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e-Learning

Basics of Op-amps

Chapter1 What is an op-amp?

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Chapter1 What is an op-amp?

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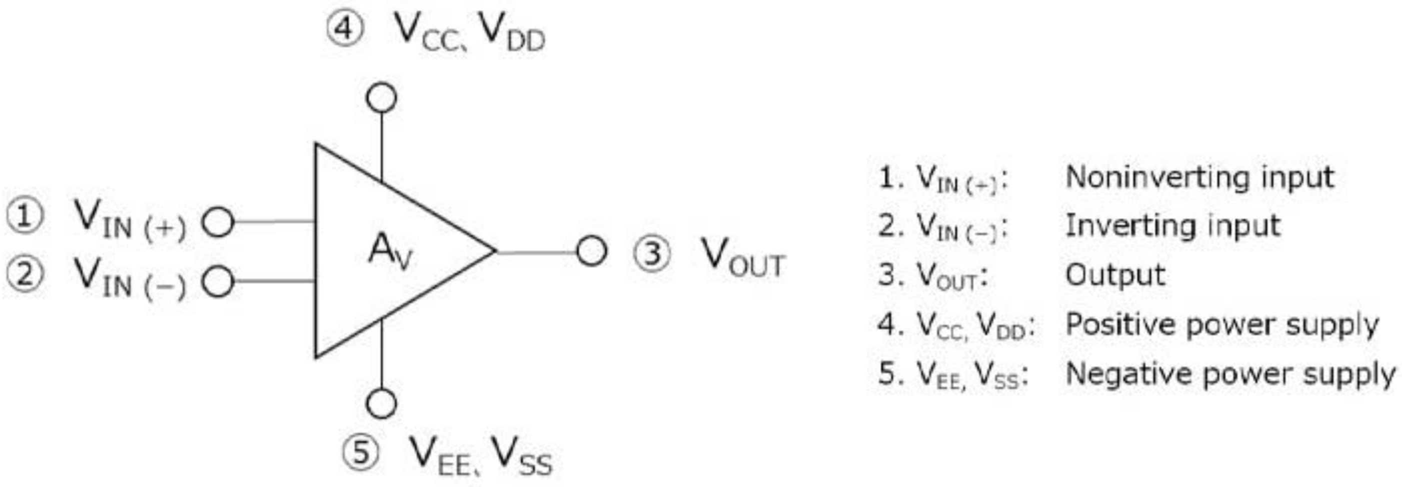
What is an op-amp?

Op-amp stands for “operational amplifier.” An op-amp is so called because it is used for various computational operations such as comparison, addition, subtraction, differentiation, and integral.

Figure shows the electronic symbol for op-amps. An op-amp has five terminals: 1) noninverting input, 2) inverting input, 3) output, 4) positive power supply, and 5) negative power supply. Here, “inverting” and “noninverting” indicate the polarity with respect to the output.



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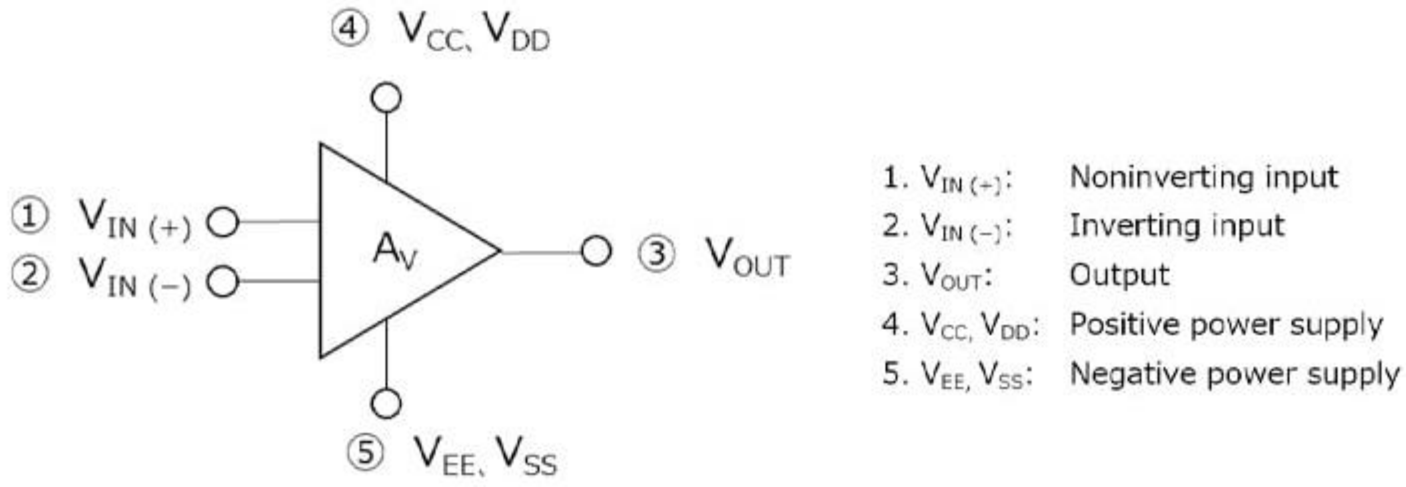
What is an op-amp?

The voltage applied to the noninverting input is amplified by a factor of A_V with respect to the inverting input potential. The output has the same phase as the noninverting input.
The voltage applied to the inverting input is also amplified by a factor of A_V with respect to the noninverting input potential. The output has the opposite phase to the inverting input.
As a result, the output provides a voltage equal to a difference in voltage between the inverting and noninverting inputs multiplied by A_V. Therefore, when the inverting and noninverting inputs have the same voltage and phase, the output voltage becomes zero. When the inverting and noninverting inputs have the same voltage and opposite phases, the output has the same phase as the noninverting input and provides a voltage equal to twice the difference between their voltages multiplied by A_V.
Despite a simple configuration, op-amps provide close-to-ideal characteristics as amplifiers. Therefore, they are widely used for various purposes in a wide range of IoT home appliance and other electronic applications. For example, op-amps are used to amplify analog signals from sensors and measuring instruments.



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Characteristics of op-amps (What is the ideal op-amp?)

Generally, amplifiers should neither affect the preceding circuit nor be affected by the subsequent circuit. Therefore, amplifiers should have high input impedance and low output impedance.
Op-amps have characteristics close to these requirements. The following compares the ideal and real op-amps:

Ideal op-amps	Real op-amps
・Infinite input impedance (zero input current)	⇒ Very high but finite input impedance
・Zero output impedance	⇒ On the order of several tens of ohms
・Infinite input dynamic range (common-mode input voltage range, CMVIN)	⇒ Constrained by power supply and GND
・Infinite open-loop voltage gain (AV)	⇒ On the order of 4th to 10 to 5th power of 10
・Infinite frequency bandwidth (unity gain cross frequency, fT)	⇒ Several hundreds of kHz to several tens of MHz
・Zero input offset voltage (VIO)	⇒ Several millivolts
・Infinite common-mode input signal rejection ratio (CMRR)	⇒ High but finite CMRR (roughly 80 dB)
・Zero internal noise (equivalent input noise voltage, VNI) (Thermal noise region)	⇒ Several nV/√Hz to several tens of nV/√Hz

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Characteristics of op-amps (What is the ideal op-amp?)

Although there is no such thing as an ideal op-amp, you can assume the ideal op-amp early in the design stage. However, you should consider the differences between the ideal and real op-amps when you proceed to the detailed design stage.

For example, if the input impedance of an op-amp is low, its input voltage is derived from the input impedance of that op-amp and the output impedance of the preceding device. The low input impedance of an op-amp also affects its feedback loop. If the output impedance of an op-amp is large, its output voltage is derived from the output impedance of that op-amp and the impedance of its load.
In typical applications, however, the input impedance of an op-amp is negligibly large compared with the output impedance of the preceding circuit, and the output impedance of the op-amp is negligibly small compared with the impedance of the subsequent load. Therefore, these impedances do not normally have a significant impact. The same is true of the other parameters shown above.
It is necessary, however, to check their impact when creating a detailed design.

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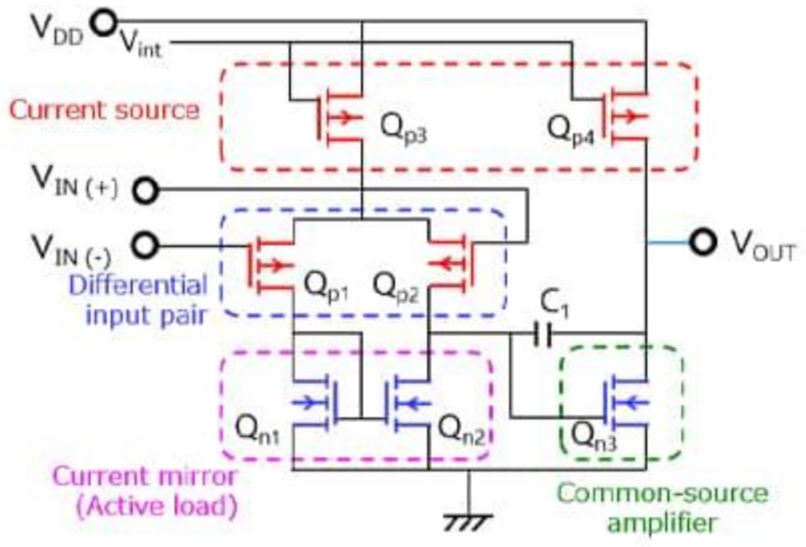
Internal operation of an op-amp

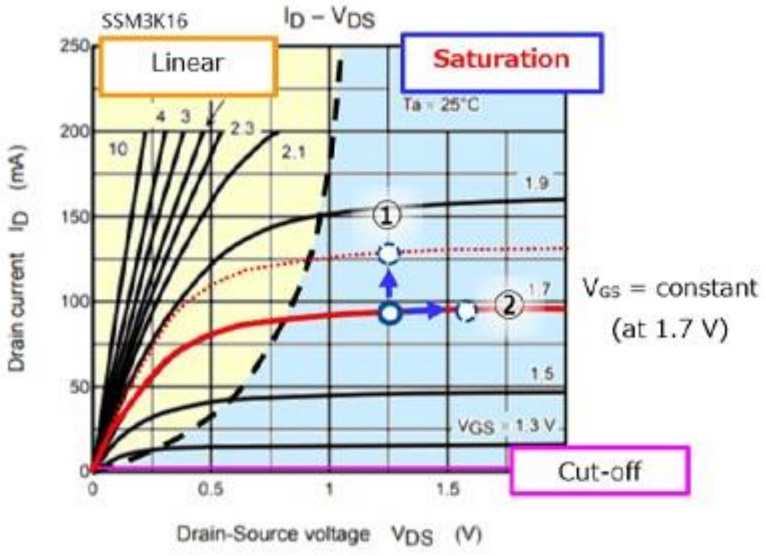
Figure shows a simplified equivalent circuit for an op-amp. As you see, it is composed of multiple MOSFETs. For a CMOS op-amp to work properly, these MOSFETs need to operate in the saturation region. Figure shows the saturation region of the MOSFET.

In this region, the MOSFET operates as follows:

1. As the gate-source voltage increases, the drain current increases.
2. As the drain-source voltage increases, the drain current increases slightly.
   A slight change in drain current causes a considerable change in drain-source voltage.



Simplified equivalent circuit for an op-amp



I_D-V_{DS} curves of an N-channel MOSFET

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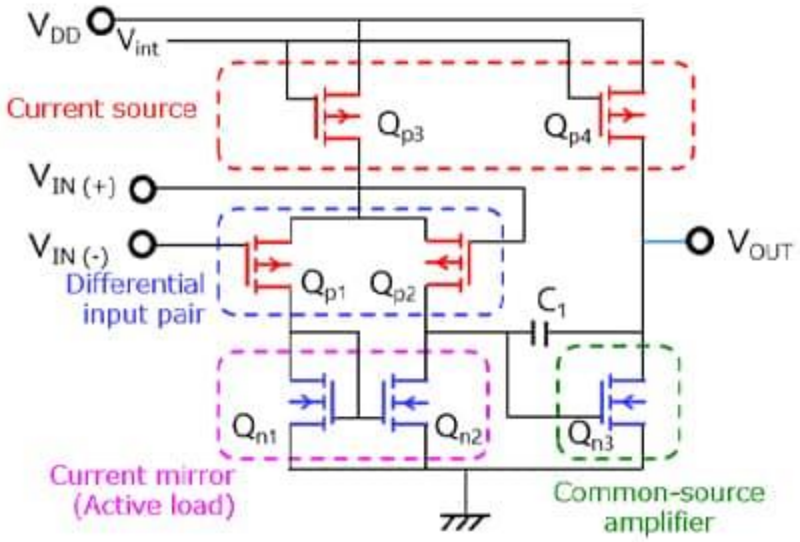
Internal operation of an op-amp

The portions of the op-amp provide the following functions:

- Differential input pair: Amplifies a difference in voltage between the $V_{IN\,(+)}$ and $V_{IN\,(-)}$ inputs
- Current mirror: Provides an equal amount of current to Q_{p1} and Q_{p2} comprising the differential input pair. The current mirror acts as load resistance for the differential input pair. Typically, the output of the current mirror (i.e., the drain terminal of the differential input pair) has high impedance, which is difficult to obtain with a typical resistor. As a result, the first-stage differential amplifier has a high gain. Such a resistive load composed of transistors is called an active load.
- Current source: Determines the amount of current that flows to the differential input pair and the common-source amplifier. The current source acts as an active load for the common-source amplifier.
- Common-source amplifier: Provides the drive current for an external load connected to the output and compensates for the gain of the first-stage differential amplifier



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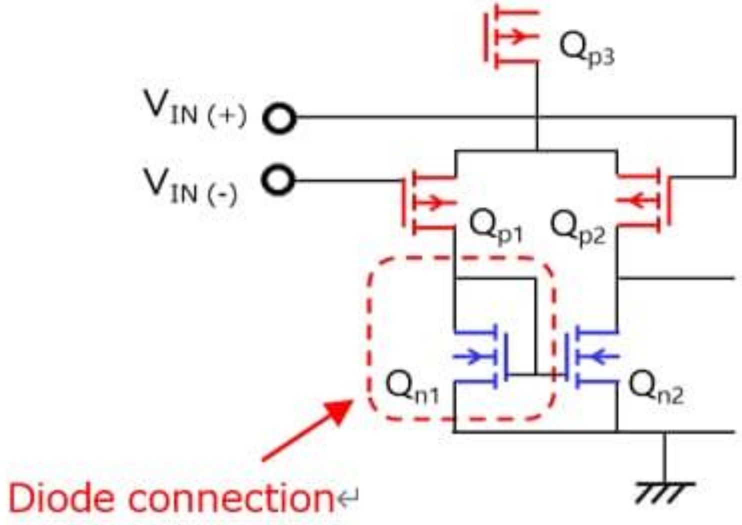
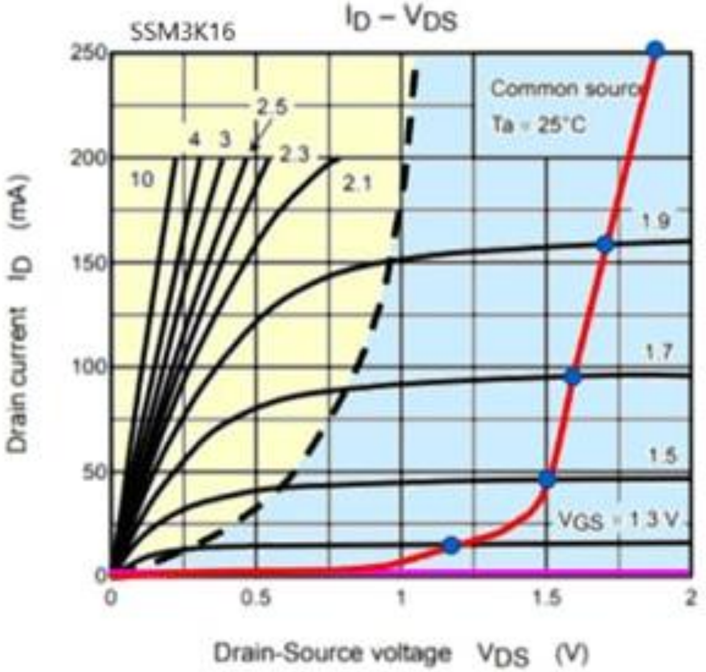
Internal operation of an op-amp

Before going into the operation of an op-amp, let's discuss the drain voltage of Q_{n1} in the current mirror.

The drain-source voltage (V_{DS_n1}) and the drain-gate voltage (V_{DG_n1}) of Q_{n1} are equal. Figure plots the conditions under which $V_{DS} = V_{DG}$ is satisfied. Since the resulting curve looks like the I_F-V_F curve of a diode, the connection of Q_{n1} is called a diode connection. In Figure, the drain current is large because it is the I_D-V_{DS} curves of a discrete N-channel MOSFET with a large channel area. The internal MOSFETs of an IC have a drain current two to three orders of magnitude lower than this.
As Figure indicates, after the drain current exceeds a certain point (at a V_{DS} of 1.5 V or higher), a slight change in the drain current hardly affects the drain-source voltage.



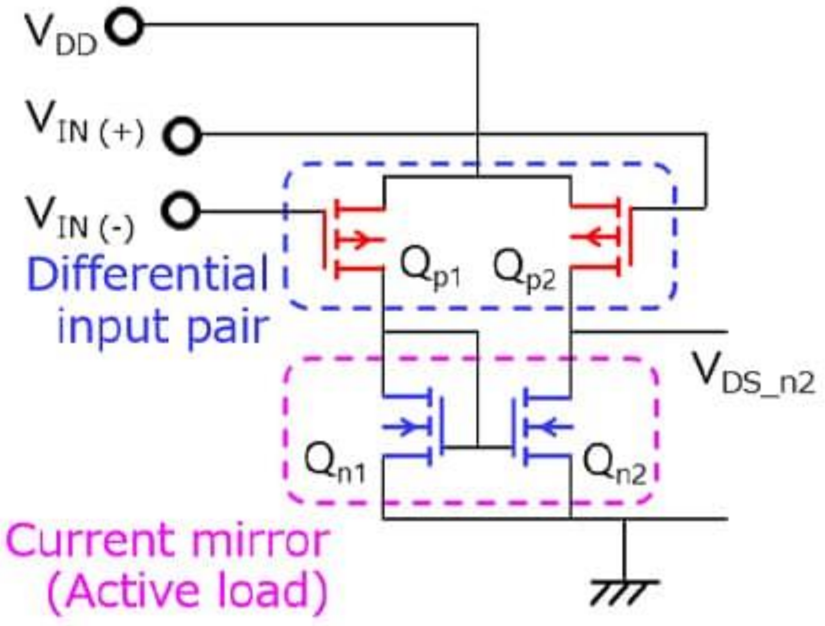
MOSFET diode connection



I_D-V_{DS} curves of Q_{n1} (diode connection)

Internal operation of an op-amp

Next, let’s consider how the current source works. First, let’s consider a circuit without a current source as shown in Figure. The subsequent common-source amplifier is identical to that of the previous op-amp.
An equal voltage ($V_{DD} - V_{IN}$) is applied to the differential inputs, $V_{IN(+)}$ and $V_{IN(-)}$. Hence, $V_{SG} = V_{IN}$. At this time, when the drain current (I_{D_p1}) is conducted, the drain voltage of Q_{p1} settles to a voltage at which $V_{SD\_p1} + V_{DS\_n1} = V_{DD}$. Since I_{D_p1} is copied by the current mirror, the circuit composed of Q_{p2} and Q_{n1} has the same voltage relationship as this.



Circuit without a current source

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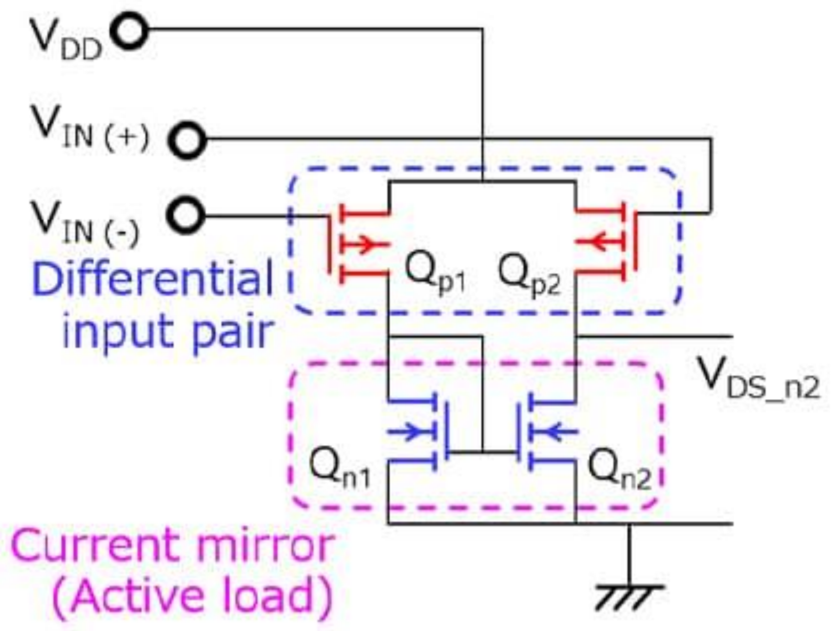
Internal operation of an op-amp

Suppose that the voltage applied to $V_{IN(+)}$ and $V_{IN(-)}$ increases by ΔV to (V_{DD} – V_{IN} + ΔV). Since the circuit of Figure has a current mirror, the same amount of current flows to the differential input pair. However, without a current source, the currents flowing to the differential input pair decrease by the same amount. As a result, the drain-source voltage of Q_{n2} connected to the common-source amplifier also decreases.



Circuit without a current source

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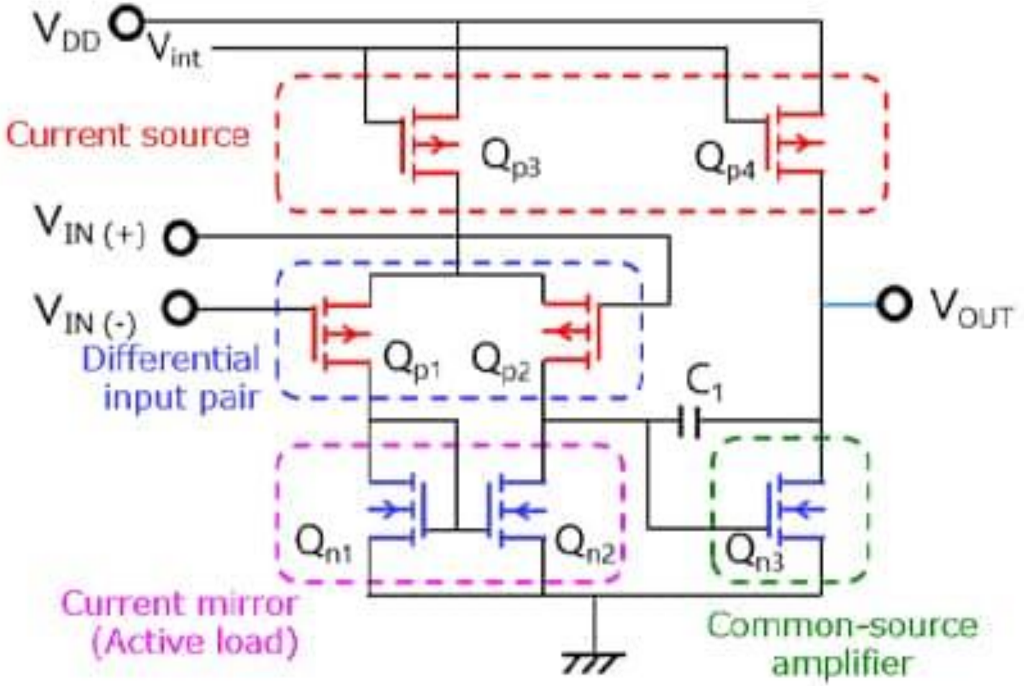
Internal operation of an op-amp

This is equivalent to a decrease in the gate-source voltage of Q_{n3} (V_{GS_n3}) of the common-source amplifier. The common-source amplifier has a current source (Q_{p4}), which raises the drain-source voltage (V_{DS_n3}) to oppose a decrease in V_{GS_n3}, keeping the current constant. In other words, the output voltage (V_{OUT}) increases even though the $V_{IN(+)}$ and $V_{IN(-)}$ inputs have the same voltage and phase. It is essential that the op-amp have a constant output when a common-mode input (same input voltage) within the range shown in the datasheet is applied to $V_{IN(+)}$ and $V_{IN(-)}$. The circuit of Figure cannot satisfy this requirement.



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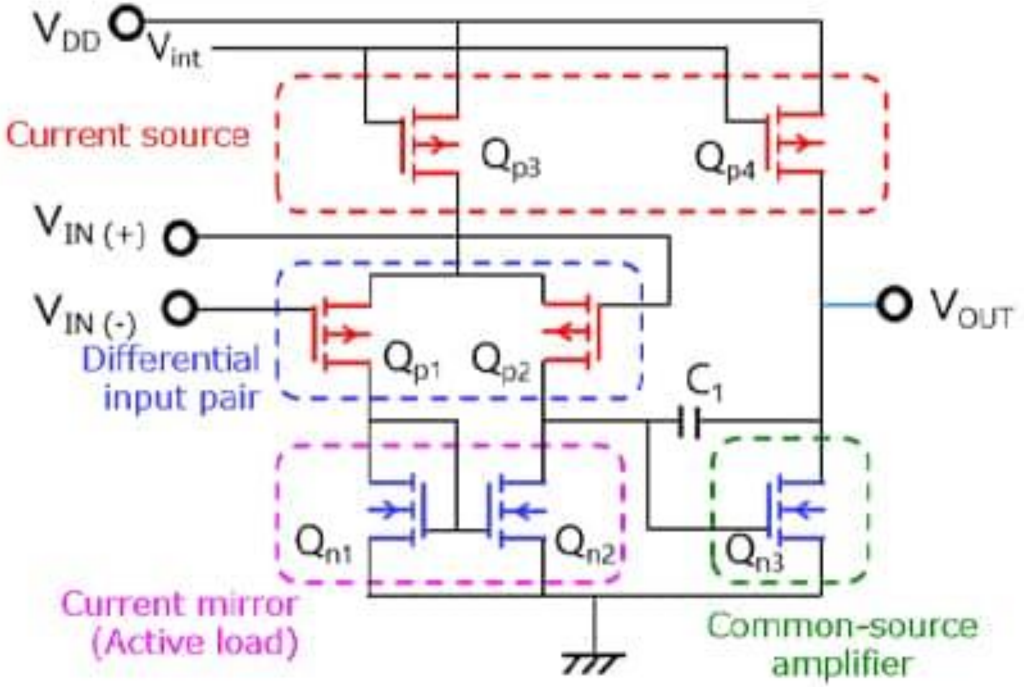
Internal operation of an op-amp

Next, let's consider the circuit of Figure with a current source (Q_{p3}). Suppose, for example, that the input voltage applied to $V_{IN(-)}$ and $V_{IN(-)}$ increases by ΔV to (V_{DD} – V_{IN} + ΔV). Since this circuit has a current source, the current flowing to the differential input pair remains unchanged. Therefore, the drain-source voltage of Q_{n1} (V_{DS_n3}) remains unchanged. Likewise, V_{DS_n2} remains unchanged. Therefore, the output voltage is constant for the common-mode input voltage.
(The V_{SD_p3} of Q_{p3} compensates for ΔV. The current flowing to the differential input pair changes because the source-drain voltage of the current source changes. Since the drain-source voltage of the current source changes, the drain current (I_D) changes. However, I_D changes only slightly with V_{DS}. Therefore, I_D does not change significantly.)
So, the role of the current source is to keep the output voltage constant when the common-mode input voltage is applied to $V_{IN(+)}$ and $V_{IN(-)}$.



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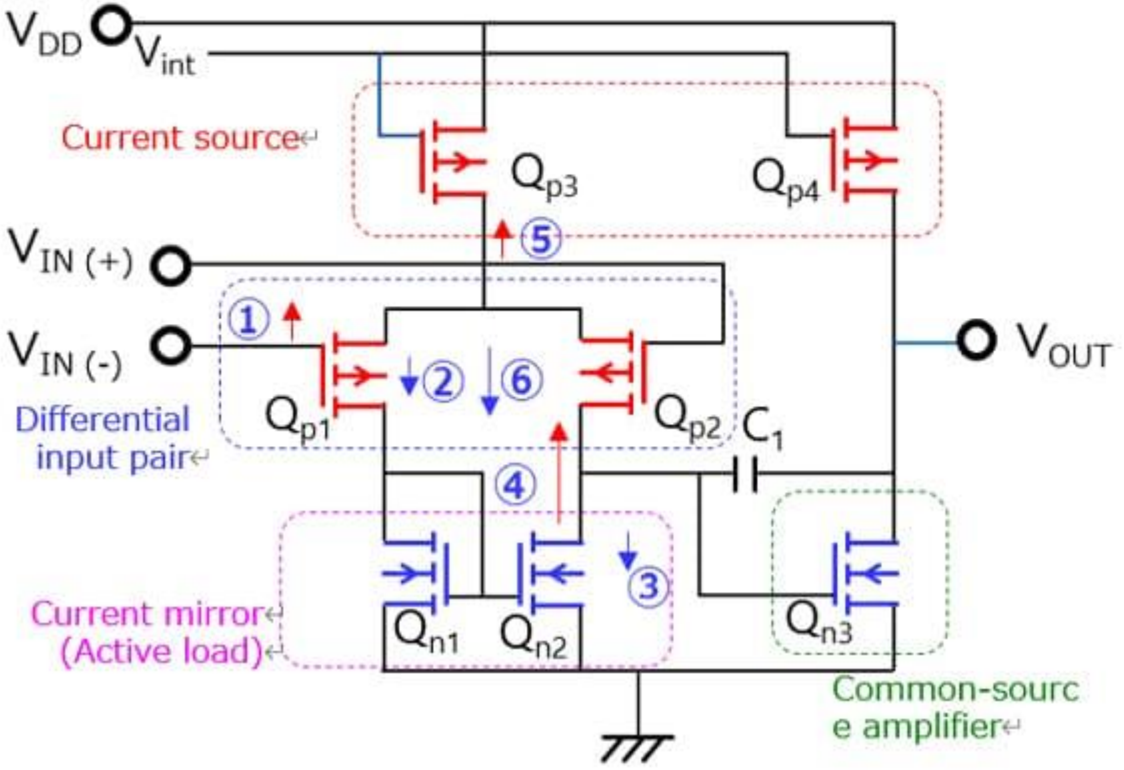
Internal operation of an op-amp

Next, let's consider the case in which different voltages are applied to $V_{IN(+)}$ and $V_{IN(-)}$.

1. Suppose that $V_{IN(+)}$ and $V_{IN(-)}$ initially have the same voltage ($V_{DD} – V_{IN}$) and then the $V_{IN(-)}$ voltage increases by ΔV.
2. V_{SG_p1} decreases, causing I_{D_p1} to decrease by ΔI_{p1}. However, as explained above, Q_{n1} has a diode connection. Therefore, V_{DS_n1} remains unchanged. So, the drain voltage of Q_{p1} remains constant.
3. The current mirror copies the decreased I_{D_p1} to the drain current of Q_{n2} (I_{D_n2}).
4. This is contradictory since the drain current of Q_{n3} (I_{D_p3}) in the current source remains unchanged. Therefore, the drain voltage of Q_{n2} (V_{DS_n2}) increases to increase the current flowing through Q_{n2}.



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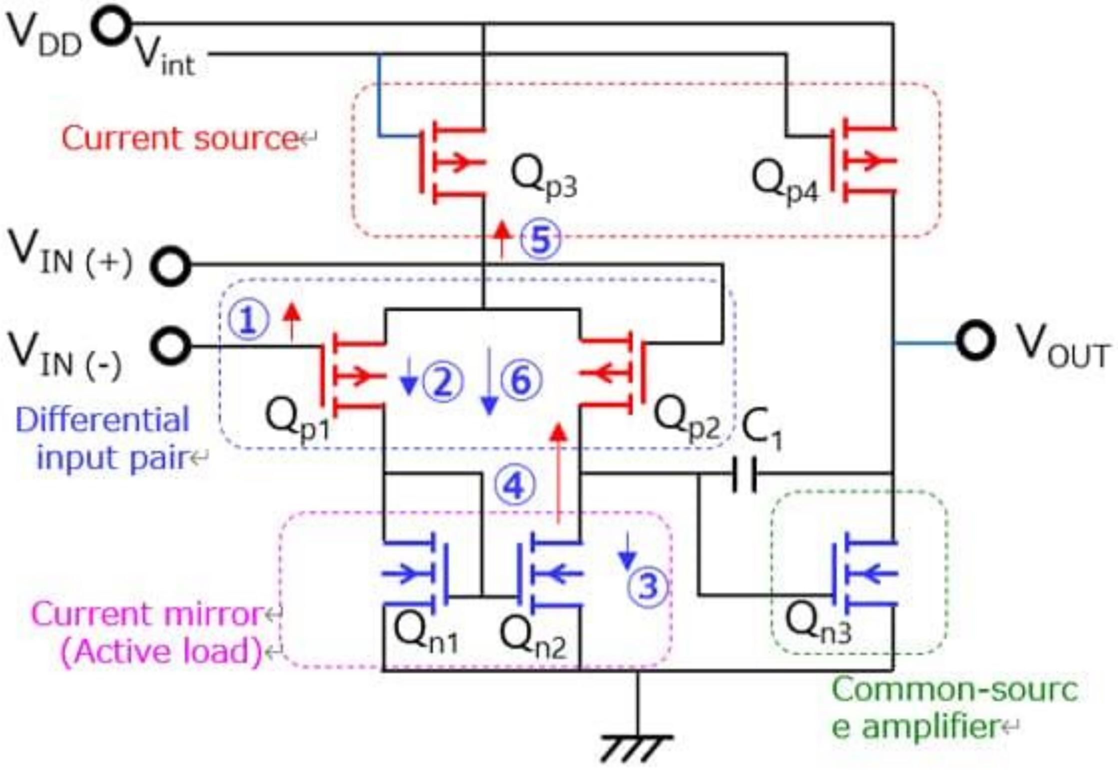
Internal operation of an op-amp

5. You might think that an increase in V_{DS_n2} causes V_{SD_p2} to decrease, causing I_{D_p2} to decrease. Note, however, that the current from the current source (I_{D_p3}) remains unchanged. Since I_{D_p1} has decreased by ΔI_{p1}, I_{D_p2} should increase, not decrease. Therefore, the source voltage of Q_{p2} increases.
6. The source-gate voltage of Q_{p1} (V_{SG_p1}) increases, causing its drain current (I_{D_p1}) to increase.
7. I_{D_p1} is copied to the drain current of Q_{n2} (I_{D_n2}). Then, the operation returns to Step 3.

Eventually, the drain voltage of Q_{n2} (V_{D_n2}) increases from the initial voltage.



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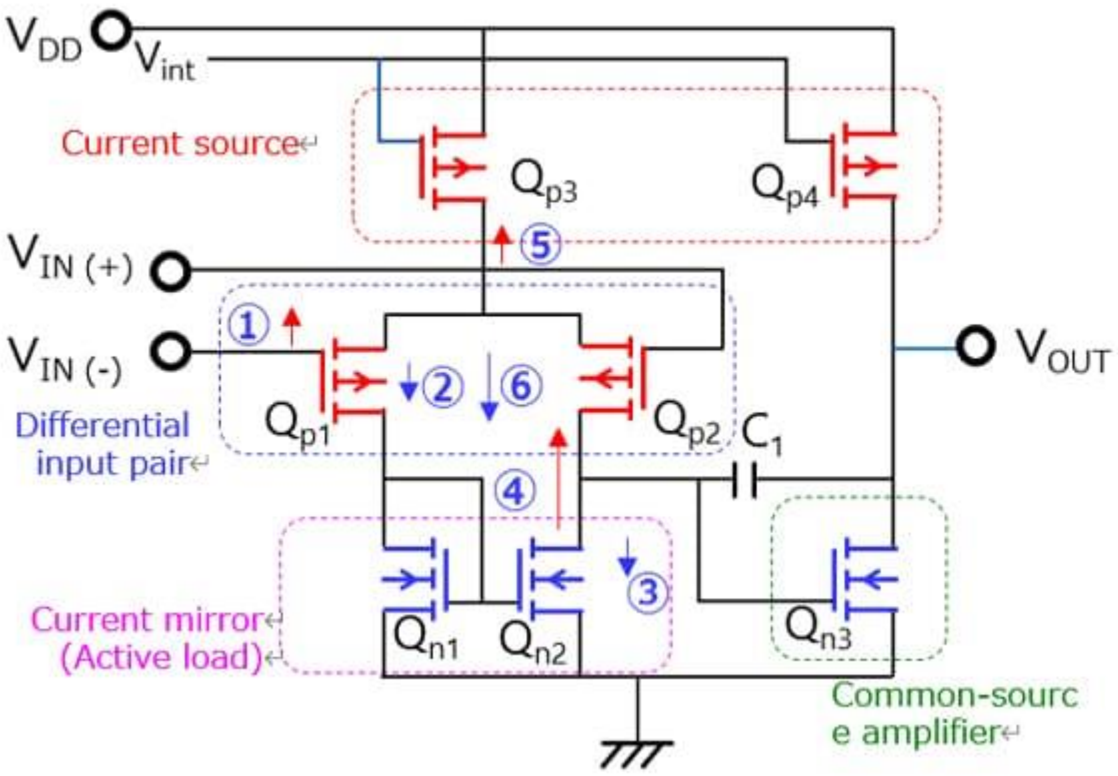
Internal operation of an op-amp

The increased V_{D_n2} is transferred to the subsequent common-source amplifier.
The V_{GS_n3} of the common-source amplifier increases, causing I_{D_n3} to increase. However, the increase in I_{D_n3} is constrained by Q_{p4} of the current source. Since the increase in V_{GS_n3} does not lead to an increase in I_{D_n3}, the drain-source voltage of Q_{n3} (V_{DS_n3}) decreases.
This means that when the $V_{IN(-)}$ voltage increases, the V_{OUT} voltage decreases.



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