

IC Design Tutorial

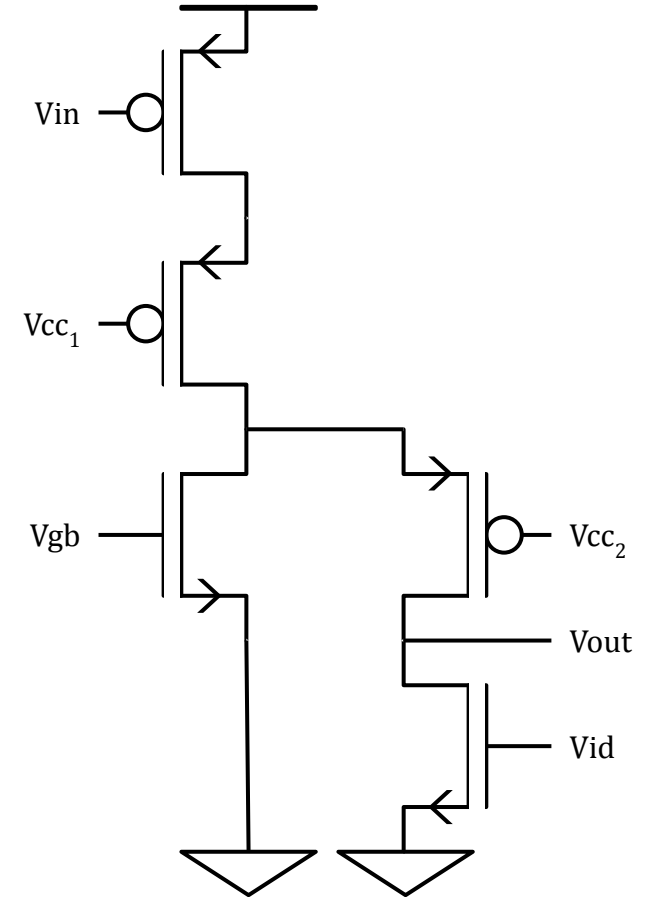
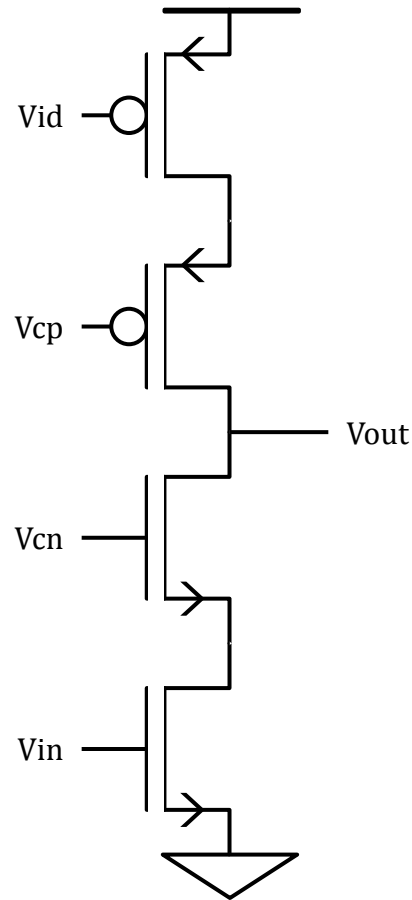
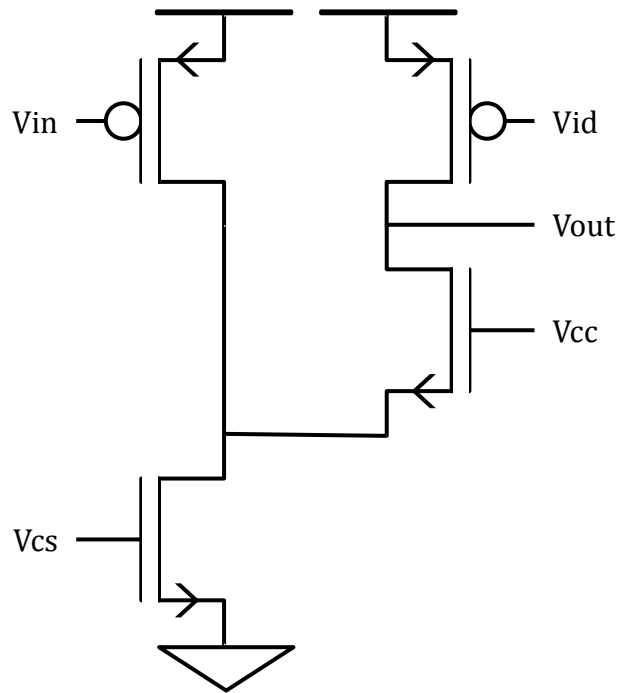
HEPIC Summer Week

Victor Turbiner

2025

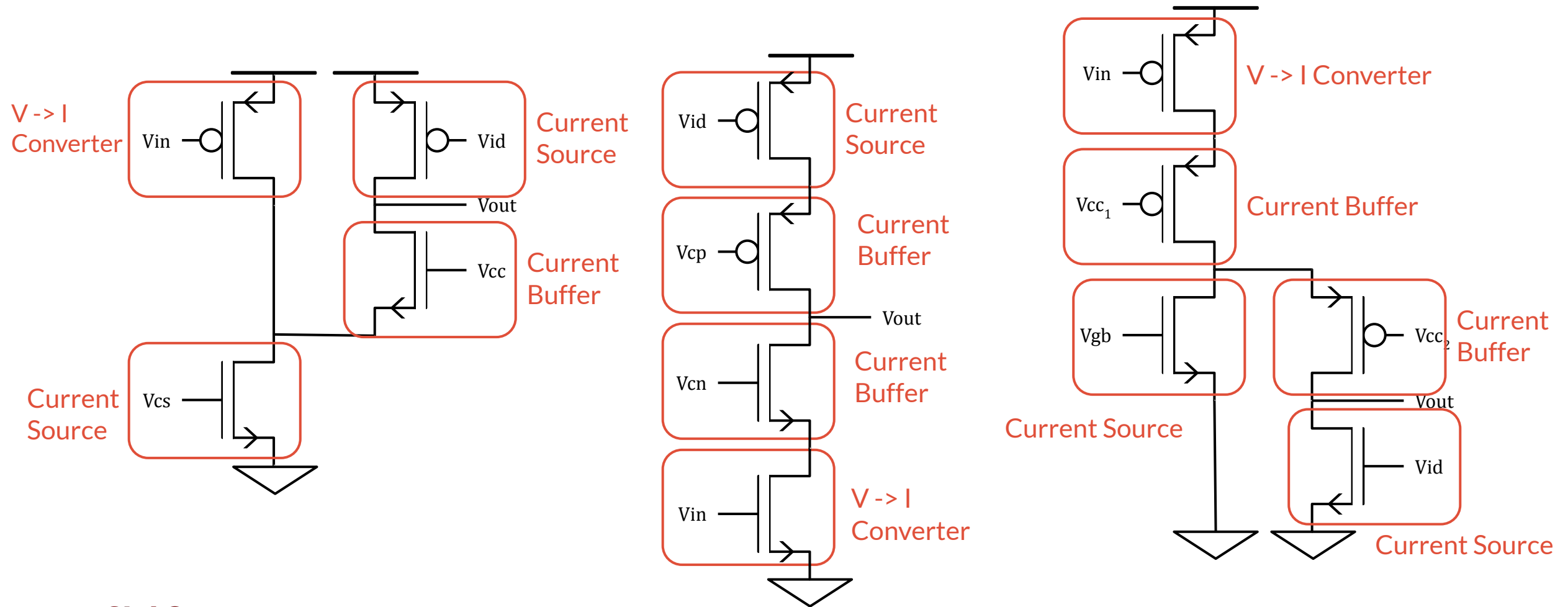
The End Goal

Look at these circuits and intuitively understand what they do



The Approach

Break circuits down into modular blocks



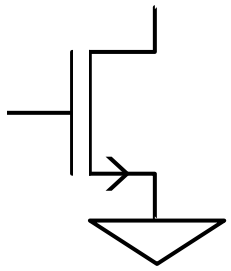
The Steps

1. Small Signal DC Analysis
 - a. The three types of building blocks
 - i. $I \rightarrow V$ and $V \rightarrow$ Converters
 - ii. Impedance Transformers
 - b. How to quickly solve any circuit with no feedback loops
 - c. Designing circuits with building blocks
2. DC Biasing And Sizing Transistors
 - a. Device equations and g_m/I_d
 - b. How to size transistors to get a desired g_m
 - c. Current sources
3. AC Analysis And Feedback
 - a. Charge-sensitive amplifiers and diode readouts
 - b. The open-loop intrinsic gain stage
 - c. Adding capacitive feedback
 - d. Working with multi-stage amplifiers

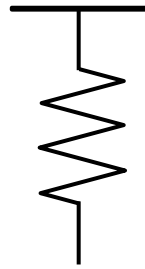
Small Signal DC Analysis

Three types of building blocks

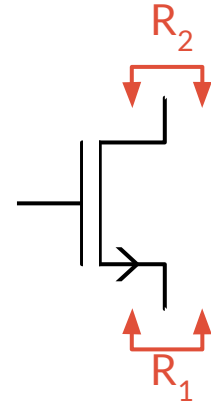
The Three Types of Building Blocks



$V \rightarrow I$
Converters

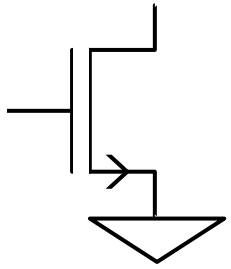


$I \rightarrow V$
Converters

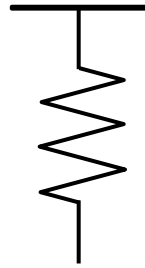


Impedance
Transformers

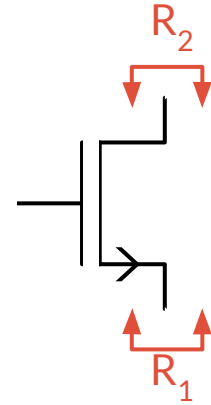
The Three Types of Building Blocks



$V \rightarrow I$
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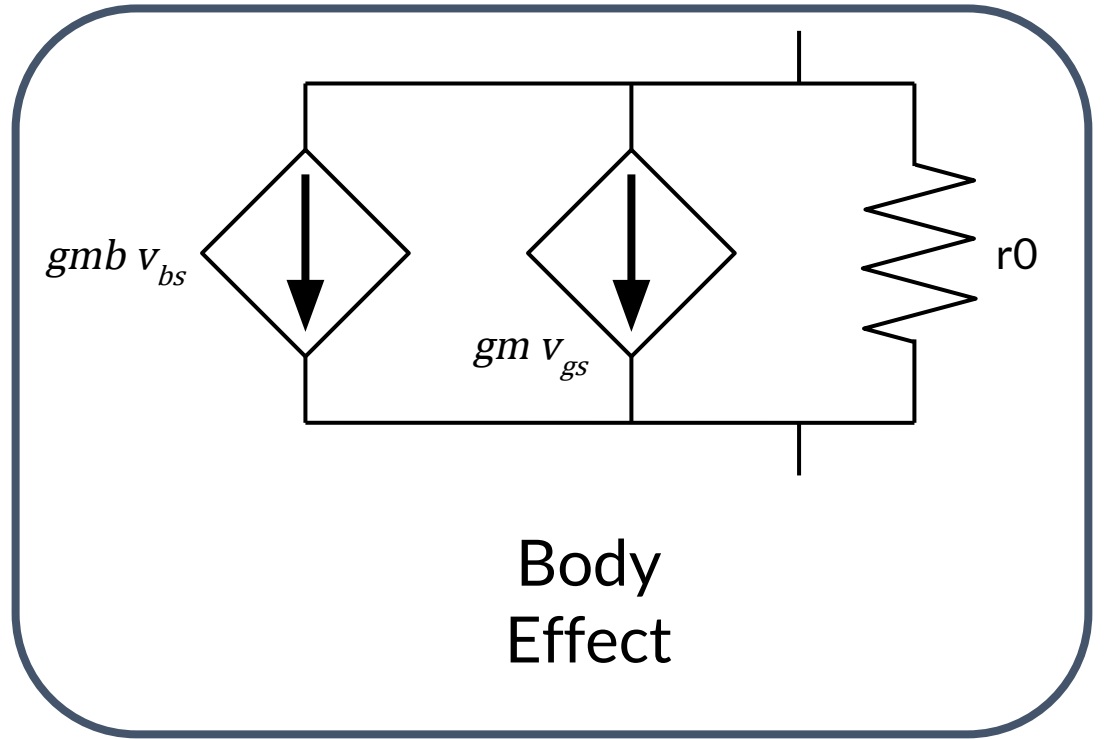
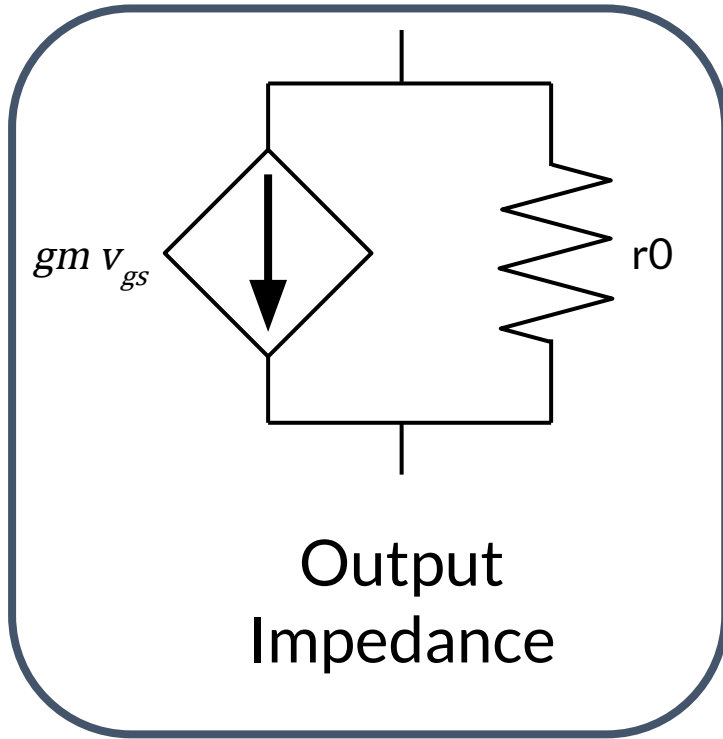
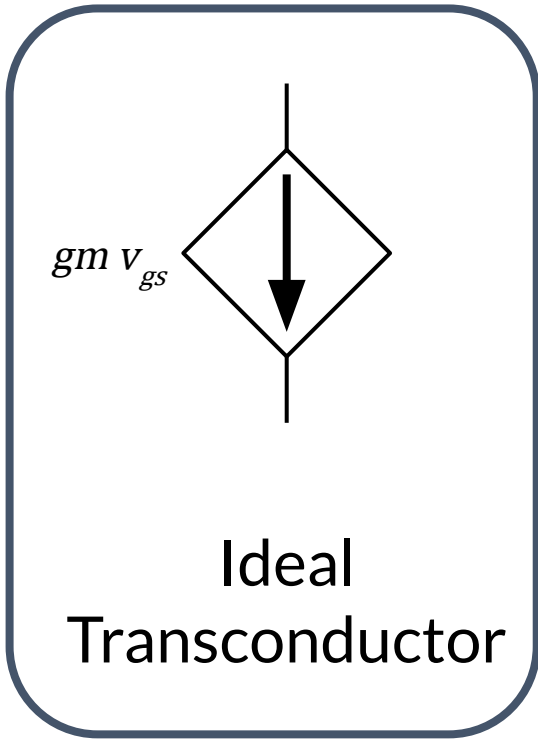


$I \rightarrow V$
Converters

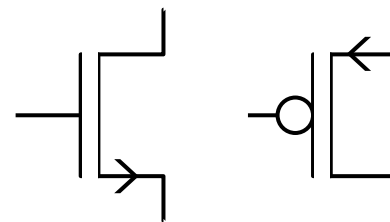


Impedance
Transformers

MOSFET Small Signal Models

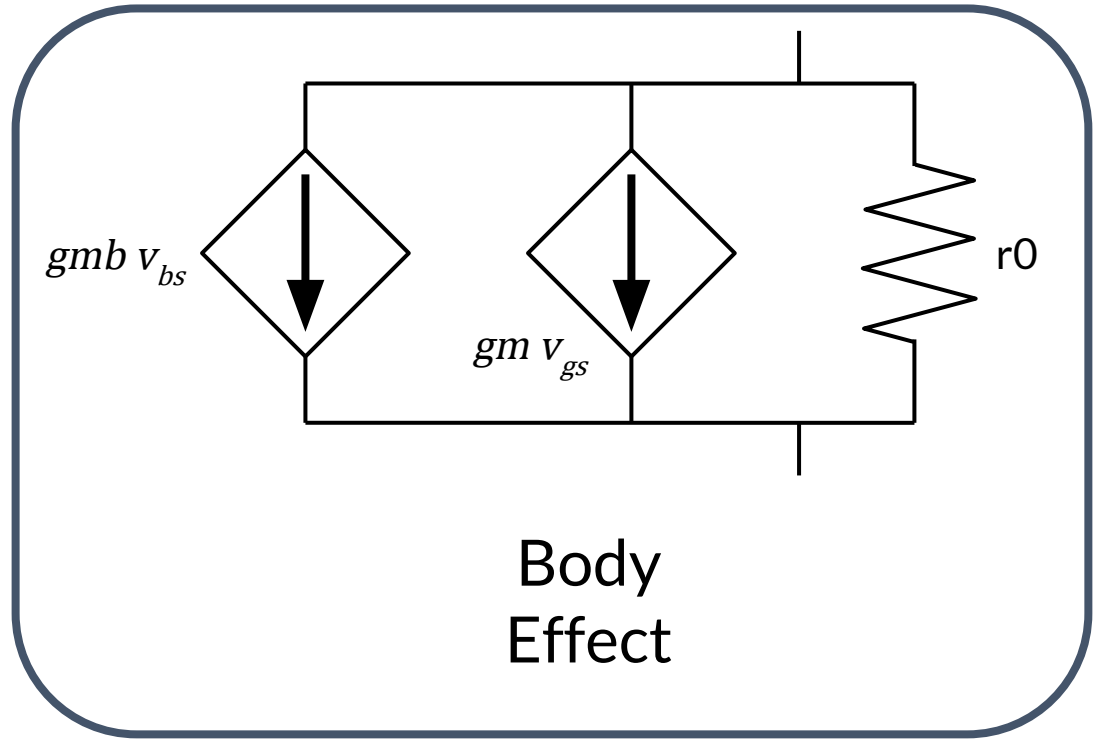
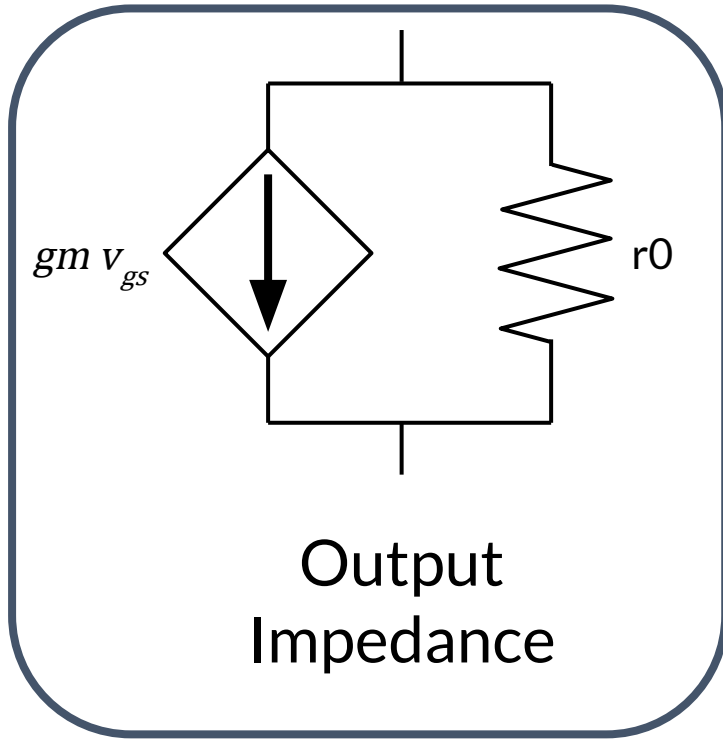
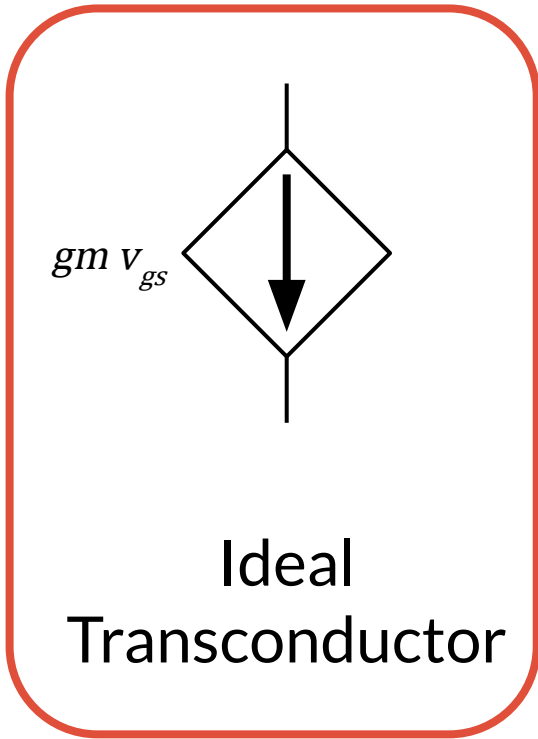


Same model for both:

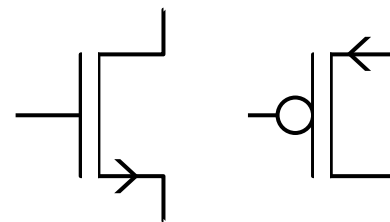


MOSFET Small Signal Models

We'll start with ideal transconductor

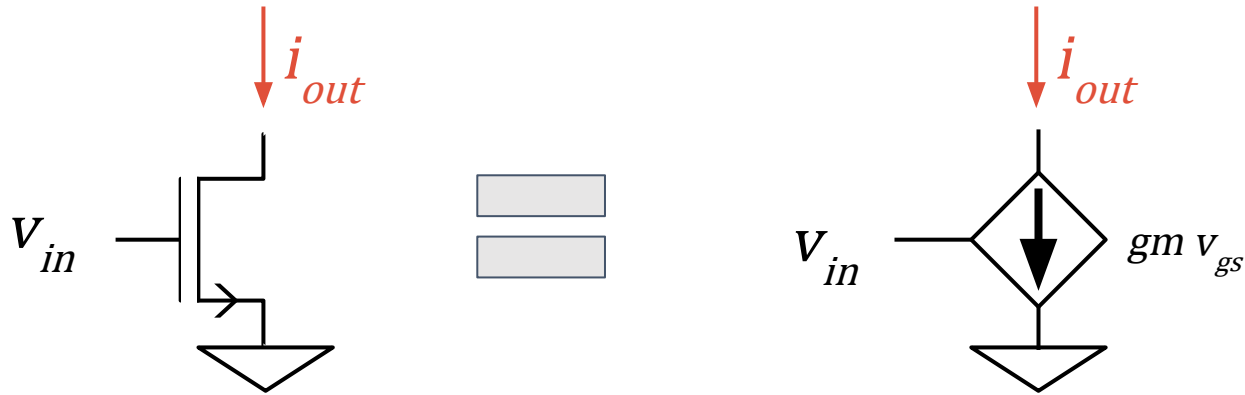


Same model for both:



V → I Converters

A MOSFET in the common-source configuration is used as a voltage to current converter.



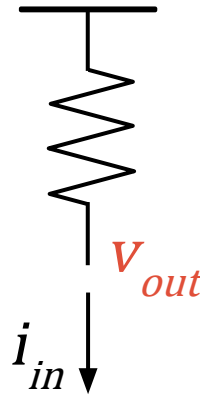
$$i_{out} = g_m (v_{gate} - v_{source})$$

$$i_{out} = g_m (v_{in} - 0)$$

$$i_{out} = g_m v_{in}$$

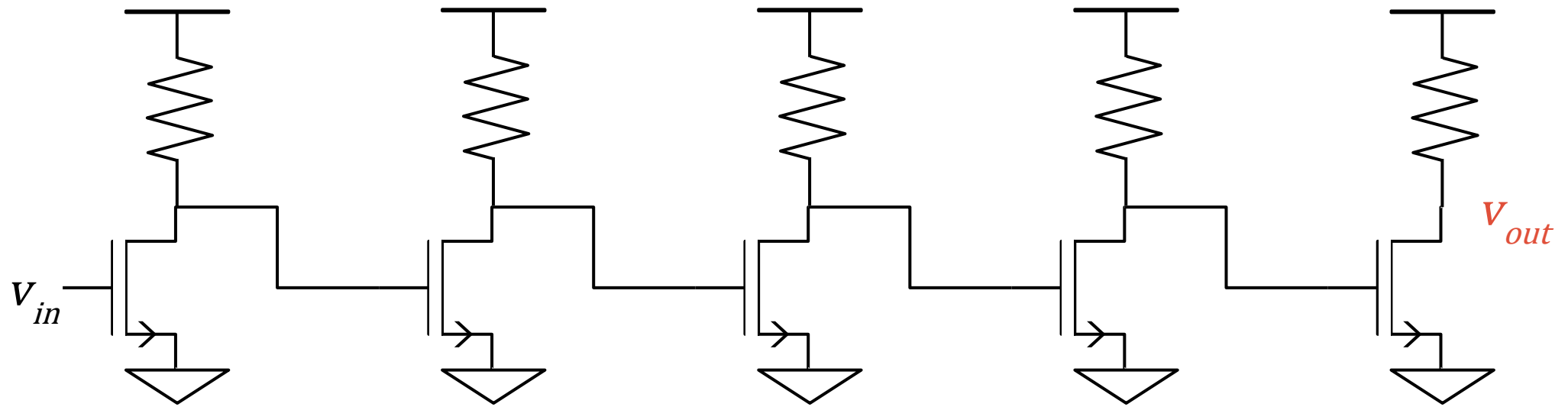
I \rightarrow V Converters

A resistor is commonly used when we need to convert a current back into a voltage.



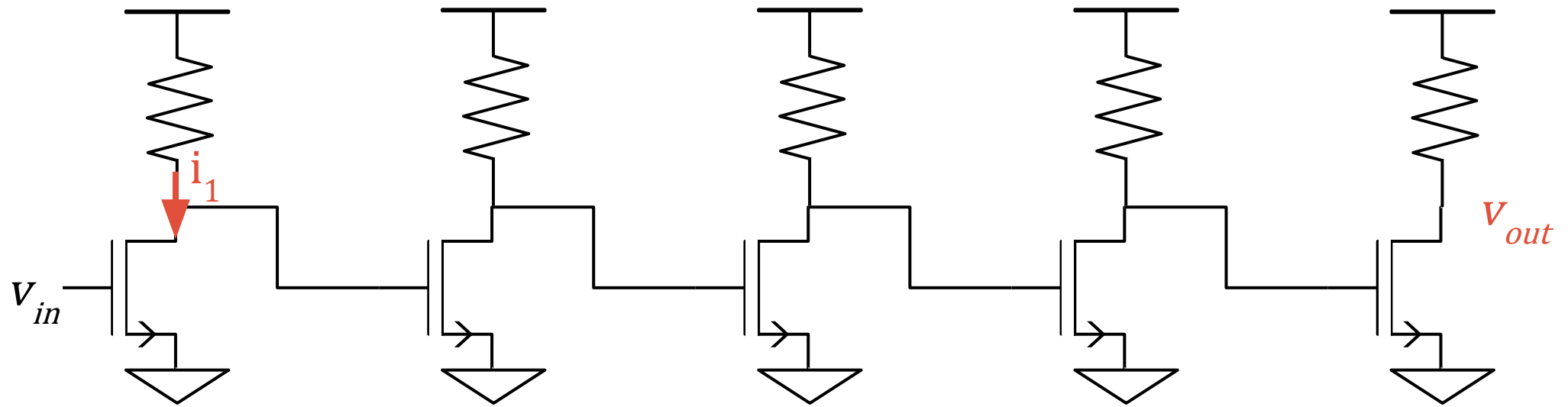
$$v_{out} = i_{in}R$$

Chaining stages together



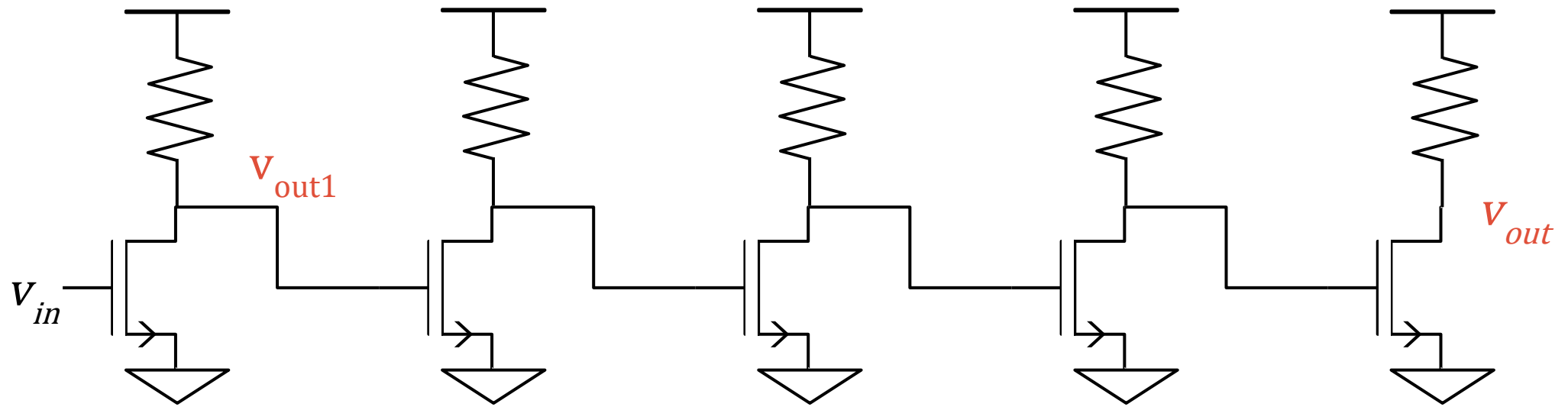
Chaining stages together

$$i_1 = g_{mn1} V_{in}$$



Chaining stages together

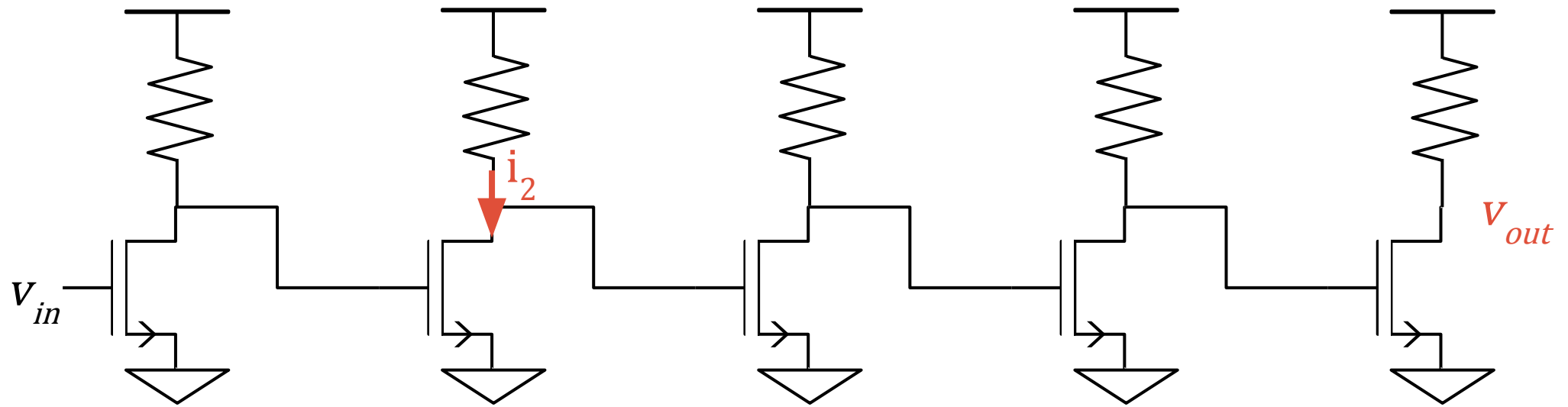
$$i_1 = g_{m1} V_{in}$$



$$v_{out1} = i_1 R_1 = g_{m1} R_1 v_{in}$$

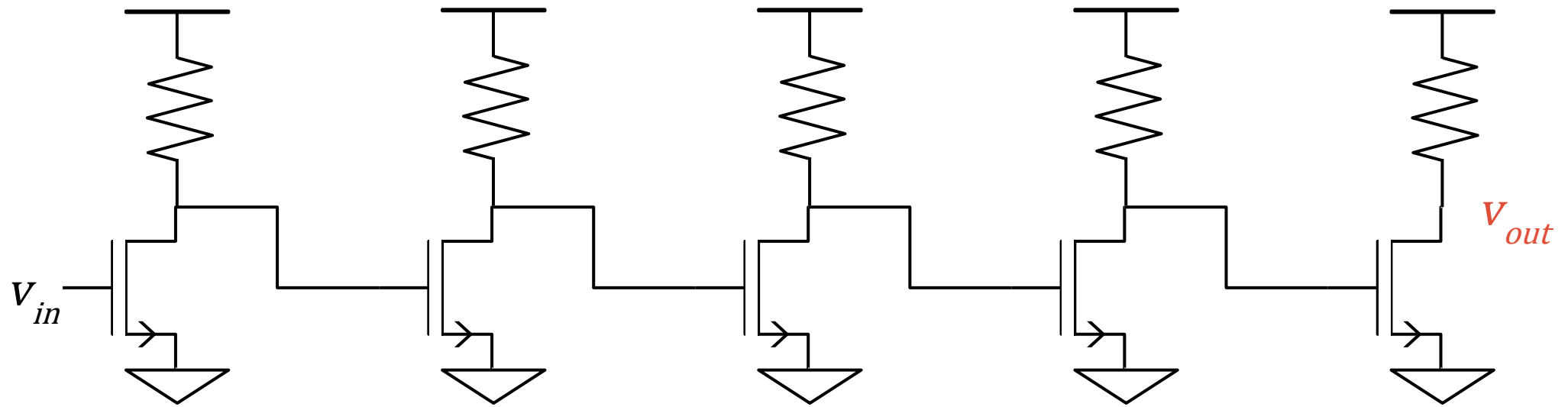
Chaining stages together

$$i_1 = g_{m1}V_{in} \quad i_2 = g_{m2}v_{out1} = g_{m1}R_1g_{m2}v_{in}$$



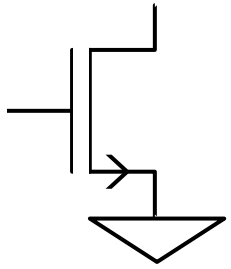
$$v_{out1} = i_1R_1 = g_{m1}R_1v_{in}$$

Chaining stages together

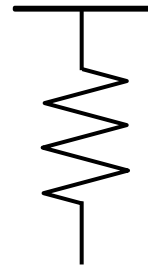


$$\frac{v_{out}}{v_{in}} = \prod_{i=1}^N g_{mi} R_i$$

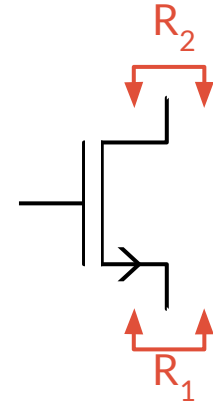
The Three Types of Building Blocks



$V \rightarrow I$
Converters

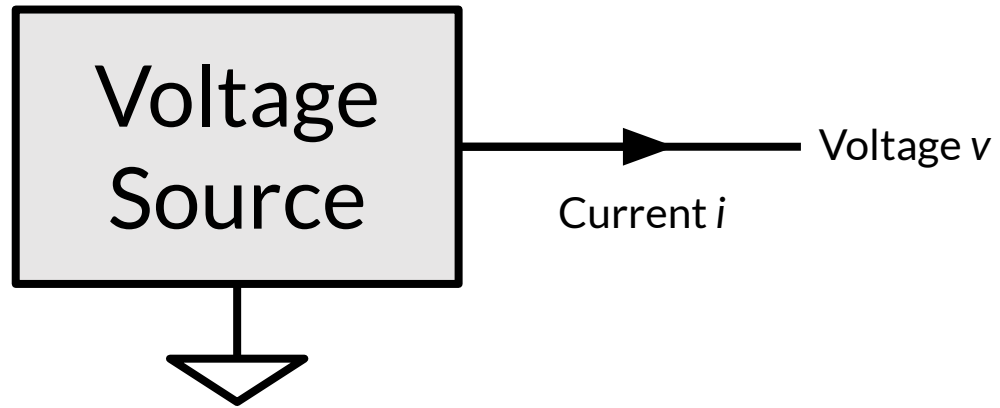


$I \rightarrow V$
Converters



Impedance
Transformers

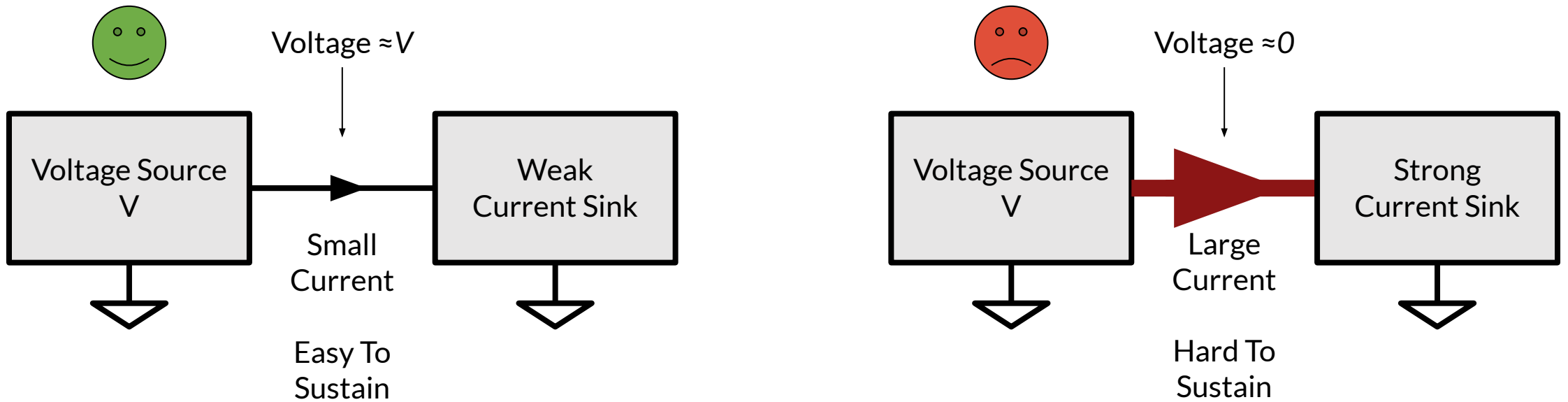
Consider a generic source of voltage



$$v = v(i) = v_0 + iR_{eq}$$

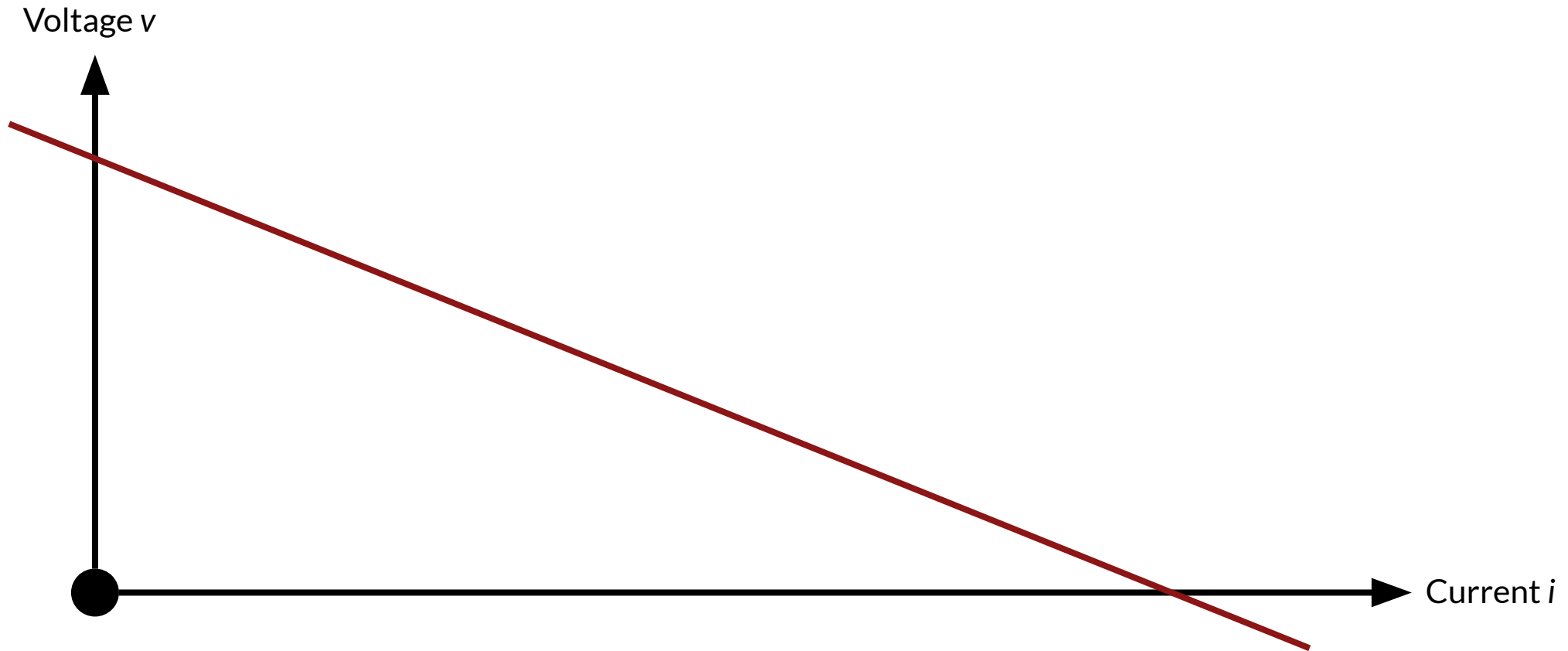
It takes “effort” to emit a current

The more current is taken from the voltage source, the more it struggles to maintain its voltage



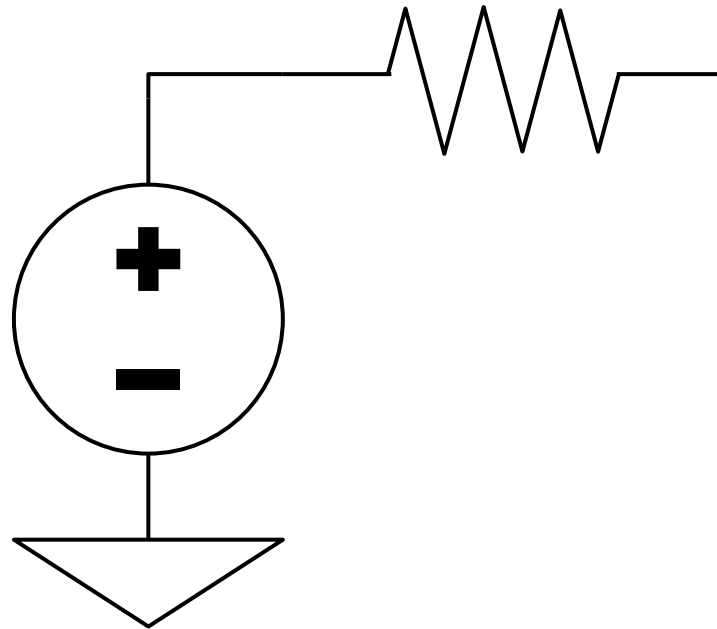
It takes “effort” to emit a current

The more current is taken from the voltage source, the more it struggles to maintain its voltage



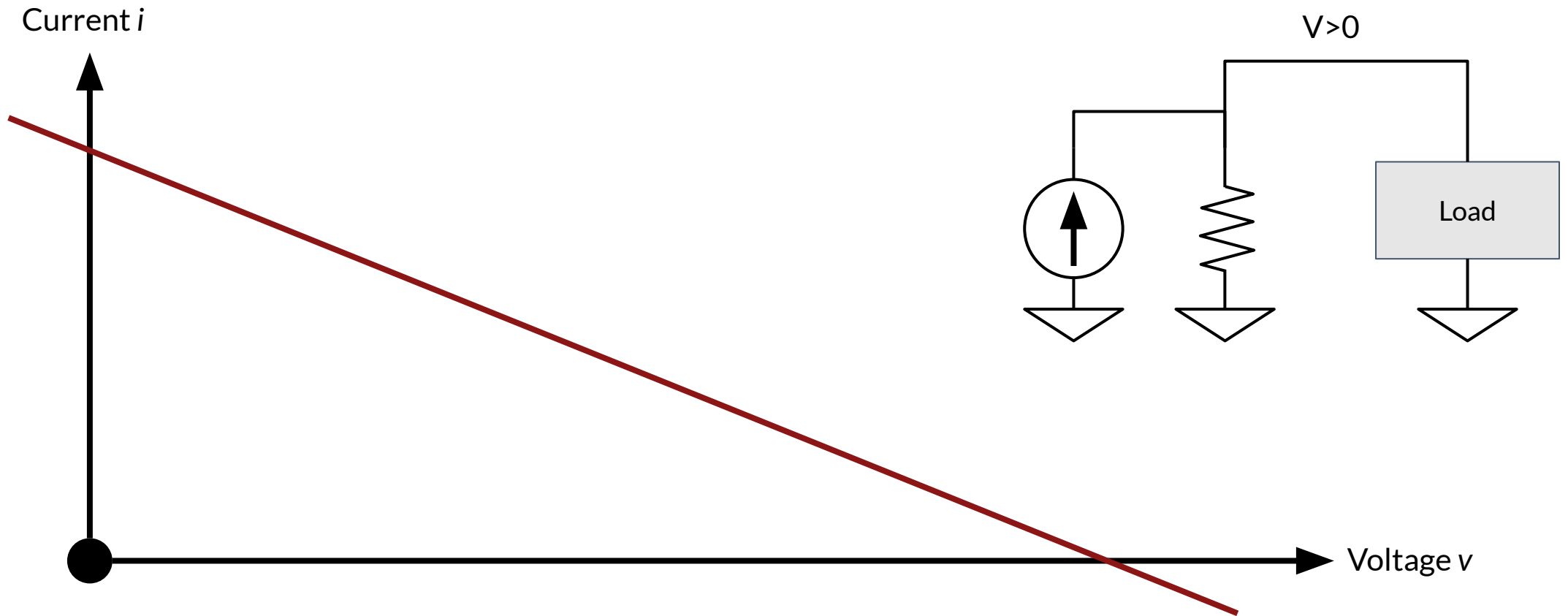
So a voltage source has some impedance

Once too much current is drawn from the voltage source, the resistor cancels it out



Similarly, it takes “effort” to maintain a voltage

The more voltage is needed, the more the source struggles to maintain it. Once too much voltage is applied, the current is controlled by the resistor, not the current source.

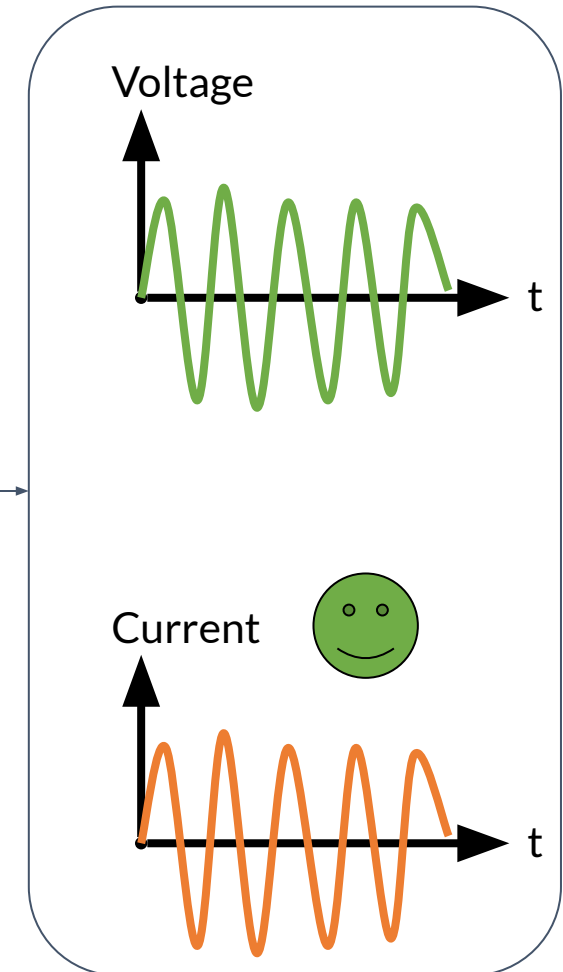
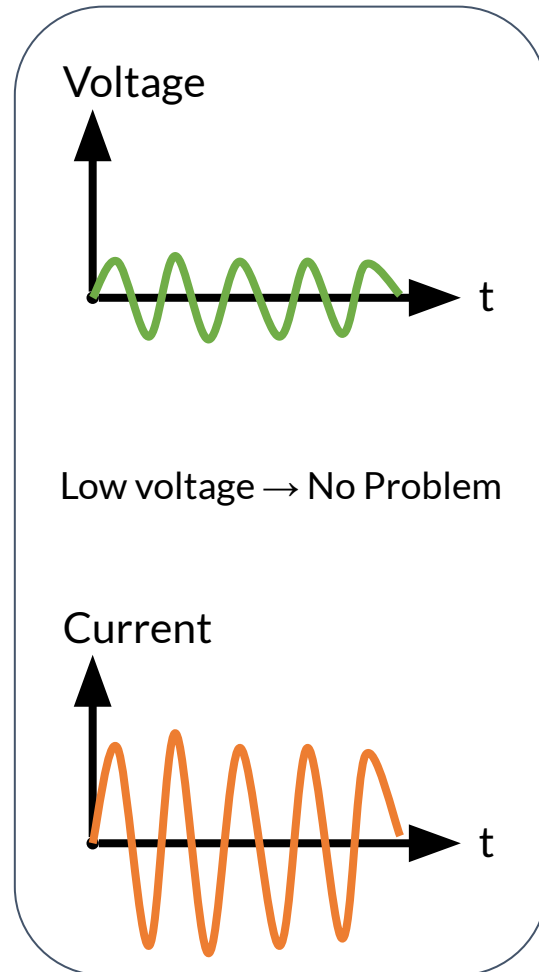
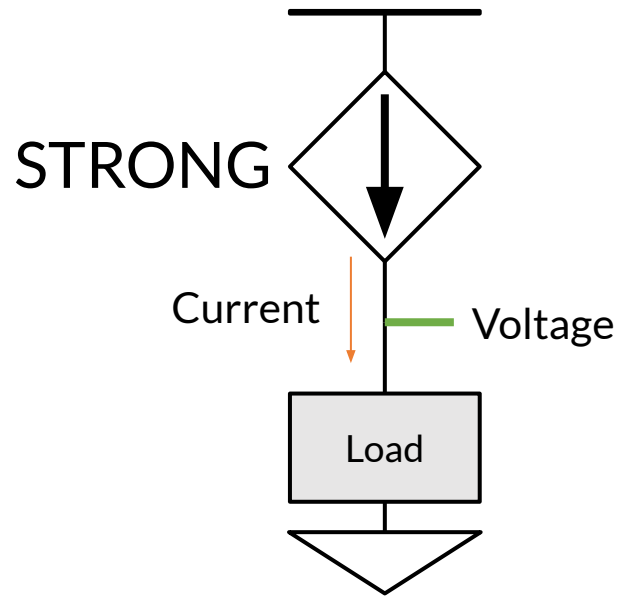


Sources of voltage and current are never ideal

Can we improve the “strength” of a current source?

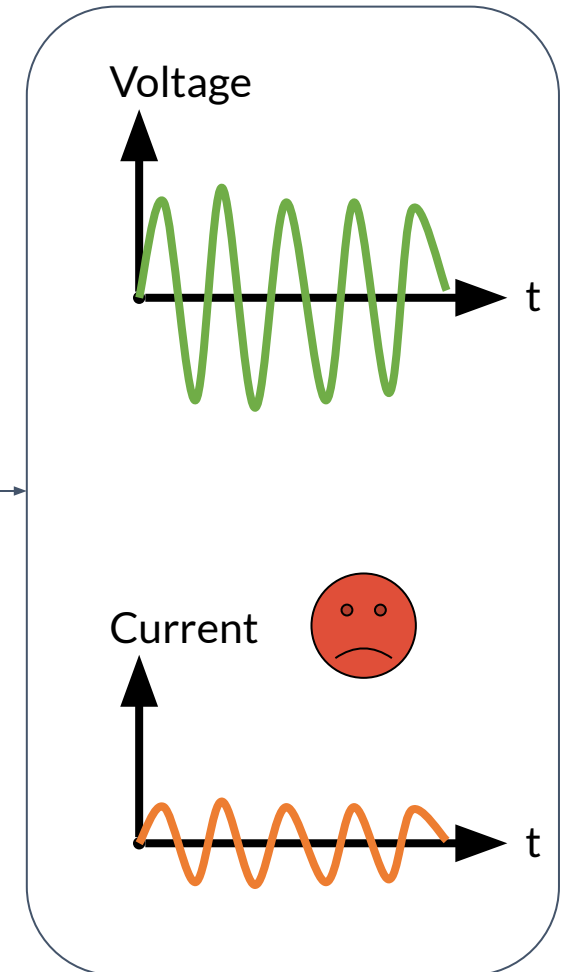
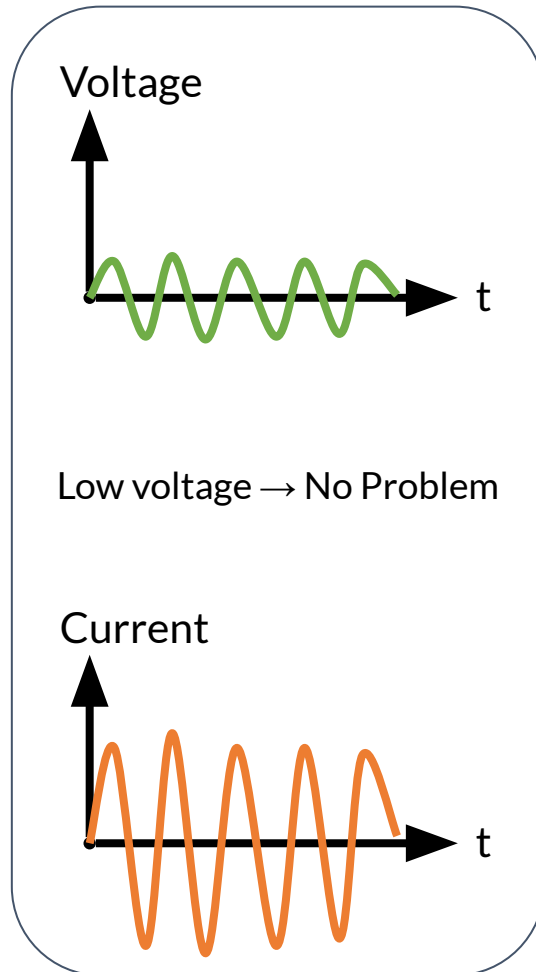
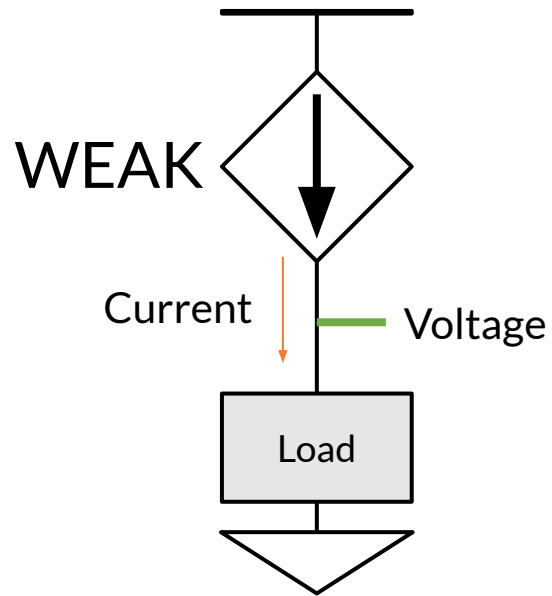
What is a “strong” source of current?

A strong source maintains a constant current at any voltage



What is a “strong” source of current?

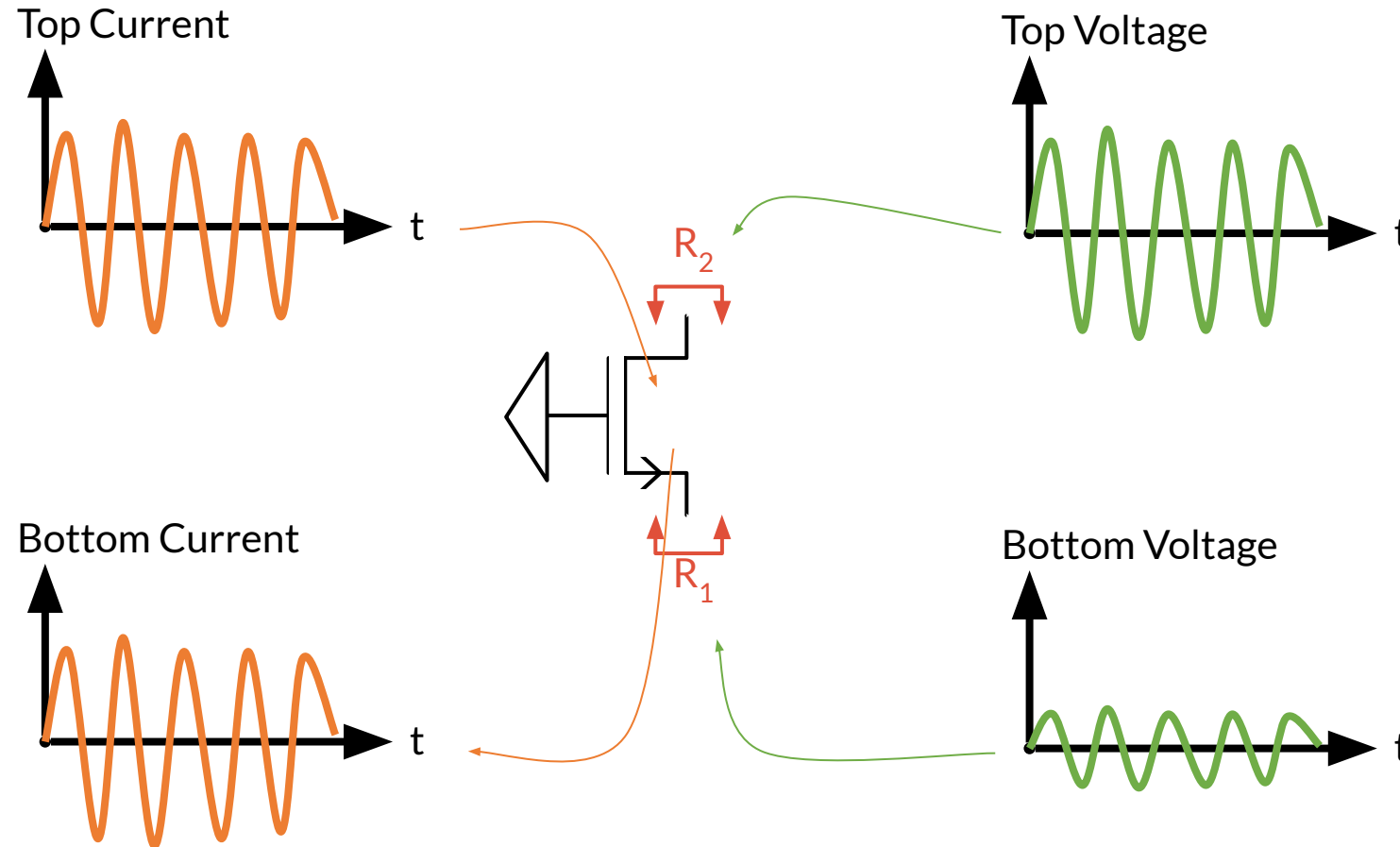
A weak source is unable to maintain its current at high voltages



The common gate stage provides “isolation”

The drain of the transistor can freely “wiggle” while the source remains at a fixed voltage.

The current across the common gate stage is constant.



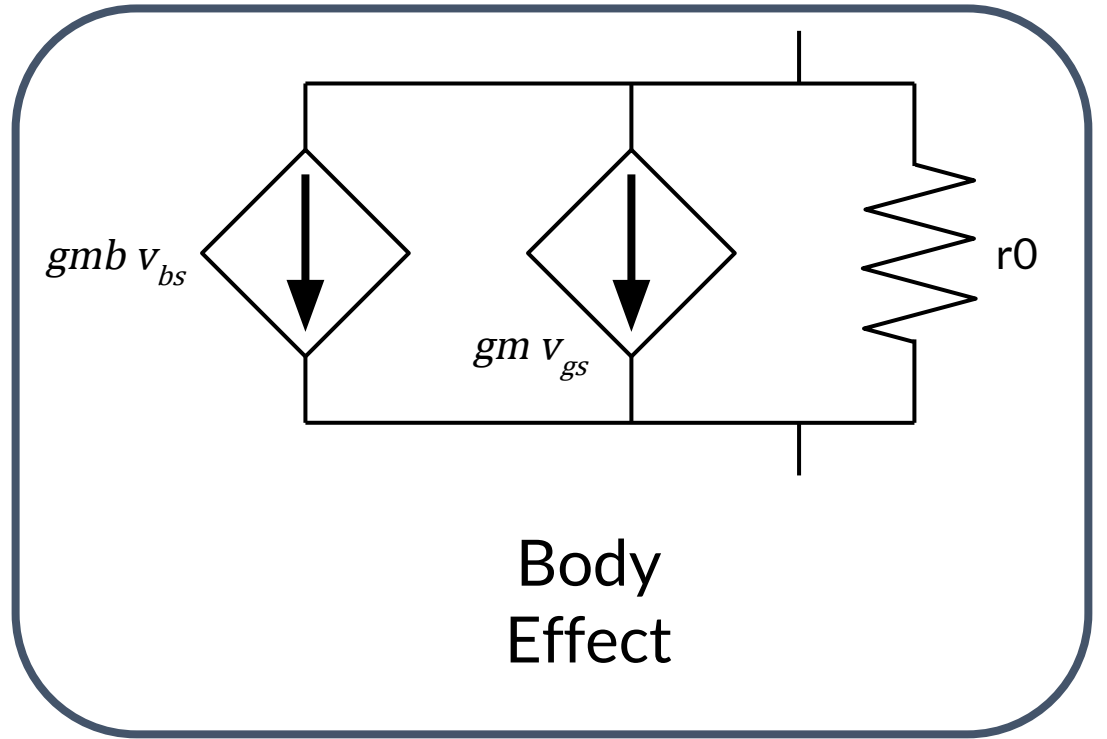
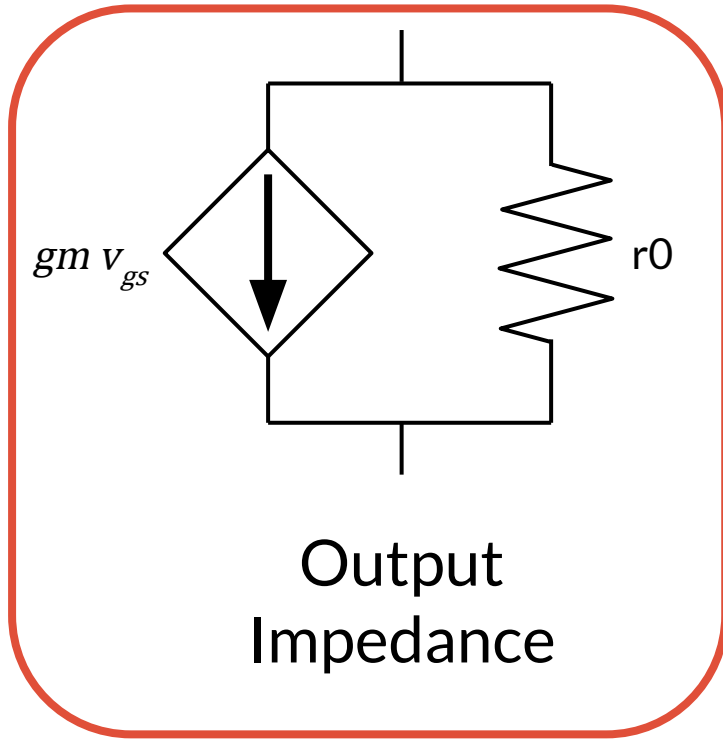
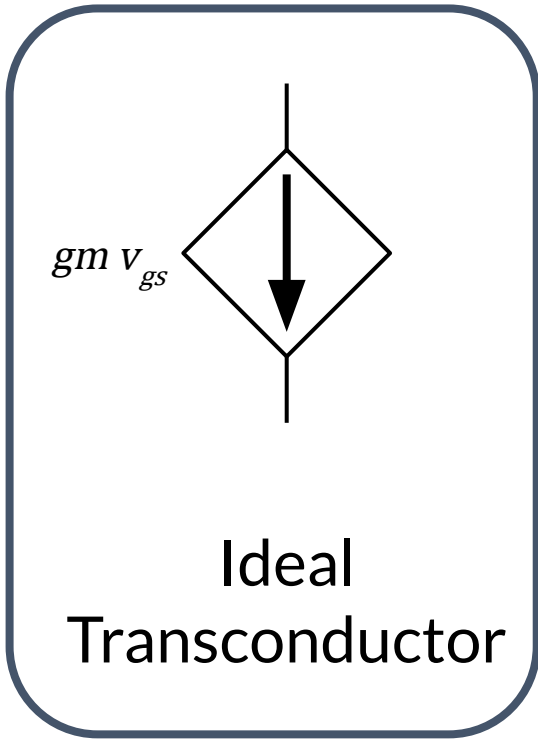
$$R_2 \gg R_1$$

Small Signal DC Analysis

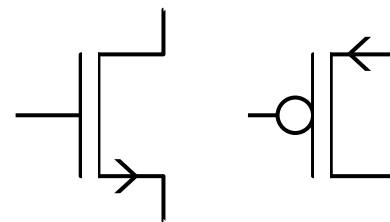
How to quickly solve circuit problems without feedback

MOSFET Small Signal Models

We'll start with ideal transconductor

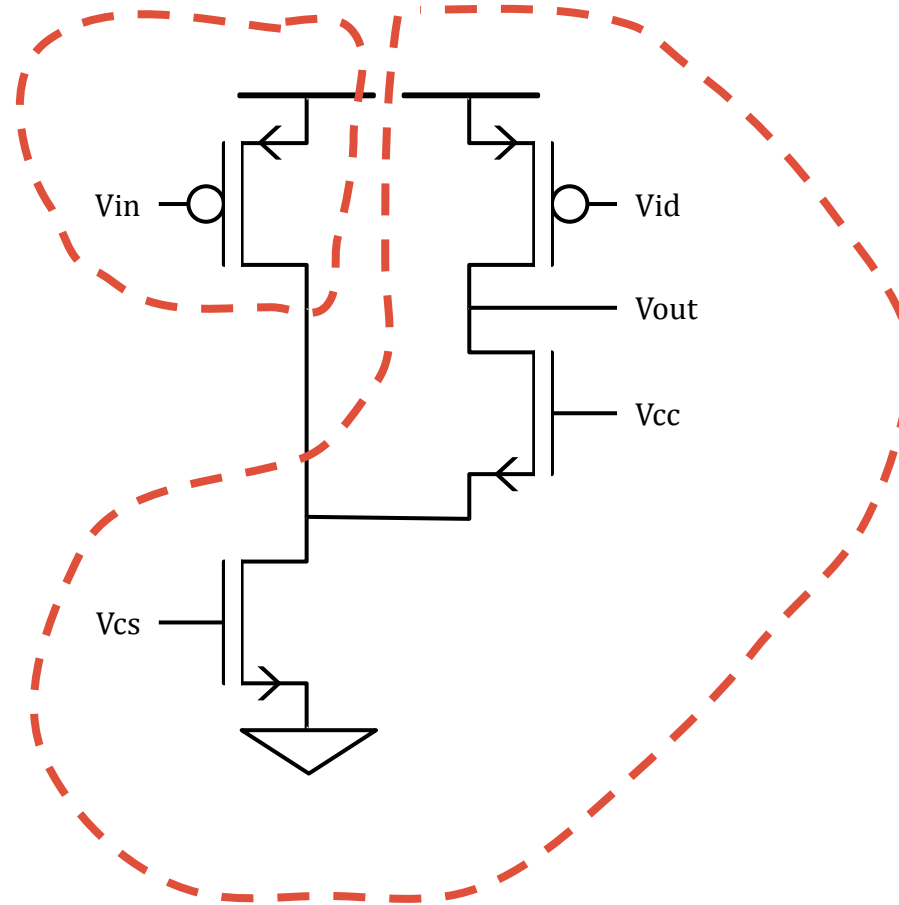


Same model for both:



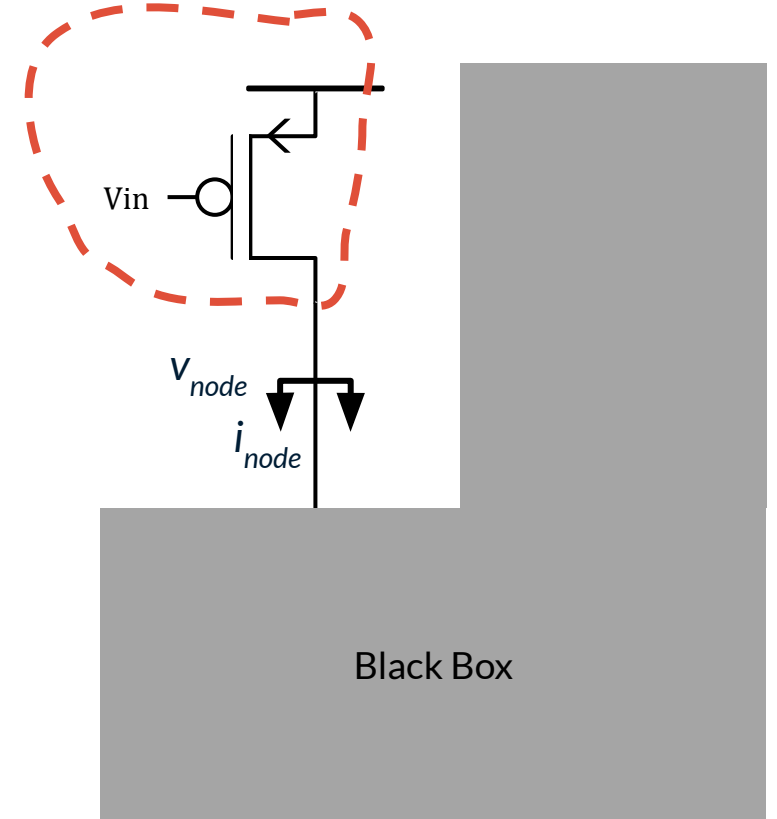
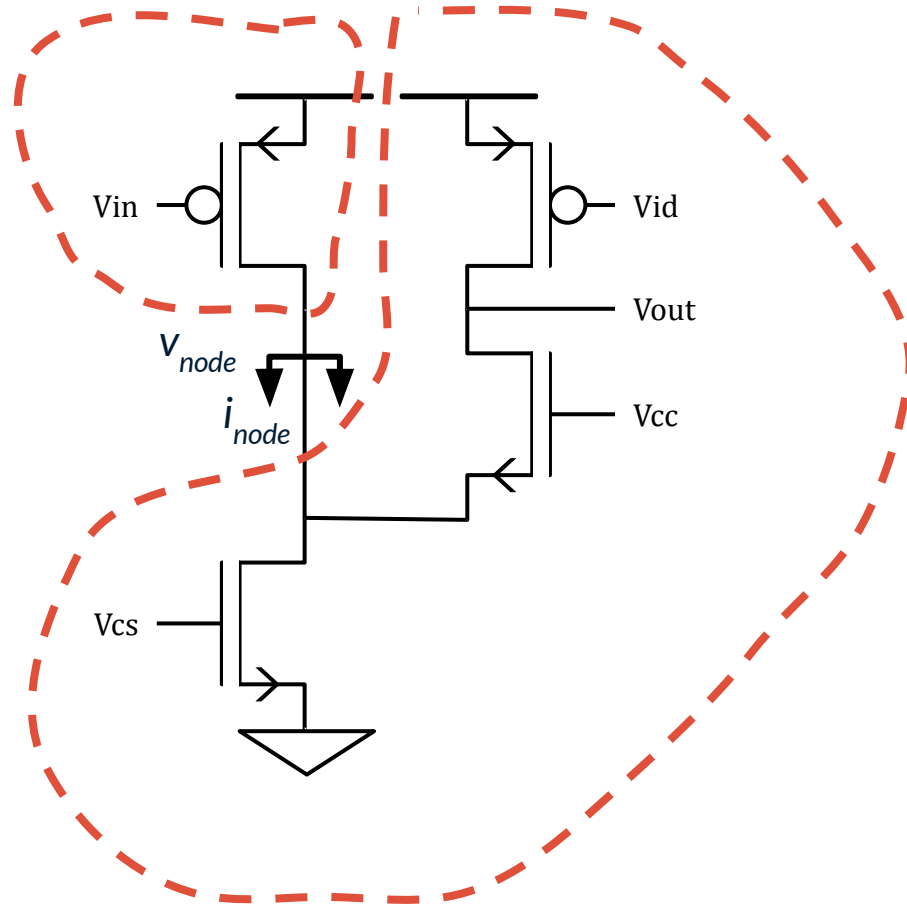
What can we do?

These two halves of the circuit only connect in one point!



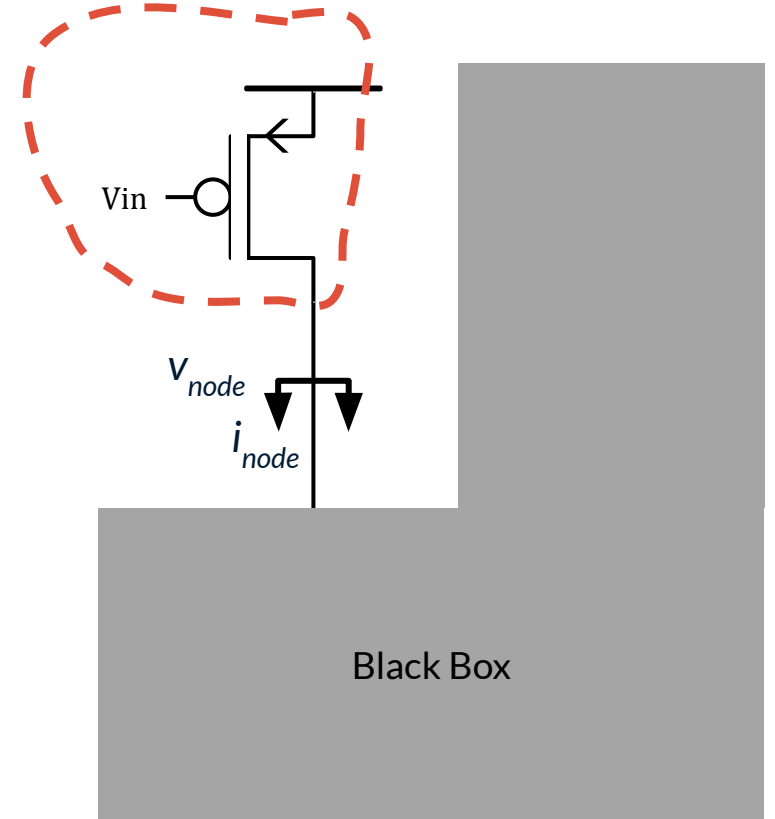
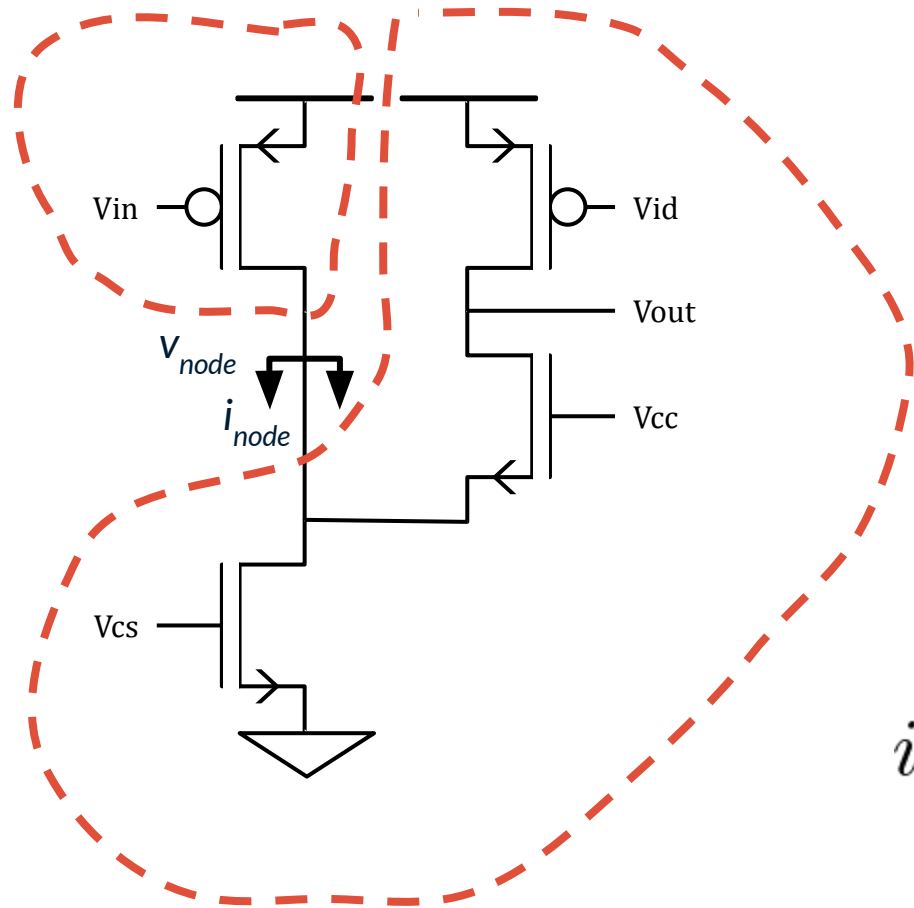
What can we do?

Let's split the circuit into two



What can we do?

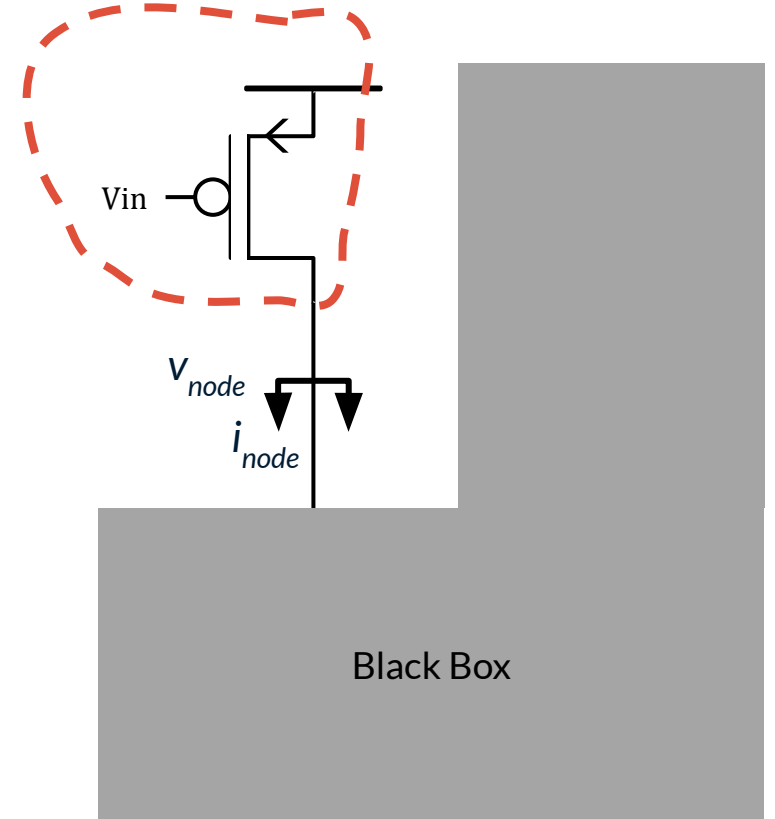
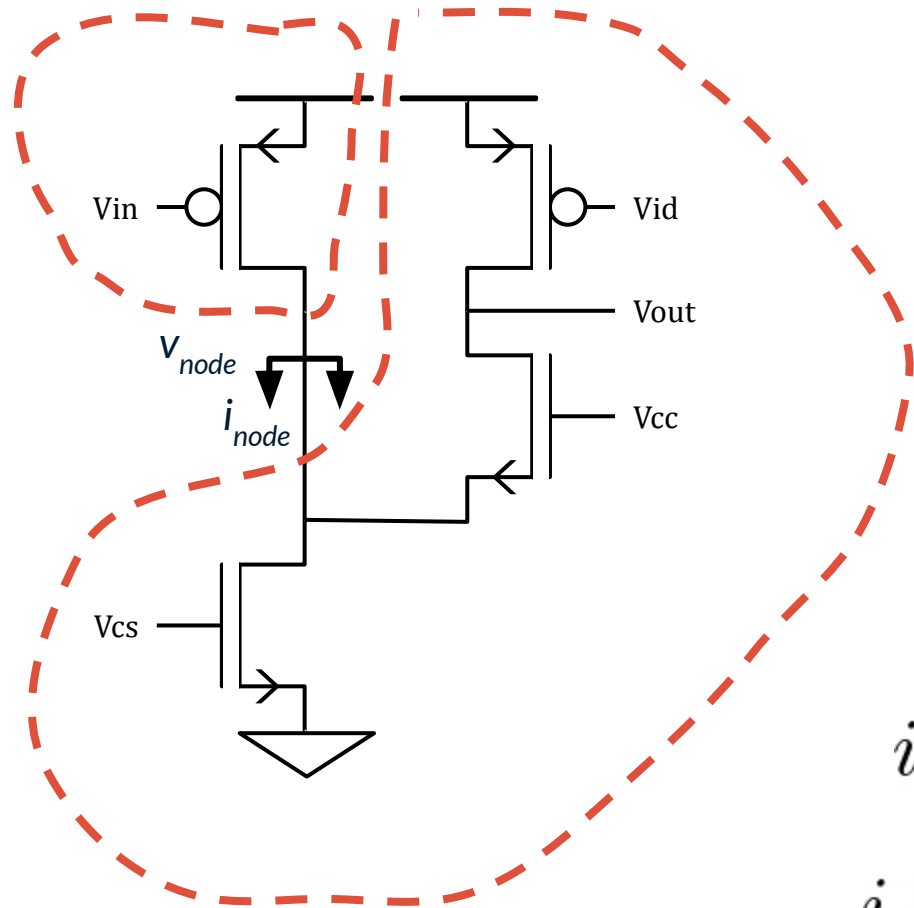
Let's split the circuit into two



$$i_{node} = f(v_{node})$$

What can we do?

Let's split the circuit into two

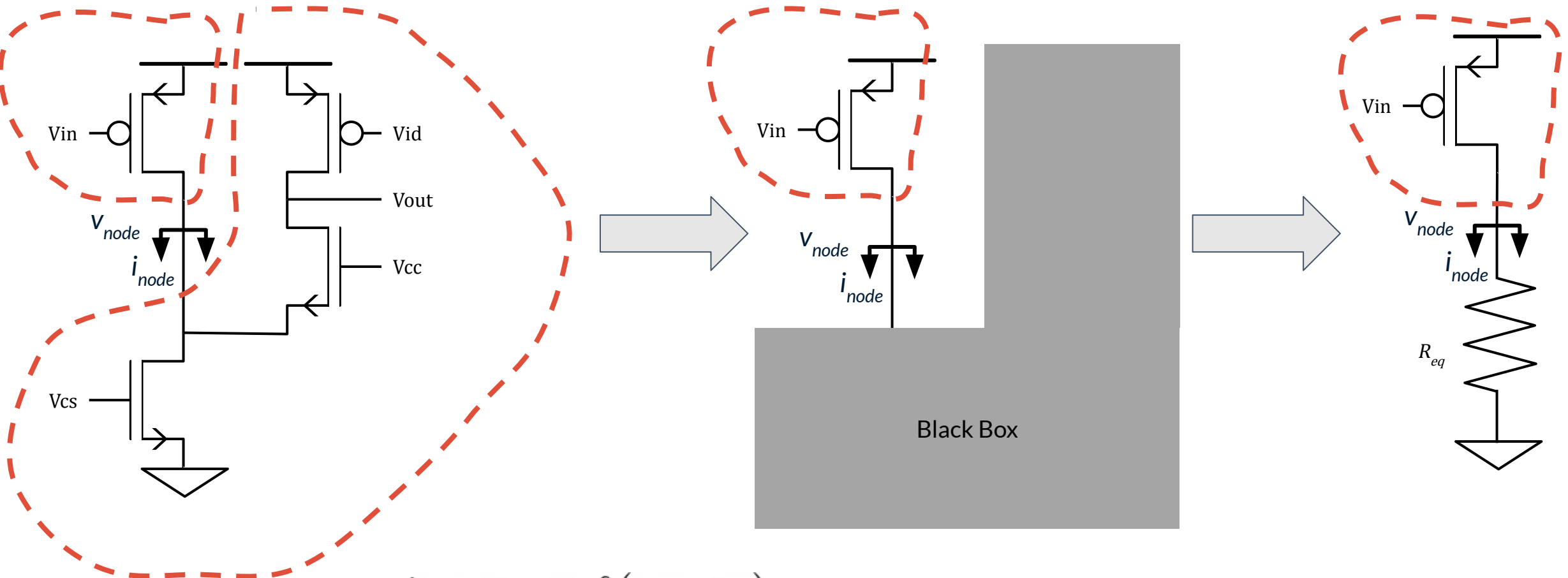


$$i_{node} = f(v_{node})$$

$$i_{node} = v_{node} / R_{eq}$$

What can we do?

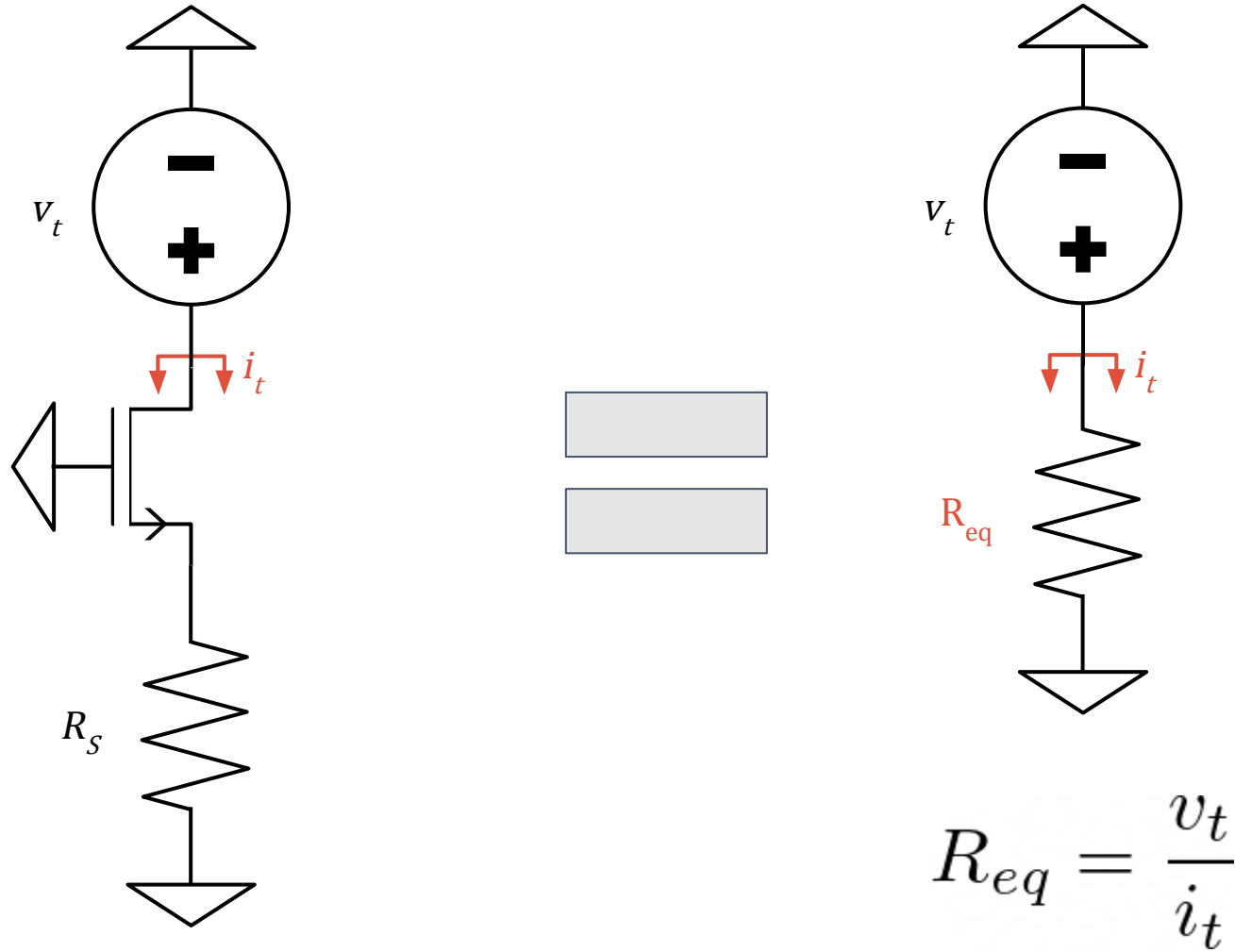
Let's split the circuit into two



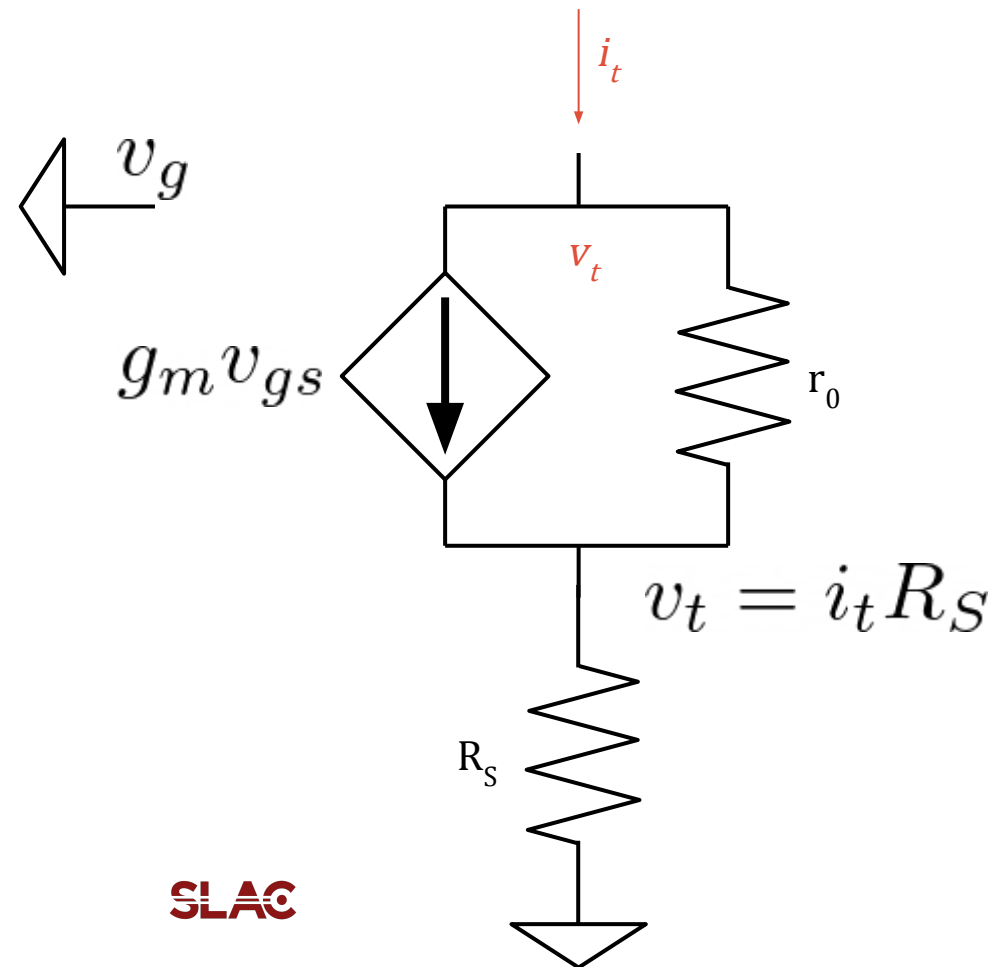
SLAC

$$i_{node} = f(v_{node})$$
$$i_{node} = v_{node} / R_{eq}$$

Deriving the drain impedance of a current buffer



Deriving the downwards impedance

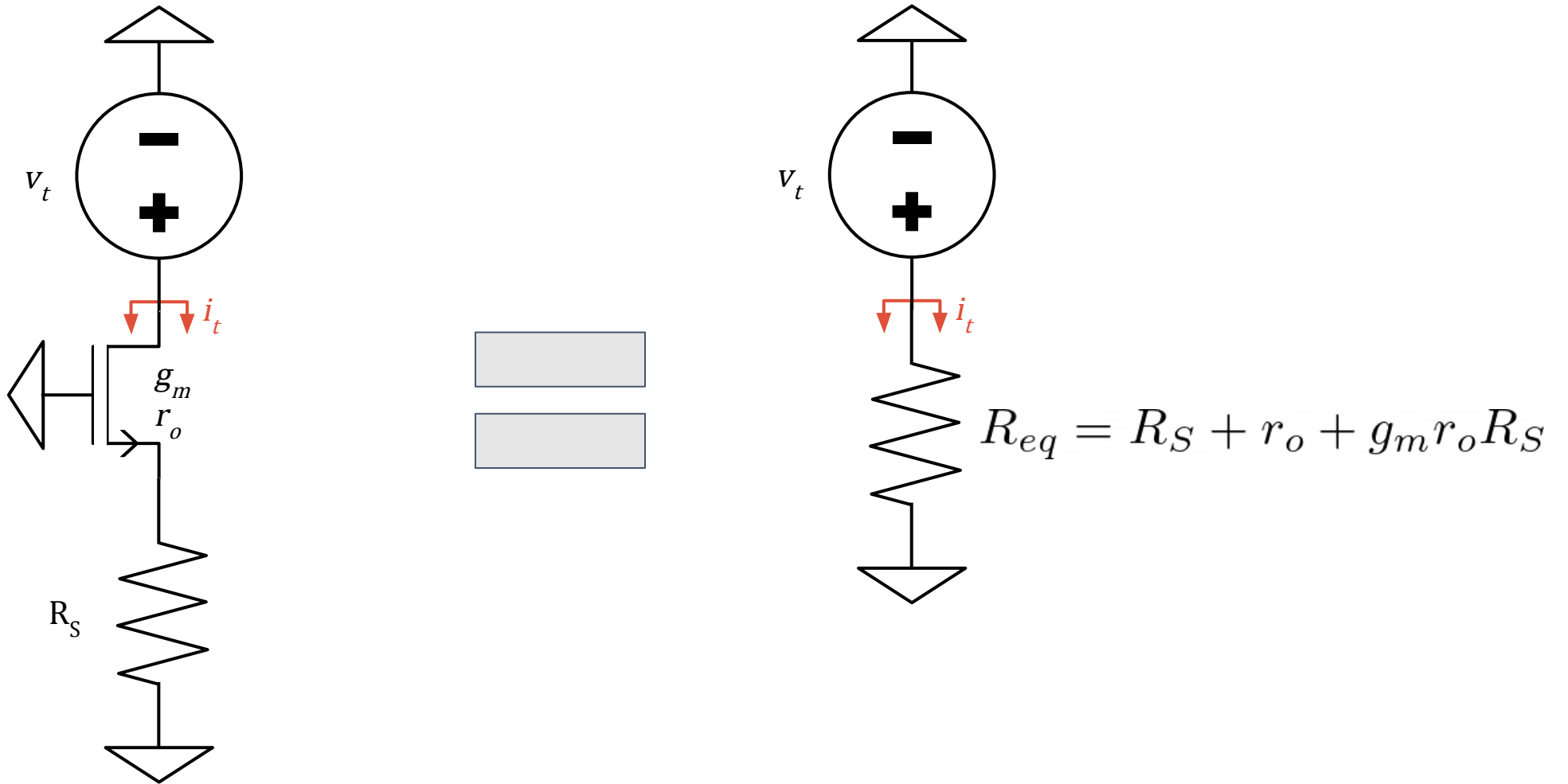


$$i_t = g_m v_{gs} + \frac{v_t - v_s}{r_o}$$

$$i_t = -g_m R_S i_t + \frac{v_t - R_S i_t}{r_o}$$

$$R_{eq} = \frac{v_t}{i_t} = R_S + r_o + g_m r_o R_S$$

The result



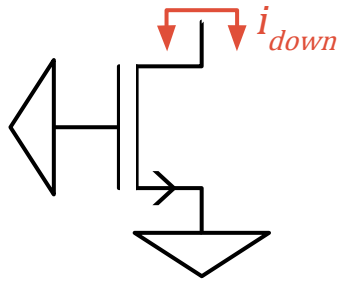
Taking Limits

$$R_{eq} = R_S + r_o + g_m r_o R_S$$

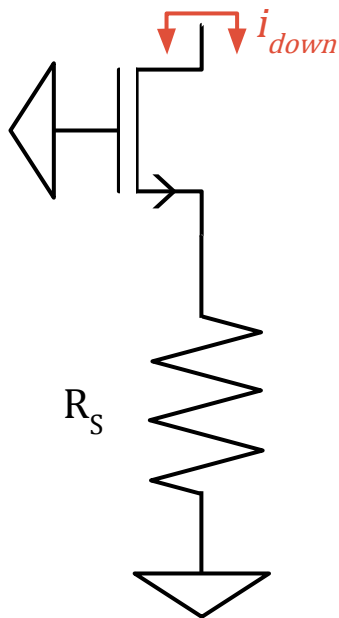
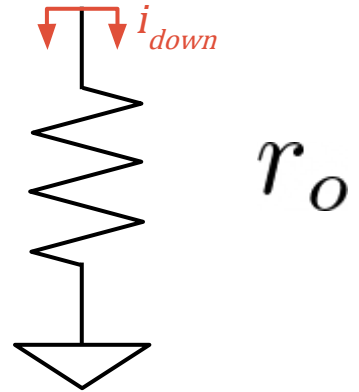
$$R_S = 0 \quad \longrightarrow \quad R_{eq} = r_o$$

$$g_m r_o \gg 1 \quad \longrightarrow \quad R_{eq} \approx g_m r_o R_S$$

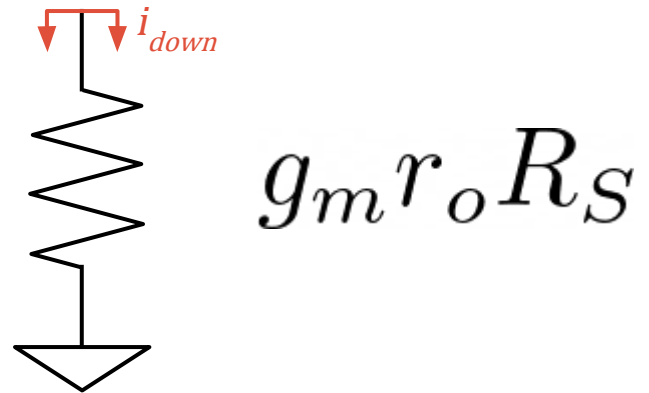
The Result



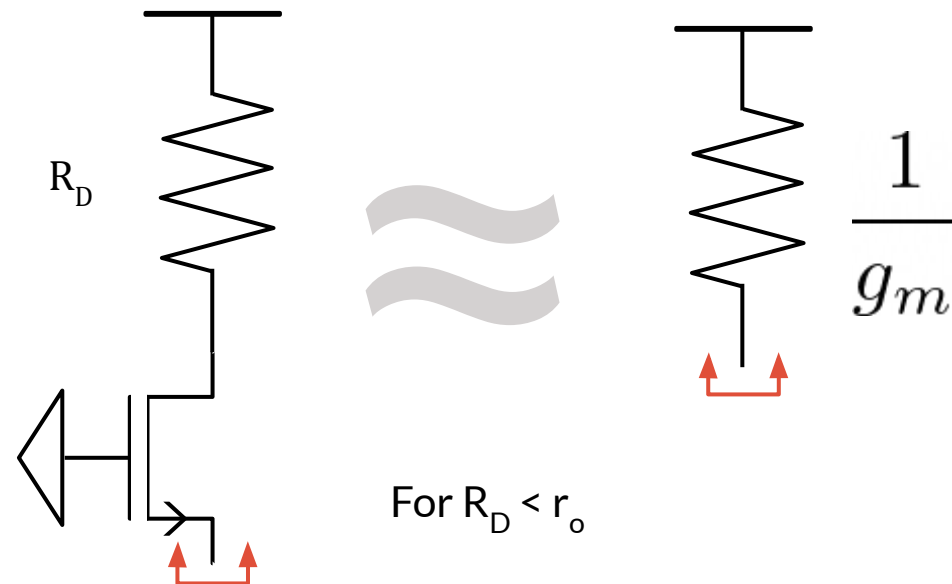
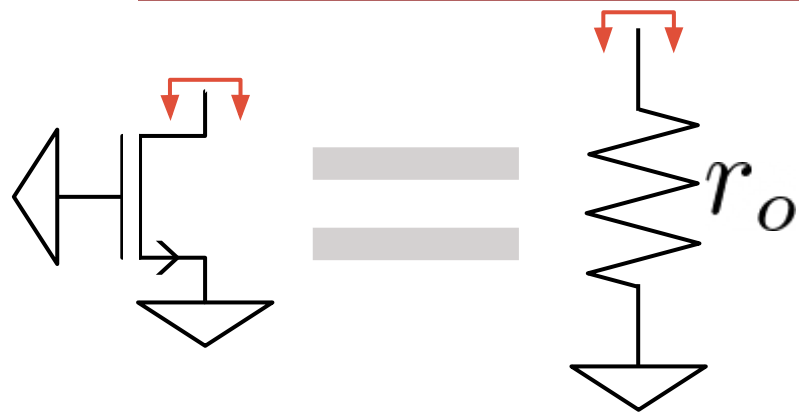
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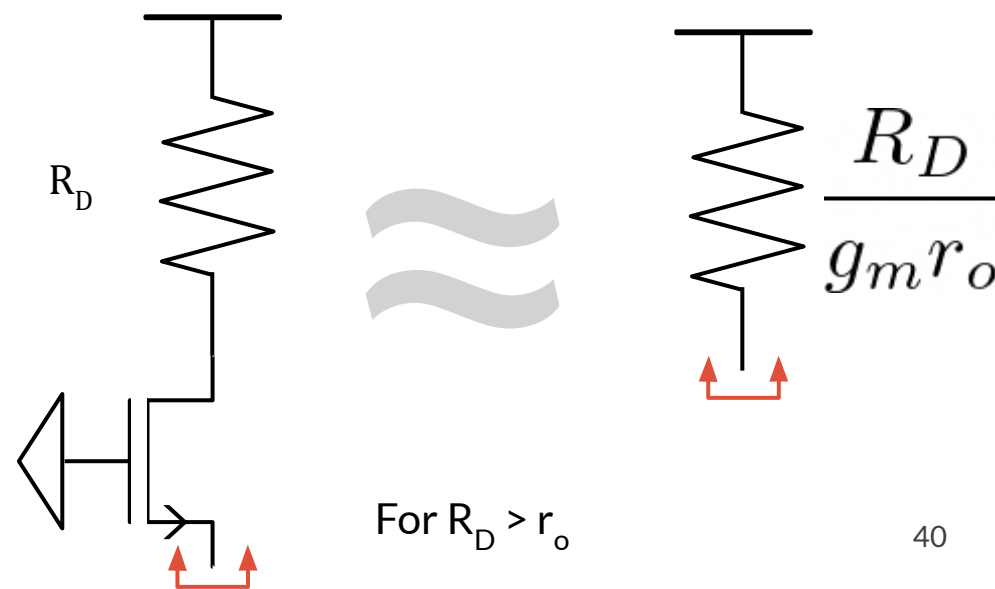
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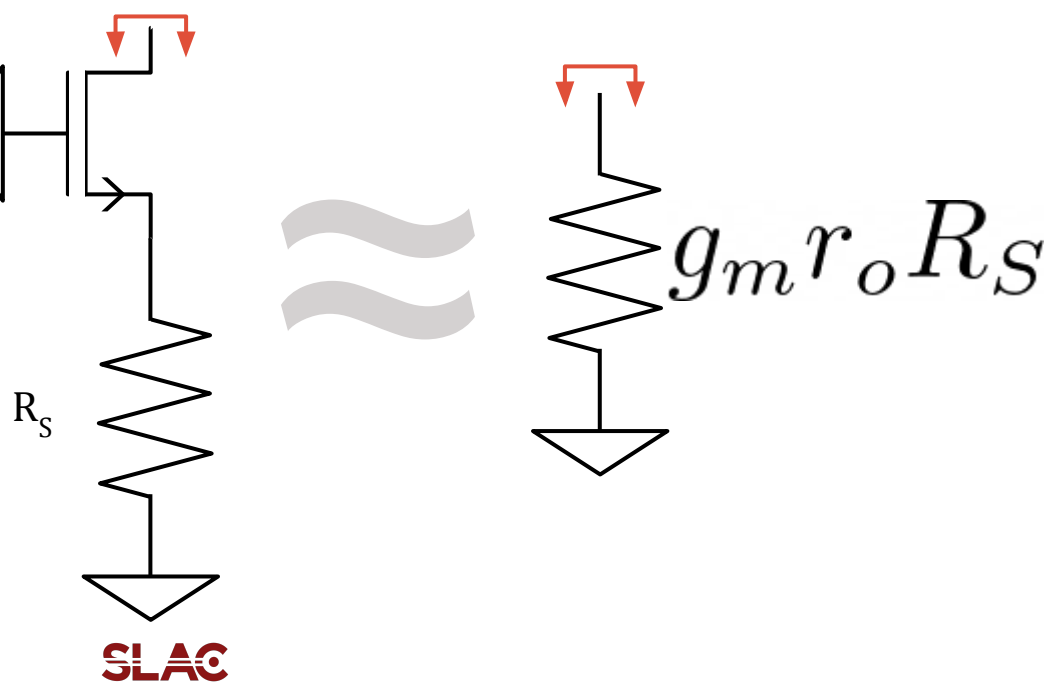
Transistor cheat-sheet (assuming $g_m r_o \gg 1$)



For $R_D < r_o$



For $R_D > r_o$

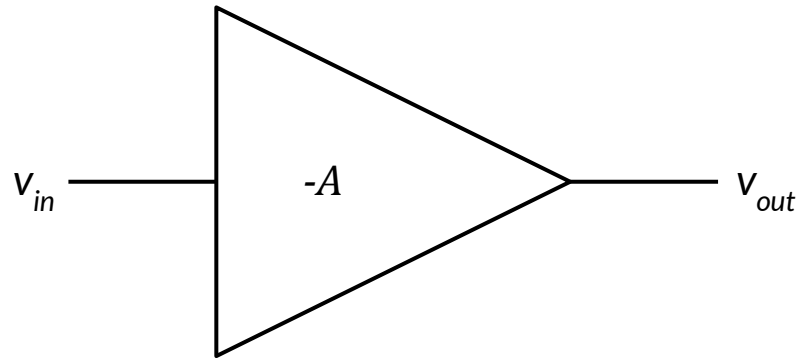


Small Signal DC Analysis

How can we use what we learned to design new circuits?

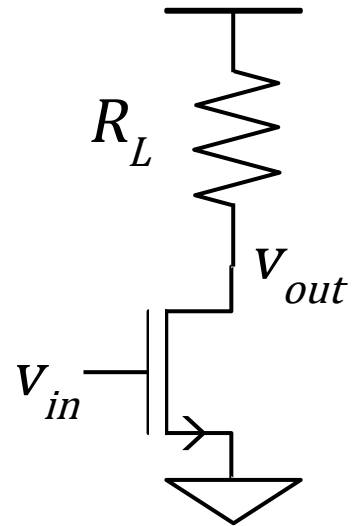
Let's Build A Voltage Amplifier!

We want to maximize $|v_{out}/v_{in}|$



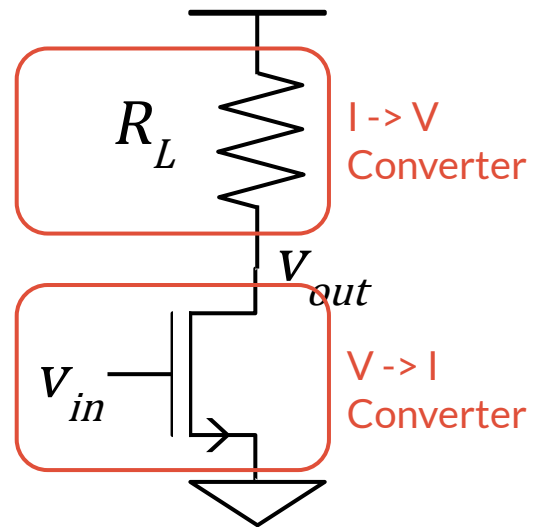
The Simplest Amplifier There Is

Let's start with a common source amplifier.



The Simplest Amplifier There Is

Let's start with a common source amplifier.

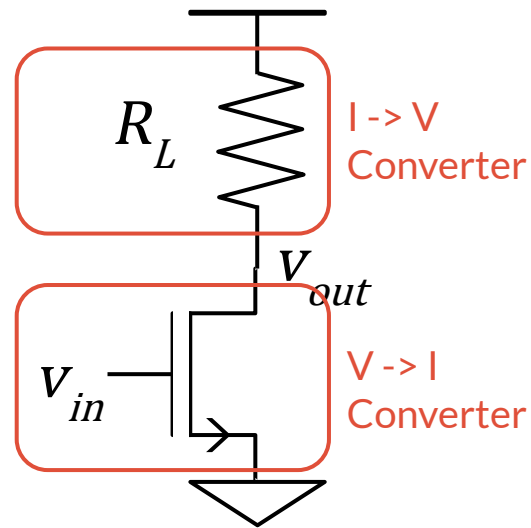


The Simplest Amplifier There Is

Gain should increase with load resistance

$$v_{out} = iR_L$$

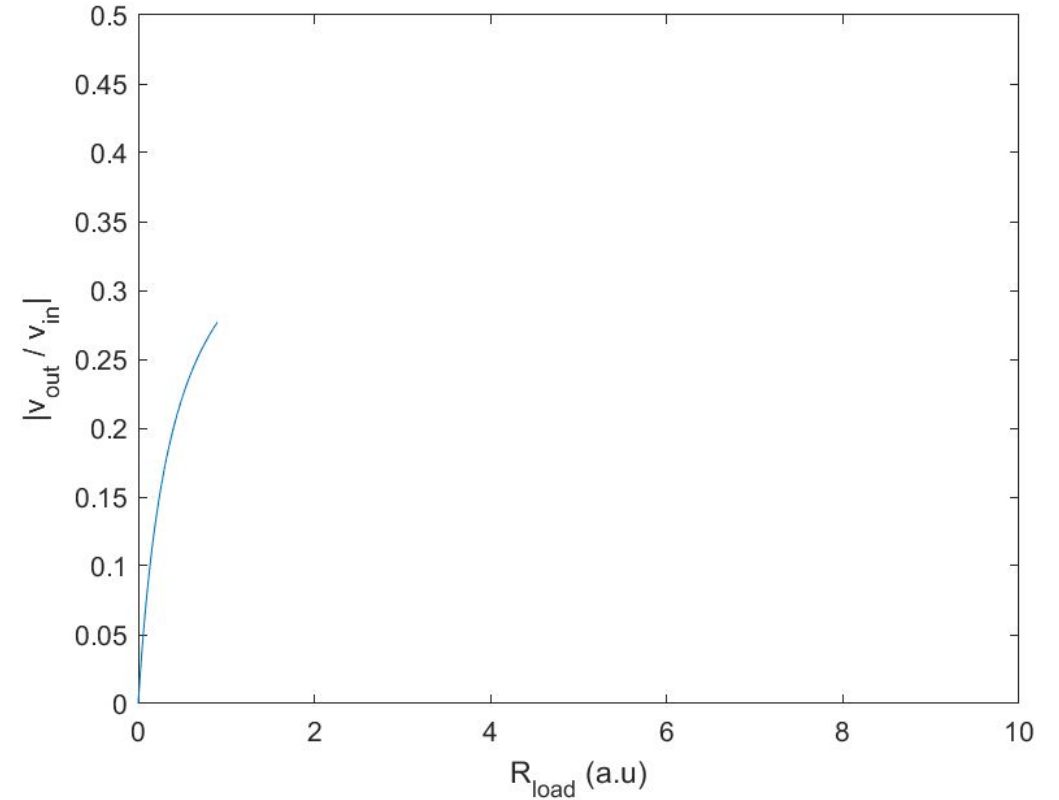
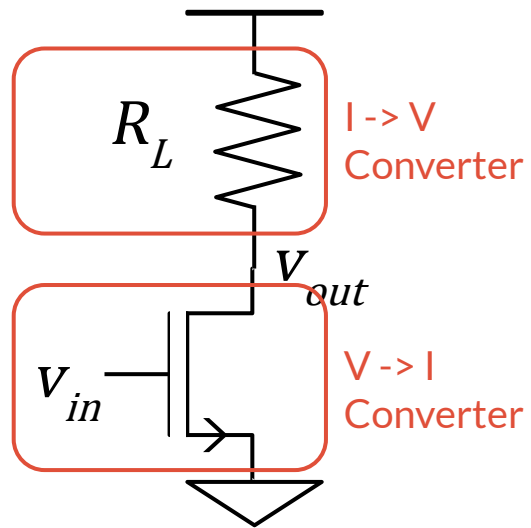
$$i \approx -g_m v_{in}$$



$$\frac{v_{out}}{v_{in}} \approx -g_m R_L$$

The Simplest Amplifier There Is

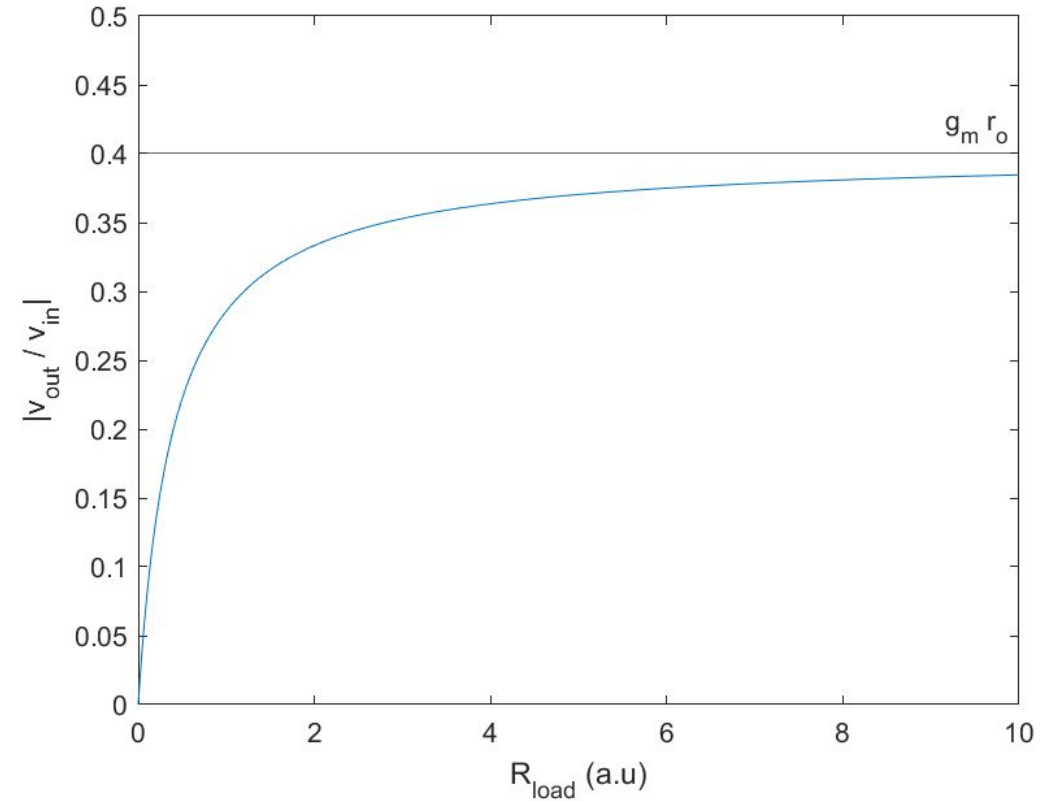
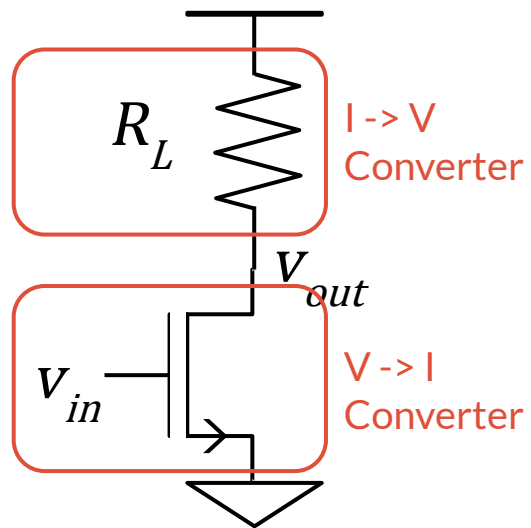
Gain should increase with load resistance



$$\frac{v_{out}}{v_{in}} \approx -g_m R_L$$

The Simplest Amplifier There Is

But the gain eventually flattens out!

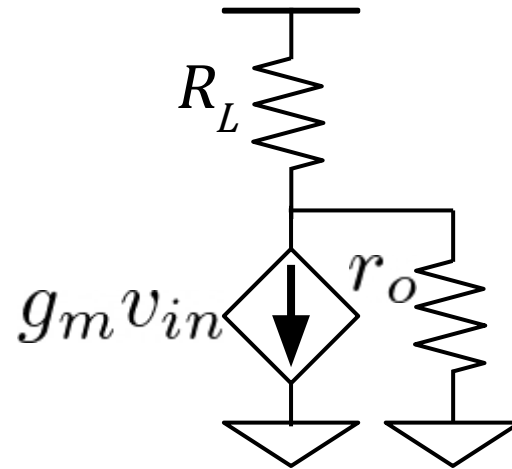
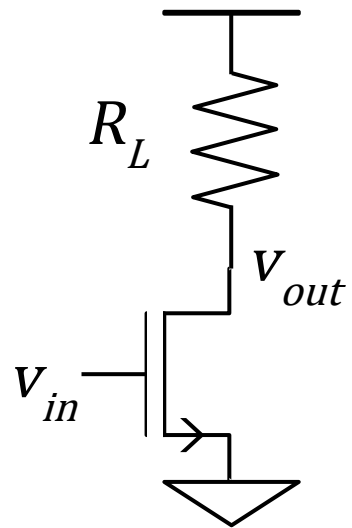


$$\frac{v_{out}}{v_{in}} \approx -g_m R_L$$

The equation is crossed out with a large red 'X', indicating that this simple approximation is invalid for large load resistances.

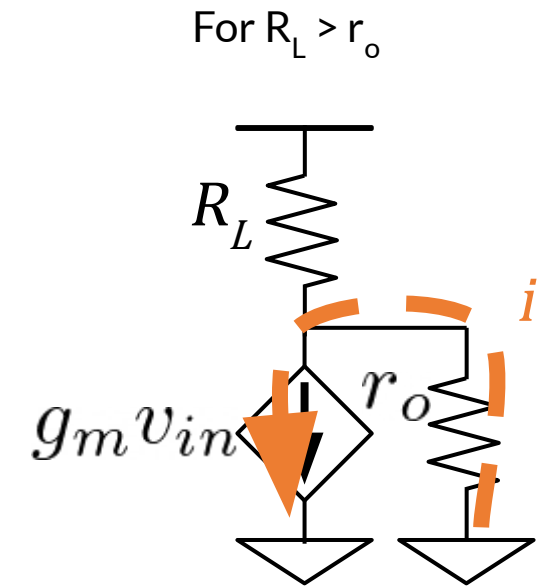
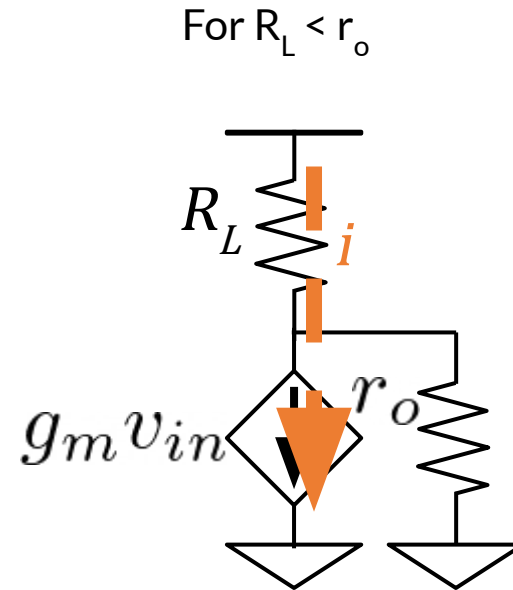
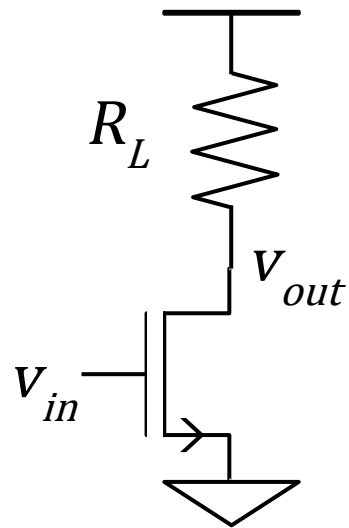
Why Does The Common Source Have Limited Gain?

Let's draw the full equivalent circuit

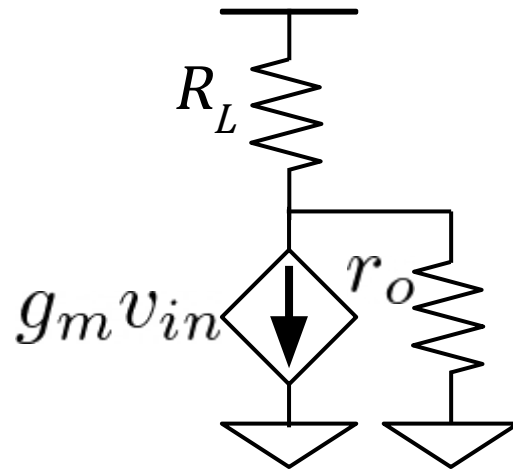
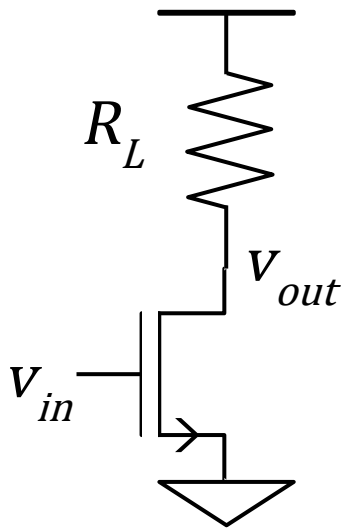


Why Does The Common Source Have Limited Gain?

Let's draw the full equivalent circuit



The Most Gain We Can Get Out Of A CS Amplifier

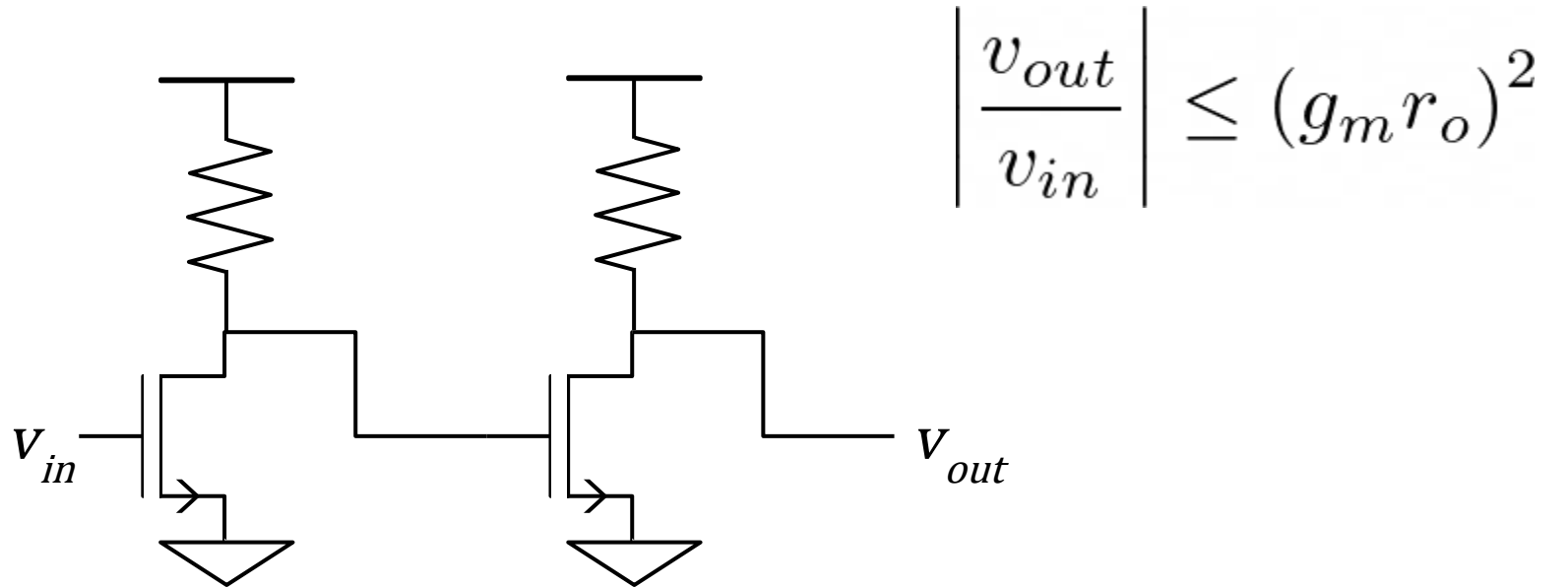


$$\frac{v_{out}}{v_{in}} = -g_m (R_L || r_o)$$

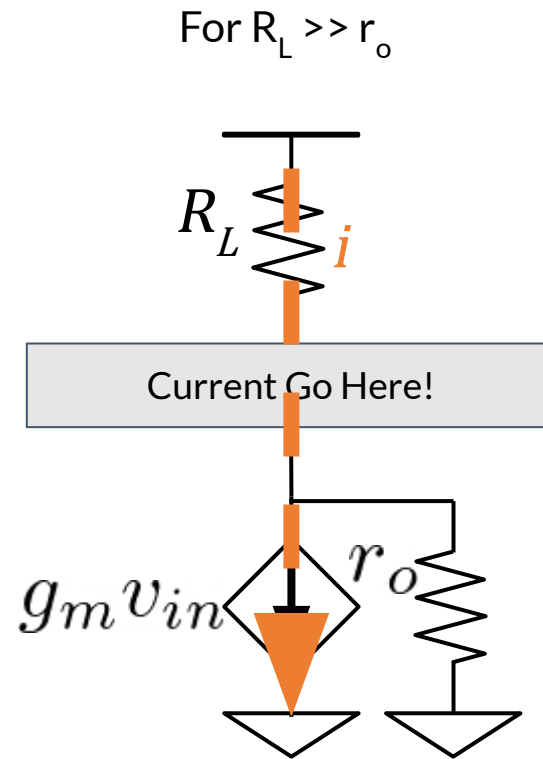
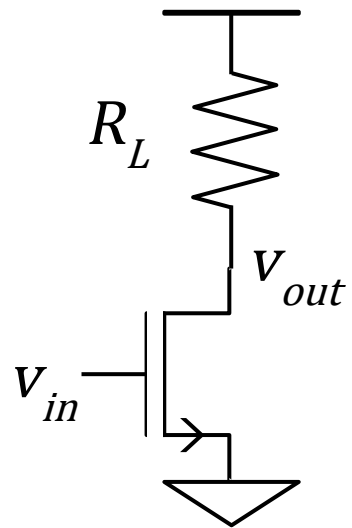
$$\left| \frac{v_{out}}{v_{in}} \right| \leq g_m r_o$$

What if we need more gain?

We can square the gain, but double the power

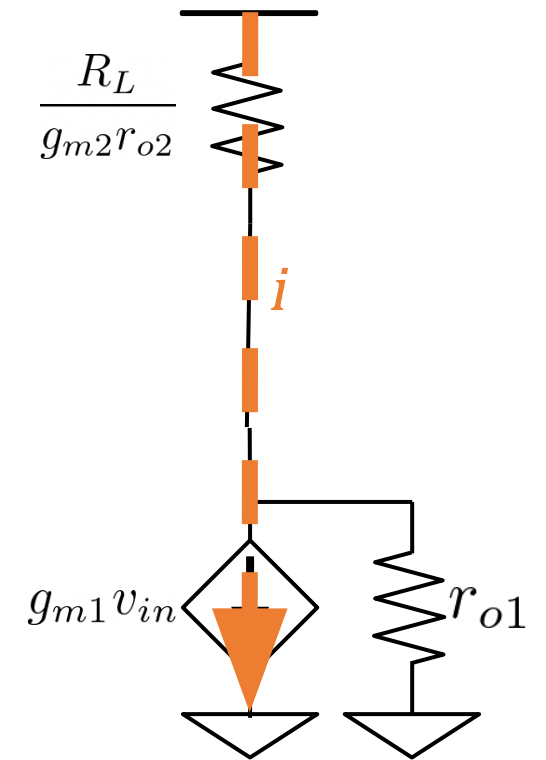
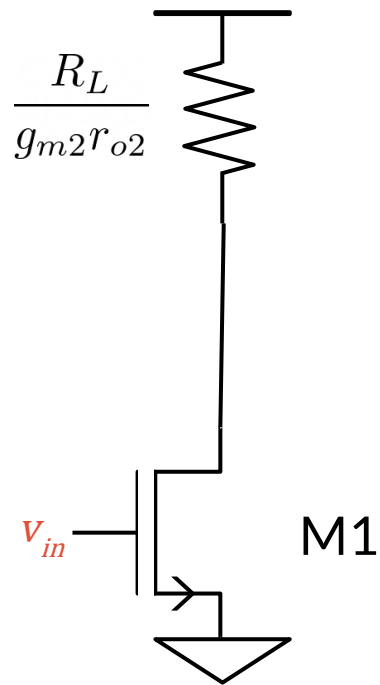
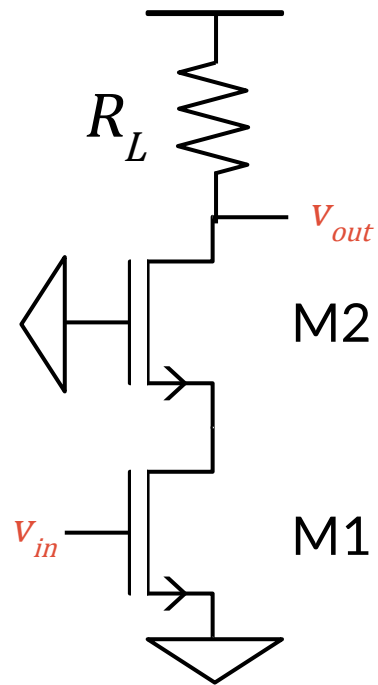


Can We “Trick” The Current Into Going Into A Large Load?



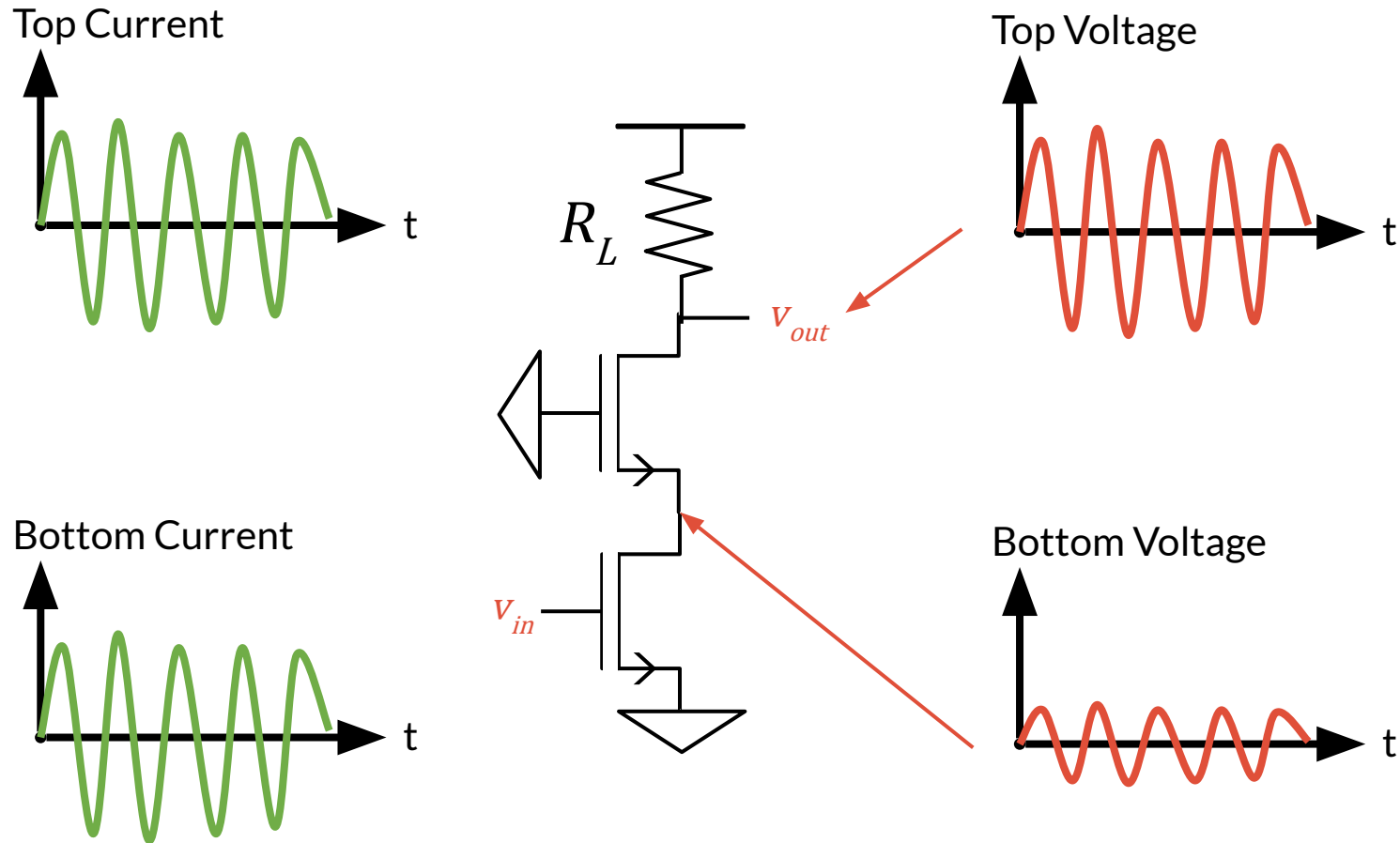
Can We “Trick” The Current Into Going Into A Large Load?

Yes we can!



Can We “Trick” The Current Into Going Into A Large Load?

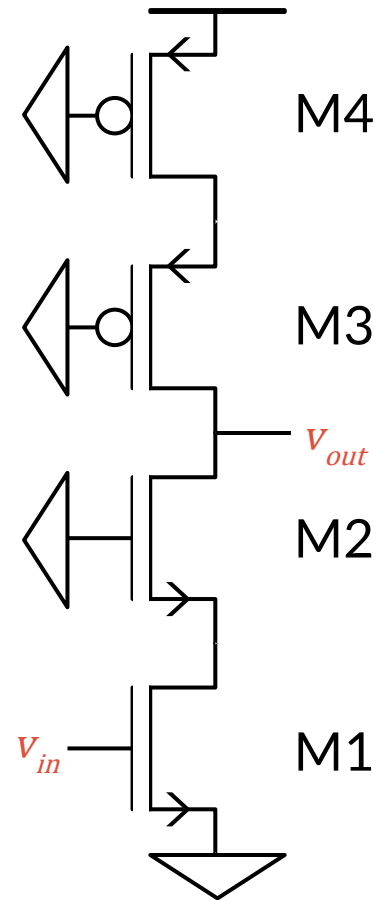
Yes we can!



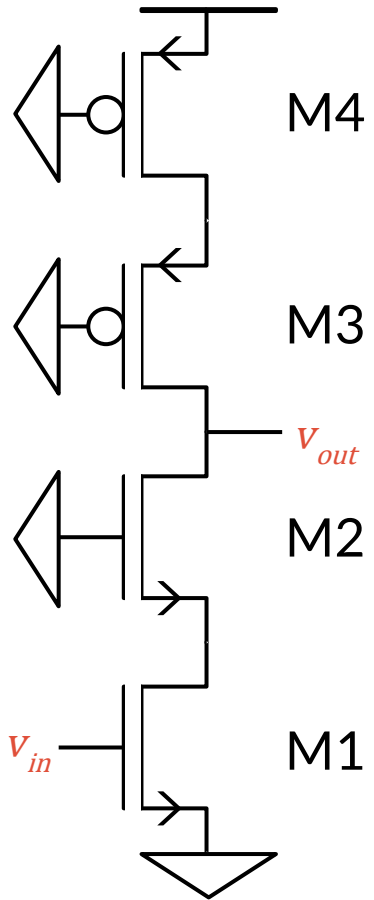
Small Signal DC Analysis

Let's make it quantitative

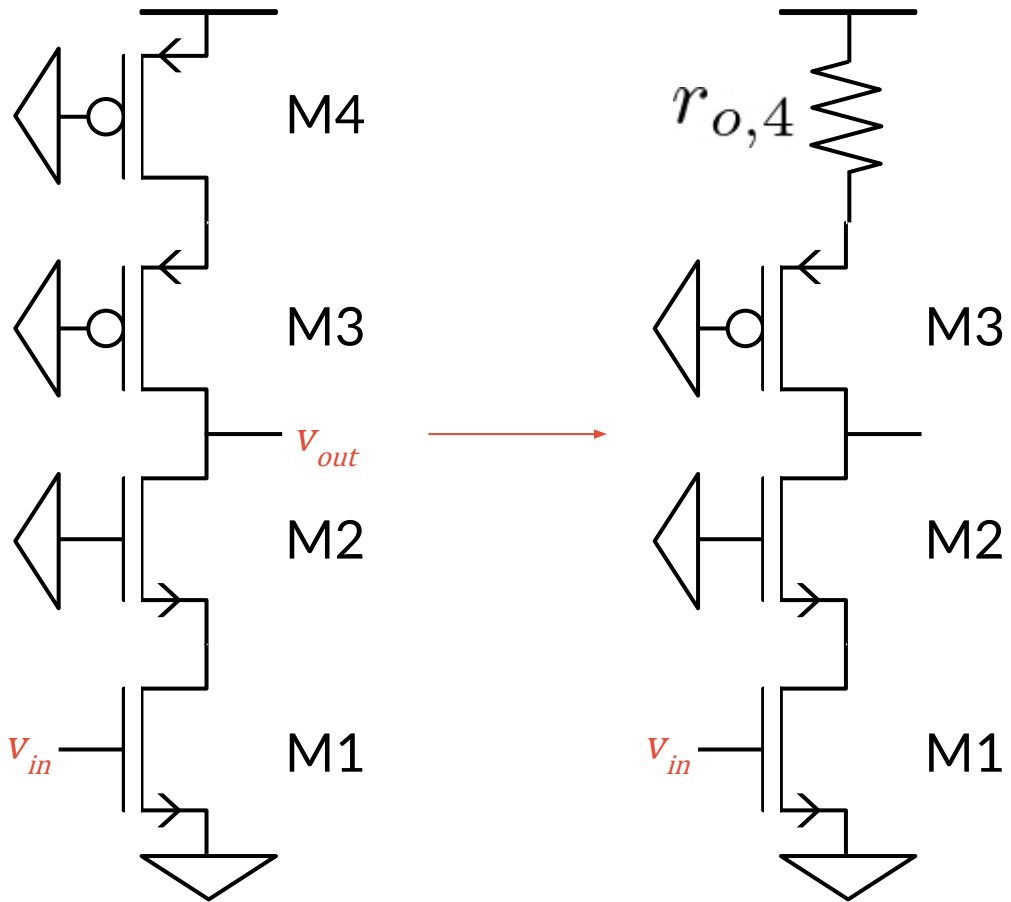
Quantitative walkthrough



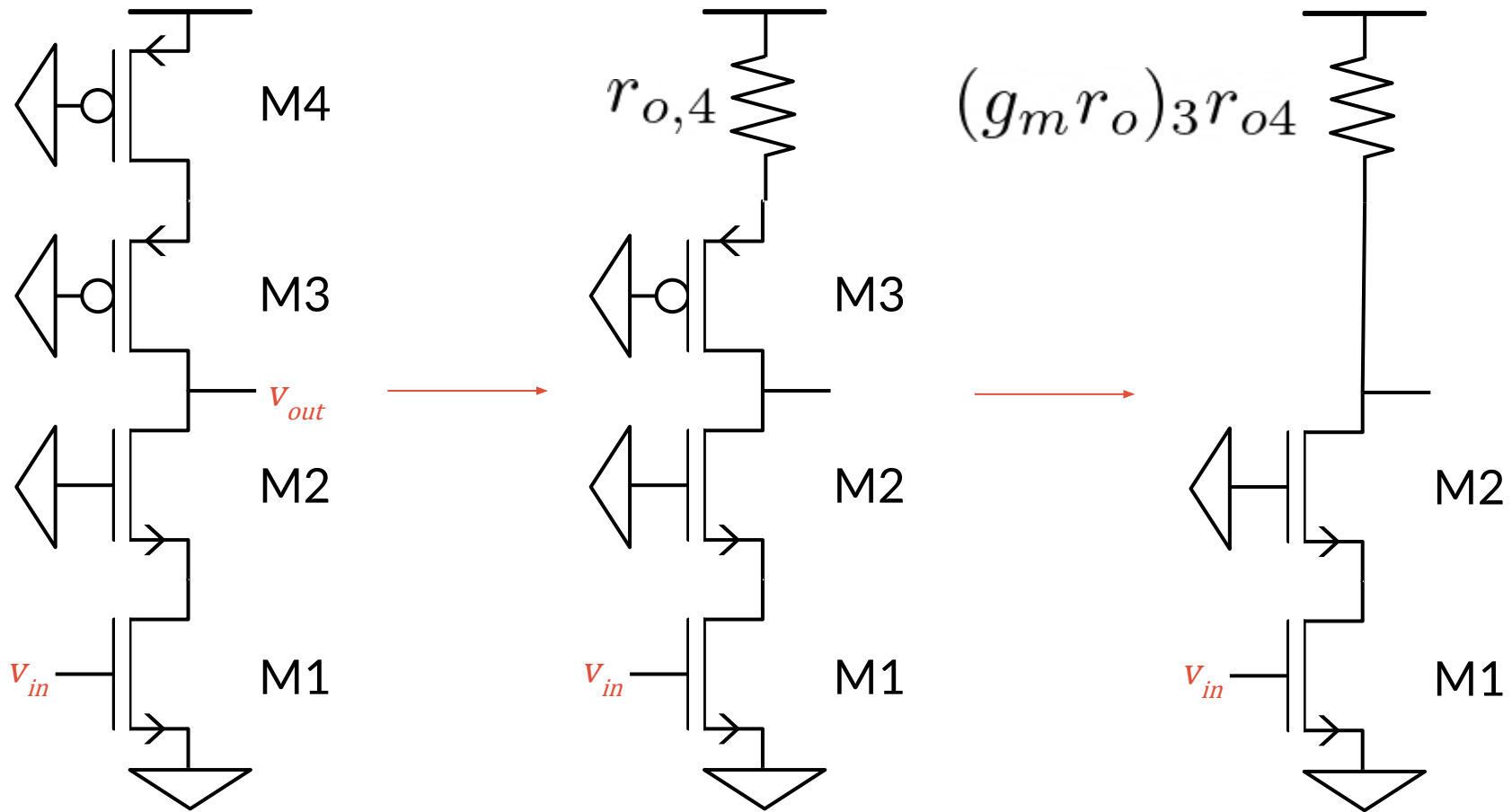
Quantitative walkthrough



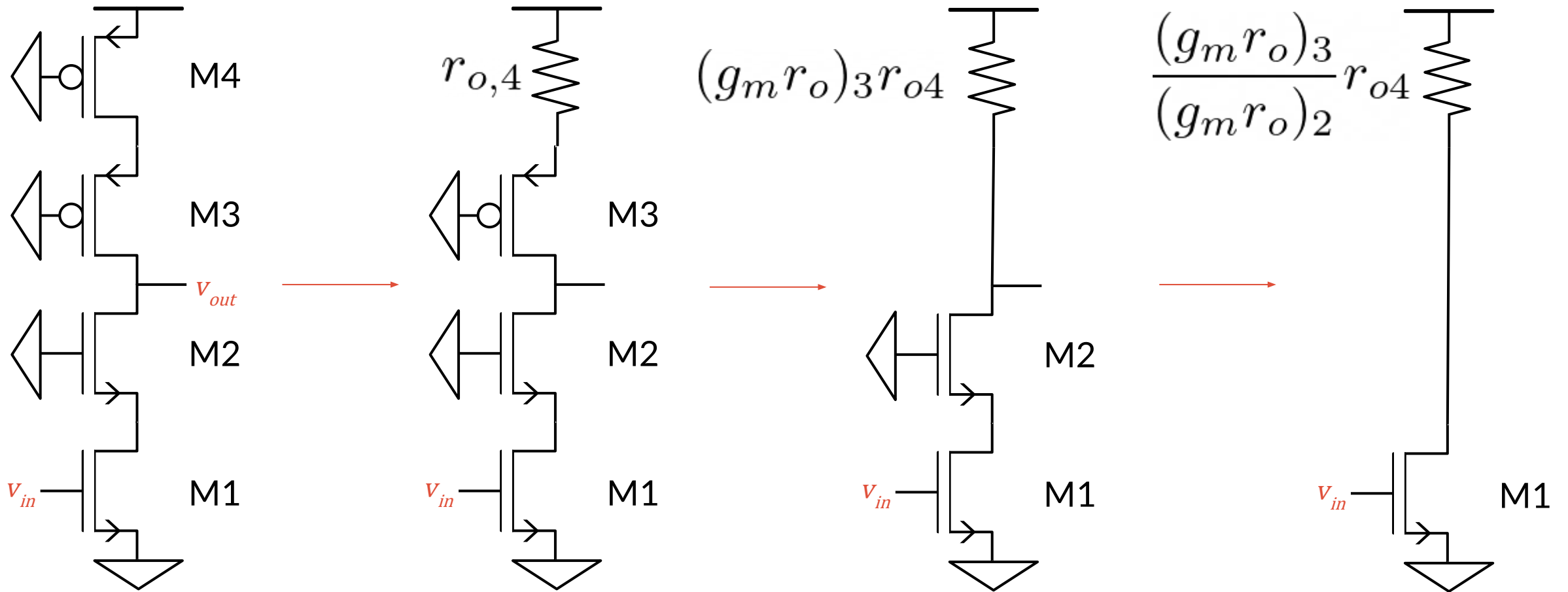
Quantitative walkthrough



Quantitative walkthrough



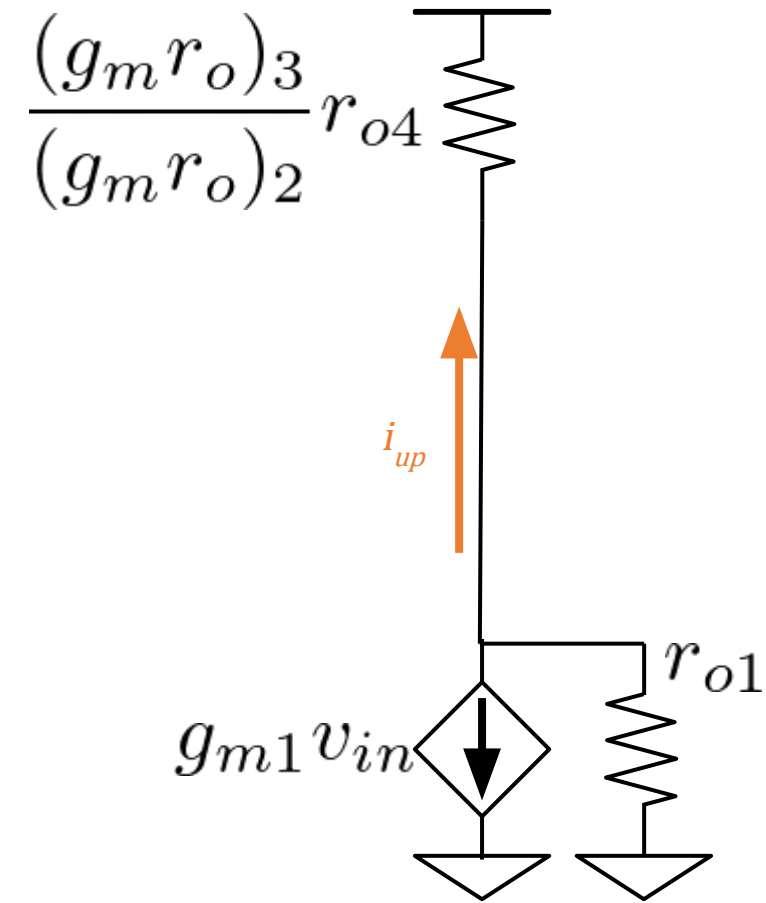
Quantitative walkthrough



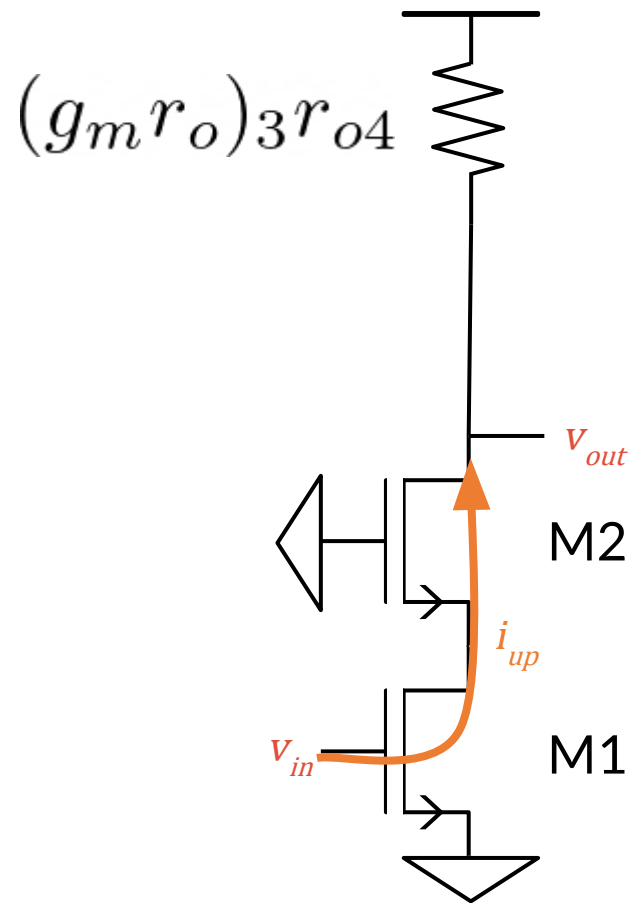
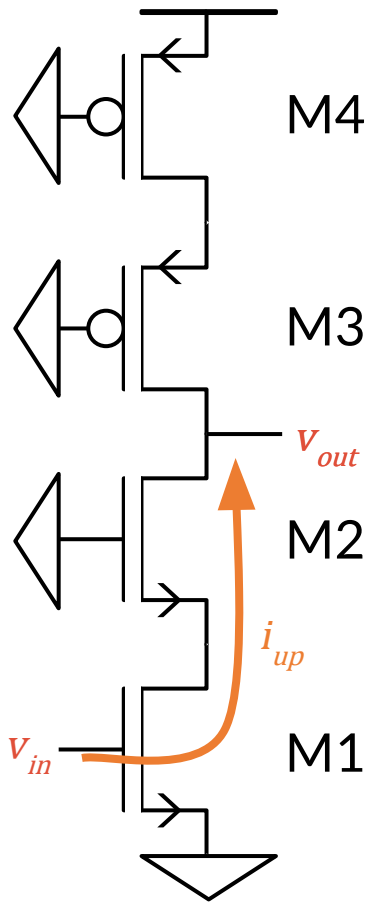
Quantitative walkthrough

We have a current divider!

$$i_{up} = - \frac{r_{o1}}{r_{o1} + \frac{(g_m r_o)_3}{(g_m r_o)_2} r_{o4}} g_{m1} v_{in}$$



Quantitative walkthrough



$$i_{up} = - \frac{r_{o1}}{r_{o1} + \frac{(g_m r_o)_3 r_{o4}}{(g_m r_o)_2}} g_{m1} v_{in}$$

$$v_{out} = (g_m r_o)_3 r_{o4} i_{up}$$

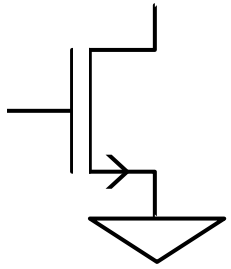
If we assume all transistors have the same g_m , r_o

$$\frac{v_{out}}{v_{in}} = -\frac{1}{2} (g_m r_o)^2$$

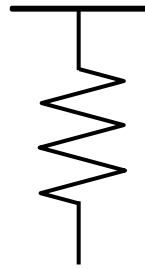
Small Signal DC Analysis

Summary: Designing circuits with building blocks

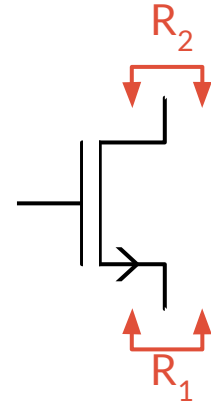
The Three Types of Building Blocks



$V \rightarrow I$
Converters

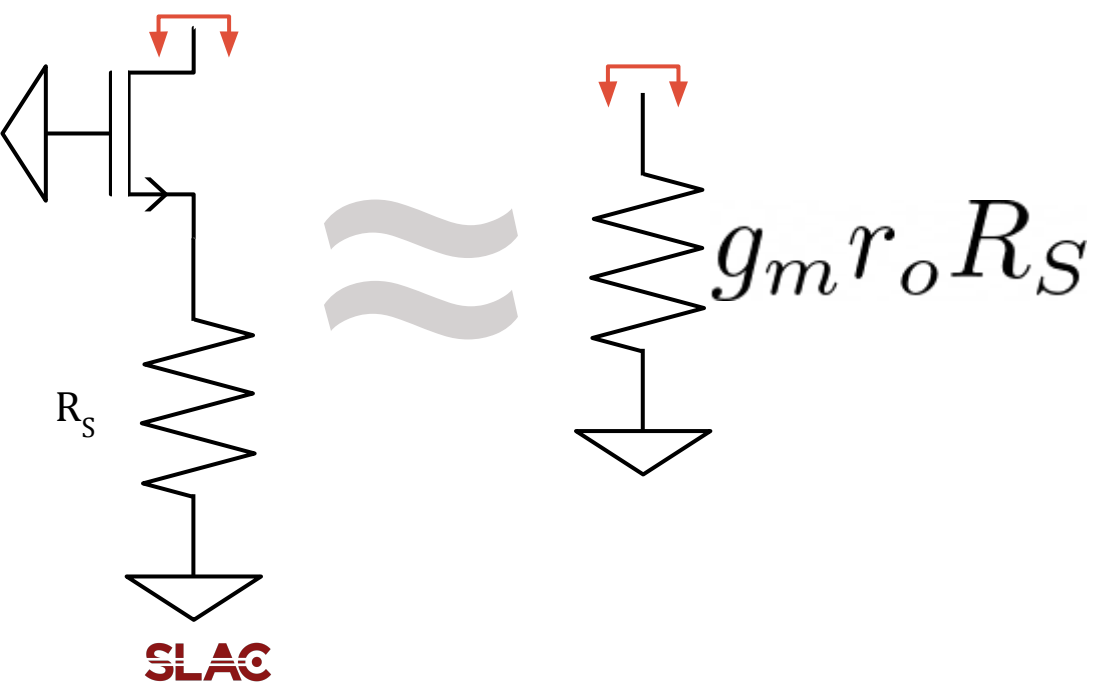
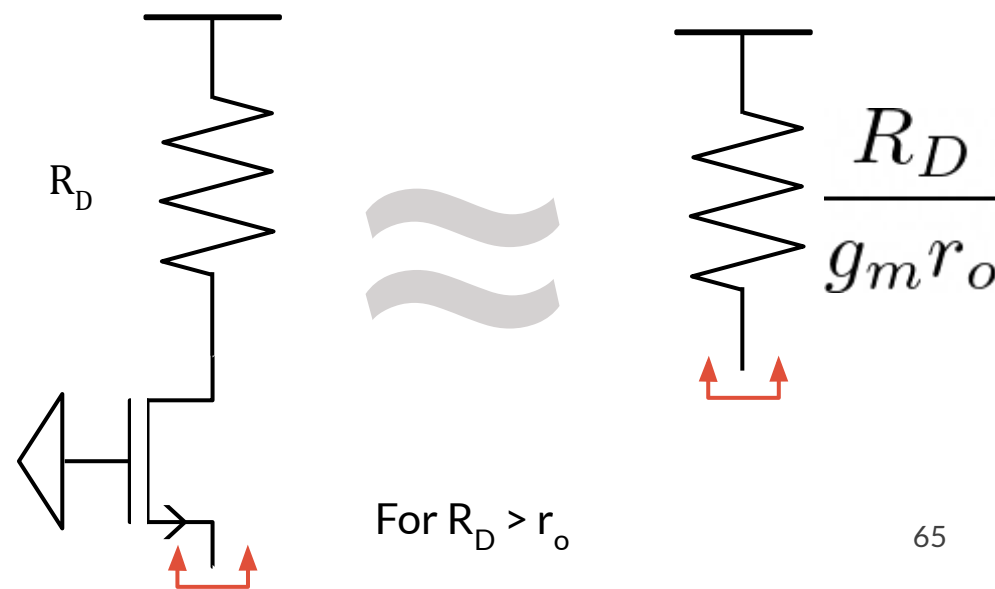
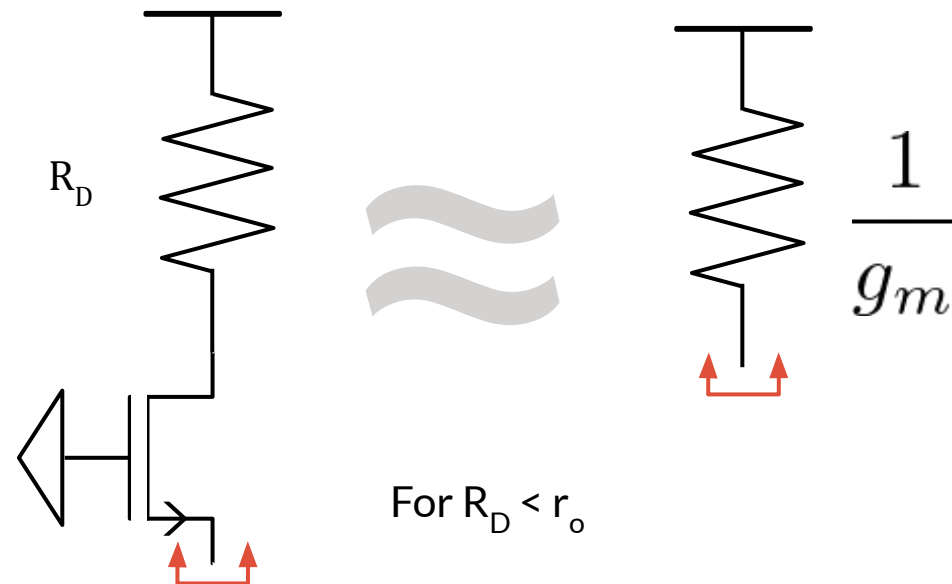
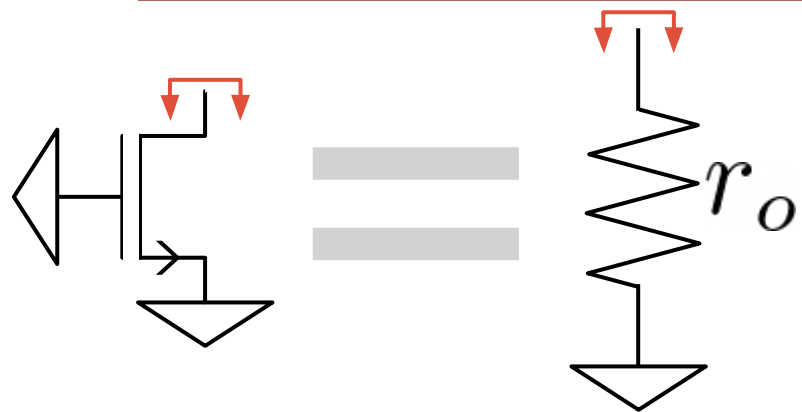


$I \rightarrow V$
Converters



Impedance
Transformers

Transistor cheat-sheet (assuming $g_m r_o \gg 1$)



DC Biasing And Sizing Transistors

Device equations and g_m/I_d

Back to the MOSFET I-V equation

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{gs} - V_{th})^2$$

Key Observation

Current is linear in the width (intuitive)

$$I_D = W f(V_{gs}, L)$$

Consequences: g_m/I_D is independent of W !

$$I_D = W f(V_{gs}, L)$$

$$g_m = \frac{\partial I_D}{\partial V_{gs}} = W f'(V_{gs}, L)$$

$$\frac{g_m}{I_D} = h(V_{gs}, L)$$

Observation: Other Quantities Are Independent Of W

$$\frac{g_m}{I_D} = h(V_{gs}, L)$$

$$\frac{g_m}{C_{gg}} = h_1(V_{gs}, L)$$

$$\frac{I_D}{W} = h_2(V_{gs}, L)$$

We can express quantities independent of W in terms of g_m/I_D

$$\frac{I_D}{W} = f_\alpha \left(\frac{g_m}{I_D}, L \right)$$

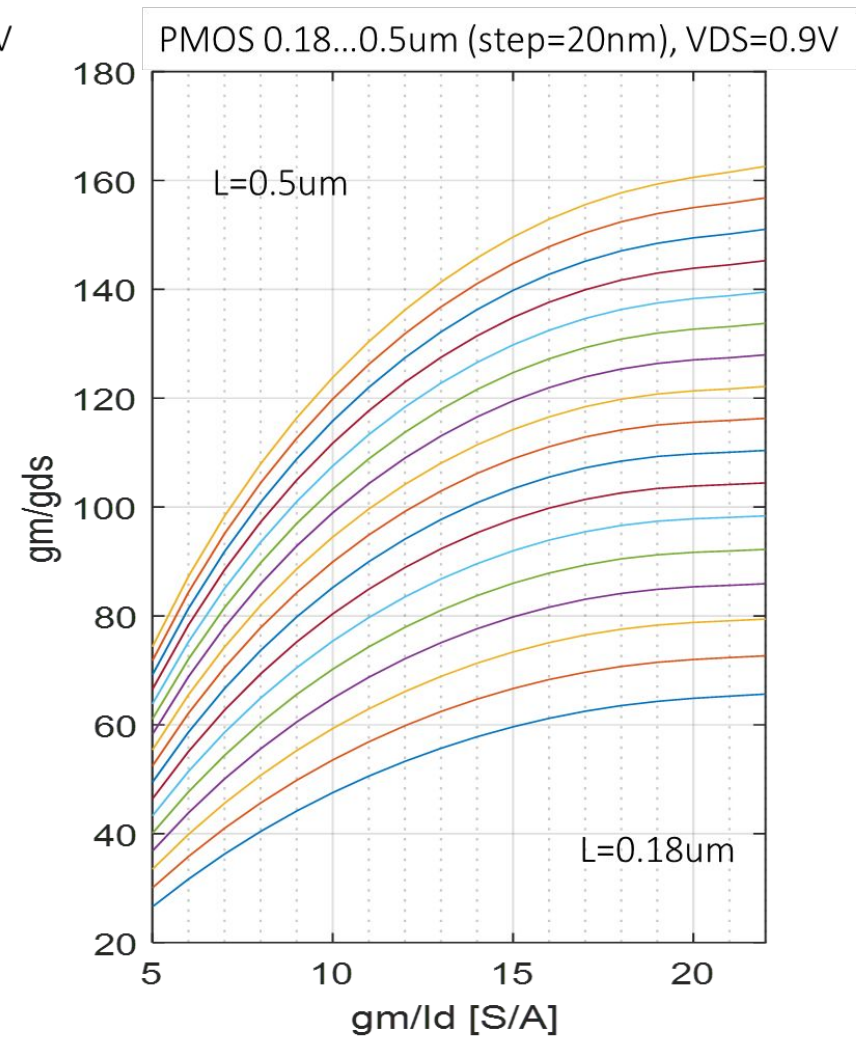
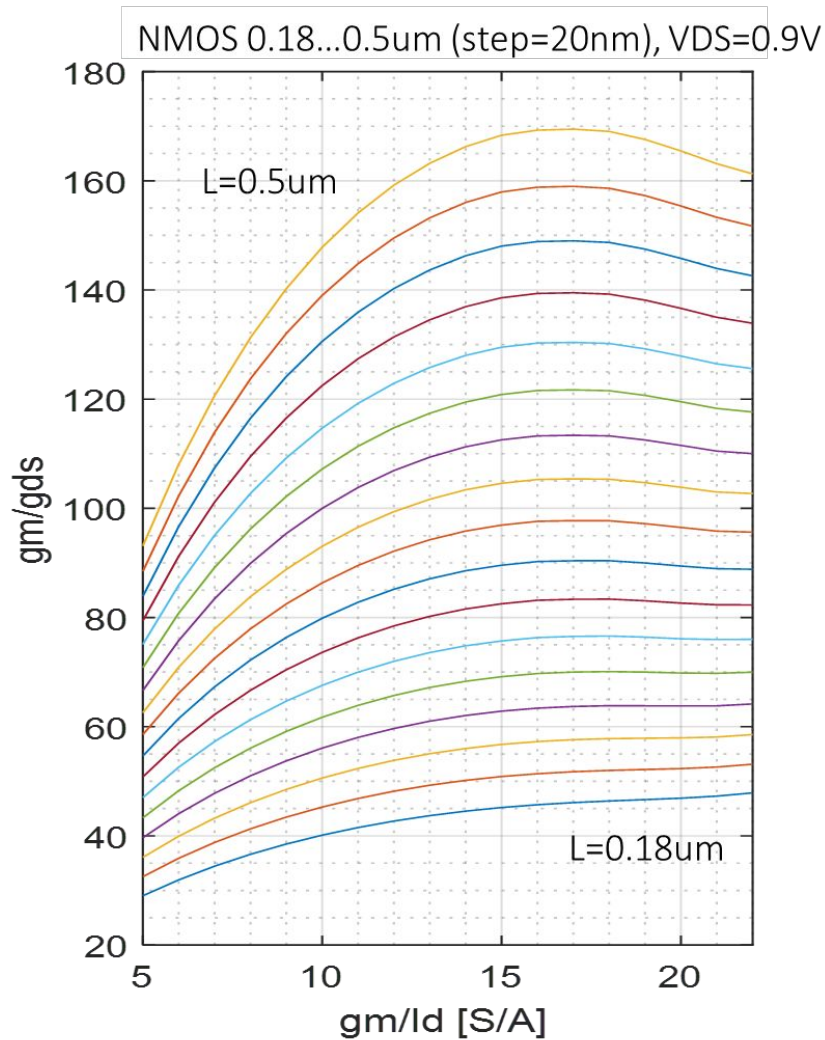
$$\frac{g_m}{C_{gg}} = \omega_T = f_\beta \left(\frac{g_m}{I_D}, L \right)$$

$$V_{gs} = f_\gamma \left(\frac{g_m}{I_D}, L \right)$$

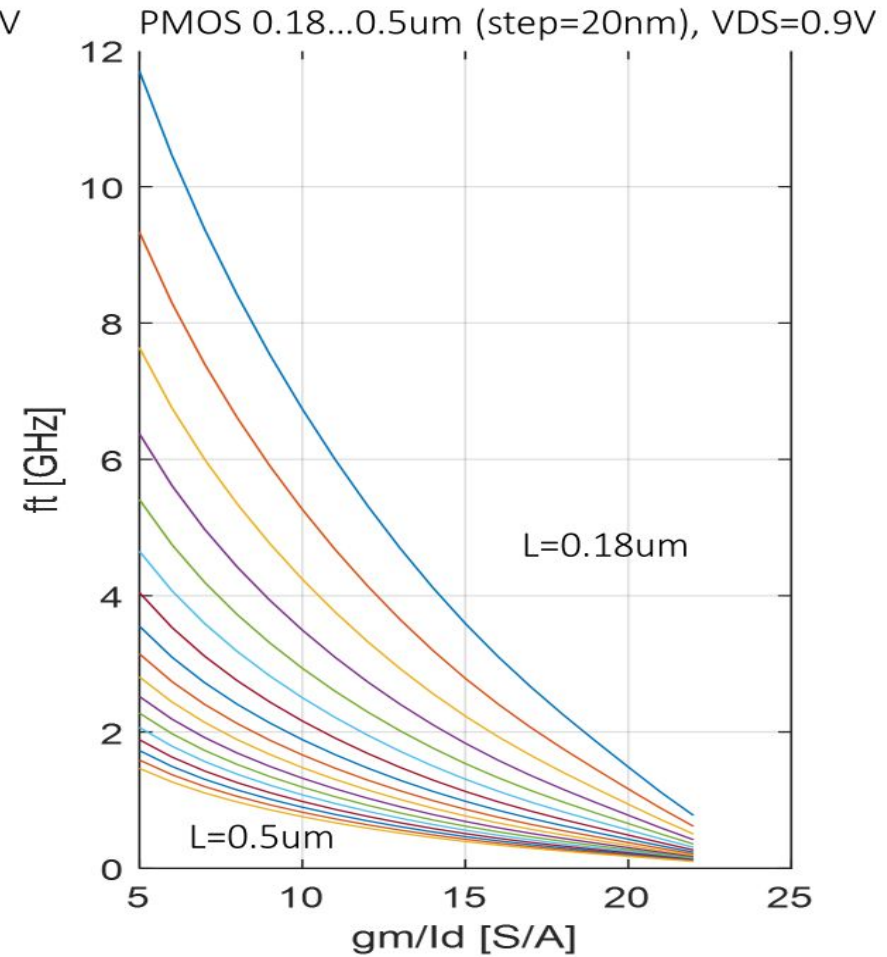
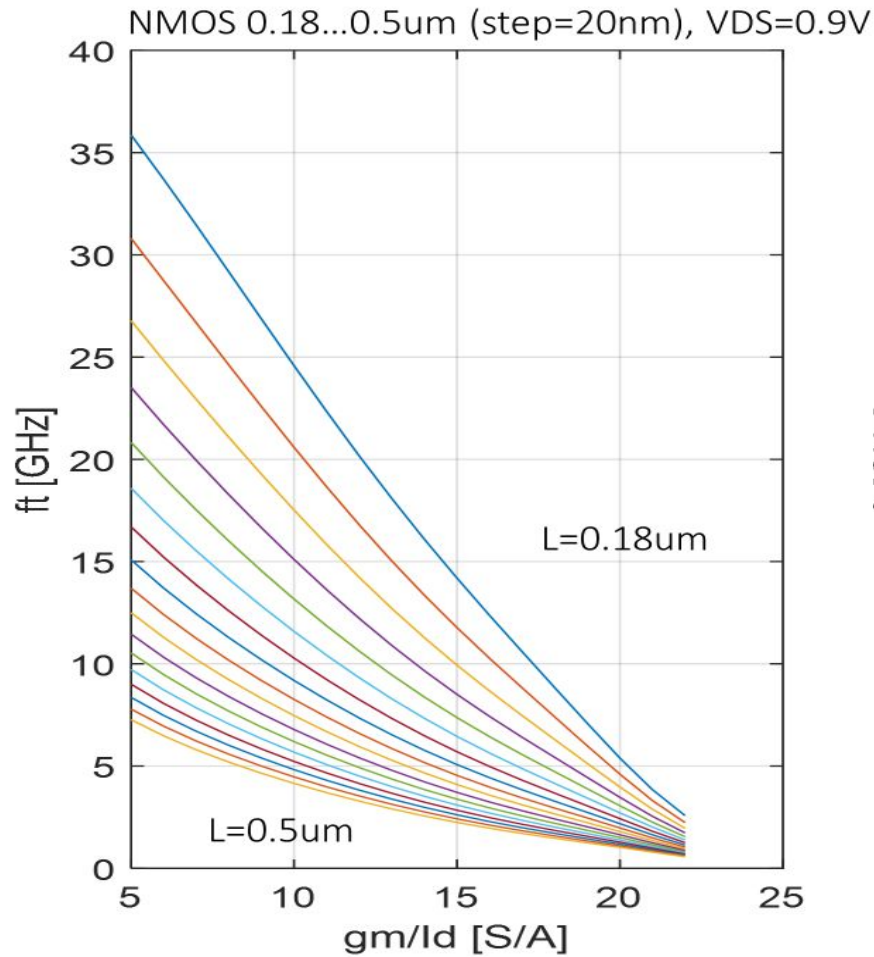
Design Methodology

Use g_m/I_d to describe how a transistor is biased and operating

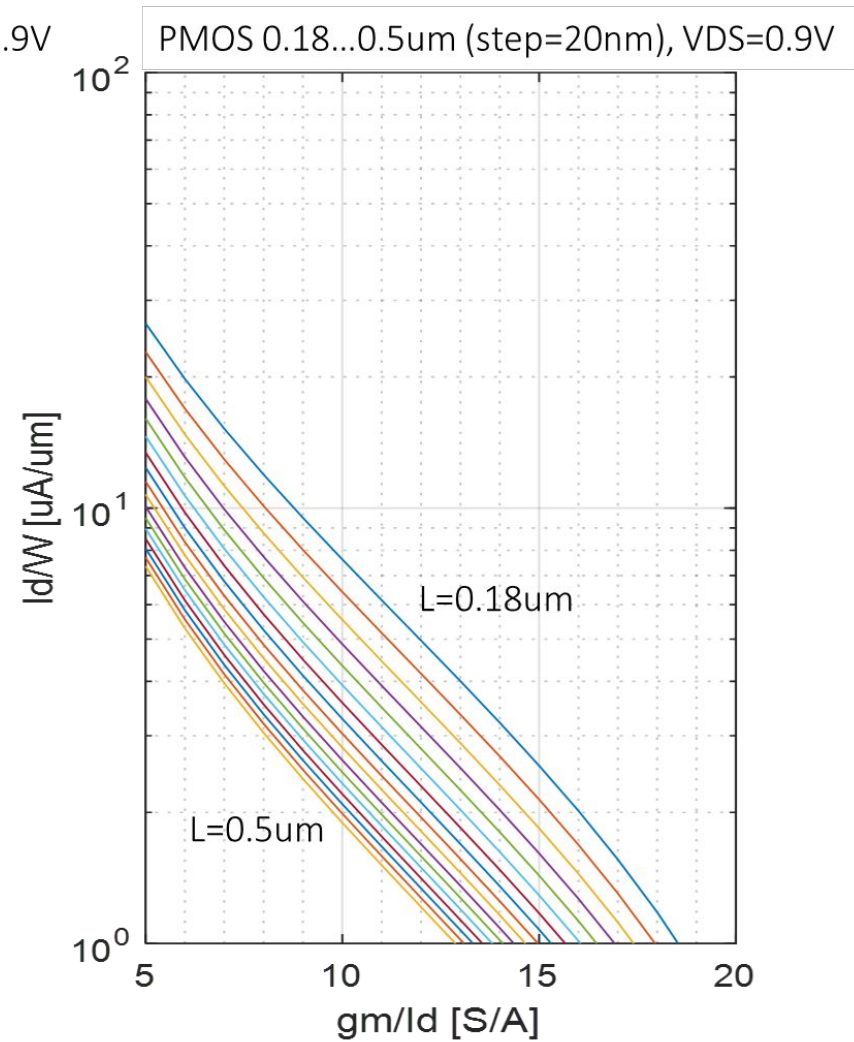
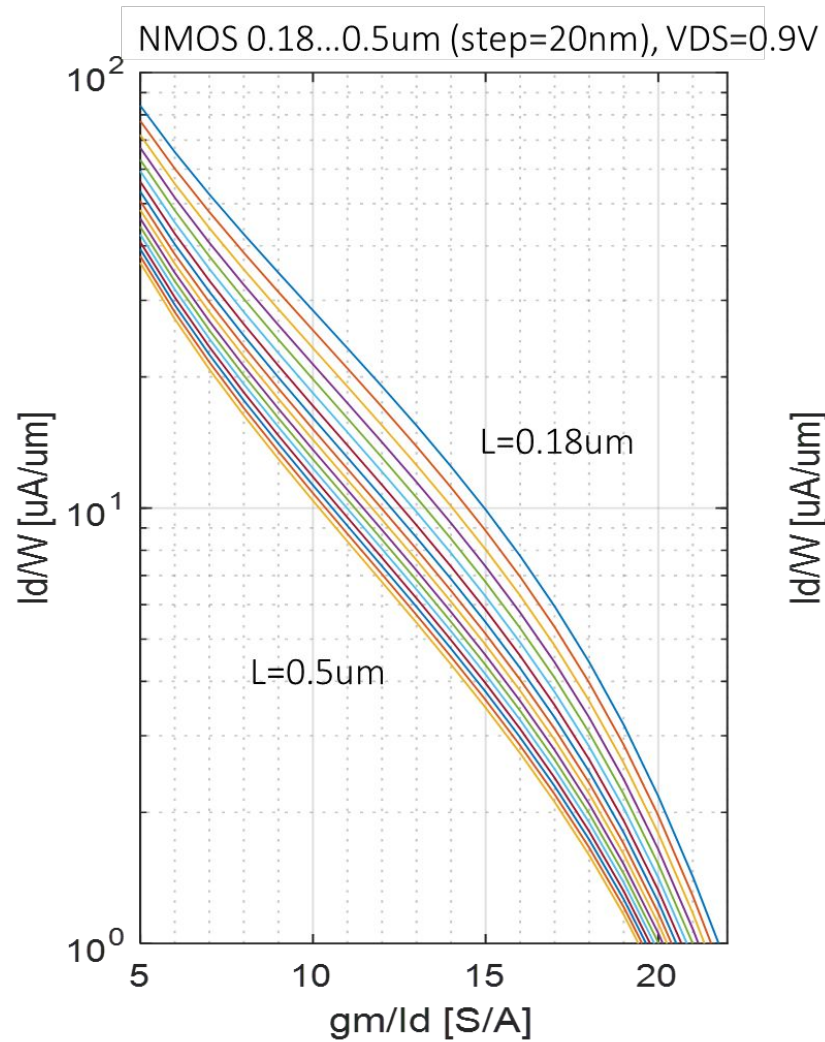
$gm/gds = gm^*ro \rightarrow$ Intrinsic Gain Plots



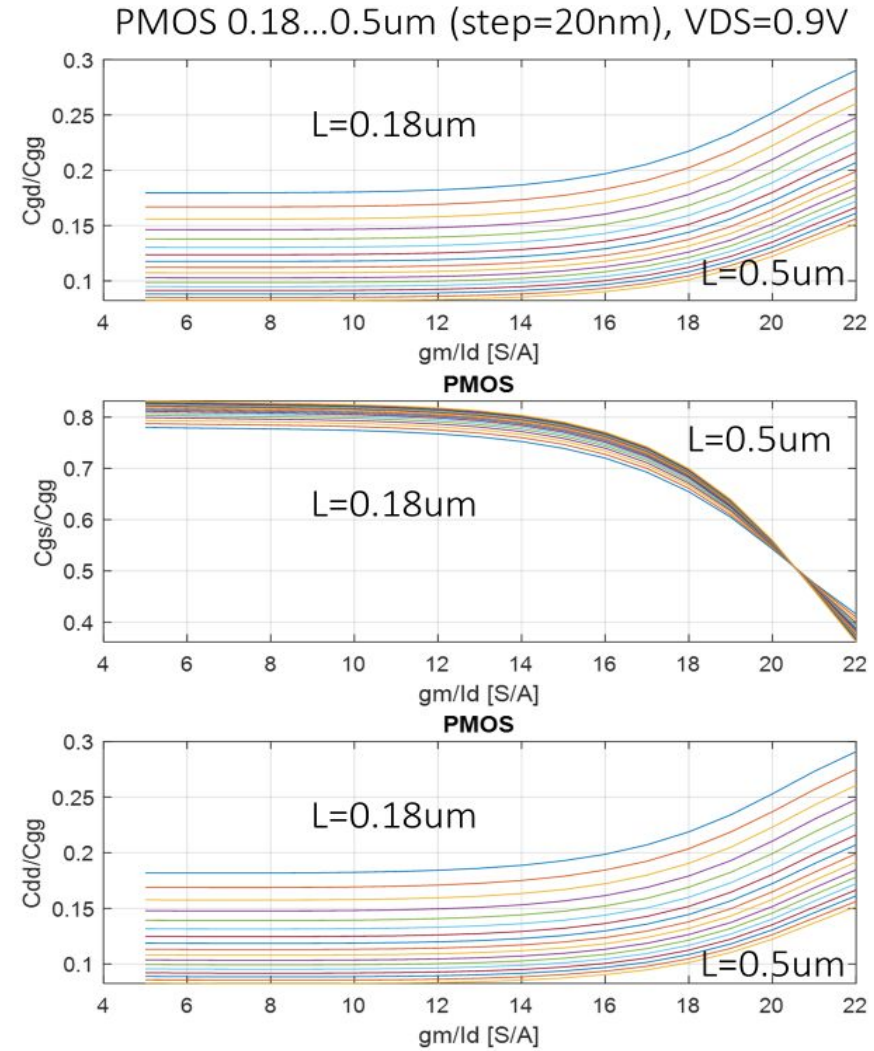
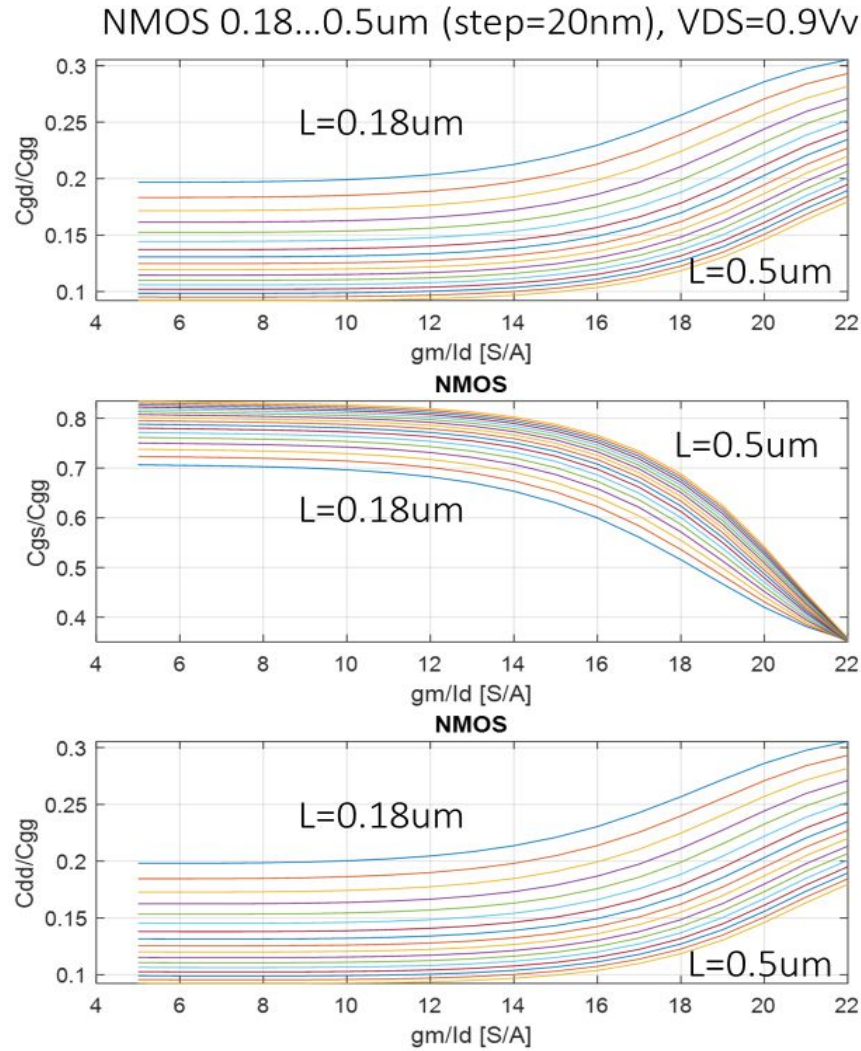
$f_T = gm/C_{gg}/2\pi \rightarrow$ Transit Frequency Plots



$I_d/W \rightarrow$ Current Density Plots



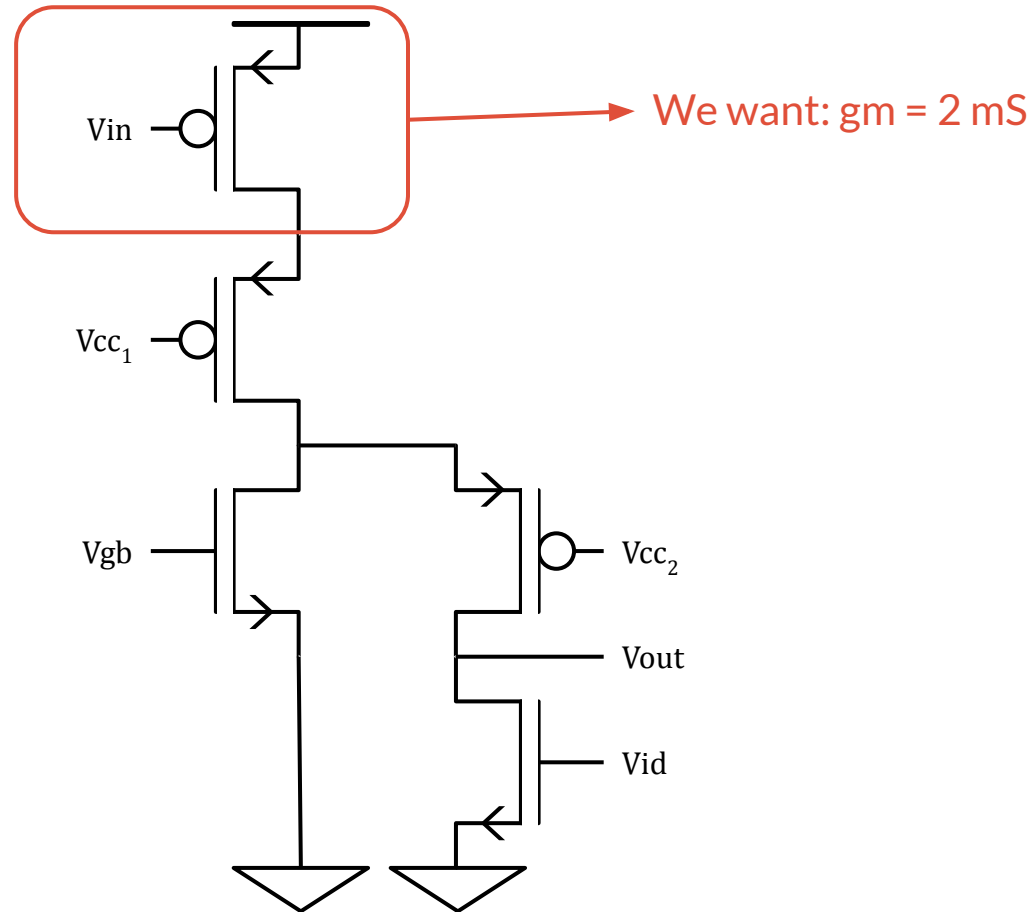
Extrinsic Capacitances ratios



DC Biasing And Sizing Transistors

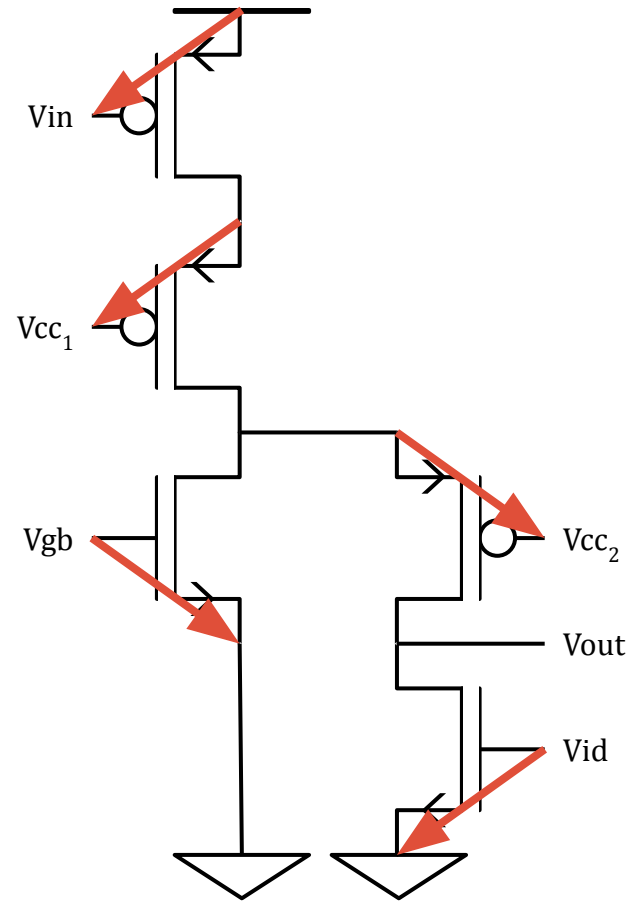
How to size transistors to get a desired gm

Typical situation: We want some gm



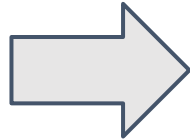
Step 1: Obtain g_m/I_d , L

We will cover later how their optimal values can be found from noise and bandwidth considerations.

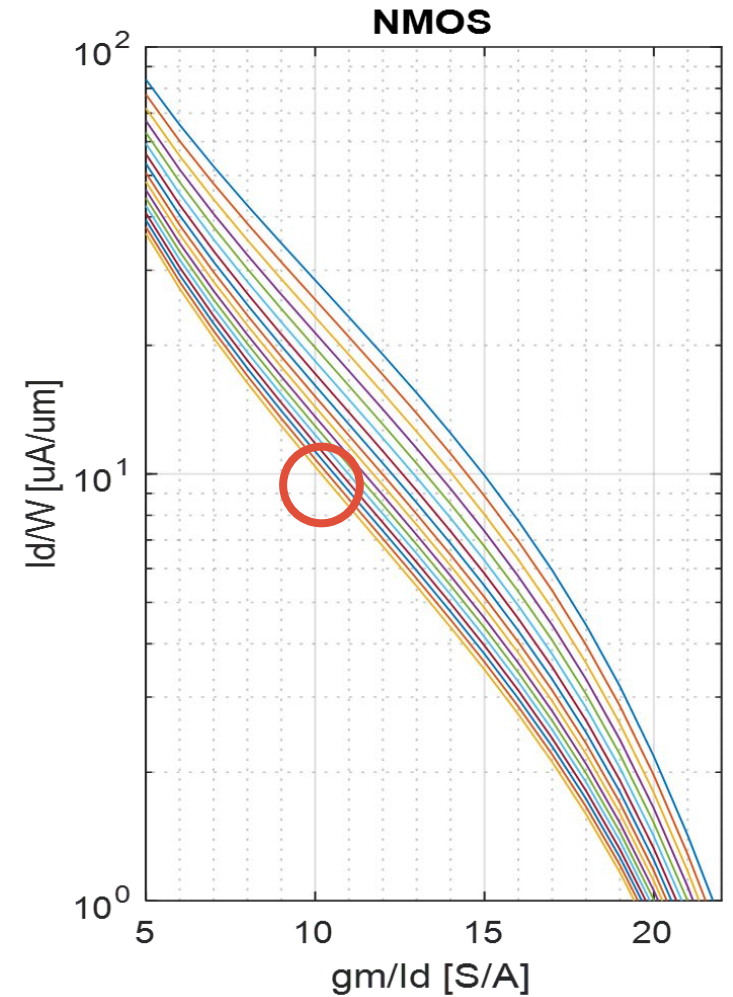


Step 2: Given gm/Id, we can find the current density, etc

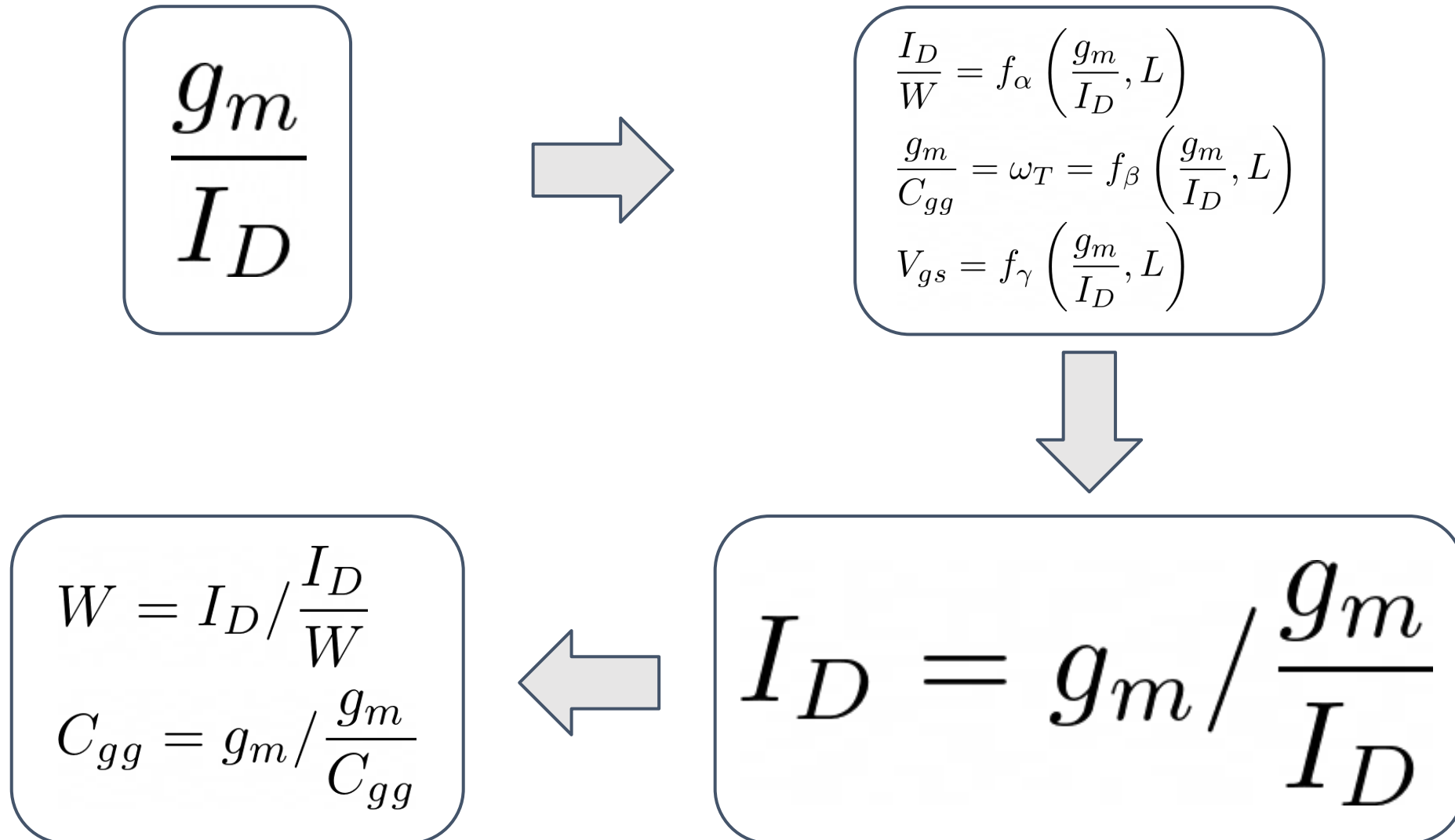
$$\frac{g_m}{I_D}$$



$$\begin{aligned} \frac{I_D}{W} &= f_\alpha \left(\frac{g_m}{I_D}, L \right) \\ \frac{g_m}{C_{gg}} &= \omega_T = f_\beta \left(\frac{g_m}{I_D}, L \right) \\ V_{gs} &= f_\gamma \left(\frac{g_m}{I_D}, L \right) \end{aligned}$$



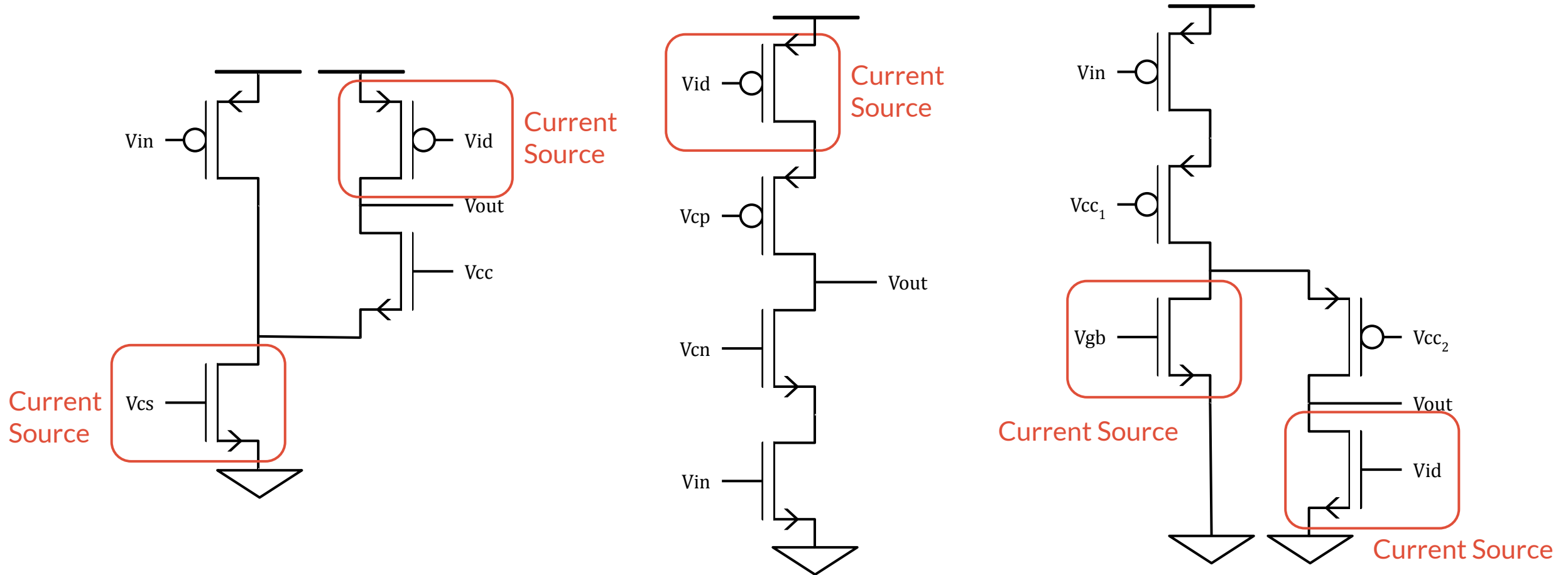
Step 3: Given the ratios, we can find transistor widths, etc



DC Biasing And Sizing Transistors

Current sources

The current sources simply set the desired amount of g_m



Intermission

Our first design exercise

Generic 180nm PDK / 1.8V Supply

No Deep N-Wells: MOSFET body connected to GND/VDD

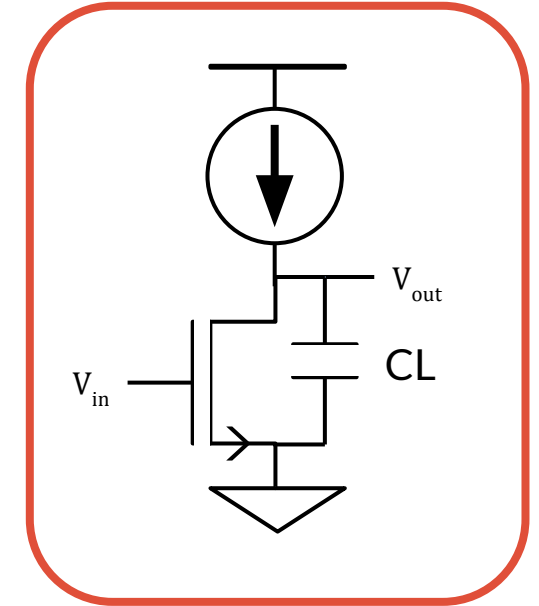
Task: Designing An Open Loop Intrinsic Amplifier

Part 1: Intrinsic Gain Stage

- $I_d < 5\mu\text{A}$
- $C_L = 250\text{fF}$
- $V_{\text{out}} = 0.9\text{V}$ at DC (see next slide)
- Goals:
 - Gain-Bandwidth Product: $> 16\text{MHz}$
 - Maximize Gain

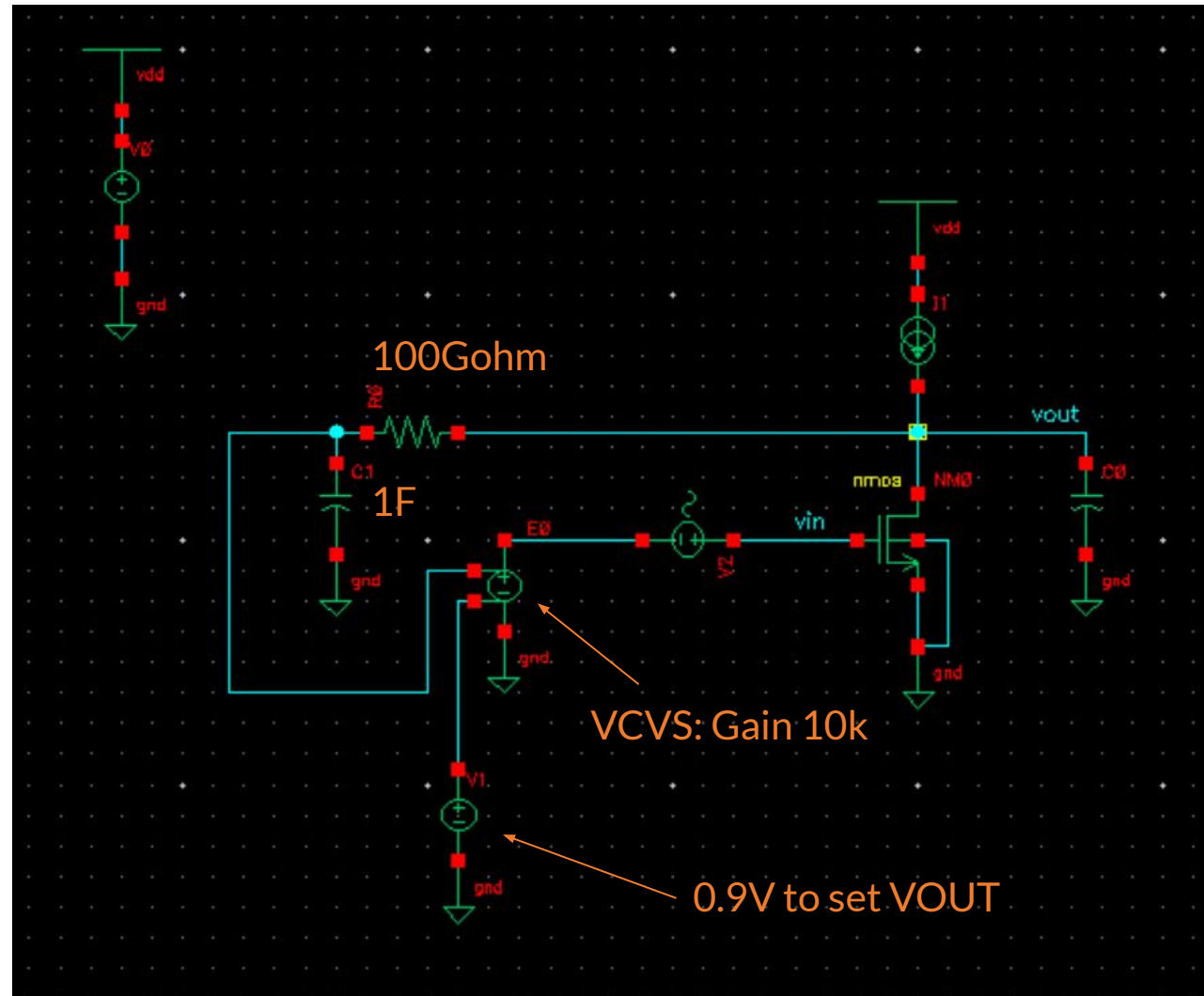
Methodology:

1. By hand: derive gain in terms of g_m , g_{ds} then derive the expression of the pole and the GBW product
2. Calculate g_m to obtain needed GBW
3. Pick an appropriate g_m/g_{ds} and L to achieve desired gain.
4. Given g_m/g_{ds} and L , we've fixed g_m/I_d , f_T and I_d/W .
5. Using I_d/W , find the needed W
6. Run a simulation



Sample Intrinsic Gain Stage Implementation

Note: The auxiliary circuit is an ideal op-amp connected to a lowpass filter. The lowpass filter only lets the DC signal through. The op-amp biases the nMOS such that $V_{OUT} = 0.9V$ in DC



Task: Designing An Open Loop Amplifier

Part 2: Cascoded Stage

- $I_d < 5\mu\text{A}$
- $C_L = 250\text{fF}$
- $V_{\text{out}} = 0.9\text{V}$ at DC (see previous slide)
- Goals:
 - Gain-Bandwidth Product: $> 16\text{MHz}$
 - Maximize Gain

Methodology:

1. Simply add a cascode with the same dimensions of the input transistor
2. Derive the equations
3. See what maximum gain can be achieved
4. Run a simulation. You may need to try different voltages for V_c

