Review: Field effect transistors

The NPN and PNP transistors we’ve discussed so far are called bi-polar junction transistors (BJT). FETs operate under a different mechanism.

This is a junction FET (jFET) where a p-type region is implanted within an n-type bulk. The depletion region can be controlled by the gate. Lower $V_G$ increases the depletion.

$I = n A q v$

So changing the gate voltage controls $n$ and $I$. Like pinching off a hose. “Depletion mode”
Field effect transistors (FETs)

Note that the MOSFET has large input impedance since little current flows through capacitor; just induces charge to enable $I_D$ current flow.

![Diagram of MOSFET](image-url)
Operational amplifiers

We developed a variety of transistor based circuits that can be used to amplify signals. A general purpose one would be a differential amp, where we could ground one side if needed. And, it should include all the optimization features: temperature compensation, controllable gain, high current push-pull output.
Operational amplifiers

We developed a variety of transistor based circuits that can be used to amplify signals. A general purpose one would be a differential amp, where we could ground one side if needed. And, it should include all the optimization features: temperature compensation, controllable gain, high current push-pull output.

This is the ideal tool for the amp stage in our original experiment circuit.

But we don’t want to have to build all the details in every time. Better to have an off-the-shelf solution that incorporates all the higher order details, like temperature stability, and lets us control at a high-level. Then we can use that for all the stages with only minor configuration.

Operational amplifiers are just that — a general tool that handles the details with a simple external interface.
Operational amplifiers - internals

The (simplified) internals of an operational amplifier (op-amp) are:

- Differential amplifier with high gain and large CMMR
- High gain inverting amp
- High current output stage
Operational amplifiers - external view

The external view of an op-amp is two inputs and one output.

\[ V_+ \quad + \quad - \quad V_- \quad \rightarrow \quad V_{out} \]
Operational amplifiers - external view

The external view of an op-amp is two inputs and one output, and power.

![Operational amplifier diagram](image)
The external view of an op-amp is two inputs and one output, and power.

It operates as an enormous gain differential amplifier, so:
- if $V_+ > V_-$ that difference is amplified to make $V_{out} = V_{DD}$.
- if $V_+ < V_-$ that difference is amplified to make $V_{out} = V_{SS}$. 
Operational amplifiers - external view

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- if $V_+ < V_-$ that difference is amplified to make $V_{out} = V_{SS}$.

That would be useful to compare the two inputs, but we can use it for much more using negative feedback…
Negative feedback

The versatility of op-amps comes when their enormous gain is combined with external negative feedback. E.g., consider this circuit where we have feedback from the output to $V_-$. 

If $V_{out} = V_{in}$ then $V_+ = V_-$ and there is no difference to amplify, so no change. If $V_{in} > V_{out}$ then $V_+ > V_-$, and that positive difference is strongly amplified to rapidly increase $V_{out}$ until it reaches $V_{in}$. If $V_{in} < V_{out}$ then $V_+ < V_-$, and that negative difference is strongly amplified to rapidly decrease $V_{out}$ until it reaches $V_{in}$. This robustly holds $V_{out}$ equal to $V_{in}$, even as $V_{in}$ changes. ⇒ It’s a follower.
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If $V_{out} = V_{in}$ then $V_+ = V_-$ and there is no difference to amplify, so no change.

If $V_{in} > V_{out}$ then $V_+ > V_-$, and that positive difference is strongly amplified to rapidly increase $V_{out}$ until it reaches $V_{in}$.

If $V_{in} < V_{out}$ then $V_+ < V_-$, and that negative difference is strongly amplified to rapidly decrease $V_{out}$ until it reaches $V_{in}$.

This robustly holds $V_{out}$ equal to $V_{in}$, even as $V_{in}$ changes. ⇒ It’s a follower.

And it has high input impedance due to FET inputs.
Negative feedback

The versatility of op-amps comes when their enormous gain is combined with external negative feedback. E.g., consider this circuit where we have feedback from the output to $V_-$. 

If $V_{\text{out}} = V_{\text{in}}$, then $V_+ = V_-$, and there is no difference to amplify, so no change. If $V_{\text{out}} < V_{\text{in}}$, then $V_+ > V_-$, and that positive difference is strongly amplified to rapidly increase $V_{\text{out}}$ until it reaches $V_{\text{in}}$. If $V_{\text{out}} > V_{\text{in}}$, then $V_+ < V_-$, and that negative difference is strongly amplified to rapidly decrease $V_{\text{out}}$ until it reaches $V_{\text{in}}$. This robustly holds $V_{\text{out}}$ equal to $V_{\text{in}}$, even as $V_{\text{in}}$ changes. 

⇒ It's a follower. And it has high input impedance due to FET inputs.
Negative feedback

The versatility of op-amps comes when their enormous gain is combined with external negative feedback.

E.g., consider this circuit where we have feedback from the output to \( V_- \).

\[
V_{\text{out}} = V_{\text{in}}
\]

This robustly holds \( V_{\text{out}} \) equal to \( V_{\text{in}} \), even as \( V_{\text{in}} \) changes.

⇒ It's a follower.

And it has high input impedance due to FET inputs.
Negative feedback

This has no gain, but we traded large gain for precise control (and large $X_{in}$). That is the idea of negative feedback: use the large differential gain of the op-amp to allow simple external connections between the output and the inverting input (negative feedback) to define a relation between $V_{out}$ and $V_{in}$.

You can think of this as defining a potential distribution; deviations from equilibrium push the system back to equilibrium. Changing $V_{in}$ changes the equilibrium point and the op-amp readjusts. Here the equilibrium is at $V_{out} = V_{in}$, which is $r=0$ in the spring analogy. We’ll see how to adjust the equilibrium $V_{out}(V_{in})$ relationship soon.
Negative feedback

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![Diagram of operational amplifier with negative feedback](image)

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We know how it does that, by using a differential amplifier and large gain. But, we don’t need to know how; we only need to know that it does that.
Negative feedback

The versatility of op-amps comes when their enormous gain is combined with external negative feedback.

E.g., consider this circuit where we have other feedback from the output to $V_-$. If $V_{out} = 2V_{in}$ then $V_+ = V_-$ and there is no difference to amplify, so no change.

If $V_{in} > 2V_{out}$ then $V_+ > V_-$, and that positive difference is strongly amplified to rapidly increase $V_{out}$ until it reaches $2V_{in}$.

If $V_{in} < 2V_{out}$ then $V_+ < V_-$, and that negative difference is strongly amplified to rapidly decrease $V_{out}$ until it reaches $2V_{in}$.

This robustly holds $V_{out}$ equal to $2V_{in}$, even as $V_{in}$ changes. $\Rightarrow$ It’s an amplifier.
Op-amp golden rules

The “golden rules” for op-amp operation encode this idea in two simple rules that are sufficient to analyze the behavior of most op-amp circuits:

1. No current flows into the inputs, i.e.,
   \[ I_+ = 0 \quad \& \quad I_- = 0 \]
   This follows from the FET inputs.

2. The op-amp output will do whatever it can to force the inputs to be equal, i.e.,
   \[ V_+ = V_- \]

Rule 2 can only work when there is some sort of feedback from \( V_{out} \) to \( V_- \), i.e., some negative feedback. Otherwise, \( V_{out} \) is “at a rail” if \( V_+ \neq V_- \).
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So, rule 2 immediately identifies this as a follower. Rule 1 means it is a high impedance follower.
Op-amp non-inverting amplifier

Using the golden rules we can analyze the circuit for a non-inverting amplifier.

Rule 1 means high impedance.
Rule 2 means that $V_{out}$ relates to $V_{in} = V_+ = V_-$ through a simple voltage divider relationship.

$$V_- = V_{out} \frac{R_1}{(R_1+R_2)} = V_{in}$$
Op-amp non-inverting amplifier

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Rule 1 means high impedance.
Rule 2 means that $V_{out}$ relates to $V_{in}$ through a simple voltage divider relationship:

$$V_- = V_{out} \frac{R_1}{R_1 + R_2} = V_{in}$$

Solving for $V_{out}$ in terms of $V_{in}$ gives

$$V_{out} = V_{in} \left( 1 + \frac{R_2}{R_1} \right)$$

$$G \equiv \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}$$

Check the limits on $R_1$ & $R_2$ at 0 & $\infty$
Op-amp inverting amplifier

Using the golden rules we can analyze the circuit for an inverting amplifier.

Rule 2 means $V_- = \text{ground}$. Called a “virtual ground”.

Rule 1 means that no current flows into inverting input. So,
Op-amp inverting amplifier

Using the golden rules we can analyze the circuit for an inverting amplifier

Rule 2 means $V_- = \text{ground}$. Called a “virtual ground”.

Rule 1 means that no current flows into inverting input. So, $I_1 = I_2$
Op-amp inverting amplifier

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$V_{in} = I_1R_1$

$V_{out} = -I_2R_2 = -I_1R_2 = -V_{in}R_2/R_1$

$G = -R_2/R_1$
Op-amp integrator

Using the golden rules we can analyze the circuit for an integrator

\[ V_{\text{out}} = \int V_{\text{in}} \, dt \]

\[ V_{\text{out}} = \frac{1}{RC} \int V_{\text{in}} \, dt \]

\[ V_{\text{out}} = \frac{1}{RC} \left( \int V_{\text{in}} \, dt + V_{\text{in}}(0) \right) \]
Op-amp integrator

Using the golden rules we can analyze the circuit for an integrator

Rule 2 means $V_- = \text{ground}$. Called a “virtual ground”.

Rule 1 means that no current flows into inverting input. So, $I_R = I_C = I$

$V_{in} = I \cdot R$
Op-amp integrator

Using the golden rules we can analyze the circuit for an integrator:

Rule 2 means $V_- = $ ground. Called a “virtual ground”.

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$V_{in} = I R$

$dV_{out} / dt = - I / C = -V_{in} / RC$

$I$ or $-I$
Op-amp integrator

Using the golden rules we can analyze the circuit for an integrator

Rule 2 means $V_{-} = \text{ground}$. Called a “virtual ground”.

Rule 1 means that no current flows into inverting input. So, $I_R = I_C = I$

$V_{in} = I R$

$\frac{dV_{out}}{dt} = - \frac{I}{C} = -\frac{V_{in}}{RC}$

$dV_{out}(t) = -V_{in}(t) \frac{dt}{RC}$
Op-amp integrator

Using the golden rules we can analyze the circuit for an integrator

\[
\int \frac{dV_{out}}{dt} = -(1/RC) \int V_{in} \, dt
\]

\[
V_{out} (t) = -(1/RC) \int V_{in}(t) \, dt
\]

Rule 2 means \(V_- = \) ground. Called a "virtual ground".

Rule 1 means that no current flows into inverting input. So, \(I_R = I_C = I\)

\[
V_{in} = I R
\]

\[
dV_{out} /dt = - I / C = -V_{in} / RC
\]

\[
dV_{out} (t) = -V_{in} (t) \, dt / RC
\]

So we get the integrator behavior we saw before, but without approximation.
Op-amp integrator

Using the golden rules we can analyze the circuit for an integrator

This will integrate forever, and a small input offset will eventually cause it to saturate.

\[ V_{out}(t) = -(1/RC) \int V_{in}(t) \, dt \]
Op-amp integrator

Using the golden rules we can analyze the circuit for an integrator:

\[
V_{\text{out}}(t) = -(1/RC) \int V_{\text{in}}(t) \, dt
\]

This will integrate forever, and a small input offset will eventually cause it to saturate.

Can leak off that ~DC build up with a large "leakage" resistor.
Op-amp integrator

Using the golden rules we can analyze the circuit for an integrator

This will integrate forever, and a small input offset will eventually cause it to saturate.

Can leak off that ~DC build up with a large resistor.

Or specifically reset it at appropriate times with a switch. Can use a FET switch for computer control.

\[ V_{\text{out}}(t) = -(1/RC) \int V_{\text{in}}(t) \, dt \]
Op-amp integrator

Using the golden rules we can analyze the circuit for an integrator

\[ V_{\text{out}}(t) = -(1/RC) \int V_{\text{in}}(t) \, dt \]
Op-amp differentiator

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Rule 2 means $V_- = \text{ground}$. Called a “virtual ground”.

Rule 1 means that no current flows into inverting input. So, $I_R = I_C = I$

$V_{out} = -IR$
Op-amp differentiator

Using the golden rules we can analyze the circuit for a differentiator

Rule 2 means $V_- = \text{ground}$. Called a “virtual ground”.

Rule 1 means that no current flows into inverting input. So, $I_R = I_C = I$

$$V_{out} = -IR \quad \rightarrow \quad I = -\frac{V_{out}}{R}$$

$$\frac{dV_{in}}{dt} = I / C = -\frac{V_{out}}{RC}$$

$$V_{out} = -RC \frac{dV_{in}}{dt}$$
Op-amp differentiator

Using the golden rules we can analyze the circuit for a differentiator

Rule 2 means $V_\text{e} = \text{ground}$. Called a “virtual ground”.

Rule 1 means that no current flows into inverting input. So, $I_R = I_C = I$

$V_\text{out} = -I R \quad \rightarrow \quad I = -V_\text{out} / R$

$dV_{\text{in}} / dt = I / C = -V_\text{out} / RC$

$V_\text{out} = -RC \ dV_{\text{in}} / dt$

$V_{\text{out}}(t) = -RC \ dV_{\text{in}}(t) / dt$
Summing amplifier

Using the golden rules we can analyze the circuit for a summing amp

\[ V_{out} = -IR_F \]

I is sum of all input currents

\[ I_1 = \frac{V_{in1}}{R_1} \]
\[ I_2 = \frac{V_{in2}}{R_2} \]
\[ I_3 = \frac{V_{in3}}{R_3} \]
Etc
Summing amplifier

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\[ I_3 = \frac{V_{\text{in}3}}{R_3} \]
Etc

\[ V_{\text{out}} = -IR_F = -\frac{R_F}{R_1} V_{\text{in}1} - \frac{R_F}{R_2} V_{\text{in}2} - \frac{R_F}{R_3} V_{\text{in}3} - \cdots \]
Summing amplifier

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\[ I_1 = \frac{V_{\text{in}1}}{R_1} \]
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Etc

Suppose we made

\[ R_1 = R_F \]
\[ R_2 = \frac{R_F}{2} \]
\[ R_3 = \frac{R_F}{4} \]
\[ R_4 = \frac{R_F}{8} \]
Summing amplifier

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Then, we get

\[ V_{\text{out}} = -V_{\text{in}1} - 2V_{\text{in}2} - 4V_{\text{in}3} - 8V_{\text{in}4} \]

This allows the inputs to be binary-coded signals, e.g., 0.0 and 0.1 V, then the output reconstructs the analog voltage.
Summing amplifier

Using the golden rules we can analyze the circuit for a summing amp

\[ V_{out} = -I R_F \]

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Op-amp current amplifier
Op-amp current amplifier

Rule 2 means $V_-=\text{ground}$. Called a “virtual ground”.

Rule 1 means that no current flows into inverting input. So, $I_R = I_{in}$

$I_2 = I_1 = V_{in}/R_1$
Op-amp current amplifier

Rule 2 means $V_- = \text{ground}$. Called a “virtual ground”.

Rule 1 means that no current flows into inverting input. So, $I_R = I_{in}$

$V_{out} = -I_{in} R$

If $R = 1\, \Omega$ then we get $1\, \text{V}/\mu\text{A}$. 
Op-amp current amplifier

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If $R = 1\,\text{M}\Omega$ then we get $1\,\text{V}/\mu\text{A}$. 

Diagram:

- **PD** → **Amp** → **Filter** → **ADC**
More complex feedback loops

The golden rules work even when we have other things in the feedback loop.

Rule 2 makes $V_{\text{out}} = V_{\text{in}}$ regardless of any voltage dropped across the resistor.
More complex feedback loops

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Rule 2 makes $V_{out} = V_{in}$ regardless of any voltage dropped across the resistor.

The op-amp output, $A$, will have to be higher than $V_{out}$ to make $V_{out} = V_{in}$, but the op-amp can do that, with a tiny difference between $V_+$ and $V_-$. 
More complex feedback loops

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What about a transistor in the loop?
More complex feedback loops

The golden rules work even when we have other things in the feedback loop.

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The op-amp output, $A$, will have to be higher than $V_{out}$ to make $V_{out} = V_{in}$, but the op-amp can do that, with a tiny difference between $V_+$ and $V_-$.

What about a transistor in the loop? The load can be the emitter resistor, which can be a low resistance, e.g., a speaker, with a high power transistor driving it.
More complex feedback loops

The golden rules work even when we have other things in the feedback loop

Rule 2 makes $V_{out} = V_{in}$ regardless of any voltage dropped across the resistor.

The op-amp output, $A$, will have to be higher than $V_{out}$ to make $V_{out} = V_{in}$, but the op-amp can do that, with a tiny difference between $V_+$ and $V_-$.

What about a transistor in the loop? The load can be the emitter resistor, which can be a low resistance, e.g., a speaker, with a high power transistor driving it.

The $0.6 \text{ V}$ diode drop is compensated by the op-amp, so $V_{out} = V_{in}$ without a $0.6 \text{ V}$ drop.
Peak detector

The golden rules work even when we have other things in the feedback loop.

\[ V_{\text{in}} \quad V_+ \quad V_{\text{out}} \quad V_- \quad C \]

The output will follow on the way up.
The op-amp will compensate the diode drop.
The diode won’t let the op-amp pull it back down.
The capacitor will hold the maximum voltage reached.
The \( V_- \) input will not allow current flow to discharge the capacitor.
Peak detector

The golden rules work even when we have other things in the feedback loop.

\[ V_{\text{in}} \]

\[ V_{+} \]

\[ V_{-} \]

\[ V_{\text{out}} \]

The output will follow on the way up.
The op-amp will compensate the diode drop.
The diode won’t let the op-amp pull it back down.
The capacitor will hold the maximum voltage reached.
The \( V_{-} \) input will not allow current flow to discharge the capacitor.
Can add a follower to avoid discharging the capacitor through the load.
Peak detector

The golden rules work even when we have other things in the feedback loop.

\[ \text{The output will follow on the way up.} \]

\[ \text{The op-amp will compensate the diode drop.} \]

\[ \text{The diode won’t let the op-amp pull it back down.} \]

\[ \text{The capacitor will hold the maximum voltage reached.} \]

\[ \text{The V}_- \text{ input will not allow current flow to discharge the capacitor.} \]

\[ \text{Can add a follower to avoid discharging the capacitor through the load.} \]

\[ \text{Add a controlled resistor to leak off the charge with a long time constant.} \]
Peak detector

The golden rules work even when we have other things in the feedback loop.

\[ V_{\text{in}} \]
\[ + \]
\[ V_+ \]
\[ + \]
\[ C \]
\[ - \]
\[ R_{\text{Leak}} \]
\[ \rightarrow \]
\[ V_- \]
\[ + \]
\[ V_+ \]
\[ + \]
\[ + \]
\[ - \]
\[ V_{\text{out}} \]

The output will follow on the way up.
The op-amp will compensate the diode drop.
The diode won’t let the op-amp pull it back down.
The capacitor will hold the maximum voltage.
The \( V_- \) input will not allow current to discharge the capacitor.
Can add a follower to avoid discharging the capacitor through the load.
Add a controlled resistor to leak off the charge with a long time constant.
Peak detector

The golden rules work even when we have other things in the feedback loop.

The output will follow on the way up.
The op-amp will compensate the diode drop.
The diode won’t let the op-amp pull it back down.
The capacitor will hold the maximum voltage reached.
The $V_-$ input will not allow current flow to discharge the capacitor.
Can add a follower to avoid discharging the capacitor through the load.
Add a controlled resistor to leak off the charge with a long time constant.
Or, add a MOSFET switch to reset the capacitor.
Sample and hold

We can often time measurements, e.g., pump and probe. So we can use MOSFET switches from a control computer to time controls: reset, sample, hold, [readout], reset.
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How could you use something like this to “count” photons per second in our example experiment?
Sample and hold

We can often time measurements, e.g., pump and probe. So we can use MOSFET switches from a control computer to time controls: reset, sample, hold, [readout], reset.

How could you use something like this to “count” photons per second in our example experiment?
Integrate, sample, and hold
Negative feedback

We also saw negative feedback with a current mirror.

\[ E = \frac{k}{2} (q - q_0)^2 \]
Op-amp differentiator

Using the golden rules we can analyze the circuit for a differentiator

Can also think of this in terms of complex impedance, where it is an inverting amplifier with gain

\[ G = -\frac{R}{j\omega C} = -\frac{R}{-j\omega C} \]

\[ G = j\omega RC \]

The gain increases with frequency, while the simple, passive differentiator leveled off at high frequency.

The \( j \) indicates a phase shift.

\[ G = -\frac{R_2}{R_1} = -\frac{X_2}{X_1} \]
Op-amp integrator

Using the golden rules we can analyze the circuit for an integrator

Can also think of this in terms of complex impedance, where it is an inverting amplifier with gain

\[ G = -\frac{X_C}{X_R} = -\left(-\frac{j}{\omega C}\right)/R \]

\[ G = \frac{j}{\omega RC} \]

Gain increases for low frequency.