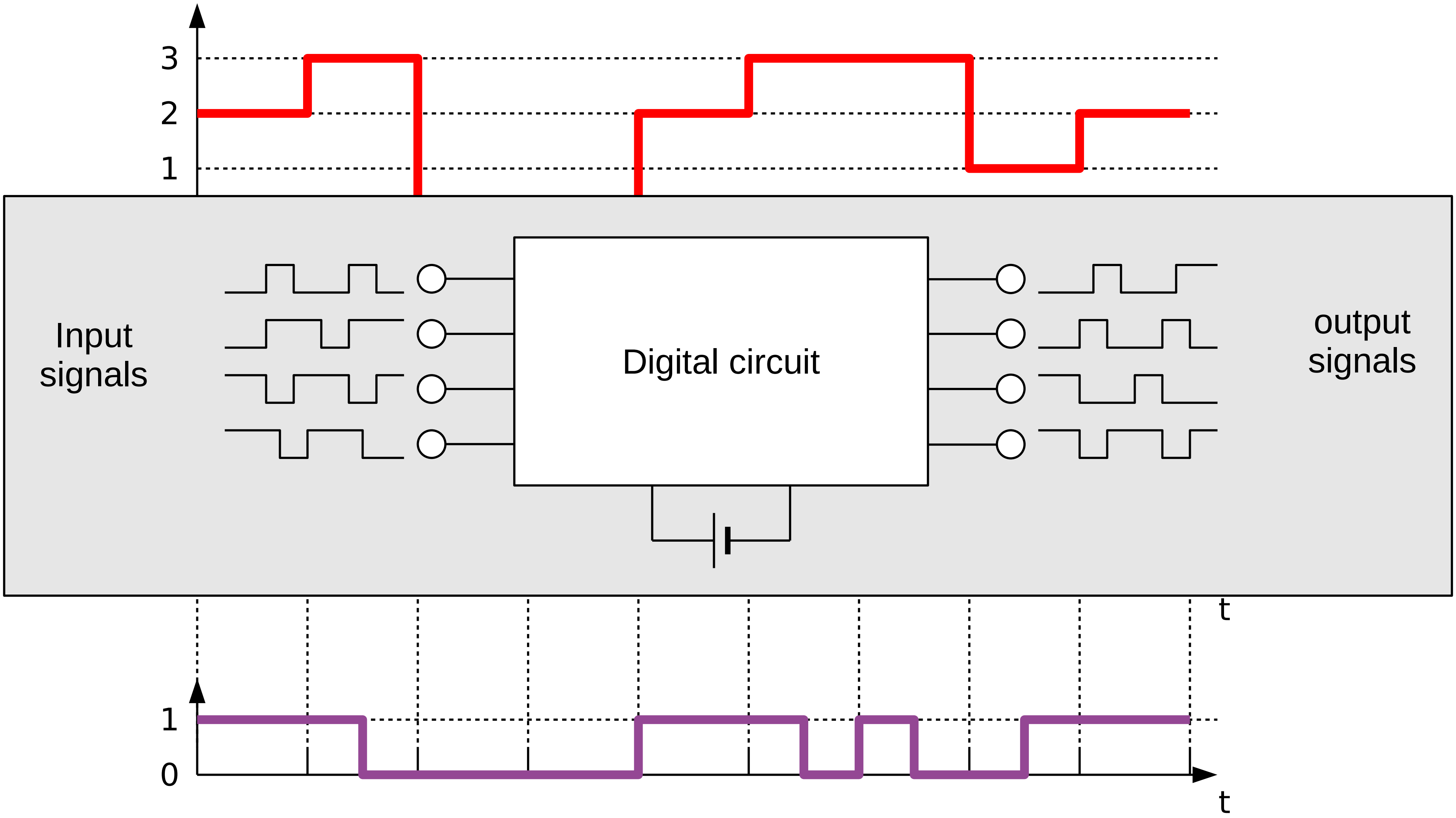


Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

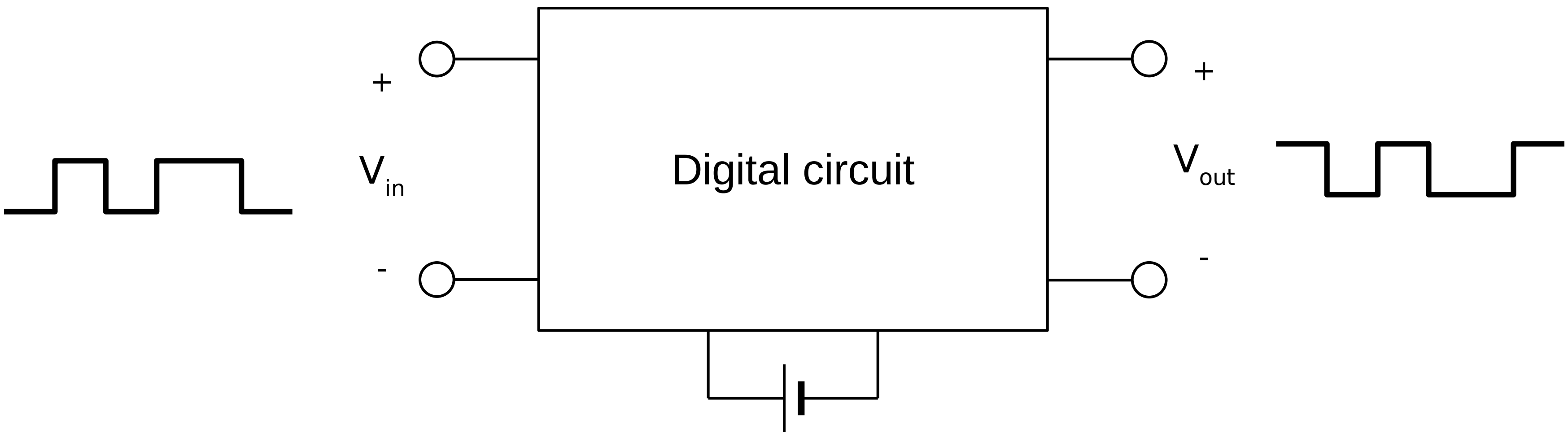
Digital circuits and logic families

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

Digital circuits

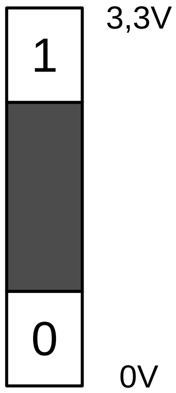


Digital circuits. Logic levels

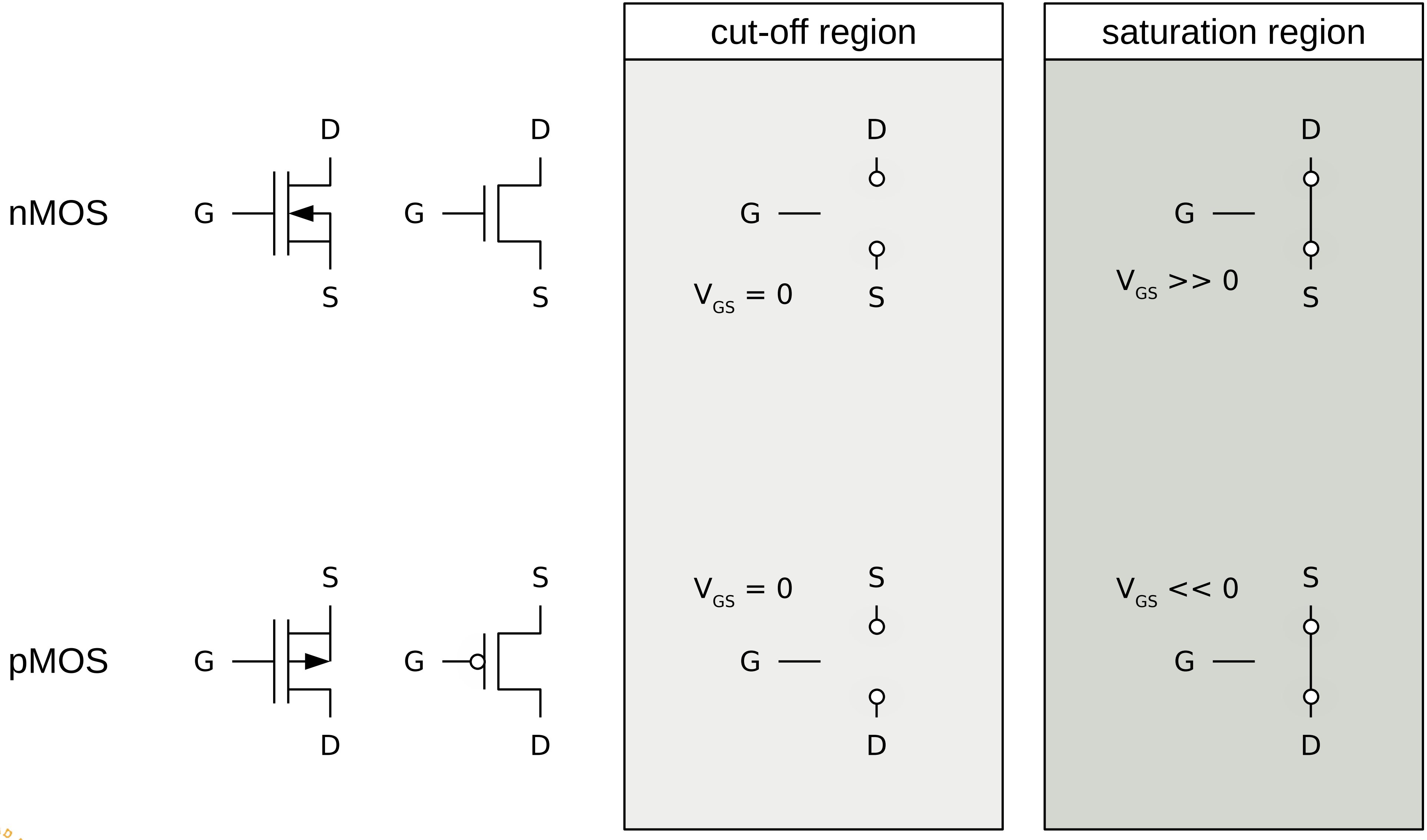


Electric value (V_X) vs. logic value (X)
Ejemplo: 3,3V

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

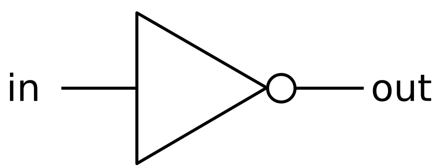


Transistors in switching mode (MOS example)

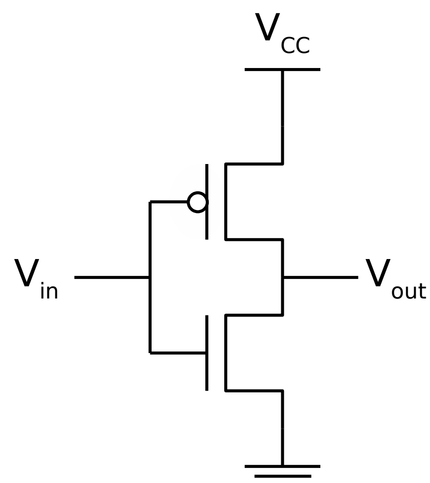


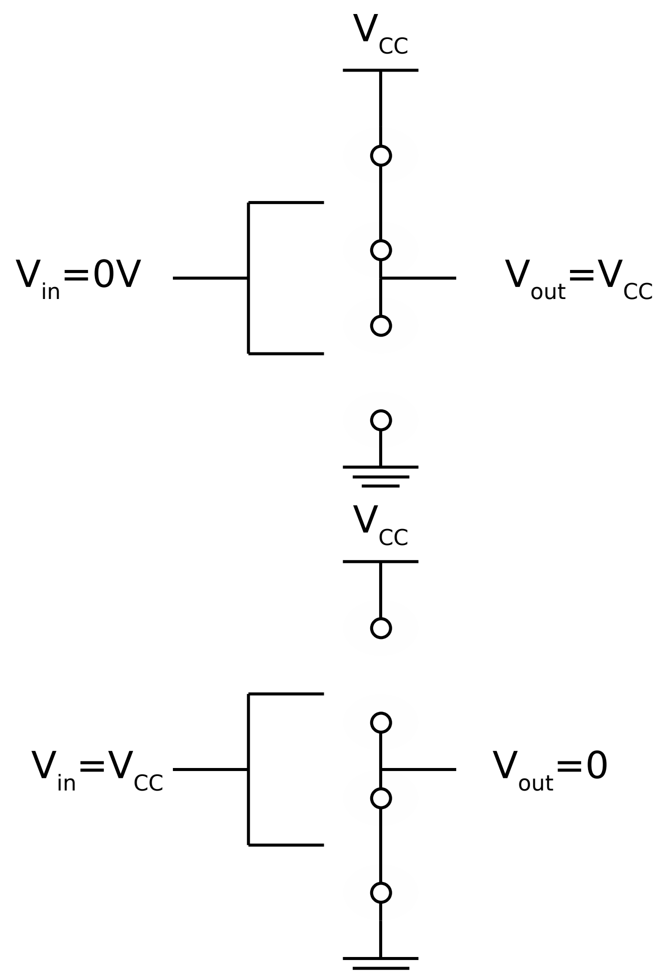
Logic gates. CMOS Inverter

- 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

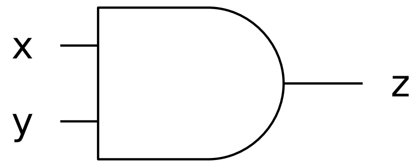




Simulación

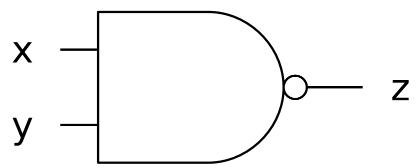
Logic gates and logic operators

AND



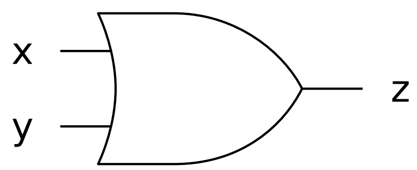
x y	z
0 0	0
0 1	0
1 0	0
1 1	1

NAND



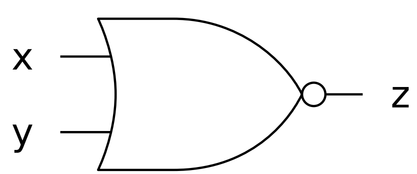
x y	z
0 0	1
0 1	1
1 0	1
1 1	0

OR



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

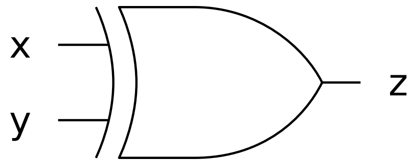
NOR



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

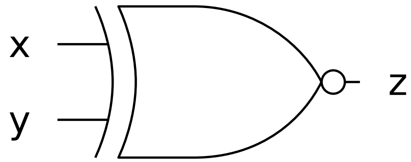
Logic gates and logic operators

XOR



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

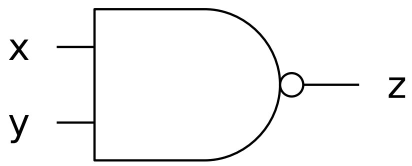
XNOR

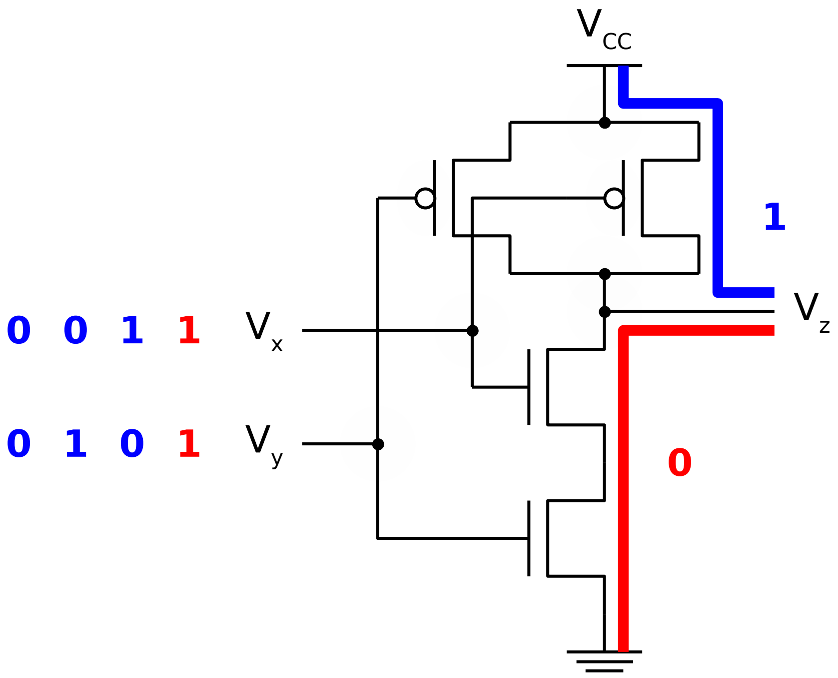


x y	z
0 0	1
0 1	0
1 0	0
1 1	1

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

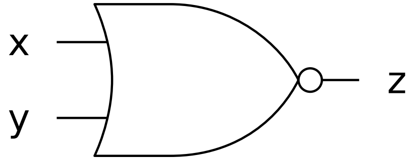
Logic gates. CMOS NAND

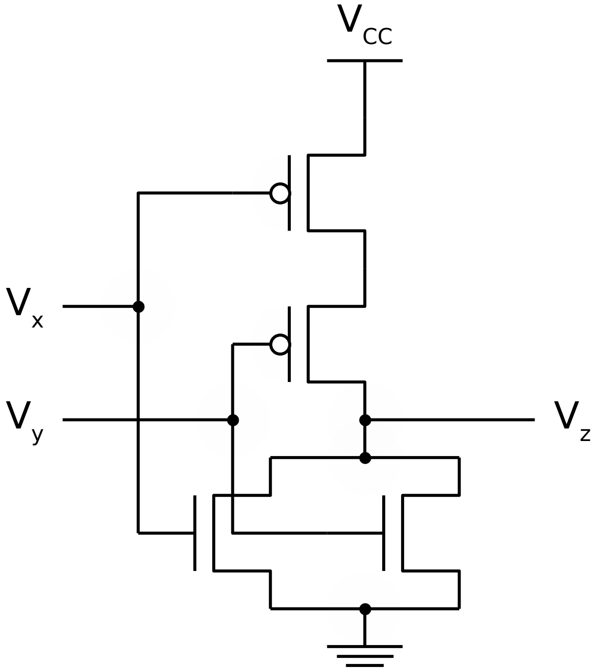




Simulation

Logic Gates. CMOS NOR





Simulation

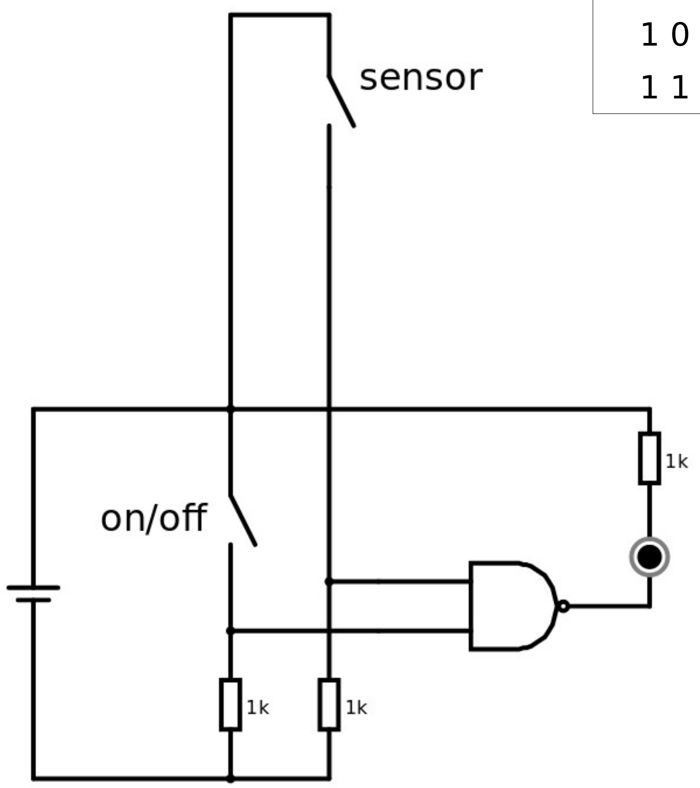
Examples: digital interface

- 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.

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)

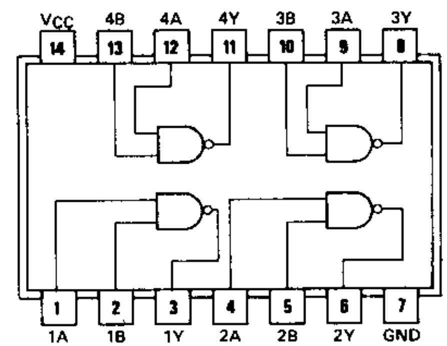
Logic families

- 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

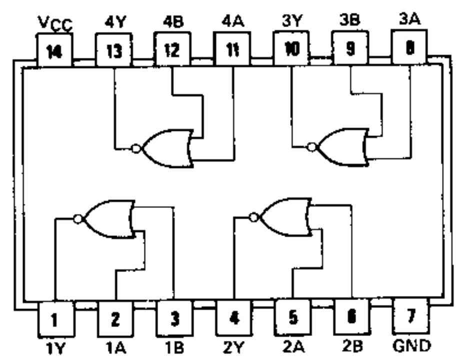
Logic families

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

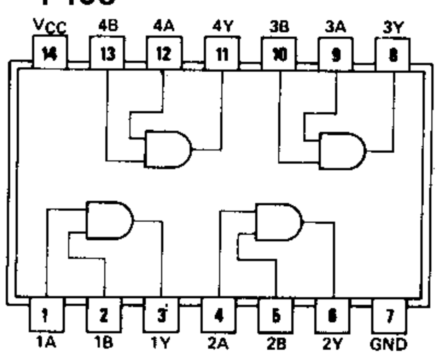
7400



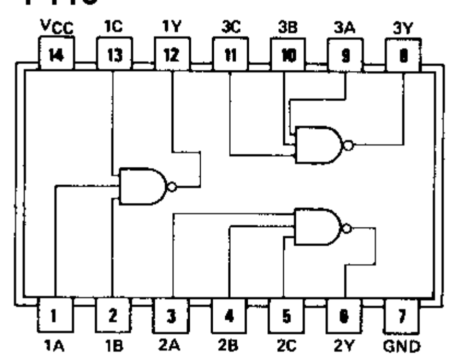
7402



7408



7410



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

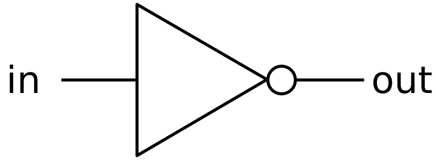
NOTE 4: All unused inputs of the device must be held at V_{CC} or GND to ensure proper device operation. Refer to the TI application report, *Implications of Slow or Floating CMOS Inputs*, literature number SCBA004.

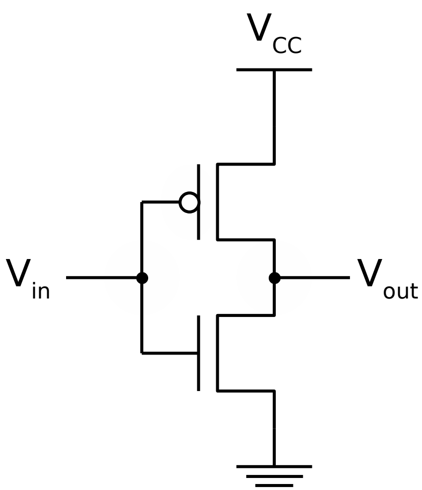
electrical characteristics over recommended operating free-air temperature range (unless otherwise noted)

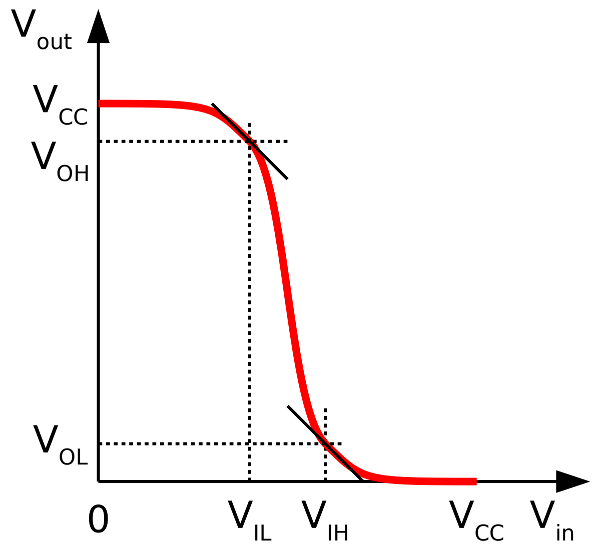
PARAMETER	TEST CONDITIONS†			SN54LS00			SN74LS00			UNIT
				MIN	TYP‡	MAX	MIN	TYP‡	MAX	
V_{IK}	V_{CC} = MIN,	I_I = –18 mA				–1.5			–1.5	V
V_{OH}	V_{CC} = MIN,	V_{IL} = MAX,	I_{OH} = –0.4 mA	2.5	3.4		2.7	3.4		V
V_{OL}	V_{CC} = MIN,	V_{IH} = 2 V	I_{OL} = 4 mA		0.25	0.4		0.25	0.4	V
			I_{OL} = 8mA					0.35	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

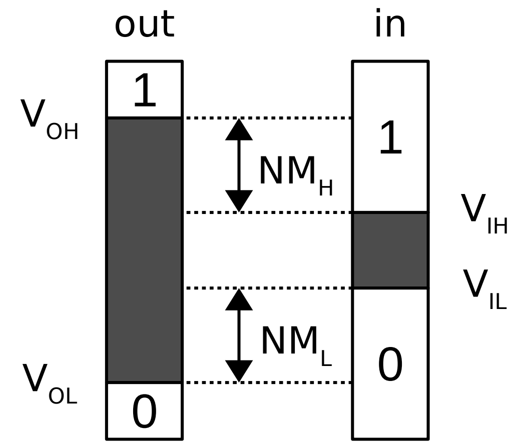
† For conditions shown as MIN or MAX, use the appropriate value specified under recommended operating conditions.
‡ All typical values are at V_{CC} = 5 V, T_A = 25°C.
§ Not more than one output should be shorted at a time.

Electrical parameters
Logic levels and noise margins

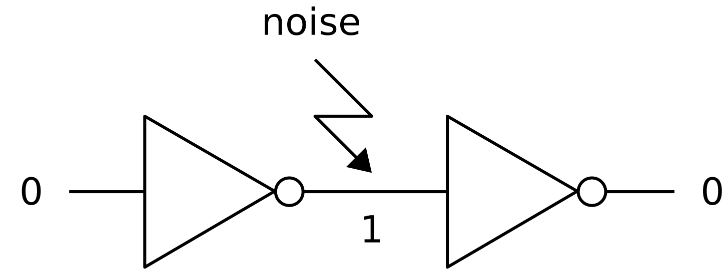






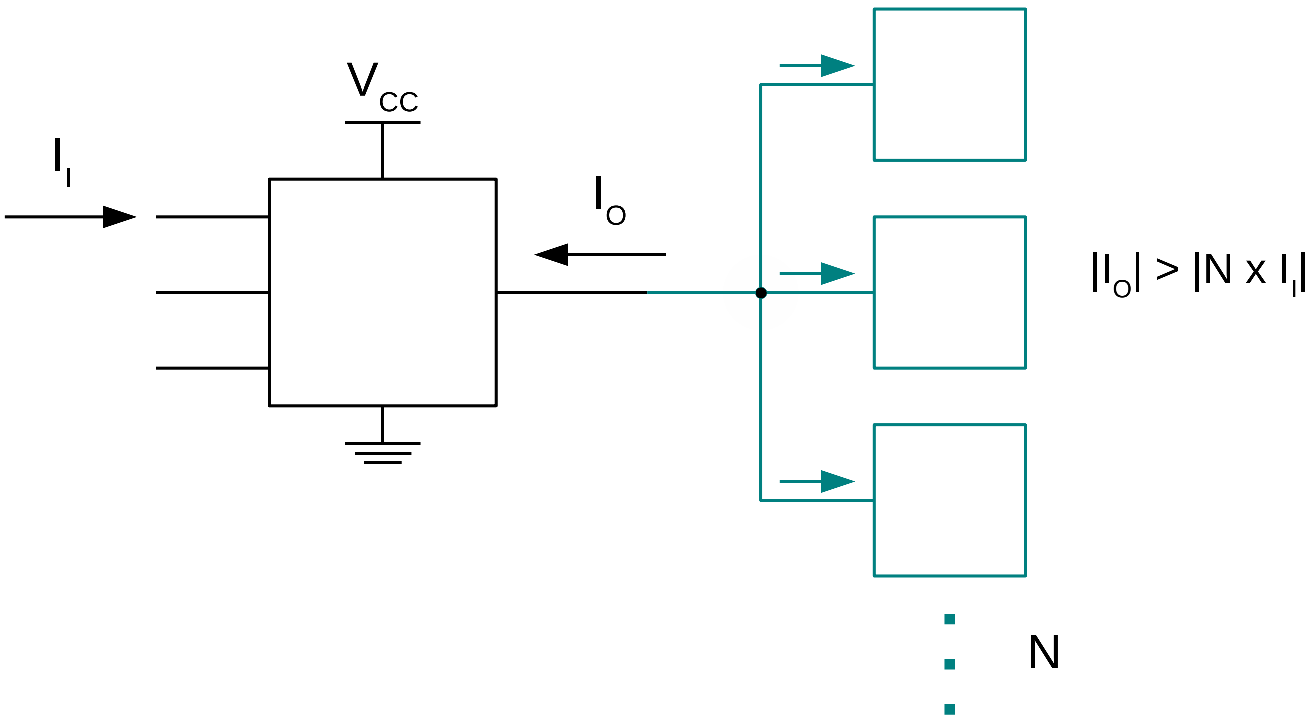


$NM_L = V_{IL} - V_{OL}$
$NM_H = V_{OH} - V_{IH}$
$NM = \min(NM_L, NM_H)$



Simulation

Electrical parameters
Fan-out

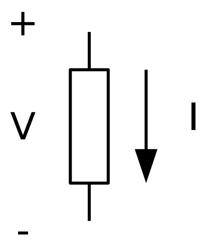


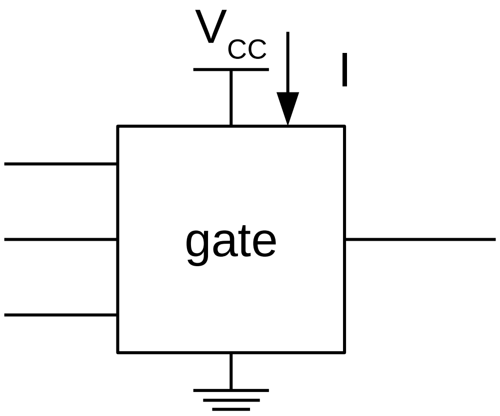
FAN-OUT
Maximum value of N so that $|I_O| > |N \times I_I|$ in both cases (high and low output levels)

Electrical parameters
Power consumption

- Static
- Dynamic
  - Depends on the frequency

$$P = VI$$





$$P = V_{CC} I$$

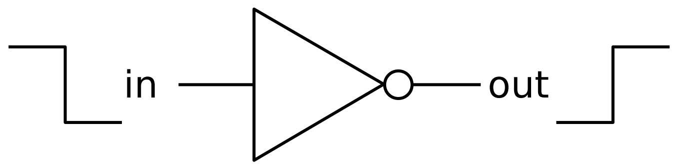
Switching parameters

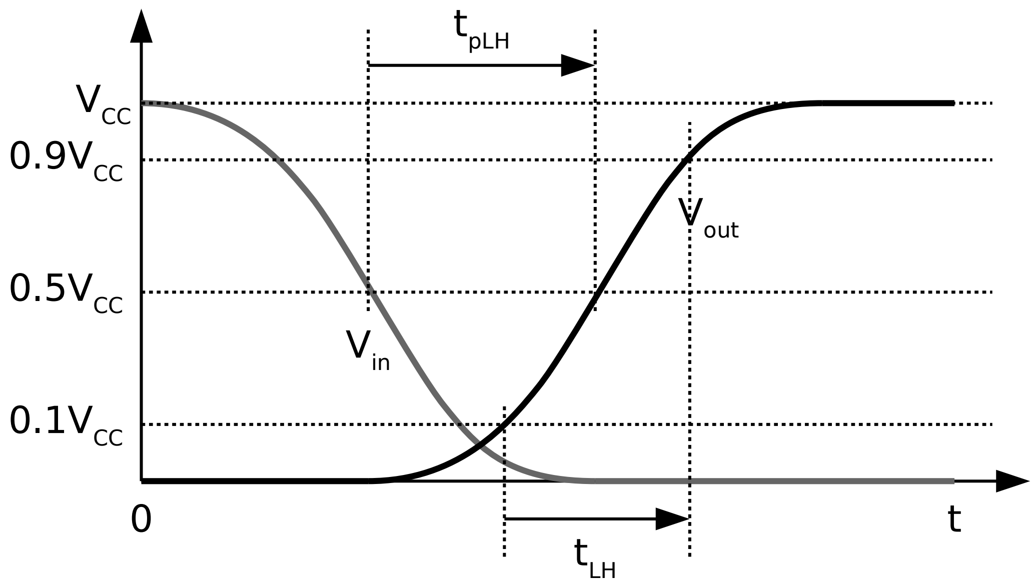
- Transition time: time for a transition to change from:
  - 10% V_{CC} to 90% V_{CC} (rising transition): t_{LH}
  - 90% V_{CC} to 10% V_{CC} (falling transition): t_{HL}
  - Depends on many factors, specially gate's strength and load.
- Propagation delay: time elapsed from the input transition to the 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)