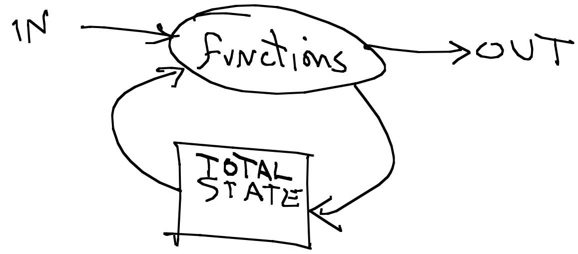
FSM implementation



need to build

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

Any technology will do!

mechanical: Babbage, etc.

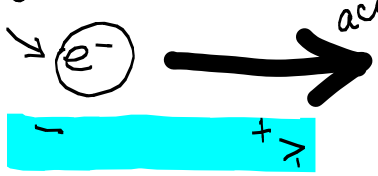
electro-mechanical ← we start here

electronic

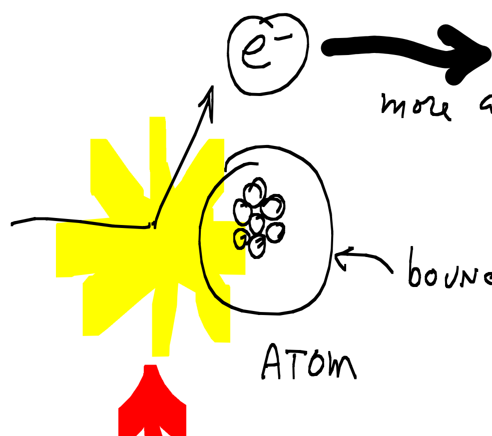
?

Electrons and heat

free electrons

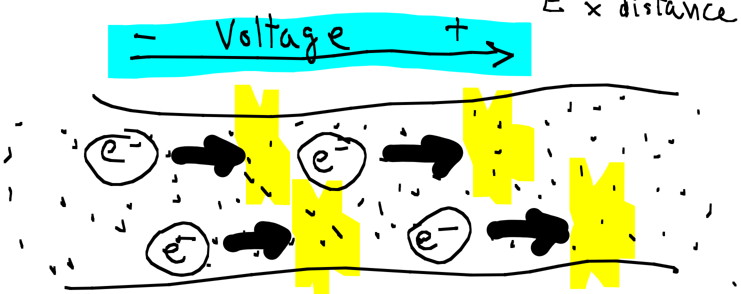


Elec. field ≈ gravity



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

E × distance = Voltage



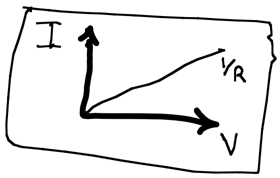
High current = Lots of moving e⁻

High voltage = Lots of acceleration

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

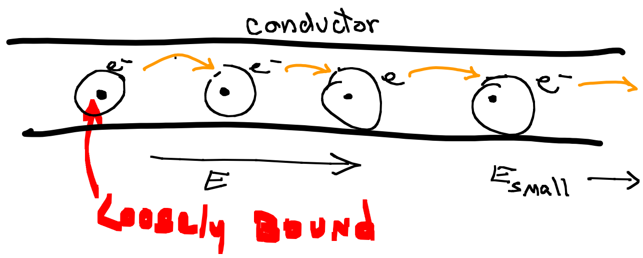
Ohm's Law, conductors, ...

$R \overset{def.}{=} V/I$

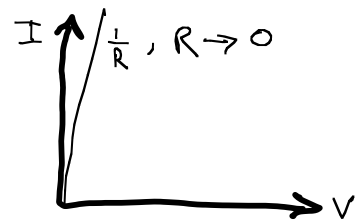


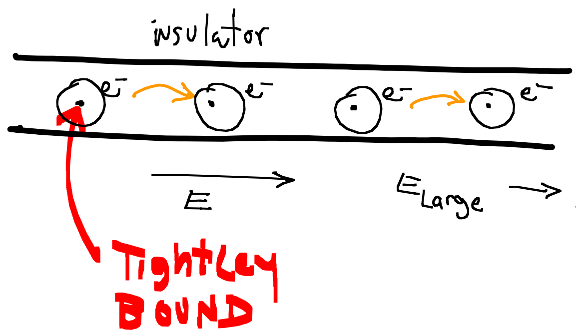
$\Rightarrow I = \left(\frac{1}{R}\right)V \qquad \Rightarrow V = IR$

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

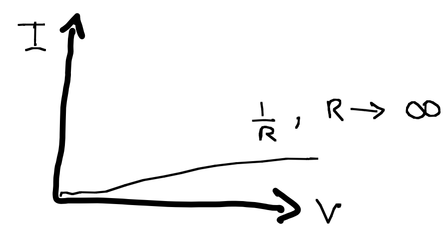


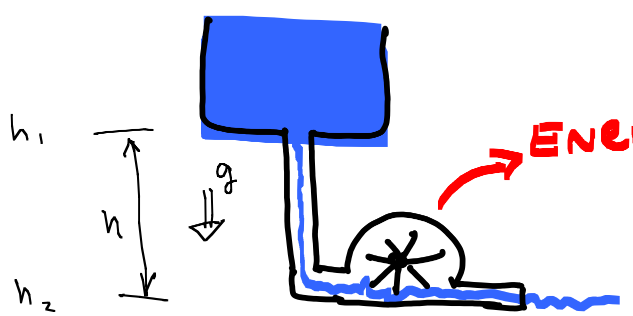
$E_{small} \longrightarrow$ Lots of e^- moving





$E_{Large} \longrightarrow$ Few e^- moving





Energy/sec = Power

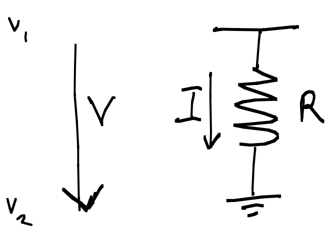
Big Pipe $\Rightarrow$ Lots of Flow : $(R\downarrow)$

Small Pipe $\Rightarrow$ Little Flow : $(R\uparrow)$

$V \sim h \cdot g$ Power $=$ Flow $(h \cdot g)$

$V = E \times$ distance

$\sim$ Tower height $\times$ 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 $= I\,V$

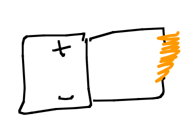
Energy over distance per e^-

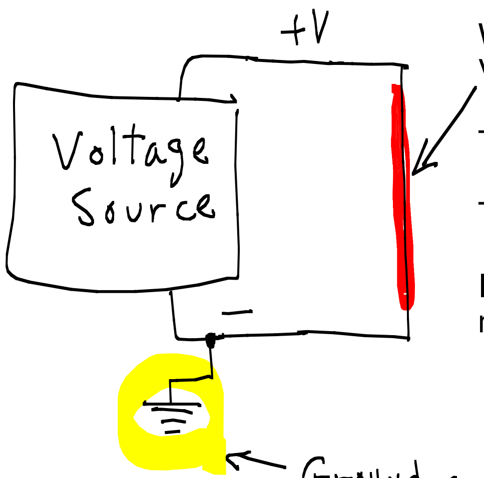
#e^- per second

$R \to 0$ 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





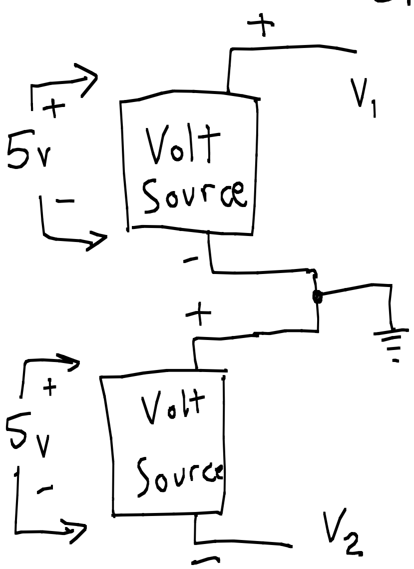
What if this is wire, ie., R is nearly 0?
Voltage source holds constant V voltage difference.

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

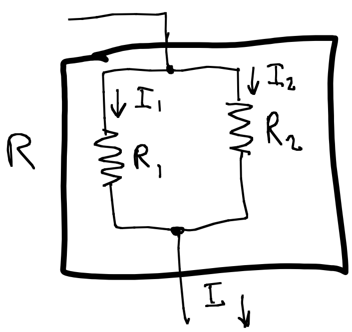


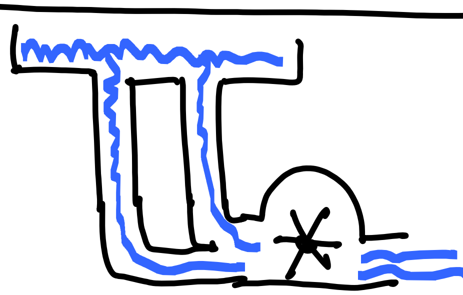
Measure voltage difference from voltage point at GROUND.

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.

i = i1 + i2

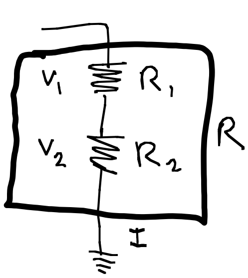
If R1 = R2 Then i1 = V/R1 = i2

i = i1 + i2 = 2*V/R1

What is total R?

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

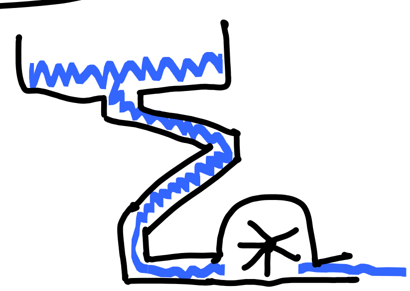
V



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.

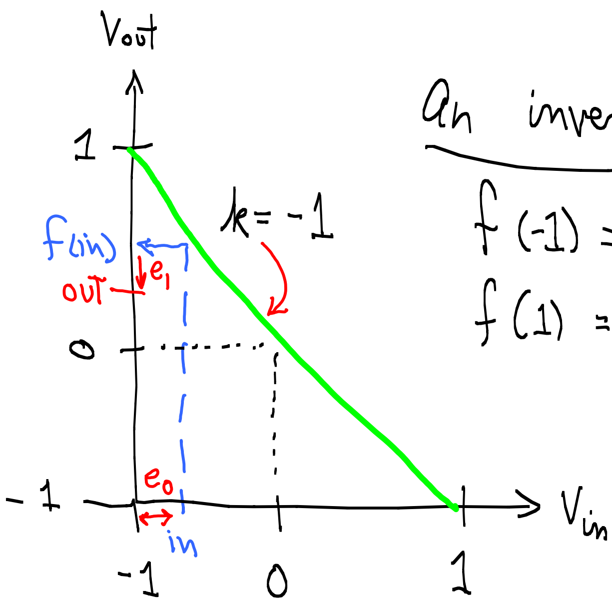
Suppose we had only linear devices (or something very nearly linear), then signal output has errors proportional to input errors.

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— $= f_2(f_1(in))$

$f_1 \quad f_2$

(v is nominal signal: ± 1)

$$\begin{aligned} f_1(in) = f_1(v+e) &= kv + ke_0 + e_1 \\ &= (-1)(-1) + (-1)e_0 + e_1 \\ &= 1 - e_0 + e_1 \end{aligned}$$

$$\begin{aligned} f_2(f_1(in)) &= f_2(1 - e_0 + e_1) \\ &= -1 + e_0 - e_1 + e_2 \end{aligned}$$

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

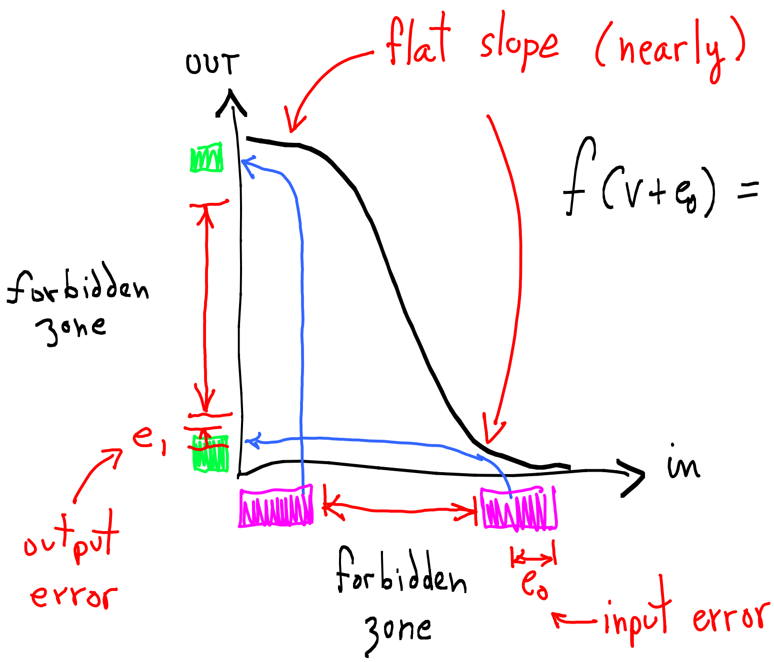
The errors include signs = random walk with random size steps.

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.

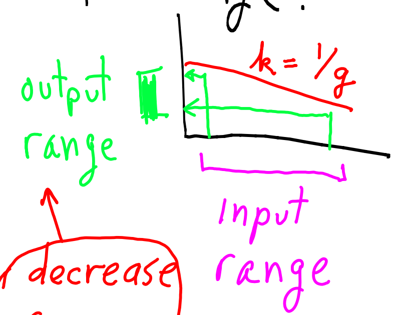
We must Reduce error at each stage ==> exponentially decreasing effect in later stages.

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

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

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

and

if output error size is not too big,

Then

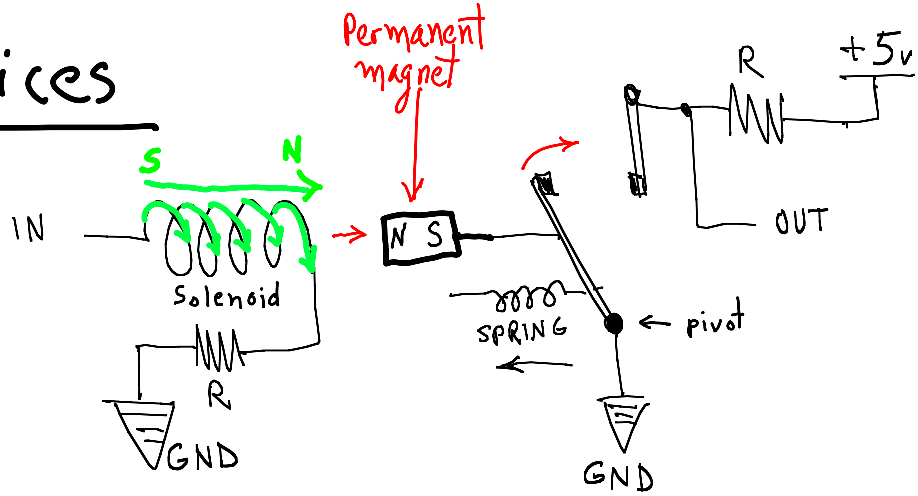
output after k stages never hits FORBIDDEN ZONE.

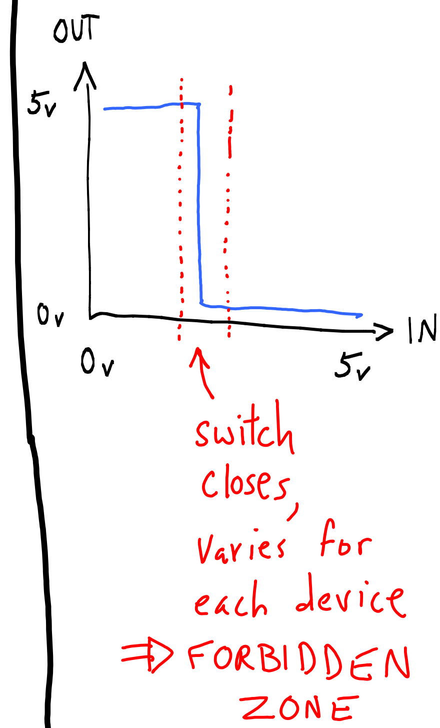
So, if we plan to have a circuit with long device chains, we must
have non-linear devices w/ suitable response curves.

Do we plan to have long chains? YES:

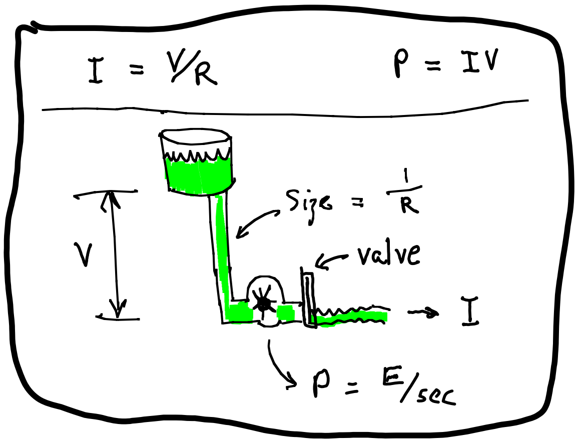
(1) feedback in system,
(2) chained data operations: D1 ==> D2 ==> D3 ==> D4 ...
(3) 1 Billion devices per cpu

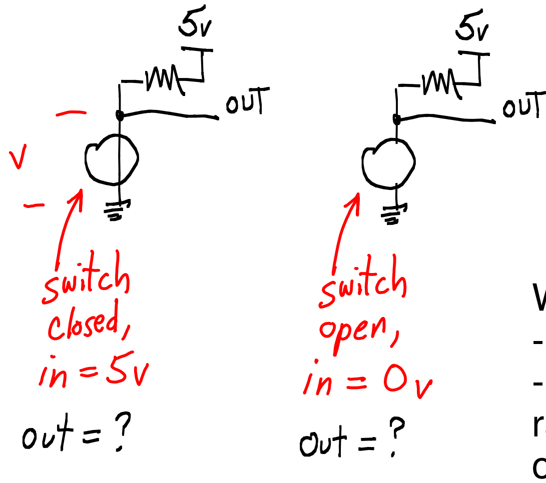
Devices





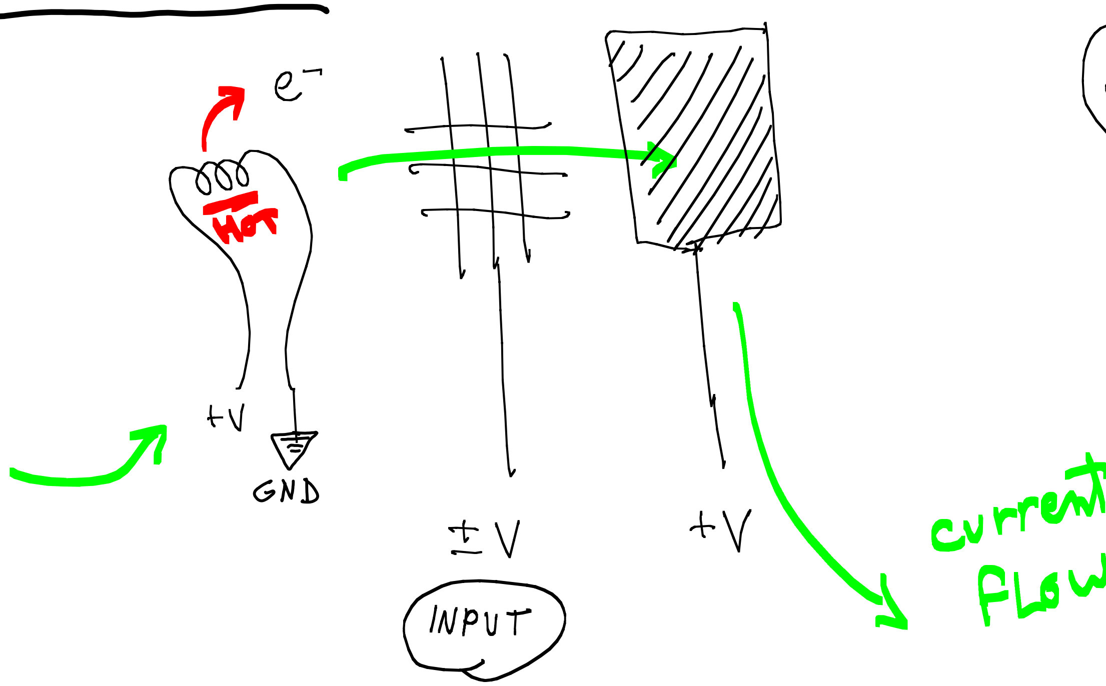
$V = IR$

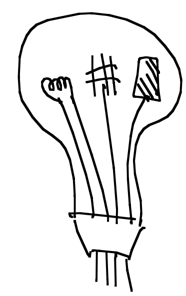




What is the function?
--- non-linear response
--- any voltage in allowed range will yield "clean" output. Easy to prevent input voltages in forbidden zone.

Electronic Switches: Vacuum Tubes



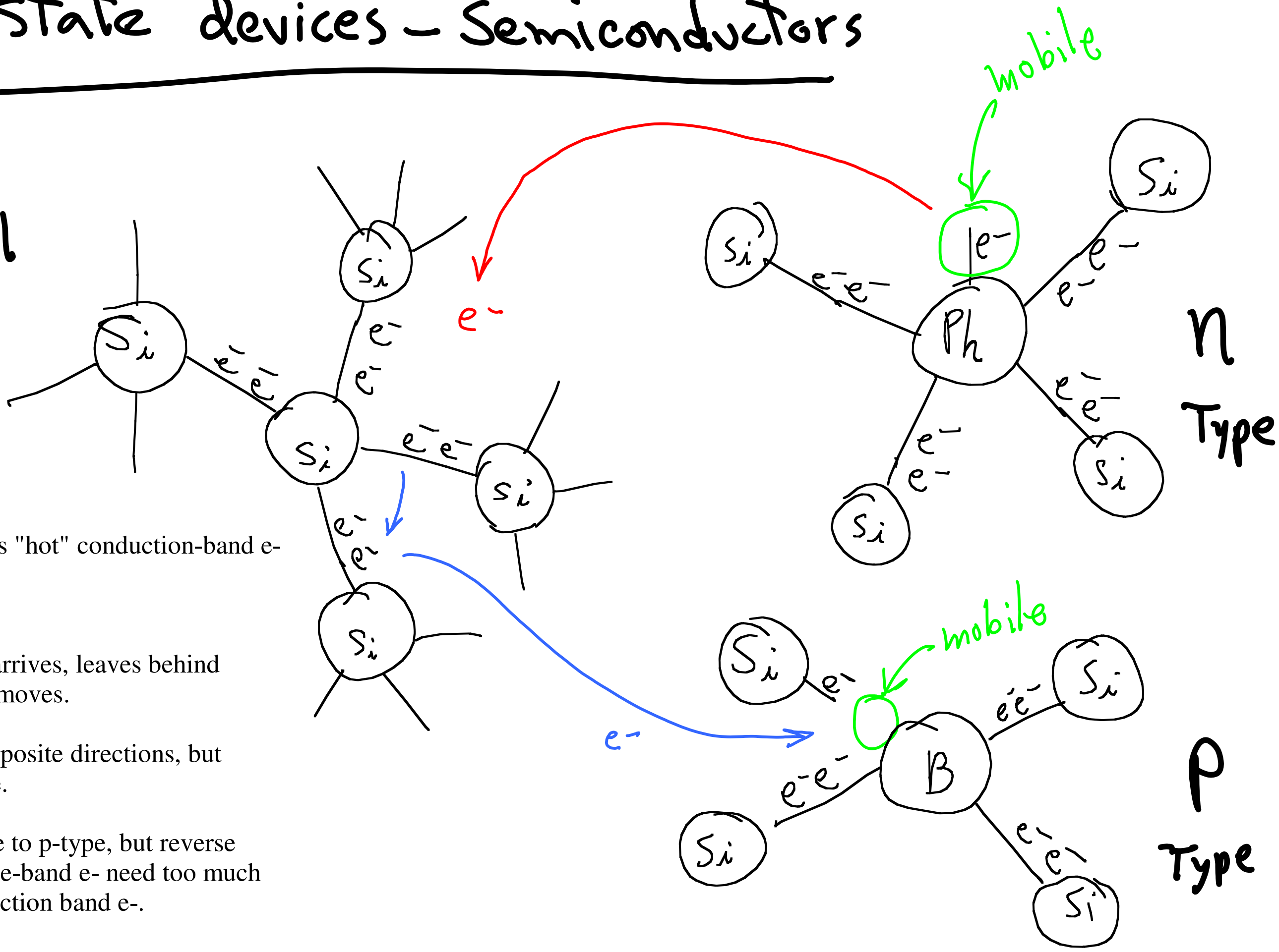


Faster, more reliable, less power

⇒ Voltage Controlled Switch

Solid State devices – Semiconductors

Silicon Crystal



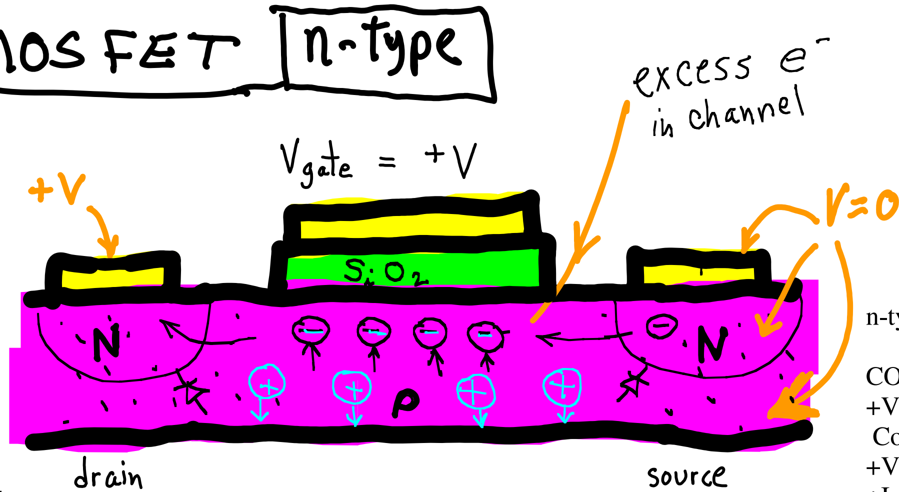
Phosphorous impurity:
e- leaves easily, becomes "hot" conduction-band e-
.

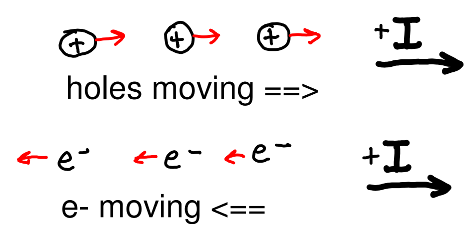
Boron impurity:
"cold" valence-band e- arrives, leaves behind +valence "hole" which moves.

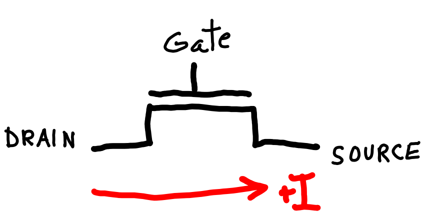
Holes and e- move in opposite directions, but current direction is same.

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







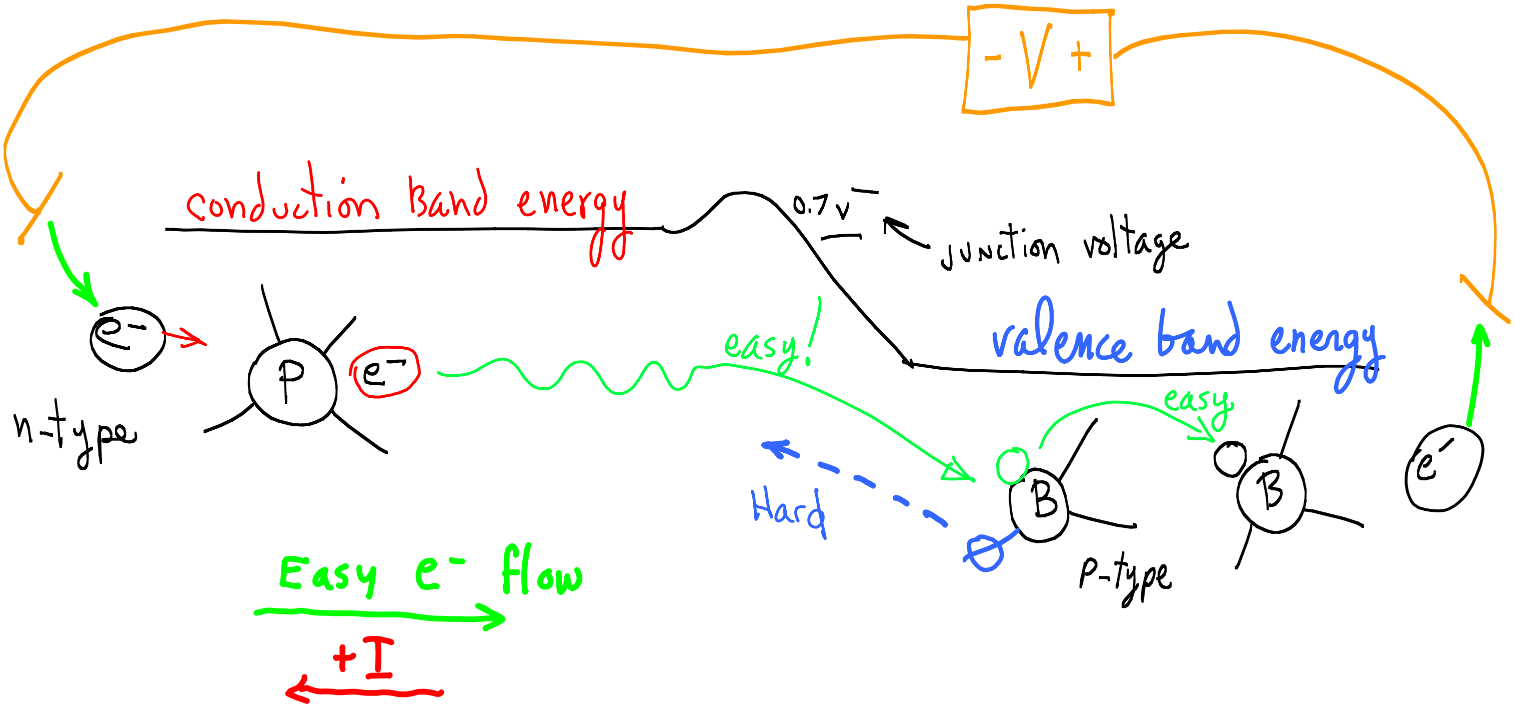
n-type MOSFET (n-transistor)

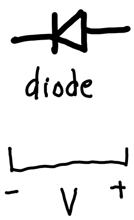
CONDUCTING (Vgate = +V, R-drain-to-source ~= 0):
+V on gate drives holes away from P-type channel.
Conduction-band e- move from source N-type well.
+V on drain pulls conduction-band e- off.
+I current flows left-to-right.

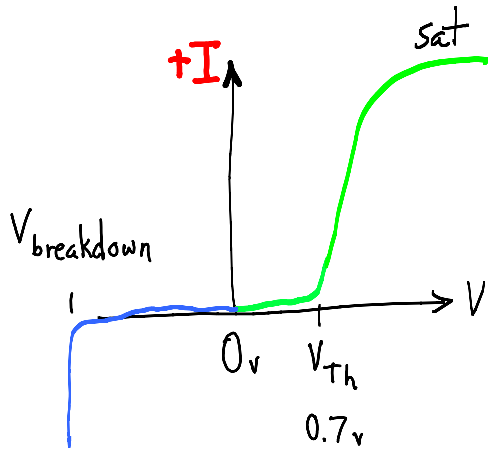
NOT-CONDUCTING (Vgate = 0, R-drain-source = BIG)
Vgate = 0, holes populate channel.
Source N-well e- drop into valence band in channel.
+V at drain cannot pull valence-band e- from P-type to N-type.

n-type transistor

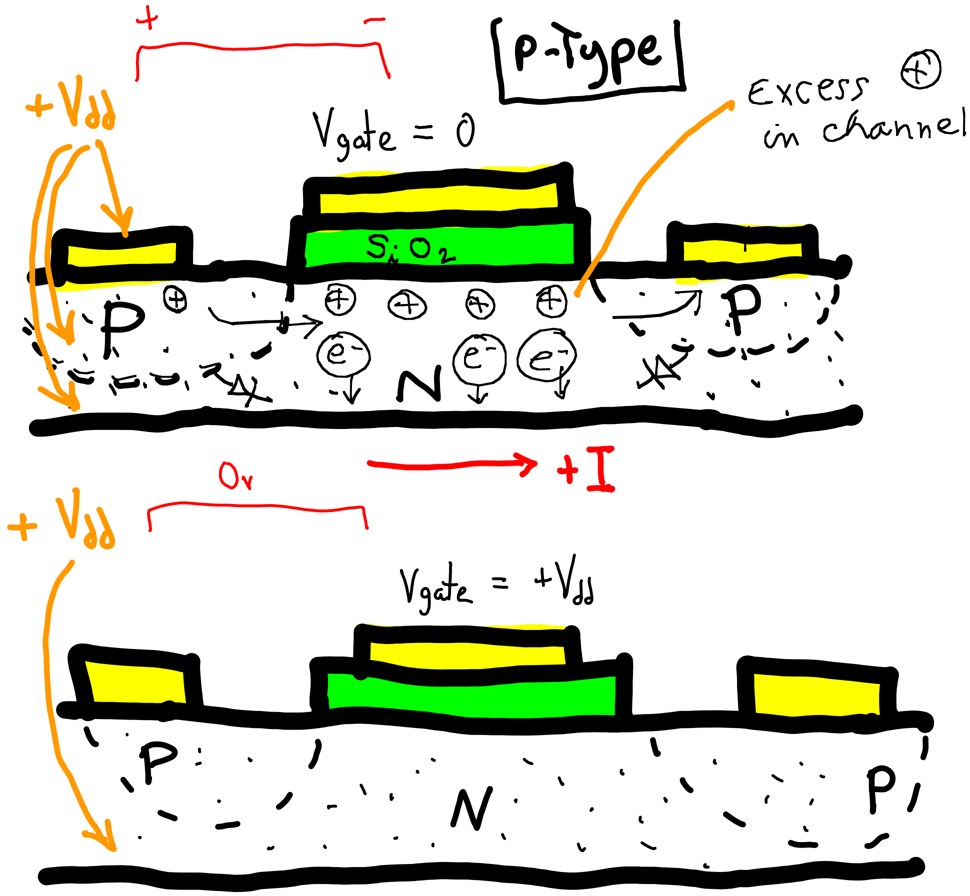
Vgate	Rdrain-source	
0	∞	not conducting
+V	0	conducting







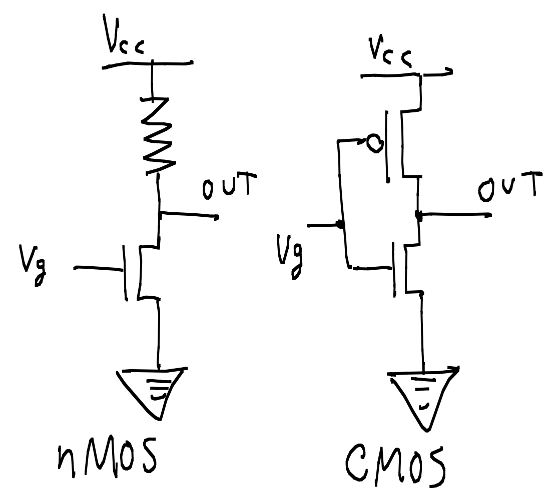
Just what we want: nice non-linear switch.



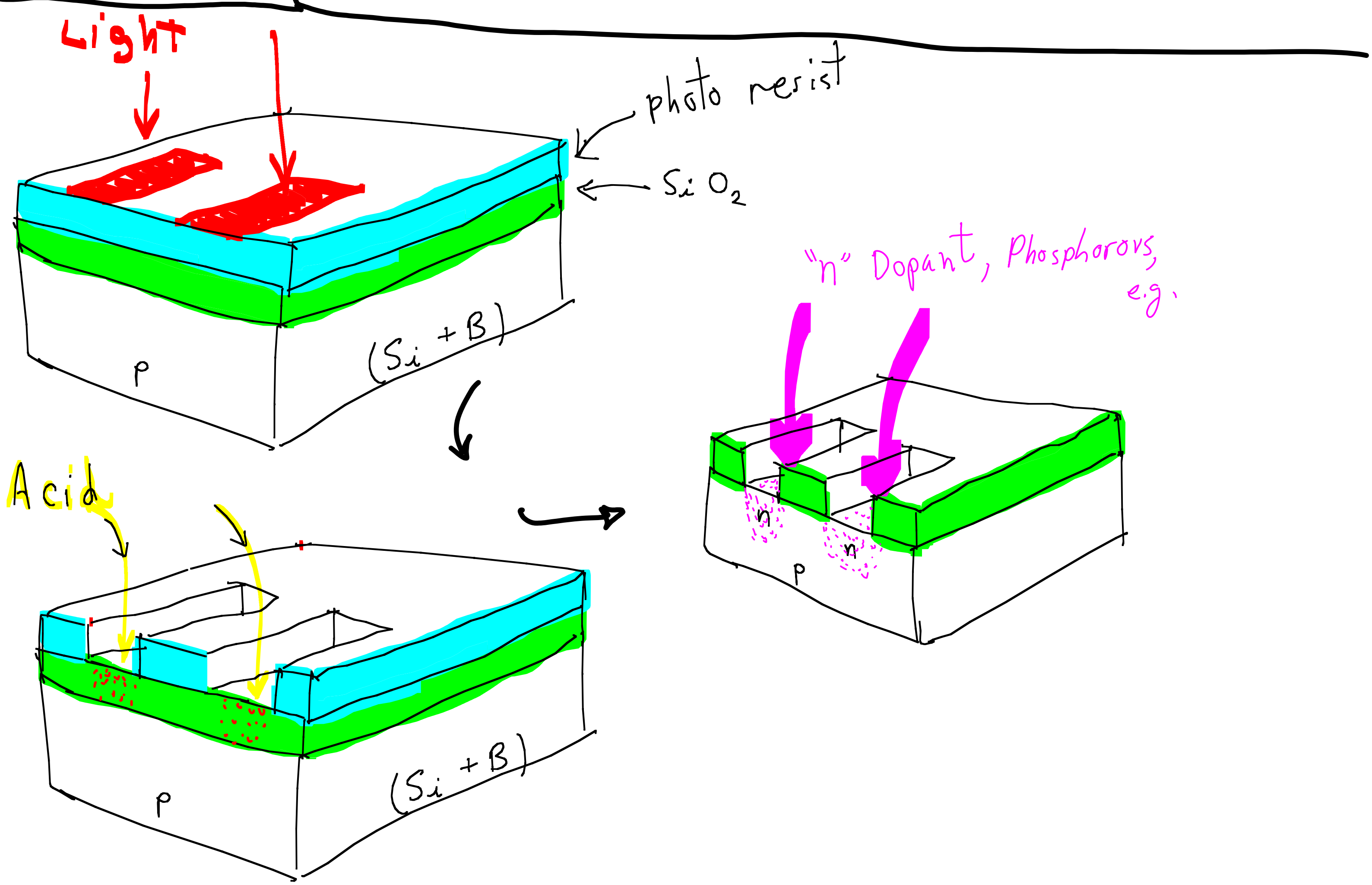
P-type (n-channel) transistor

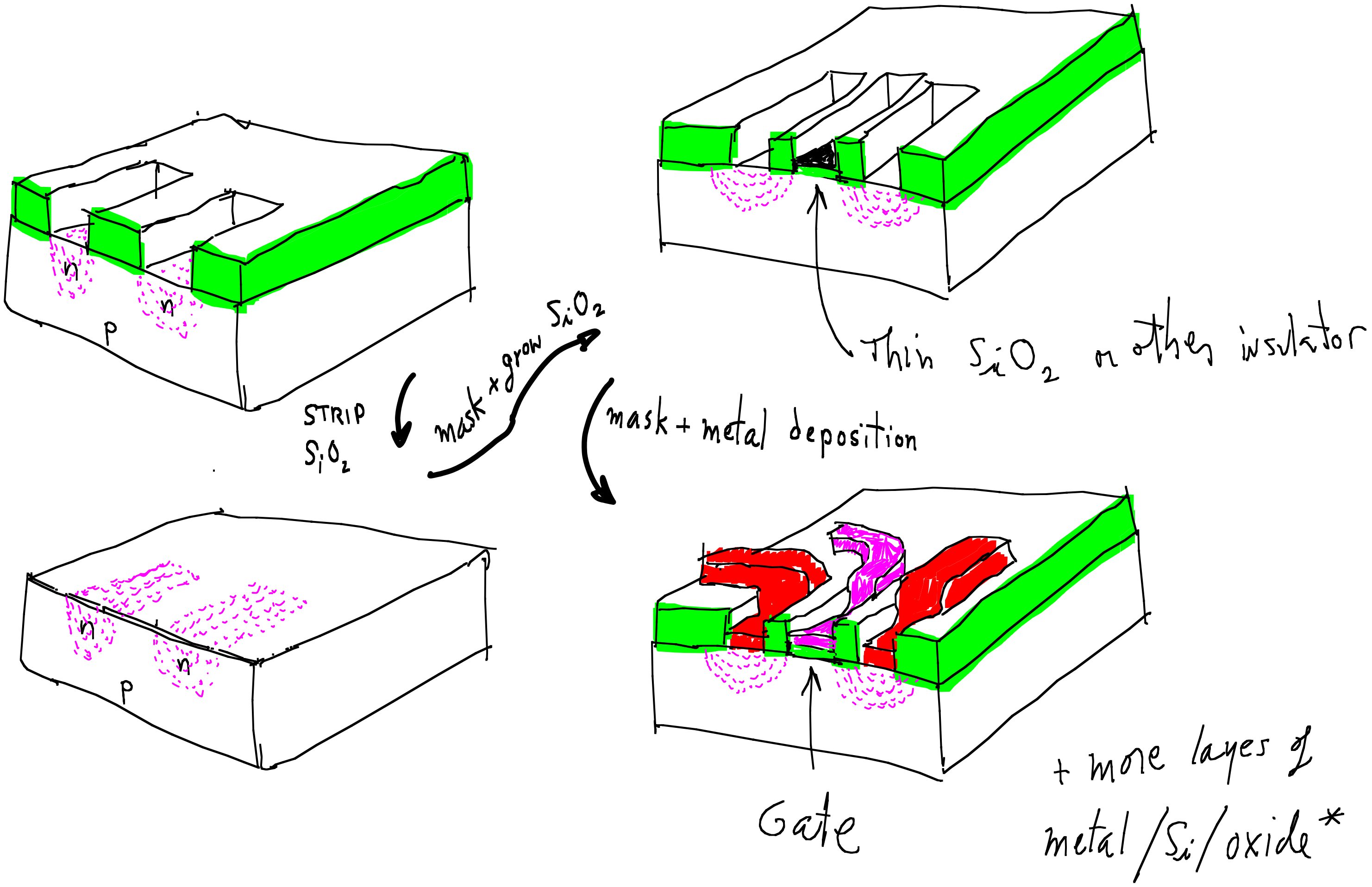
Vgate = 0:
Vgate = -Vdd wrt to base,
pushes e- away from channel, leaves excess holes, current flows.
R = 0, conducting.

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

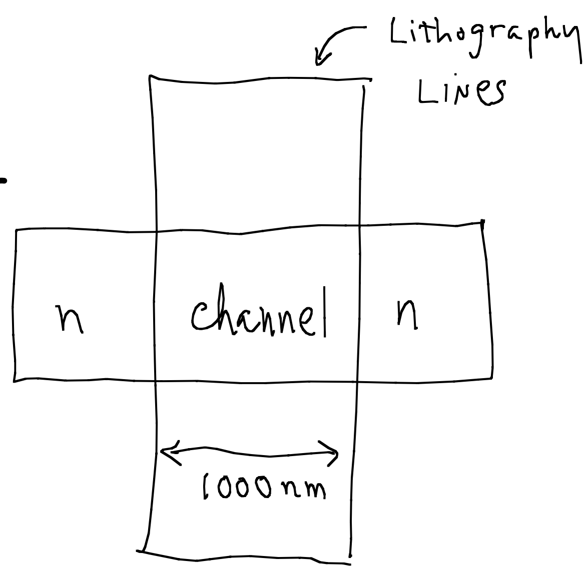


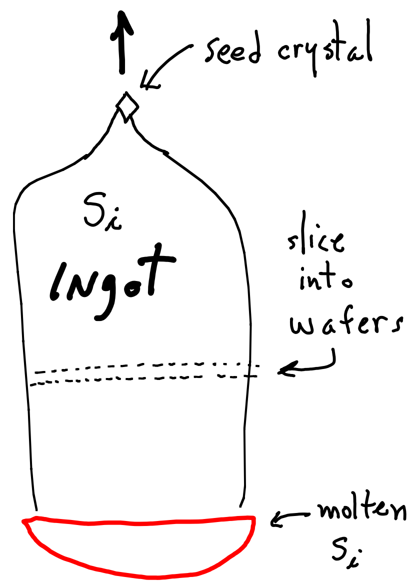
chip fab.



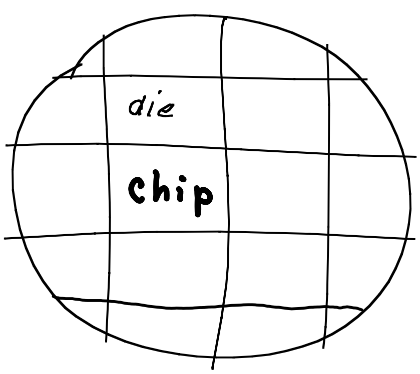


Line Sizes



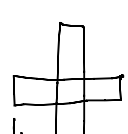


wafer



Better Process
more expenisve equipment
+$

lines shrink

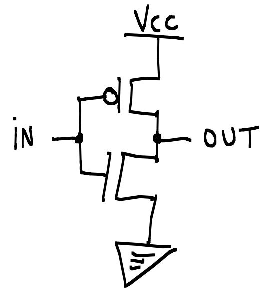


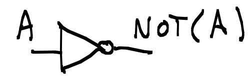
faster switching
→ faster clock

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

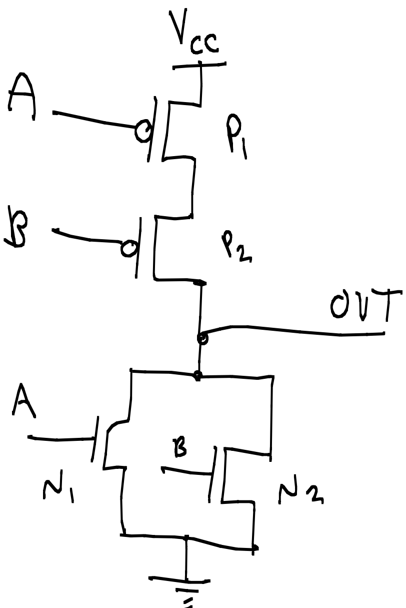
smaller features → More defects, lower die yield, but smaller die → Moore's Law

Basic Logic Gates





A	NOT(A)
0	1
1	0



A	B	P_1	P_2	N_1	N_2	OUT
0	1	||	X	X	||	0V
1	0	X	||	||	X	0V
0	0	||	||	X	X	Vcc
1	1	X	X	||	||	0V

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

NOT(OR)

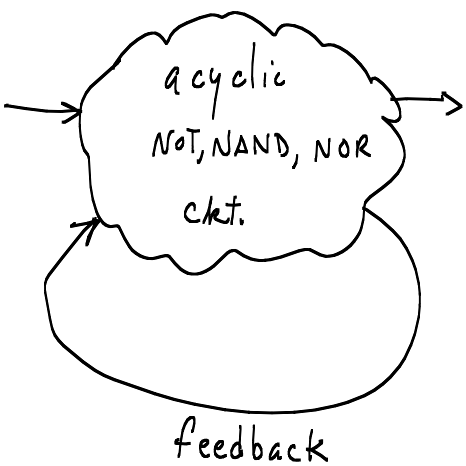
NOR

Logic CIRCUITS

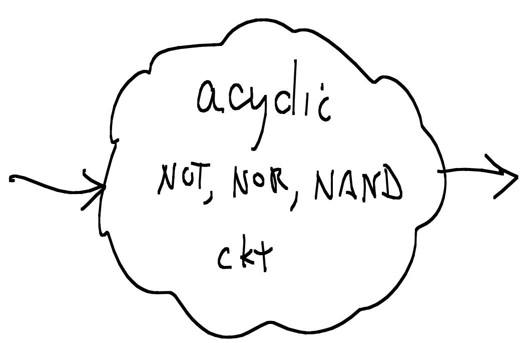
Two kinds of logic circuits:
(1) w/ feedback, SEQUENTIAL: can hold STATE
(2) w/o feedback, COMBINATORIAL: realize FUNCTIONS

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.)

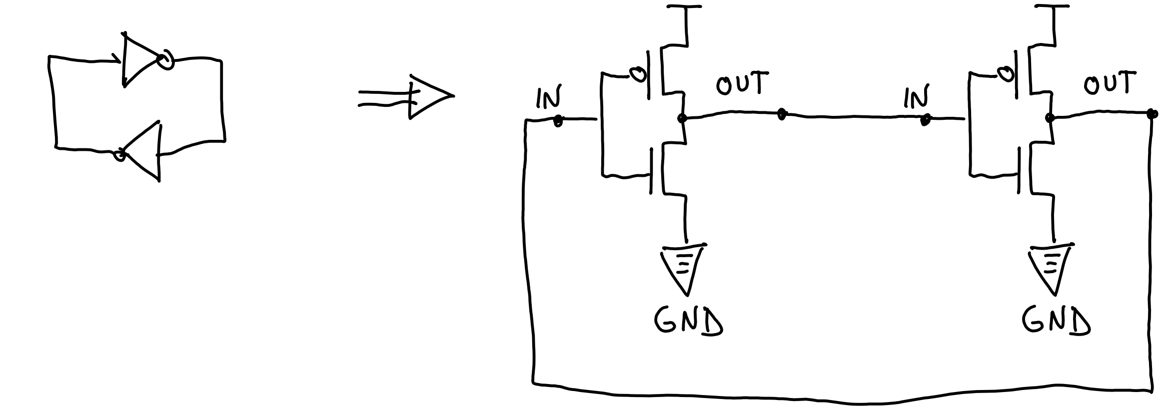


Sequential



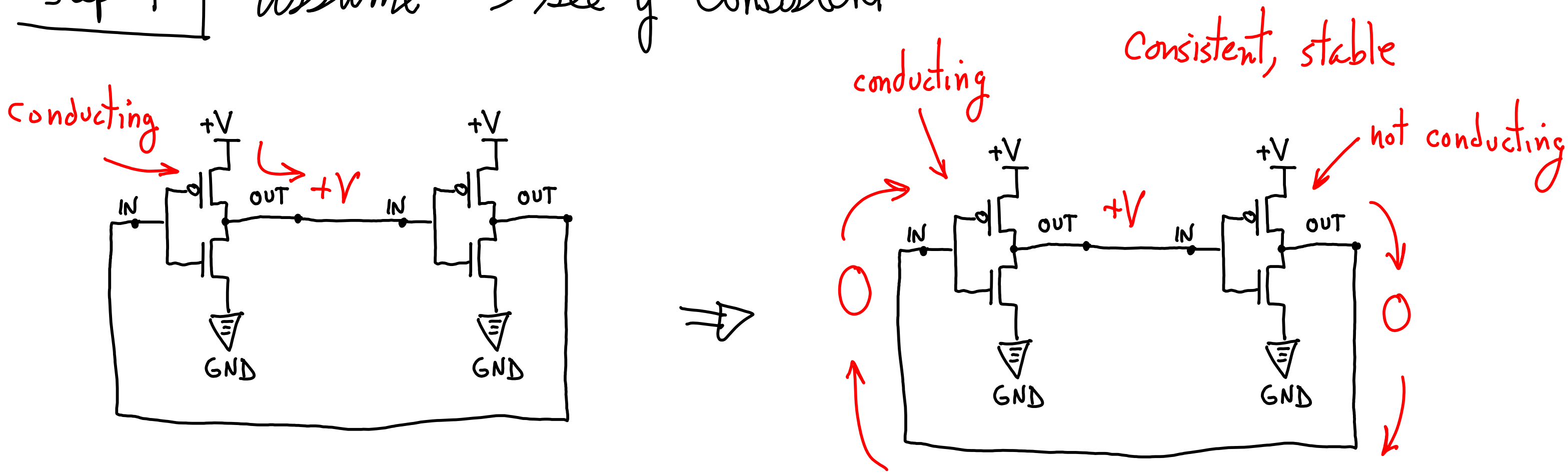
Combinatorial

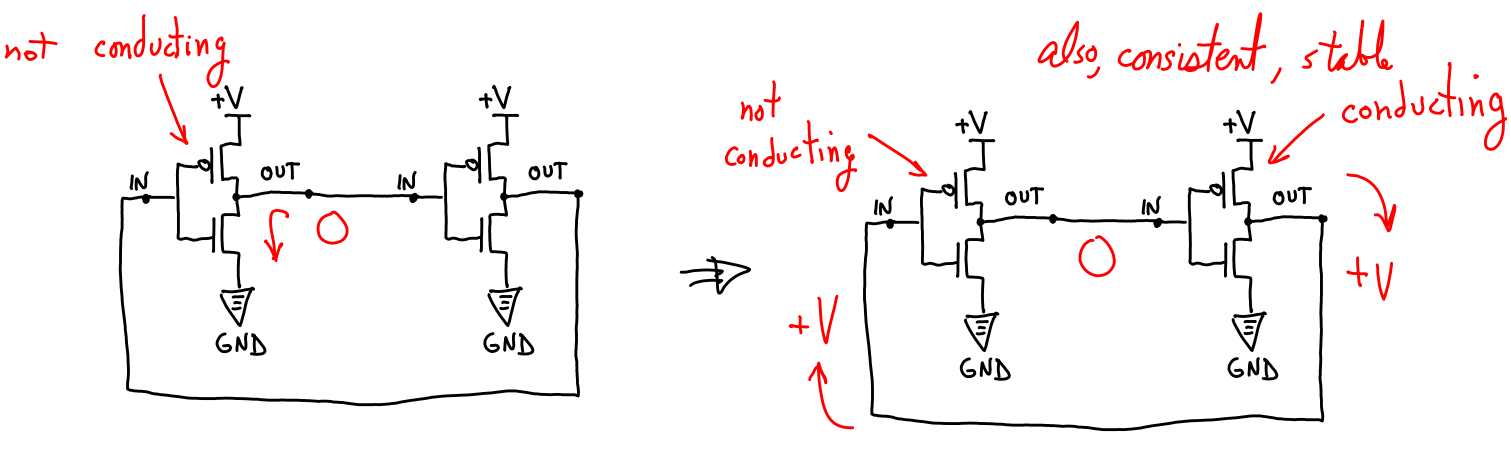
State] feedback



what are the voltages?

Step 1] Assume → see if consistent



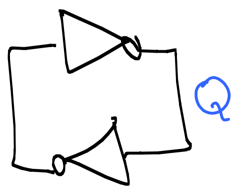


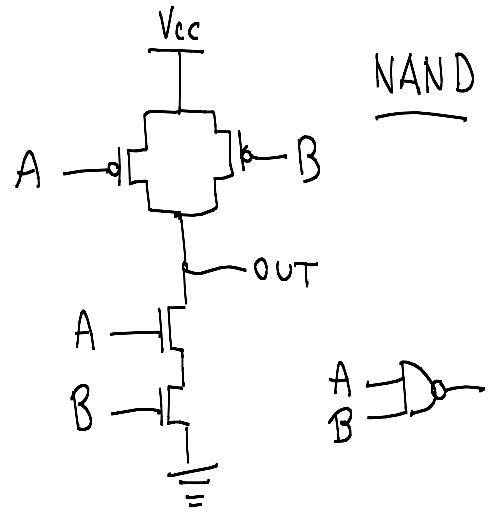
Circuit has two stable states: aka, meta-stable, bi-stable.

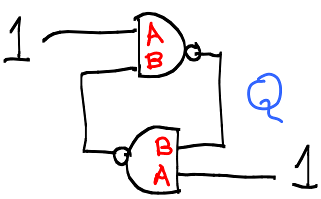
What state when power is first turned on? Unknown, random.

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

Basic Sequential elements





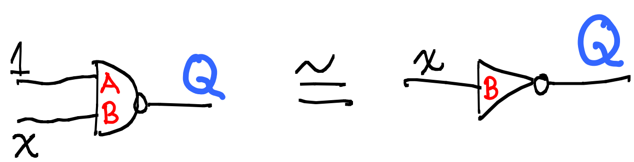


NAND

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

A = 1

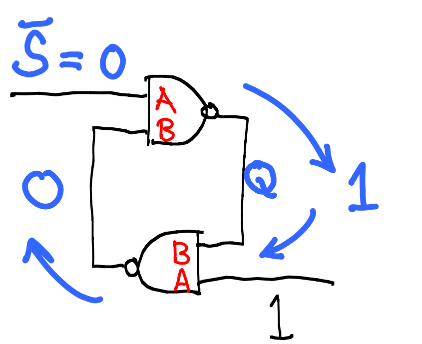
when $A = 1$, $Q = \text{NOT}(B)$



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.

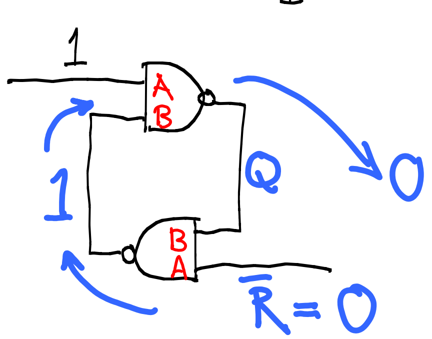


NAND

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

A = 0

$\Rightarrow Q = 1$



$\bar{R} = \bar{S} = 1$: stable

$\bar{R} = 1, \bar{S} = 0$: set $Q = 1$

$\bar{R} = 0, \bar{S} = 1$: reset $Q = 0$