Non-ideal op-amp properties
Review: Op-amp golden rules

The op-amp golden rules were:
1). No input current, $I_+ = 0$ and $I_- = 0$, i.e., $X_{in} = \infty$
2). $V_- = V_+$ with negative feedback
   Or, output is enormous gain differential amp

This simple view allowed analyzing many op-amp circuits, but it is only a first approximation.

Now we’ll see some of the corrections, or limitations of this model and how to mitigate them.
Rail-to-rail

What is the output of this circuit?
Rail-to-rail

What is the output of this circuit? And this one?

\[ V_{DD} \]

\[ V_{SS} \]
Rail-to-rail

What is the output of this circuit? And this one?

The golden answers are $V_{DD}$ and $V_{SS}$.
The “non-ideal” answers are \textit{a bit below} $V_{DD}$ and \textit{a bit above} $V_{SS}$.
Real op-amps can’t go all the way to the power supply rails.
Rail-to-rail

Real op-amps can’t go all the way to the power supply rails. E.g., here is a simplified schematic of the KA358; note the output stage.
Slew rate

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Slew rate

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The output has a maximum “slew rate” that is ~ linear.

KA358 slew rate is ~0.15 V/µs. Fast amps can reach > 1000 V/µs.

This limits speed, particularly for large $V_{DD}$. 
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KA358 slew rate is \( \sim 0.15 \) V/\( \mu \)s.
Fast amps can reach \( > 1000 \) V/\( \mu \)s.

This limits speed, particularly for large \( V_{DD} \).

Also can have a propagation delay.
Roll off of open-loop gain

The gain degrades at high frequency.

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Roll off is often intentional to avoid oscillation at high frequency due to parasitic positive feedback.

![Gain vs Frequency Graph for KA358 Op-Amp](attachment:KA358_gain_graph.png)
Roll off of open-loop gain

The gain degrades at high frequency
(This op-amp has lower supply limits, 5V not 15V)

THS4304
$6 op-amp
Input offset

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The output “follows” the voltage across the capacitor.
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This limits stability time for integrators or S&H.
Input offset current

This biases an inverting amplifier with large resistors. Want $R_1$ large for input impedance, but $I_B*R$ is a voltage offset.

$10 \text{ nA} \times 1\text{M} = 10\text{mV}$. Then gain of 10 gives an output bias of 100 mV.
**Input offset current**

This biases an inverting amplifier with large resistors. Want $R_1$ large for input impedance, but $I_B*R$ is a voltage offset.

10 nA*1M = 10mV. Then gain of 10 gives an output bias of 100 mV. Solution is to give the other input the same voltage offset; works if $I_{OS}$ small compared to $I_B$. 
Input offset current

Similar solution works for non-inverting amplifiers.
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But, again, it is best not to amplify the DC offsets.
Noise

There is intrinsic noise in the inputs.

Typically 10 nV/$\sqrt{\text{Hz}}$ and 1 pA/$\sqrt{\text{Hz}}$

Really only critical for precision measurements, and we will talk about ways to suppress it next week.
Pick your optimum

There are thousands of op-amp designs. They optimize on various parameters:

Rail-to-rail
Power supply range
Power consumption
Speed
  - GBP, Slew-rate
Input bias current
Input offset current
Input offset voltage
Flexibility
  - Multi-circuits
  - Offset-null
Package
Operating temperature range
Price
  - Often dominated by batch size.
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Electronics component vendors:
- Newark
- Digikey
- Arrow
Lab 9 and extra credit projects

Lab 9 will be a grab-bag of options

No lab 10 during dead week.
That time available for extra credit project work.

Extra credit projects due (ELOG complete) Sunday, June 13\textsuperscript{th} at noon.
Email me when you have completed it.
What is wrong with this circuit?
What is wrong with this circuit?
\[ V_{in} \rightarrow 1\mu F \rightarrow 50k \rightarrow 100k \rightarrow +15\, V \rightarrow \text{Op Amp} \rightarrow - \rightarrow 10k \rightarrow 2k \rightarrow 1\mu F \rightarrow \text{Ground} \rightarrow V_{out} \]