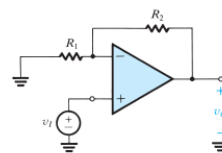


Op Amp Discovery



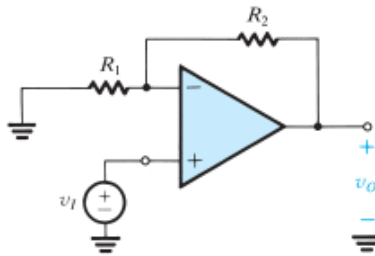
Circuit Examples for Guided Learning

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1 Introduction

Guided Learning is like a buffet table: **take as much or as little as you need!**



Choose one of three paths to discovery.

1. Follow a walk-through of circuits to observe op amp functions and behaviors.
2. Borrow ideas from circuit examples and follow-through on your own.
3. Explore circuits entirely on your own with self-directed learning.

The examples are intended to help you

- ✓ build your circuit discovery and learning skills.
- ✓ explore op amps in a fun, engaging way.

Download the **User's Guide** and project files at Github

<https://github.com/rick-ecircuit>

2 Four Key Steps

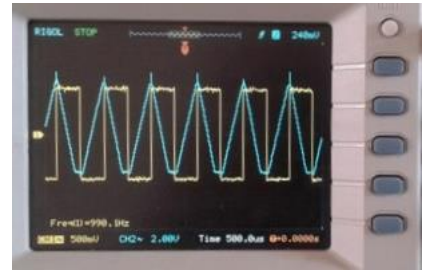
The topics walk-through an op amp circuit with 4 basic steps.

1. **Define It** - Draw Schematic, choose gains, signal levels, etc.
2. **Design It** - Calculate component values, signal levels.
3. **Build It** - Find a way to create it (sketch circuit, install parts on Discovery Bd.)
4. **Test & Learn It** - Plan setup, make measurements, verify levels, observe, connect to theory.

3 What You'll Need

The Op Amp Discovery Bd provides the Quick Proto-Board, Supplies and Signal Source. You'll need a few additional items to learn and explore.

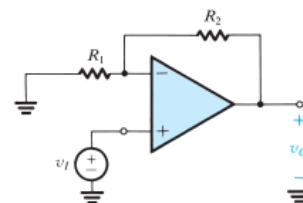
- Oscilloscope
 - *Observing waveforms provides key insight into how circuits work.*
 - Suggested: 2 channels with >1MHz Bandwidth.
 - Budget Scopes (hand-held or USB type) are available from \$40 to \$100.
- DMM
 - *A low-budget alternative to a scope is a basic Digital Mult-Meter (DMM) available from \$10 and up.*
 - Select the DC input source on the Discovery Bd and observe the op amp's behavior with the DMM.
 - See Section 10 for more info.
- Paper Pad & Excel Calculator
 - Let your pencil flow freely onto the paper with schematics, equations and waveforms.
 - The paper is your sandbox to play with ideas - *brainstorm, gain clarity, try and adjust.*
 - Get the Excel Design Calculator - Scroll to bottom of page.
<https://ecircuitcenter.com/op-amp-discovery/op-amp-discovery.html>



4 Op Amp Circuit Collection

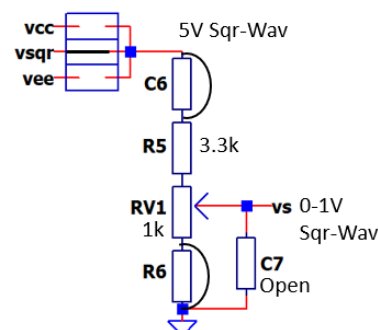
Use the guided examples any way you like!

- *Just follow your interest and curiosity!*
- *No rigid order or method.*



Default Signal Source

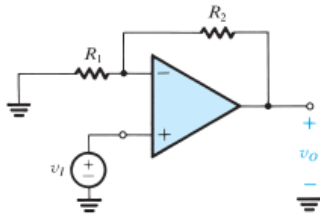
- *DC Coupled, Square-Wave, 5kHz*
- *Trimpot adjusts V_s from 0 - 1.2V*
- *Default signal setup (unless noted)*
 - *C6 = short*
 - *R5 = 3.3k*
 - *RV1 = 1k trimpot*
 - *R6 = short, C7 = open*



4.1 Non-Inverting Amplifier

Application Example: Boost a weak signal from a small microphone.

1. **Define It** – Draw Schematic and choose gains, signal levels, etc.



Let's amplify a signal by $K = +2$.

$$K = V_{out}/V_s = R_2/R_1 + 1 = 2$$

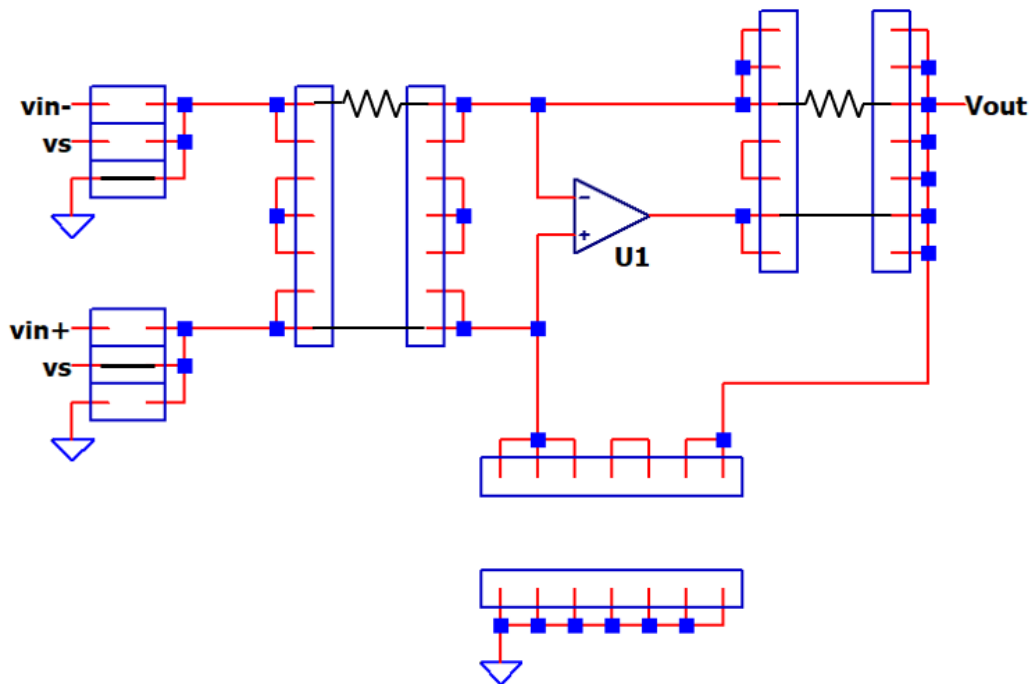
Choose $V_s = 0.5V$

2. **Design It** – Calculate component values and signal levels.

Choose $R_1 = 10k$,
Calc $R_2 = (K-1) * R_1 = 10k$

$$\begin{aligned} V_{out} &= V_s * K \\ &= 0.5V * 2 \\ &= 1.0V \end{aligned}$$

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
Connect Probe 1 to V_S (Jumper at J3,4).
Connect Probe 2 to V_{OUT} (R_2 at V_{out} side).

Verify a unipolar square wave at V_S .

Adjust RV_1 for $V_S = 0.5V$ peak.
Did V_{out} achieve the goal?

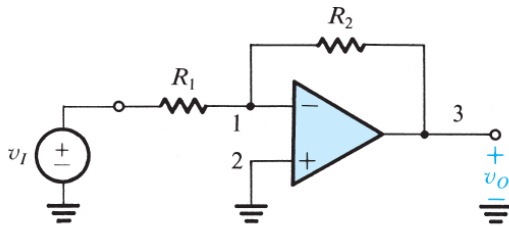
Move Probe 2 to U_1 's negative input (R_1 at U_1 side).
Does $U_1.in-$ follow V_S ?

What happens if you double R_1 or R_2 ?

4.2 Inverting Amplifier

Application Example: Create a Negative Reference voltage from a Positive one (for a bipolar input ADC).

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



Let's amplify a signal by -1.

$$V_s = +1V$$

$$K = V_{out}/V_s = -R_2/R_1 = -1$$

2. **Design It** – Calculate component values and signal levels.

Choose $R_1 = 10k$,

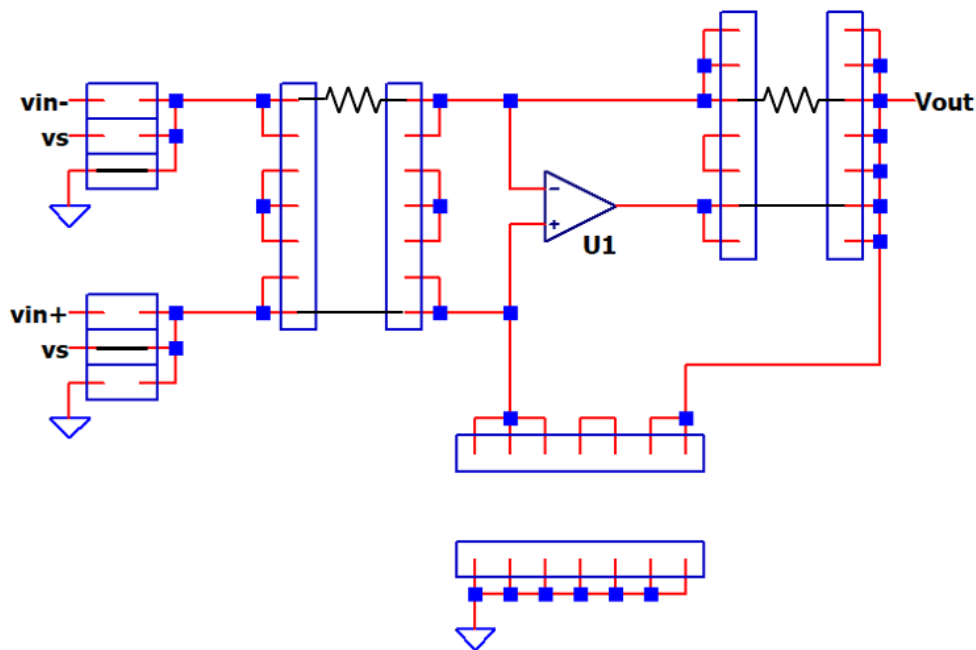
Calc $R_2 = -K * R_1 = 10k$

$$V_{out} = V_s * K$$

$$= 1V * -1$$

$$= -1V$$

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
 Connect Probe 1 to VS (R1 at VS side).
 Connect Probe 2 to VOUT (R2 at Vout side).

Verify a square wave at VS.

Adjust RV1 for $V_s = 1V$ peak.
 Did V_{out} achieve the goal?

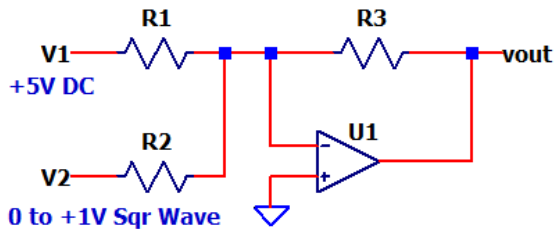
Move Probe 2 to U1's neg input (R1 at U1 side).
 Does $U1.in-$ follow GND (0V)?

What happens if you double R_1 or R_2 ?

4.3 Summing Amplifier

Application Example: Mix together signals from 2 audio channels into a single channel.

1. **Define It** – Draw schematic, choose gains, signal levels, etc.



What happens when a DC signal (V_{cc}) is summed with a Square Wave (V_S)?

$$V_1 = V_{cc} = +5VDC$$

$$K_1 = V_{out} / V_{cc} = -R_3/R_1 = -1/10$$

$$V_2 = V_{sqr} = 0 \text{ to } +1V \text{ (Sqr Wave)}$$

$$K_2 = V_{out} / V_{sqr} = -R_3/R_2 = -1$$

2. **Design It** – Calculate component values and signal levels.

Choose $R_3 = 10k$

Calc $R_2 = R_3 / -K_1 = 100k$

Calc $R_1 = R_3 / -K_2 = 10k$

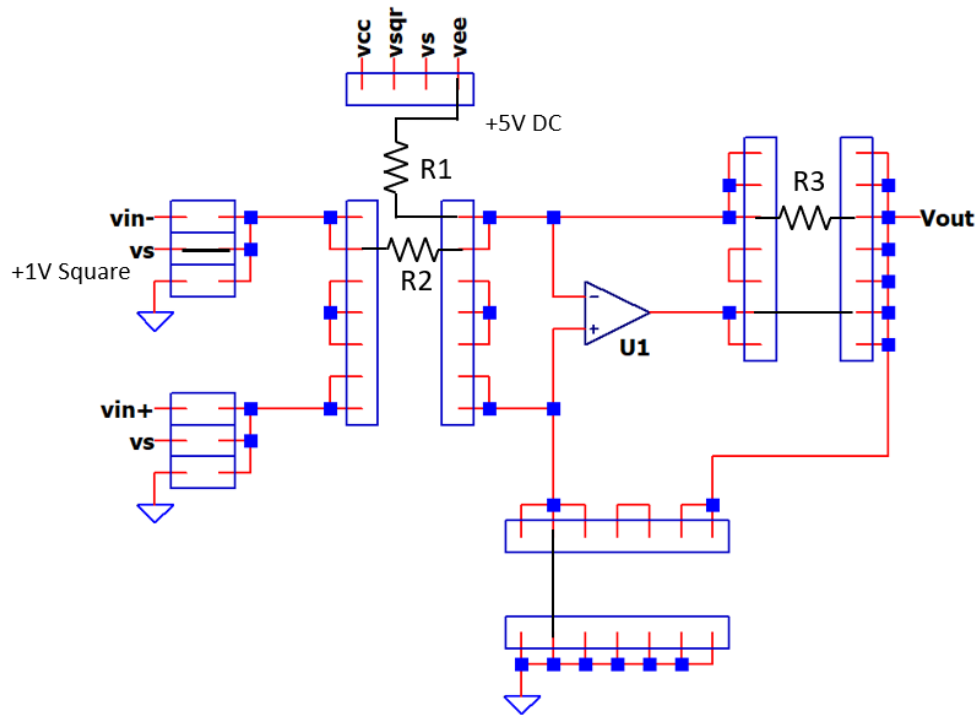
$$V_{out} = V_{cc} * K_1 + V_{sqr} * K_2$$

$$= V_{cc} * -0.1 + V_{sqr} * (-1)$$

$$= -0.5 \text{ DC level} + (0 \text{ to } -1.0V) \text{ Sqr wave}$$

Note: RV_1 adjusts Square Wave amplitude

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
Connect Probe 1 to V_S (R_1 at V_S side).
Connect Probe 2 to V_{OUT} (R_3 at V_{out} side).

Adjust RV_1 for $V_S = 0V$ peak.

Slowly adjust RV_1 for $V_S = 1V$ peak.

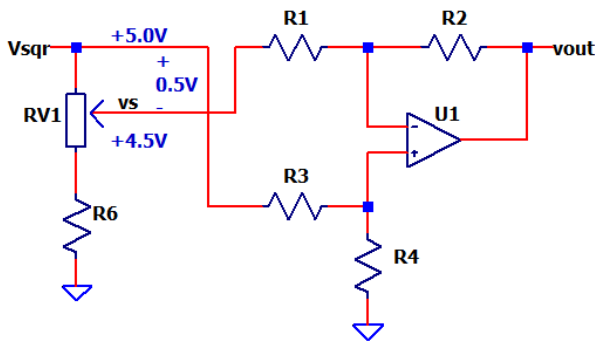
Does the Square Wave get summed with V_{out} ?

What if R_2 were halved or doubled?

4.4 Differential Amplifier

Application Example: Extract the temperature voltage from sensor signal riding on top of a bias voltage.

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



Can the amp sense the difference between $V_{sqr} = 5V$ and $V_s = 4.5V$?

$$V_{in+} = V_{sqr} = +5V$$

$$V_{in-} = V_s = 4.5V$$

$$V_{in} = (V_{sqr} - V_s) = 0.5V$$

$$K = V_{out} / V_{in} = R_2/R_1 = 1$$

2. **Design It** – Calculate component values and signal levels.

Choose $R_1 = R_3 = 10k$

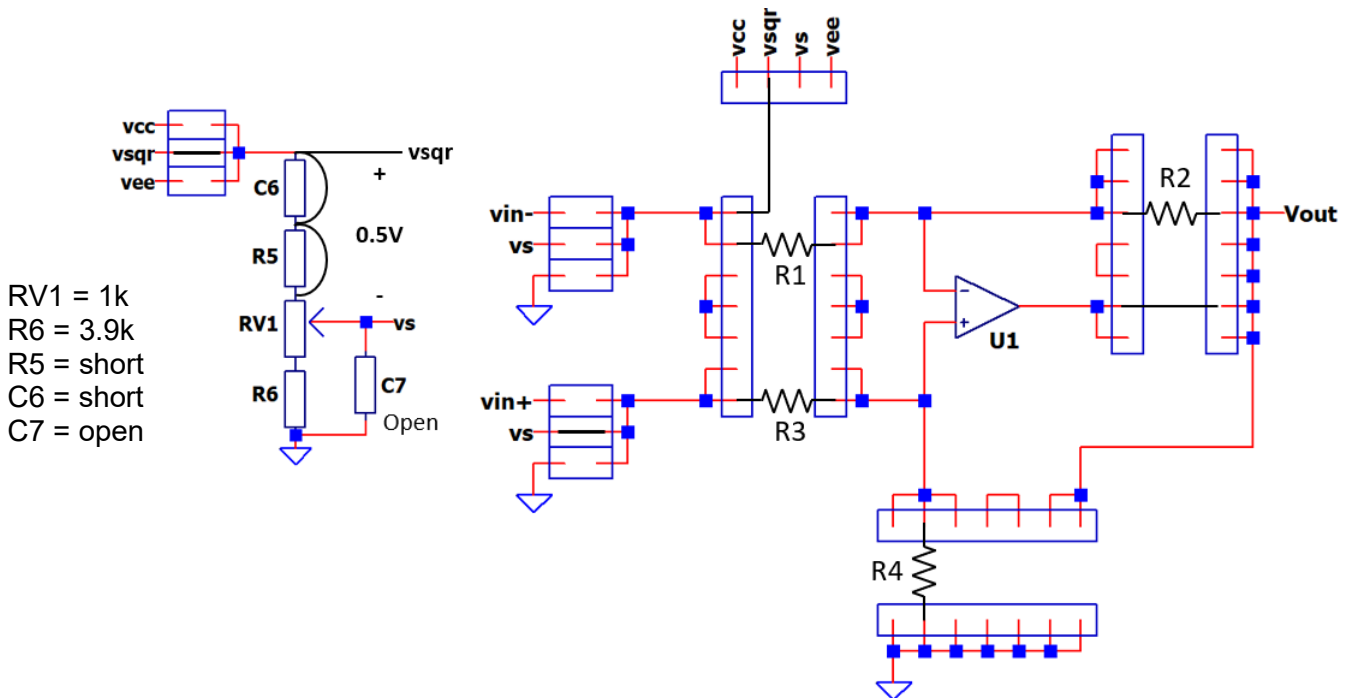
Calc $R_2 = R_4 = R_1 * K = 10k$

$$V_{out} = (V_{in+} - V_{in-}) * K$$

$$= 0.5V * 1$$

$$= 0.5V$$

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).

Connect Probe 1 to VS (R3 at Vs side).

Connect Probe 2 to VOUT (R2 at Vout side).

Adjust RV1 for $V_s = +4.5V$.

V_{sqr} should be +5V.

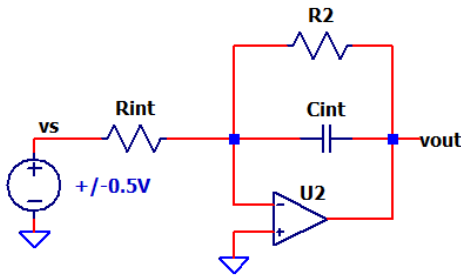
Does V_{out} achieve its goal?

What happens if you halve or double R_2 and R_4 ?

4.5 Integrator

Application Example: Create a triangle-wave (ramp) as part of a PWM motor drive.

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



Can the integrator generate a ramp from a square wave input?

$V_s = \pm 0.25V$ (Square Wave AC coupled)
 $dT = 100\mu s$ (Square wave half-cycle)

2. **Design It** – Calculate component values and signal levels.

Choose $R_{int} = 100k$, $C_{int} = 100pF$

Choose $R_2 = 4.7M$

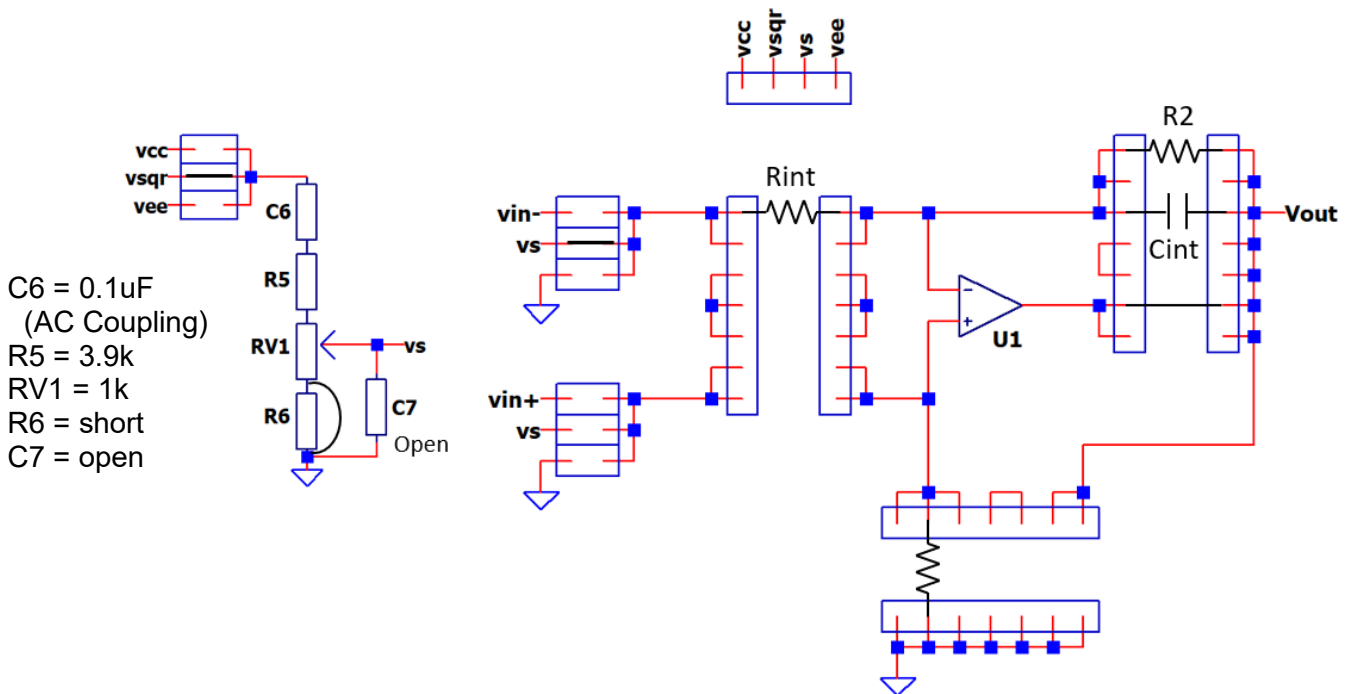
(R_2 makes finite DC gain, keeps offset low.)

$$dV_{out} = V_s / (R_{int} * C_{int}) * dT$$

$$= 2.5V$$

$$V_{out} = \pm 1.25V$$

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
 Connect Probe 1 to VS (Rint at Vs side).
 Connect Probe 2 to VOUT (Cint at Vout side).

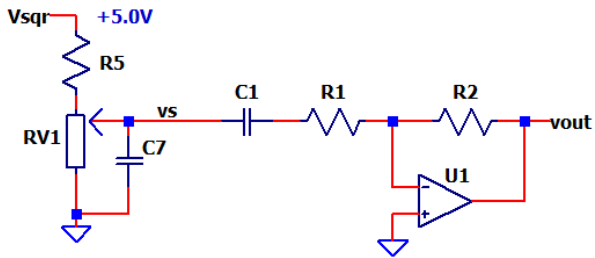
Adjust RV1 for $V_s = \pm 0.5V$
 Does V_{out} ramp as expected?

What happens if you increase R_{int} or C_{int} ?

4.6 Differentiator

Application Example: Implement the Differentiator (D) signal for a PID temperature control circuit.

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



Can the differentiator find the rate-of-change of a triangle wave input?

Vs = "Triangle" Wave
Triangle wave approximated by a Square-Wave passed thru LP Filter with long time-constant (Tau).

2. **Design It** – Calculate component values, signal levels.

Choose R5 = 10k, C7 = 0.1uF

$\tau = R5 * C7 = 0.001s$

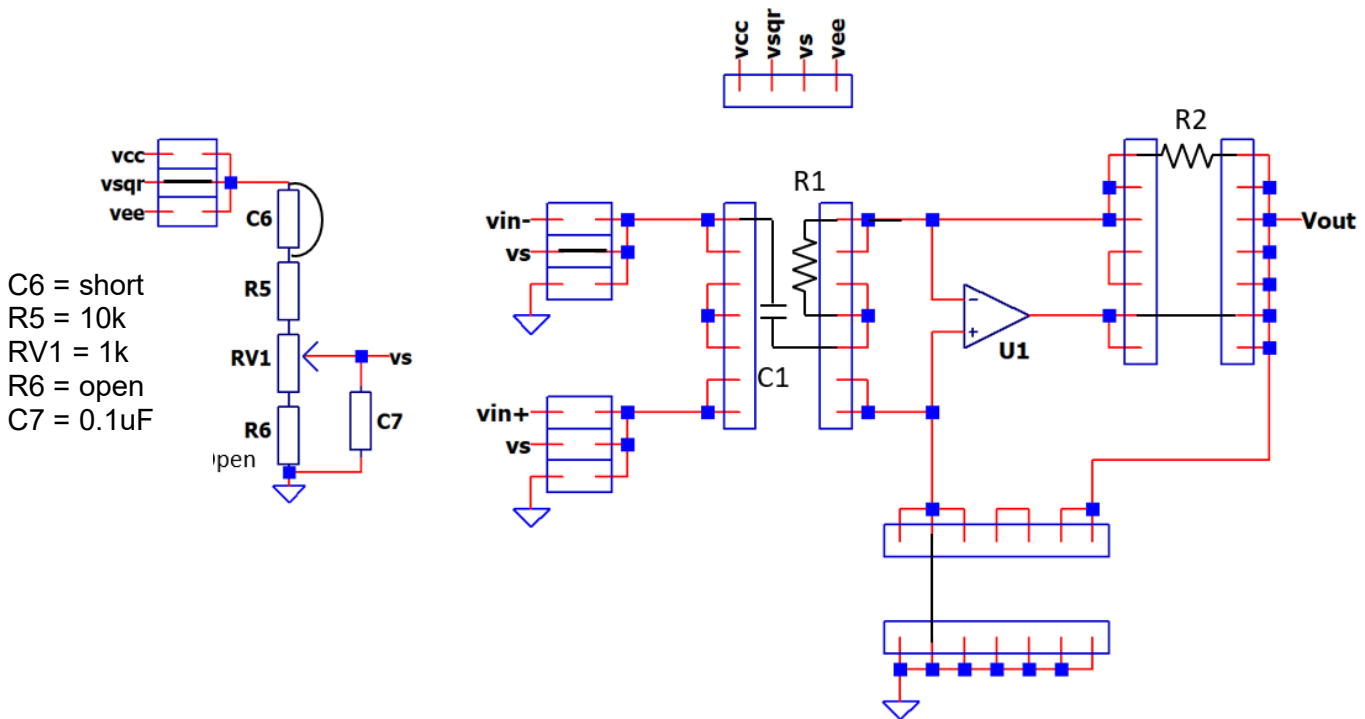
$dV/dt = (Vsqr/2)/\tau = 2.5V/0.001s = 2500V/s$

Choose C1 = 1nF, R2 = 100k

Choose R1 = 4.7k (keeps amp stable.)

$Vout = R2 * C1 * dV/dt = 0.25V$

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



C6 = short
R5 = 10k
RV1 = 1k
R6 = open
C7 = 0.1uF

4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
Connect Probe 1 to VS (C1 at Vs side).
Connect Probe 2 to VOUT (C2 at Vout side).

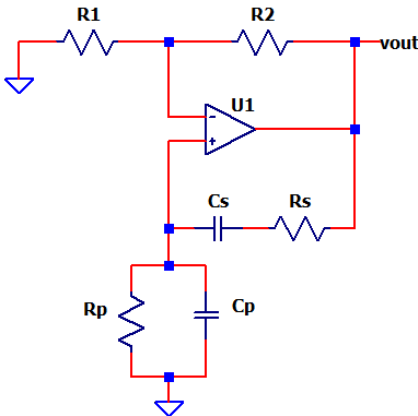
Adjust RV1 fully CW (max signal)
Does Vout show slope as expected?

What happens if R2 increases?

4.7 Wien-Bridge Oscillator

Application Example: Generate a sine-wave as a test signal for an audio circuit tester.

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



Can you produce a Sine-Wave output with $T_{per} = 300 \mu s$?

$$f_o = 1/(2*\pi*R*C)$$

2. **Design It** – Calculate component values, signal levels.

Requires gain $K > 3$ for osc.

Choose $R1=4.7k$,

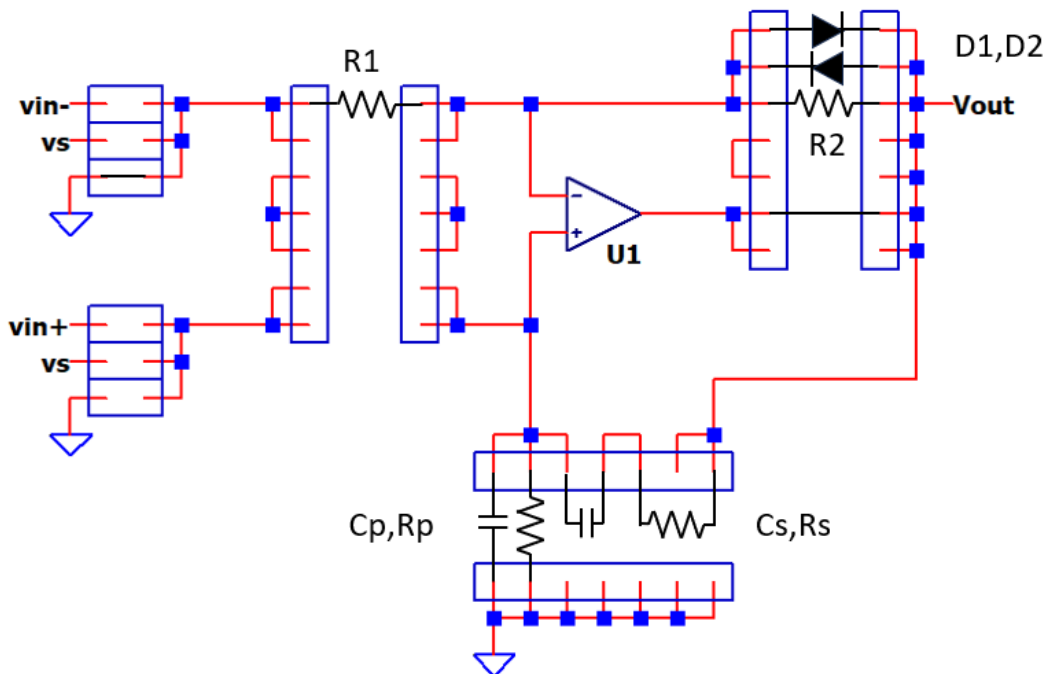
Calc $R2 = (K-1)*R1 = 9.4k$, round up to $10k$

Choose $C = 1nF$, $f_o = 3.3 \text{ kHz}$

Calc $R = 1/(2*\pi*C*f_o)$

$= 47.8k$ (use $47k$)

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
Connect Probe 1 to VOUT (C2 at Vout side).

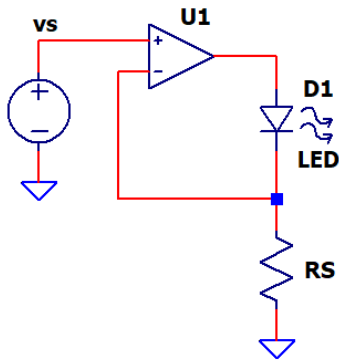
Does Vout show the sinewave as designed?

How is Vout related to Vdiode?

4.8 V-to-I Converter (LED Drive)

Application Example: Light a front panel LED in proportion to a sensor level (soil moisture for example).

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



How can VS be converted into a current through the LED?

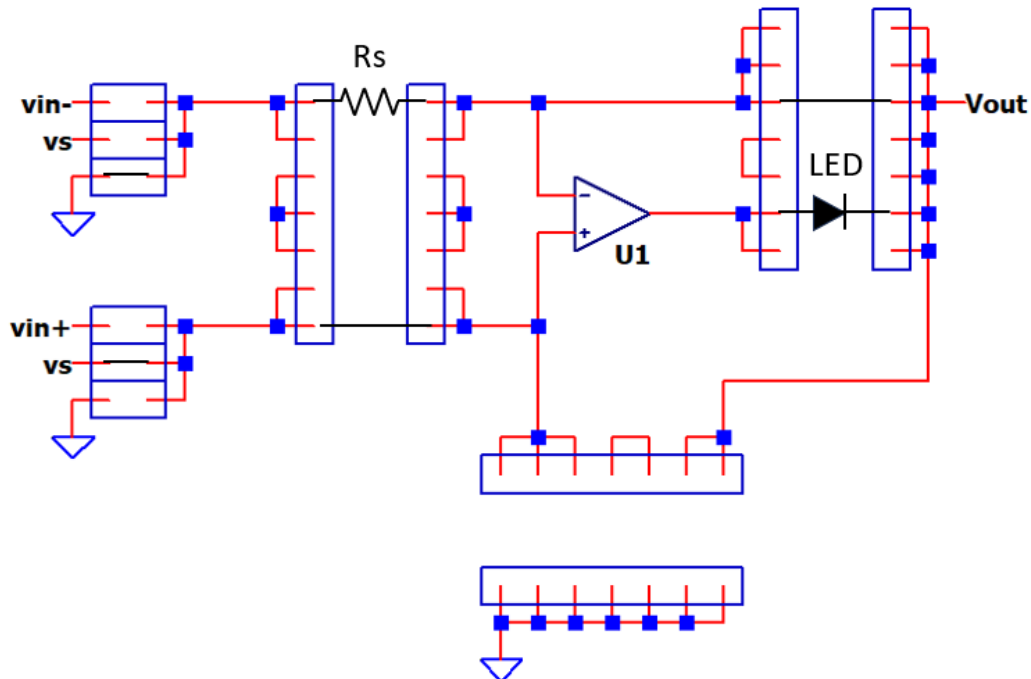
$$I_o = V_s / R_s$$

2. **Design It** – Calculate component values, signal levels.

Choose $I_o = 2\text{mA}$ at $V_s = 1\text{V}$
 Calc $R_s = V_s / I_o = 500\ \text{ohms}$
 Choose 510 if available

$$\text{Calc } I_o = 1\text{V} / 510 = 1.98\ \text{mA}$$

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
 Connect Probe 1 to VS (Jumper).
 Connect Probe 2 to RS (U1 side).

Move Probe 2 to LED anode (U1.vout).
 How much LED voltage is needed above the RS voltage?

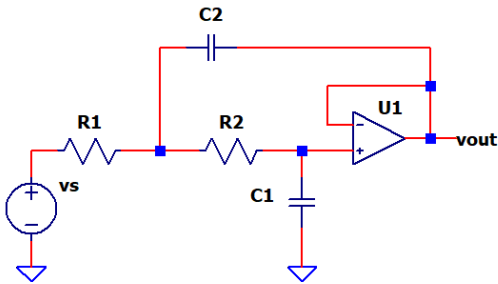
Adjust RV1 for VS = 1V max (Square Wave)
 Does the RS voltage follow VS?

What happens to LED current (and brightness) if RS = 1k?

4.9 Sallen-Key Low-Pass Filter

Application Example: Convert a square-wave output from a digital tachometer to a DC level.

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



How much can the amplitude of a square wave (5Vp-p, 5kHz) be reduced using a 2-pole filter?

$$f_c = 1 / (2 * \pi * R * C)$$

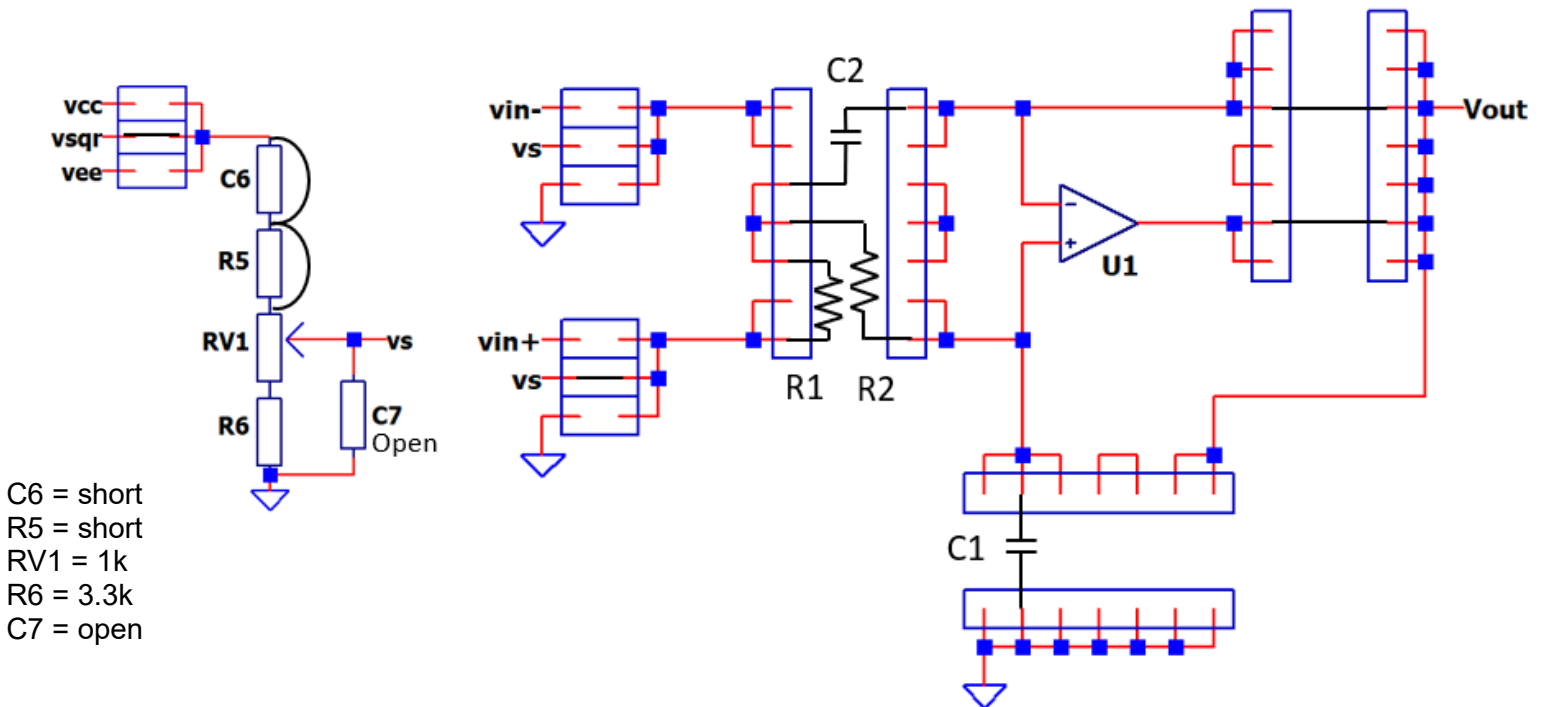
$$H \approx (f_c / f_{osc})^2$$

2. **Design It** – Calculate component values, signal levels.

Choose $f_c = 333\text{Hz}$ and $C1 = 10\text{nF}$
 Calc $C1 = 1 / (2 * \pi * 10\text{nF} * 333\text{Hz}) = 47.8\text{k}$
 Choose 47k
 Calc $H \approx (f_c / f_{osc})^2$
 ≈ 0.0044

Calc expected output with
 $V_S = 5\text{V}$, $f_{osc} = 5\text{k}$
 $V_{out} \approx V_S * (f_c / f_{osc})^2$
 $\approx 22\text{ mVp-p}$

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



C6 = short
 R5 = short
 RV1 = 1k
 R6 = 3.3k
 C7 = open

4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
 Connect Probe 1 to R1 (VS side).
 Connect Probe 2 to Vout (Jumper).

How much voltage (peak to peak) appears at Vout?

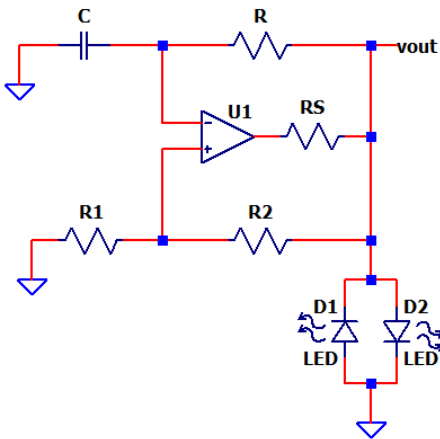
What is the DC level at Vout and why?

Adjust RV1 for max 5V Square wave.

4.10 RC Comparator Oscillator

Application Example: Create a square-wave signal to drive a speaker in a smoke detector.

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



What is the oscillation frequency of this Square-Wave output circuit?

$$f_o = 1/(2 * R_o * C_o \ln((1+B)/(1-B)))$$

$$\text{where } B = R_1/(R_1+R_2)$$

2. **Design It** – Calculate component values, signal levels.

Choose handy components

$$R_o = 100k, C_o = 10nF$$

$$R_1 = 10k, R_2 = 10k$$

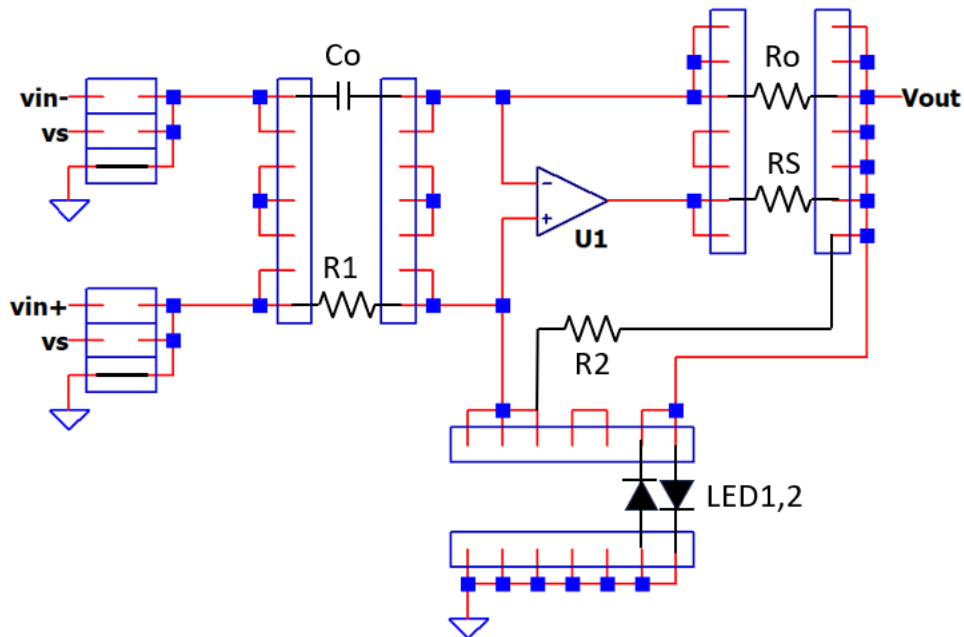
$$R_S = 1k, \text{LED}_{1,2} = \text{pick two}$$

Calc osc frequency

$$f_o = 1/(2 * 100k * 10nF * \ln((1+0.5)/(1-0.5))) = 80 \text{ Hz}$$

$$\text{Calc } B = R_1/(R_1+R_2) = 0.5$$

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
Connect Probe 1 to VOUT (Ro at Vout side).

Does Vout show the sinewave as designed?

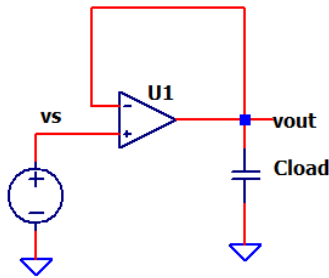
How is Vout related to Vdiode?

4.11 Driving a Capacitive Load

Application Example: Drive a sensor signal down a long coaxial cable of high capacitance.

PART 1 - The Overshoot Problem

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.

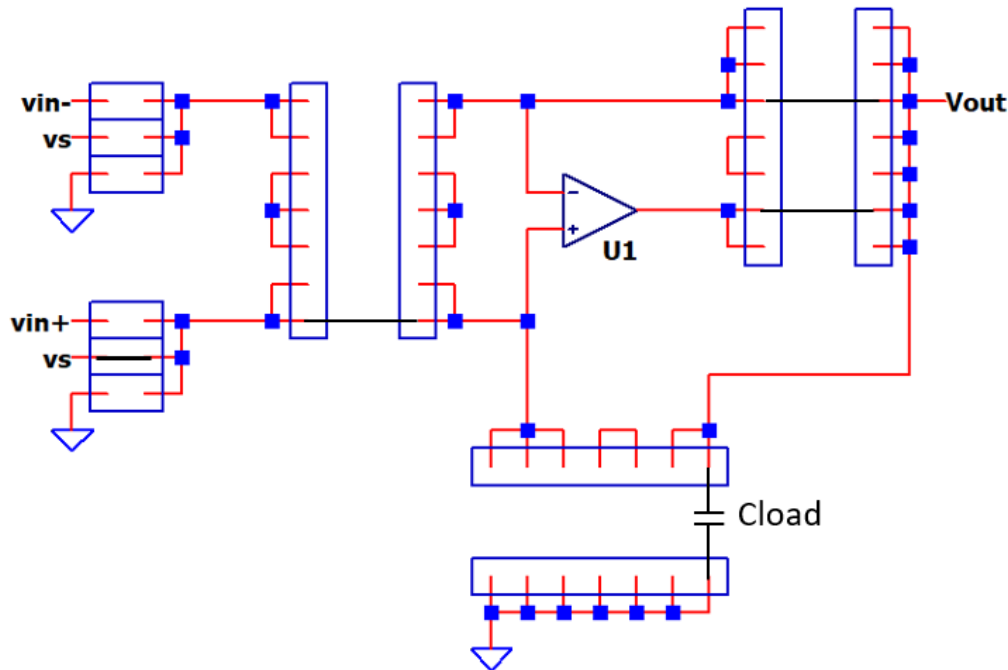


What is the overshoot when driving a high capacitive load?

2. **Design It** – Calculate component values, signal levels.

Choose Cload = 0.1 μ F or 1 μ F to observe the effects of a capacitive load.

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
Connect Probe 1 to VS (Jumper at U1.+).
Connect Probe 2 to Vout (Jumper).

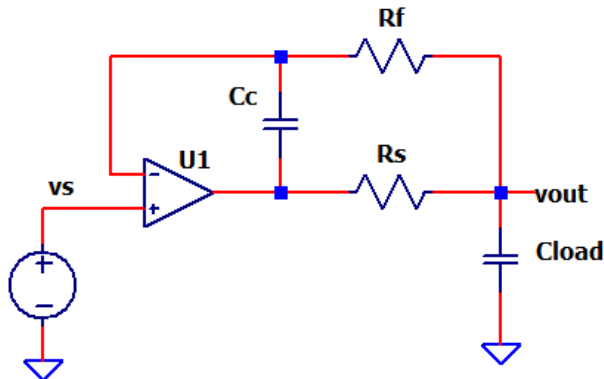
Adjust RV1 for max 1V Square wave.

How much overshoot appears at Vout?

How long Vout take to settle to within +/-0.1V of the final value?

PART 2 - The Overshoot Solution

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



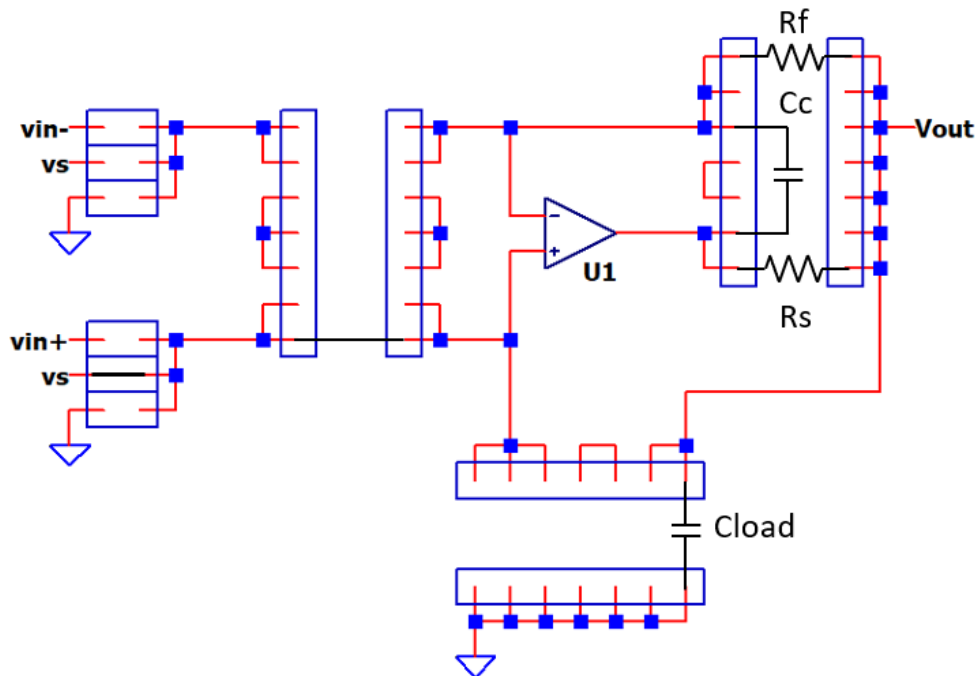
Can we reduce the large overshoot when driving a 1uF capacitive load?

2. **Design It** – Calculate component values, signal levels.

Choose $R_s = 100 \text{ ohms}$
 Choose $R_f = R_s \cdot 100$
 $= 10\text{k}$

Solution by experiment!
 Adjust CC incrementally: 100pF, 1nF, etc. until the overshoot reduces to an acceptable level.

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
 Connect Probe 1 to VS (Jumper at U1.in+).
 Connect Probe 2 to Vout (Rf at Vout)

Adjust RV1 for max 1V Square wave.
 Install CC = 100pF

How much overshoot appears at Vout?
 Any overshoot reduction over Part 1?

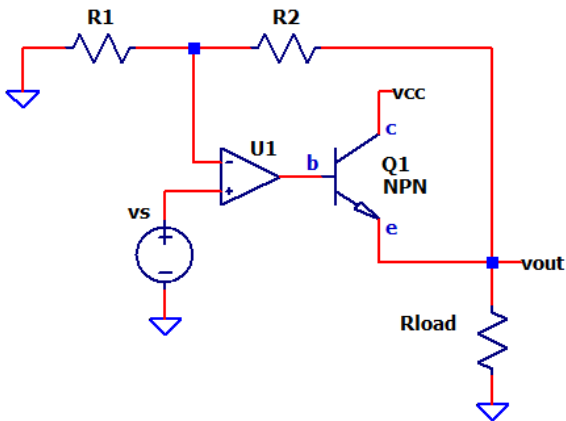
Install $C_c = 1\text{nF}$, then try 10nF.

What value of C_c reduces overshoot without sacrificing too much settling time?

4.12 BJT Regulator

Application Example: Generate a low-voltage supply for motors and relays in a Remote Controlled (RC) car.

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



How can a BJT increase the output current drive of an op amp?

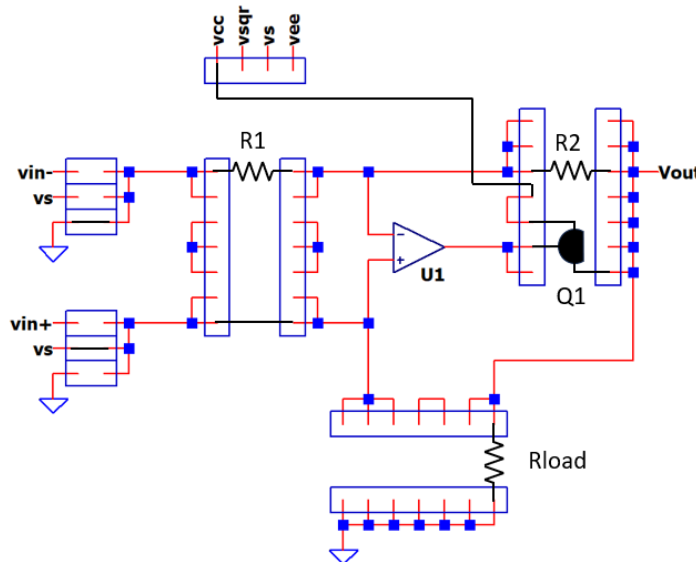
$$K = V_{out}/V_s = R_2/R_1 + 1$$

2. **Design It** – Calculate component values, signal levels.

Choose $V_s = 0.75V$, $R_1 = 10k$, $K = 2$
 $R_{load} = 1k$

$$\text{Calc } R_2 = (K-1) \cdot R_1 \\ = 10k$$

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
 Connect Probe 1 to V_s (Jumper).
 Connect Probe 2 to V_{out} (R_2 at V_{out}).

Move Probe 2 to (Q1.base).
 How much voltage does the op amp need to apply to the base to achieve V_{out} ?

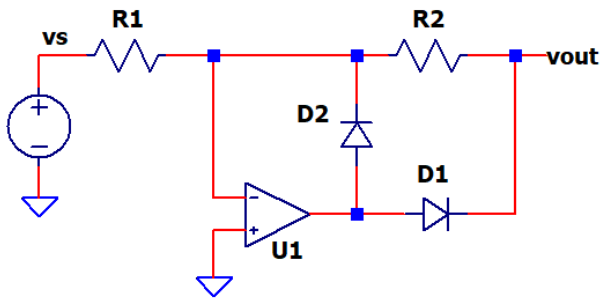
Adjust RV1 for $V_s = 0.75V$ max
 How much current is flowing into R_{load} ?

Reduce R_{load} to 100 ohms (increase load).
 Does V_{out} hold at 1.5V?
 How much voltage at Q1 base is needed now?

4.13 Half-Wave Rectifier

Application Example: Measure an Audio Level by rectifying the AC signal (before passing it to a LP filter).

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



Let's pass the positive polarity of a bipolar square wave!

$$K = V_{out} / V_s = -R_2 / R_1 = -2$$

$$V_s = +/-0.5V$$

2. **Design It** – Calculate component values, signal levels.

Choose $R_1 = 10k$,
Calc $R_2 = -K * R_1 = 20k$

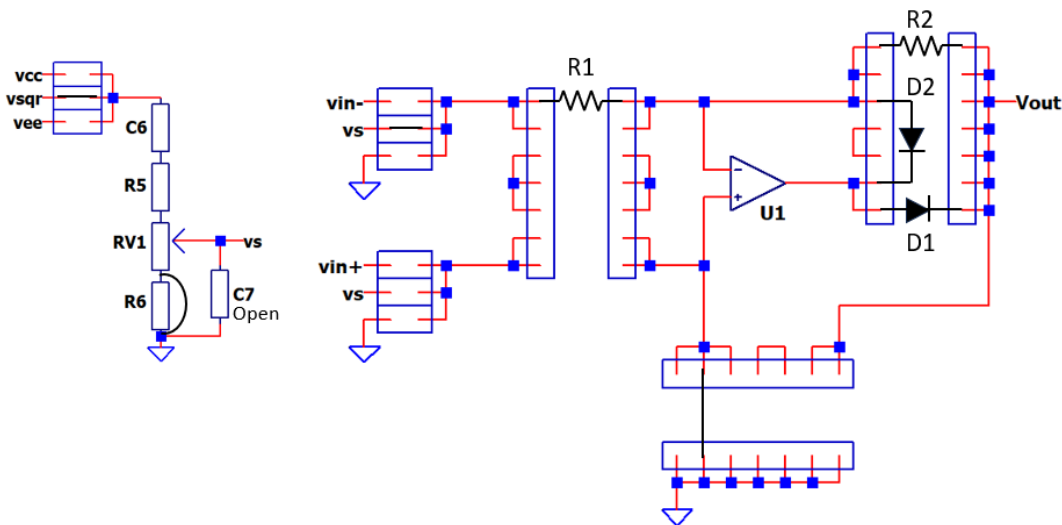
$$V_{out} = V_s * K$$

$$= -0.5V * -2$$

$$= +1V$$

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)

$C_6 = 0.1\mu F$
 $R_5 = 3.3k$
 $RV_1 = 1k$
 $R_6 = \text{short}$
 $C_7 = \text{open}$



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
Connect Probe 1 to VS (R1 at Vs side)
Connect Probe 2 to VOUT (R2 at Vout side).
Adjust RV1 for $V_s = +/-0.5V$ (Square Wave)

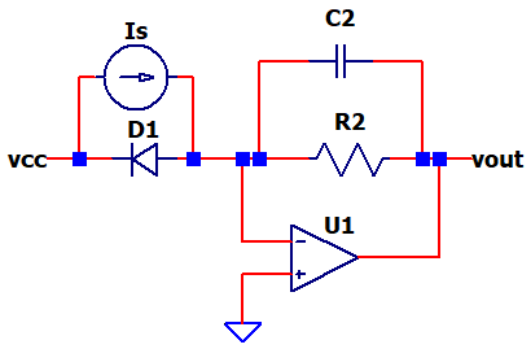
Which cycles does the recitifier pass?

What happens if you reverse both diodes D1 and D2?

4.14 I-to-V Converter (Photodiode)

Application Example: Measure the light intensity received as part of a Blood Oximeter instrument.

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



How can the photodiode current be converted to a voltage?

$$V_o = I_s * -R_2$$

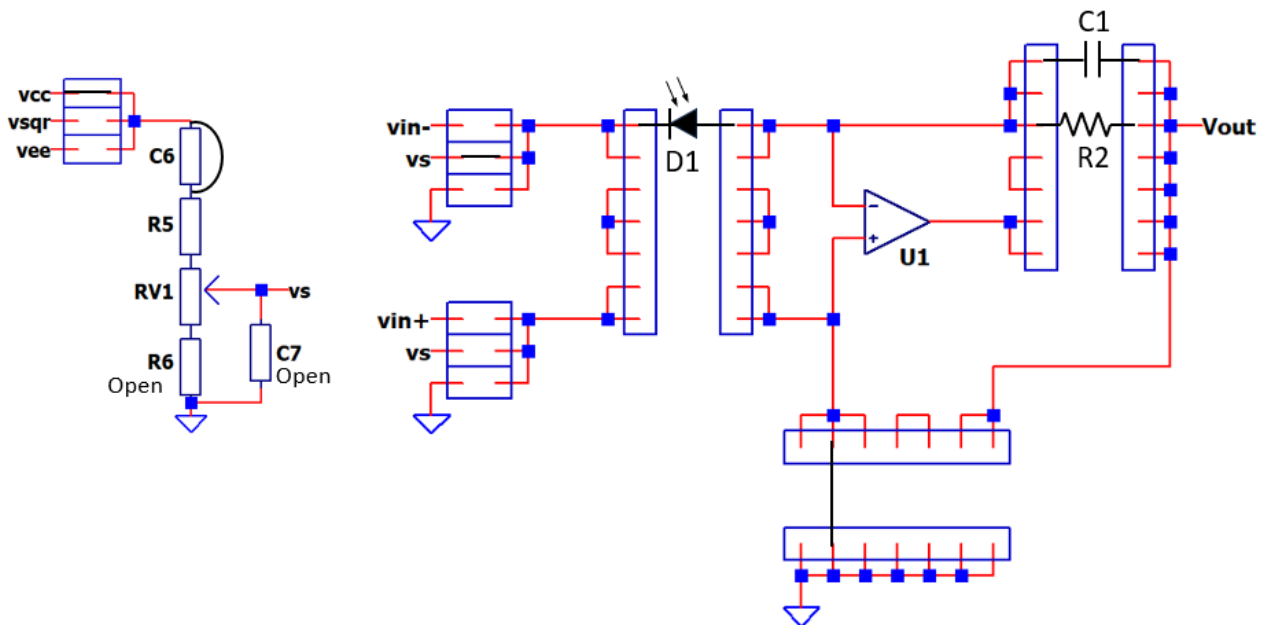
Photodiode: Vishay BV23F

2. **Design It** – Calculate component values, signal levels.

Choose $R_2 = 470k$

Ambient light level varies greatly.

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
Connect Probe 1 to Vout (R2 at Vout side)

Does Vs provide +5V reverse bias to the photodiode?

Where is Vout in ambient light?

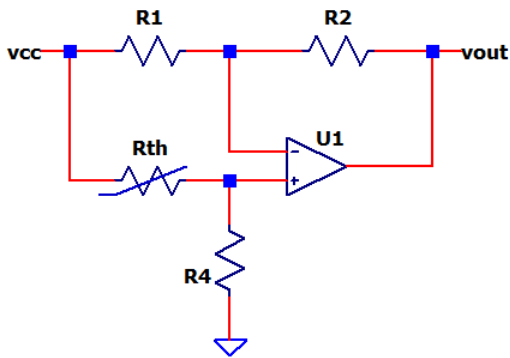
How much current is flowing out of the photodiode?

What happens when you cover the photodiode with your finger?

4.15 Thermistor Preamp

Application Example: Measure the air in-take temperature for an automotive fuel / air mixture control system.

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.



What is the voltage change at Vout versus a temperature change?

$$V_{out} = V_{cc} * R_S / (R_{th} + R_S) * (R_2 / R_1 + 1) + V_{cc} * (-R_2 / R_1)$$

2. **Design It** – Calculate component values, signal levels.

Choose $R_{th} = 10k @ 25C$
Sensitivity: $\Delta R_{th} / \Delta T = -4\% \text{ per } C$

Choose $R_S = R_1 = R_2 = 10k$

Calc Vout with $R_{th} = 10k @ 25C$
 $V_{out} = 5 * (1/2) * (+2) + 5 * (-1)$
 $= 0V$

Calc Vout with $R_{th} = 9.96k @ 26C$
 $V_{out} = 5 * (0.501) * (+2) + 5 * (-1)$
 $= +0.1V$

$$\Delta V_{out} / \Delta T = +0.1V / \text{deg } C$$

3. **Build It** - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)

4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

Power up the circuit (connect 9V Battery).
Connect Probe 2 to Vout (Jumper).

What is Vout in free air?

Room Temp: Test Thermistor in free air. (77F or 25C)

What is Vout with sensor at an elevated temperature

Elevated Temp Test: Hold thermistor between thumb and index finger. (90F or 32C)

Did ΔV_{out} approximate the temp change by 0.1V/deg C?

Temp rise: $\Delta T = 32 - 25 = 7 \text{ deg } C$.

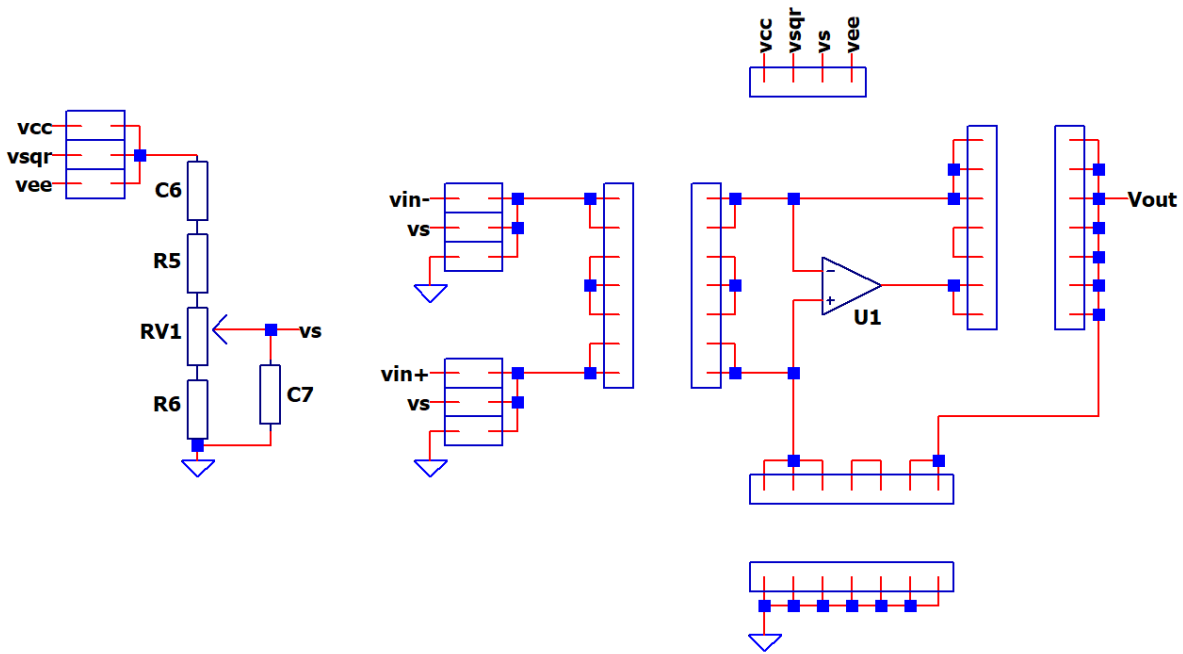
Voltage rise: $\Delta V_{out} = 7 \text{ deg } C * 0.1V/C = 0.7V$

5 Discovery Sheets - Circuit:

1. **Define It** – Draw Schematic, choose gains, signal levels, etc.

2. **Design It** – Calculate component values, signal levels.

Build It - Find a way to create it (sketch circuit below, install parts on Discovery Bd.)



4. **Test & Learn It** – Plan setup, make measurements, verify levels, observe, connect to theory.

6 Op Amp Learning with a DMM Only

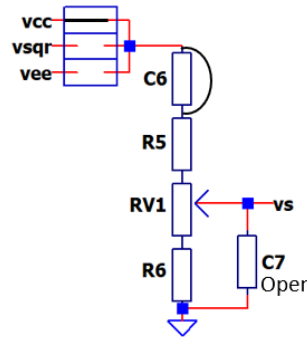
Learn and explore op amps with only budget Digital Multi-Meter (DMM)!

- Multimeters available for \$10 and up.
- Use manual ranging to observe voltage changing.



Select a DC signal for the input to VS.

- Remove JP1 for Square Wave
- Install JP2 for VCC (+5V)
or JP3 for VEE (-5V)
- Install short across C6 for DC coupling.

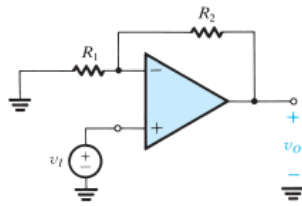


Explore 10+ topologies with just a DMM.

<i>Op Amp Topology</i>	<i>Comment</i>
Non-Inverting Amplifier Inverting Amplifier Summing Amplifier Differential Amplifier Unity-Gain Buffer	Select VCC or VEE as DC source. Vary the input with RV1. Observe Vout with a Volt Meter Function.
V-to-I Converter (LED Drive)	RV1 controls brightness
Wien-Bridge Oscillator RC Bridge Oscillator	Design for low frequency 1 to 5 Hz. Watch LEDs (D1,D2) flash.
Thermistor Preamp	Touch temp sensor, observe Vout change.
I-to-V Converter (Photodiode)	Cover light sensor, observe Vout change.
BJT Regulator	Vary Rload, check Vout stability.

7 The Power of Play

- Key to analog success:
play, play, play with circuits!



- Analog circuits appear more inviting (less intimidating) when playing / tinkering.
- Learning and passion grow when you
 - Ask “what if” questions
 - Play with component values
Predict outcome!
 - Get energized with small discoveries and learning.

