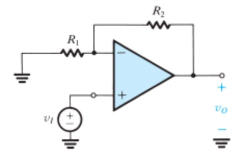
eCircuit Center

Op Amp Discovery

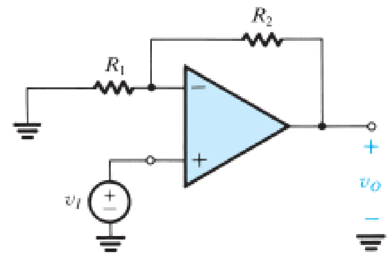


Circuit Examples for Guided Learning

Contents

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.*

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.*

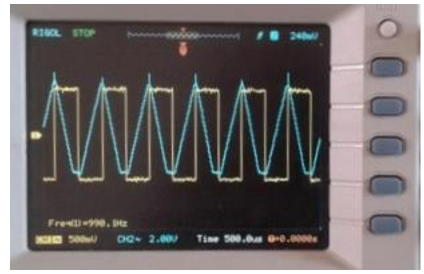
3. Build It *- Find a way to create it (sketch circuit, install parts on Discovery Bd.)*

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.

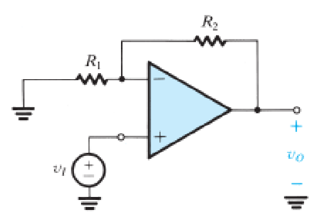
- Oscilloscope
  - *Observing waveforms provides key insight into how circuits work.*
  - Suggested: 2 channels with >1MHz Bandwidth.
  - Budget Scopes (hand-held or USB type) are available from $40 to $100.



- DMM
  - A *low-budget alternatve 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 & 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*.

4 Op Amp Circuit Collection

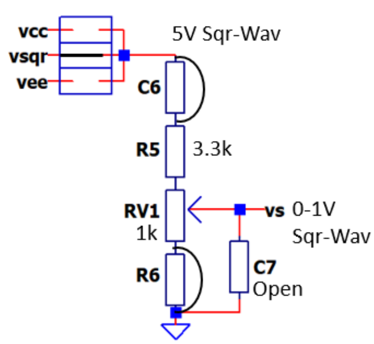


Use the guided examples any way you like!

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

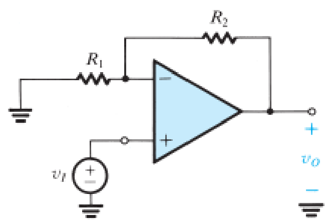
Default Signal Source

- *DC Coupled, Square-Wave, 5kHz*
- *Trimpot adjusts Vs 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

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



Let's amplify a signal by K = +3.

K = Vout/Vs = R1/R2+1 = 3

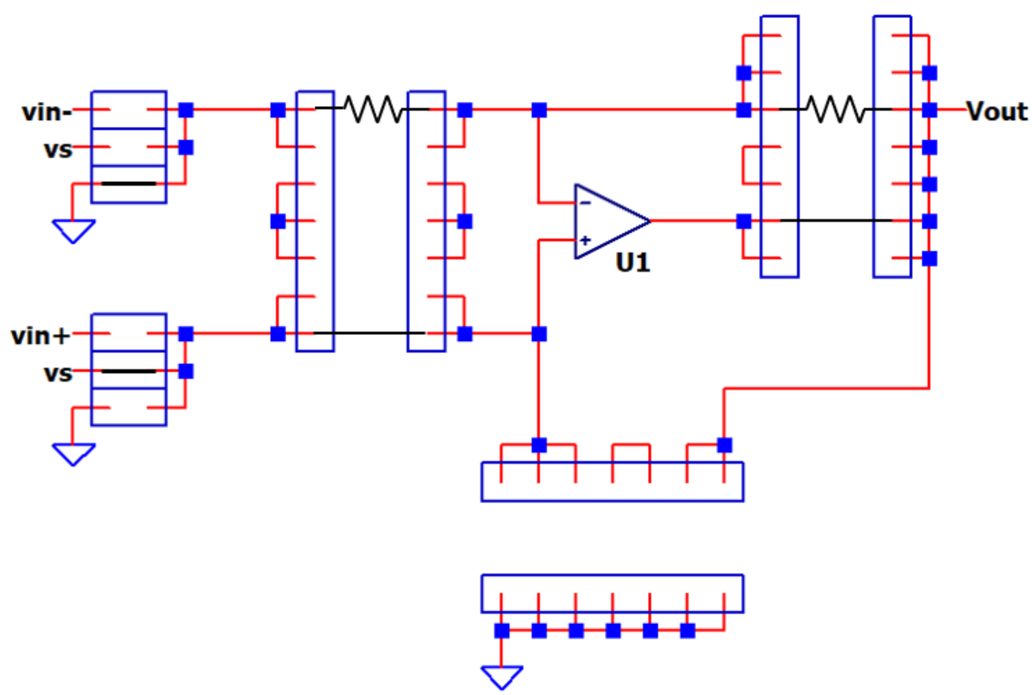
Choose Vs = 0.5V

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

Choose R1 = 10k,
Calc R2 = (K-1) * R1 = 20k

Vout = Vs*K
= 0.5V*3
= 1.5V

***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 (Jumper at J3,4).
Connect Probe 2 to VOUT (R2 at Vout side).

Verify a unipolar square wave at VS.

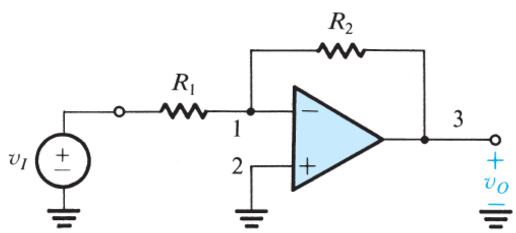
Adjust RV1 for VS = 0.5V peak.
Did Vout achieve the goal?

Move Probe 2 to U1's negative input (R1 at U1 side).
Does U1.in- follow VS?

What happens if you double R1 or R2?

4.2 Inverting Amplifier

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



Let't amplify a signal by -2.

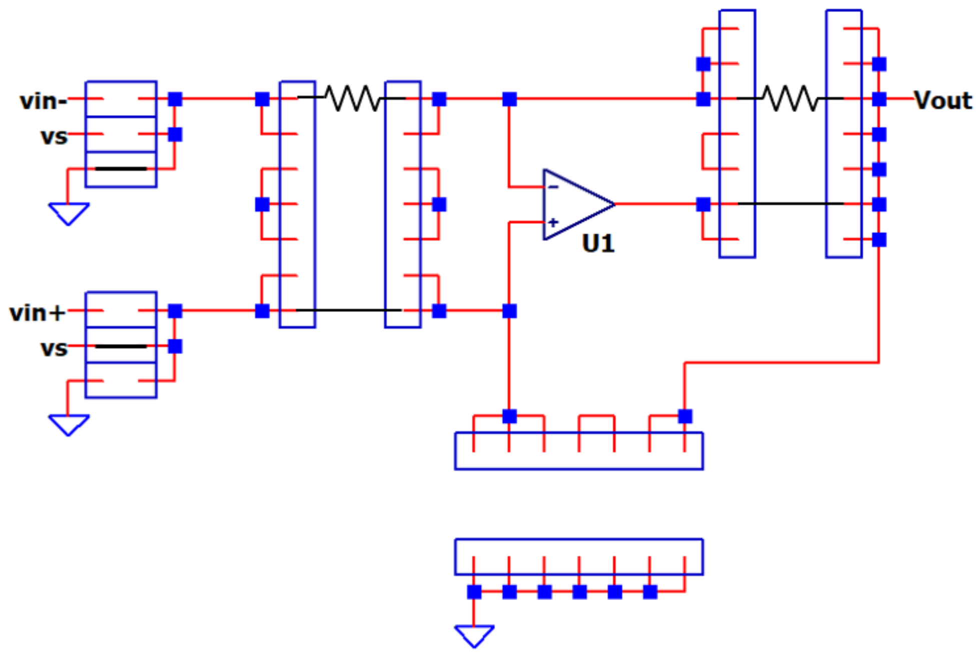
Vs = +1V
K = Vout/Vs = -R2/R1 = 2

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

Choose R1 = 10k,
Calc R2 = K * R1 = 20k

Vout = Vs*K
= 1V*-2
= -2V

***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.

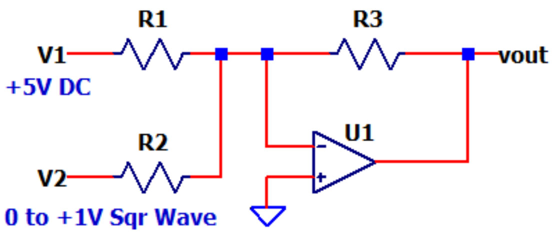
Adjust RV1 for Vs = 1V peak.
Did Vout achieve the goal?

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

What happens if you double R1 or R2?

4.3 Summing Amplifier

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



What happens when a DC signal (Vcc) is summed with a Square Wave (VS)?

V1 = Vcc = +5VDC
K1 = Vout / Vcc = -R3/R1 = -1/10

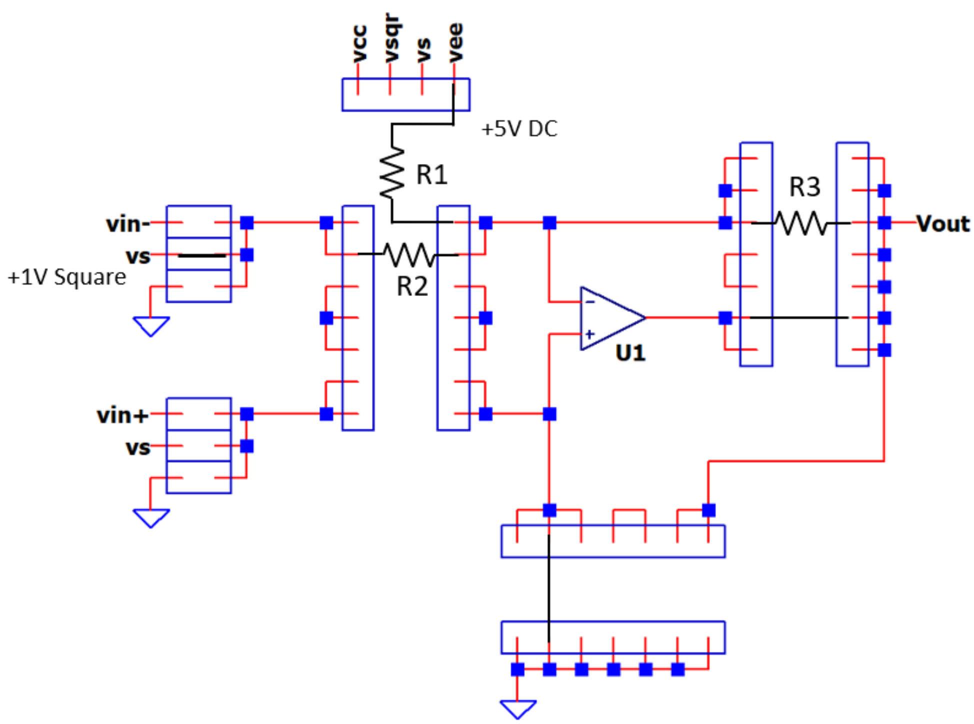
V2 = Vsqr = 0 to +1V (Sqr Wave)
K2 = Vout / Vsqr = -R3/R2 = -1

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

Choose R3 = 10k
Calc R2 = R3 / -K1 = 100k
Calc R1 = R3 / -K2 = 10k

Vout = Vcc*K1 + Vsqr*K2
= Vcc*-0.1 + Vsqr*(-1)
= -0.5 DC level + (0 to -0.5V) Sqr wave
Note: RV1 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.*

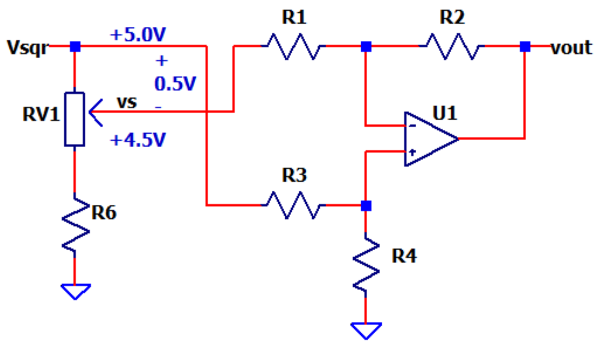
Power up the circuit (connect 9V Battery).
Connect Probe 1 to VS (R1 at VS side).
Connect Probe 2 to VOUT (R3 at Vout side).

Adjust RV1 for VS=0V peak.
Slowly adjust RV1 for VS=1V peak.
Does the Square Wave get summed with Vout?

What if R2 were halved or doubled?

4.4 Differential Amplifier

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



Can the amp sense the difference between Vsqr = 5V and Vs = 4.5V?

Vin+ = Vsqr = +5V
Vin- = Vs = 4.5V
Vin = (Vsqr - Vs) = 0.5V

K = Vout / Vin = R2/R1 = 1

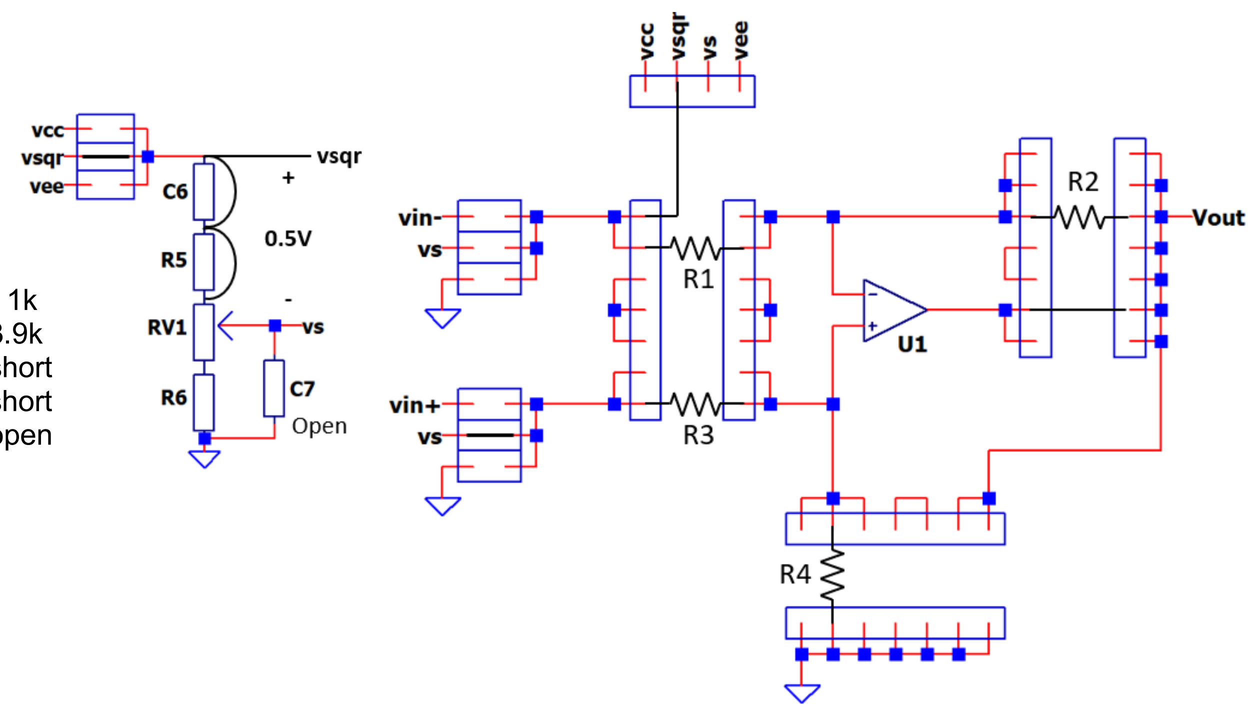
***2. Design It** – Calculate component values and signal levels.*

Choose R1 = R3 = 10k
Calc R2 = R4 = R1*K = 10k

Vout = (Vin+ - Vin-) * K
= 0.5V * 1
= 0.5V

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

RV1 = 1k
R6 = 3.9k
R5 = short
C6 = short
C7 = open



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

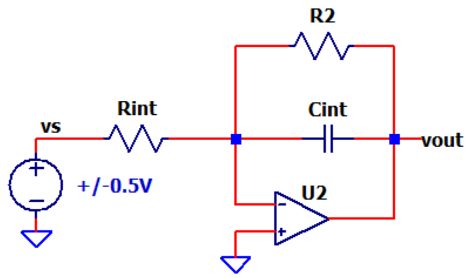
Power up the circuit (connect 9V Battery).
Connect Probe 1 to VS (R3 at Vs side).
Connect Probe 2 to VOUT (R2 at Vout side).

Adjust RV1 for Vs = +4.5V.
Vsqr should be +5V.
Does Vout achieve its goal?

What happens if you halve or double R2 and R4?

4.5 Integrator

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



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

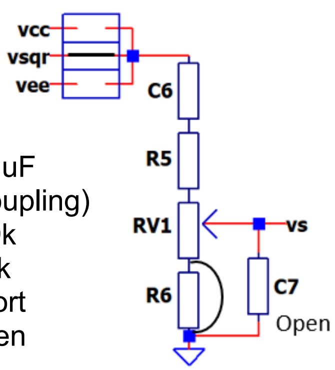
Vs = +/-0.25V (Sqr Wave AC coupled)
dT = 100us (Square wave half-cycle)

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

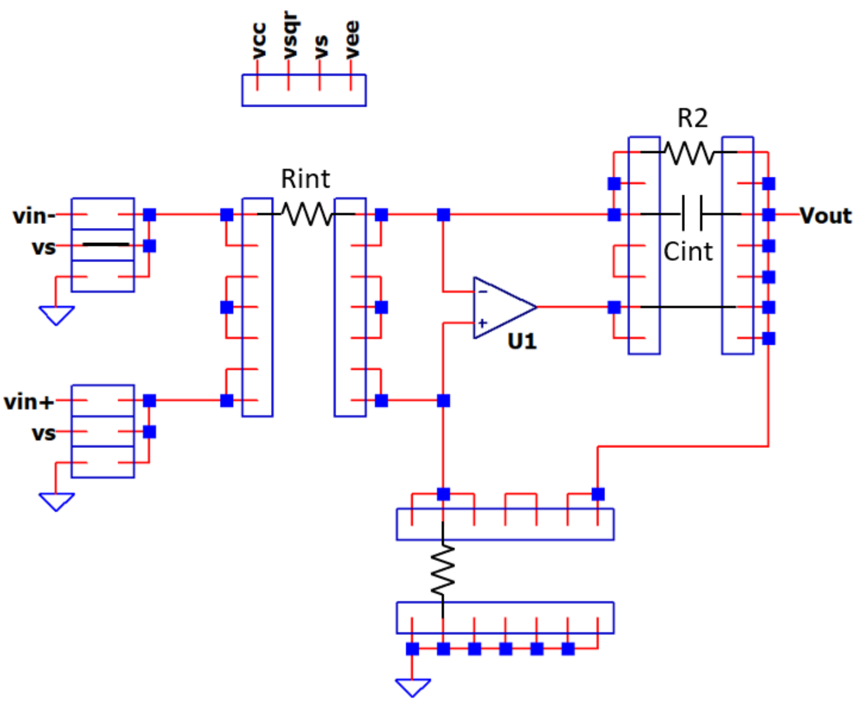
Choose Rint = 100k, Cint = 100pF
Choose R2 = 4.7M
(R2 makes finite DC gain, keeps offset low.)

dVout = Vs/(Rint*Cint)*dT
= 2.5V
Vout = +/-1.25V

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



C6 = 0.1uF
(AC Coupling)
R5 = 3.9k
RV1 = 1k
R6 = short
C7 = open



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

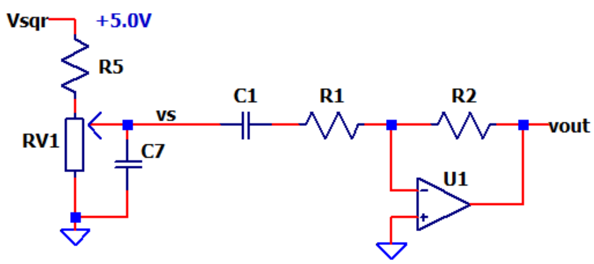
Power up the circuit (connect 9V Battery).
Connect Probe 1 to VS (Rint at Vs side).
Connect Probe 2 to VOUT (Cint at Vout side).

Adjust RV1 for Vs = +/-0.5V
Does Vout ramp as expected?

What happens if you increase Rint or Cint?

4.6 Differentiator

***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

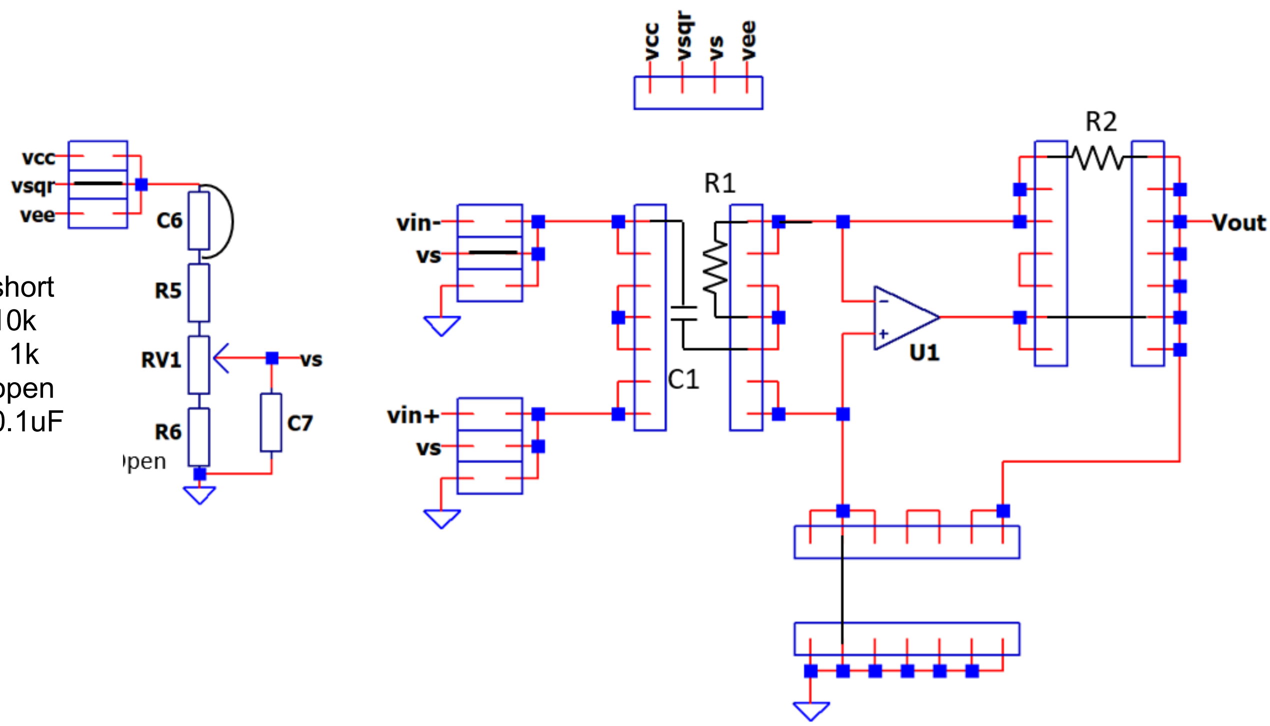
Choose C1 = 1nF, R2 = 100k
Choose R1 = 4.7k (keeps amp stable.)

Tau = R5*C7 = 0.001s
dV/dt = (Vsqr/2)/Tau = 2.5V/0.001s = 2500V/s

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.*

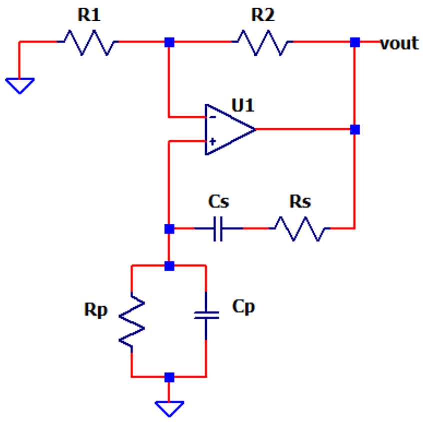
Power up the circuit (connect 9V Battery).
Connect Probe 1 to VS (C1 at Vs side).
Connect Probe 2 to VOUT (C2 at Vout side).

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

What happens if R2 increases?

4.7 Wien-Bridge Oscillator

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



Can you produce a Sine-Wave output with Tper = 300 us?

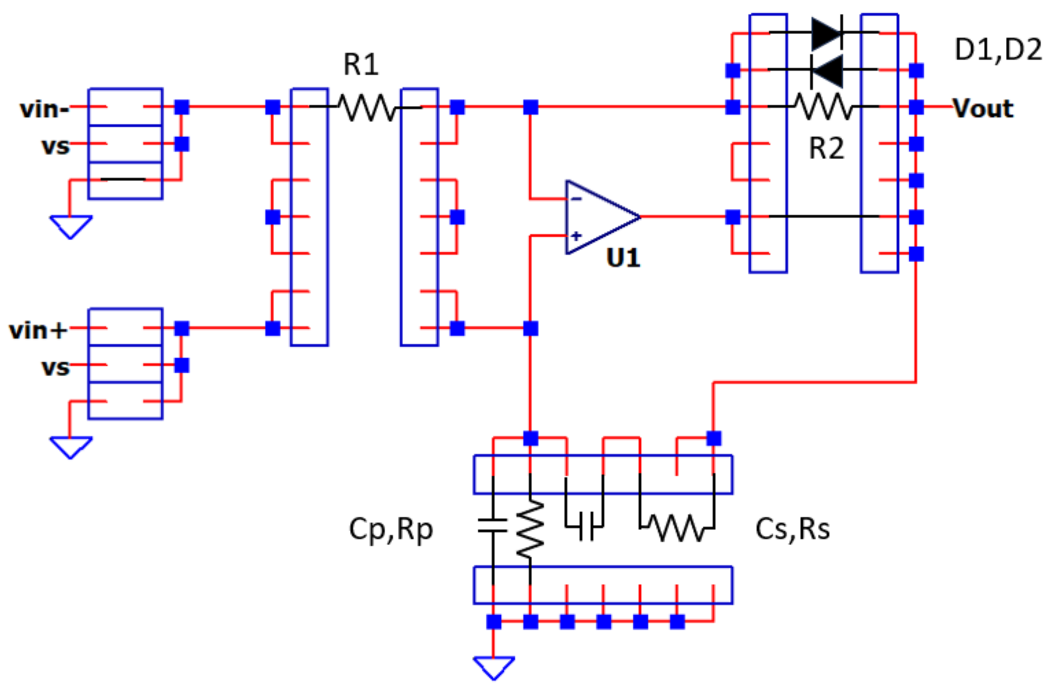
fo = 1/(2*pi*R*C)

***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, fo = 3.3 kHz
Calc R = 1/(2*pi*C*fo)
= 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.*

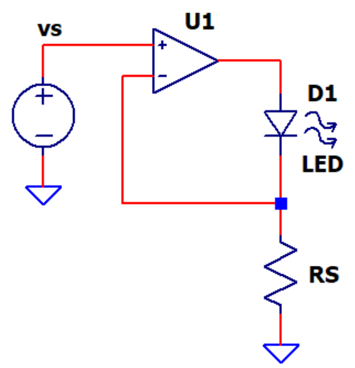
Power up the circuit (connect 9V Battery).
Connect Probe 1 to VOUT (C2 at Vout side).

Does Vout show the sinewave as designed?

How is Vout related to Vdiode?

4.8 V-to-I Converter (LED Drive)

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



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

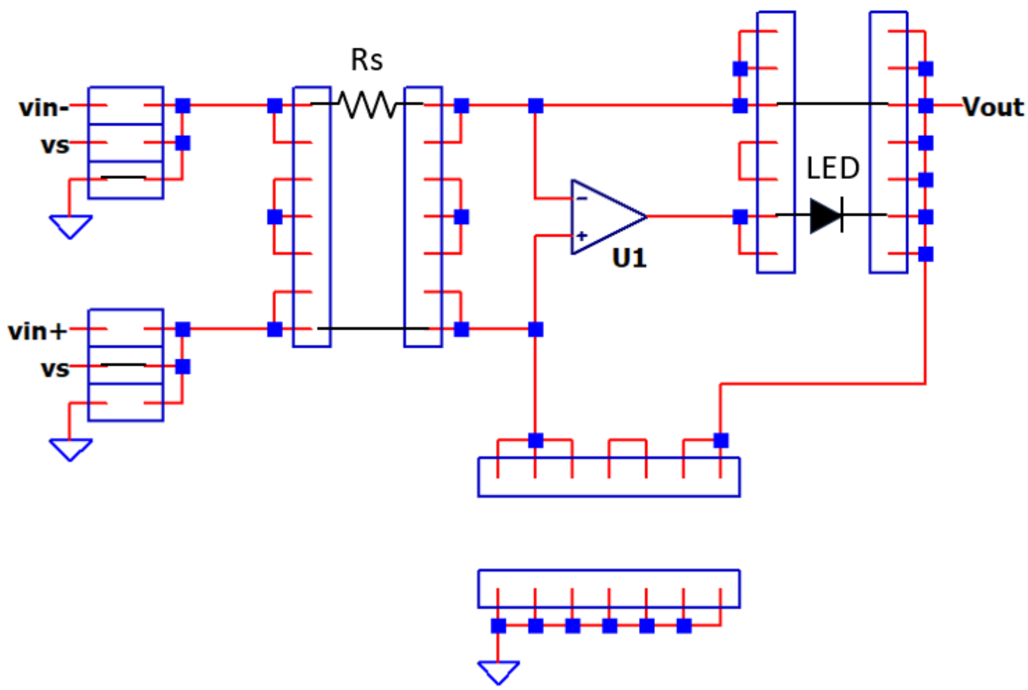
Io = Vs / Rs

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

Choose Io = 2mA at VS = 1V
Calc RS = VS / Io = 500 ohms
Choose 510 if available

Calc Io = 1V / 510
= 1.98 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).

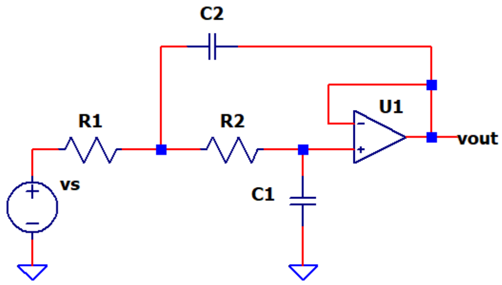
Adjust RV1 for VS = 1V max (Square Wave)
Does the RS voltage follow VS so that Io = VS/RS?

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

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

4.9 Sallen-Key Low-Pass Filter

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?

fc = 1 / (2*pi*R*C)

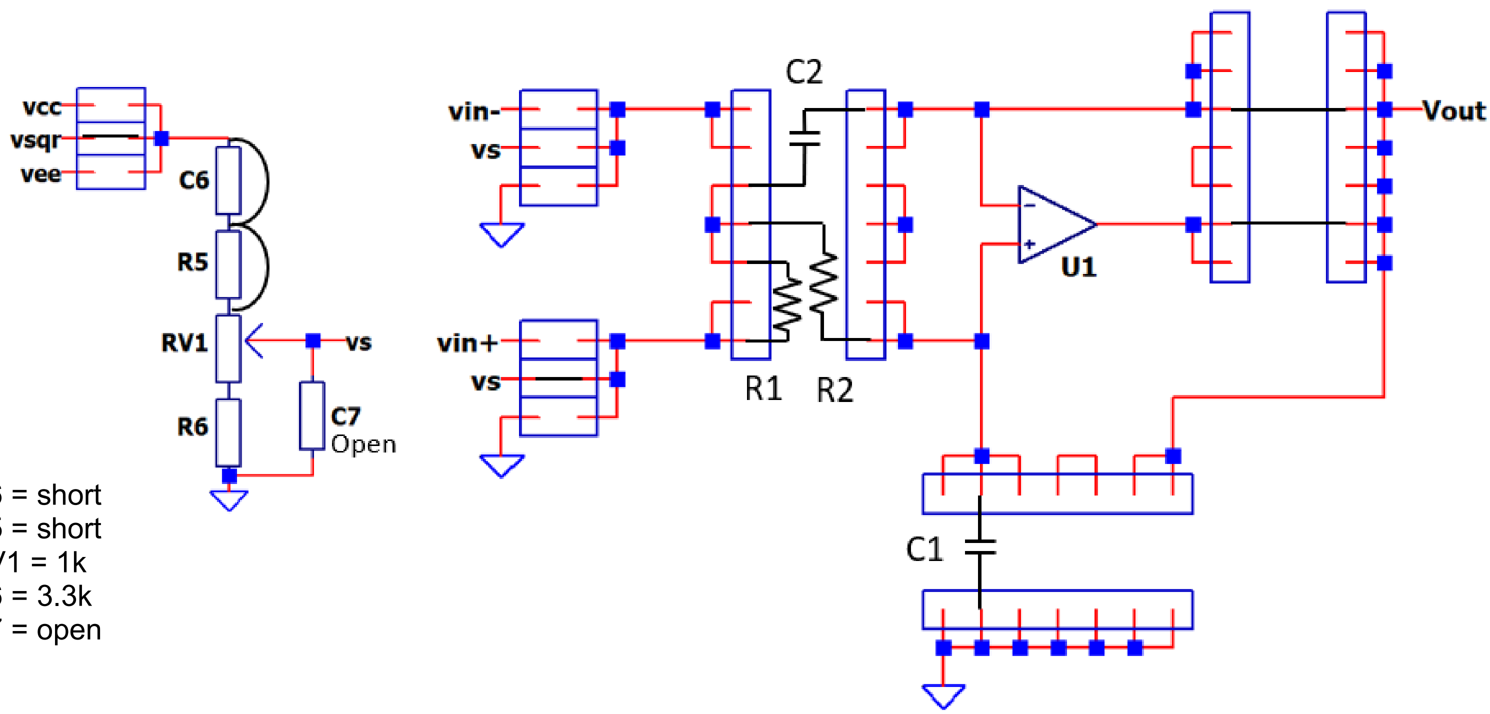
H ≈ (fc/fosc)^2

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

Choose fc = 333Hz and C1 = 10nF
Calc C1 = 1/(2*pi*10nF*333Hz) = 47.8k
Choose 47k
Calc H ≈ (fc/fosc)^2
≈ 0.0044

Calc expected output with
VS = 5V, fosc = 5k
Vout ≈ VS * (fc/fosc)^2
≈ 22 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).

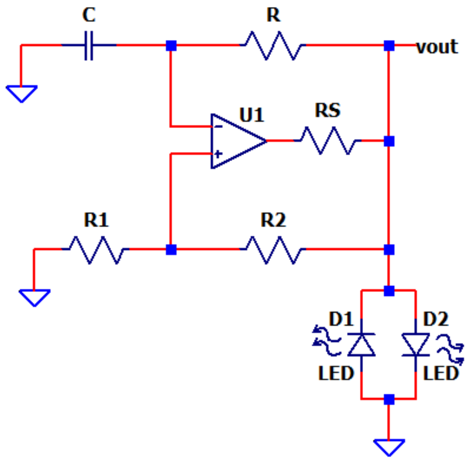
Adjust RV1 for max 5V Square wave.

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

What is the DC level at Vout and why?

4.10 RC Comparator Oscillator

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



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

fo = 1/(2*Ro*Co ln((1+B)/(1-B))

where B = R1/(R1+R2)

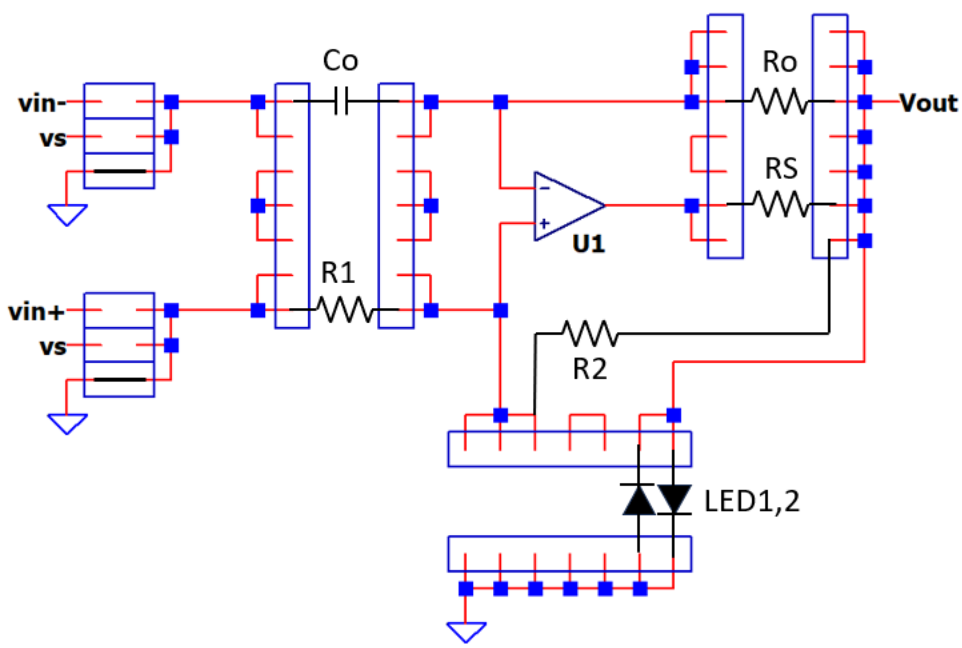
2. Design It *– Calculate component values, signal levels.*

Choose handy components
Ro = 100k, Co = 10nF
R1 = 10k, R2 =10k
RS = 1k, LED1,2 = pick two

Calc B = R1/(R1+R2) = 0.5

Calc osc frequency
fo = 1/(2*100k*10nF*ln((1+0.5)/(1-0.5)))
= 80 Hz

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).

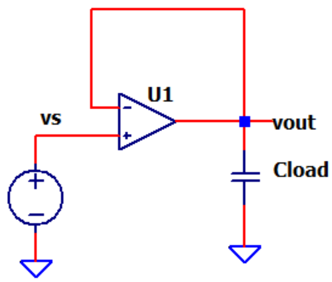
Does Vout show the sinewave as designed?

How is Vout related to Vdiode?

4.11 Driving a Capacitive Load

PART 1 - The Overshoot Problem

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

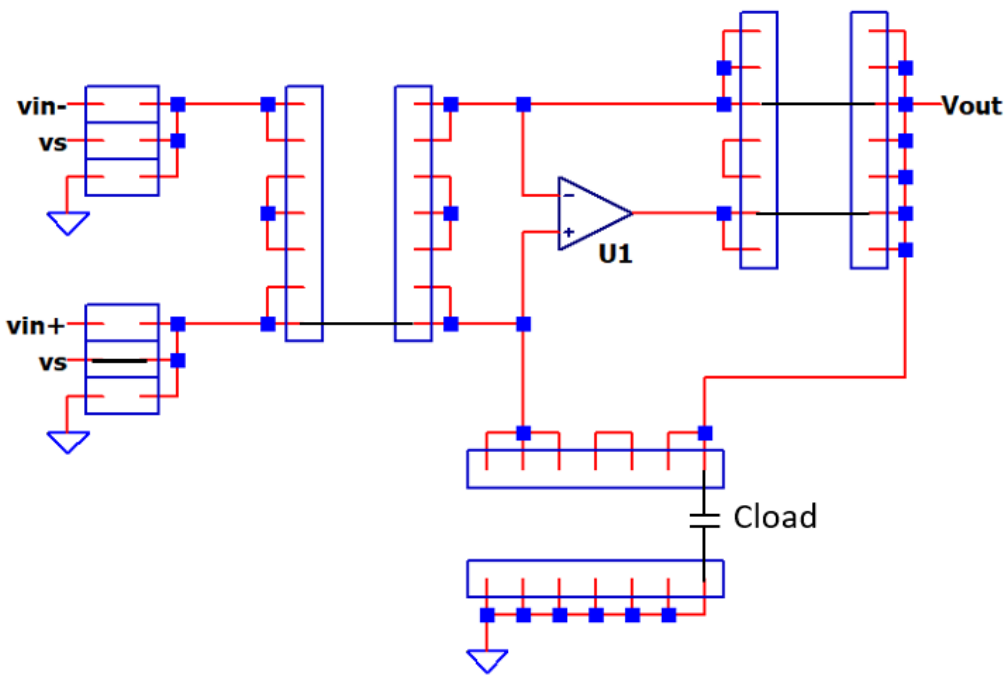


What is the overshoot when driving a 1uF capacitive load?

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

Choose Cload = 1uF or 0.1uF to observe the effects of a capcitive 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).

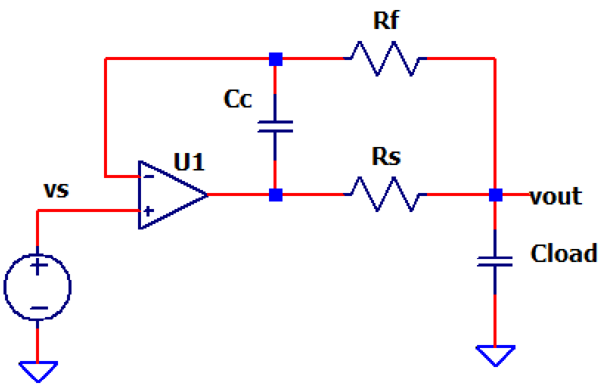
Adjust RV1 for max 1V Square wave.

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.*



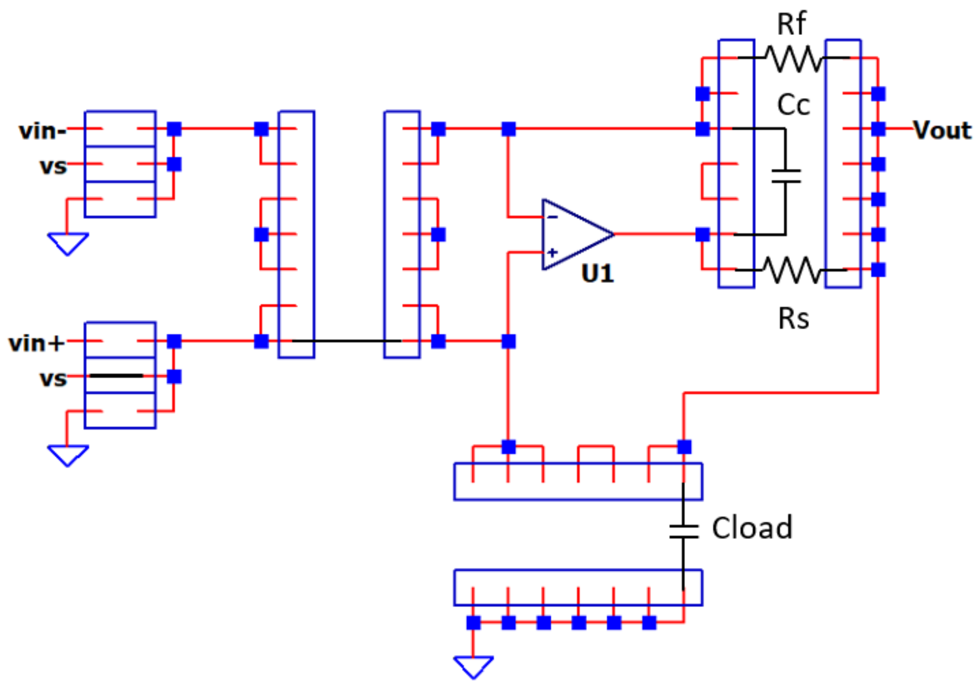
Can we reduce the large overshoot when driving a 1uF capacitive load?

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

Choose Rs = 100 ohms
Choose Rf = Rs*10
= 1k

Solution by experiment!
Bump up 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

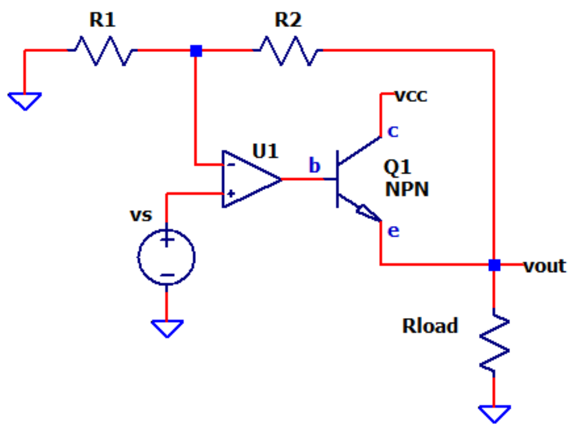
How much overshoot appears at Vout?
Any overshoot reduction over Part 1?

Install Cc = 1nF, then try 10nF.

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

4.12 BJT Regulator

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



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

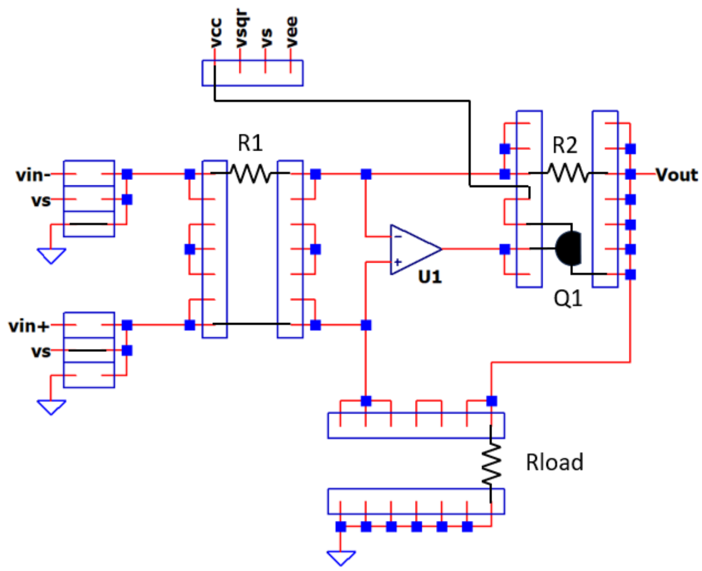
K = Vout/Vs = R2/R1+1

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

Choose Vs = 0.5V, R1 = 10k, K = 2
Rload = 1k

Calc R2 = (K-1)*R1
= 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 Vs (Jumper).
Connect Probe 2 to Vout (R2 at Vout).

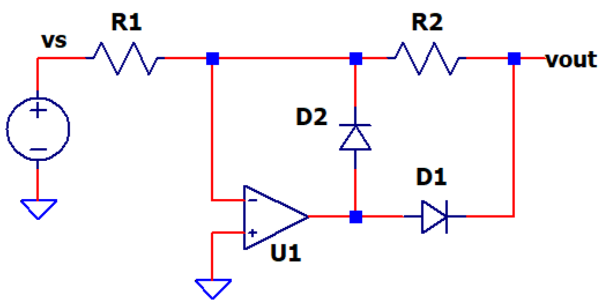
Adjust RV1 for VS = 1V max
How much current is flowing into Rload?

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

Reduce Rload to 100 ohms (increase Iload).
Does Vout hold at 1V?
How much voltage at Q1 base is needed now?

4.13 Half-Wave Rectifier

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



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

K = Vout / Vs = -R2 / R1 = -2
Vs = +/-0.5V

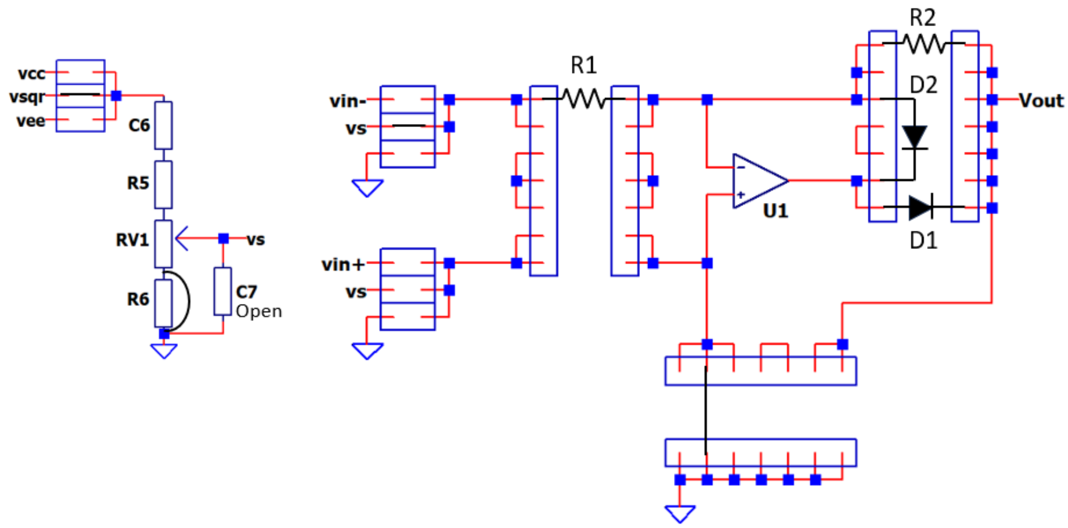
2. Design It *– Calculate component values, signal levels.*

Choose R1 = 10k,
Calc R2 = -K * R1 = 20k

Vout = Vs*K
= -0.5V*-2
= +1V

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

C6 = 0.1uF
R5 = 3.3k
RV1 = 1k
R6 = short
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 VS (R1 at Vs side)
Connect Probe 2 to VOUT (R2 at Vout side).

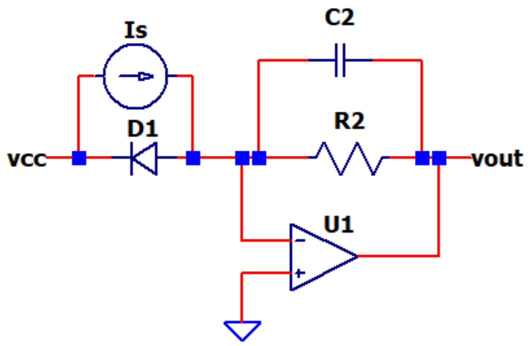
Adjust RV1 for Vs = +/-0.5V (Square Wave)

Which cycles does the recitifier pass?

What happens if you reverse both diodes D1 and D2?

4.14 I-to-V Converter (Photodiode)

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



How can the photodiode current be converted to a voltage?

Vo = Is * -R2

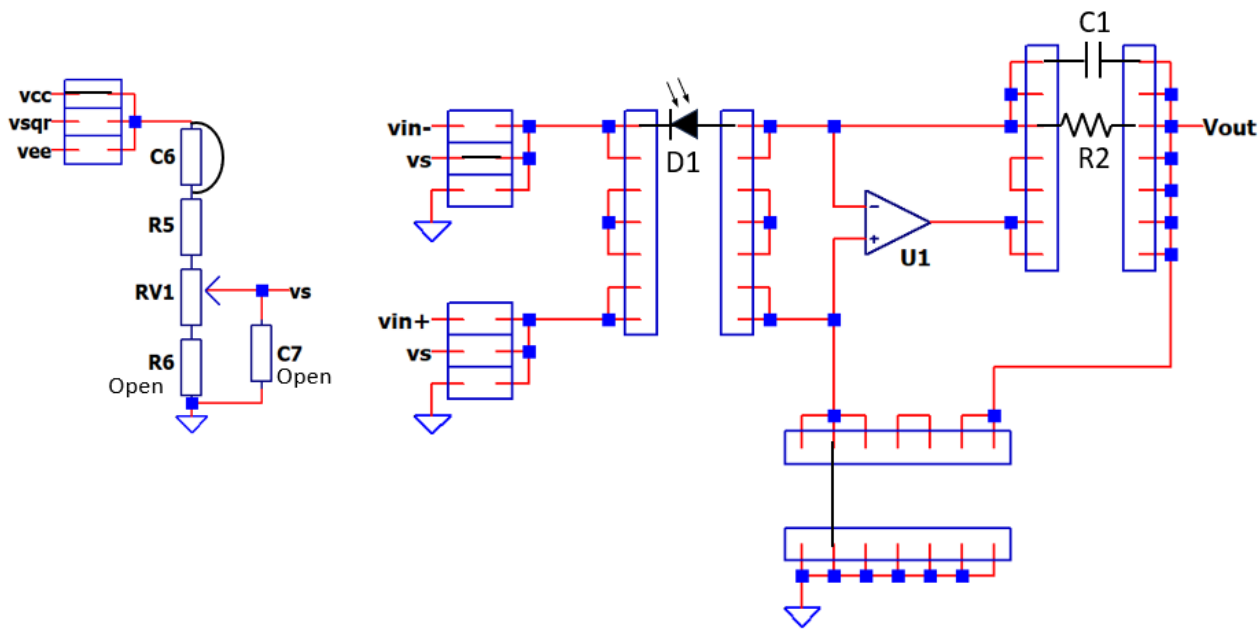
Photodiode: Vishay BV23F

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

Choose R2 = 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?

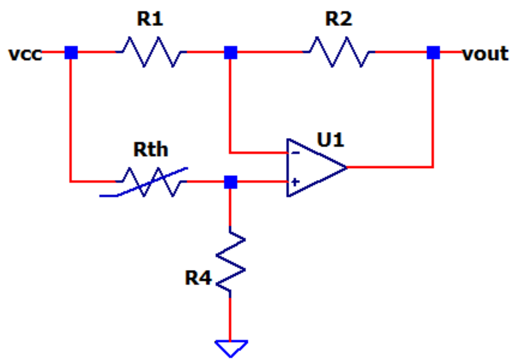
Where is Vout in ambient light?

How much current is flowing out of the photodiode?

What happens when you cover the photodiode with your finger?

4.15 Thermistor Preamp

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



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

Vout = Vcc * RS/(Rth+RS) * (R2/R1+1) +
Vcc*(-R2/R1)

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

Choose Rth = 10k @ 25C
Sensitivity: ΔRth / ΔdT = -4% per C

Choose RS = R1= R2 = 10k

Calc Vout with Rth = 10k @ 25C
Vout = 5 * (1/2) * (+2) + 5 *(-1)
= 0V

Calc Vout with Rth = 9.96k @ 26C
Vout = 5 * (0.501) * (+2) + 5 *(-1)
= +0.1V

ΔVout / ΔT = +0.1V / degC

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).

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

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

Temp rise: ΔT = 32 - 25 = 7 deg C.
Voltage rise: ΔVout = 7 deg C * 0.1V/C = 0.7V

What is Vout in free air?

What is Vout with sensor at an elevated temperature

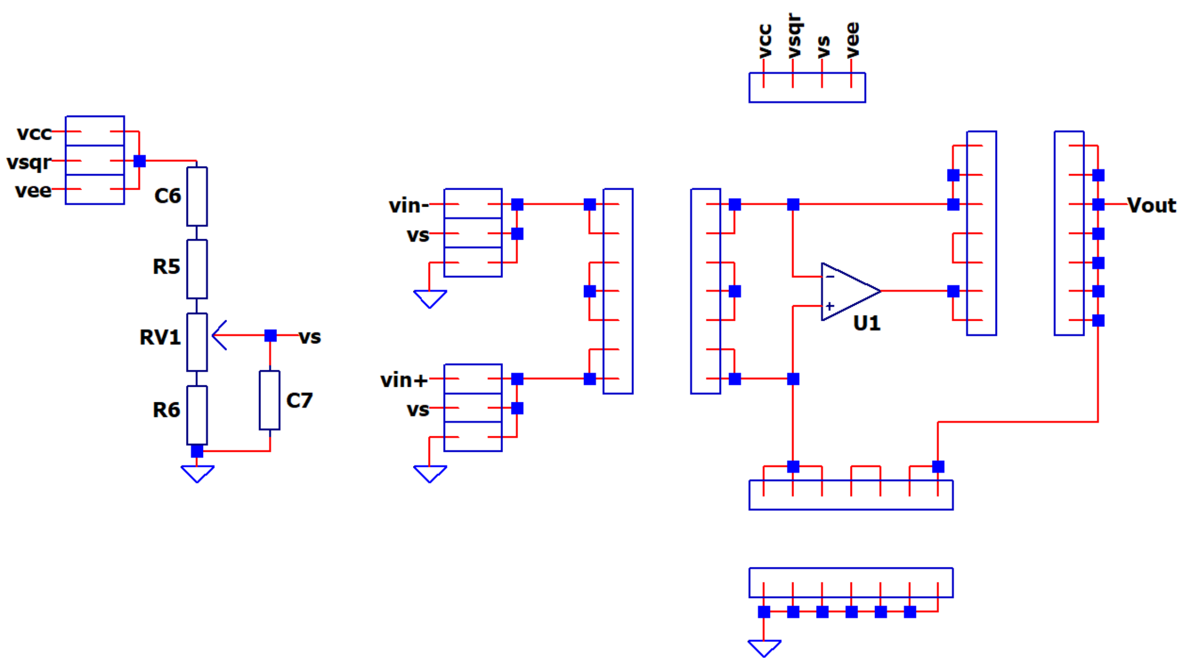
Did ΔVout approximate the temp change by 0.1V/deg C?

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.*

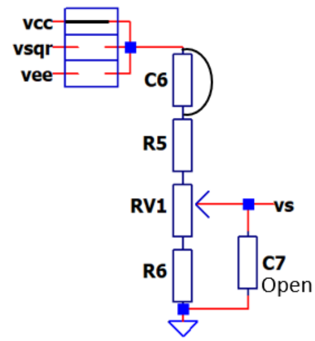
6 Op Amp Learning with a DMM Only

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.

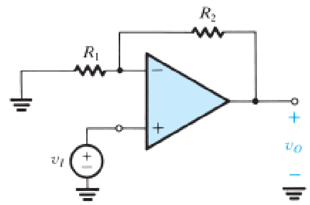


Explore 10+ topologies with just a DMM.

Op Amp Topology	Comment
Non-Inverting Amplfier 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.