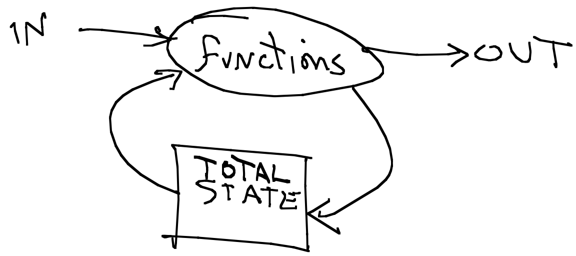
FSM implementation



need to build
1. Symbols
2. functions
3. State
(4. tape, for UTM/computer)

Any technology will do!

mechanical: Babbage, etc.

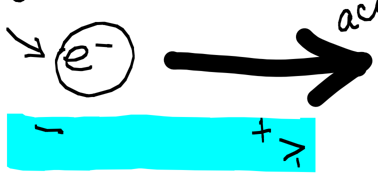
electro-mechanical ← we start here

electronic

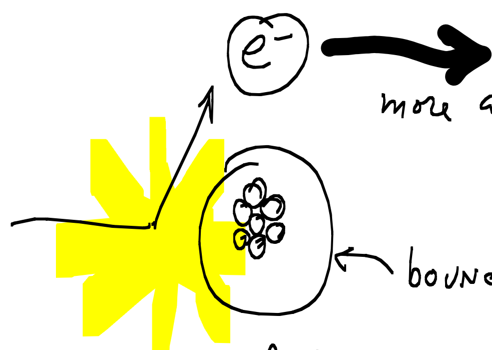
?

Electrons and heat

free electrons

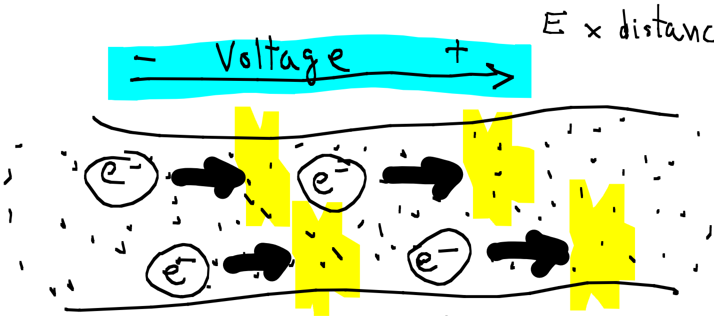


Elec. field ≈ gravity



Collision transfers energy to atoms of material, e.g. wire.
Atom motion = heat.
~ All collision energy goes to heat.

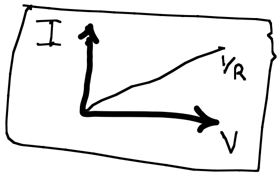
E × distance = Voltage



High current = Lots of moving e⁻
High voltage = Lots of acceleration
High Voltage + High current = Lots of Heat = $\frac{\text{energy}}{\text{sec}}$ = Power = $I \cdot V$

Ohm's Law, conductors, ...

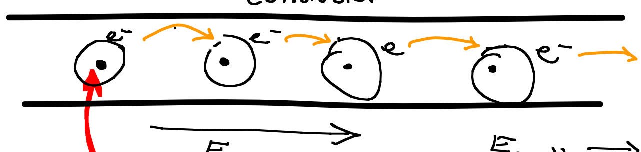
$R \stackrel{\text{def.}}{=} V/I$



$\Rightarrow I = \left(\frac{1}{R}\right)V \qquad \Rightarrow V = IR$

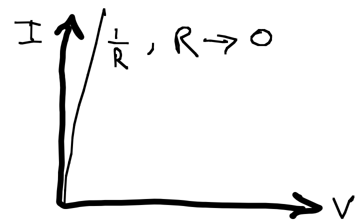
(if relationship is linear, then Ohm's Law Resistor)
or Linear device.

conductor

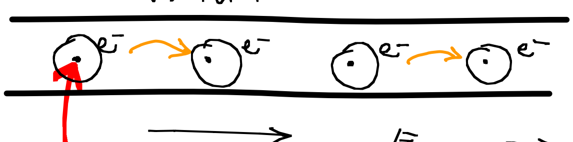


loosely bound e⁻

$E_{small} \longrightarrow$ Lots of e⁻ moving

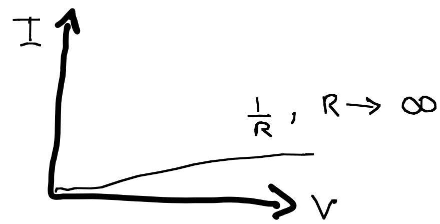


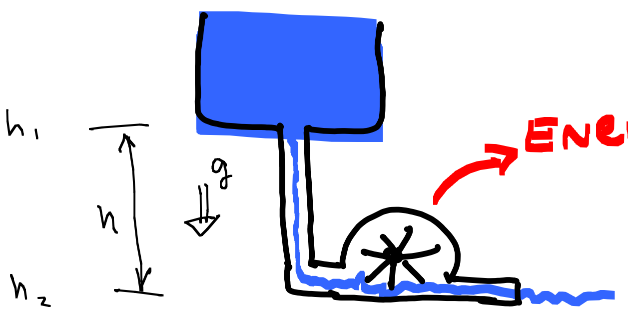
insulator



tightly bound e⁻

$E_{Large} \longrightarrow$ Few e⁻ moving



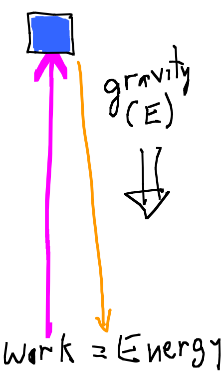


Energy/sec = Power

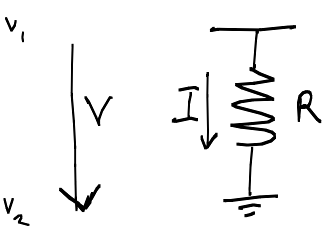
Big Pipe ⇒ Lots of Flow : (R↓)
Small Pipe ⇒ Little Flow : (R↑)

$V \sim h \cdot g$

Power = flow $(h \cdot g)$



V = E x distance
~ Tower height x gravity



$V = IR$

fix V: as $R \to 0$ then $I \to \infty$
as $R \to \infty$ then $I \to 0$

$V = V_1 - V_2$

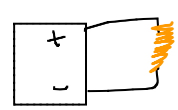
Power = I V

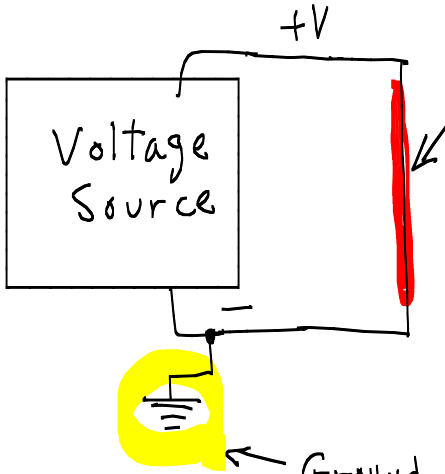
Energy over distance per e⁻

#e⁻ per second

$R \to 0$ then Power $\to \infty$
$R \to \infty$ then Power $\to 0$

power = energy/sec
= I*V = I*(I*R) = I*I*R
= I*V = (V/R)*V





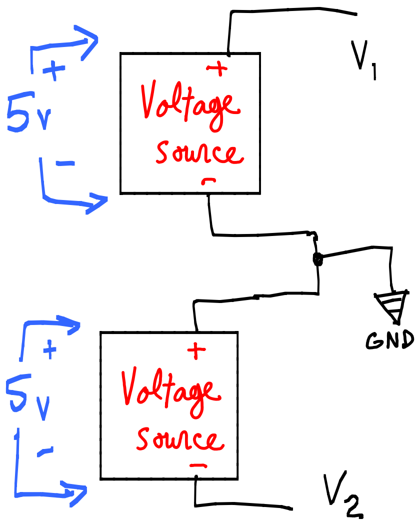
What if this is wire, ie., R is nearly 0?
Voltage source holds constant V voltage difference.

Then current I = V/R goes to infinity.

Then power dissipated to heat = I*V goes to infinity.

Infinite release of ENERGY! BOOM! (Actually, wire and/or supply melts, Ohm's Law not a good approximation at that point.)

Ground symbol ≡ 0 volts, by definition

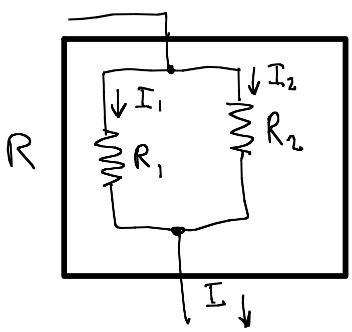


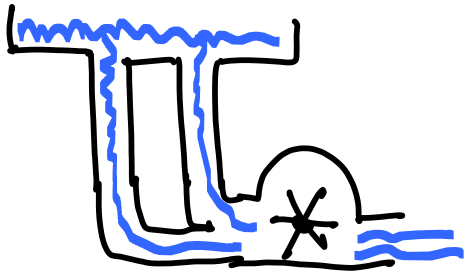
Measure voltage difference from voltage point at GROUND.

What voltage do we call V1?

What voltage do we call V2?

V1 = +5v relative to GND
V2 = -5v relative to GND





Resistors connected in PARALLEL.

Same as two water pipes in parallel: less resistance to flow, total flow is sum of flow in both.

Water pressure, voltage, is same for both paths.

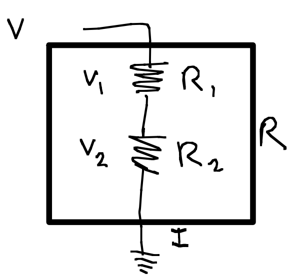
If R1 = R2 Then i1 = V/R1 = i2

i = i1 + i2

i = i1 + i2 = 2*V/R1

What is total R?

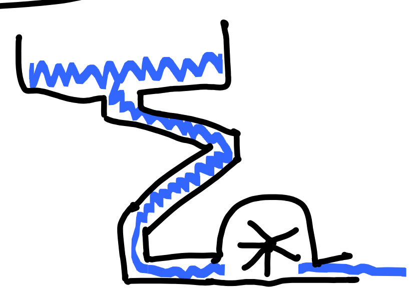
R = V/i = V/(2V/R1) = 1/2 R1



Resistors connected in SERIES.

Same as two pipes end-to-end: more resistance, less flow, same flow in both.

R = V/i = (V1 + V2)/i
V1 = i*R1 V2 = i*R2
R = (i*R1 + i*R2)/i = (R1 + R2)



We need Signal-Restoring, Non-Linear Logic. Ohm's Law devices are LINEAR.

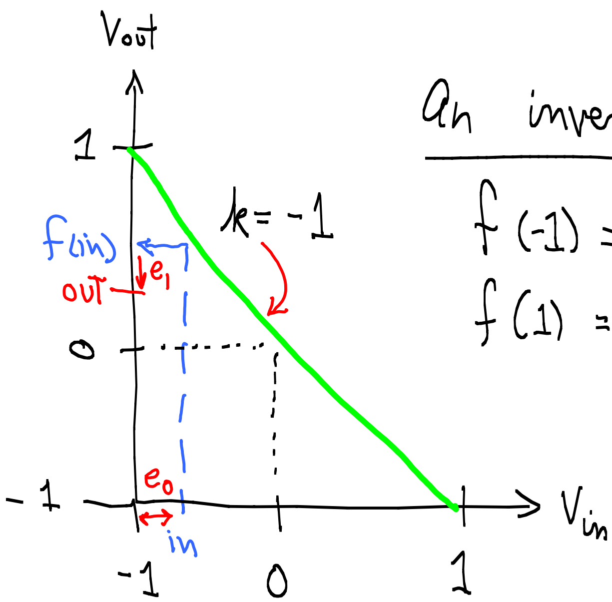
Suppose we had only linear devices (or something very nearly linear), then signal output has errors proportional to input errors.

Errors/noise:

$$\underbrace{x}_{\text{input, nominal}} + \underbrace{e_{in}}_{\text{input error}} \to \boxed{f} \to \underbrace{f(x+e_{in})}_{\text{output}} + \underbrace{e_{out}}_{\text{output error}}$$

Linearity:

$$f(v+e_{in}) = k(v+e_{in}) + e_{out} = kv + \underbrace{ke_{in} + e_{out}}_{\text{Total error}}$$



An inverter ckt.

$f(-1) = 1$

$f(1) = -1$

in —▷o— f(in)

Suppose we connect 2 in series

IN —▷o—▷o— $= f_2(f_1(\text{in}))$

f_1 f_2

(v is nominal signal: ±1)

$$f_1(\text{in}) = f_1(v+e) = kv + ke_0 + e_1$$
$$= (-1)(-1) + (-1)e_0 + e_1$$
$$= 1 - e_0 + e_1$$

$$f_2(f_1(\text{in})) = f_2(1 - e_0 + e_1)$$
$$= -1 + e_0 - e_1 + e_2$$

k stages $\Rightarrow$ $1 + \sum_{i=0}^{k} (-1)^i e_i$

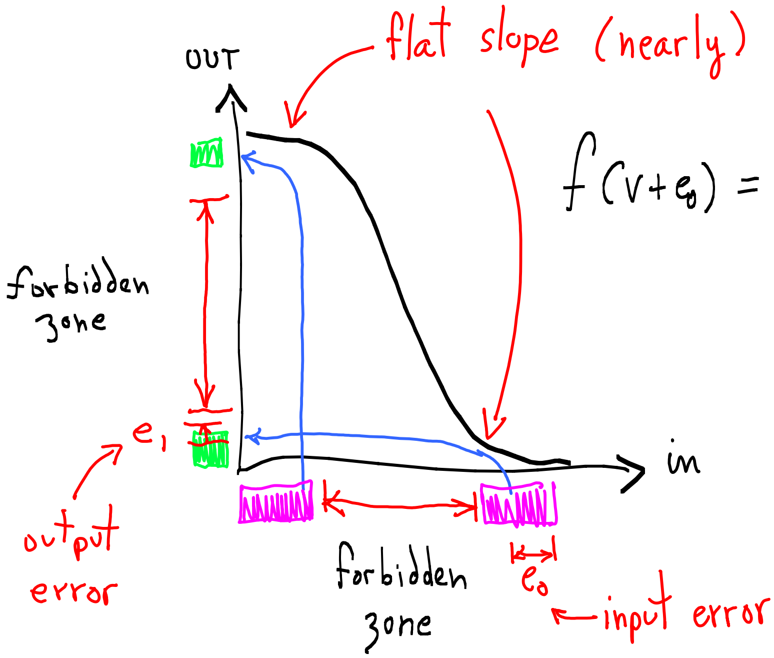
The errors include signs = random walk with random size steps.

Errors independently random w/ average 0 ==> variance increases w/ k.
Total error grows w/o bound!

Take random step (either in the -1 or +1 direction).
How far from 0 can you expect to be after k steps? About k^1/2 away.
With probability 0 you will be at 0, and error gets unboundedly large.

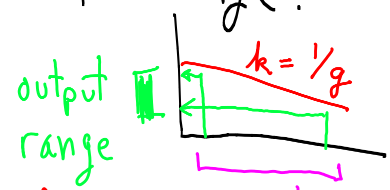
We must Reduce error at each stage ==> exponentially decreasing effect in later stages.

Non-Linear



$$f(v+e_0) = f(v) + \frac{1}{g} e_0 + e_1$$

in flat areas output range is smaller than input range:



decrease range by $1/g$

after k stages: $= 1 + \sum_{i=0}^{k} \underbrace{\left(\frac{1}{g}\right)^i}_{} e_i$

Converges!

If g is large enough (flat areas of curve are flat enough),

and

if output error size is not too big,

Then

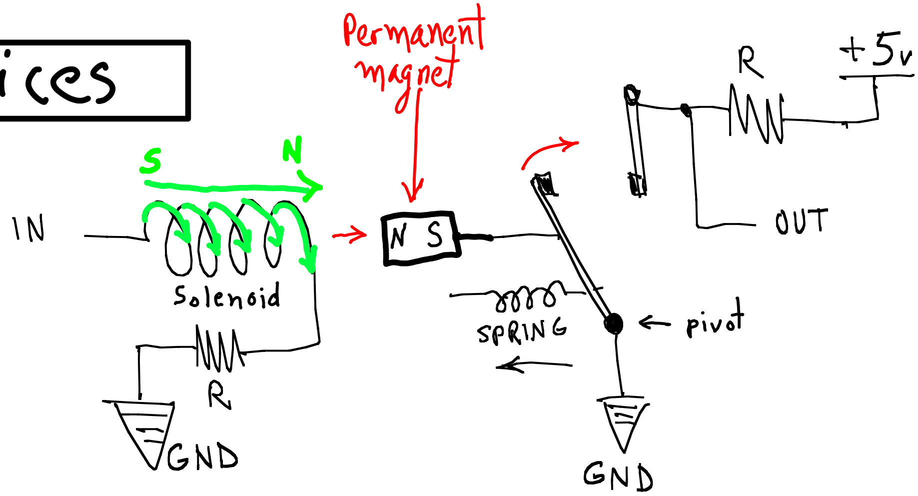
output after k stages never hits FORBIDDEN ZONE.

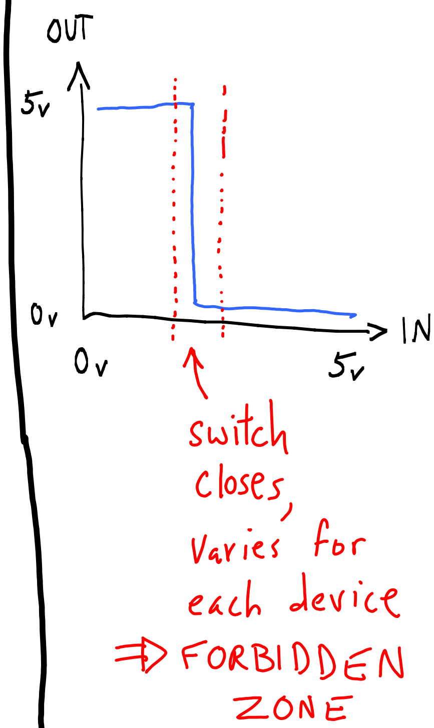
So, if we plan to have a circuit with long device chains, we must
have non-linear devices w/ suitable response curves.

Do we plan to have long chains? YES:

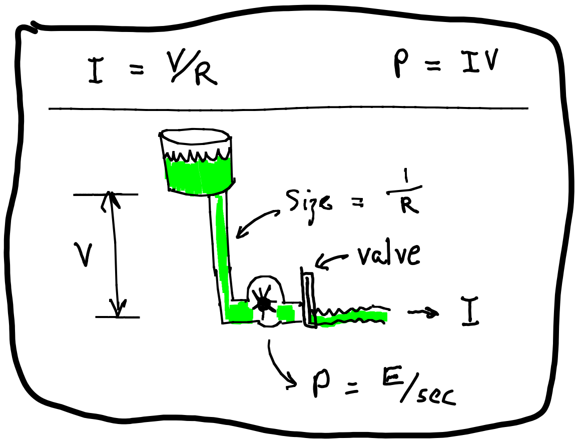
(1) feedback in system,
(2) chained data operations: D1 ==> D2 ==> D3 ==> D4 ...
(3) 1 Billion devices per cpu

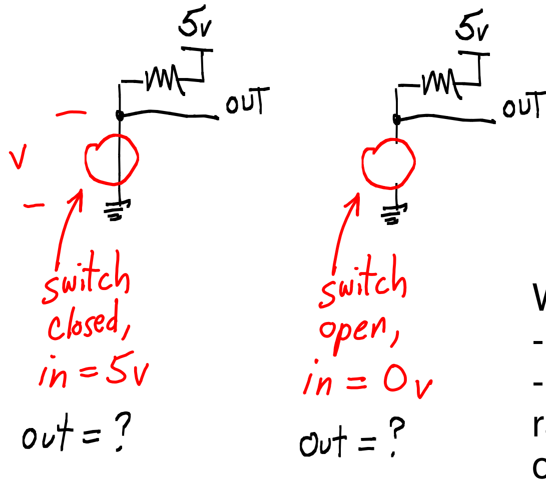
Devices





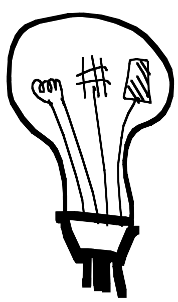
$V = IR$

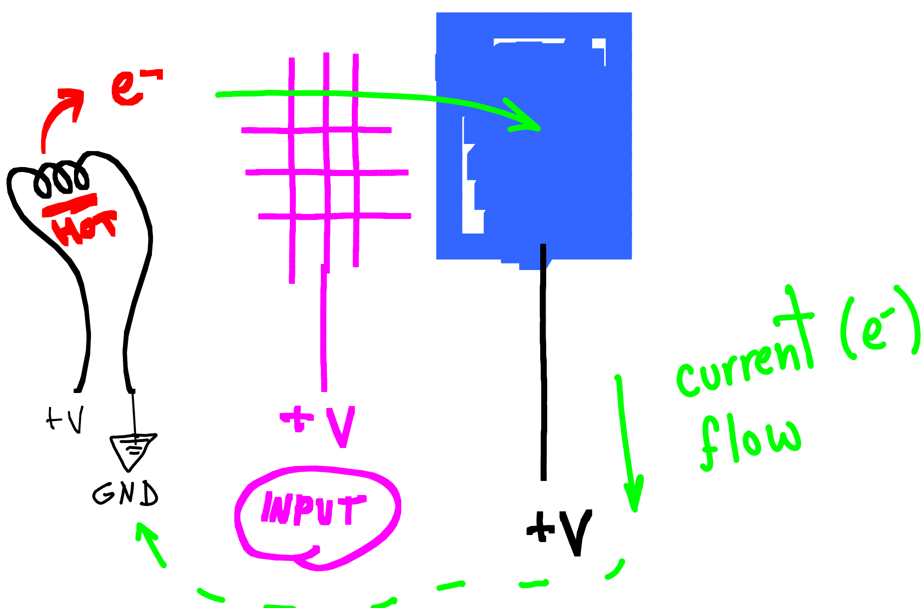




What is the function?
--- non-linear response
--- any voltage in allowed range will yield "clean" output. Easy to prevent input voltages in forbidden zone.

Electronic Switches: Vacuum Tubes



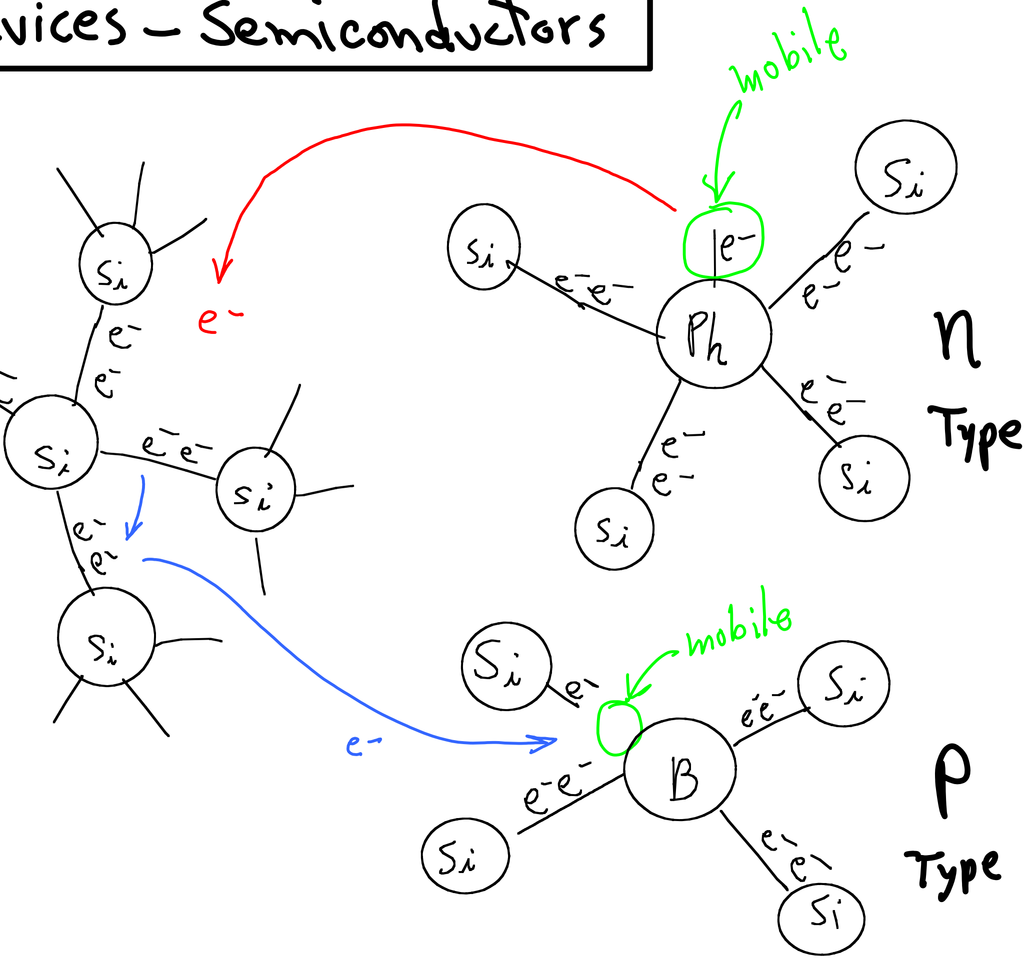


But if input = −V

Voltage Controlled Switch
faster, more reliable, less power

Solid State devices – Semiconductors

Silicon Crystal



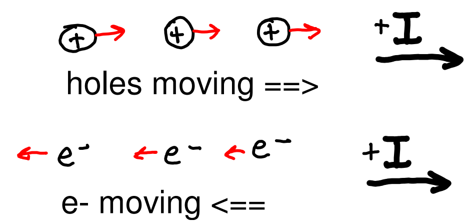
Phosphorous impurity:
e- leaves easily, becomes "hot" conduction-band e- .

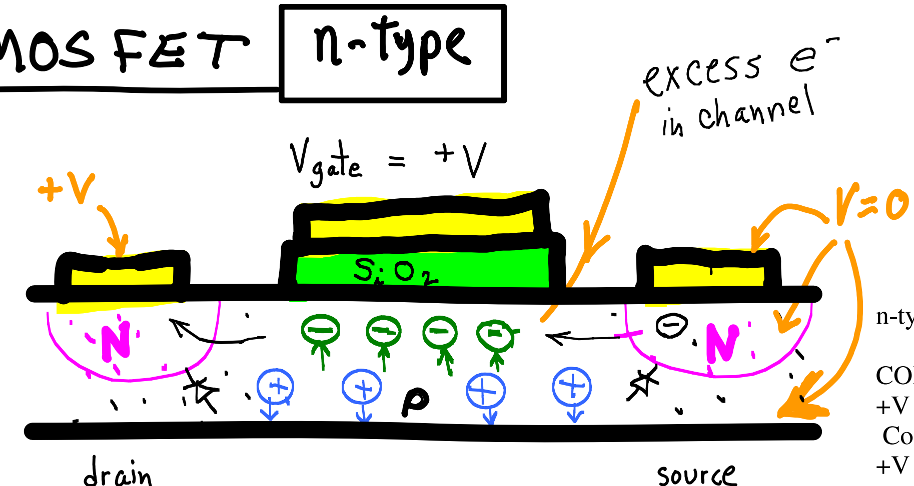
Boron impurity:
"cold" valence-band e- arrives, leaves behind +valence "hole" which moves.

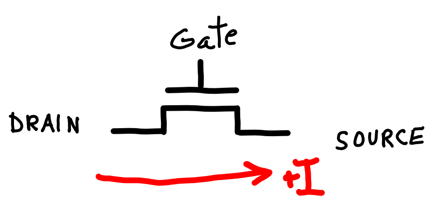
Holes and e- move in opposite directions, but current direction is same.

Easy e- flow from n-type to p-type, but reverse flow hard: "cold" valence-band e- need too much energy to become conduction band e-.

MOSFET n-type







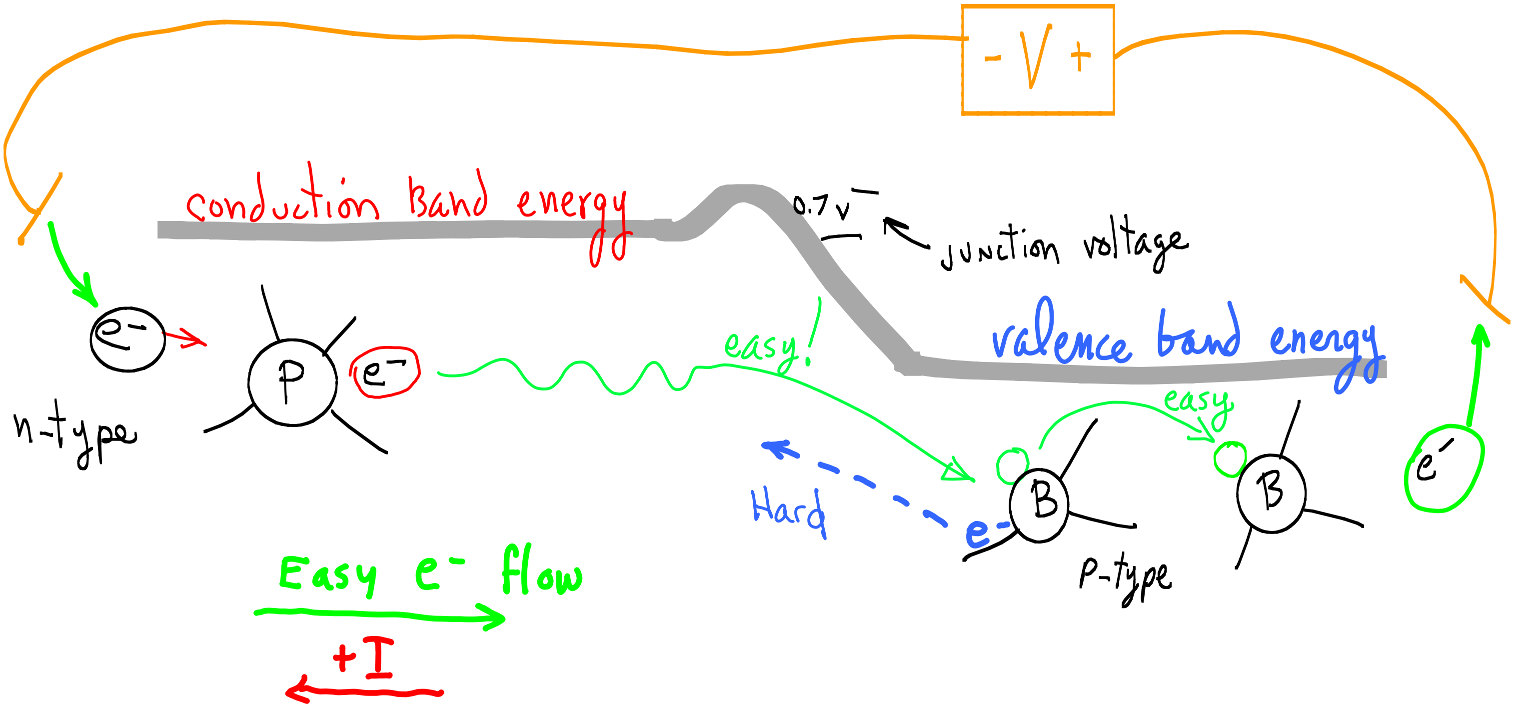
n-type MOSFET (n-transistor)

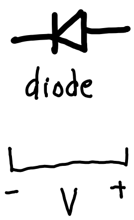
CONDUCTING (Vgate = +V, R-drain-to-source ~= 0):
+V on gate drives holes away from P-type channel.
Conduction-band e- move from source N-type well.
+V on drain pulls conduction-band e- off.
+I current flows left-to-right.

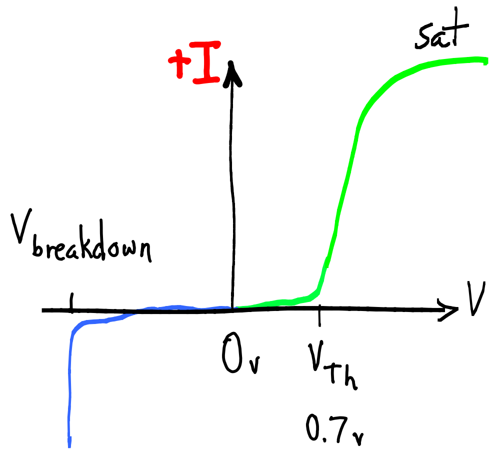
NOT-CONDUCTING (Vgate = 0, R-drain-source = BIG)
Vgate = 0, holes populate channel.
Source N-well e- drop into valence band in channel.
+V at drain cannot pull valence-band e- from P-type to N-type.

n-type transistor

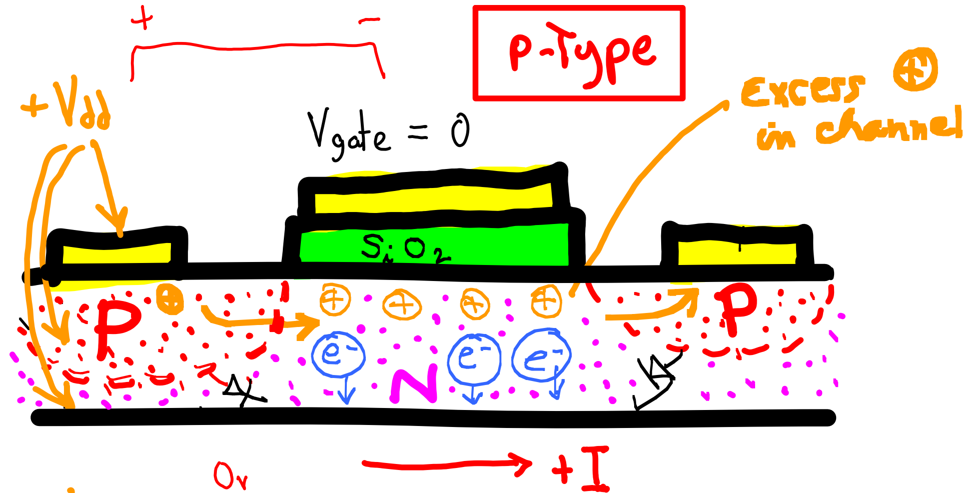
Vgate	Rdrain-source
0	∞ not conducting
+V	0 conducting







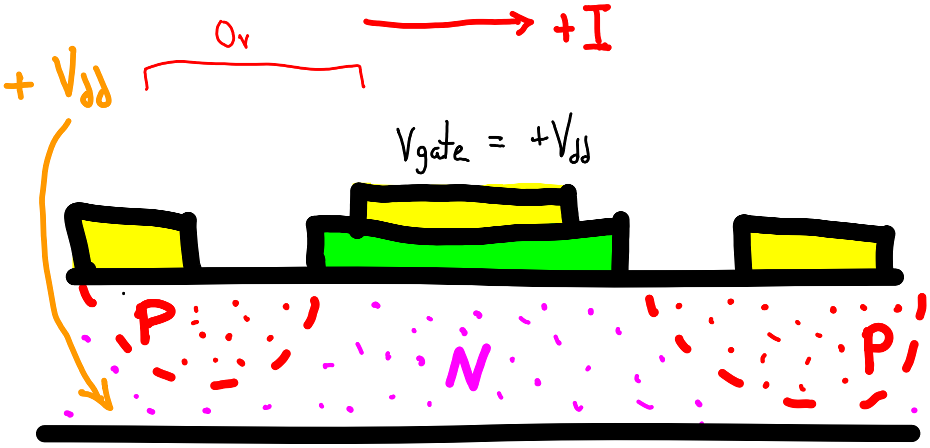
Just what we want: nice non-linear switch.

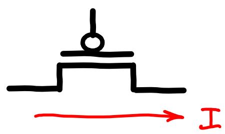


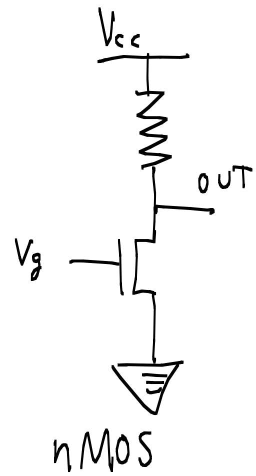
P-type (n-channel) transistor

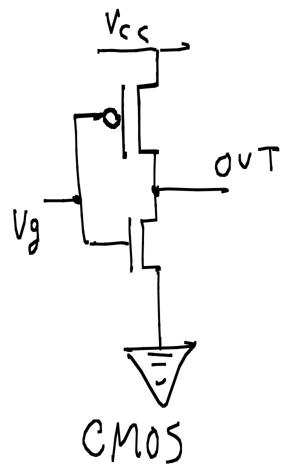
Vgate = 0:
Vgate = -Vdd wrt to base,
pushes e- away from channel, leaves excess holes, current flows.
R = 0, conducting.

Vgate = Vdd:
Vgate = 0 wrt to base
channel is neutral
only random thermal e- available for current flow.
R = infinity, not conducting

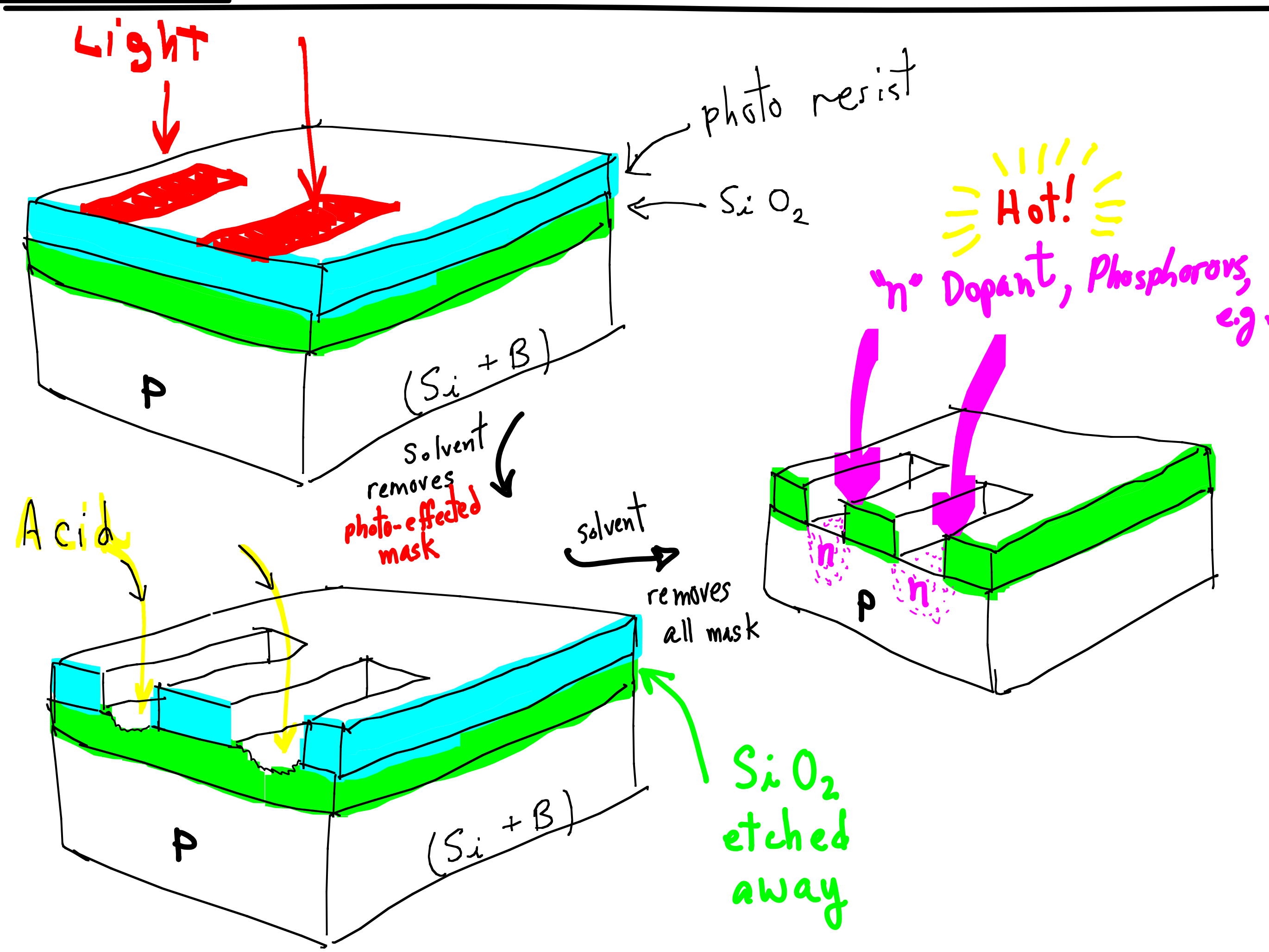


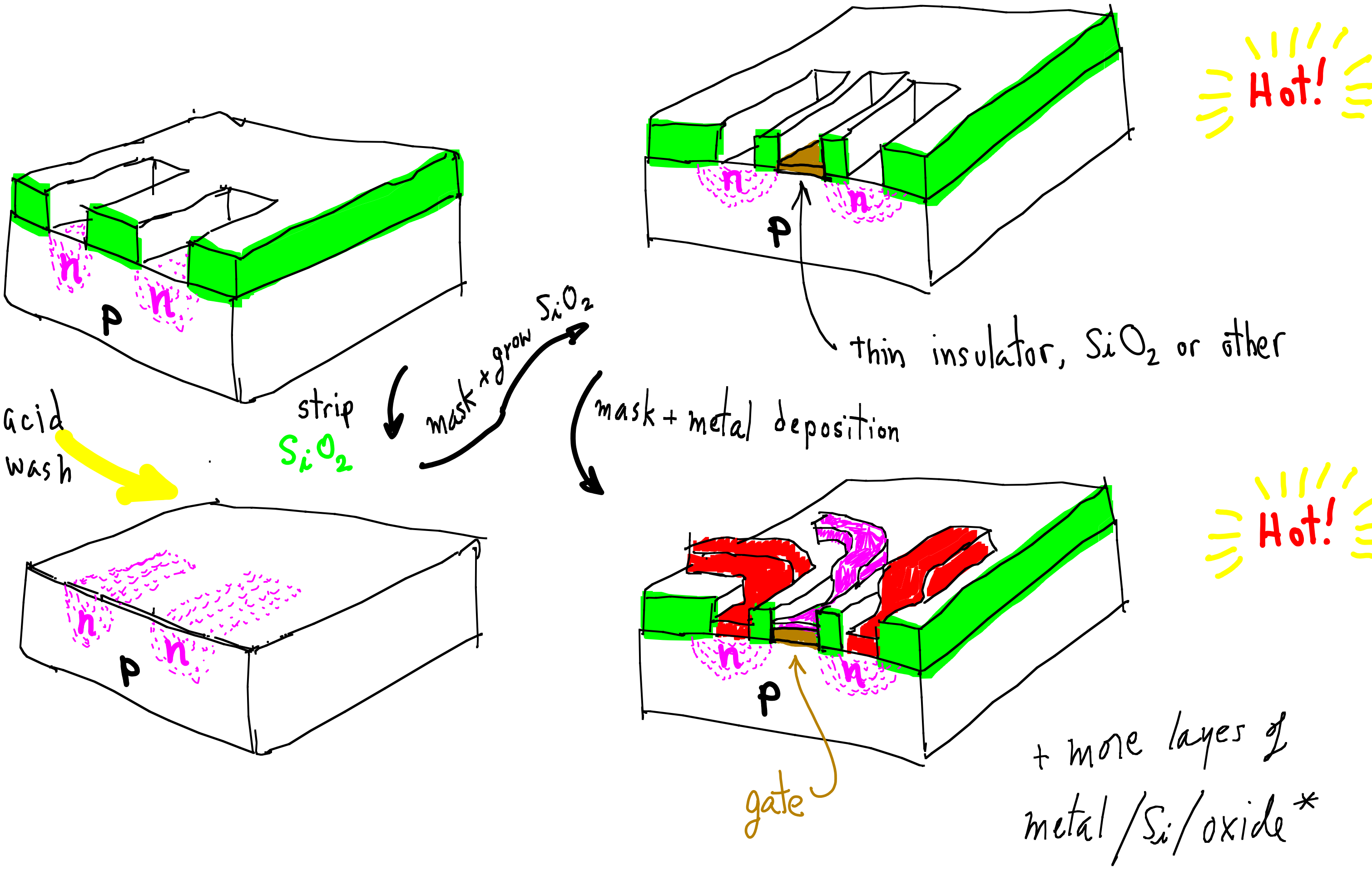




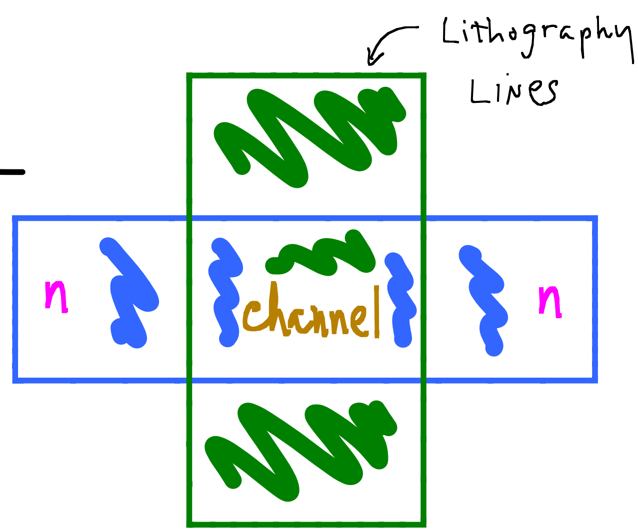


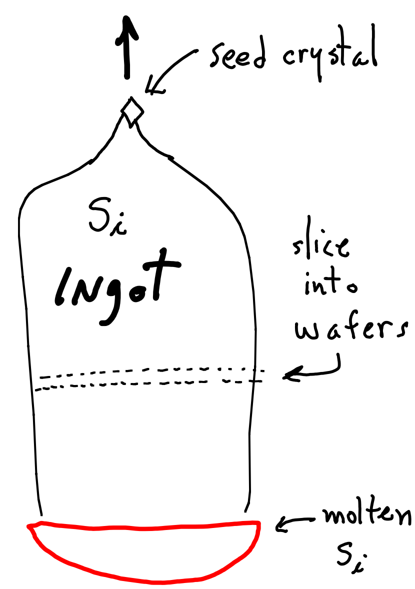
chip fab.



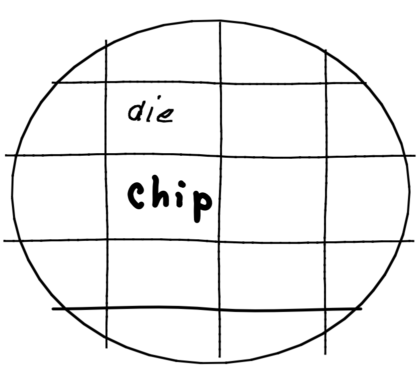


Line Sizes



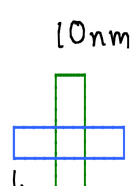


Wafer



Better Process
more expenisve equipment
+$

lines shrink

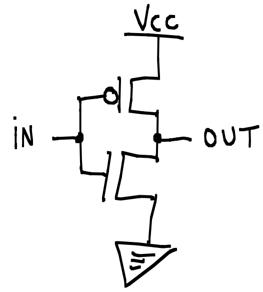


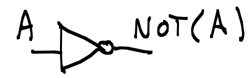
Faster switching
→ faster clock

more transistors
→ more function
→ more usage
→ more sales
→ same price

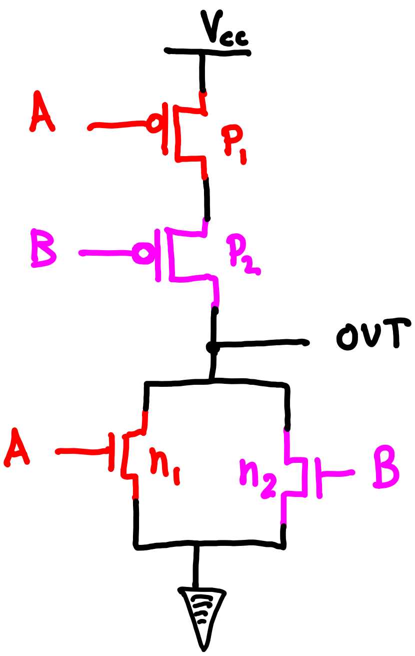
smaller features → More defects, lower die yield, but smaller die → Moore's Law

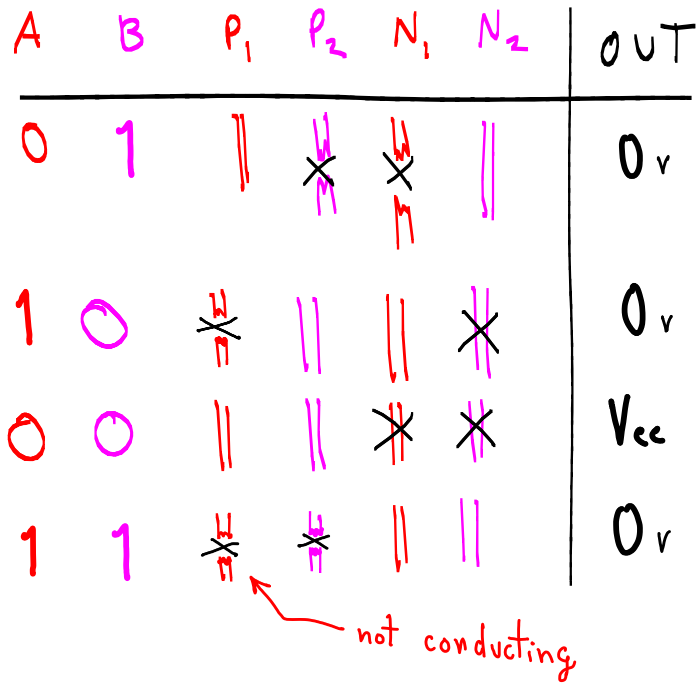
Basic Logic Gates





A	NOT(A)
0	1
1	0





NOT(OR)

A	B	out
0	0	1
0	1	0
1	0	0
1	1	0

NOR

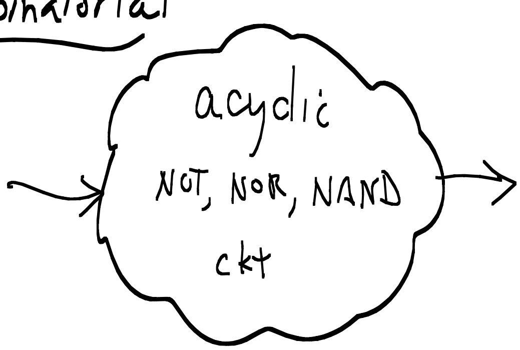
Logic CIRCUITS

Two kinds of logic circuits:
(1) w/ feedback, SEQUENTIAL: can hold STATE
(2) w/o feedback, COMBINATORIAL: realize FUNCTIONS

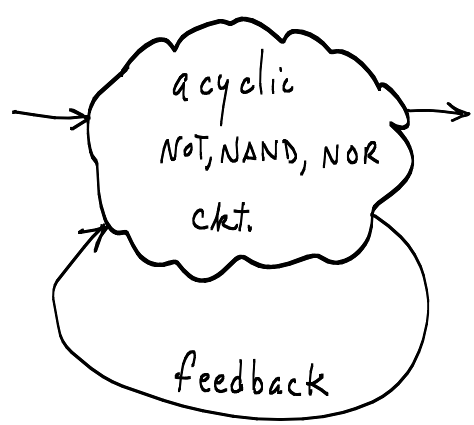
Basic logic gates: NOT, 2-input NOR, 2-input NAND.
That's all we need for both sequential and combinatorial circuits.

(NAND alone is sufficient, also NOR alone is sufficient.)

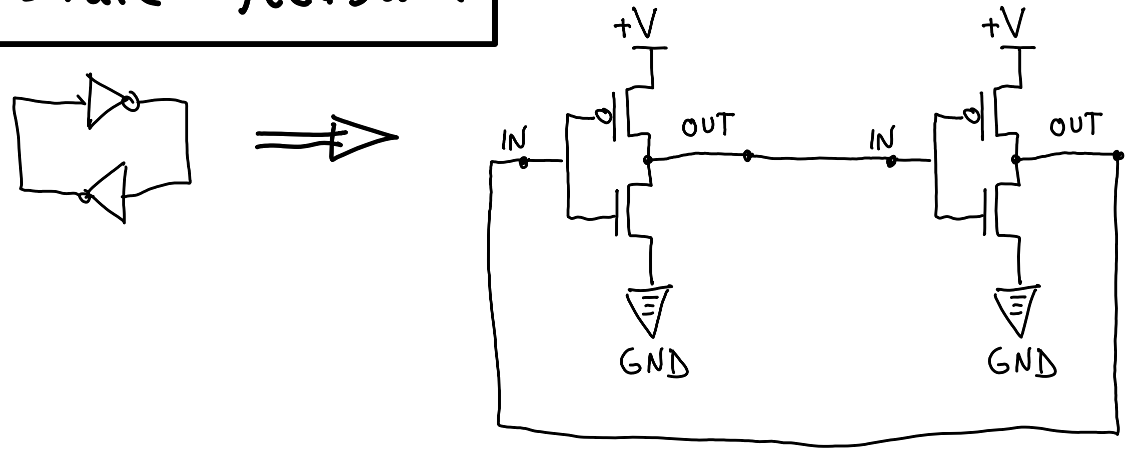
Combinatorial



Sequential

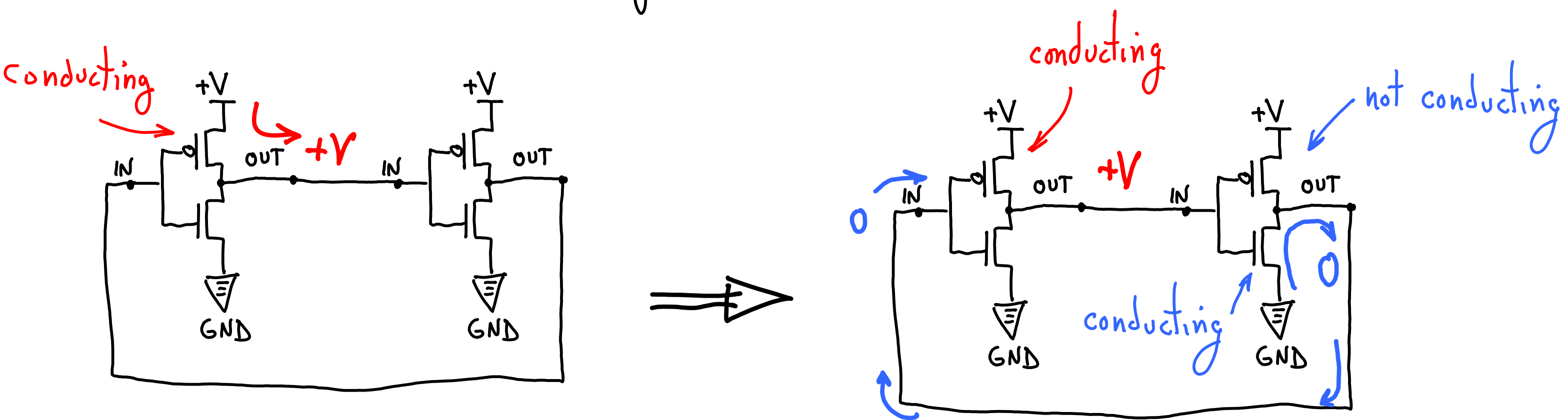


State feedback

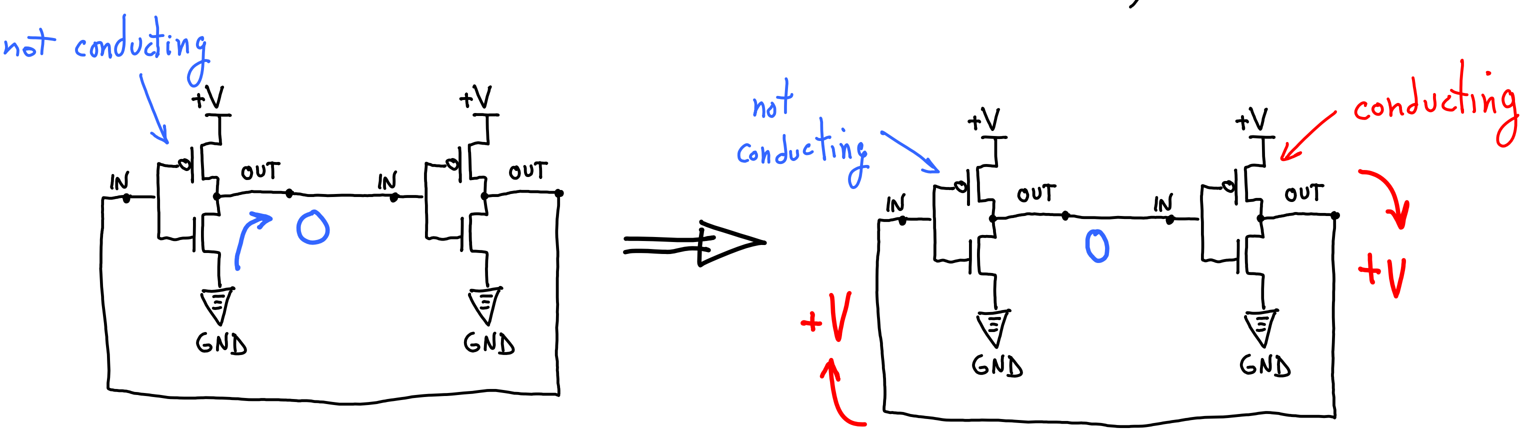


what are the voltages?

Assume state → see if consistent



Consistent, stable



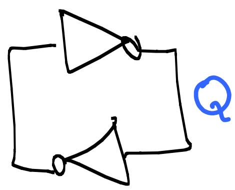
also, consistent, stable

Circuit has two stable states: aka, meta-stable, bi-stable.

What state when power is first turned on? Unknown, random.

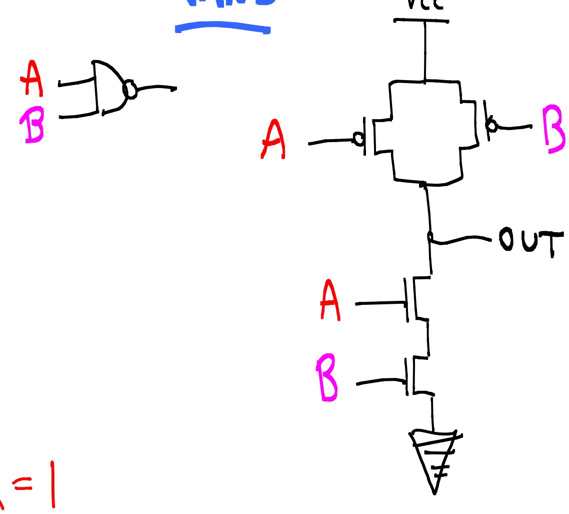
Can we set the state, using voltage inputs? No, useless!?!

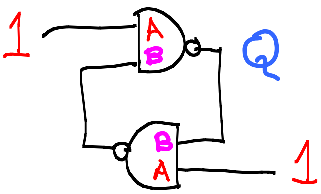
Basic Sequential elements



not-not loop stores data,
but we want control.

NAND



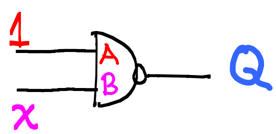


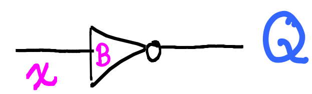
NAND

A	B	Q
0	0	1
0	1	1
1	0	1
1	1	0

A = 1

when A = 1 $\Rightarrow$ Q = NOT(B)

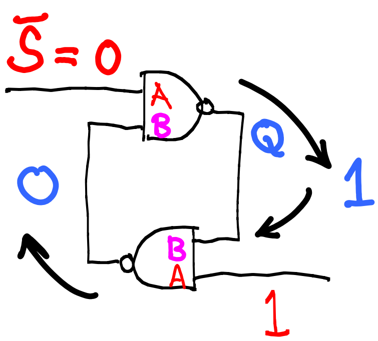




CIRCUITS W/ STATE

NOT-NOT circuit is stable in either of two states: BISTABLE element.

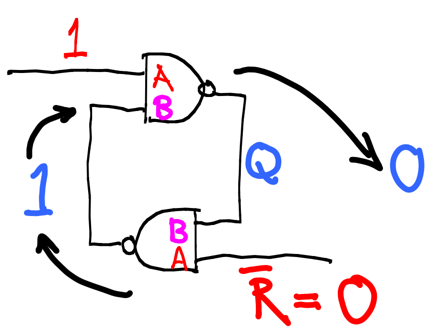
NAND-NAND circuit with both A inputs = 1,
same as a NOT-NOT circuit.



NAND

A	B	Q
0	0	1
0	1	1
1	0	1
1	1	0

A = 0 $\Rightarrow$ Q = 1



$\bar{S}$	$\bar{R}$	
1	1	stable
0	1	set Q = 1
1	0	reset Q = 0