

► Concept:

1. micro-electronic devices are based on micro-electronic **switches**:

switch is <i>on</i>	$\Rightarrow$	connected	$\leadsto$	allows flow of electrons
switch is <i>off</i>	$\Rightarrow$	disconnected	$\leadsto$	disallows flow of electrons

2. however, we need those switches to be

- efficient in terms of space, i.e., their physical size
- efficient in terms of time, i.e., how quickly they operate
- reliable, i.e., low probability of failure
- useable, i.e., packaged into high(er)-level building blocks
- manufacturable, e.g., high yield, even given high complexity and density

► **Agenda:**

semi-conductors $\leadsto$ **transistors** $\leadsto$ **logic gates,**

i.e.,

1. physical foundations,
2. semi-conductors and transistors,
3. logic gates, and
4. physical constraints and properties.

► **Caveat!**

- this is CS not EE, so we carefully limit the level of detail,
- e.g., “transistors are just switches” *is* reasonable (although clearly there’s more to it than that).

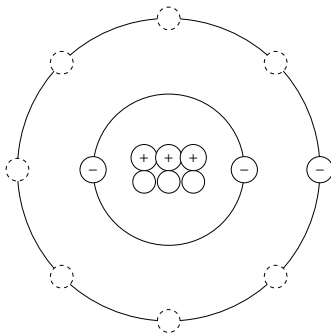
Part 1: foundations (1)

► Fact #1:

- A given **atom** is built from

1. a group of nucleons, either **protons** or **neutrons**, called the nucleus, and
2. a cloud of **electrons** arranged in **shells**,

e.g., lithium (**Li**):



- The number of protons dictates **atomic number**; the number of neutrons dictates **isotope**.
- The electron configuration is not arbitrary: the n -th shell can accommodate upto $2n^2$ electrons.
- An unfilled slot within a shell is called a **hole**.

Part 1: foundations (2)

► Fact #2:

- Each sub-atomic particle has an associated electrical **charge**, i.e.,

electrons $\mapsto$ negative charge (hence $-$)

protons $\mapsto$ positive charge (hence $+$)

neutrons $\mapsto$ neutral charge

and an **ion** is an atom with a non-zero overall charge.

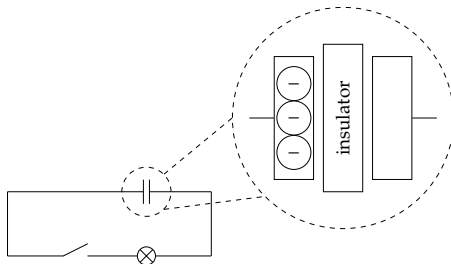
► Fact #2:

- The binding between particles can be disrupted:
 - As an electron absorbs more energy, it becomes excited; at some threshold, it will be displaced and then becomes **free**.
 - A free electron can move between shells, *or* between atoms (i.e., between their outer shells); roughly speaking, they are “attracted” by holes.

Part 1: foundations (3)

► Fact #3:

- An electrical **current** is a flow of electrons, i.e., a flow of charge.
- Free electrons (bound to atoms or not) “move” from low to high potential: this is how



i.e., a **capacitor** (or **battery**) works.

- A given material can be classified in terms of how easily electrons can move:

conductor (e.g., a metal)	⇒ high-conductivity $\equiv$ low-resistivity
	⇒ does allow electrons to move easily

insulator (e.g., a vacuum)	⇒ low-conductivity $\equiv$ high-resistivity
	⇒ does not allow electrons to move easily

Part 1: foundations (4)



WE WERE GOING TO USE THE TIME MACHINE TO PREVENT THE ROBOT APOCALYPSE, BUT THE GUY WHO BUILT IT WAS AN ELECTRICAL ENGINEER.

Part 1: foundations (5)

► Fact #4:

► Silicon (Si) is really useful, because

1. it's **abundant**, i.e., there's lots of it and so it doesn't cost much,
2. it can be **doped** with a donor material, e.g.,

silicon (Si)	+	(	phosphorus (P)	or	arsenic (As)	)	↪	extra electrons
silicon (Si)	+	(	boron (B)	or	aluminium (Al)	)	↪	extra holes

and

3. it's fairly **inert**, i.e., it's stable enough not to react in weird ways with other things, allowing construction of materials with specific sub-atomic properties.

► Fact #4:

- The result is a ***semi-conductor***:

extra electrons $\rightsquigarrow$ N-type semi-conductor

extra holes $\rightsquigarrow$ P-type semi-conductor

- A “sandwich” of P-type and N-type layers can be used to control if and how electrons can flow, e.g., from an N-type layer to a P-type layer but *not* vice versa.

An Aside: some history



- ▶ A historically dominant switch technology was the **vacuum tube**:
 - ▶ Looks like a light-bulb with a glass envelope holding a vacuum.
 - ▶ Inside vacuum is an electron producing filament (or cathode) and a metal plate (or anode).
 - ▶ When filament is heated, electrons are produced into vacuum which are attracted by plate.
 - ▶ Reliability of vacuum tubes was reasonably good, but most failed during power-on or power-off ...
 - ▶ ... the terms **bug** and **debug** both allegedly stem (in part) from failure of this sort.

<https://en.wikipedia.org/wiki/File:6P1P.jpg>

An Aside: some history

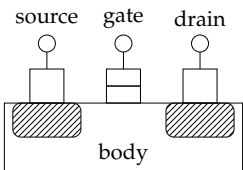


- ▶ The replacement for this generation of technology is the **transistor**.
 - ▶ There are *many* types, e.g.,
 - ▶ **1925**: Field Effect Transistor (FET).
 - ▶ ...
 - ▶ **1953**: Junction FET (or JFET).
 - ▶ ...
 - ▶ **1959**: Metal Oxide Semi-conductor FET (MOSFET).
- which span a range of properties and use-cases.

<https://en.wikipedia.org/wiki/File:Replica-of-first-transistor.jpg>

- **Concept:** a **Metal Oxide Semi-conductor Field-Effect Transistor (MOSFET)**

Circuit



where

- FET transistors allow charge to flow through a conductive channel between source and drain terminals,
- the channel width, and hence conductivity, is controlled by the potential difference applied to gate terminal,
- in a MOSFET transistor, the channel is *induced* (versus a JFET, where an explicit semi-conductor layer is used).

Part 2: semi-conductors and transistors (2)

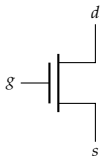
Design

Definition

An **N-MOSFET** (or **N-type MOSFET**, or **N-channel MOSFET**, or **NPN MOSFET**) is constructed from N-type semi-conductor terminals and a P-type body:

- ▶ applying a potential difference to the gate widens the conductive channel, meaning source and drain are connected (i.e., act like a conductor); the transistor is activated.
- ▶ removing the potential difference from the gate narrows the conductive channel, meaning source and drain are disconnected (i.e., act like an insulator); the transistor is deactivated.

Using d , s and g to denote the drain, source and gate terminals, an N-MOSFET is described symbolically as

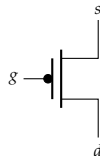


Definition

A **P-MOSFET** (or **P-type MOSFET**, or **P-channel MOSFET**, or **PNP MOSFET**) is constructed from P-type semi-conductor terminals and an N-type body:

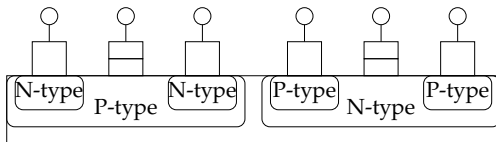
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Using d , s and g to denote the drain, source and gate terminals, an P-MOSFET is described symbolically as



- **Concept:** a **Complementary Metal Oxide Semi-conductor (CMOS)** *cell*

Circuit



where

1. each cell combines one N-MOSFET and one P-MOSFET,
2. only switching from one state to another consumes much power (or **dynamic consumption**) since one transistor does the opposite of the other,
3. there isn't much "leakage" (or **static consumption**) at other times.

Part 2: semi-conductors and transistors (4)

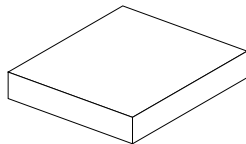
Fabrication (or manufacture)

► **Concept:** Complementary Metal-Oxide-Semiconductor (CMOS) *fabrication*

Algorithm

1. Start with a clean, prepared **wafer**.
2. Apply a layer of **substrate** material, e.g., metal or semi-conductor.
3. Apply a layer of **photoresist** material.
4. Expose the photoresist to a precise negative or **mask** of design; this hardens the exposed photoresist.
5. Wash away unhardened photoresist.
6. Etch away uncovered substrate.
7. Strip hardened photoresist.

Example



where

- the algorithm iterates to produce many layers, i.e., the result is 3D not 2D,
- regularity offers a significant advantage: we can manufacture *many* similar components in a layer within one iteration,
- the feature size (e.g., 90nm CMOS), and so density, relates to the resolution of this process.

Part 2: semi-conductors and transistors (4)

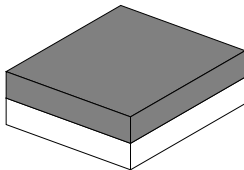
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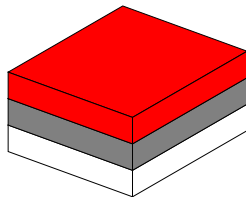
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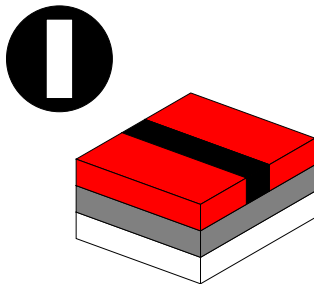
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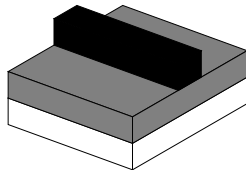
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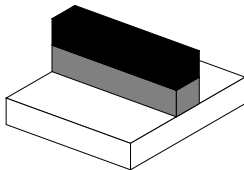
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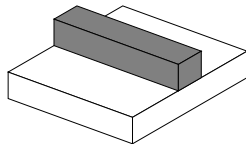
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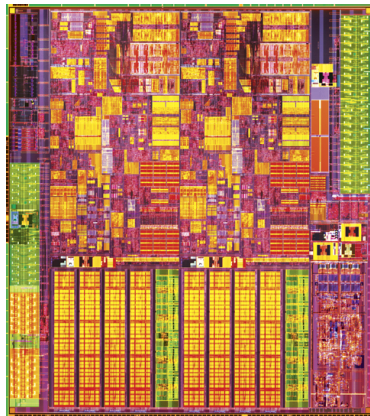
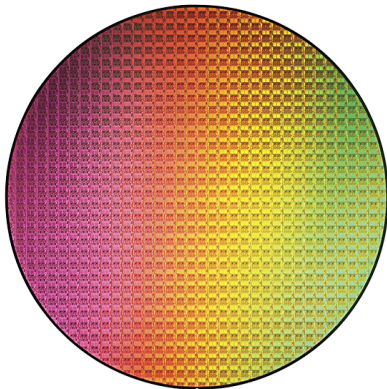
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Part 2: semi-conductors and transistors (5)

Fabrication (or manufacture)

- **Concept:** the result is a processed **wafer**, e.g.,



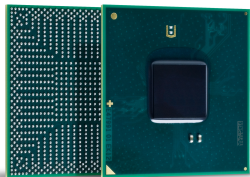
comprising multiple individual blocks, or components.

https://www.intel.com/pressroom/archive/releases/2010/20100107comp_sm.htm

Part 2: semi-conductors and transistors (6)

Fabrication (or manufacture)

- **Concept:** each component is **packaged** before use, e.g.,



which

- protects against damage, often including a heat sink as well, *and*
- provides a usable interface, via external **pins** bonded to internal inputs and outputs.

https://www.intel.com/pressroom/archive/releases/2010/20100107comp_sm.htm

Part 2: semi-conductors and transistors (7)

Fabrication (or manufacture)

Moore's Law: originally an observation

The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years. That means by 1975, the number of components per integrated circuit for minimum cost will be 65,000.

– Moore [8]

and later updated: in short “number of transistors in unit area doubles roughly every two years”.



https://download.intel.com/pressroom/images/events/moores_law_40th/Gordon_Moore/GordonMoore_young.jpg

Part 2: semi-conductors and transistors (8)

Fabrication (or manufacture)

Example (Moore's Law [8], from 1970 to 2005)

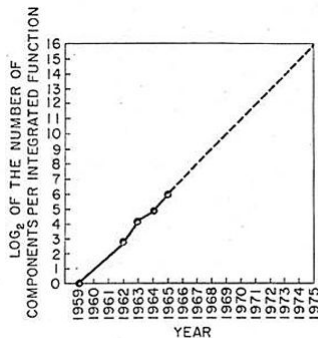
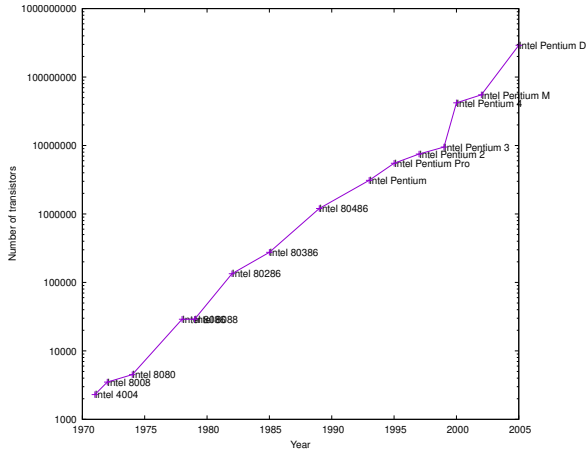


Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.

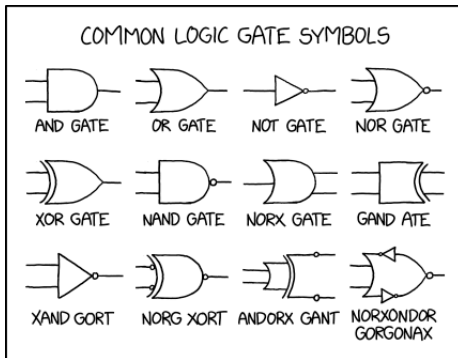
Part 2: semi-conductors and transistors (8)

Fabrication (or manufacture)

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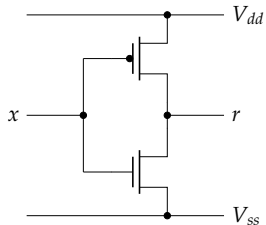
Part 3: logic gates (1)



<https://xkcd.com/2497>

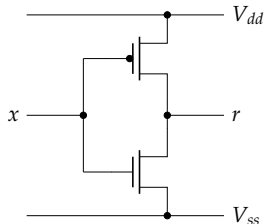
Part 3: logic gates (2)

Circuit



► **Question:** what does this organisation of MOSFET transistors *do*?

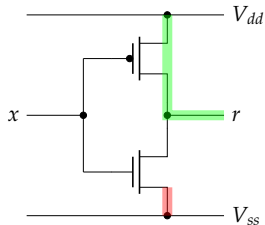
Circuit



- ▶ Connect x to V_{ss} :
 1. the top P-MOSFET will be connected,
 2. the bottom N-MOSFET will be disconnected,
 3. r will be connected to V_{dd} .
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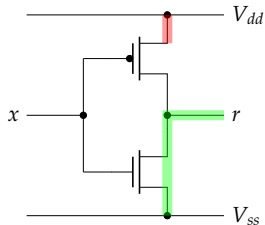
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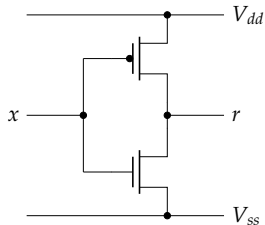
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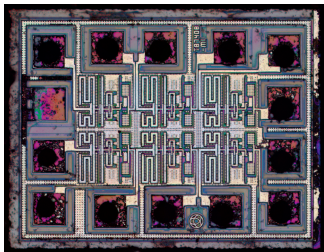
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- ▶ **Answer:** this matches the behaviour of NOT, i.e., it's an **inverter**!

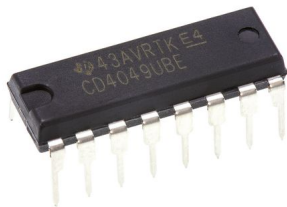
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<https://zeptobars.com/en/read/CD4049-cmos-inverter-metal-gate>

Circuit



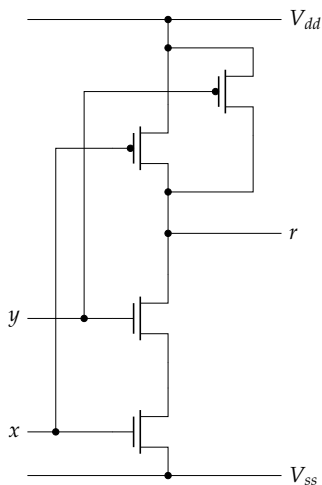
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<https://www.ti.com/product/CD4049UB>

Part 3: logic gates (3)

A NAND gate

Circuit

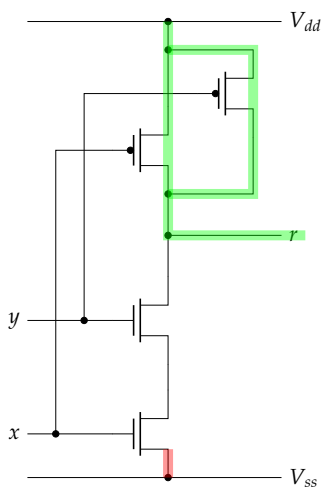


- ▶ Connect both x and y to V_{ss} :
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- ▶ Connect x to V_{dd} and y to V_{ss} :
 1. the right-most P-MOSFET will be connected,
 2. the upper-most N-MOSFET will be disconnected,
 3. r will be connected to V_{dd} .
- ▶ Connect x to V_{ss} and y to V_{dd} :
 1. the left-most P-MOSFET will be connected,
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Part 3: logic gates (3)

A NAND gate

Circuit

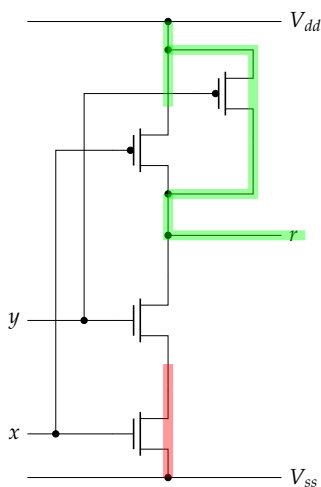


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A NAND gate

Circuit

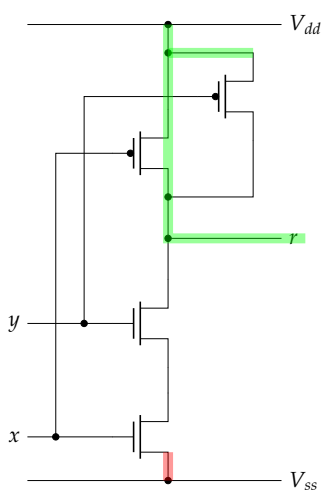


- ▶ Connect both x and y to V_{ss} :
 1. both top P-MOSFETs will be connected,
 2. both bottom N-MOSFETs will be disconnected,
 3. r will be connected to V_{dd} .
- ▶ Connect x to V_{dd} and y to V_{ss} :
 1. the right-most P-MOSFET will be connected,
 2. the upper-most N-MOSFET will be disconnected,
 3. r will be connected to V_{dd} .
- ▶ Connect x to V_{ss} and y to V_{dd} :
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 3. r will be connected to V_{ss} .

Part 3: logic gates (3)

A NAND gate

Circuit

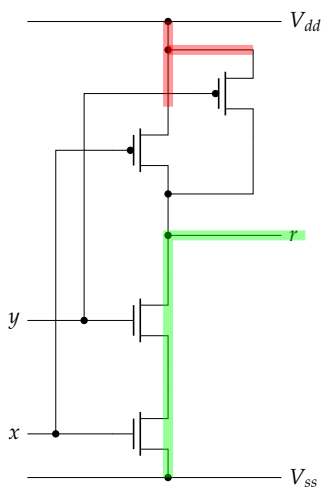


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Part 3: logic gates (3)

A NAND gate

Circuit

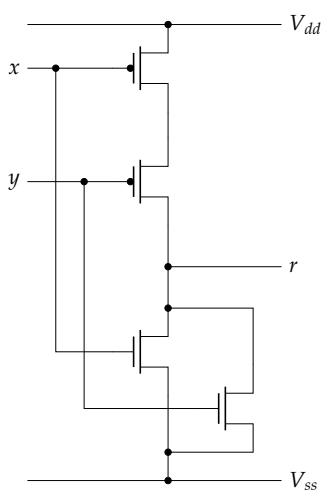


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 3. r will be connected to V_{ss} .

Part 3: logic gates (4)

A NOR gate

Circuit

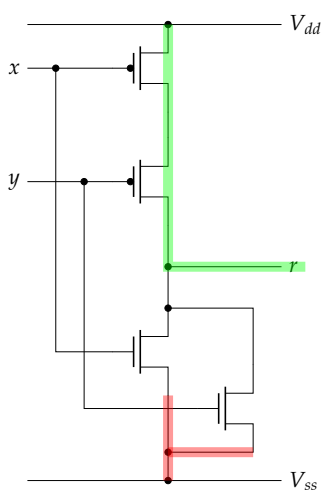


- ▶ Connect both x and y to V_{ss} :
 1. both top P-MOSFETs will be disconnected,
 2. both bottom N-MOSFETs will be connected,
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 1. the upper-most P-MOSFET will be disconnected,
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Part 3: logic gates (4)

A NOR gate

Circuit

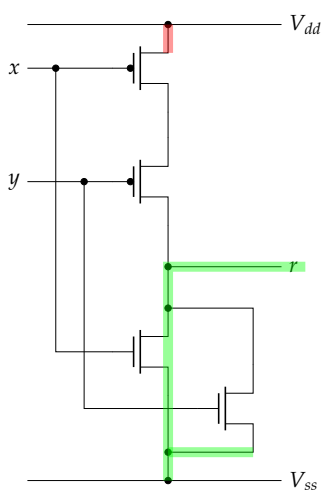


- ▶ Connect both x and y to V_{ss} :
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Part 3: logic gates (4)

A NOR gate

Circuit

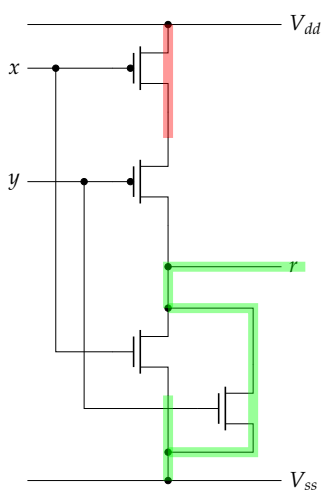


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 1. both top P-MOSFETs will be disconnected,
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 3. r will be connected to V_{ss} .

Part 3: logic gates (4)

A NOR gate

Circuit

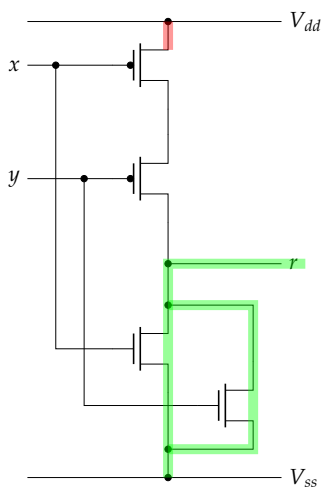


- ▶ Connect both x and y to V_{ss} :
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Part 3: logic gates (4)

A NOR gate

Circuit



- ▶ Connect both x and y to V_{ss} :
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- ▶ Connect both x and y to V_{dd} :
 1. both top P-MOSFETs will be disconnected,
 2. both bottom N-MOSFETs will be connected,
 3. r will be connected to V_{ss} .

Part 3: logic gates (5)

In summary, we should

1. relabel

$$\begin{array}{rclcl} V_{ss} & = & 0V \simeq GND & \models & 0 \\ V_{dd} & = & 5V & \models & 1 \end{array}$$

and assume the power rails are everywhere,

2. form a

- ▶ **pull-up network** of P-MOSFET transistors connected to V_{dd} ,
- ▶ **pull-down network** of N-MOSFET transistors connected to V_{ss} ,

3. specify the functionality of each logic gate using a truth table, e.g.,

x	r
0	1
1	0

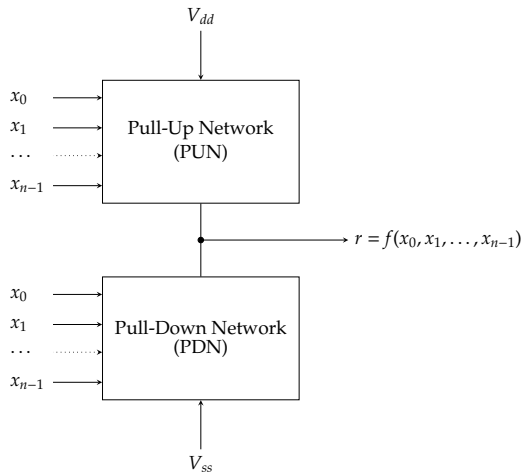
x	y	r
0	0	1
0	1	1
1	0	1
1	1	0

x	y	r
0	0	1
0	1	0
1	0	0
1	1	0

and represent it using an associated symbol.



Part 3: logic gates (6)



Definition

r is x	$\equiv$	$r = x$	$\equiv$	$x \rightarrow r$
r is NOT x	$\equiv$	$r = \neg x$	$\equiv$	$x \rightarrow \neg r$
r is x NAND y	$\equiv$	$r = x \bar{\wedge} y$	$\equiv$	$x \bar{\wedge} y \rightarrow r$
r is x NOR y	$\equiv$	$r = x \bar{\vee} y$	$\equiv$	$x \bar{\vee} y \rightarrow r$
r is x AND y	$\equiv$	$r = x \wedge y$	$\equiv$	$x \wedge y \rightarrow r$
r is x OR y	$\equiv$	$r = x \vee y$	$\equiv$	$x \vee y \rightarrow r$
r is x XOR y	$\equiv$	$r = x \oplus y$	$\equiv$	$x \oplus y \rightarrow r$

Part 4: physical limitations (1)

Delay

Definition

Within some combinatorial logic, two classes of **delay** (which is often described as **propagation delay**, with a hint toward delay of signals more generally) dictate the time between change to some input and corresponding change (if any) in an output: these are

- ▶ **wire delay**, which relates to the time taken for current to move through the conductive wire from one point to another, and
- ▶ **gate delay**, which relates to the time taken for transistors in each gate to switch between connected and unconnected states.

The latter is typically larger than the former, and both relate to the associated implementations: the latter relates to properties of the transistors used, the former to properties of the wire (e.g., conductivity, length, and so on).

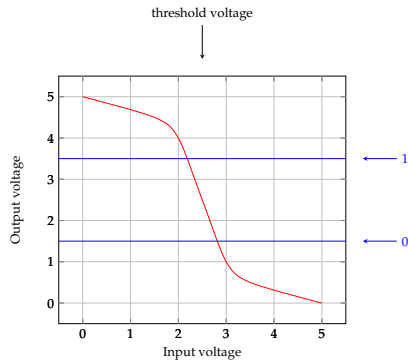
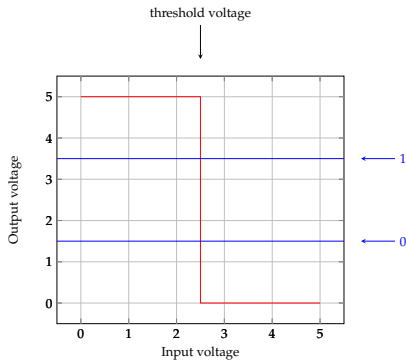
Definition

The **critical path** through some combinatorial logic is the longest sequential path between an input and output, i.e., the path which has the largest total delay (stemming from the individual wire and/or gate delays).

Part 4: physical limitations (2)

Delay

- **Example:** consider the MOSFET-based NOT gate



where

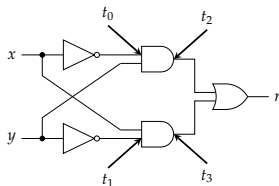
- the left-hand side illustrates an idealised, square response, whereas
- the right-hand side illustrates a (more) realistic, curved response.

Part 4: physical limitations (3)

Delay

- **Example:** *static* (i.e., time-agnostic) evaluation:

Circuit



setting $x = 0, y = 1$ means the circuit will compute

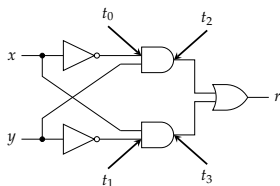
$$\begin{array}{llll} x & = & & = 0 \\ y & = & & = 1 \\ t_0 & = & \neg x & = 1 \\ t_1 & = & \neg y & = 0 \\ t_2 & = & t_0 \wedge y & = 1 \\ t_3 & = & t_1 \wedge x & = 0 \\ r & = & t_2 \vee t_3 & = 1 \end{array}$$

Part 4: physical limitations (3)

Delay

- **Example:** *dynamic* (i.e., time-considerate) evaluation:

Circuit



imagine that

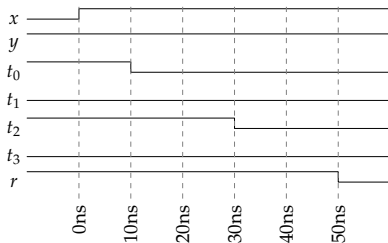
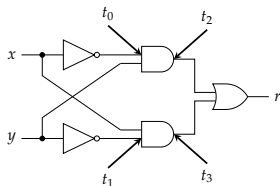
NOT gate	$\leadsto$	10ns
AND gate	$\leadsto$	20ns
OR gate	$\leadsto$	20ns

Part 4: physical limitations (3)

Delay

- **Example:** *dynamic* (i.e., time-considerate) evaluation:

Circuit



flipping $x = 0, y = 1$ to $x = 1, y = 1$ means the circuit will compute

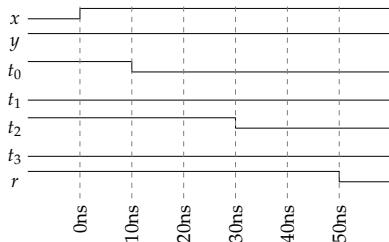
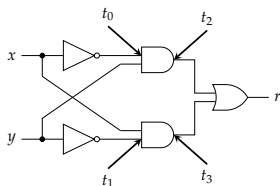
$$\begin{array}{lll} x & = & 1 \\ y & = & 1 \\ t_0 & = \neg x & = 0 \\ t_1 & = \neg y & = 0 \\ t_2 & = t_0 \wedge y & = 0 \\ t_3 & = t_1 \wedge x & = 0 \\ r & = t_2 \vee t_3 & = 0 \end{array}$$

Part 4: physical limitations (3)

Delay

- **Example:** *dynamic* (i.e., time-considerate) evaluation:

Circuit



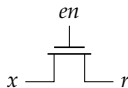
but, crucially,

1. it takes some time matching the **critical path** (i.e, 50ns through a NOT, an AND and an OR gate) to settle into the correct state, so
2. at some points in time, the output doesn't match the inputs.

Part 4: physical limitations (4)

3-state Logic

- **Concept:** 3-state logic, which introduces an “extra” pseudo-value where
 1. 0 represents **false**,
 2. 1 represents **true**, and
 3. Z represents **high impedance**,can be a useful model of real circuits.
- Think of high impedance as being the null value; the idea is to allow a wire to be “disconnected” per



x	en	r
0	0	Z
1	0	Z
Z	0	Z
0	1	0
1	1	1
Z	1	Z
0	Z	Z
1	Z	Z
Z	Z	Z

such that the ENABLE gate is really just a switch.

Part 4: physical limitations (5)

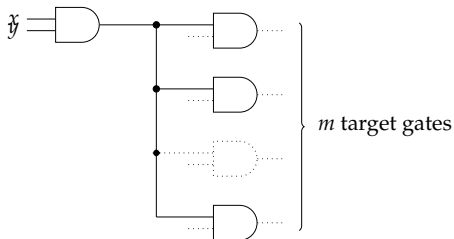
Fan-in and Fan-out

Definition

Consider a specific logic gate within some larger design:

- ▶ The term **fan-in** is used to describe the number of other gates that produce an input consumed by that logic gate.
- ▶ The term **fan-out** is used to describe the number of other gates that consume the output produced by that logic gate.

Example



► Take away points:

1. We now have a suite of logic gates, where it's clear

functional properties $\Leftrightarrow$ Boolean algebra
 $\Leftrightarrow$ Mathematics

behavioural properties $\Leftrightarrow$ transistors
 $\Leftrightarrow$ semi-conductors
 $\Leftrightarrow$ Physics

i.e., there's no longer the same gap between theory and practice.

► Take away points:

2. Arguably, tougher challenges stem from design and optimisation tasks, i.e., how do we
 - match some specification, e.g., “implement some function f ”, and
 - satisfy some design goals, e.g., “use less than X gates (or Y transistors)” or “ensure a delay less than Z ns”.
3. Modern transistor design and manufacture imply various constraints: at least a high-level, understanding of these (e.g., Moore’s Law etc.) is valuable.

Additional Reading

- ▶ *Wikipedia: Transistor*. URL: <https://en.wikipedia.org/wiki/Transistor>.
- ▶ *Wikipedia: Logic gate*. URL: https://en.wikipedia.org/wiki/Logic_gate.
- ▶ D. Page. “Chapter 2: Basics of digital logic”. In: *A Practical Introduction to Computer Architecture*. 1st ed. Springer, 2009.
- ▶ R.J. Smith and R.C. Dorf. “Chapter 12: Transistors and Integrated Circuits”. In: *Circuits, Devices and Systems*. 5th ed. Wiley, 1992.
- ▶ W. Stallings. “Chapter 11: Digital logic”. In: *Computer Organisation and Architecture*. 9th ed. Prentice Hall, 2013.
- ▶ A.S. Tanenbaum and T. Austin. “Section 3.1: Gates and Boolean algebra”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012.
- ▶ A.S. Tanenbaum and T. Austin. “Section 3.2.1: Integrated circuits”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012.

References

- [1] [Wikipedia: Logic gate](https://en.wikipedia.org/wiki/Logic_gate). URL: https://en.wikipedia.org/wiki/Logic_gate (see p. 58).
- [2] [Wikipedia: Transistor](https://en.wikipedia.org/wiki/Transistor). URL: <https://en.wikipedia.org/wiki/Transistor> (see p. 58).
- [3] D. Page. “Chapter 2: Basics of digital logic”. In: *A Practical Introduction to Computer Architecture*. 1st ed. Springer, 2009 (see p. 58).
- [4] R.J. Smith and R.C. Dorf. “Chapter 12: Transistors and Integrated Circuits”. In: *Circuits, Devices and Systems*. 5th ed. Wiley, 1992 (see p. 58).
- [5] W. Stallings. “Chapter 11: Digital logic”. In: *Computer Organisation and Architecture*. 9th ed. Prentice Hall, 2013 (see p. 58).
- [6] A.S. Tanenbaum and T. Austin. “Section 3.1: Gates and Boolean algebra”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012 (see p. 58).
- [7] A.S. Tanenbaum and T. Austin. “Section 3.2.1: Integrated circuits”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012 (see p. 58).
- [8] G.E. Moore. “Cramming more components onto integrated circuits”. In: *Electronics Magazine* 38.8 (1965), pp. 114–117 (see pp. 24–26).