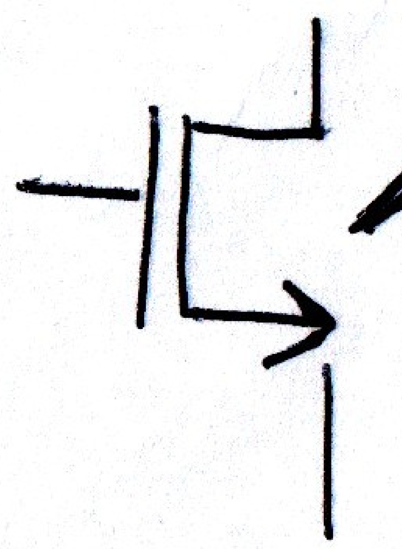
Transistors Demistified

(HOPEFULLY)

By now, you have seen a very large number of equations describing what you have always been told is a switch,



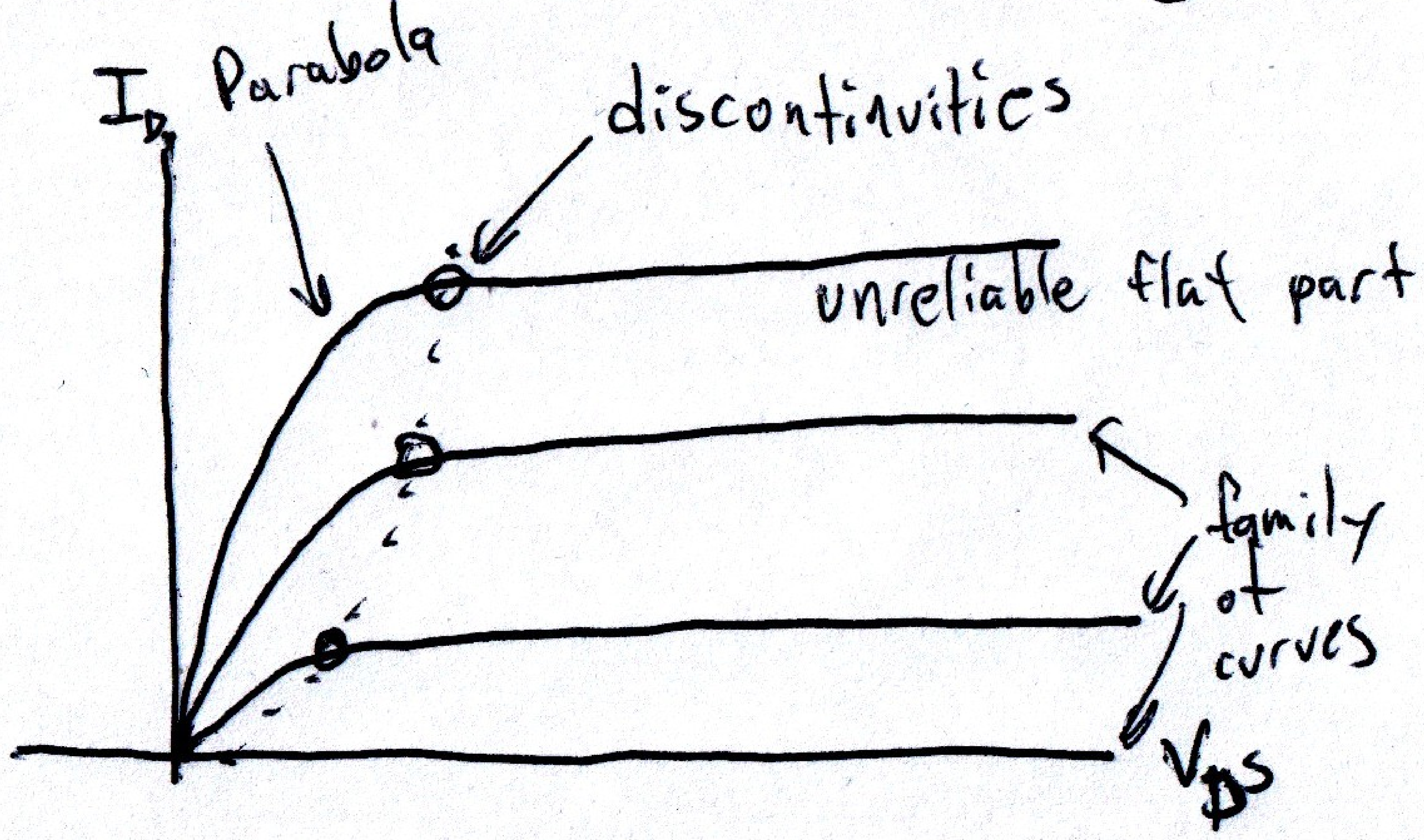
$I_D = K_n(V_{GS}$ …

$I_D = K_n' \frac{W}{L}\left(V_{GS}-V_{TN}-\frac{V_{DS}}{2}\right)V_{DS}$

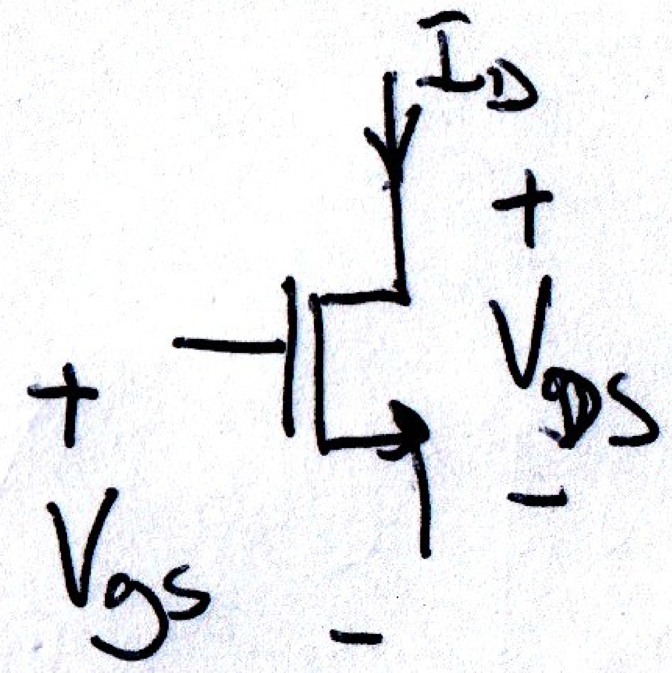
$K_n' = \mu_n C_{ox}''$ $\quad V_{DSAT} = V_{GS}-V_{TN}$

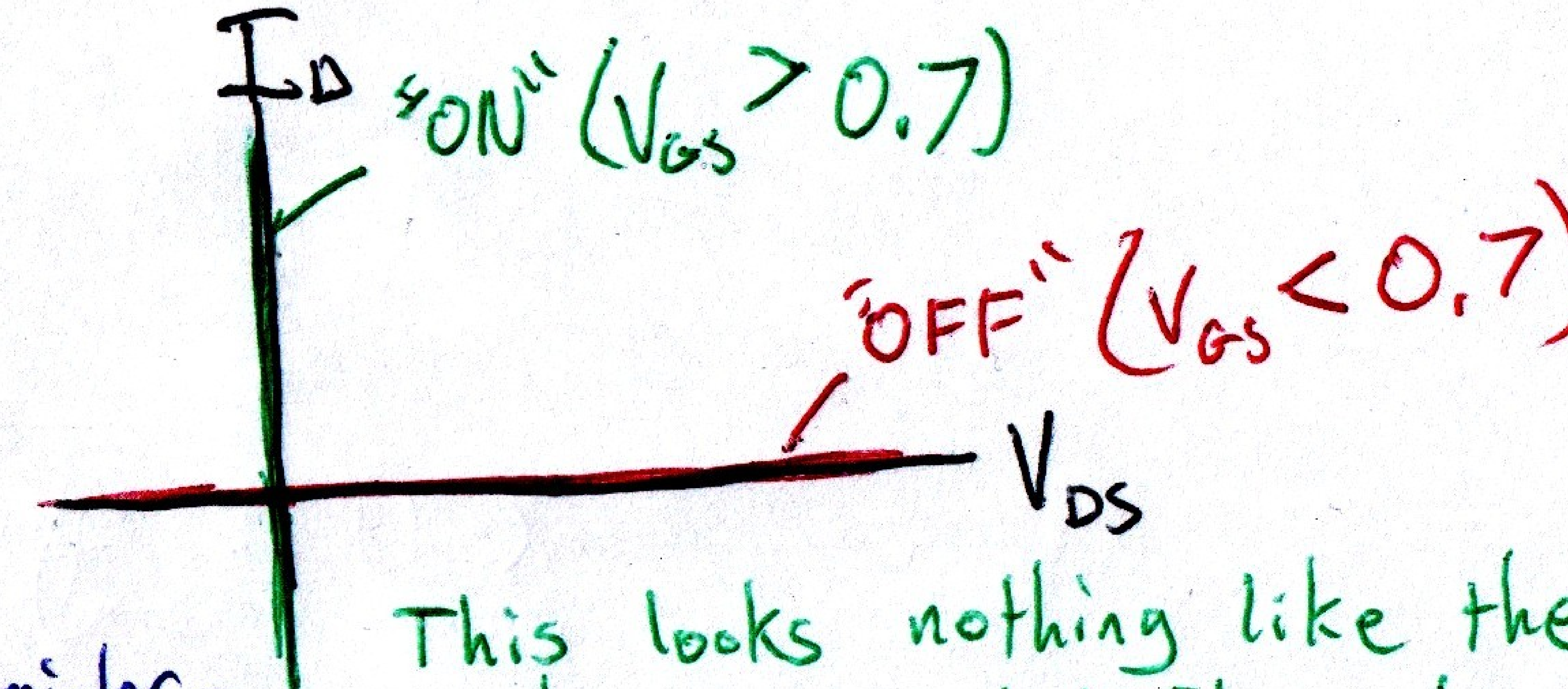
$C_{ox}'' = \varepsilon_{ox}/T_{ox}$ $\quad V_{TP} = V_{TO} - \gamma(\sqrt{\;}$ …

You have also seen an I·V curve that looks like your AP Calculus teacher's idea of a cruel joke:



So let's back up a bit and look at a transistor <u>as</u> a switch.





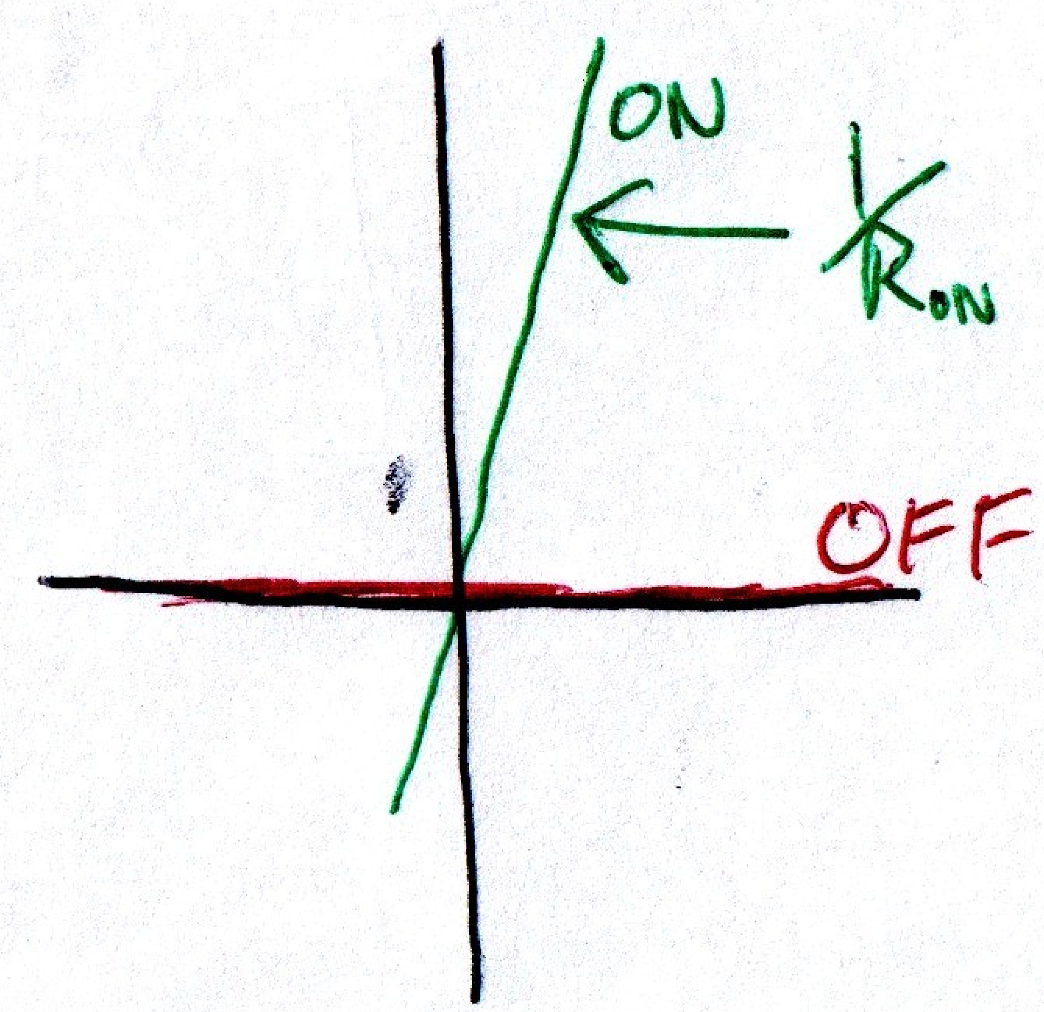
Reminder

- A horizontal line at $I=0$ is an <u>open</u>
- A vertical line at $V=0$ is a <u>short</u>.

This looks nothing like the real curve, but it acts like a true switch.

ON: $V_{DS}=0$
OFF: $I_D=0$

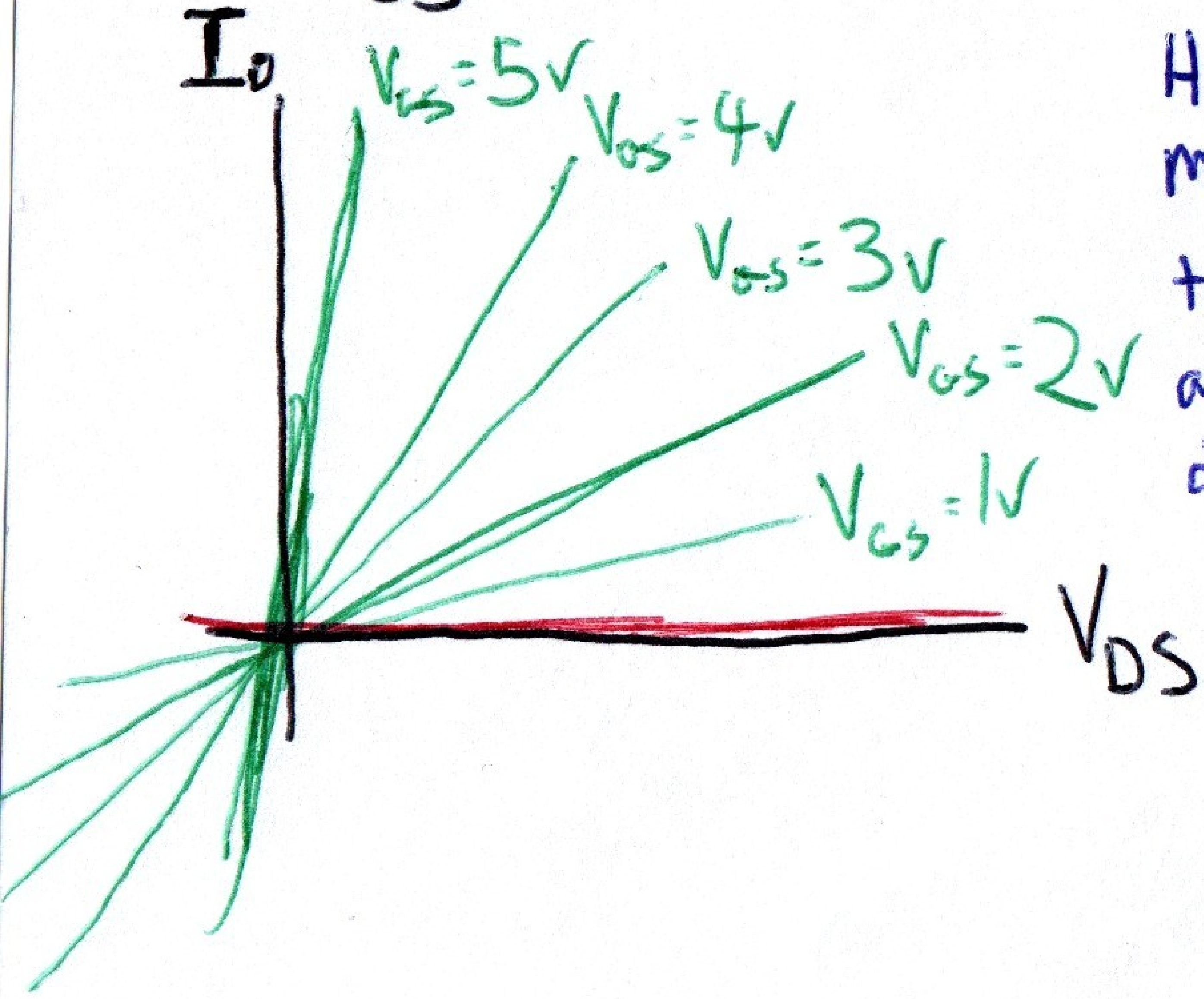
Believe it or not, this is often a good enough model for basic analysis, although sometimes you may go a little better with a series on resistance:



$$R_{ON} = \frac{V_{DS}}{I_D} \Big\} \text{(triode only)}$$

$$= \frac{1}{K_n' \frac{W}{L}\left(V_{GS}-V_{TN}-\frac{V_{DS}}{2}\right)}$$

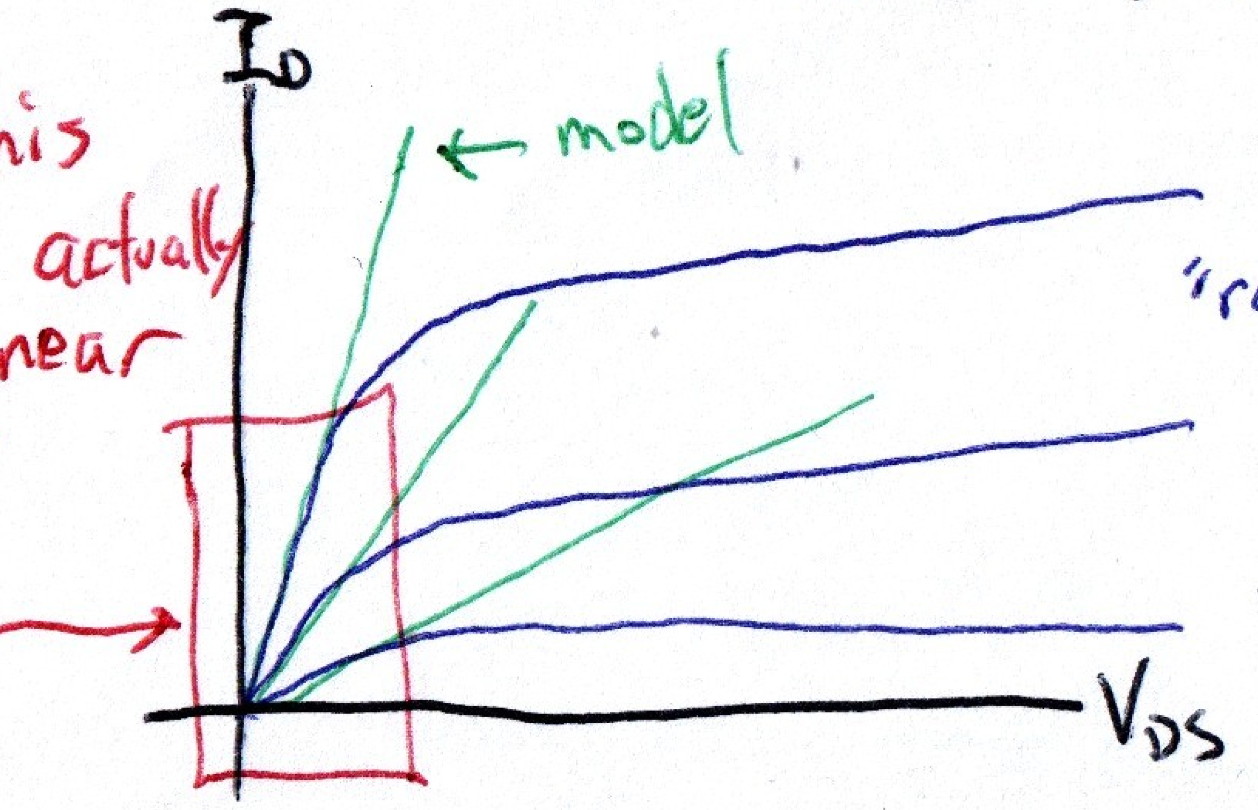
Another popular simple model is as a variable resistance, where "R_{on}" becomes a variable, dependant on V_{GS}:



Here, we are modeling the transistor as a voltage-dependant resistor.

This is the first time we can see PART of the real IV curves in the model:

Note! This model is actually accurate near $V_{DS}=0$!



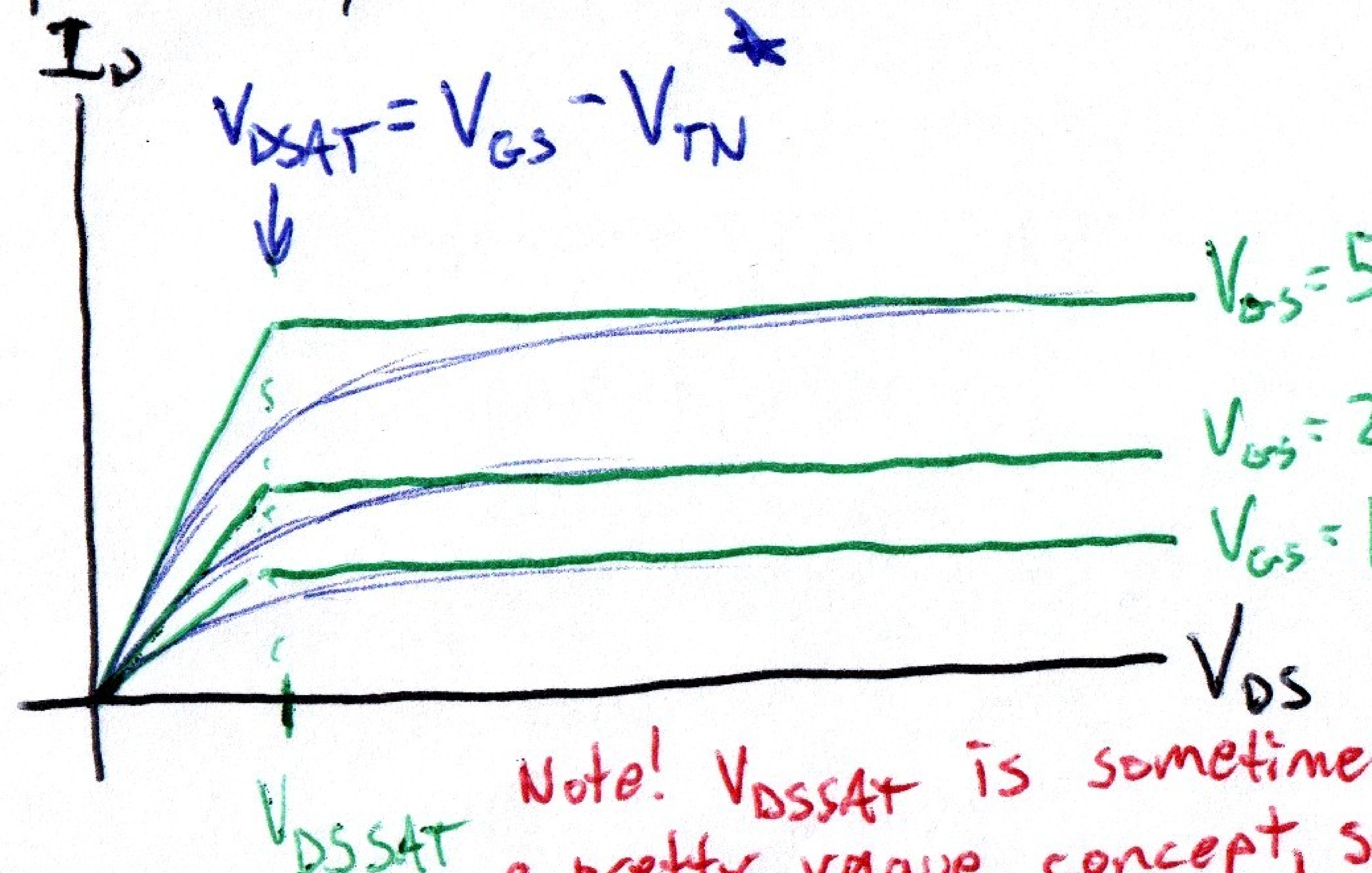
The variable resistance model only gets really bad at high V_{DS}, which is to say, saturation. In saturation, I_D is much more dependent on V_{GS} than V_{DS}, so the simplified version of this has this as a perfectly horizontal line:

Triode: USE R_{ON}

Saturation:

$$I_D = \frac{K_n'}{2}\frac{W}{L}(V_{GS}-V_{TN})^2$$

$(V_{GS}-V_{TN} \le V_{DS})$



Note! V_{DSSAT} is sometimes a pretty vague concept, so calculations near V_{DSSAT} can get ugly!

For digital applications, it's pretty rare to go more complex than this, but in Analog (Amplifiers, etc) more complex models are common.

*If you're feeling wreckless or impatient, you can use the rule of thumb $V_{DSAT} \simeq 0.3$
(Analog engineers do this all the time)

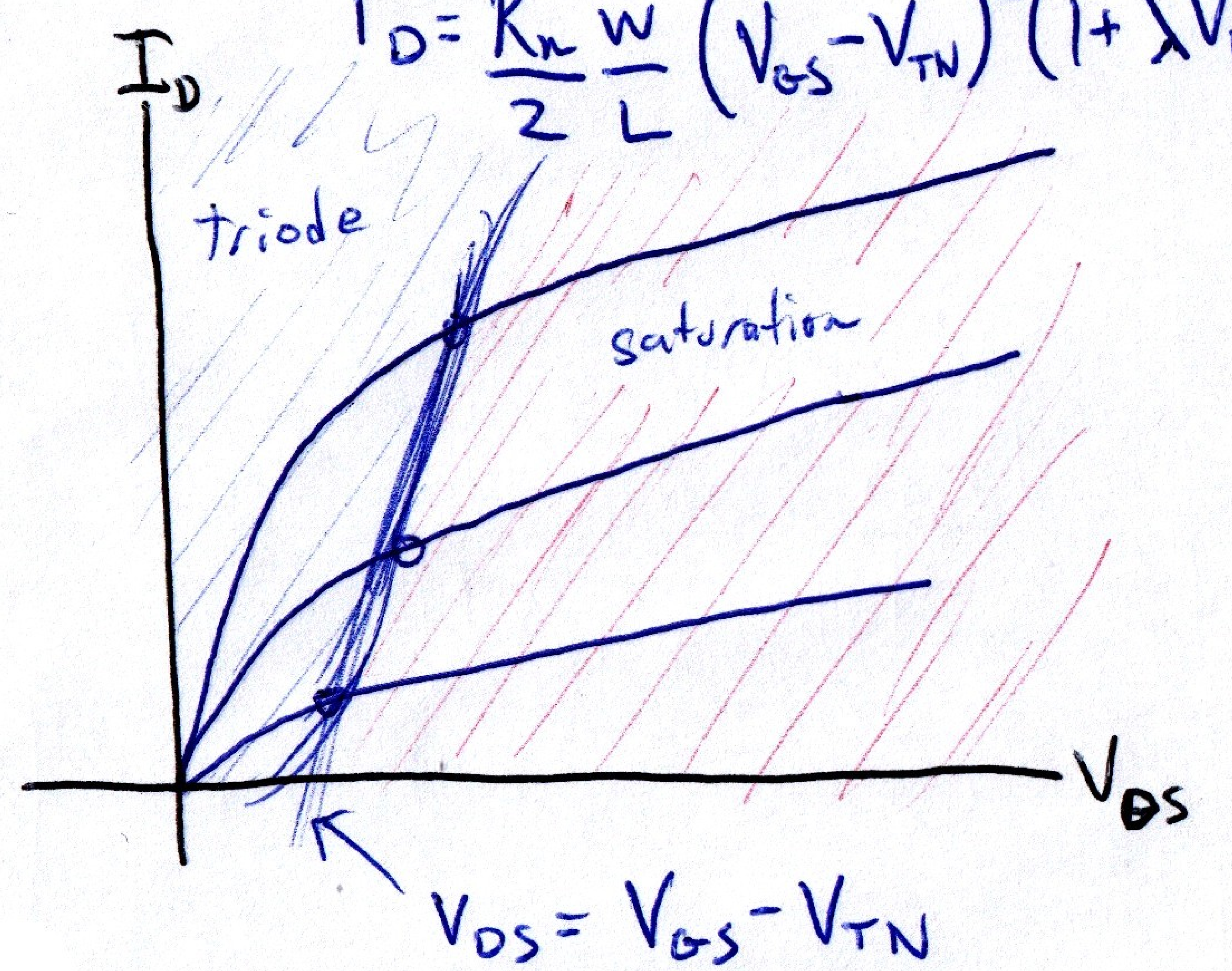
As more detailed calculations pile on, it gets more likely that you should switch to SPICE, but watch out! Even SPICE models have limits, and it is <u>very wrong</u> (although lots of people do it) to say that SPICE is the ultimate authority.

"Full" NMOS Model:

$$i_D = K_n' \frac{W}{L}\left(V_{GS} - V_{TN} - \frac{V_{DS}}{2}\right) V_{DS}$$

OR

$$i_D = \frac{K_n'}{2} \frac{W}{L} \left(V_{GS} - V_{TN}\right)^2 \left(1 + \lambda V_{DS}\right)$$



(Not Shown, the Body Effect:)

$$V_{TN} = V_{TO} + \gamma\left(\sqrt{V_{SB} + 2\phi_F} - \sqrt{2\phi_F}\right)$$

....or the many, many weird things happenning in modern SPICE models....

$$V_{th} = V_{th0} + K_1\left(\sqrt{\phi_s - V_{bs}} - \sqrt{\phi_s}\right) - K_2 V_{bs} + K_1\sqrt{\phi_s}\sqrt{1 + \frac{N_{lx}}{L_{eff}}} - 1$$

$$\frac{\pi q N_a (X_{dmax})^2}{2 C_{ox} W} = 3\pi \frac{T_{ox}}{W} \phi_s$$

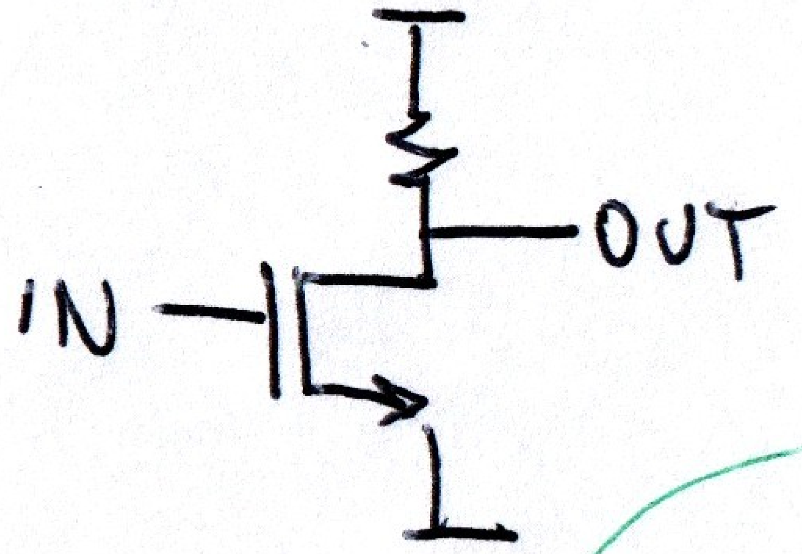
$$I_{DS} = \mu_{eff} C_{ox} \frac{W}{L} \frac{1}{1 + V_{DS}/E_{SAT}L} \left(V_{gs} - V_{th} - A_{bulk} V_{ds}\right)$$

(Do not use any of these in this class)
(You will only make yourself unhappy.)

Qualitative Transistor Story Time

Amplifiers:

Always in saturation (unless clipping)



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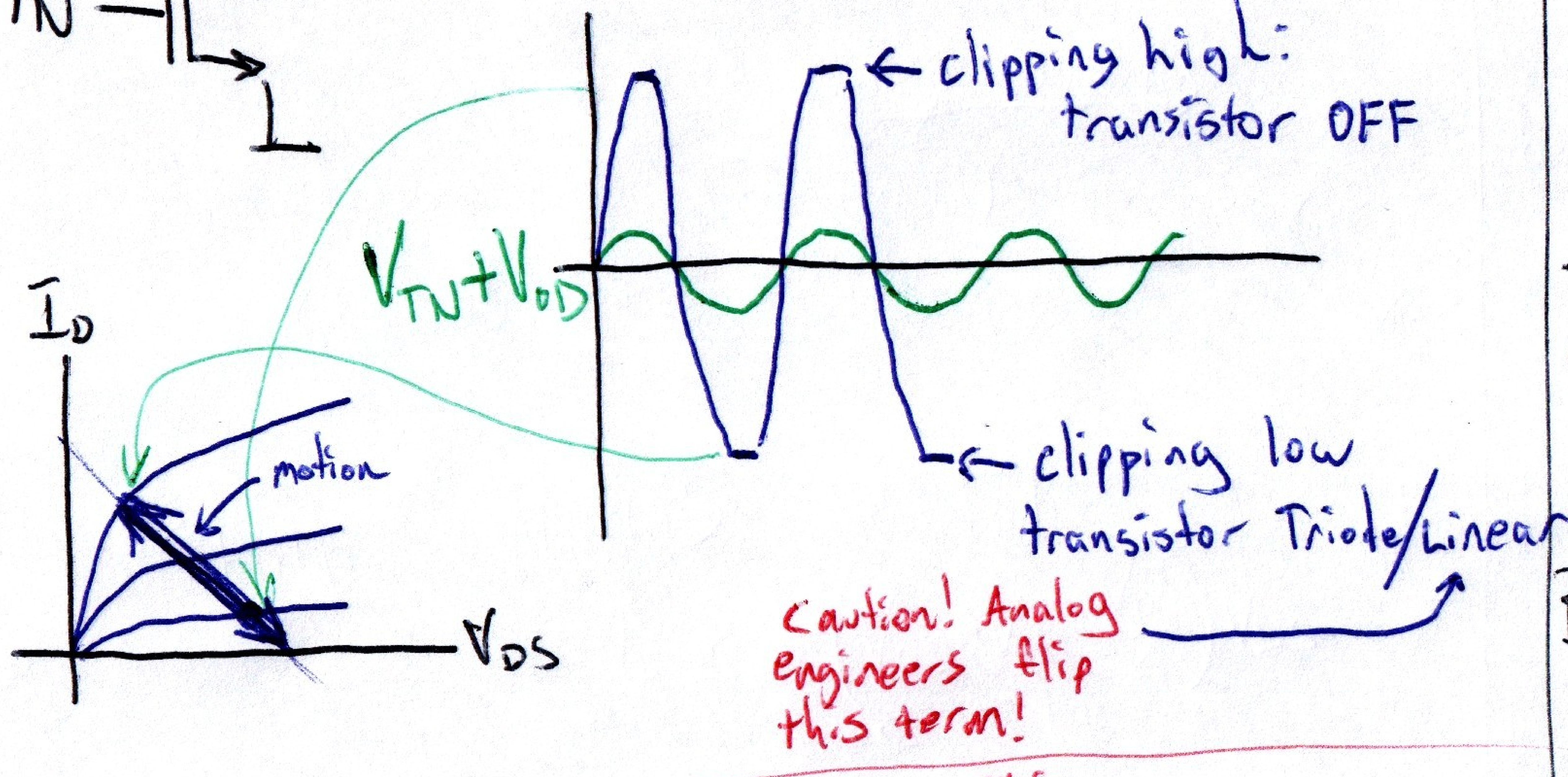
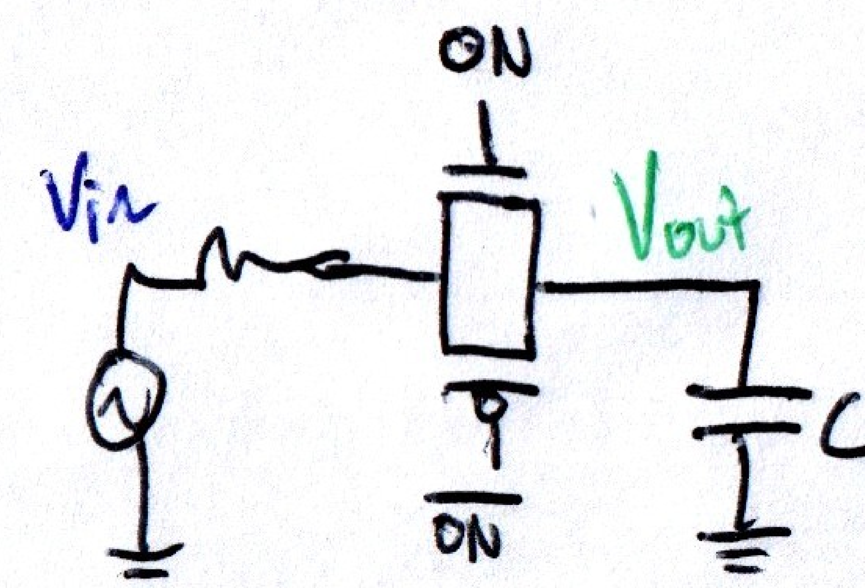
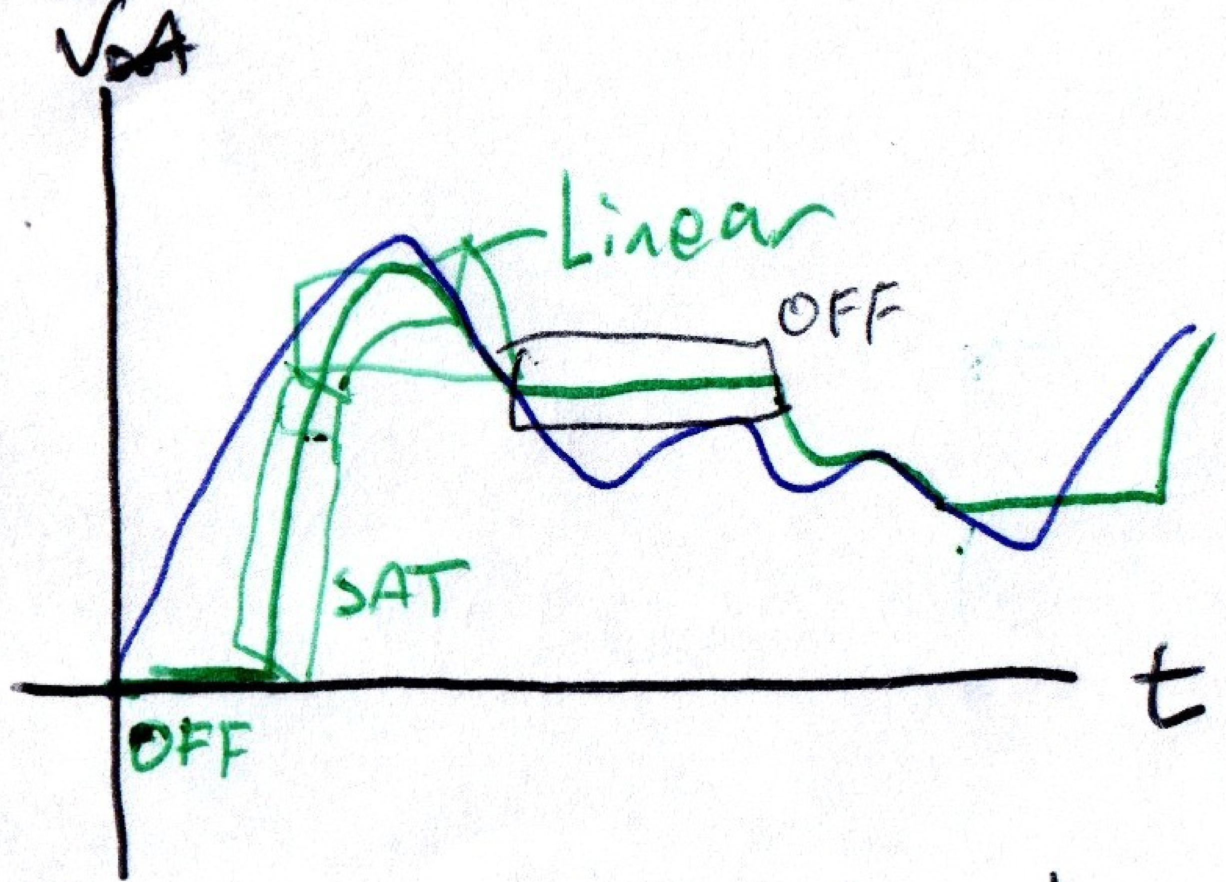


Analog Switches



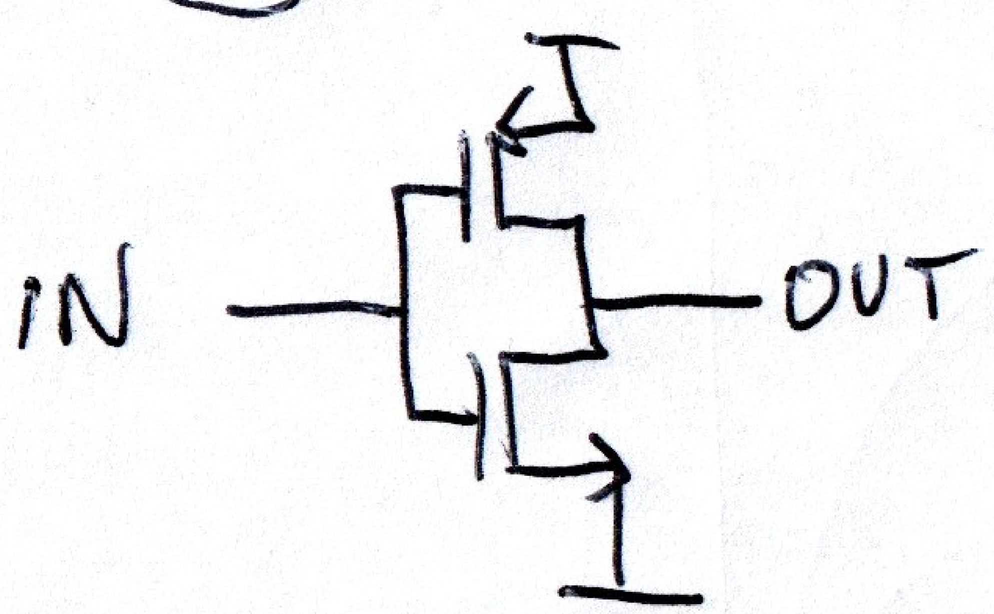


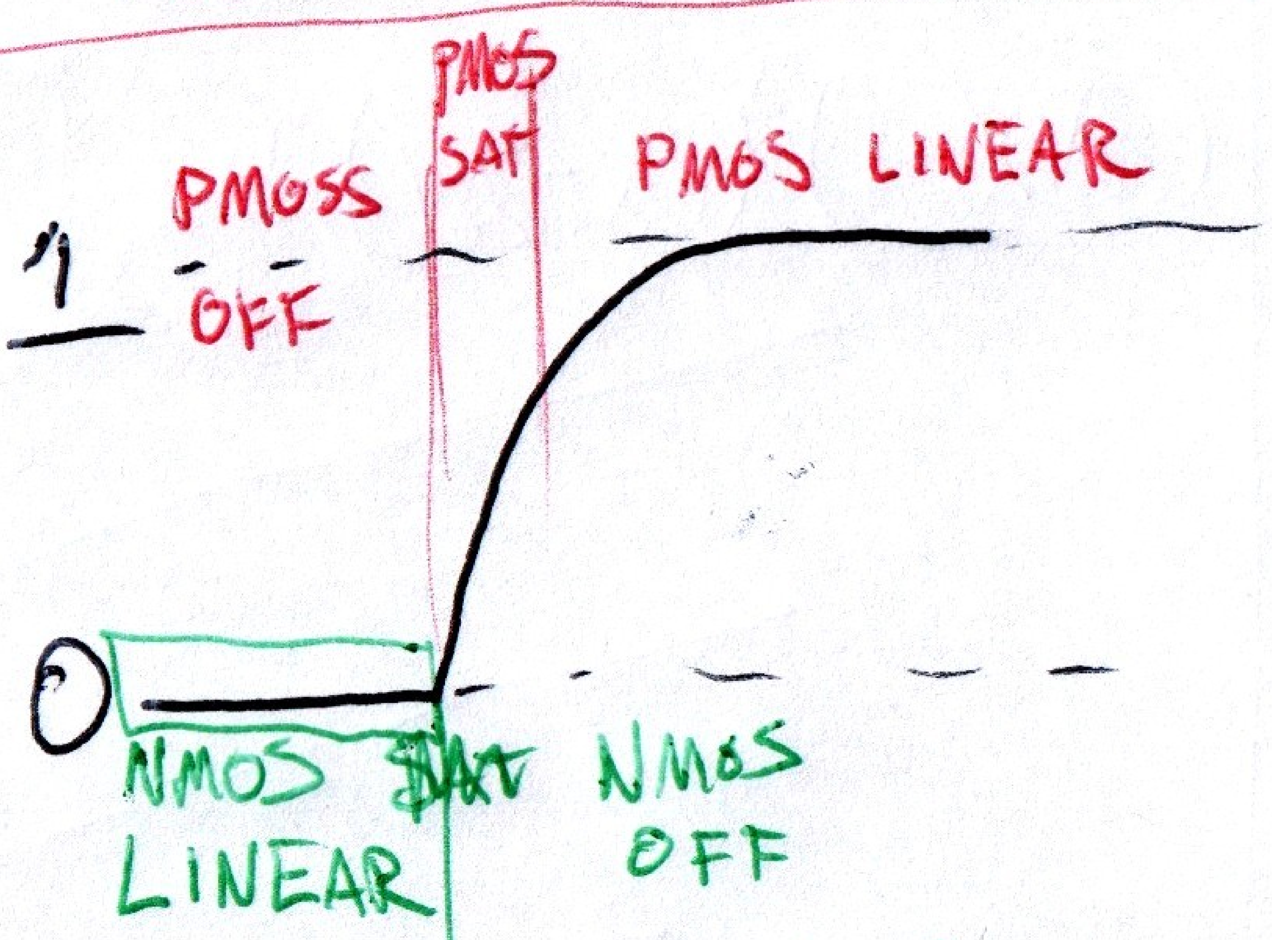
– If V_{in} and V_{out} are different with the switch on, The devices may be in saturation

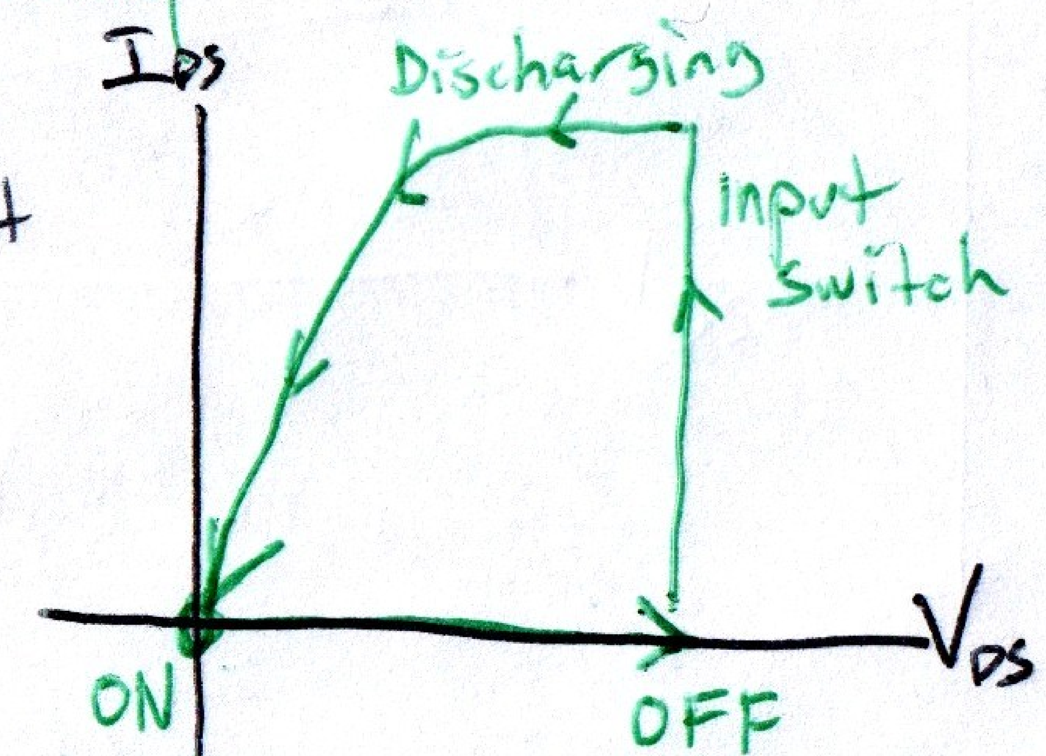
– Once C_x is charged, though, they will be in the linear region

BASICALLY, OFF: any voltage, zero current
SAT: high voltage & current
TRIODE/LINEAR: low voltage & current

Logic Gates:







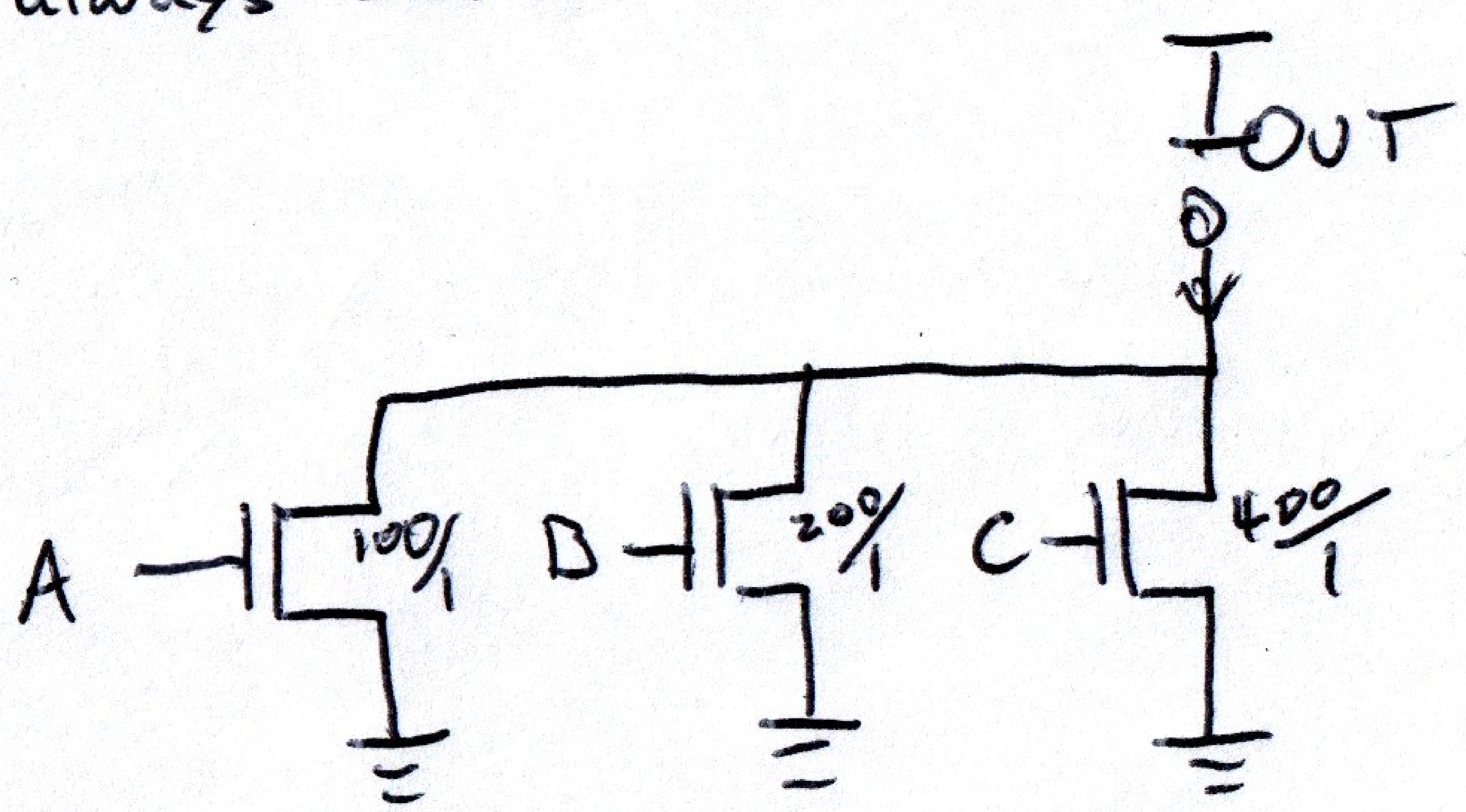
– The transistor switching off jumps from linear with no current to off with no current.

– The activating transistor is briefly in saturation before moving into the linear region

Current-Mode DAC

– The Voltage at I_{out} is always high

– A, B, C always sat or off because of this



A B C	I_{out}
0 0 0	0
1 0 0	1mA
1 1 0	3mA
0 0 1	4mA
1 0 1	5mA