12 inches

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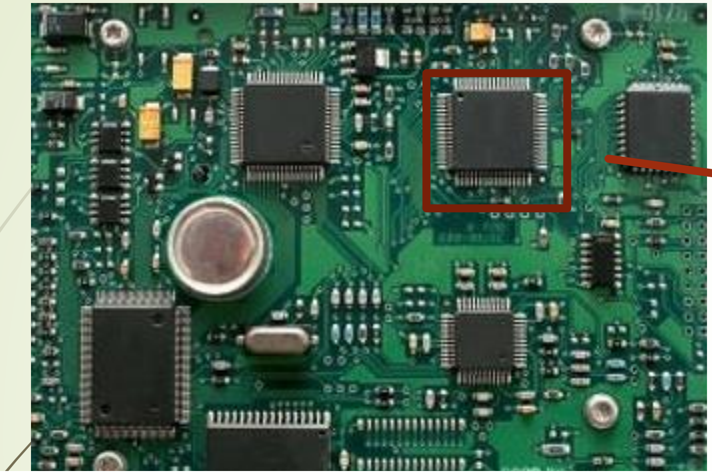
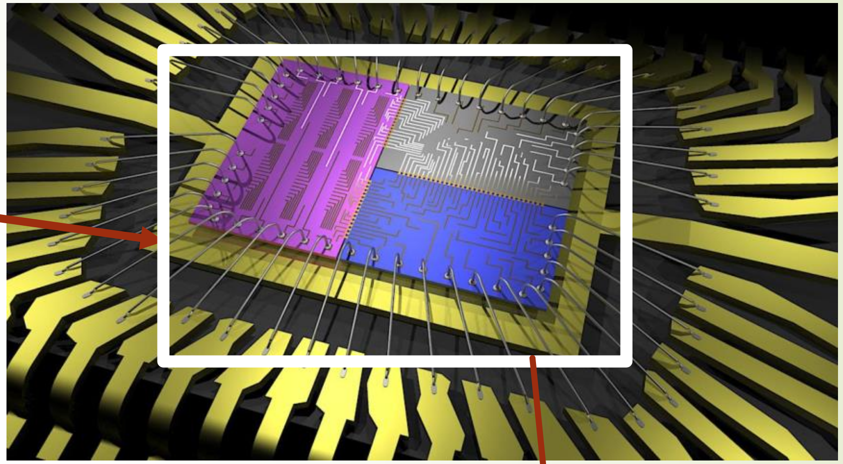
What are we going to do today?

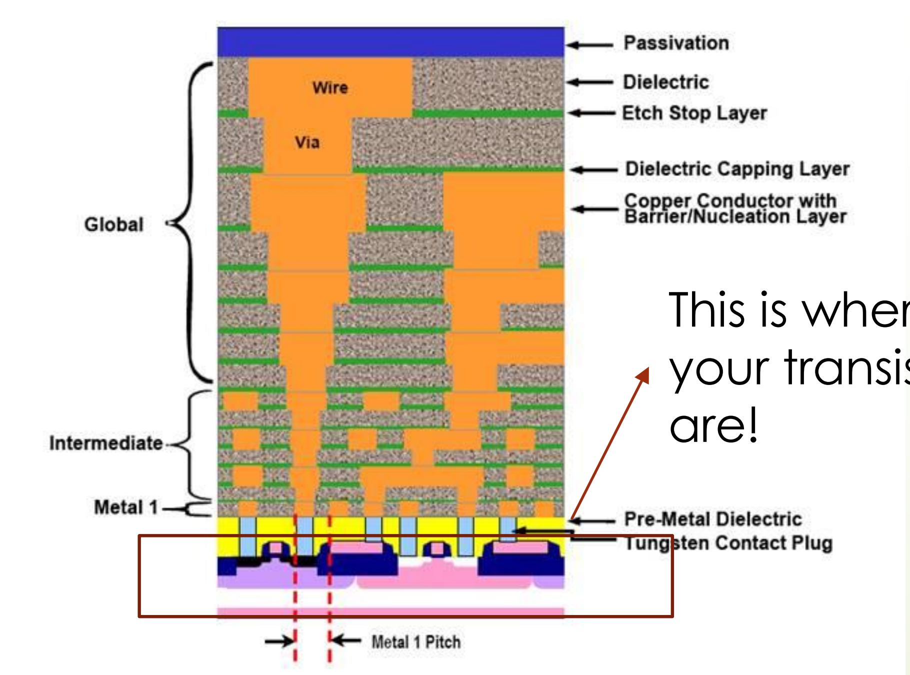
- Integrated circuits industry as it stands today.
- A lot about analog circuits and how to look at them intuitively
  - Well, I will only touch the tip of the top most molecule of the ice-berg
- Circuit simulators and how to use them:
  - We will use something called CoolSpice.
- I will give you a long list of references that you can look up
- Some of you wanted to discuss about the activities of Science Club today, so well do that.

But before that what does the little black things inside your phone look like?

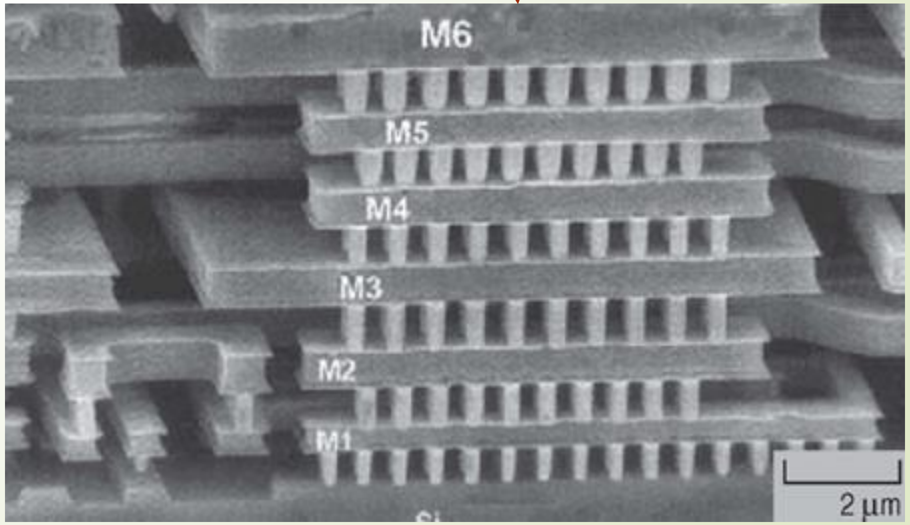
How does it look inside?

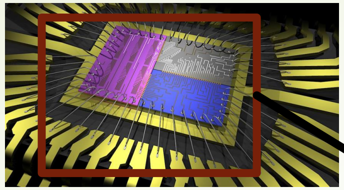


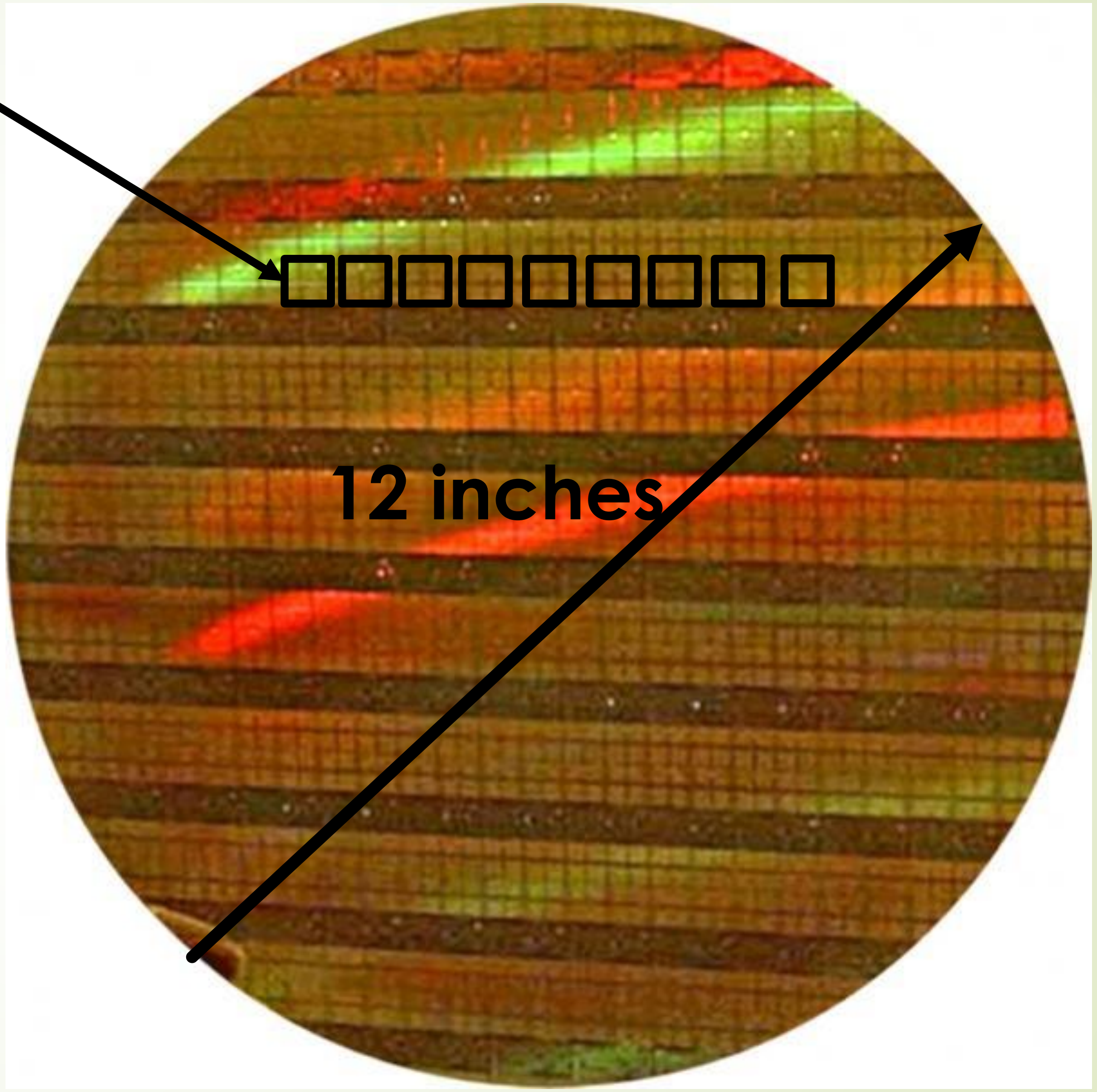




This is where your transistor are!







The figure alongside shows a typical 12 inch silicon wafer from TSMC's 28nm process.

Your phone, the pacemaker, the projector, the electronics monitoring and preventing a nuclear meltdown, the missiles which are pointed towards China and Pakistan, the servers on which Facebook.com is hosted, mainframes trying to predict monsoon.. All of them runs because this thing alongside exists.

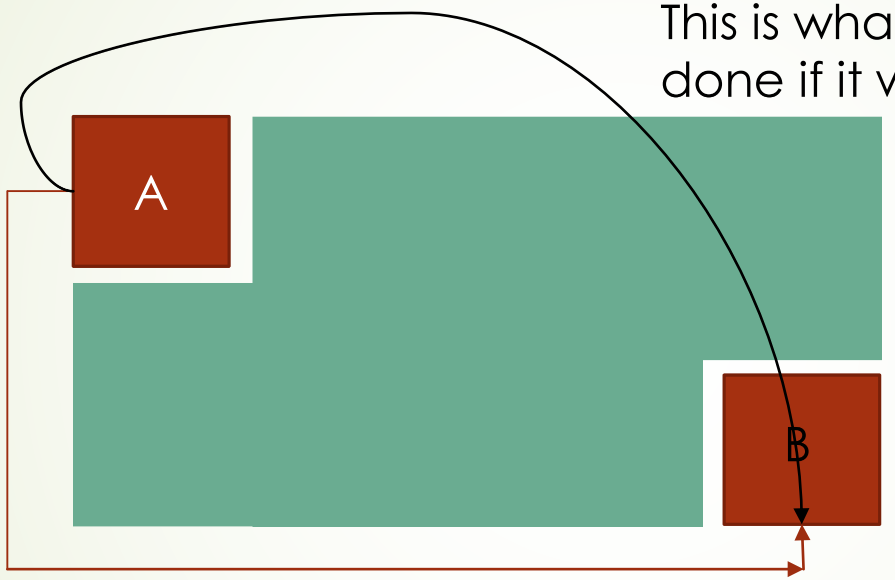
If today you were to just wipe this thing off the face of earth, we will stop having all of the above.

Imagine that.

More info: https://en.wikipedia.org/wiki/Wafer_(electronics)

But why does it really require all of these metal layers?

This is what you would have done if it was your PCB!



This is a really long metal line!

And we extrapolate this idea to an IC as well.
Instead of going in a twisted sense, you are constrained to go up, left, right or down.
[sometimes you can get 45 degrees as well (in on-chip inductors)]

Opportunities in the integrated circuit design

- Analog integrated circuit design ($$$)
  - Data converters
  - Bio medical circuits
  - Power converters
  - RF
  - Wireline communication Circuits
  - Silicon Photonics
- Digital integrated circuit design
  - Processors and computing cores ($$$)
  - Digital logic that actually controls the analog
- Mixed signal design
  - Its not really a separate field, its just that we use a lot of digital to control the analog, and analog relies upon digital.
  - The keyword is ‘CALIBRATION’

Silicon Photonics- a sneak peak

Why?

Because its fascinating

This is what a datacenter looks like today. The person as you can see needs a bicycle to cross go from one end of the data center to the other.

And these yellow racks on top? These carry all ethernet links that moves around the data from one server to the next.

Silicon photonics can shrink 10 of these cables into a single thin optical fiber! And that's assuming they are 10Gbps link each.

Imagine this: The entire Game of Thrones TV series can be transferred in 8 SECONDS flat.

Why do we need silicon photonics?

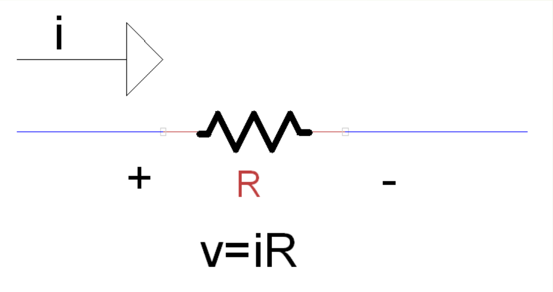
- We are generating enormous amounts of data.
  - Storage is no longer the issue.
  - Transferring is the issue
- Silicon photonics refers to the technology whereby the optics parts can be integrated directly into the silicon substrate.
  - You can leverage all the developments in CMOS.
  - Reduces the size of the PCB
  - Way higher transfer speeds.
- Example: Your processor talks to your high end GPUs. And they talk via something called PCIe lanes. Right now, with copper PCB traces, PCIe can support a maximum of 16Gbps [I worked on PCIe 2.5Gbps and 5Gbps links].
- With silicon photonics, you can imagine the speed.
- At the two ends of silicon photonics are optical devices.
  - But it's the analog circuit that drives the optical devices.
  - And when the data comes in, it's the analog circuit that conditions and tells the digital whether it's a zero or a one.

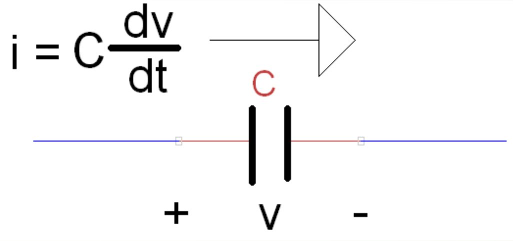
Its an analog world!!

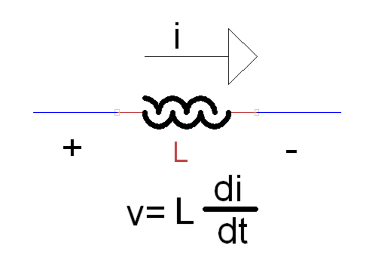
Lets delve into circuits and systems!!

The ABC(D)s of an analog world

- Resistors
  - v=iR
- Capacitors
  - q=Cv
  - $i = C\frac{dv}{dt}$
- Inductor
  - v= $L\frac{di}{dt}$
- And now, memristors



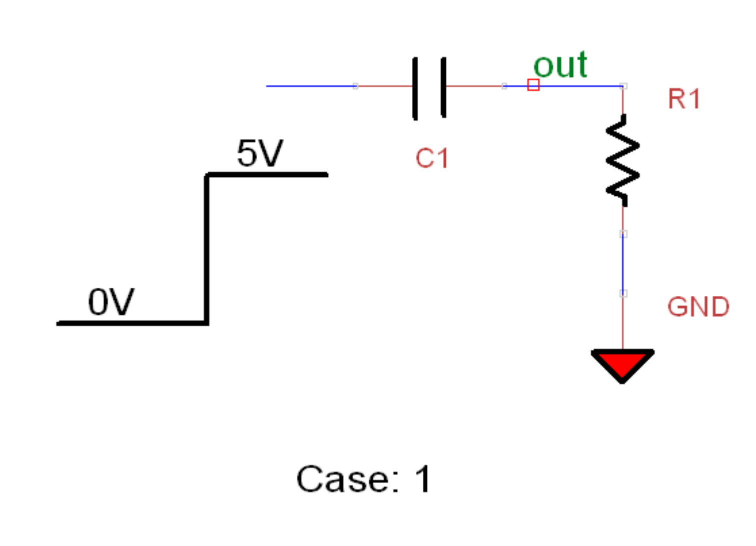


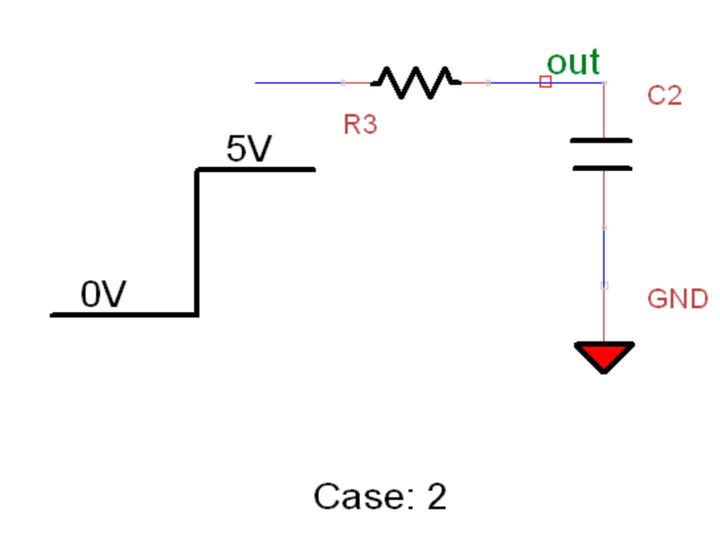


Some properties

- Resistor allows sudden changes in voltages across it and current through it
- Capacitors allow sudden current changes, but voltages are **NOT generally** permitted to change suddenly across them.
- Inductors allow sudden voltage changes across them, but sudden current changes are NOT allowed.

Lets start with a couple of easy ones:





What will be the output in either case?

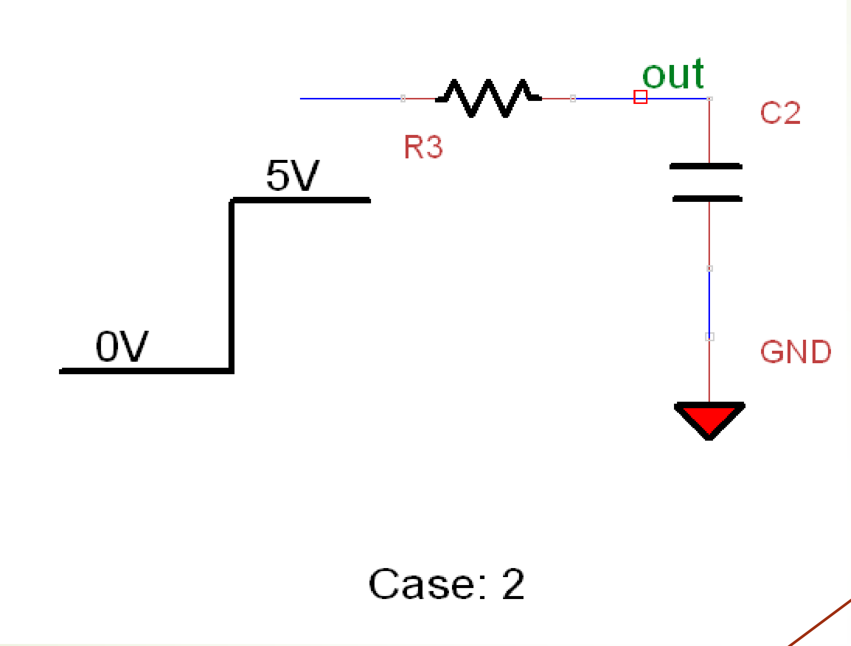
(The idea here is not to use any of the mathematical tools like ODEs or Laplace transform)

$$Q = CV$$

$$i = C\,\frac{dV}{dt}$$

Thus, for a step change (mathematical way of saying ‘a sudden change’) in voltage across a capacitor to happen, you would need an infinite current to flow into the capacitor.

Case: 2



$$\frac{V_{in} - V_{out}}{R} = C\frac{dV_{out}}{dt}$$

$$\frac{dt}{RC} = \frac{dV_{out}}{V_{in} - V_{out}}$$

$$\int_0^t \frac{dt}{RC} = \int_0^{V_{out}} \frac{dV_{out}}{V_{in} - V_{out}}$$

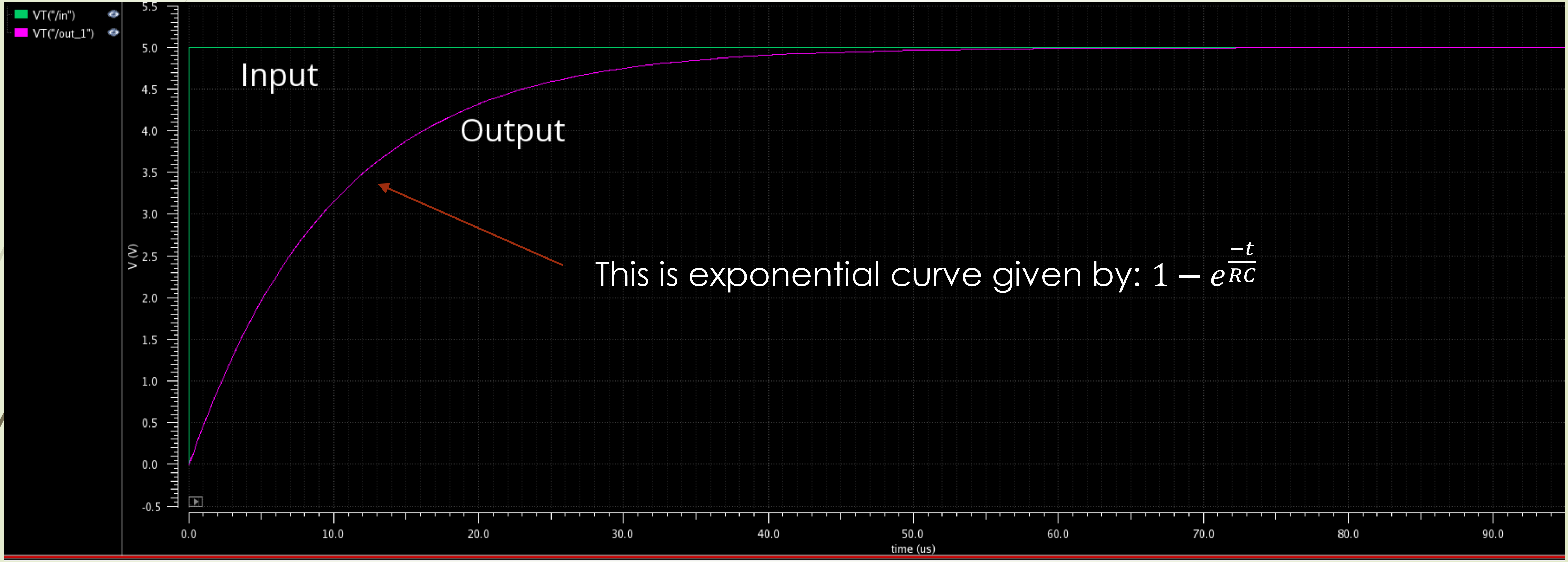
$$\frac{t}{RC} = -[\ln(V_{in} - V_{out}) - \ln(V_{in})]$$

$$\frac{t}{RC} = \ln\left(\frac{V_{in}}{V_{in} - V_{out}}\right); 1 - \frac{V_{out}}{V_{in}} = e^{\frac{-t}{RC}};$$

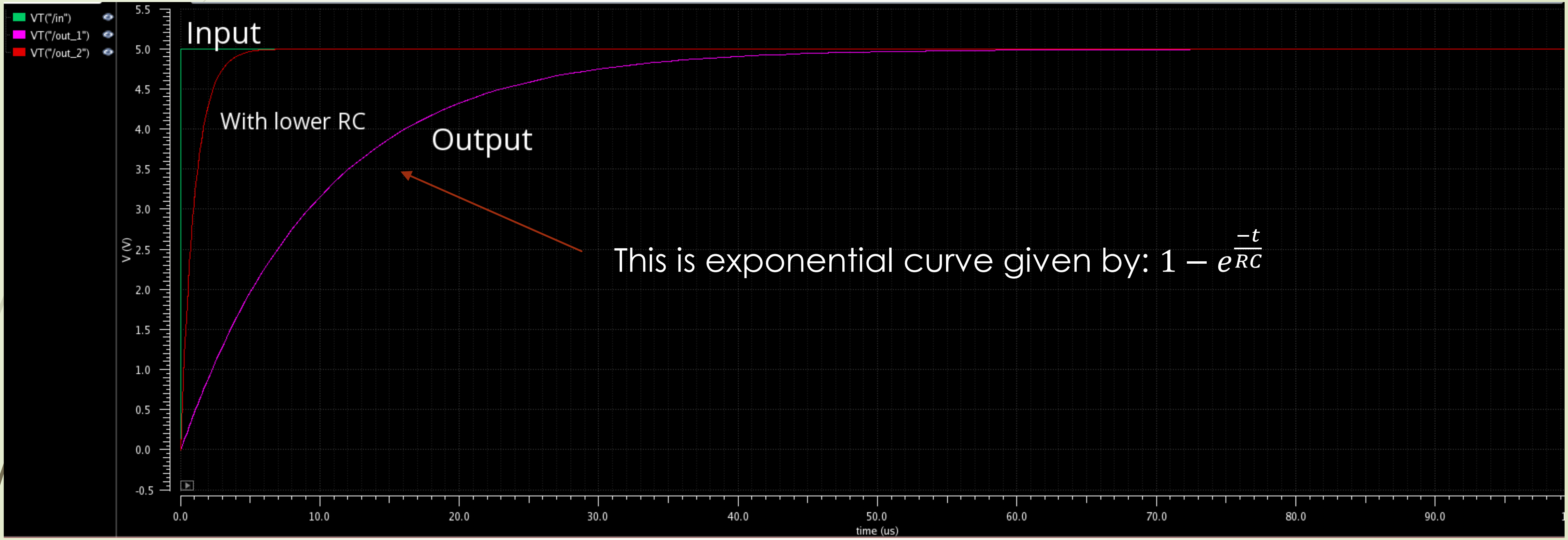
$$\boldsymbol{V_{out} = V_{in}(1 - e^{\frac{-t}{RC}})}$$

This is the part to which most people do not give much thought about.

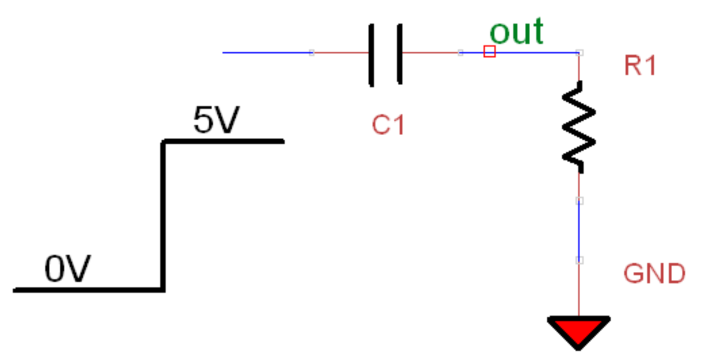
Case 2 (R=10K; C=1n):



Case 2 (R=1K; C=1n):



Case: 1



Case: 1

The voltage across a capacitor cannot change simultaneously.
Assume that the initial voltage across the capacitor is 0V.
Then, when the 'in' node suddenly changes by Vin, to maintain the same voltage across the cap, out will also go to Vin

$$\frac{V_{out}}{R} = C\frac{d(V_{in} - V_{out})}{dt}$$

Because for $t = 0^+$, V_{in} is constant

$$\frac{dt}{RC} = \frac{-dV_{out}}{V_{out}}$$

$$\int_0^t \frac{dt}{RC} = \int_{V_{in}}^{V_{out}} \frac{-dV_{out}}{V_{out}}$$

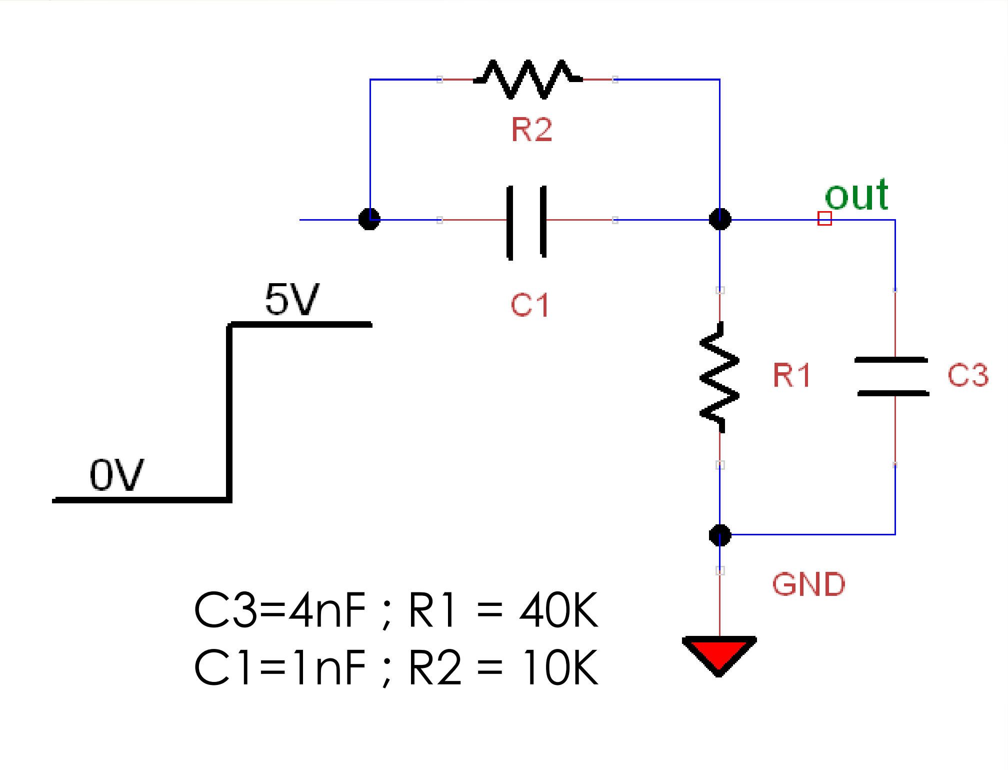
$$\frac{t}{RC} = -[\ln(V_{out}) - \ln(V_{in})]$$

$$-\frac{t}{RC} = \ln\left(\frac{V_{in}}{V_{out}}\right);$$

$$\boldsymbol{V_{out} = V_{in}e^{\frac{-t}{RC}}}$$

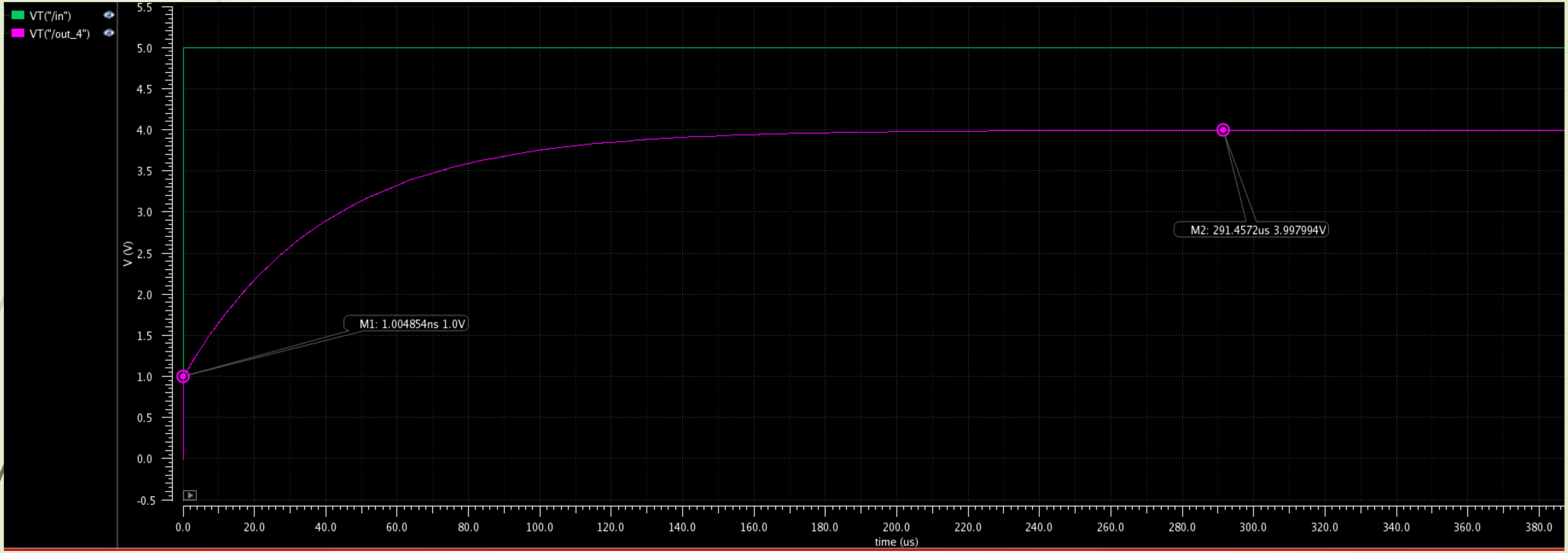
Case 1 (R=10K; C=1n):

How about this one?



When I said that voltage across a capacitor cannot change instantaneously, it was because you CANNOT NORMALLY get a voltage source that can supply an infinite amount of current.

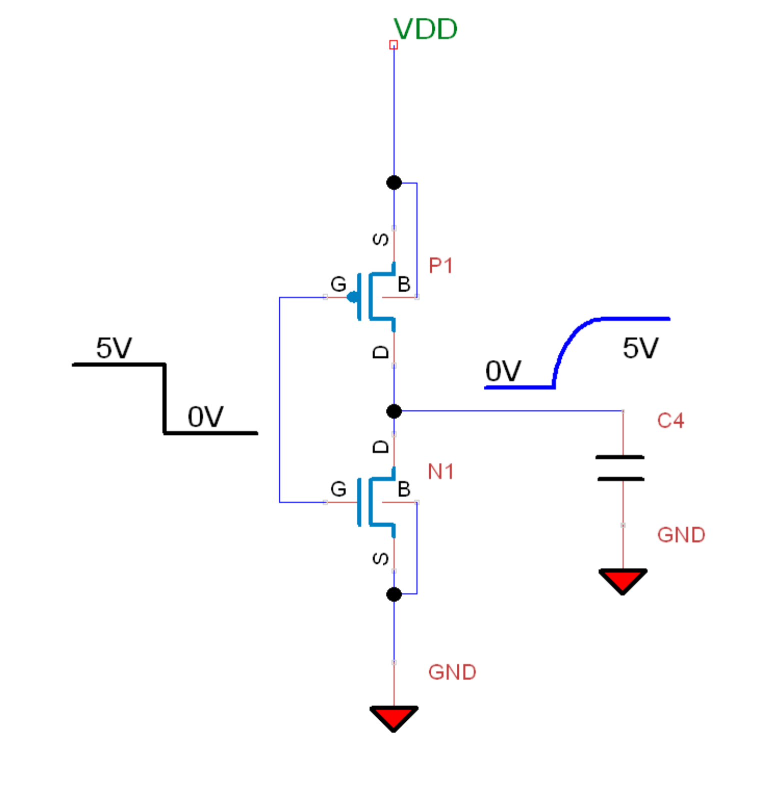
But charge re-distribution between two plates of a capacitor (connected in series) can happen instantaneously.



VT("/in")
VT("/out_4")
V (V)
M1: 1.004854ns 1.0V
M2: 291.4572us 3.997994V
time (us)

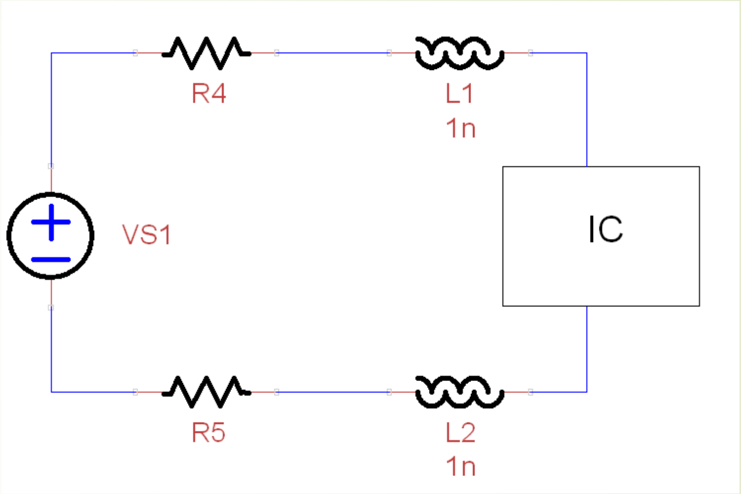
Boring.. Real life example please.. 'Decoupling capacitors'

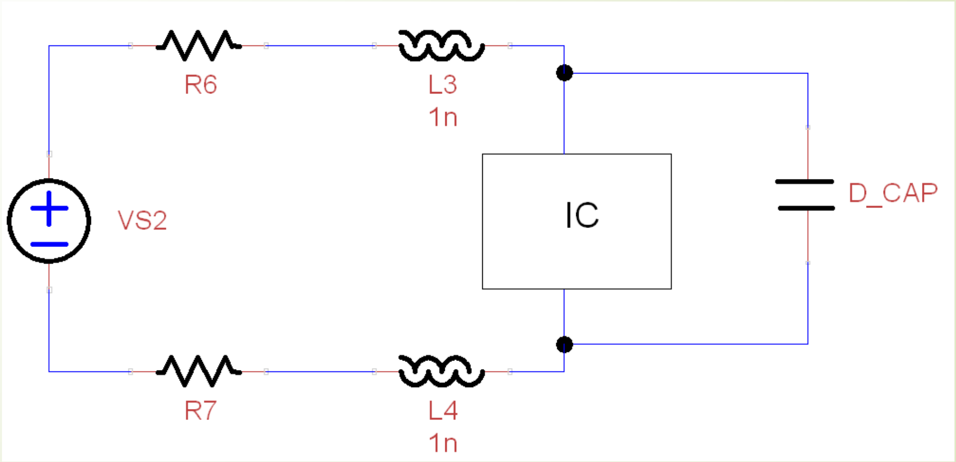
- A CMOS circuit does not dissipate any static power, however it does dissipate dynamic power.
  - See the inverter example alongside. When the input switches to a logic low, the output node needs to go to VDD. The PMOS turns on charges the C4 to VDD drawing power from the supply.
- Whenever a digital circuit switches, there is a current spike.
- Now imagine many such transistors switching simultaneously



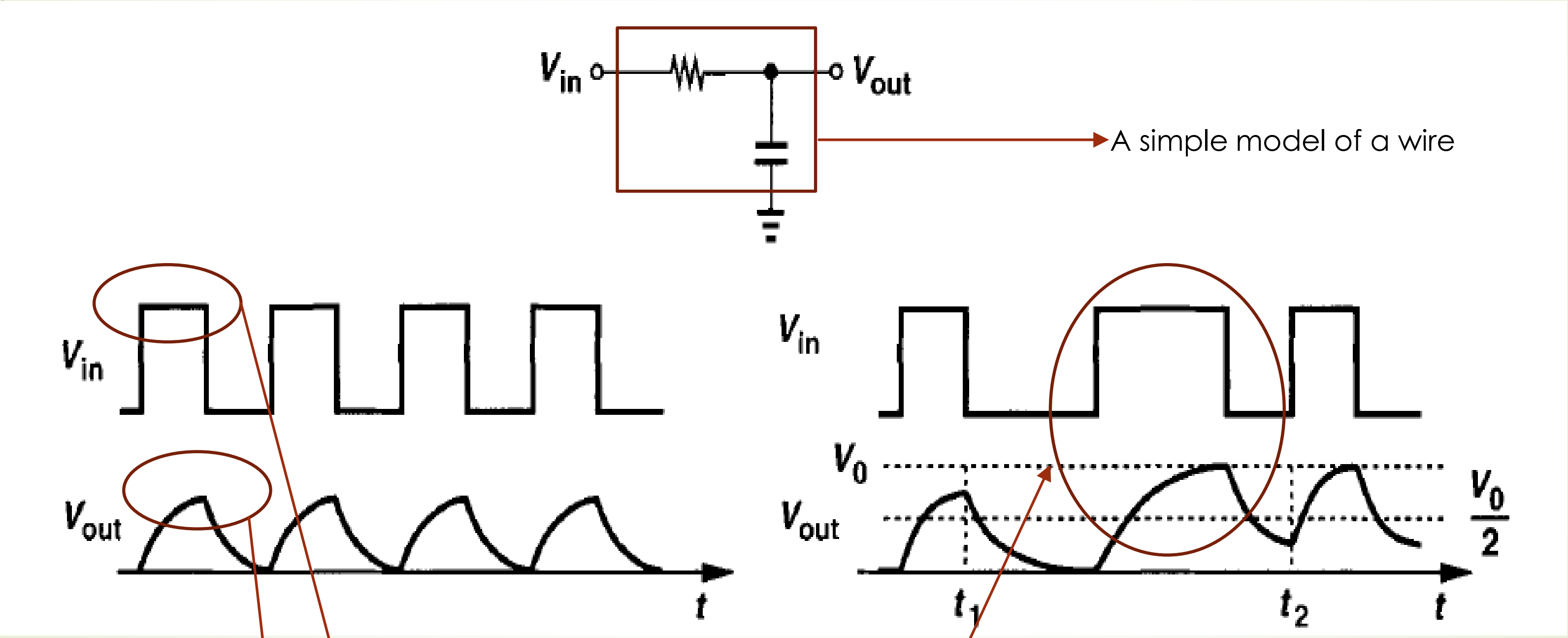
Decoupling capacitors [continued]

- Just like a capacitor hates sudden changes in voltages, an inductor despises sudden change in current.
- When the IC tries to draw in (suddenly) a large current spike, the inductor resists it
  - $V = L * \frac{di}{dt}$
  - The effective voltage across the IC dips
- You don't want the above to be happening.
- The decoupling capacitor placed parallel to the chip does not allow any sudden changes in voltages.
  - The capacitor provides the IC with the high frequency current.





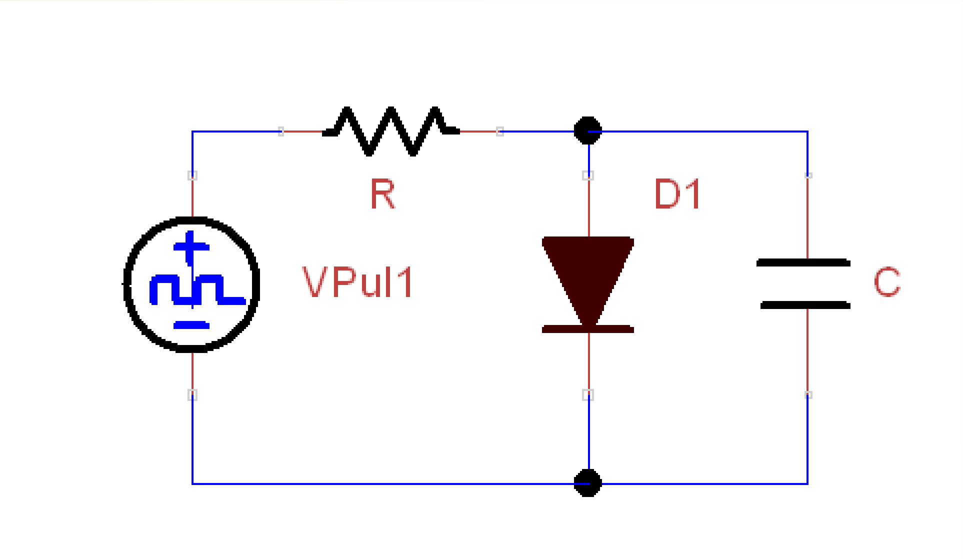
Wireline communication



But if you had a longer series of 1s, then you might reach to a value close to the supply rail.

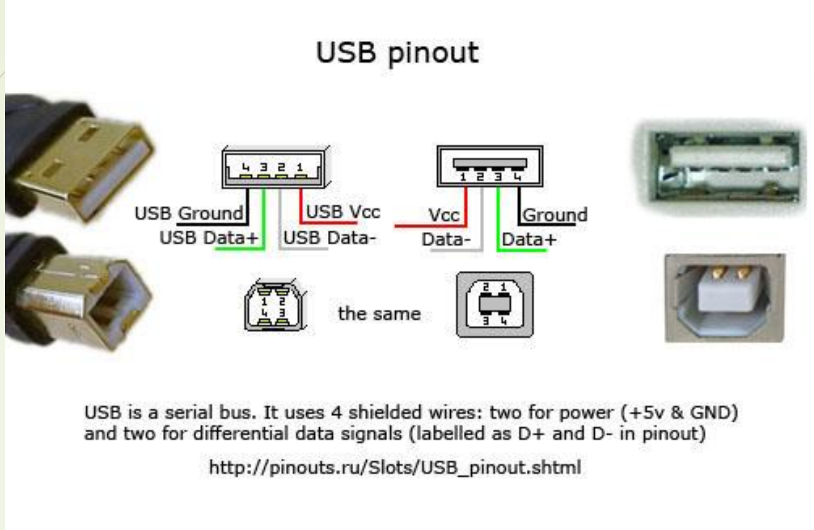
The output voltage waveform may not even get the time to reach the supply rail or its thereabouts

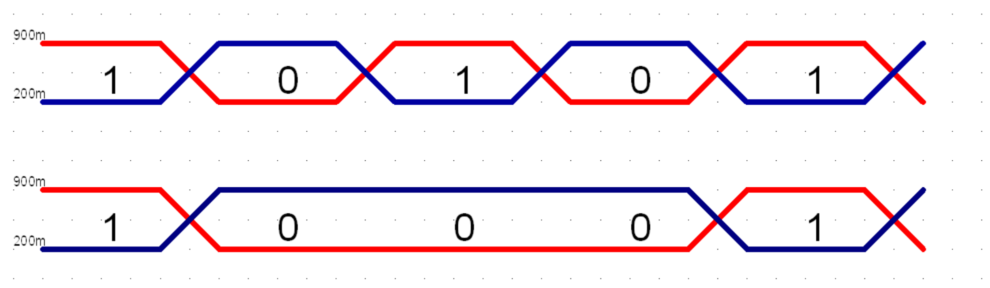
Quick problem:



V is a square voltage source with voltage levels 0 and 2V, and a duty cycle of 50% and a period of 10usec.
The RC time constant is 1usec.
Given that the diode is a normal Si diode, plot the output response.

How to know when has data arrived?



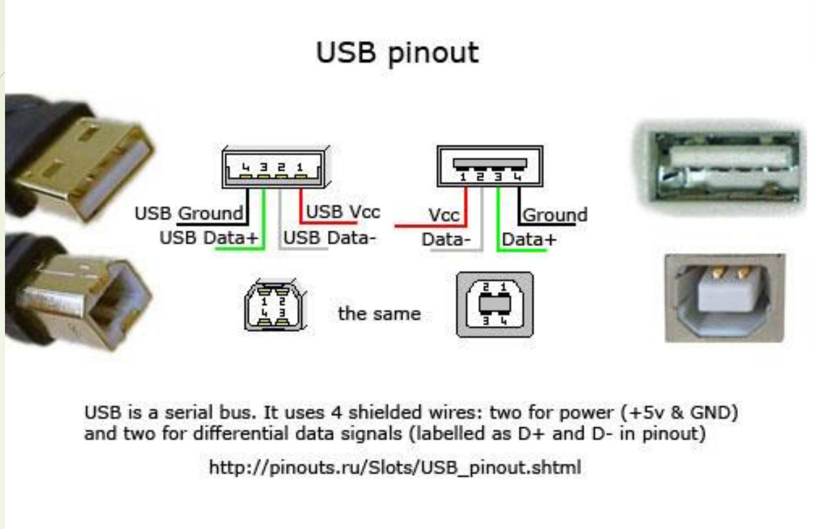


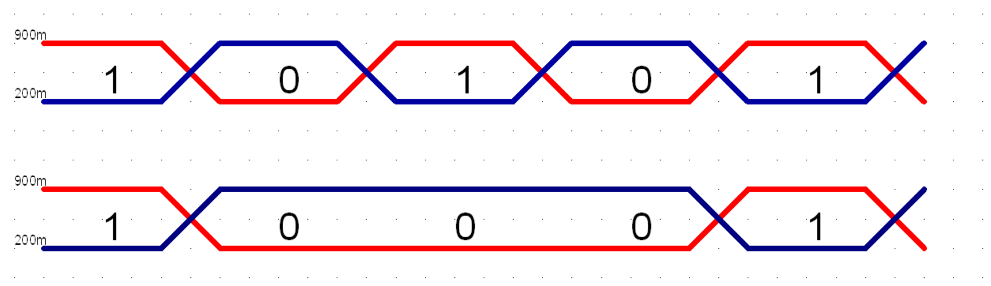
Assume Data+ is red
Assume Data- in blue

How to know whether it's a one or a zero?

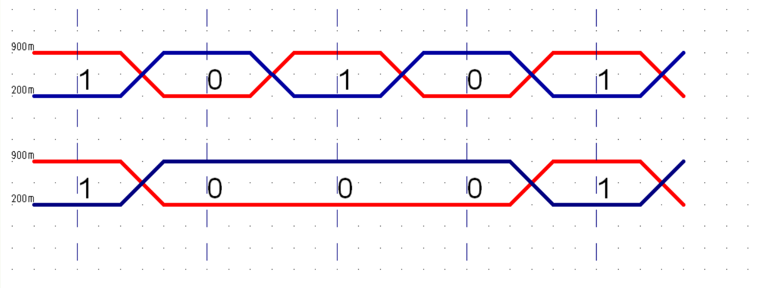
If (Data+ - Data-) ~ 400m ➔ You have received a one
Else → You have received a zero

How to know when has data arrived?





Question is when do I check the difference?



To solve this problem, there is something called a clock data recovery circuit and its ONE (if not the most) challenging blocks in communication circuits

Easiest answer is you sense a transition and you sample T/2 after that

What happens when you have a long series of identical digits?

References on switching circuits

- Pulse, Digital and Switching Waveforms by Jacob Millman and Herbert Taub.

Introduction to filtering

- Lets write the equation of a simple linear and time invariant system

$$m\frac{d^2x}{dt^2} + \gamma m\frac{dx}{dt} + m\omega_0^2 x = F(t).$$

- If its a linear and time invariant system, then if the input to the system is a sinusoid of some frequency, then the output also HAS to be a sinusoid with the SAME frequency but possibly different phase and amplitude.
  - See the equation above. Differentiation of a sinusoid gives back the same sinusoid albeit with a different phase and amplitude.
- Not that, if the input is in exponential signal, you will again get back an exponential with the part that changes with time the same.
  - That is if the input is Ae^{nt}, output will be Be^{nt}
- But sinusoids are mighty easy to see in an oscilloscope!

Fourier series and Fourier transform What does it do?

- It is sometimes easier to see things in the frequency domain, for example the filtering action of filters.
- Fourier said that any periodic signal [under certain conditions] can be written as a sum of sines and cosines, and a constant term.
  - The constant term is zero for any signal whose average value is zero.

Key Concept: Trigonometric Analysis and Synthesis Equations

Given a periodic function x_T, we can represent it by the Fourier series synthesis equations

$$x_T(t) = a_0 + \sum_{n=1}^{\infty} \left(a_n \cos(n\omega_0 t) + b_n \sin(n\omega_0 t)\right)$$

We determine the coefficients a_n and b_n are determined by the Fourier series analysis equations

$$a_0 = \frac{1}{T} \int_T x_T(t)\, dt \;=\; average$$

$$a_n = \frac{2}{T} \int_T x_T(t) \cos(n\omega_0 t) dt, \quad n \neq 0$$

$$b_n = \frac{2}{T} \int_T x_T(t) \sin(n\omega_0 t) dt$$

Source: http://lpsa.swarthmore.edu/Fourier/Series/DerFS.html

What about Fourier transform?

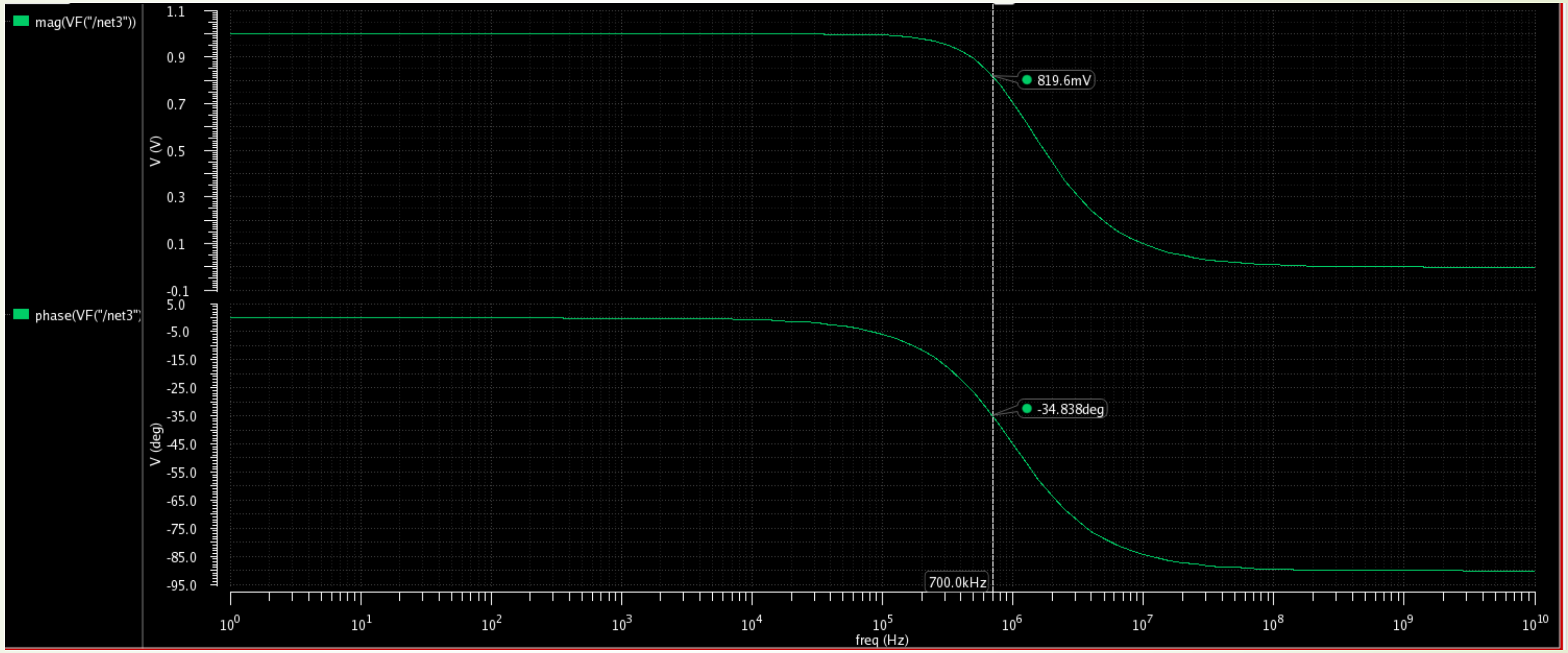
- For a non-periodic signal, like a speech, you cannot really do a Fourier series.
- You need a Fourier transform which takes a non-periodic signal and then tells you what is the component of each frequency in it.

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt$$

- Unlike Fourier series which gave discrete stems in your frequency plot, Fourier transform gives a continuous spectra.
  - For periodic signals, the stems in the frequency plot are separated by the w, which is nothing but 2*pi/T.
  - For a non-periodic signal, T tends to infinity.
  - Thus the separation between the stems of a Fourier transform plot are separated by a distance which tends to zero.
  - And hence, spectrum of a Fourier transform is continuous!

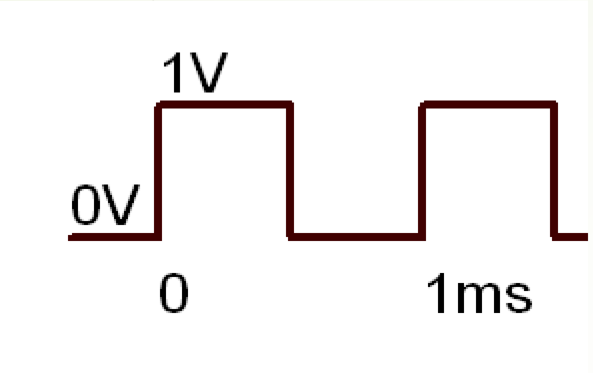
LTI system in frequency domain

- What does it really mean when I say there is block which has a given frequency response?

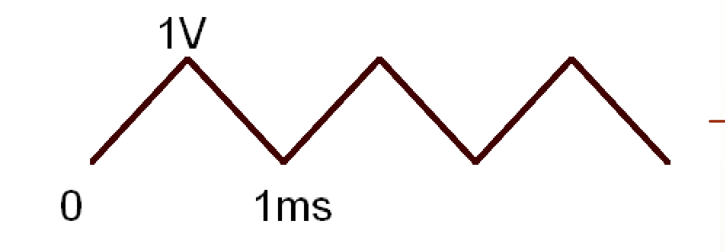


- Shown above is a frequency response of a simple RC filter with a cut-off frequency of 1MHz.
- If I were to inject a sinusoid of amplitude A at a frequency of 0f 700KHz, then I will get back a sinusoid of frequency 700KHz with:
  - Phase shift of – 35 degrees
  - Amplitude of 0.82A

Using the previous concepts, answer:



→ Low pass filter (wc=2*pi*3.5K) → Max voltage?

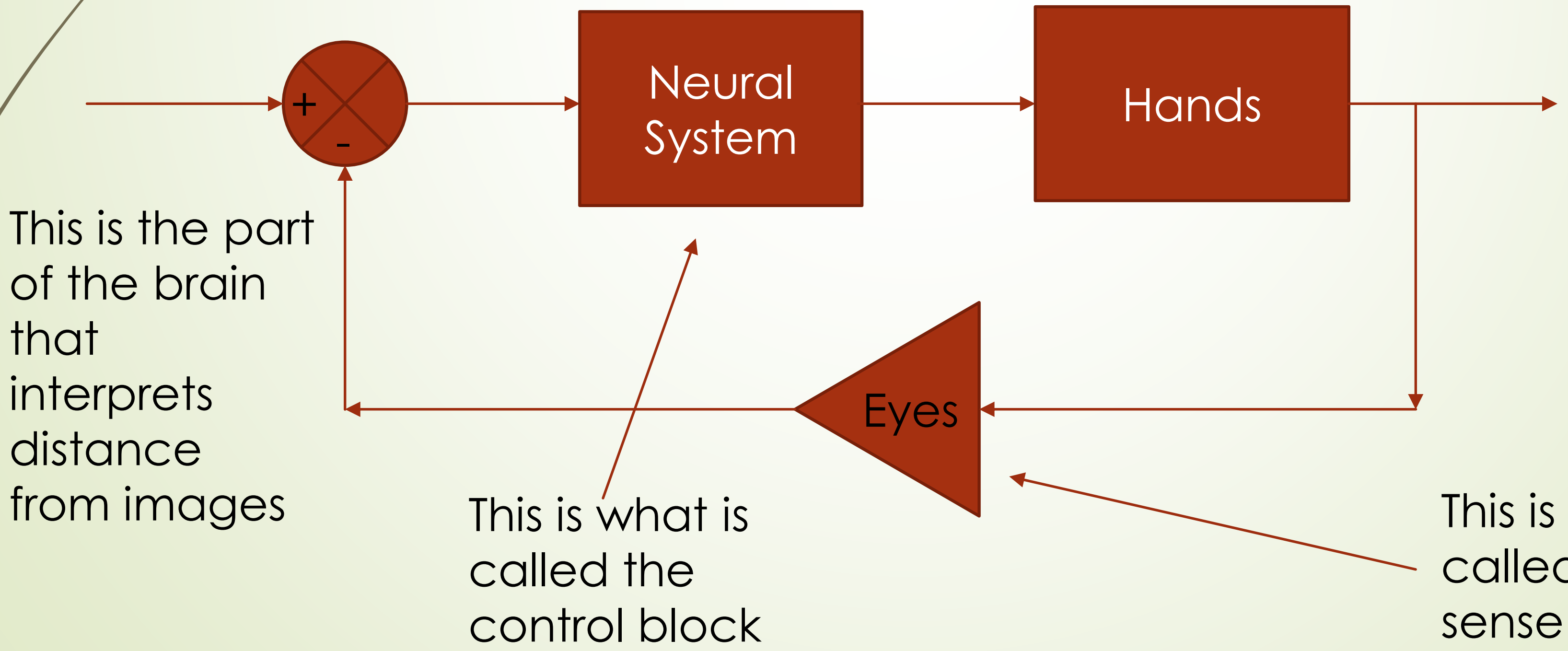


→ Band Pass Filter (wc=2*pi*3K) (wb=2*pi*100) → Max voltage?

Assume that the transition bands are extremely narrow, and gain of filters is unity

Before we proceed, let's talk about a very important concept called feedback.

- Feedback in its truest sense of the term means regulatory behavior.
- For example, lets say I would want to lift a bottle.
  - My hands are really the actuator.
  - The eyes is both a sensing and a feedback device that tells how far the hand is from the bottle.
  - The neural network in our brain and spine directs our hand.



Different ways the control block can behave:

- It can just look at the **present input** and give directions to the actuator accordingly.
- It can look at the **past inputs** and then give the directions to the actuator. This is like your girlfriend saying, 'You did that1 days 20 hours 23 minutes 3 seconds ago, and then some crap 20 hours 23 minutes and 2 seconds ago, and then some more a second later …. and sab milake yein hain uska jawab'
  - Disclaimer: I mean absolute no insult to anyone here. I apologize in case I offend someone.
- It can look at **how fast the input is changing** and give directions to the actuator. This is what is called '**pre-emptive behavior**.' This is like your grades have started falling, and your parents cut-off the cable TV and internet before your grades drop even further and you fail the course.
- Or it can be a combination of (i) and (ii); (i(and (iii) or (i), (ii) and (iii)

Proportional control

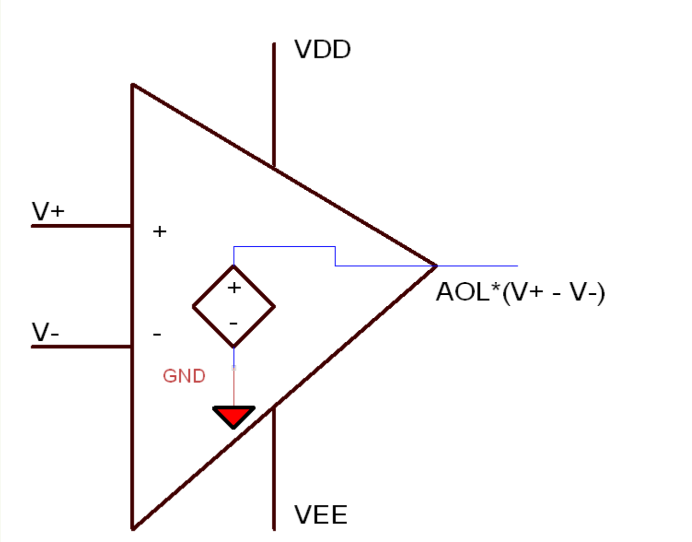
Integral control

Derivative control

Operational Amplifiers

One of the marvels of the 21st century

- It looks like the image shown below:

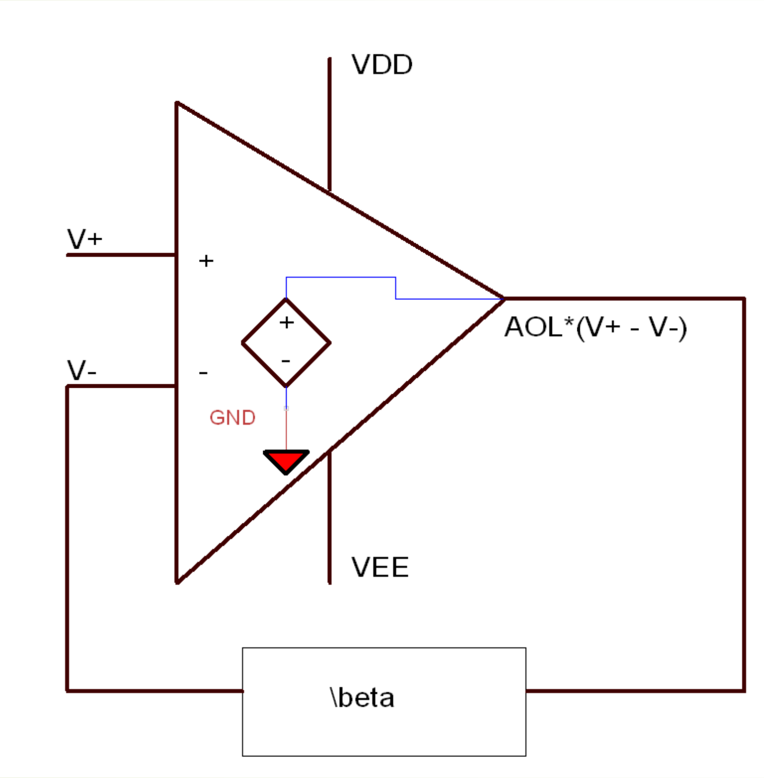


Some characteristics of the ideal operational amplifier:

- AOL tends to infinity
- No current is taken either by V+ or V- terminal. [Not true necessarily for BJT operational amplifiers]
- The maximum output voltage is VDD
- The minimum output voltage is VEE

- The op-amp shown in this configuration has rather limited uses, one of which is a comparator:
  - Because AOL→ infinity, if V+ > V-, then the output goes to VDD.
  - Similarly if V+ < V-, then the output goes to VEE
  - People use this for photodiode sensors in line follower robots.
    - Not a great idea. Use a commercial high speed comparator instead. Much better slew rate

How to make it useful? Negative feedback!!



What is negative feedback?

- Assume V+ goes up slightly.
- Then the op-amp would start going very high because of the large value of AOL.
- But then a part of output is feedback into the V- terminal.
- This decreases value of (V+ - V-).
- Thus the output will now start coming down.
- A system exhibits negative feedback if the output tries to go out of bound, the system will reel it back in!

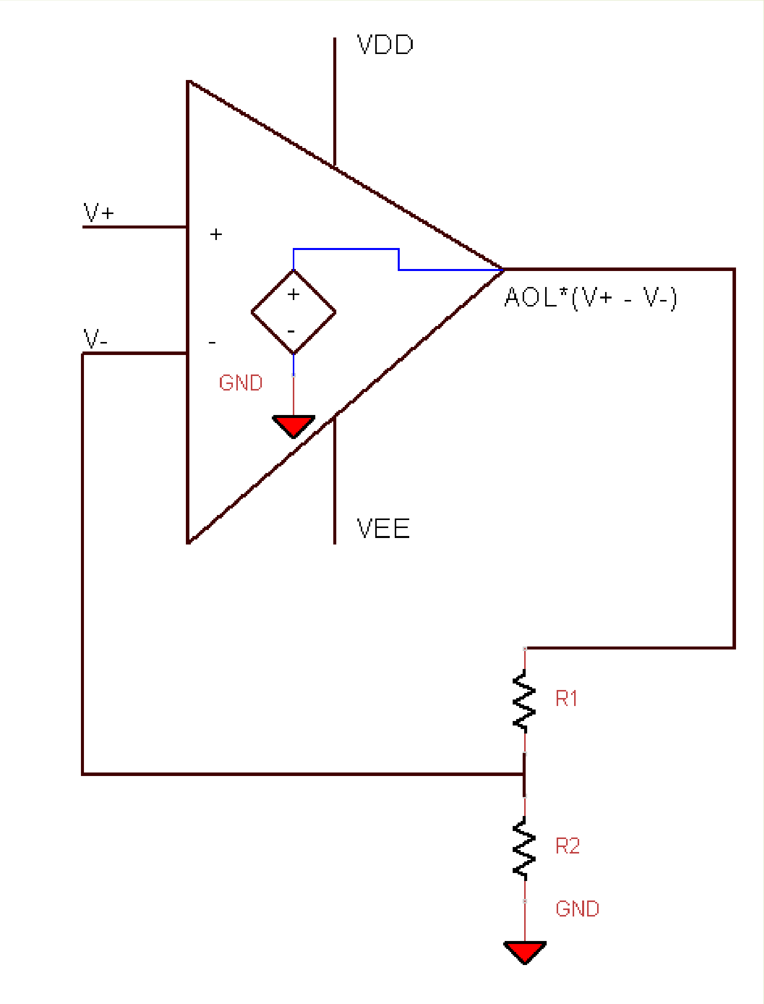
Note: Life would have been much better and simpler if AOL were constant.

Turns out AOL moves around a lot due to process variation

Some equations.

$$A_{OL} * (V_+ - \beta V_{OUT}) = V_{OUT}$$
$$\Rightarrow V_+ - \beta V_{OUT} = \frac{V_{OUT}}{A_{OL}}$$
$$\Rightarrow V_{OUT} = \frac{V_+}{(\beta + \frac{1}{A_{OL}})}$$
$$When\ A_{OL} \dashrightarrow infinity, V_{OUT} = \frac{V_+}{\beta}$$

- How do you synthesize the 'beta' network?
  - What the beta network does is that it only returns a fraction of the output voltage back to the input node.
  - Fraction of voltage… umm.. Voltage divider..
  - You can do that easily using a resistor divider.
- It's a voltage amplifier with a well defined gain
  - Passives vary less across process, and can be manufactures with greater accuracy.



$$\beta = \frac{R2}{R1 + R2} \dashrightarrow V_{OUT} = \left(1 + \frac{R1}{R2}\right) * V_+$$

Lets ponder on the equations

- If you were observant enough, then you would have noticed that V- = BVout and thus V+ = V-
- This is another property of operational amplifiers **ONLY** in **NEGATIVE FEEDBACK.**
  - We will see shortly what happens when we have a positive feedback.
  - **Also ensure that the op-amp outs are not saturated to the supply rails!**
- This is called a **VIRTUAL SHORT.**
- If you know your circuit exhibits **NEGATIVE FEEDABCK**, you can assume that the V+ and V- will be at the same potential and work out the rest of voltage and current.

$$A_{OL} * (V_+ - \beta V_{OUT}) = V_{OUT}$$

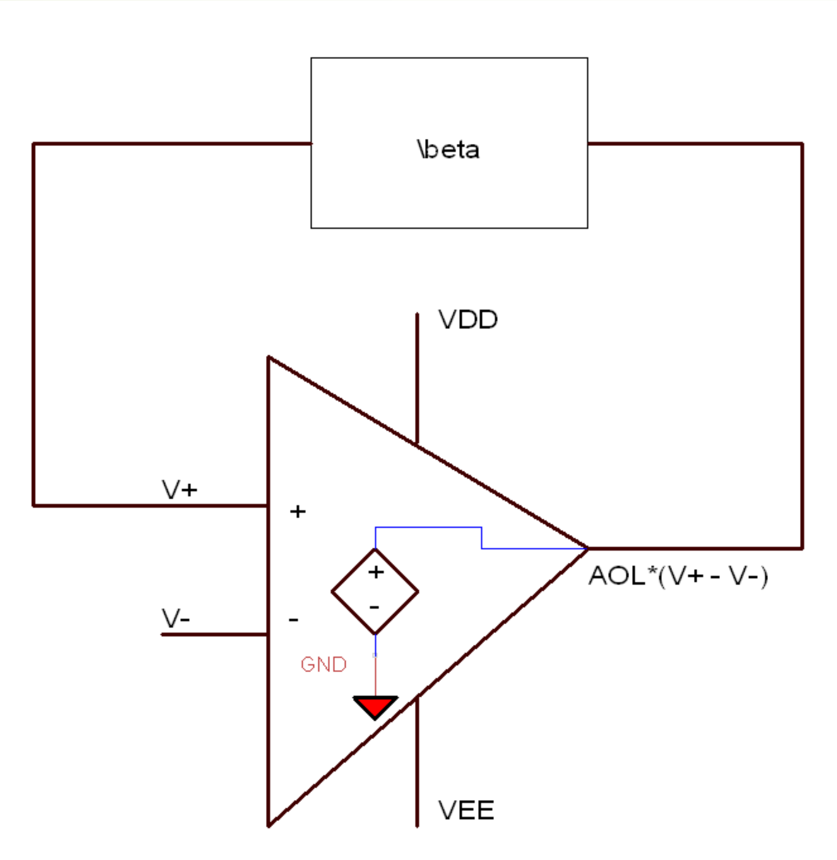
$$\Rightarrow V_+ - \beta V_{OUT} = \frac{V_{OUT}}{A_{OL}}$$

$$\Rightarrow V_{OUT} = \frac{V_+}{(\beta + \frac{1}{A_{OL}})}$$

$$When\ A_{OL} --\rightarrow infinity, V_{OUT} = \frac{V_+}{\beta}$$

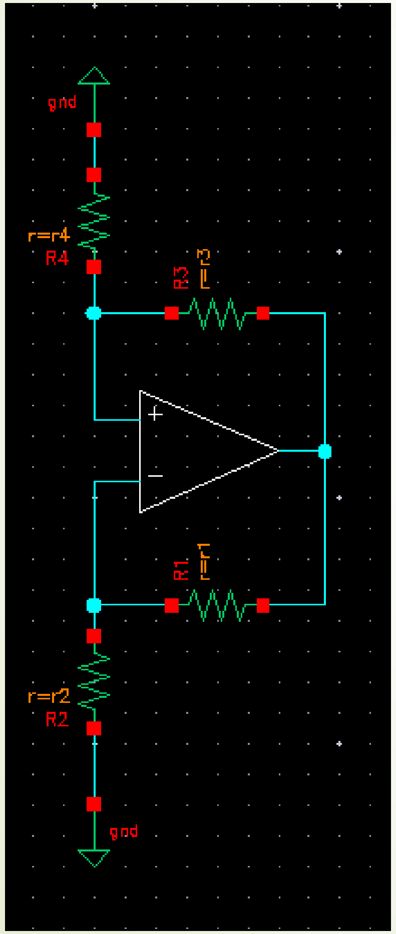
NOTE: However in reality, operational amplifiers exhibit finite AOL, so there will be some offset.

What if we swapped the terminals?

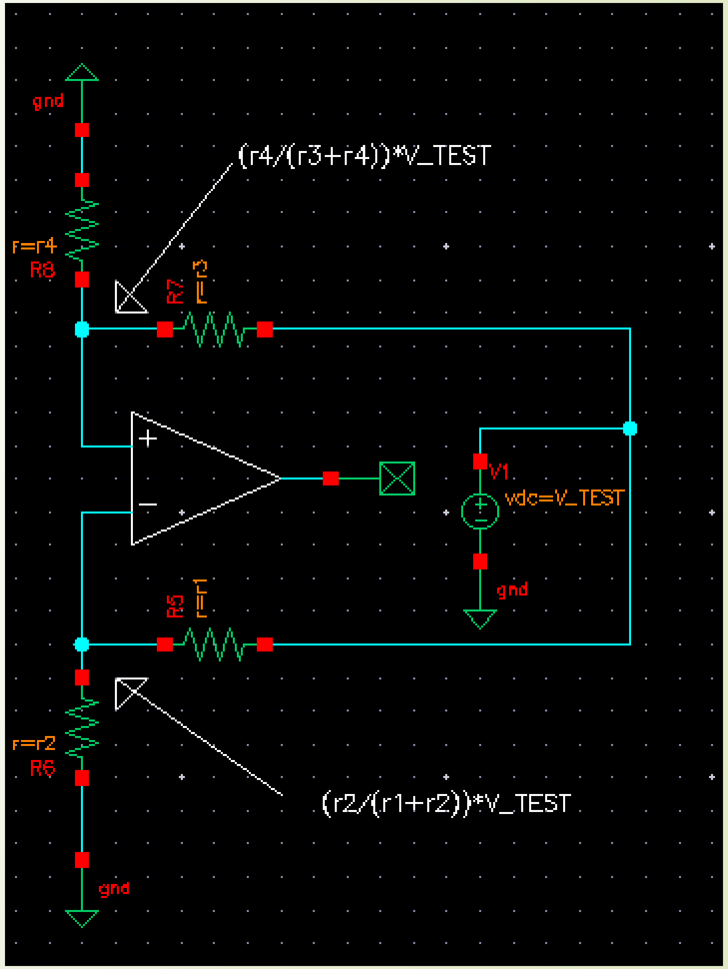


- Assume that V- goes down slightly.
- Then (V+ - V-) increases.
- AOL*(V+ - V-) goes up.
- Because beta is a **POSITIVE** thing, then V+ also goes up.
- Thus (V+ - V-) goes up.
- And this regenerative effect continues until the output voltage hits the positive supply rail.
- This is called **POSITIVE FEEDBACK,** where a system only **AIDS** the output.
- Note the equations are no longer valid and thus **VIRTUAL SHORT** is no longer valid! Be careful!

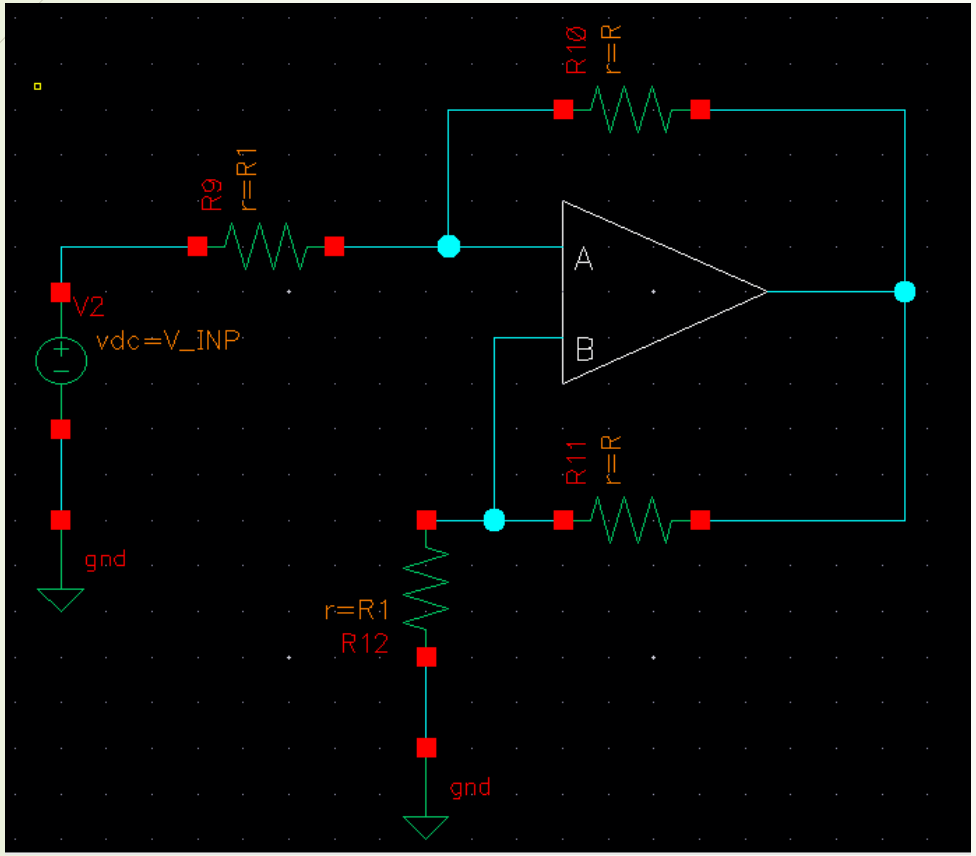
How to know whether a circuit has positive or negative feedback?



- You need to calculate which of the feedback is stronger.
- To do that, disconnect the output from the amp's output and insert a test signal.
- Short any external voltage sources and open any external current source.
- Find what fraction of the input signal returns to the V+ and V- pins.
- If the fraction of the test signal that returns to V+ is more, then your positive feedback is stronger.
- And vice versa.



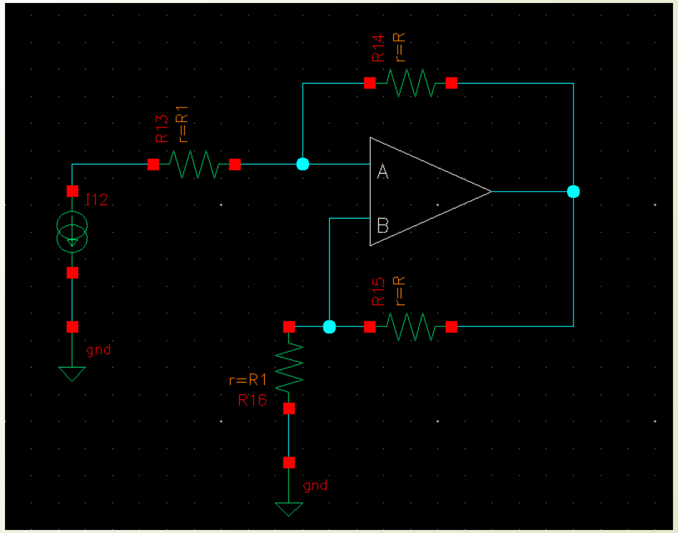
If the above points are clear, try and answer the following questions:



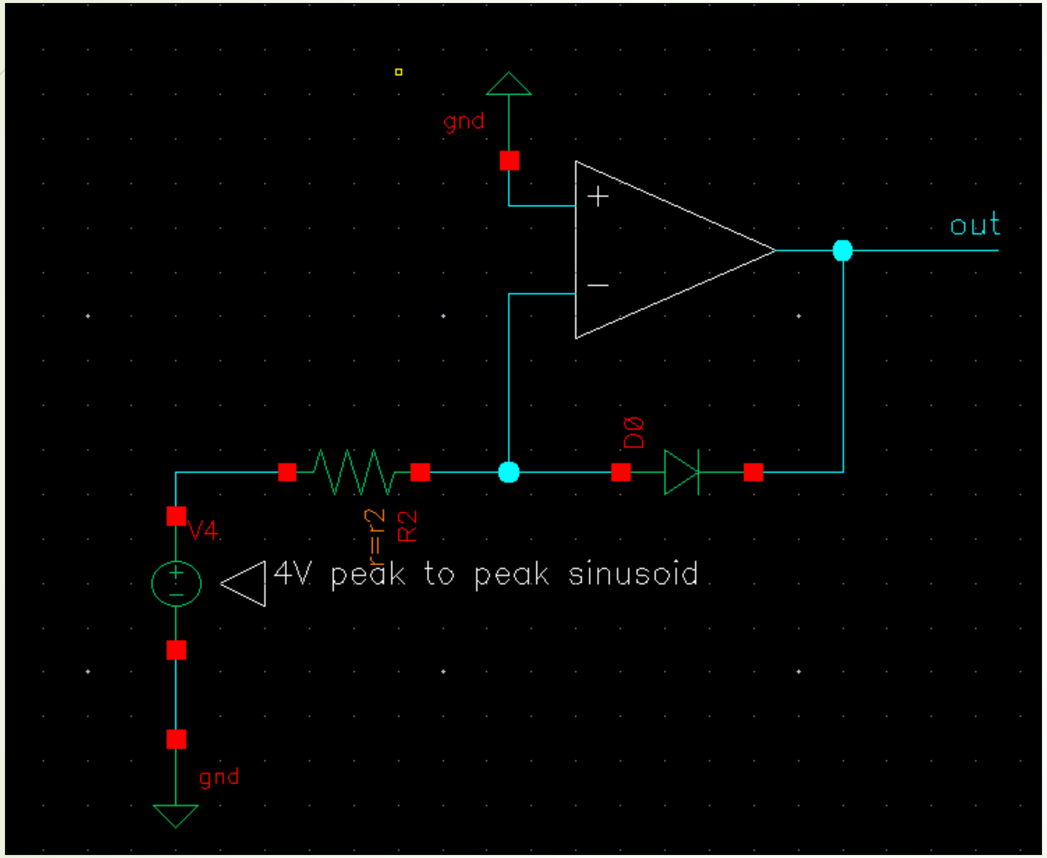
Find the sign of A and B for the operational amplifier to be in negative feedback given:

- R1=3R and R2= R
- R1=R and R2= 2R

How does the answer change if the voltage source is replaced with a current source as shown below:



Try this:



Draw the output.

Assume that the diode is a normal silicon diode.

Although, I haven't really covered much, I hope that I am able to give you a sneak peak into what are tools that an analog design engineer needs.

Because of the limited time that I have, I will quickly talk about a circuit simulator

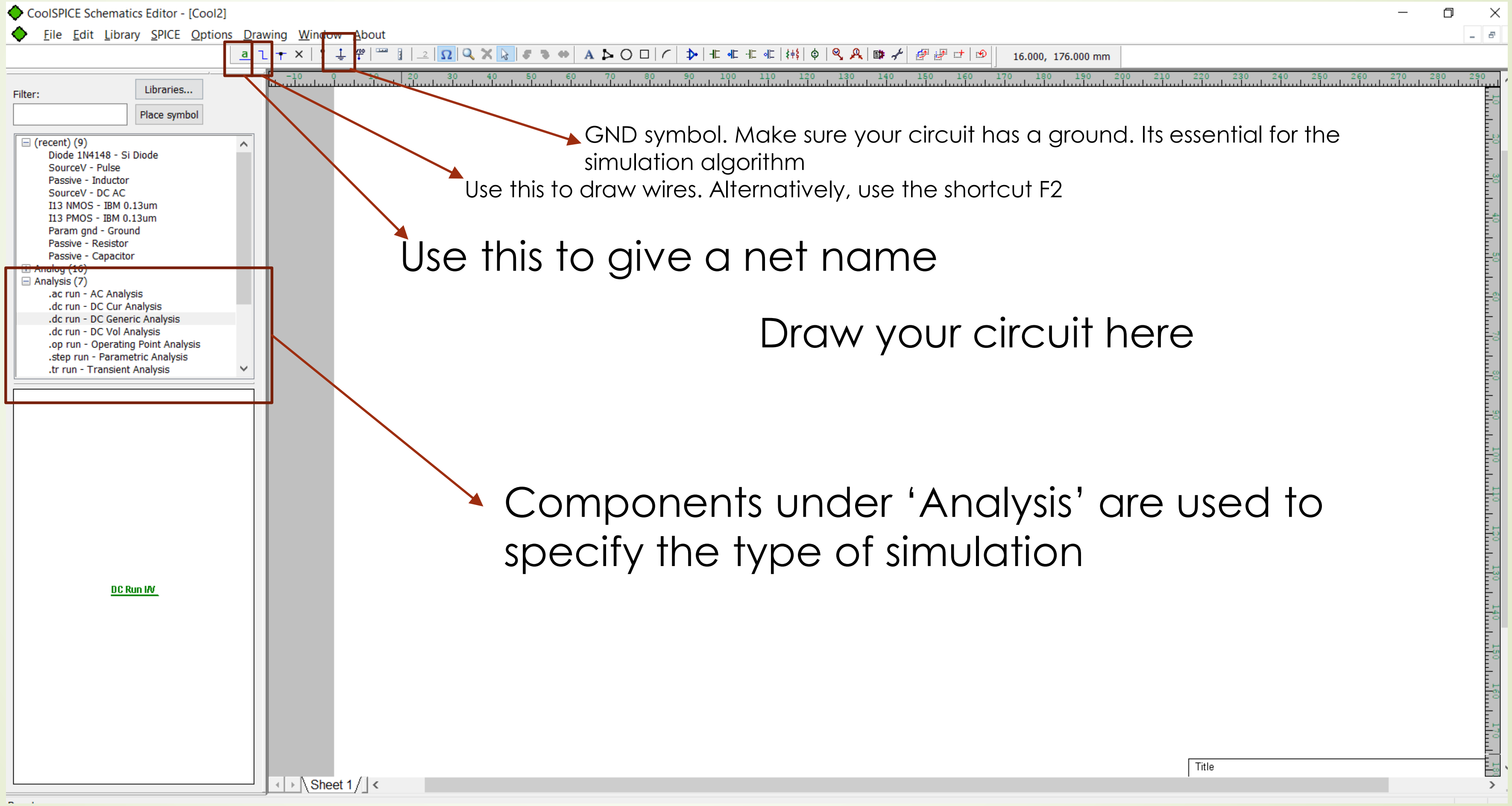
CoolSpice Circuit Simulator

Features

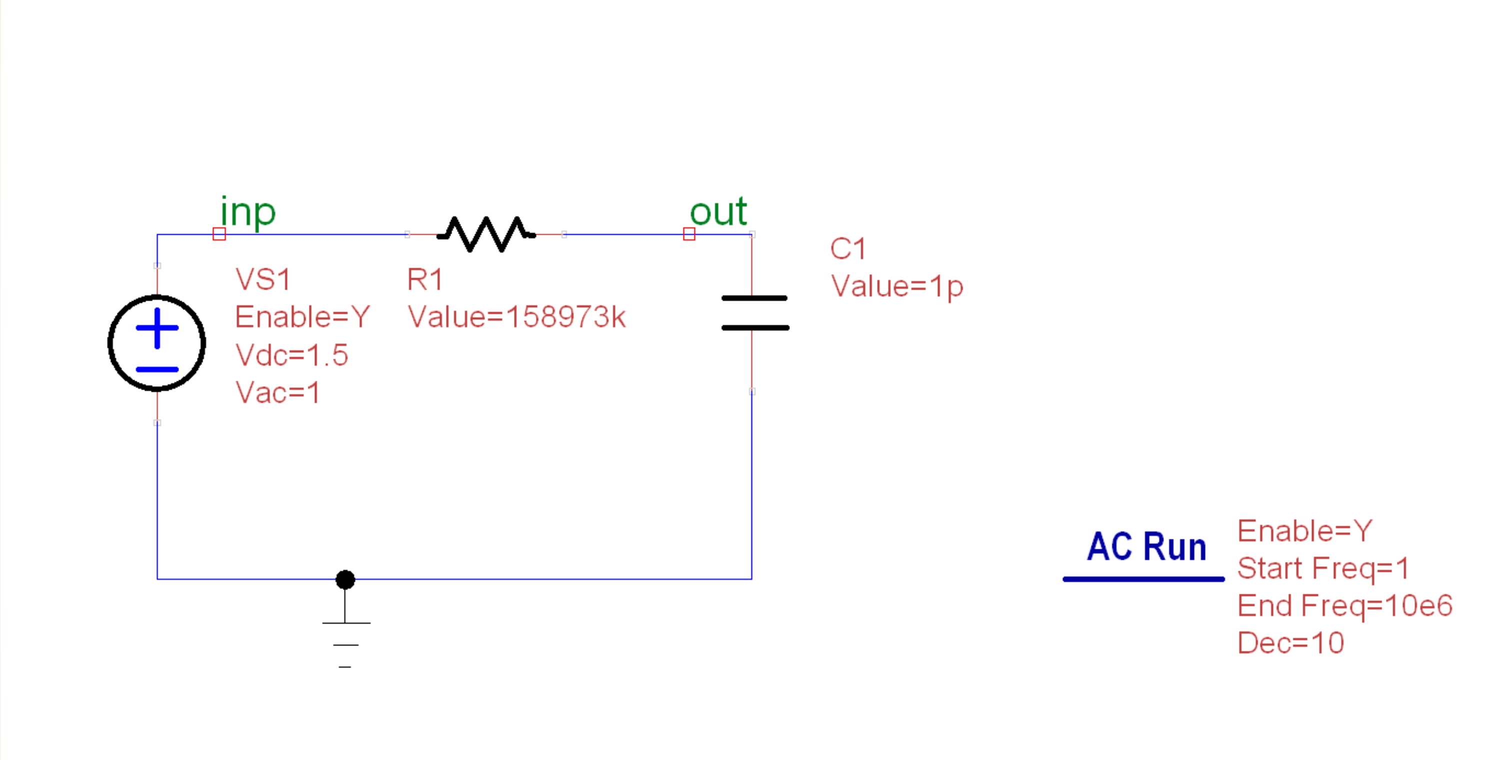
- Based on the NGSpice simulator, which supports a lot of analysis like:
  - DC: For finding the DC voltage and current of a circuit
  - AC: For finding the frequency response of a circuit
  - Transient: For finding the transient response of a circuit to various input waveforms.
- CoolSpice actually generates a netlist which can be also used directly with the NGSpice simulator.
- You can download it from: http://coolcadelectronics.com/coolspice/

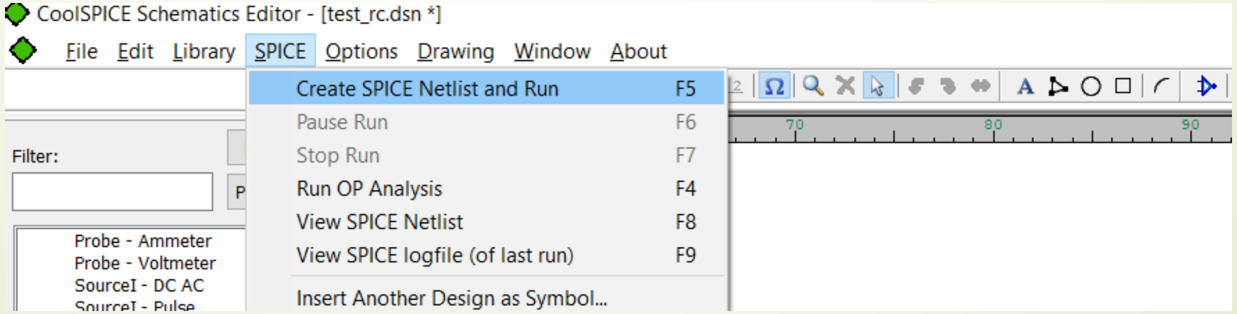
Schematic editor

- Once its downloaded and installed, you can open the schematic editor



AC analysis


inp
out
VS1
Enable=Y
Vdc=1.5
Vac=1
R1
Value=158973k
C1
Value=1p
AC Run
Enable=Y
Start Freq=1
End Freq=10e6
Dec=10


CoolSPICE Schematics Editor - [test_rc.dsn *]
File Edit Library SPICE Options Drawing Window About
Create SPICE Netlist and Run F5
Pause Run F6
Stop Run F7
Run OP Analysis F4
View SPICE Netlist F8
View SPICE logfile (of last run) F9
Insert Another Design as Symbol...
Filter:
Probe - Ammeter
Probe - Voltmeter
SourceI - DC AC

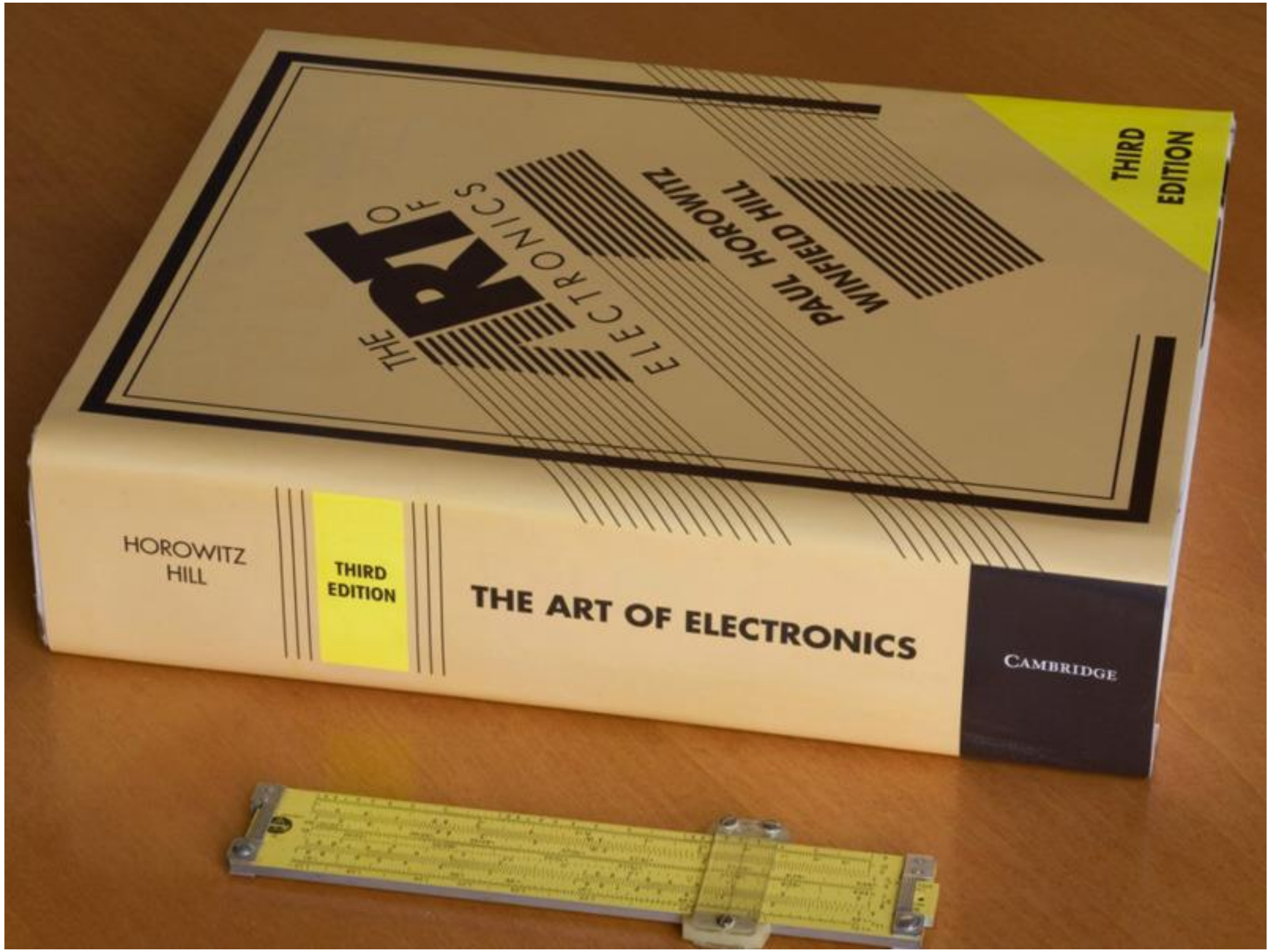
References

Books and Lectures

- Basics of circuit Theory
  - Lectures: http://www.ee.iitm.ac.in/videolectures/doku.php?id=ee1001_2015sa:start
  - Books: Engineering Circuit Analysis by Hayt and Kimberly
- Design of analog integrated circuits
  - Books:
    - **Fundamentals of Microelectronics by Behza Razavi**
      - **https://www.youtube.com/watch?v=yQDfVJzEymI&list=PL7qUW0KPfsIIOPOKL84wK_Qj9N7gvJX6v**
    - Design of Analog Integrated Circuits by Behzad Razavi [This is a graduate textbook]
      - http://www.ee.iitm.ac.in/videolectures/doku.php?id=ee3002_2015nk:start
      - http://www.ee.iitm.ac.in/videolectures/doku.php?id=ee5320_2016:start

This book is a holy grail of electronics. Its expensive, but a must have.

[Some idiot stole mine]



Capabilities of a simulator used by the mainstream IC industry

- Determination of small signal parameters.
- Phase Noise and Periodic Steady State analysis
  - Before the development of these two methods, high performance oscillator design used to be hit and trial
- Pole Zero analysis
  - Not used much.
- STB analysis
  - Extensively used in analysis of feedback circuits. It gives you the magnitude and phase response of a feedback circuit with loading

Issues?

- Prohibitively expensive for individual use.
  - Cadence does not even give software for individual use under normal circumstances.
- Jadavpur University does not want to spend the money to get hold of university licenses although that is significantly cheaper.

NGSpice Circuit Simulator

- Link: http://ngspice.sourceforge.net/download.html
- Beginners tutorial: https://www.ee.iitb.ac.in/course/~dghosh/ngspice-2.pdf

- BUT, no schematic capture capabilities are available.
    - Instead relies upon text based netlist.