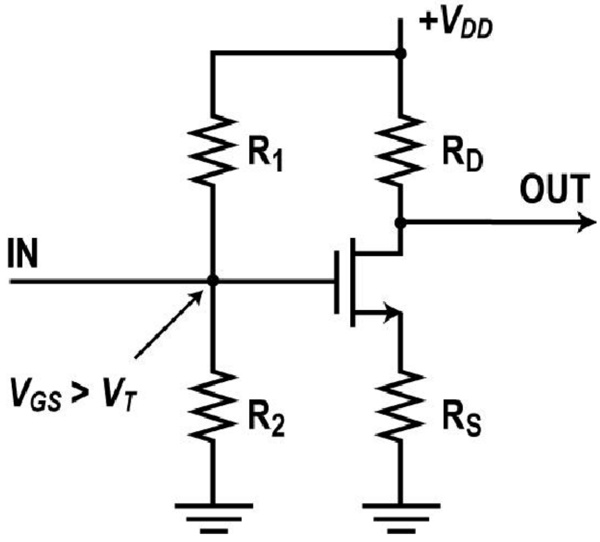
Linear MOSFET Circuit Operation

Basic Linear MOSFET Circuits

A linear circuit is one where the output is a linear or straight line function of the input. The output is proportional to the input. Linear circuits are used for amplification.

Linear operation with a transistor requires that the transistor be biased so that it operates in the linear region of its characteristics.

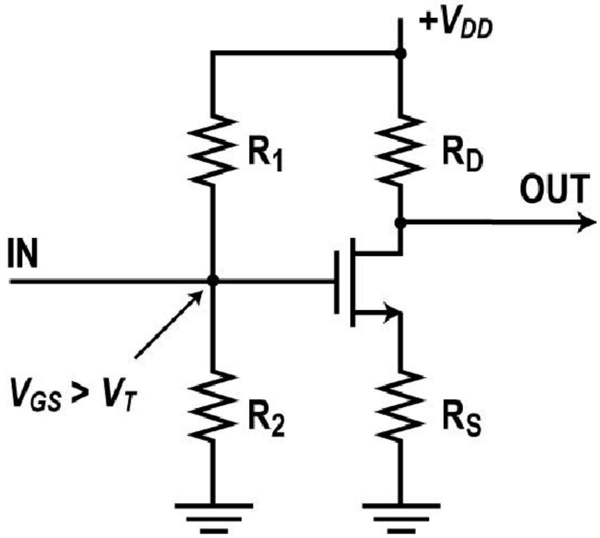
One way to bias an enhancement mode MOSFET into its linear region is shown here.



Basic Linear MOSFET Circuit Operation

A voltage divider R_1-R_2 sets the gate to some voltage above the threshold. Additional bias comes from the voltage across the source resistor R_s. The output is taken from the drain. This circuit configuration is similar to the common emitter BJT or common source JFET amplifier circuits. It produces voltage and power gain and signal inversion.

This circuit is virtually never used because other techniques are used to eliminate the resistors in integrated circuits.

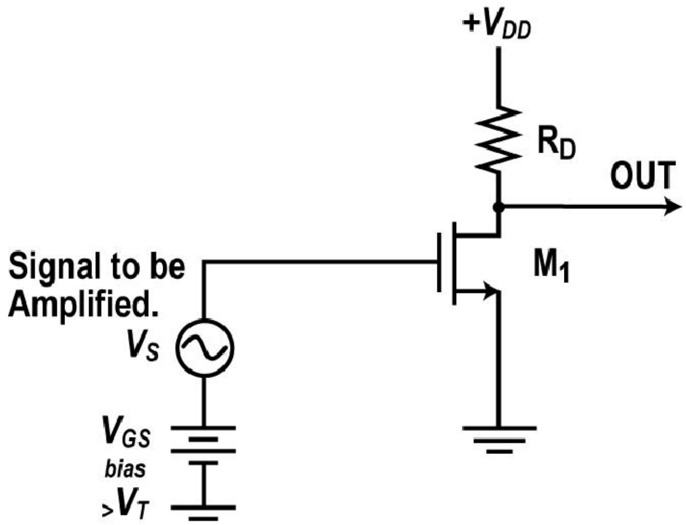


Common Linear Circuits

In a simple enhancement mode common source MOSFET amplifier, a DC bias voltage V_{bias} higher than the threshold is applied to the gate along with the input signal to be amplified. A resistor R_D is used as a load.

MOSFETs are usually designated by the letter M (M_1 in the figure here) while BJTs are designated by the letter Q.

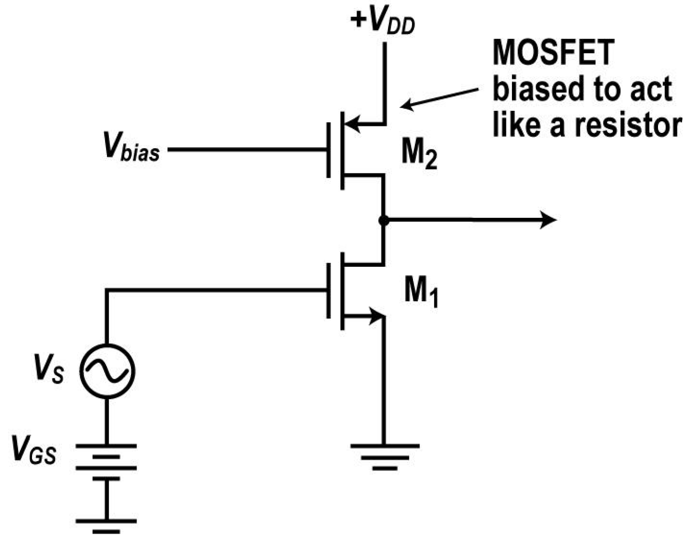
Depending upon the transistor characteristics, the voltage gain is typically in the 2 to 10 range. The circuit produces phase inversion.



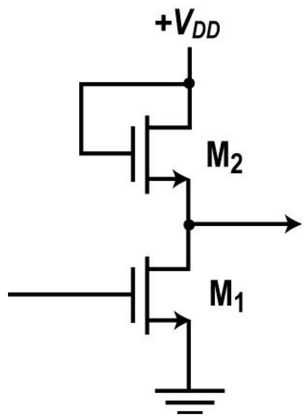
Alternative Common Linear Circuit

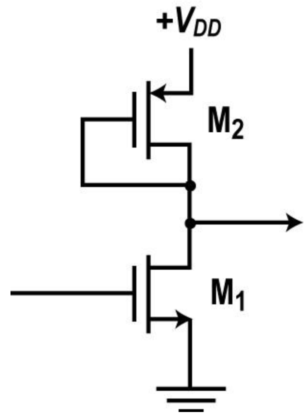
In the alternative circuit shown here, the drain resistor is replaced with another MOSFET. By applying an appropriate bias voltage to the upper MOSFET M_2, it will conduct and act like a resistor of some design value. This is called an active load. Otherwise, the circuit works like the one with a resistor in the drain circuit.

Resistors are rarely used in integrated circuits because they take up hundreds of times the area used by a MOSFET connected as an active load on a chip



Linear Circuit Variations



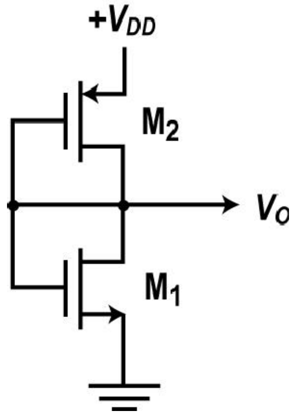


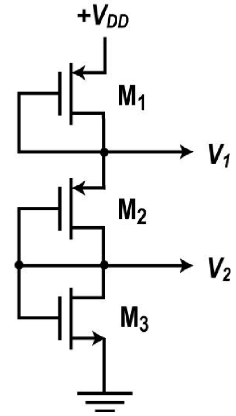
Another way to use a transistor is as a load or drain resistor (shown on the left). By connecting the gate to the drain, the MOSFET M_2 acts like a diode with a low resistance. It makes a good drain load in many circuits.

As shown in the figure on the right, a P-type MOSFET can be used at M_2 by turning it upside down so that it conducts.

Both of these circuits are common source, inverting, class A amplifiers.

Linear Circuit Biasing





One way to obtain bias voltages without resistors is to use a MOSFET voltage divider. (Left figure) It uses two diode-connected MOSFETs connected in series. M_1 is an N-type and M_2 is a P-type.

The drain currents are equal, but the characteristics of each transistor are controlled during manufacturing to get the desired voltage division ratio.

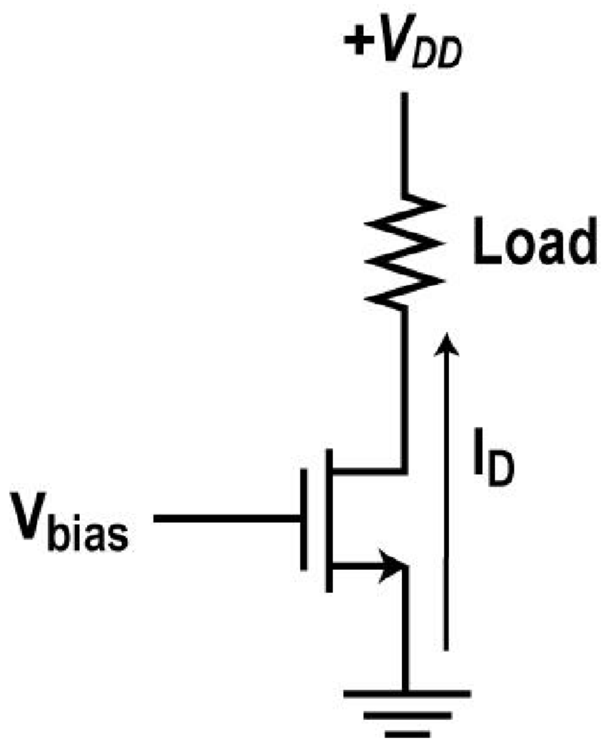
The figure on the right shows three MOSFETs connected to give two bias voltages, V_1 and V_2.

Current Source: N-Type MOSFET

A circuit widely used in MOSFET biasing is the current source.

A current source is a component or circuit with a fixed constant output current that is independent of the voltage across it.

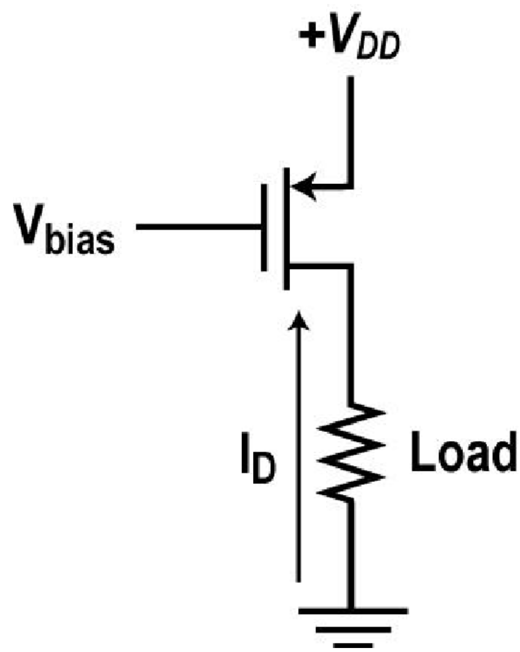
This figure shows an N-type MOSFET connected as a current source.



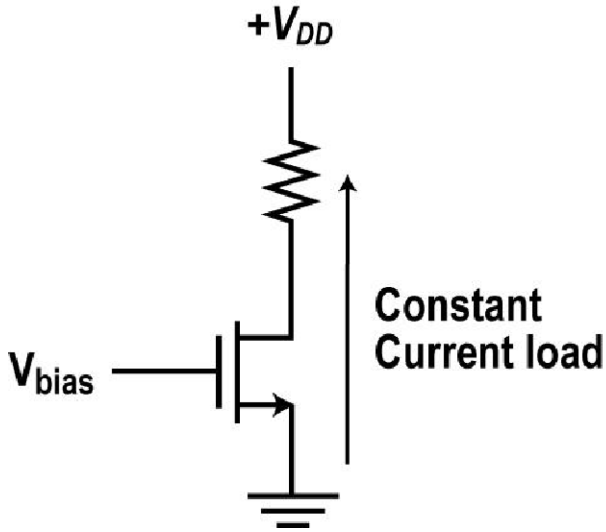
Current Source: P-Type MOSFET

In the P-type MOSFET current source, the output current is the drain current (I_D) and is dependent upon the gate input voltage (V_{bias}) and the characteristics of the MOSFET. Almost any desired output current can be produced from a few microamperes to many milliamperes.

A MOSFET voltage divider can be used to set the gate bias voltage and the resistor load is usually replaced by an active load.



Current Sink



A current sink is essentially the opposite of a current source.

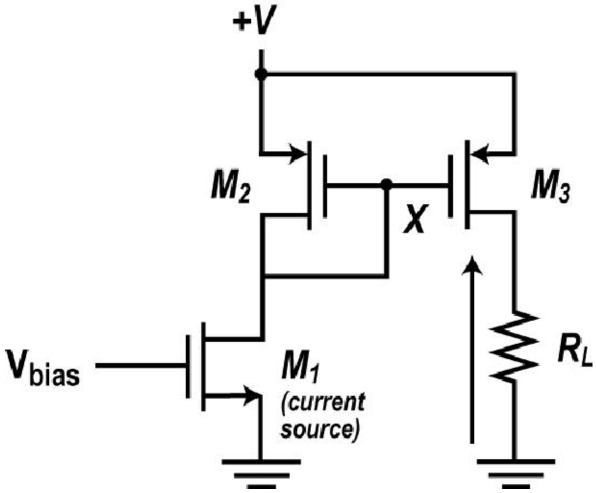
A current sink is like a load that always draws a constant current despite the voltage across it.

In the N-type MOSFET current sink shown here, the bias is usually provided by a MOSFET voltage divider.

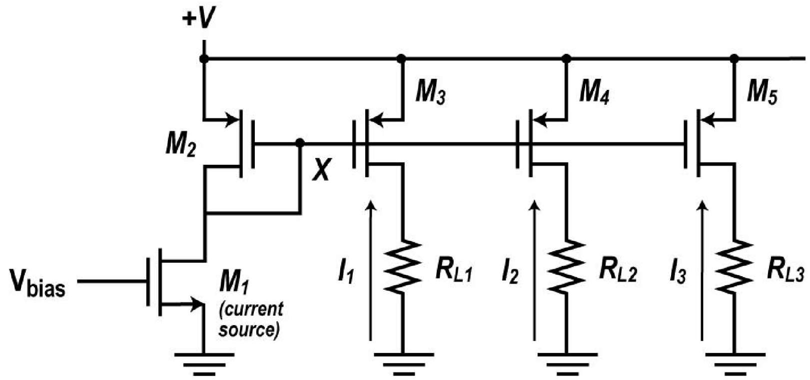
Current Mirror

A current mirror is a circuit technique using current sources and/or sinks to distribute equal (or proportional) currents to several MOSFETs needing bias.

In the P-type MOSFET current mirror, M_2 is connected as a diode and receives its current from current source M_1. If M_3 is identical in physical and electrical specifications to M_2, the current in M_3 which is called the "mirrored" current is equal to the current in M_2. The load R_L is any circuit requiring a bias current or voltage.



Current Mirror Using Other Transistors



Other transistors may be connected at point X to provide current to other loads. If M_4 and M_5 are identical to M_3, all of the load currents will be the same. M_4 and M_5 can be made with different characteristics to provide different but proportional currents to loads R_{L2} and R_{L3}.

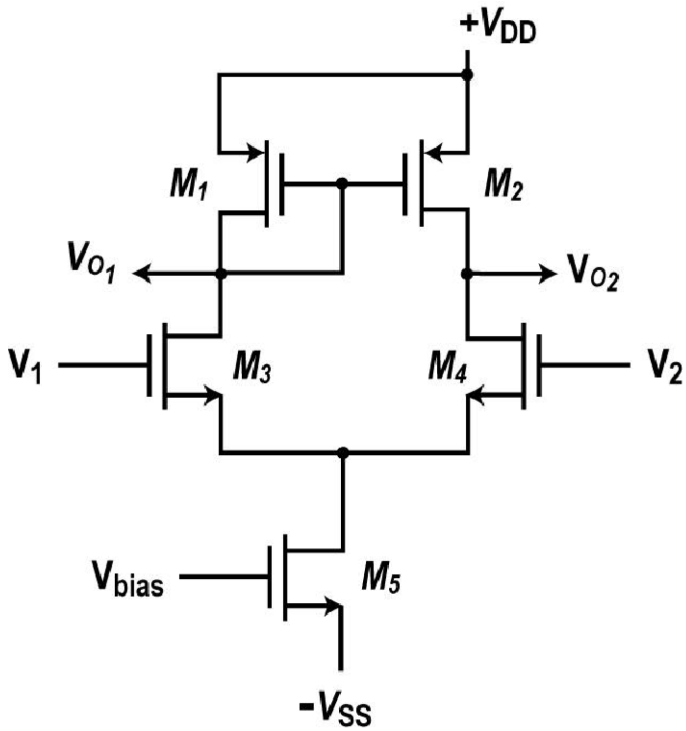
Current mirrors are the most common way of biasing MOSFETs in integrated circuits. No resistors are required.

Differential Amplifier

One of the most widely used amplifier configurations is the differential amplifier.

M_3 and M_4 form the differential pair while M_1 and M_2 form a current mirror to supply equal currents to M_3 and M_4.

M_1 and M_2 are used as active loads. M_5 is a current source.

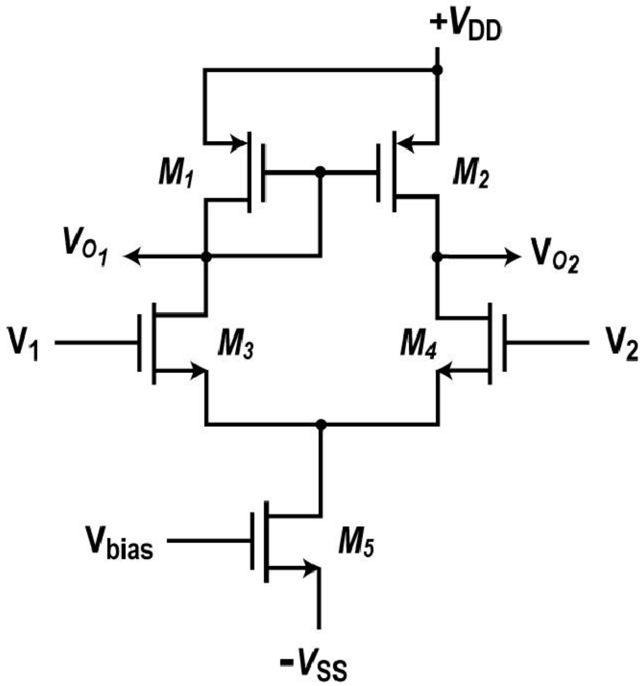


Differential Amplifier: Output Voltage

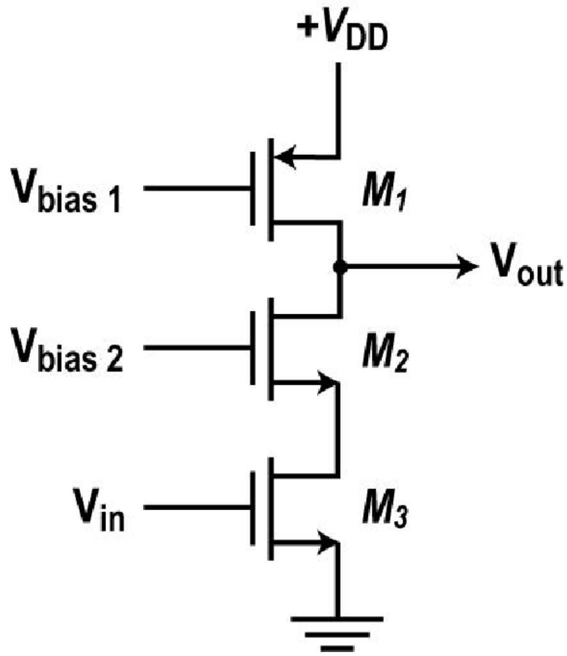
The input voltages are V_1 and V_2. The output voltage V_o may be taken from the drain of M_3 or M_4 with respect to ground (single-ended outputs) or between the two drains (differential output).

The output voltage is a function of the difference between the two inputs. $V_o = A(V_2 – V_1)$ where A is the circuit gain that is set by the circuit currents and the transistor characteristics.

Differential amplifiers are the basis for most other more complex linear circuits. An operational amplifier (op amp) is a good example.



The Cascode Amplifier



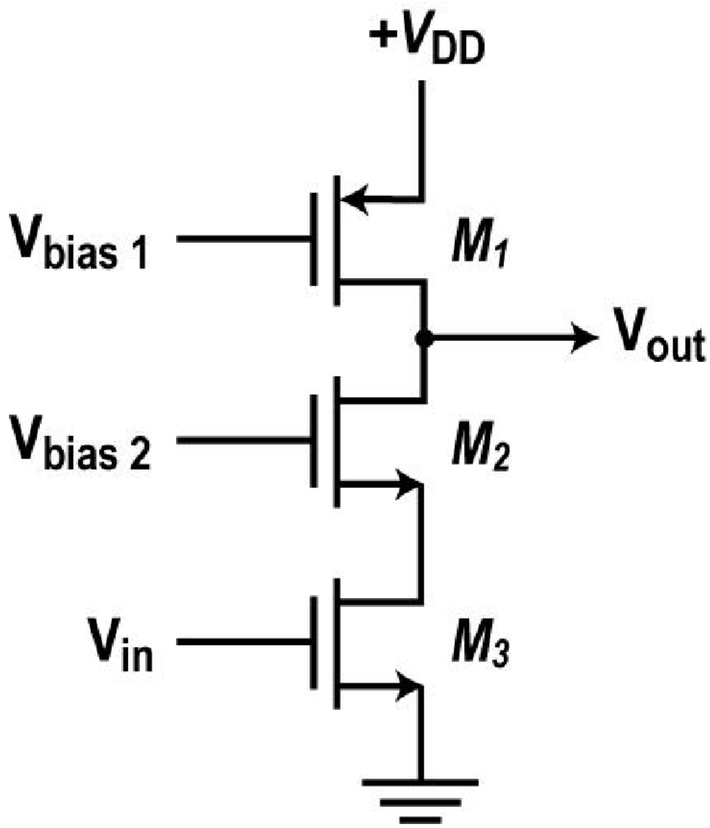
Another widely used MOSFET circuit is the cascode amplifier.

M_1 is a current source used as a resistive load. As in simpler inverting circuits, M_3 is the main amplifying transistor. M_2 isolates M_3 from the load M_1.

Advantages of the Cascode Amplifier

This circuit has two main advantages over the average inverting amplifier: higher gain and wider frequency response.

The higher gain comes from using a current source load. This makes the load resistance and output impedance higher which, in turn, translates into higher gain.

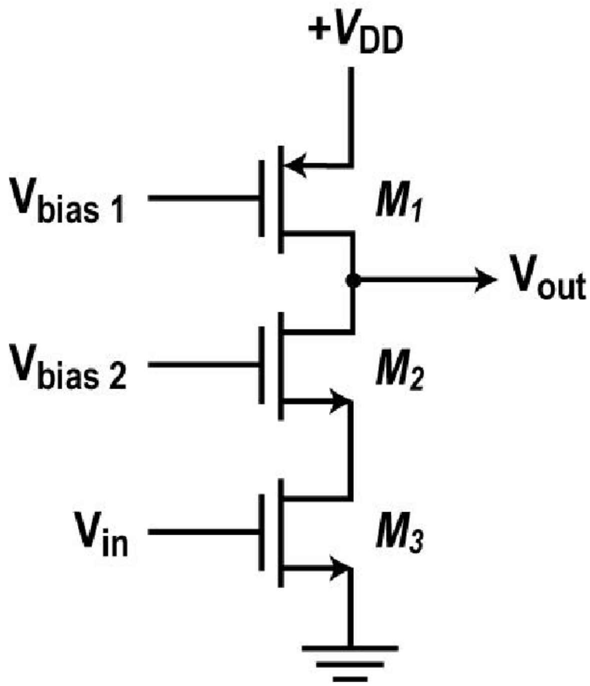


The Miller Effect

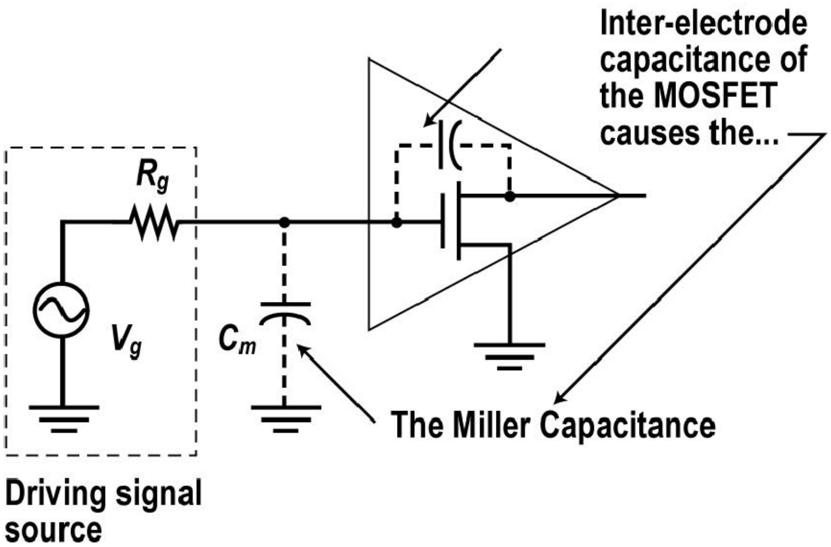
The higher frequency response comes from the fact that the Miller capacitance effect is greatly minimized by the presence of M_2 in the circuit.

The Miller effect is a condition in most inverting amplifiers that causes the inter-electrode capacitances of transistors to be multiplied by the gain of the amplifier creating what is called the Miller capacitance.

The effect occurs in between the collector and the base in a BJT and between the drain and the gate in a MOSFET.

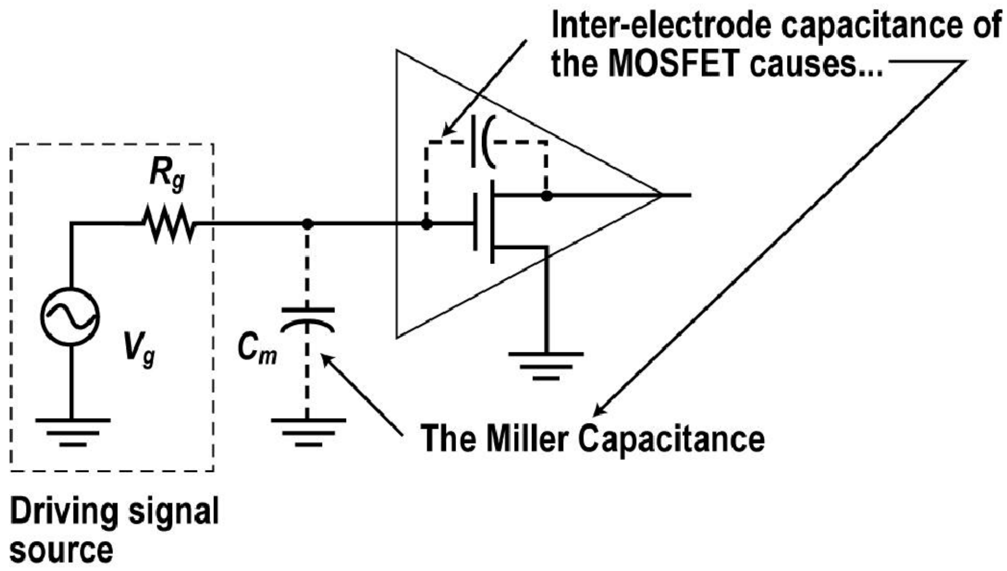


Miller Capacitance



This interelectrode capacitance produces a feedback from output to input. The effect of this feedback is to make it appear as though a larger capacitor has been connected between the input and ground. This capacitance is known as the Miller capacitance. The feedback capacitance is multiplied by (A – 1) where A is the gain of the amplifier.

Eliminating the Miller Effect



The Miller capacitance C_m appears in parallel with the amplifier input. There it forms a low pass filter with the driving circuit output impedance R_g. This low pass filter effect rolls off the higher frequencies thereby limiting the upper frequency response of the amplifier.

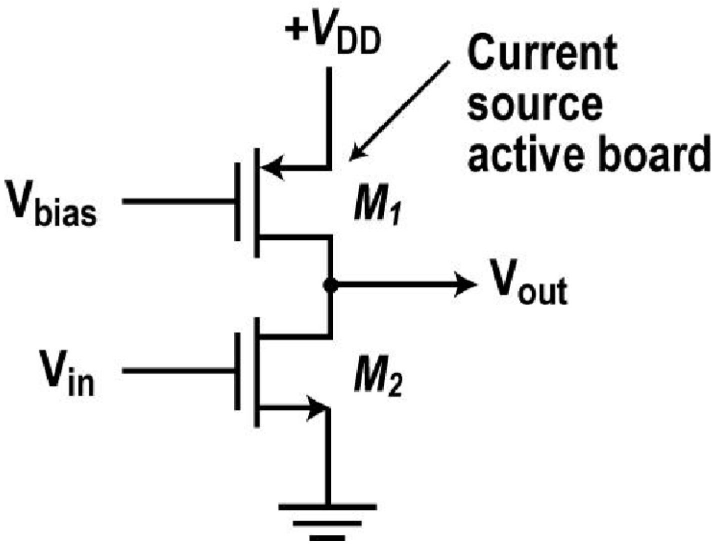
The cascode connection eliminates this problem.

Power Amplifiers

Any of the amplifier circuits discussed so far can be used for power amplification in a class A or AB configuration.

An inverting amplifier with a current source as an active load makes a good power amplifier. M_2 is the amplifying transistor.

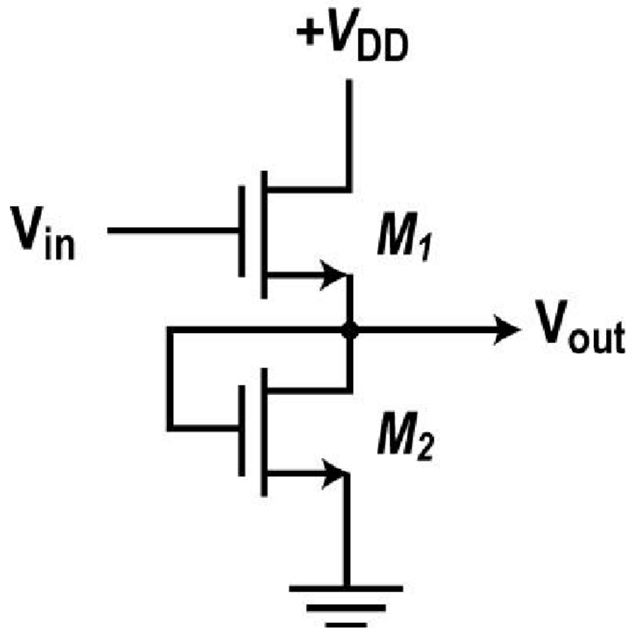
Larger transistors and higher drain currents provide higher output power to a load.



Source Follower

Emitter and source followers are also widely used circuits because they have high input impedance, low output impedance, and a unity gain. They are power amplifiers used to drive lower resistance loads or providing impedance matching between circuits.

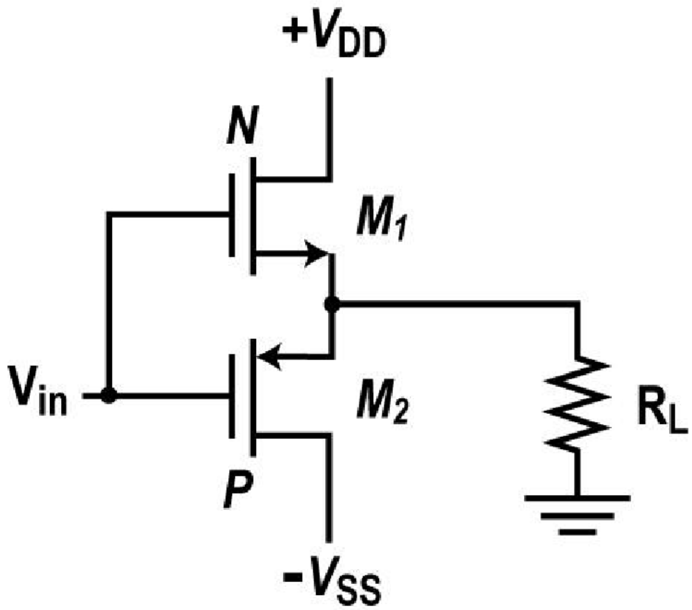
In a typical MOSFET source follower, M_1 is the amplifying transistor while M_2 is an active load replacing a source resistor or load.



Push Pull Power Amplifier

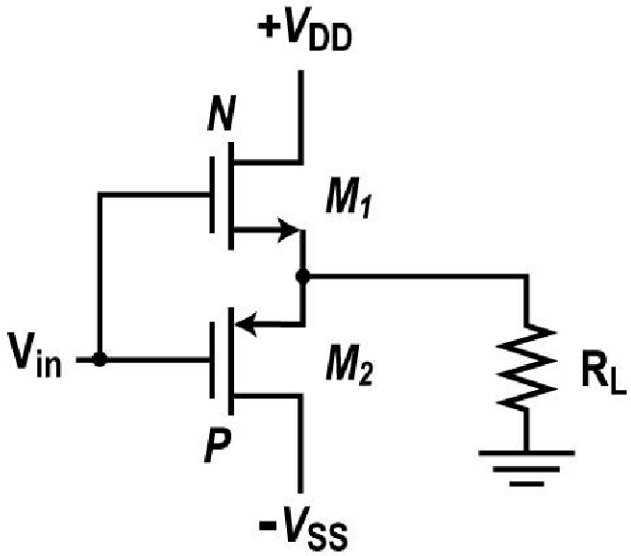
A very widely used power amplifier is the complementary symmetry push pull circuit. It is similar in operation to bipolar complementary power amplifiers found in older stereo amplifiers.

The circuit is essentially two source followers with a P-channel MOSFET M_2 to amplify the negative portion of the input signal and an N-channel MOSFET M_1 to amplify the positive portion of the input signal.



Push Pull Power Amplifier Bias Voltage

A bias voltage approximately equal to the threshold voltage of the MOSFETs is normally applied to the gates so that the transistors are just barely conducting. (Note: This bias voltage is not shown in the figure.) The bias produces class AB operation. This eliminates the crossover distortion caused by having the input signal bias the transistors on at some point above their zero crossing point.

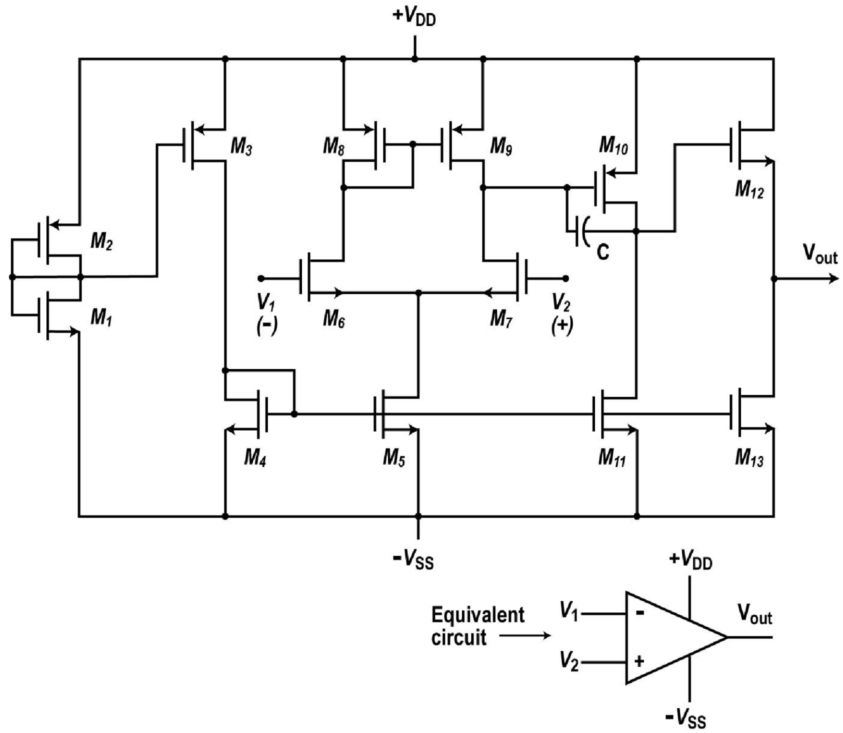


MOSFET Op Amp with No Resistors

In a complete MOSFET op amp where no resistors are used, M_1 and M_2 form a voltage divider to supply a bias voltage to current source M_3.

M_4 and M_5 form a current mirror which is used to bias to the differential pair M_6 and M_7.

Another current mirror pair, M_8 and M_9, serve as active loads to the differential pair. The differential pair provides the gain.

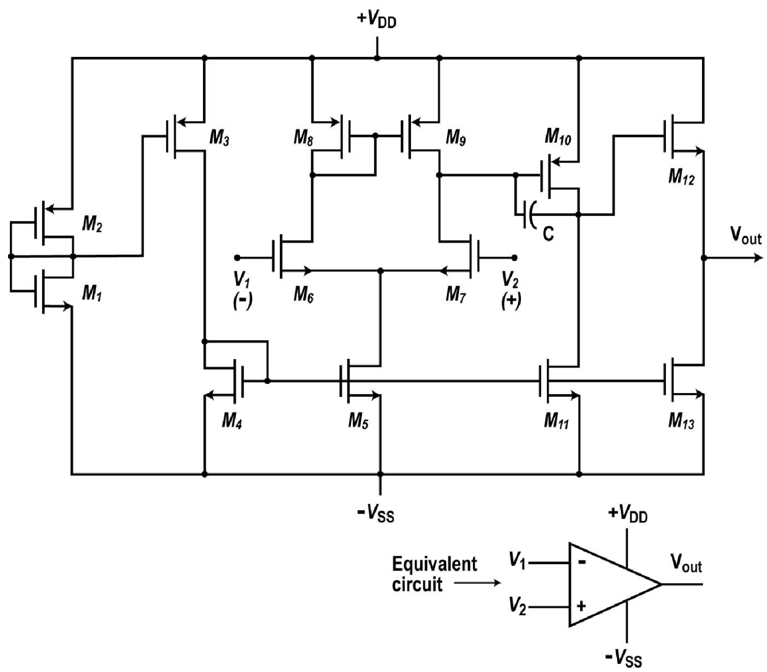


MOSFET Op Amp Operation

M_{10} is an additional common source gain stage. It is a P-type device. M_{11} is its active load which is also biased by current mirror M_4-M_5.

An output stage is made up of source follower M_{12} and its active load M_{13}. They are also biased by current mirror M_4-M_5.

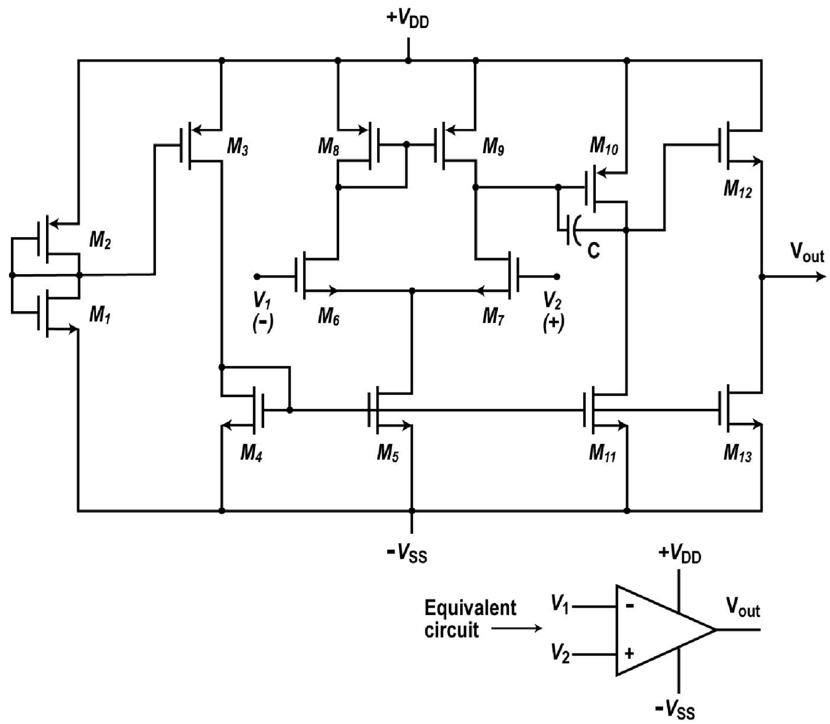
The compensating capacitor on M_{10} is used to provide feedback to stabilize the amplifier against oscillation and to set the open loop 3 dB cut-off frequency.



MOSFET Op Amp Output Voltage

Separate positive and negative supplies ($+V_{DD}$ and $-V_{SS}$) furnish power to the circuit. This permits a positive and negative output swing.

The output voltage V_{out} is the difference between the two inputs ($V_2 - V_1$) multiplied by the open loop gain A_{OL} of the circuit. A_{OL} is a function of the product of the individual stage gains in the circuit. It is typically as high as 100,000 to 200,000.

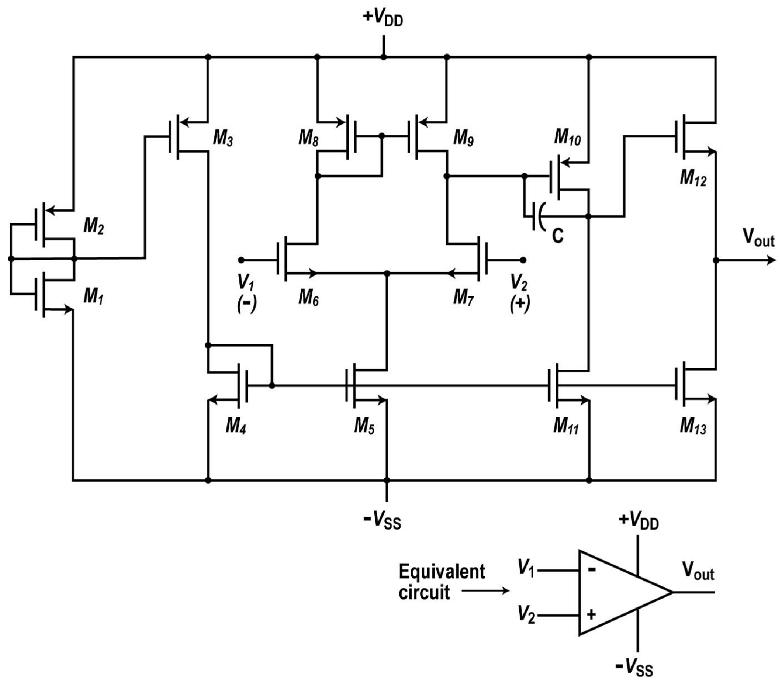


MOSFET Op Amp Impedance

Like most op amps, this one is direct coupled so it can amplify small DC inputs as well as AC. The input impedance is very high thanks to the capacitive nature of the gates of the input MOSFETs M_5 and M_6 (> 100MΩ).

The output impedance is low thanks to the source follower output.

This op amp, like any other op amp, is used with external components to produce a variety of amplifier and other circuits.



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