EE 330
Lecture 22

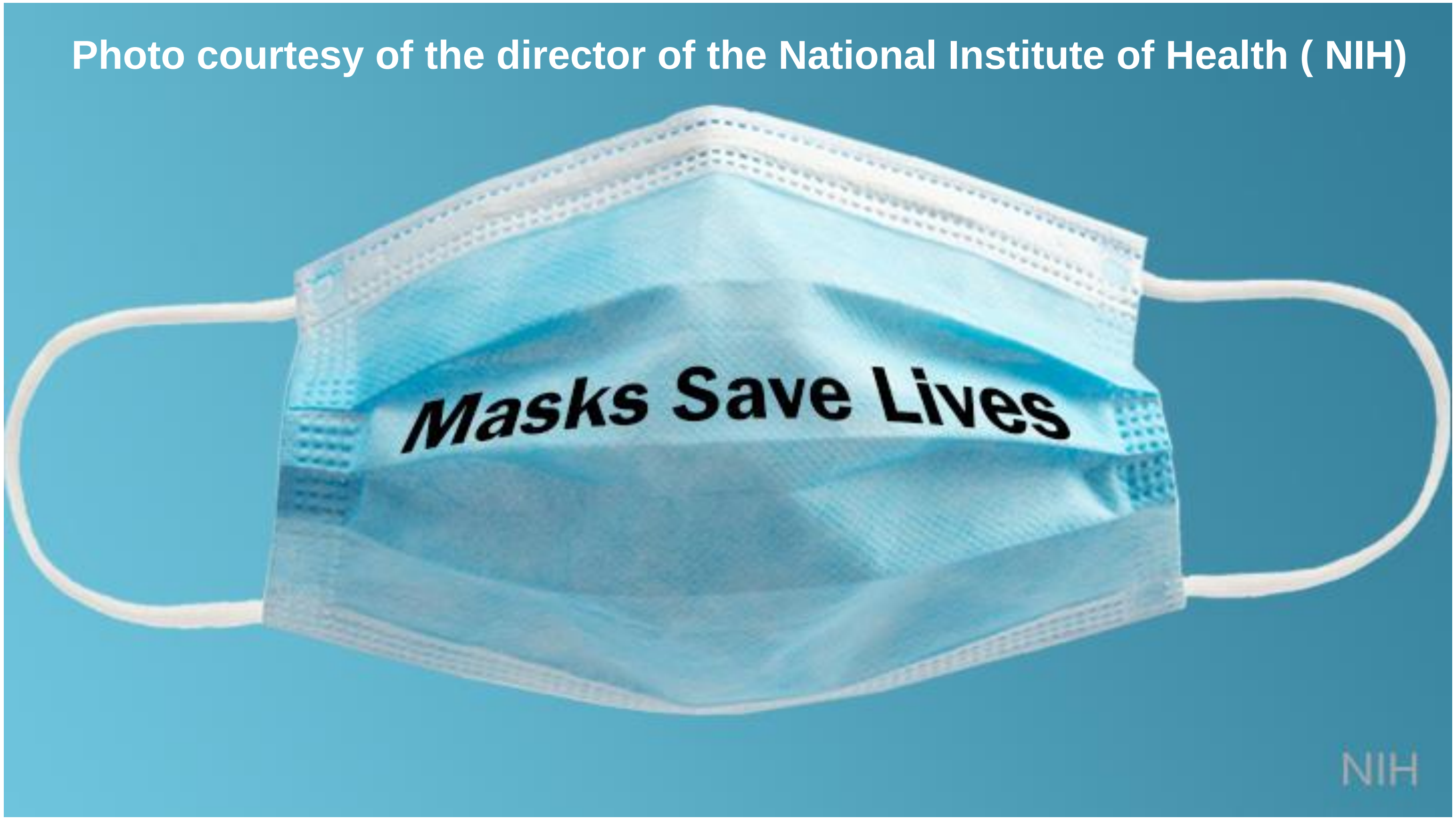
- Amplifiers
- Small Signal Analysis

Exam Schedule

Exam 2 will be given on Friday March 11

Exam 3 will be given on Friday April 15

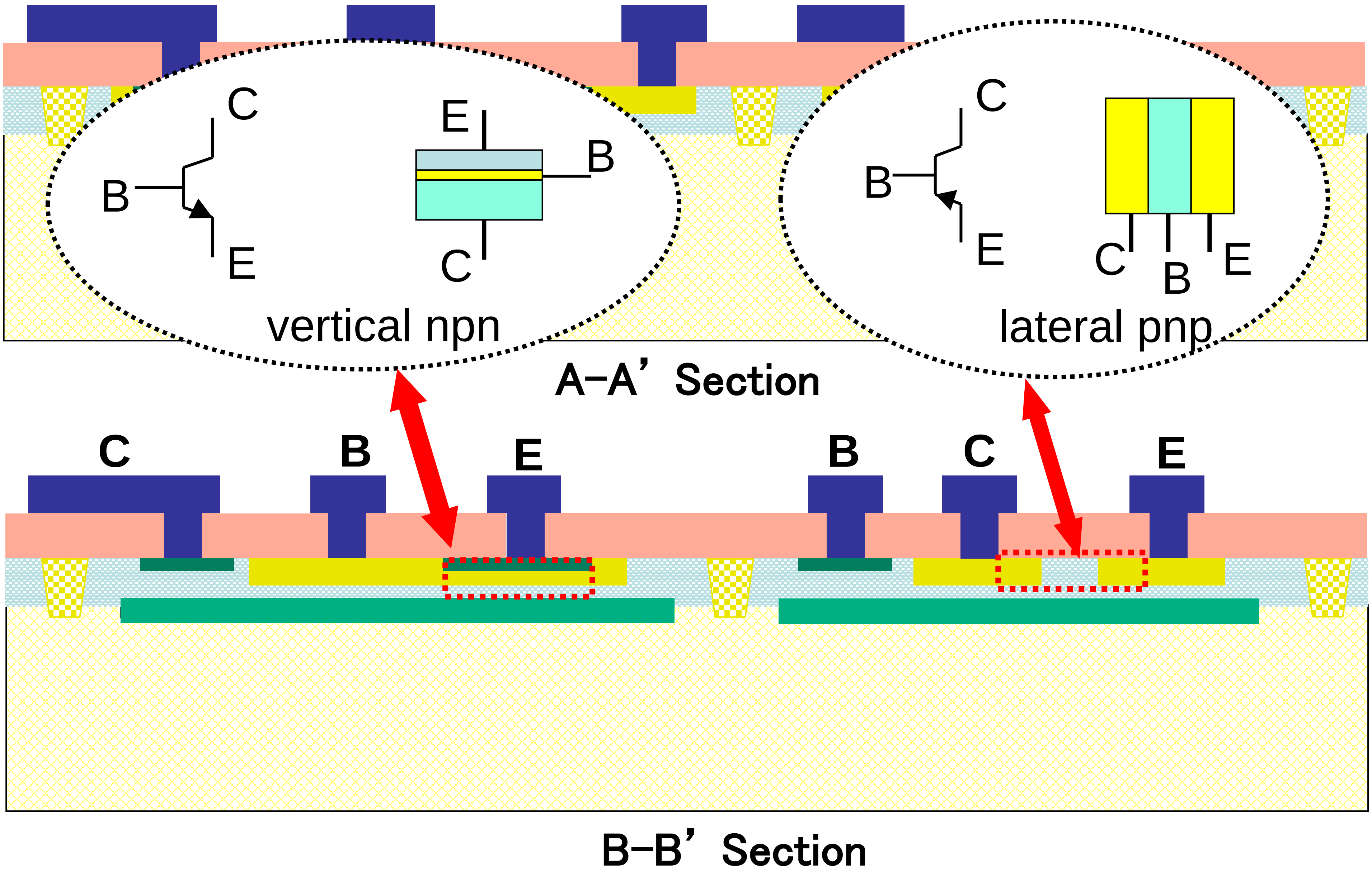
Review session Tuesday 5:00 p.m.
5:00 lab will be delayed to start at 6:00 p.m.



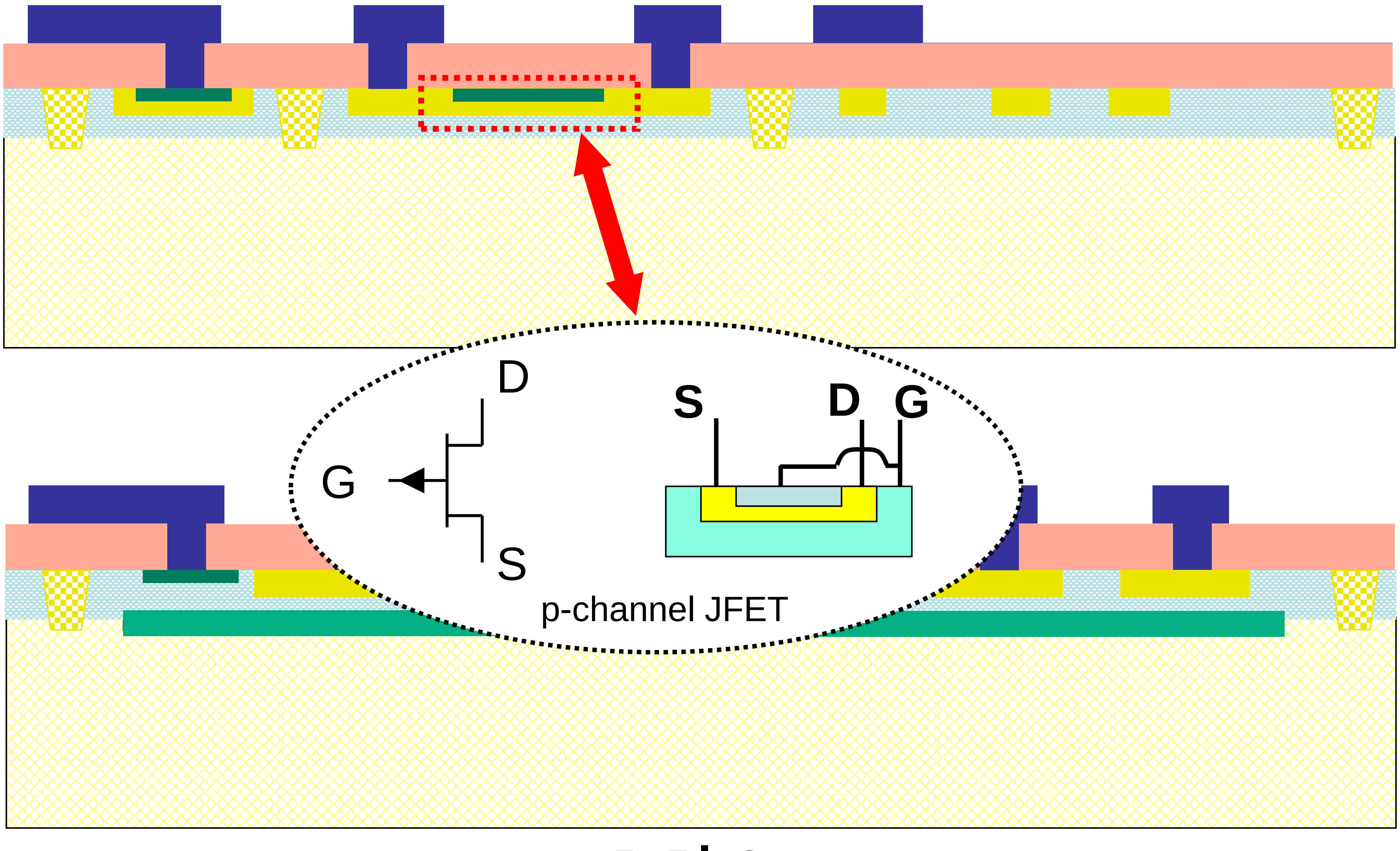
As a courtesy to fellow classmates, TAs, and the instructor

Wearing of masks during lectures and in the laboratories for this course would be appreciated irrespective of vaccination status

Review from Last Lecture

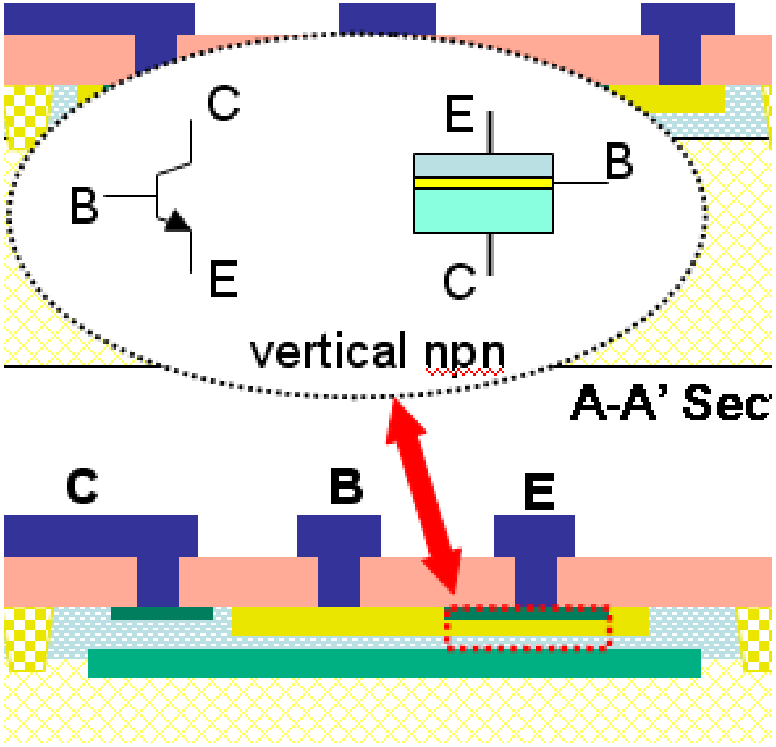


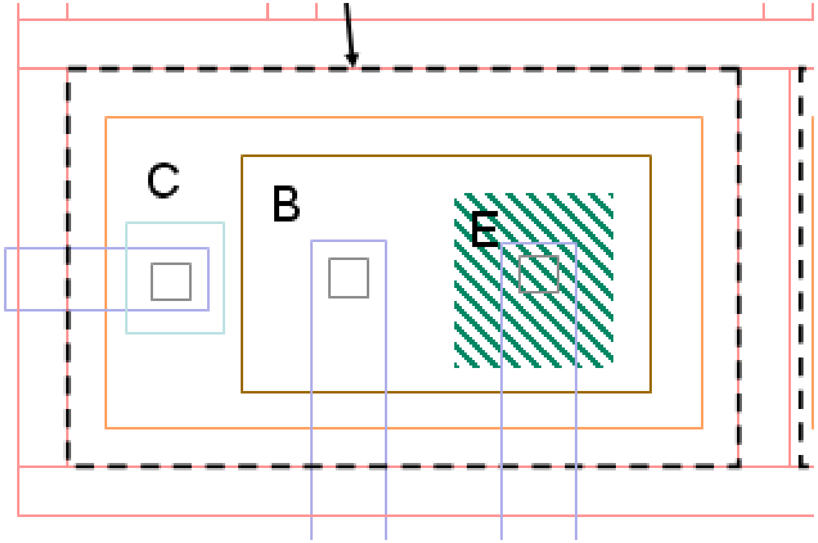
Review from Last Lecture



B-B' Section

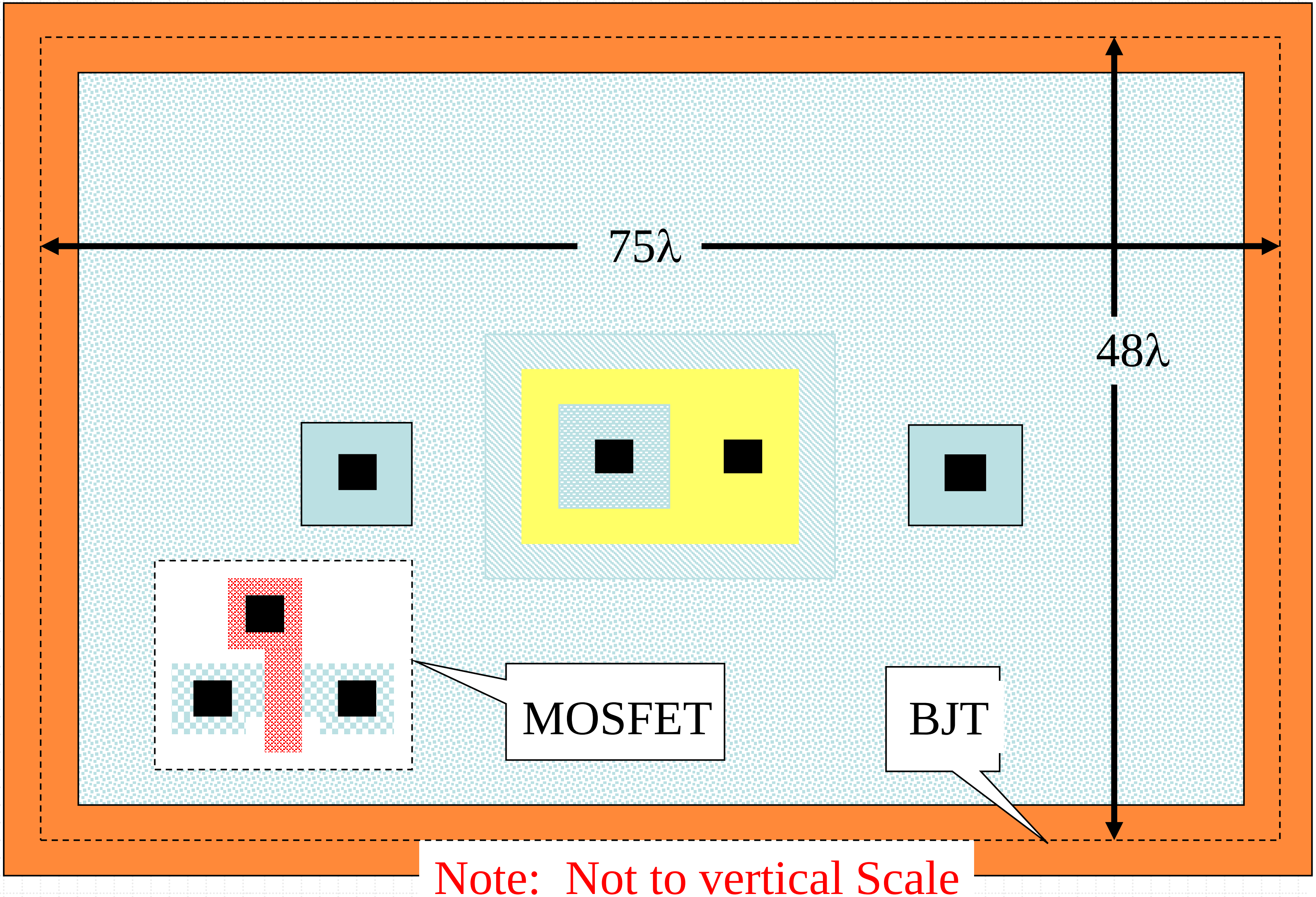
The vertical npn transistor





- Emitter area only geometric parameter that appears in basic device model !
- B and C areas large to get top contact to these regions
- Transistor much larger than emitter
- Multiple-emitter devices often used (TTL Logic) and don't significantly increase area
- Multiple B and C contacts often used (and multiple E contacts as well if A_E large)

Review from Last Lecture



Area Comparison between BJT and MOSFET

- BJT Area = 3600 λ^2
- n-channel MOSFET Area = 168 λ^2
- Area Ratio = 21:1

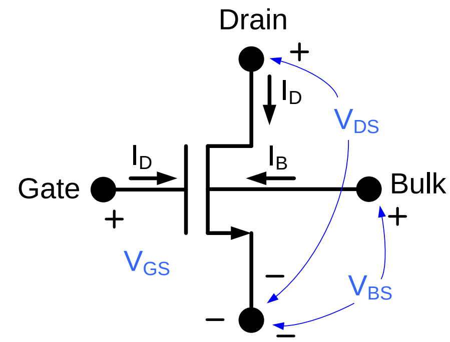
Small-Signal Models

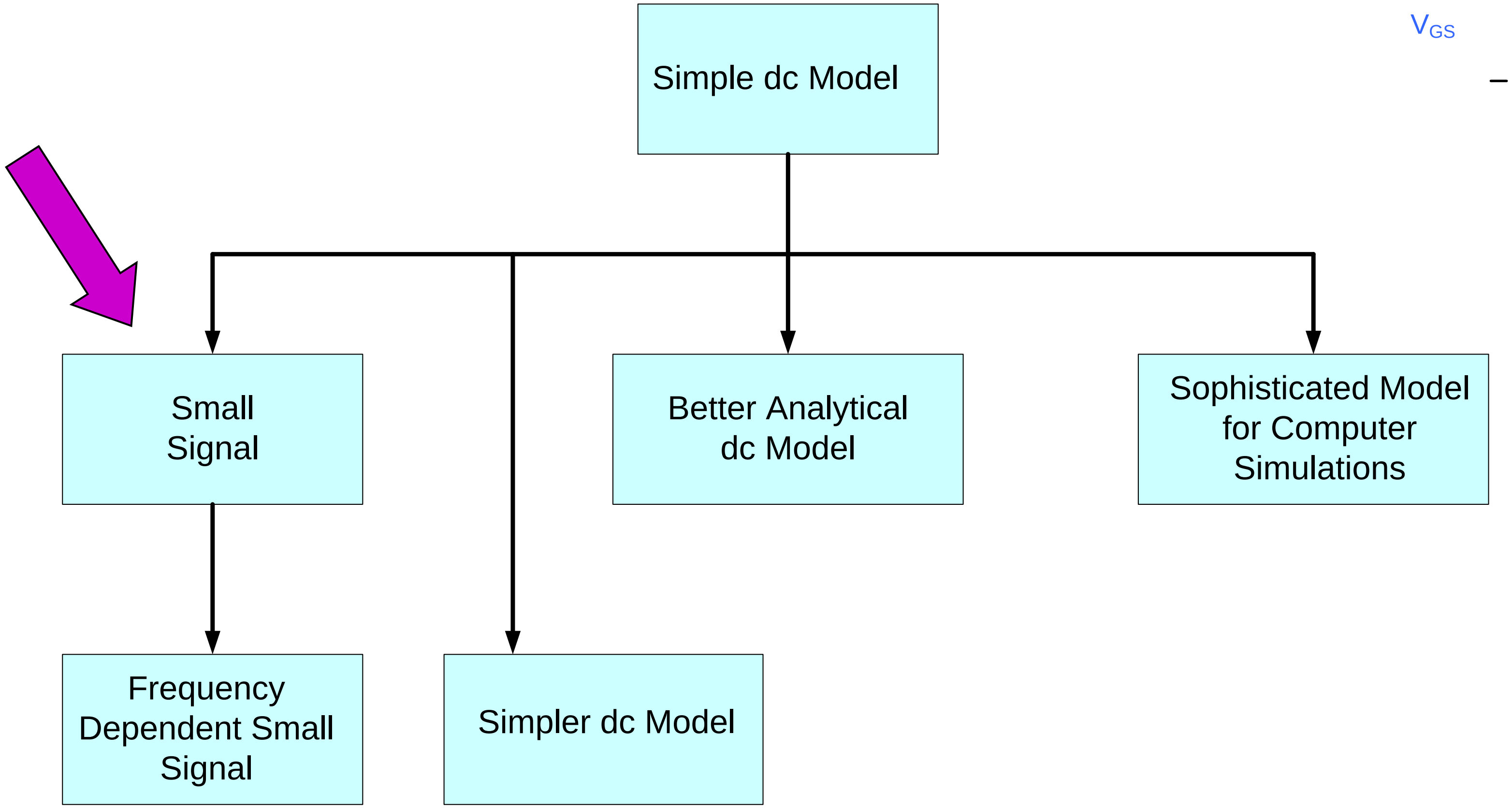
- MOSFET
- BJT
- Diode (of limited use)

Modeling of the MOSFET

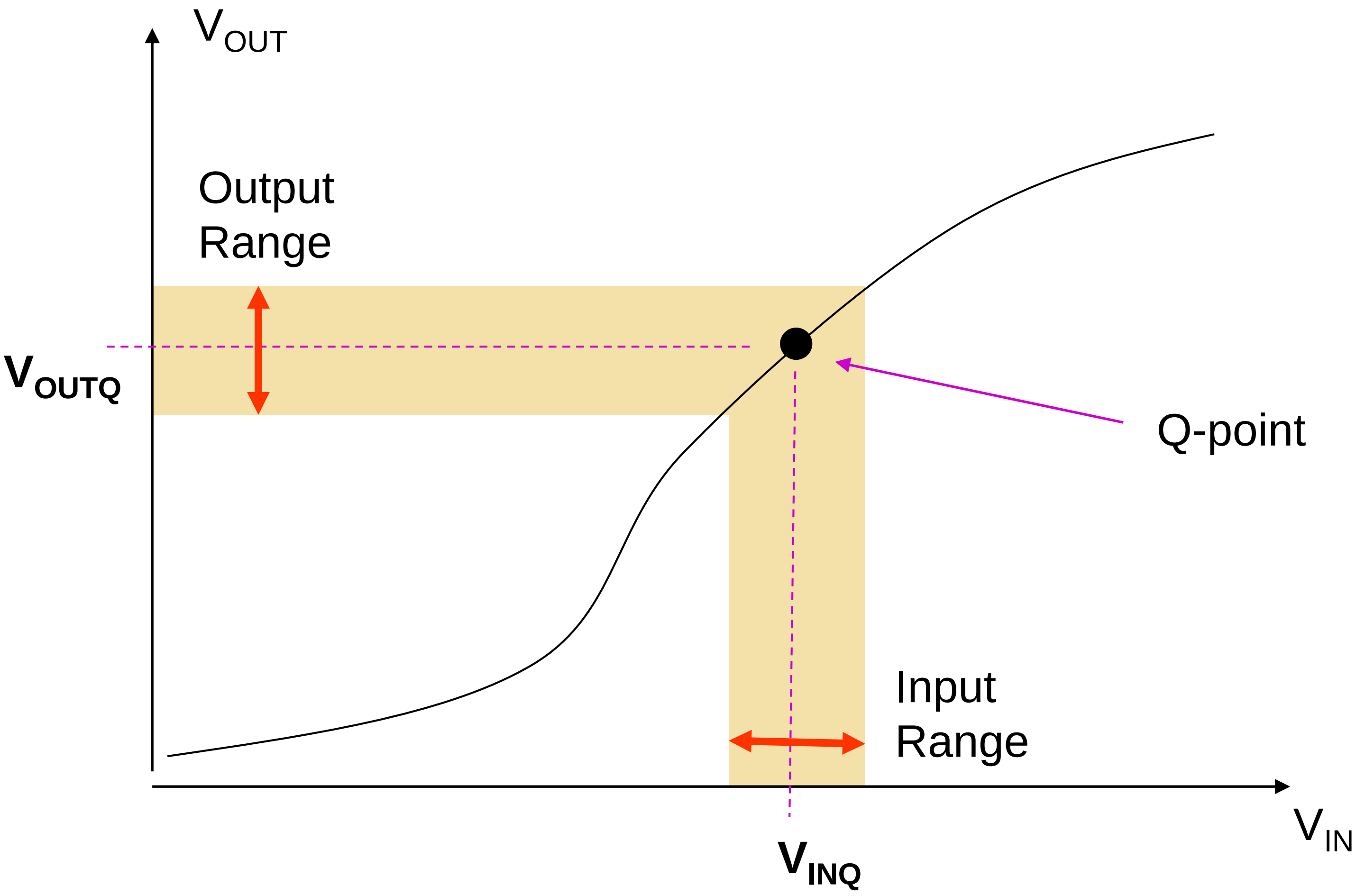
Goal: Obtain a mathematical relationship between the port variables of a device.

$$I_D = f_1(V_{GS}, V_{DS}, V_{BS})$$
$$I_G = f_2(V_{GS}, V_{DS}, V_{BS})$$
$$I_B = f_3(V_{GS}, V_{DS}, V_{BS})$$



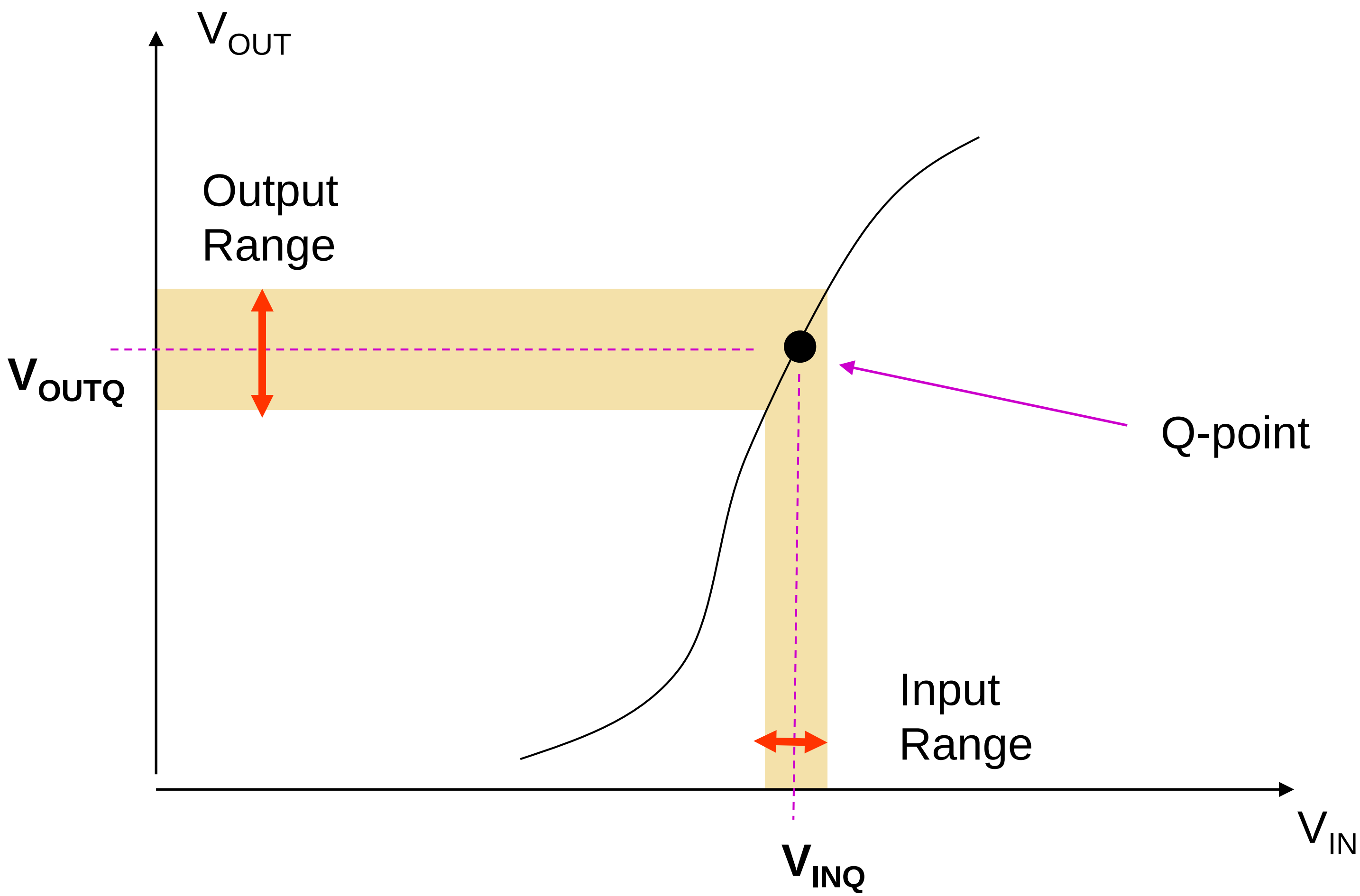


Small-Signal Operation



Throughout the small input range, the “distant” nonlinearities do not affect performance

Small-Signal Operation

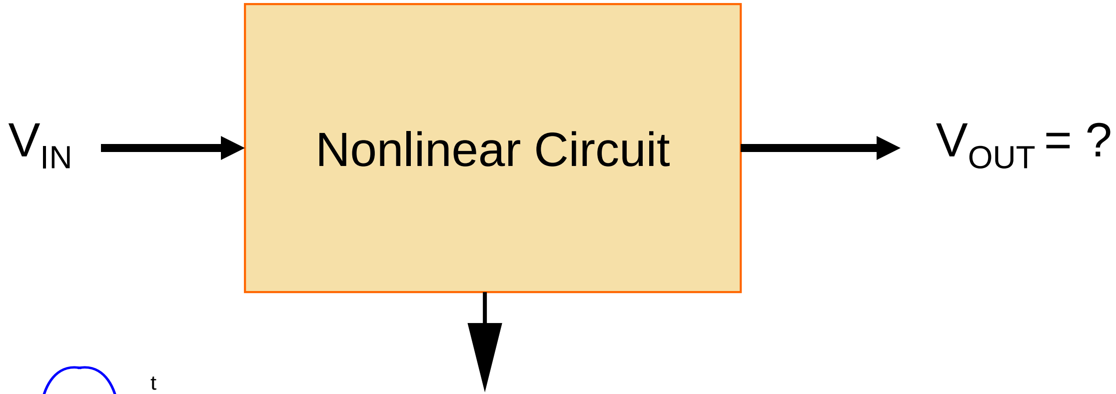


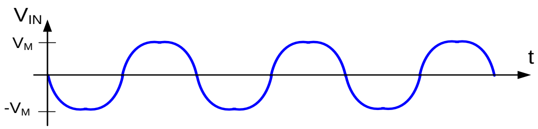
- If slope is steep, output range can be much larger than input range
- The slope can be viewed as the voltage gain of the circuit
- Nonlinear circuit behaves as a linear circuit near Q-point with small-signal inputs

Small signal operation of nonlinear circuits

$V_{IN}=V_m\sin\omega t + V_{INQ}$

V_M is small





- **Small signal concepts often apply when building amplifiers**
- **If small signal concepts do not apply, usually the amplifier will not perform well**
- **Small signal operation is usually synonymous with "locally linear"**
- **Small signal operation is relative to an "operating point"**

Operating Point of Electronic Circuits

Often interested in circuits where a small signal input is to be amplified (e.g. V_M in previous slide is small)

The electrical port variables where the small signals goes to 0 are termed the Operating Points, the Bias Points, the Quiescent Points, or simply the Q-Points

By setting the small signal inputs to 0, it means replacing small voltage inputs with short circuits and small current inputs with open circuits

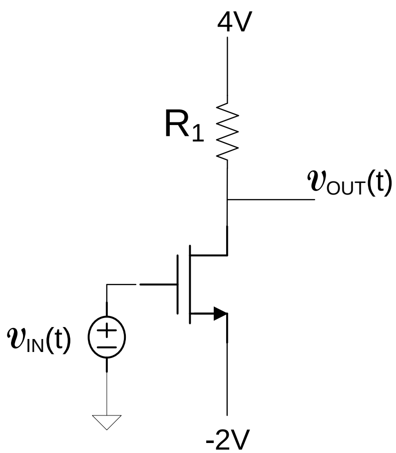
When analyzing small-signal amplifiers, it is necessary to obtain the Q-point

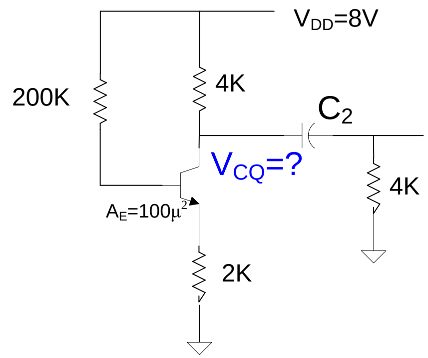
When designing small-signal amplifiers, establishing of the desired Q-point is termed "biasing"

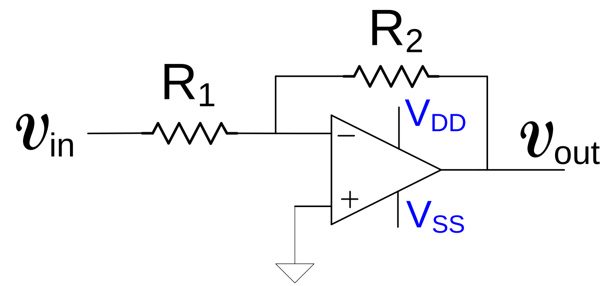
- Capacitors become open circuits (and inductors short circuits) when determining Q-points
- Simplified dc models of the MOSFET (saturation region) or BJT (forward active region) are usually adequate for determining the Q-point in practical amplifier circuits
- DC voltage and current sources remain when determining Q-points
- Small-signal voltage and current sources are set to 0 when determining Q-points

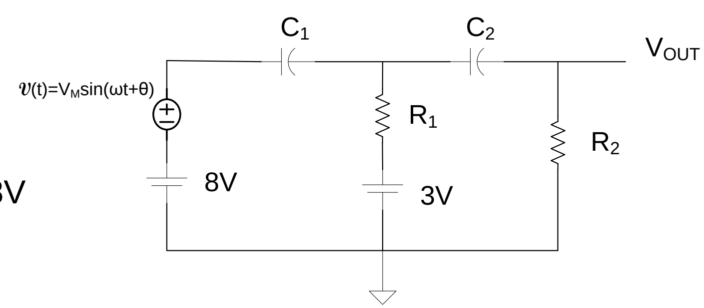
Operating Point of Electronic Circuits

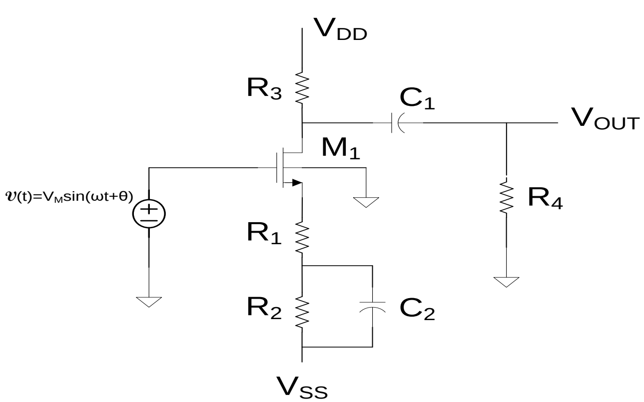
(small signal inputs, if there are any, are set to 0)

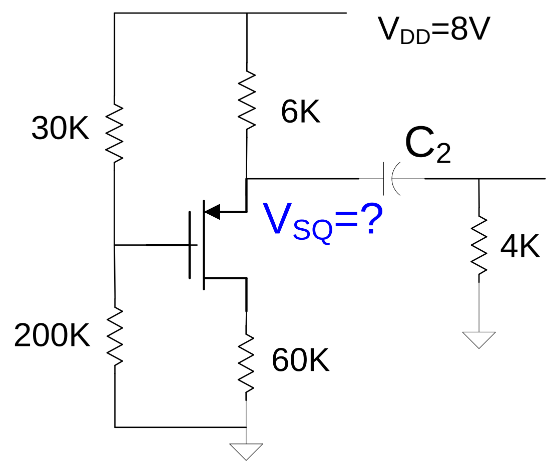








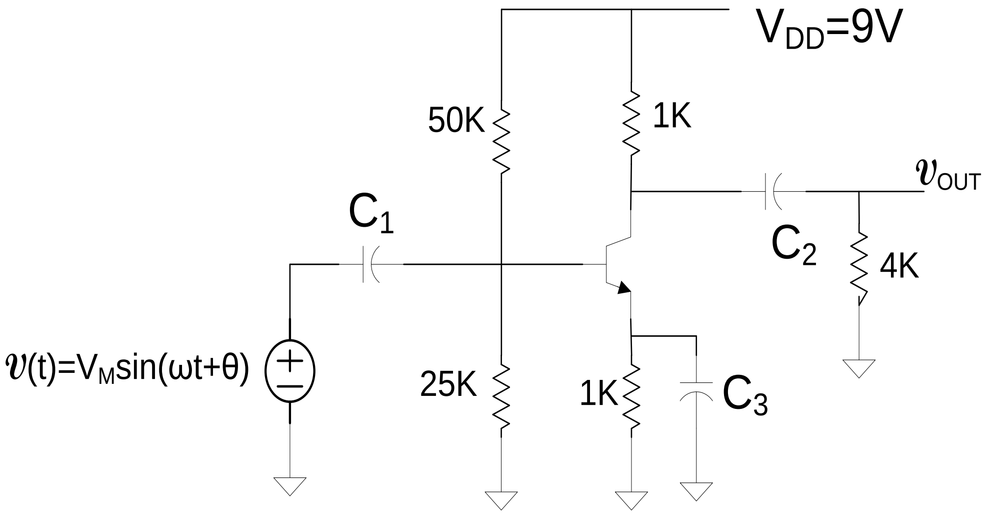




Operating Point Analysis of MOS and Bipolar Devices

Example:

Determine V_{OUTQ} and V_{CQ}

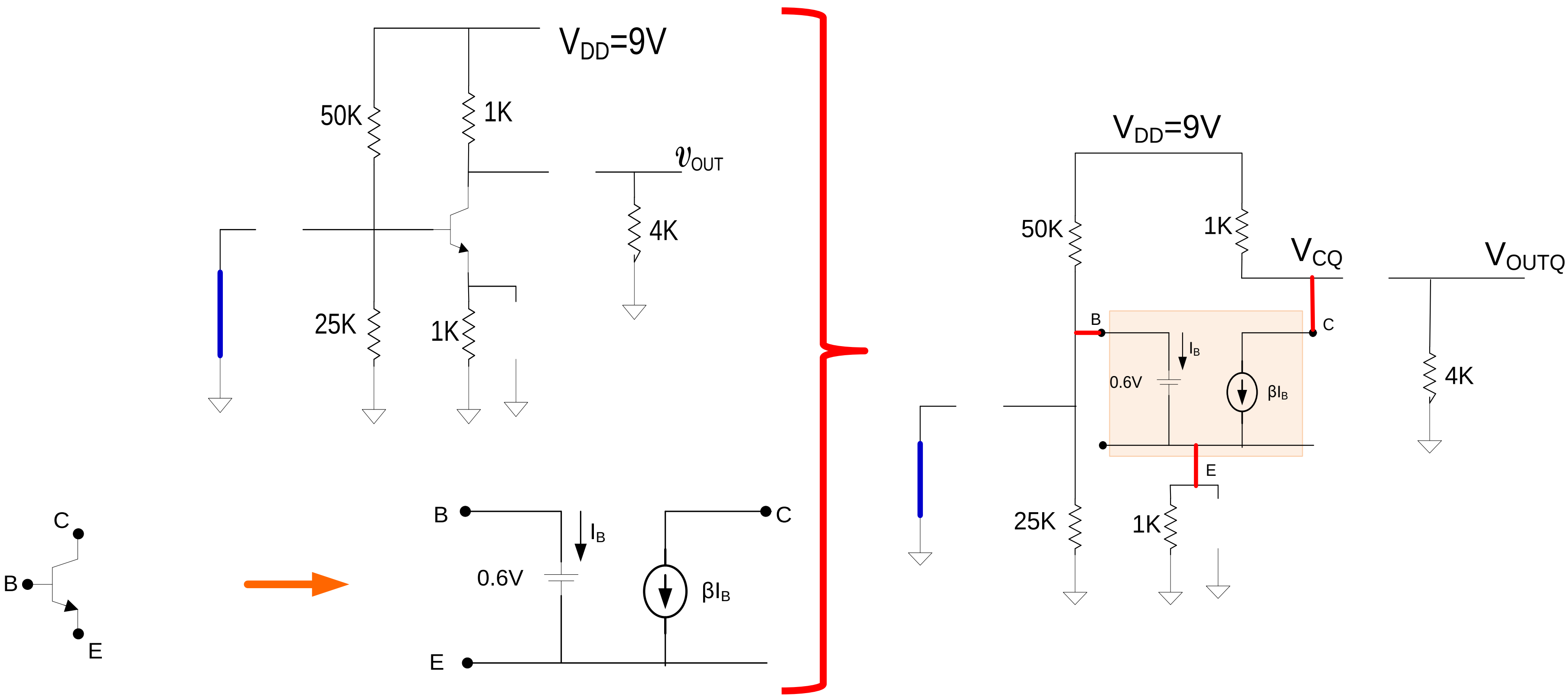


Will formally go through the process in this example, will go into more detail about finding the operating point later

Operating Point Analysis of MOS and Bipolar Devices

Example:

Determine V_{OUTQ} and V_{CQ}



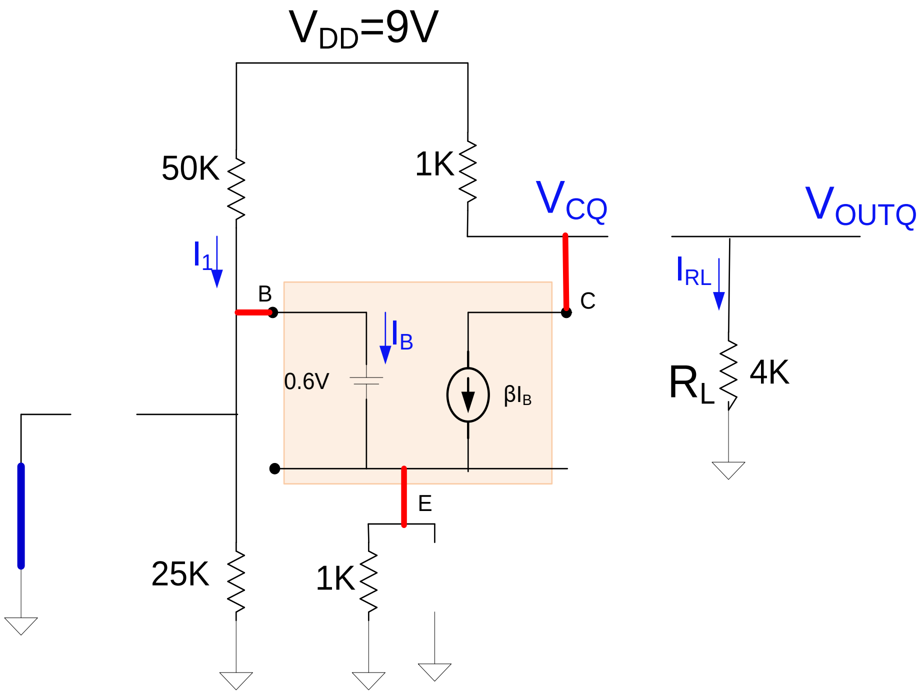
Operating Point Analysis of MOS and Bipolar Devices

Example:

Determine V_{OUTQ} and V_{CQ}

Assume β=100

Assume $I_B << I_1$ (must verify)



$$V_{BQ} = \frac{9V}{3} = 3V$$

$$V_{EQ} = 3V - 0.6V = 2.4V$$

$$I_{EQ} = I_{CQ} = \frac{2.4V}{1K} = 2.4mA$$

$$V_{CQ} = 9V - I_{CQ} \bullet 1K = 9V - 2.4V = 6.6V$$

V_{OUTQ} = I_{RL}•4K = 0V

V_{CQ}=6.6V

V_{OUTQ}=0V

Amplification with Transistors

From Wikipedia: (Oct. 2019 and October 2020)

An **amplifier**, **electronic amplifier** or (informally) **amp** is an electronic device that can increase the power of a signal (a time-varying voltage or current).

What is the "power" of a signal?

Can an amplifier make decisions?

Does Wikipedia have such a basic concept right?

Amplification with Transistors

From Wikipedia: (Oct. 2019, Oct. 2020, Oct 2021, March 2022)

An **amplifier**, **electronic amplifier** or (informally) **amp** is an electronic device that can increase the power of a signal (a time-varying voltage or current).

It is a two-port electronic circuit that uses electric power from a power supply to increase the amplitude of a signal applied to its input terminals, producing a proportionally greater amplitude signal at its output. The amount of amplification provided by an amplifier is measured by its gain: the ratio of output voltage, current, or power to input. An amplifier is a circuit that has a power gain greater than one.[1][2][3]

Self-inconsistent definition !

Amplification with Transistors

From Wikipedia: (Feb. 2017)

An **amplifier**, **electronic amplifier** or (informally) **amp** is an electronic device that increases the power of a signal (a time varying voltage or current.

From Wikipedia: (Oct. 2015)

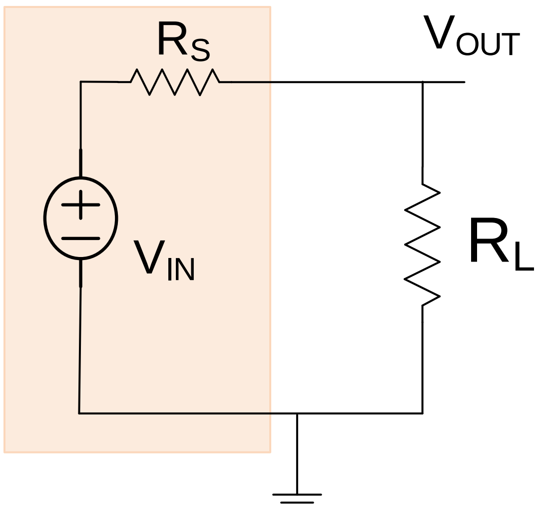
An **amplifier**, **electronic amplifier** or (informally) **amp** is an electronic device that increases the power of a signal.

From Wikipedia: (approx. 2010)

Generally, an **amplifier** or simply **amp**, is any device that changes, usually increases, the amplitude of a signal. The "signal" is usually voltage or current.

These “minor” differences in definition are not trivial !

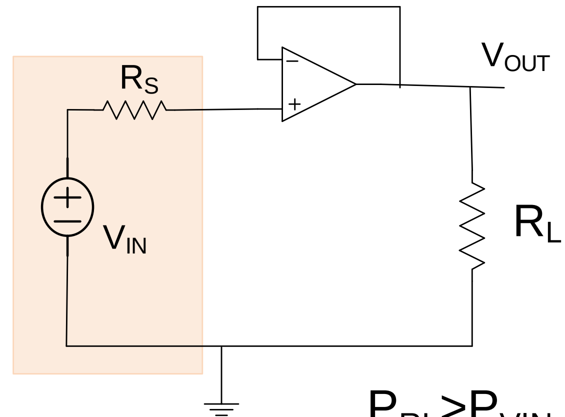
Signal and Power Levels



$P_{RL} < P_{VIN}$

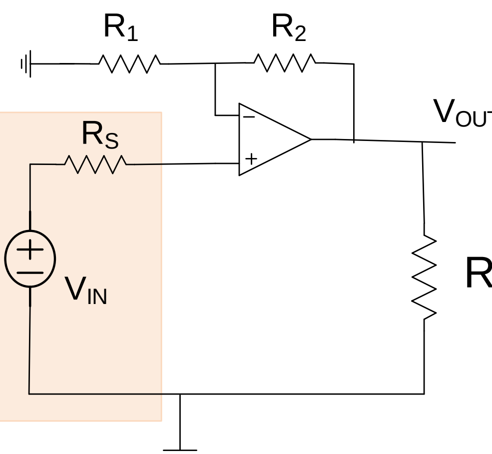
$V_{OUT} < V_{IN}$

P_{RL} will be maximum when load impedance matches source impedance



$P_{RL} > P_{VIN}$

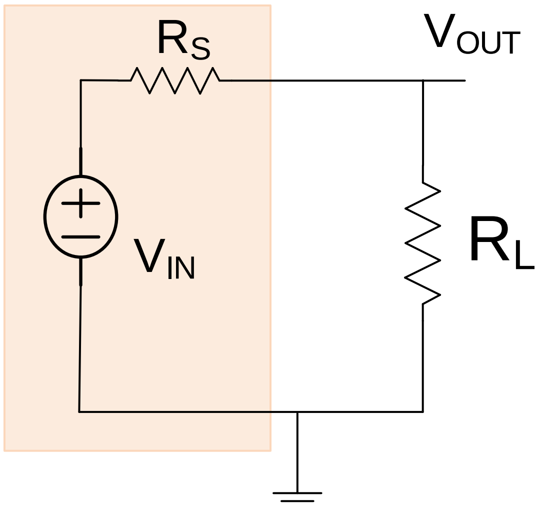
$V_{OUT} = V_{IN}$



$P_{RL} > P_{VIN}$

V_{OUT} can be larger of smaller than V_{IN}

Signal and Power Levels



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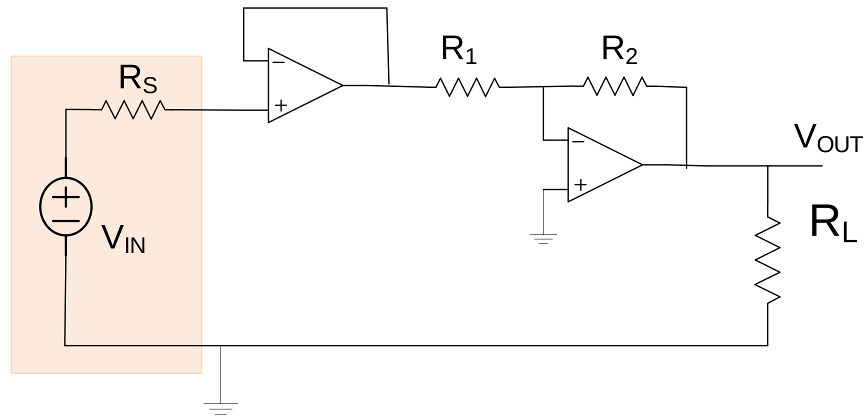
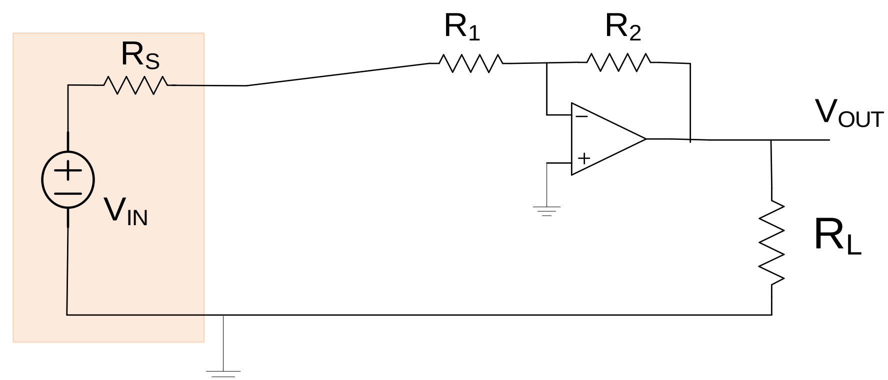


$P_{RL} > P_{VIN}$

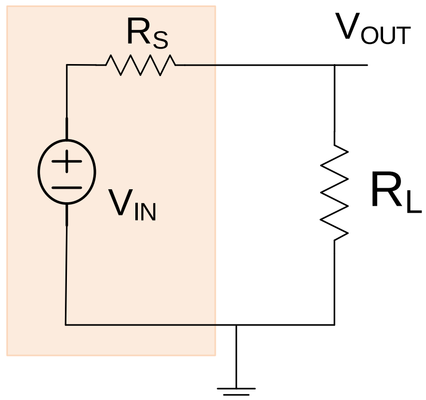
V_{OUT} can be larger or smaller than V_{IN}

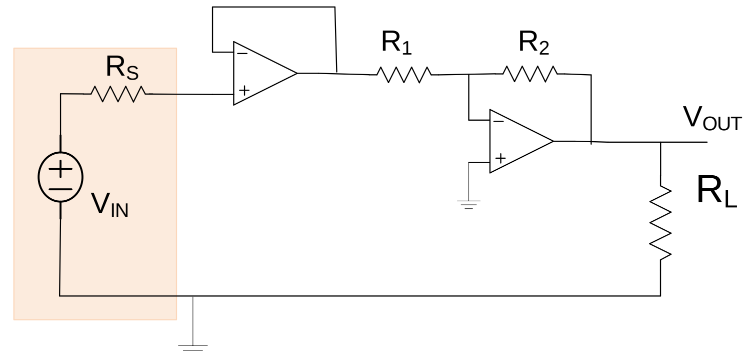


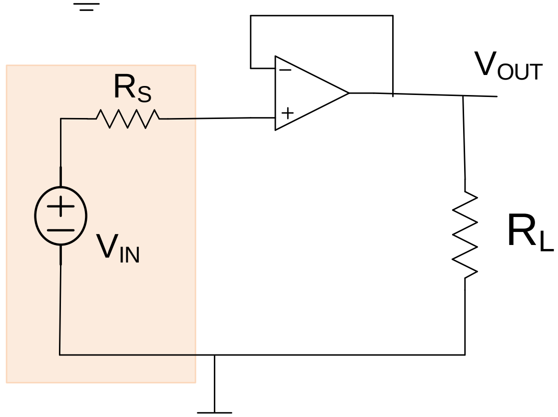
V_{OUT} can be larger of smaller than V_{IN}

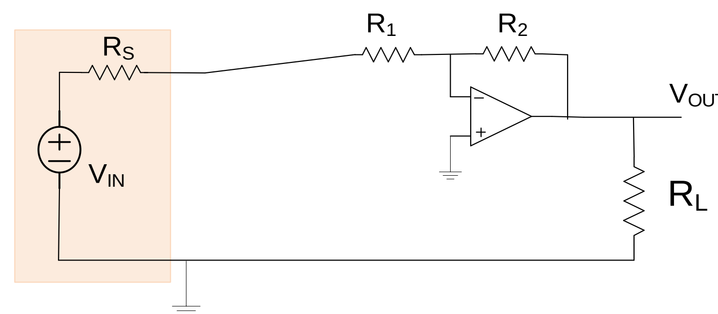
P_{RL} can be larger of smaller than P_{VIN}

Signal and Power Levels









In most electronic circuit “amplifier” applications, there is little concern about whether the power in the load is larger or smaller than the power supplied by the source

Impedance matching for the purpose of delivering power to a load is seldom of concern or even used in most electronic circuits

Amplification with Transistors

From Wikipedia: (Oct. 2019 , March 2020, Oct 2021, March 2022)

> An **amplifier**, **electronic amplifier** or (informally) **amp** is an electronic device that can increase the power of a signal (a time-varying voltage or current).

- It is difficult to increase the voltage or current very much with passive RC circuits
- Voltage and current levels can be increased a lot with transformers but transformers not practical in integrated circuits
- Power levels can not be increased with passive elements (R, L, C, and Transformers)

- Often an amplifier is defined to be a circuit that **can** be used to increase power delivered to a resistive load (be careful with Wikipedia and WWW even when some of the most basic concepts are discussed)
- Transistors can be used to increase not only signal levels but power levels to a load
- In transistor circuits, power that is delivered in the signal path is supplied by a biasing network
- Signals that are amplified are often not time varying

In the electronic community, there is often little or no concern about the power delivered to a load and the term "amplifier" generally refers to a device that changes the level of a voltage or current or converts from one unit to another (V to I or I to V)

Amplification with Transistors

From Wikipedia: (Oct. 2019 and March 2020)

An **amplifier**, **electronic amplifier** or (informally) **amp** is an electronic device that can increase the power of a signal (a time-varying voltage or current).

From Wikipedia: (Oct. 2015)

It does this by taking energy from a power supply and controlling the output to match the input signal shape but with a larger amplitude. In this sense, an amplifier modulates the output of the power supply to make the output signal stronger than the input signal.

Dependent Sources

What is a dependent source?

Did you ever see one in the EE 201 Course?

Did you have them in your parts kit for EE 201?

Did you ever see one in the EE 201 Laboratory?

Did you ever see one in the EE 230 Laboratory?

Can you buy one from Digi Key?

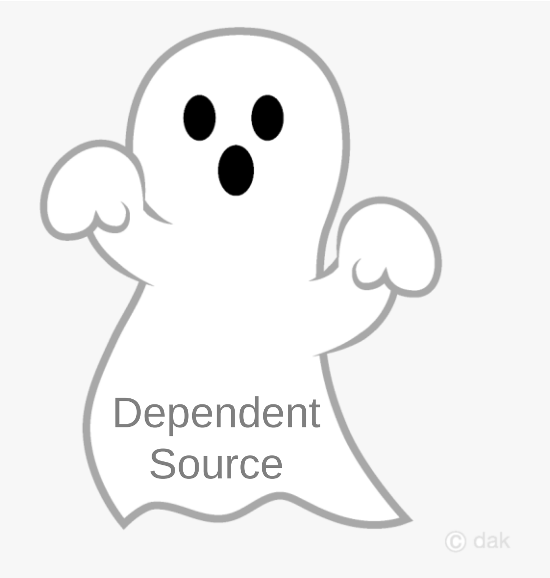
World's Largest Selection
of Electronic Components Available for Immediate Shipment!®

Digi-Key has over 9 million different parts from over 1000 suppliers !

Dependent Sources

What is a dependent source?

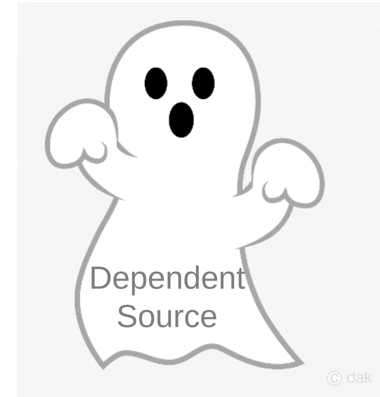
Will you suddenly find dependent sources after you graduate ?



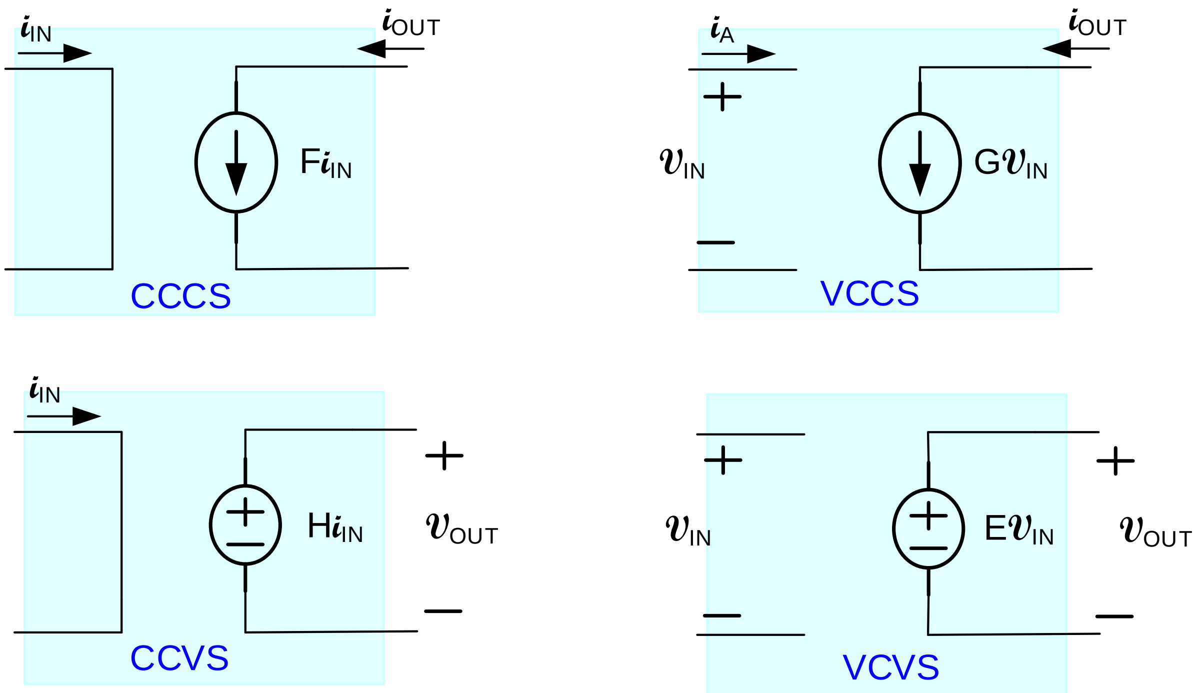
Do dependent sources really exist ?

Why do we place so much emphasis on dependent sources in EE 201?

Dependent Sources



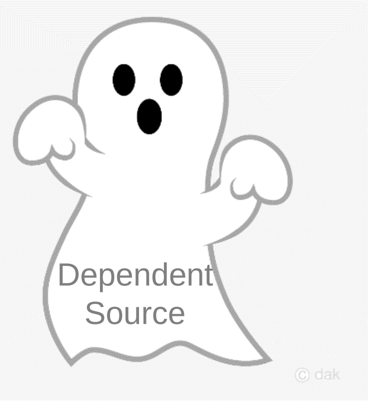
What is a dependent source?



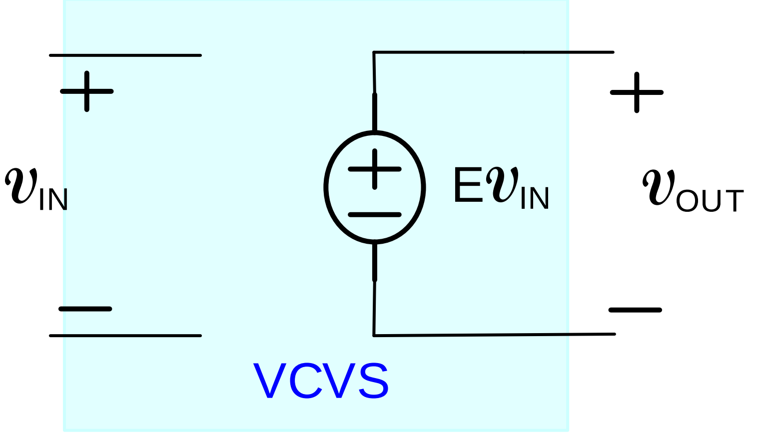
The four basic dependent sources !

Two-port networks with infinite or zero input and output impedances

Dependent Sources



Observe, as an example,

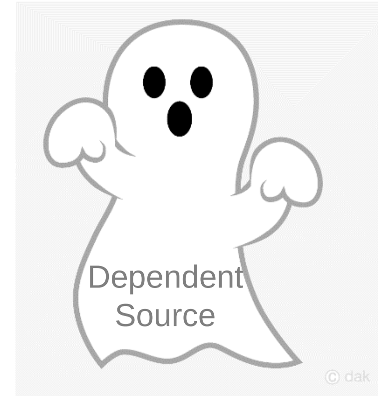


$$V_{OUT} = EV_{IN}$$

$$R_{IN}=\infty \quad R_{OUT}=0$$

Does this have anything in common with a Voltage Amplifier?

Dependent Sources



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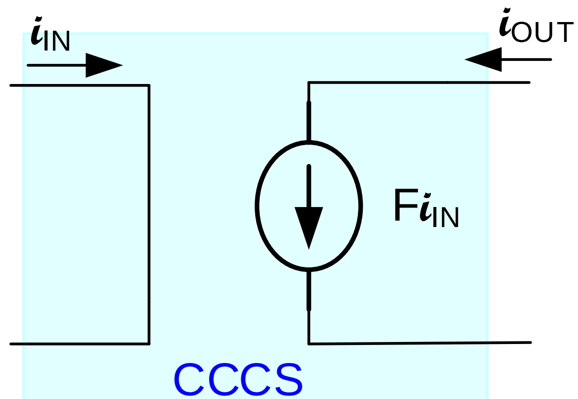
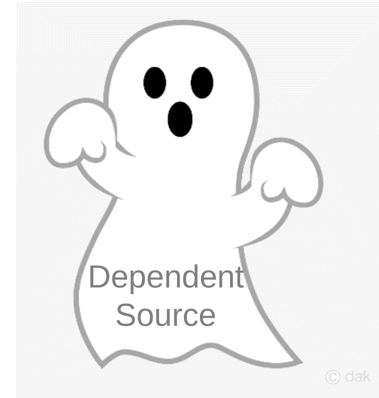


$$I_{OUT} = FI_{IN}$$

$$R_{IN}=0 \quad R_{OUT}=\infty$$

Does this have anything in common with a Current Amplifier?

Dependent Sources



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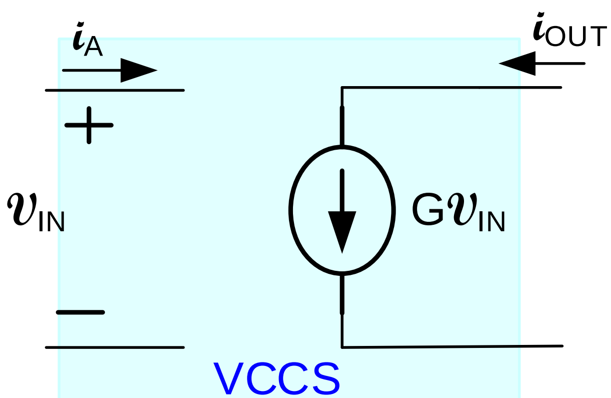
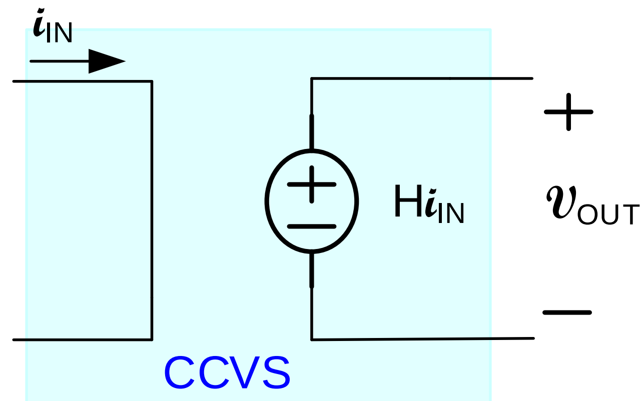




$I_{OUT} = GV_{IN}$

$R_{IN}=\infty \quad R_{OUT}=\infty$

$V_{OUT} = HI_{IN}$

$R_{IN}=0 \quad R_{OUT}=0$

What about these dependent sources?

Amplification with Transistors

Often the voltage gain of an amplifier is larger than 1

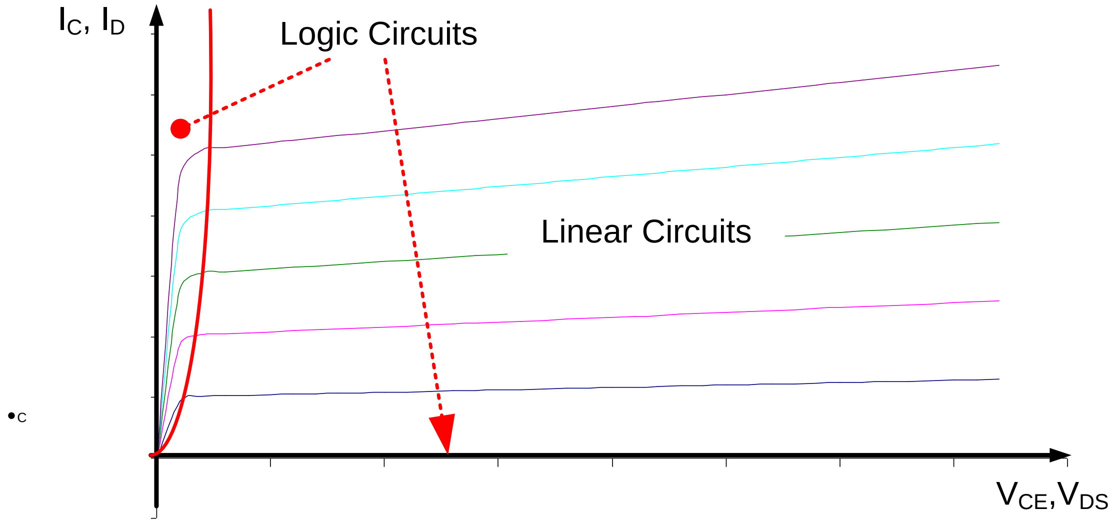
$$V_{OUT} = A_V V_{IN}$$

Often (but not always) the power dissipated by R_L is larger than the power supplied by V_{IN}

An amplifier can be thought of as a dependent source that was discussed in EE 201

Input and output variables can be either V or I or mixed

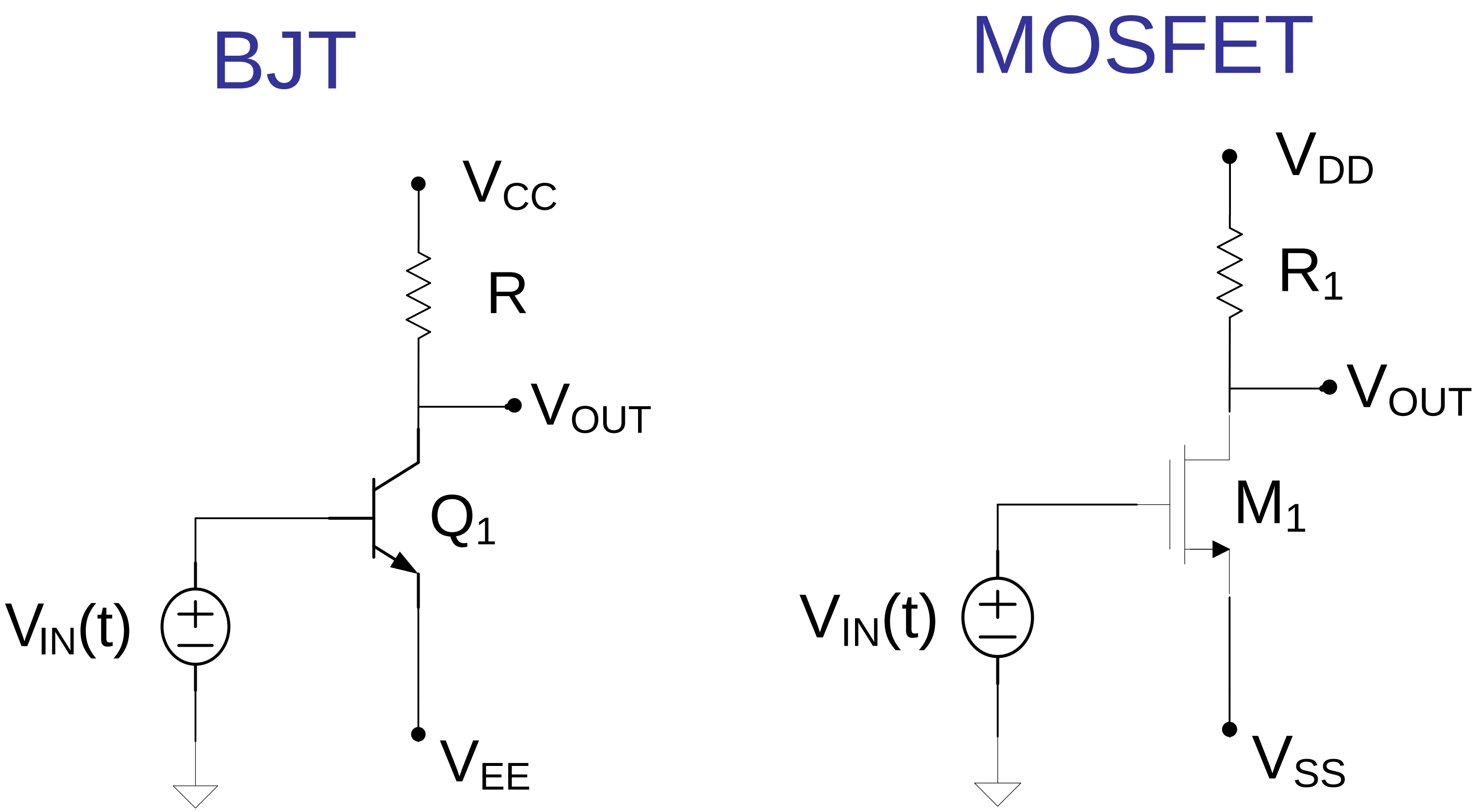
Applications of Devices as Amplifiers



Typical Regions of Operation by Circuit Function

	MOS	Bipolar
Logic Circuits	Triode and Cutoff	Saturation and Cutoff
Linear Circuits	Saturation	Forward Active

Consider the following MOSFET and BJT Circuits



Assume BJT operating in FA region, MOSFET operating in Saturation

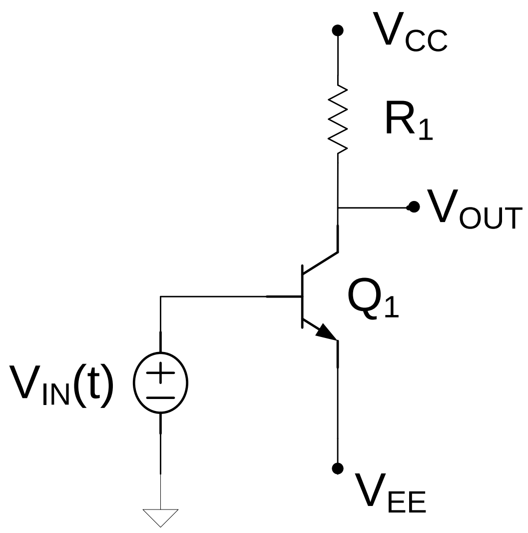
Assume same quiescent output voltage and same resistor R_1

Note architecture is same for BJT and MOSFET circuits

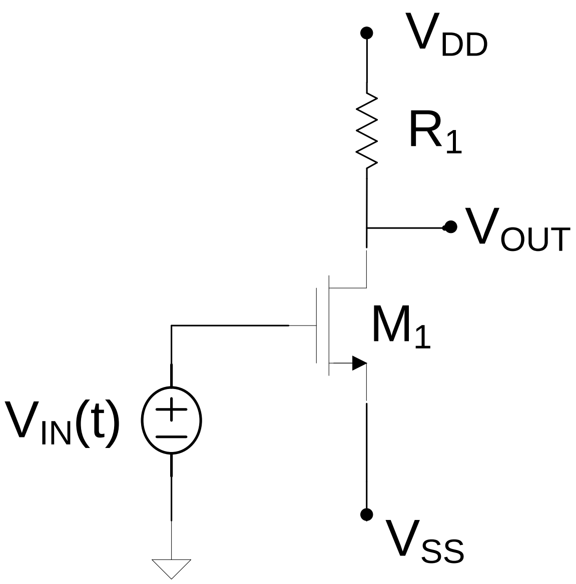
One of the most widely used amplifier architectures

Consider the following MOSFET and BJT Circuits

BJT



MOSFET



- MOS and BJT Architectures often Identical
- Circuits are Highly Nonlinear
- Nonlinear Analysis Methods Must be used to analyze these and almost any other nonlinear circuit

Methods of Analysis of Nonlinear Circuits

KCL and KVL apply to both linear and nonlinear circuits

Superposition, voltage divider and current divider equations, Thevenin and Norton equivalence apply only to linear circuits!

Some other analysis techniques that have been developed may apply only to linear circuits as well

Methods of Analysis of Nonlinear Circuits

Will consider three different analysis requirements and techniques for some particularly common classes of nonlinear circuits

1. Circuits with continuously differential devices

   Interested in obtaining transfer characteristics of these circuits or outputs for given input signals

2. Circuits with piecewise continuous devices

   Interested in obtaining transfer characteristics of these circuits or outputs for a given input signals

3. Circuits with small-signal inputs that vary around some operating point

   Interested in obtaining relationship between small-signal inputs and the corresponding small-signal outputs. Will assume these circuits operate linearly in some suitably small region around the operating point

Other types of nonlinearities may exist and other types of analysis may be required but we will not attempt to categorize these scenarios in this course

1. Nonlinear circuits with continuously differential devices

Analysis Strategy:

Use KVL and KCL for analysis

Represent nonlinear models for devices either mathematically or graphically

Solve the resultant set of nonlinear and linear equations (often differential equations) for the variables of interest

2. Circuits with piecewise continuous devices

e.g.

$$f(x)=\begin{cases} f_1(x) & x<x_1 \quad \text{region 1} \\ f_2(x) & x>x_1 \quad \text{region 2} \end{cases}$$

Analysis Strategy:

Guess region of operation

Solve resultant circuit using the previous method

Verify region of operation is valid

Repeat the previous 3 steps as often as necessary until region of operation is verified

- It helps to guess right the first time but a wrong guess will not result in an incorrect solution because a wrong guess can not be verified

- Piecewise models generally result in a simplification of the analysis of nonlinear circuits

3. Circuits with small-signal inputs that vary around some operating point

Interested in obtaining relationship between small-signal inputs and the corresponding small-signal outputs. Will assume these circuits operate linearly in some suitably small region around the operating point

Analysis Strategy:

Use methods from previous two class of nonlinear circuits

More Practical Analysis Strategy:

Determine the operating point (using method 1 or 2 discussed above after all small signal independent inputs are set to 0)

Develop small signal (linear) model for all devices in the region of interest (around the operating point or "Q-point")

Create small signal equivalent circuit by replacing all devices with small-signal equivalent

Solve the resultant small-signal (linear) circuit

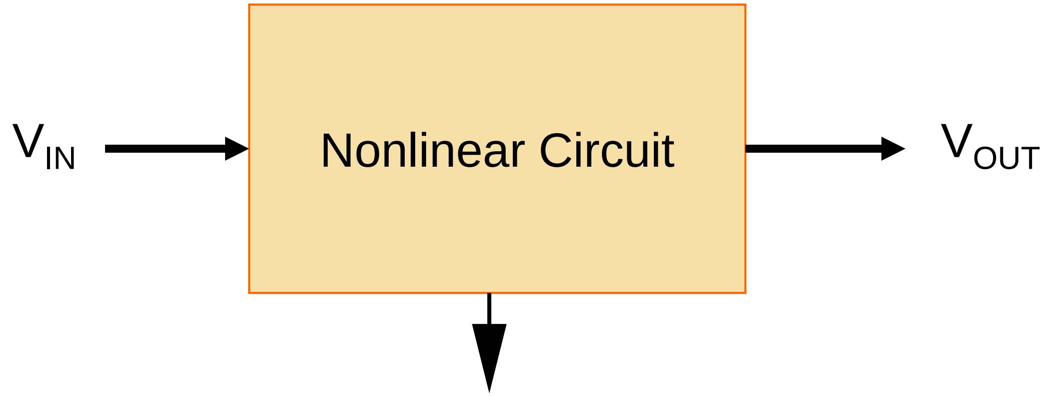
Can use KCL, DVL, and other linear analysis tools such as superposition, voltage and current divider equations, Thevenin and Norton equivalence

Determine boundary of region where small signal analysis is valid

Small signal operation of nonlinear circuits

$V_{IN}=V_M\sin\omega t$

V_M is small



If V_M is sufficiently small, then any nonlinear circuit operating at a region where there are no abrupt nonlinearities will have a nearly sinusoidal output and the variance of the magnitude of this output with V_M will be nearly linear (could be viewed as “locally linear”)

This is termed the “small signal” operation of the nonlinear circuit

When operating with “small signals”, the nonlinear circuit performs linearly with respect to these small signals thus other properties of linear networks such as superposition apply provided the sum of all superimposed signals remains sufficiently small

Other types of “small signals”, e.g. square waves, triangular waves, or even arbitrary waveforms often are used as inputs as well but the performance of the nonlinear network also behaves linearly for these inputs

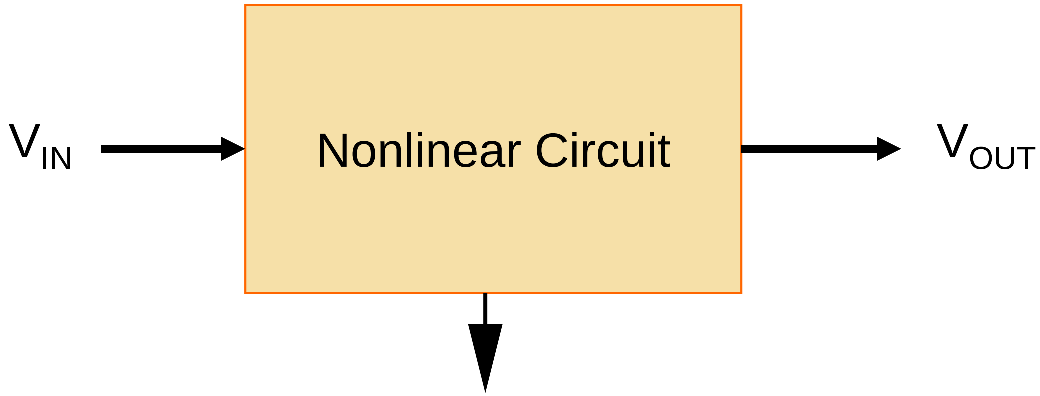
Many useful electronic systems require the processing of these small signals

Practical methods of analyzing and designing circuits that operate with small signal inputs are really important

Small signal operation of nonlinear circuits

$V_{IN}=V_M\sin\omega t$

V_M is small



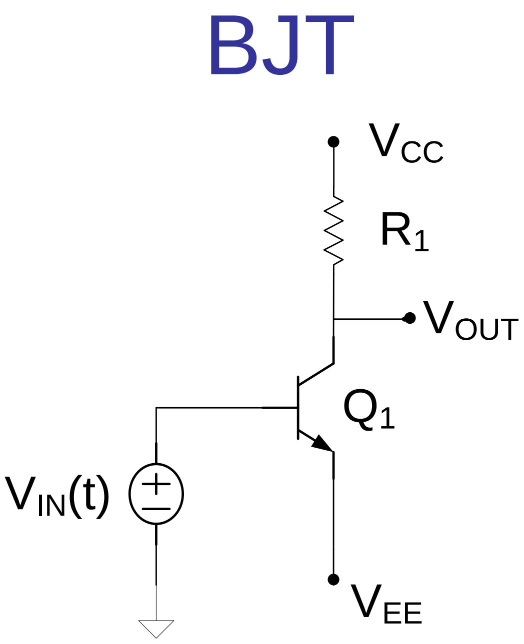
Practical methods of analyzing and designing circuits that operate with small signal inputs are really important

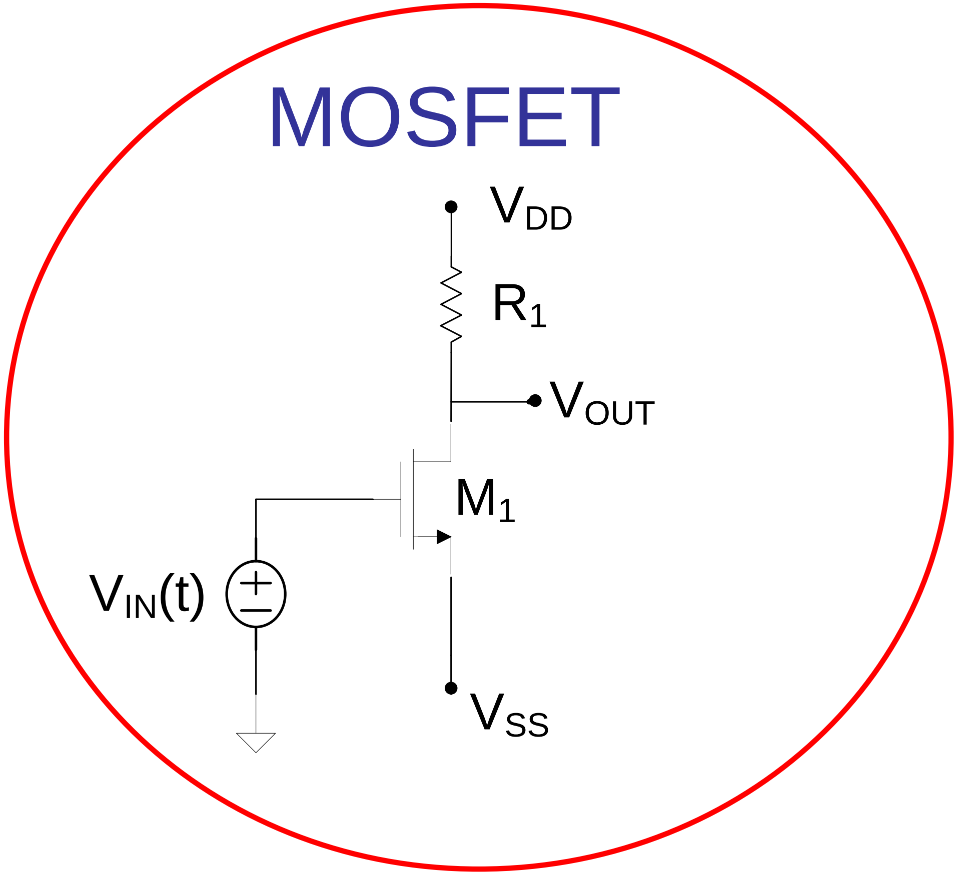
Two key questions:

How small must the input signals be to obtain locally-linear operation of a nonlinear circuit?

How can these locally-linear (alt small signal) circuits be analyzed and designed?

Consider the following MOSFET and BJT Circuits





One of the most widely used amplifier architectures

Stay Safe and Stay Healthy !

End of Lecture 22