Introductory Medical Device Prototyping

Analog Circuits Part 3 – Operational Amplifiers

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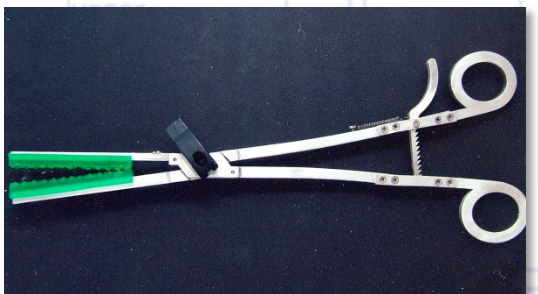
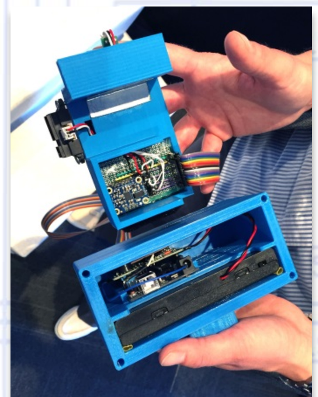
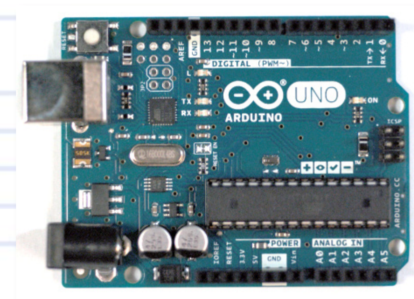
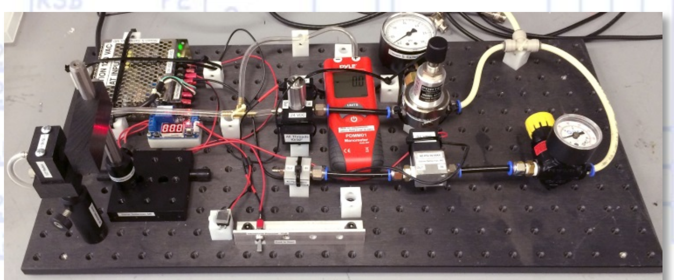
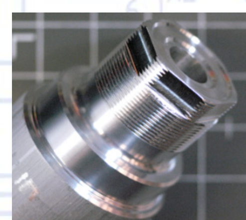






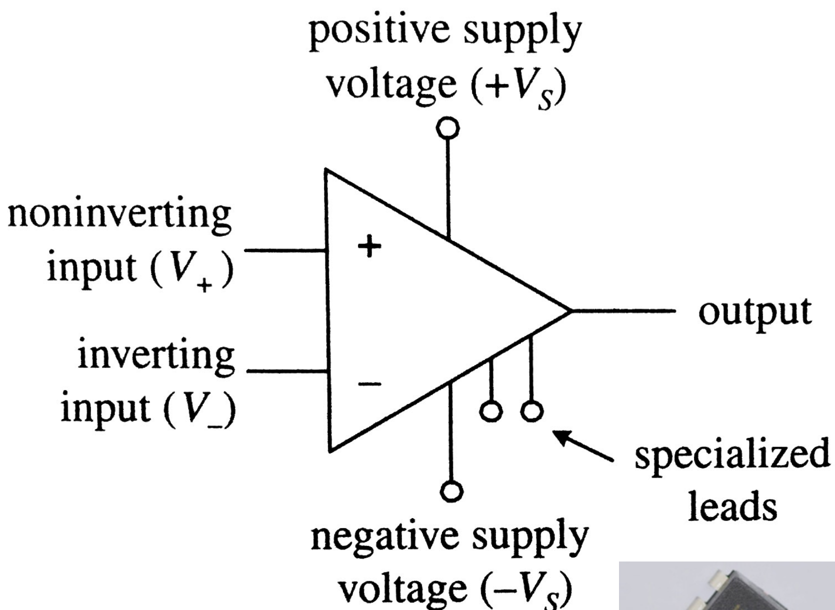


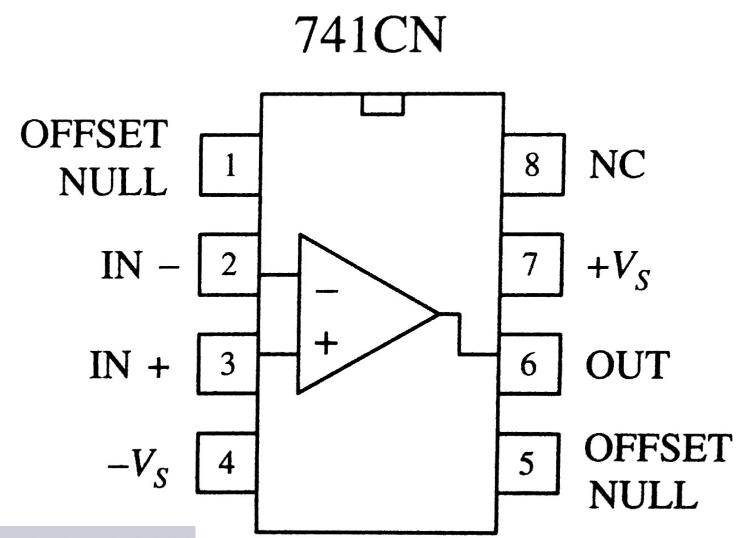


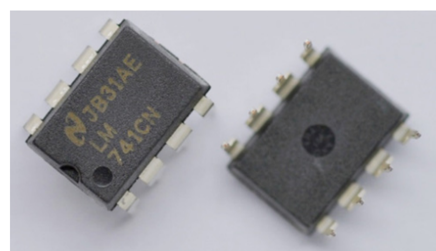
Concepts to be Reviewed

- Operational amplifiers.
  - Basics
  - Amplification
  - The 741 Op Amp
- LM555 timer
  - Monostable or “one shot”
  - Astable multivibrator (oscillator)
- Appendix - Applications
  - Transducers

Operational Amplifier





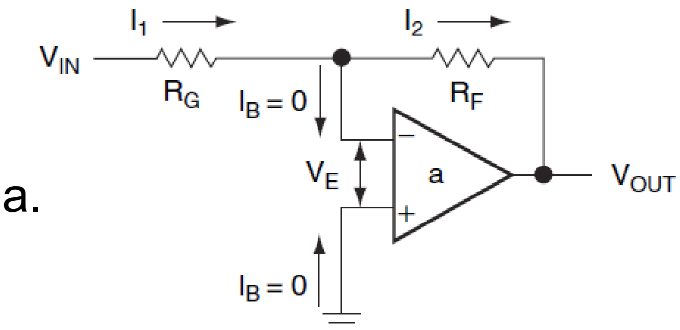


Scherz, P. and S. Monk, *Practical Electronics for Inventors*, McGraw Hill, New York (2016)

Op Amp Closed Loop Configurations

- A feedback loop allows for precise control of the voltage gain:
  - Inverting Op Amp
    - $V_{OUT} = -V_{IN}\frac{R_F}{R_G}$
    - $Voltage\ Gain = \frac{V_{out}}{V_{in}} = -\frac{R_F}{R_G}$
  - Non-Inverting Op Amp
    - $V_{OUT} = V_{IN}\frac{R_G+R_F}{R_G}$
    - $Voltage\ Gain = \frac{V_{out}}{V_{in}} = 1 + \frac{R_F}{R_G}$

a.



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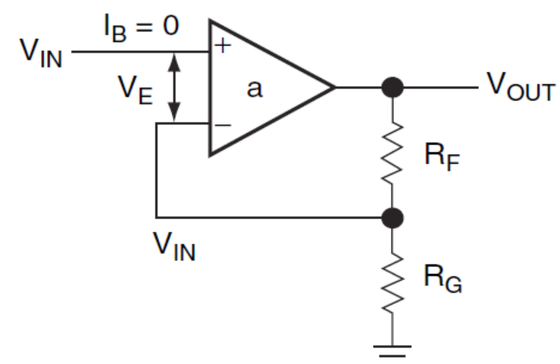
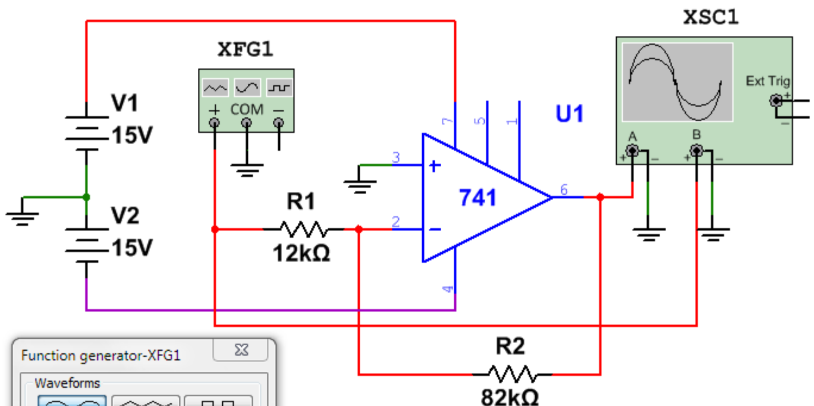
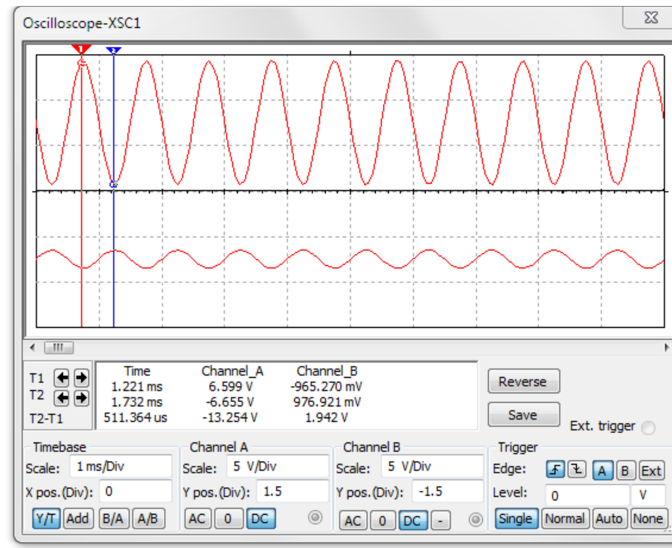
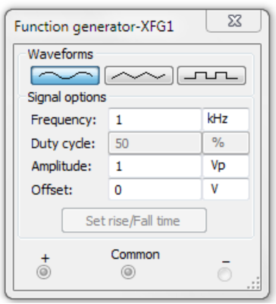


Carter, B. and R. Mancini, *Op Amps for Everyone*, Newnes & TI, Burlington, MA (2009)

Inverting Amplifier, Gain of 6.83



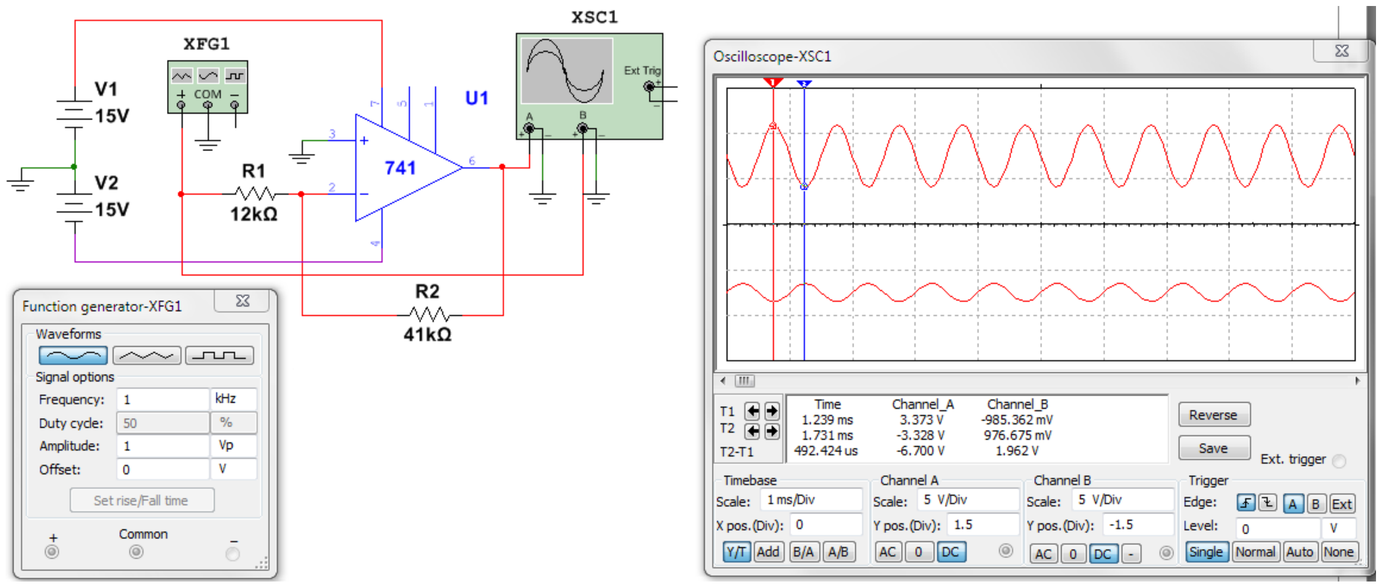




$$V_{out} = -V_{in}\left(\frac{R_2}{R_1}\right) = 2 \times \frac{82}{12} = -13.66\ V_{pp}\ \text{or}\ -6.83\ V_p$$

$$Voltage\ Gain = \frac{V_{out}}{V_{in}} = \frac{13.66}{2} = 6.83\ or\ -\frac{R_F}{R_{in}} = -\frac{82}{12} = -6.83$$

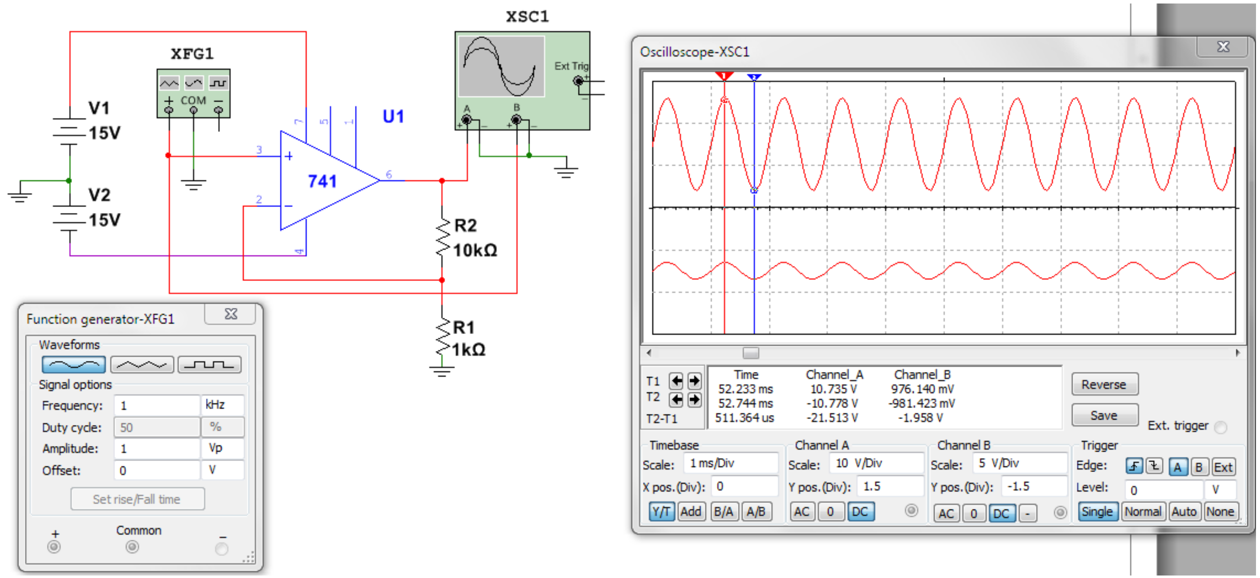
Changing R2 Changes Gain to 3.417…



$$V_{out} = -V_{in}\left(\frac{R_2}{R_1}\right) = 2 \times \frac{41}{12} = -6.83\ V_{pp} \text{ or } 3.42\ V_p$$

$$Voltage\ Gain = \frac{V_{out}}{V_{in}} = \frac{6.83}{2} = 3.42\ or\ -\frac{R_F}{R_{in}} = -\frac{41}{12} = -3.42$$

Non-Inverting Amplifier, Gain of 11



$$V_{out} = V_{in}\left(\frac{(R_1 + R_2)}{R_1}\right) = 2 \times \left(\frac{10+1}{1}\right) = 22\ V_{pp}\ or\ 11\ V_p$$

$$Voltage\ Gain = \frac{V_{out}}{V_{in}} = \frac{22}{2} = 11\ or\ 1 + \frac{R_2}{R_1} = 11$$

Op-Amp Parameters to Know!

1. **Z_{IN} (input impedance)**
   - This is the *resistive impedance* looking directly into the input terminals of the op-amp when used open-loop.
   - Typical values are 1MΩ for op-amps with bipolar input stages, and a million megohms for FET-input op-amps.
2. **Z_o (output impedance)**
   - This is the resistive impedance of the basic op-amp when used open-loop.
   - Values of a few hundred ohms are typical of most op-amps.
3. **I_b (input bias current)**
   - The input terminals of all *op-amps sink or source finite currents* when biased for linear operation.
   - The magnitude of this current is denoted by I_b, and is typically a fraction of a μA in bipolar op-amps, and a few pA in FET types.

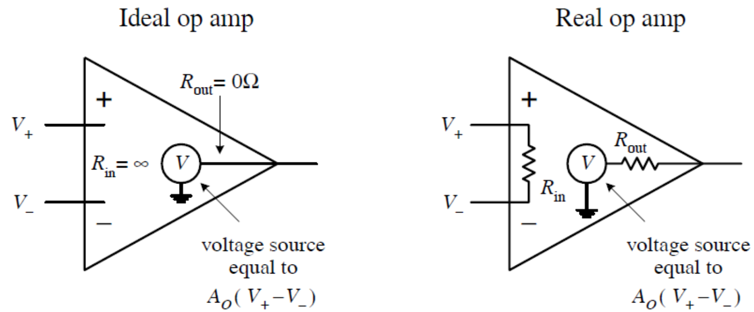
Marston, R., *Op-Amp Cookbook – Part 1*, Nuts & Volts Magazine, (July 2001)

Parameters Continued…

4. **A_o (open-loop voltage gain)**
   - *Voltage gain* occurring between the input and output terminals.
   - Typical figures are x100,000, or 100dB, where $dB = 20 \times log_{10}\left(\frac{V_{out}}{V_{in}}\right)$
5. **V_S (supply voltage range)**
   - Power supplies are typically *dual supplies with positive and negative voltages and a common,* but may also be single-ended. Typically ±3V to ±15V.
6. **$V_{i(max)}$ (input voltage range)**
   - $V_{i(max)}$ is *one or two volts less than V_S* – keep your inputs at or below.
7. **V_{io} (differential input offset voltage)**
   - *When both inputs are grounded the output should be ze*ro. In practice you need to null a slight differential input that appears as a significant gain through the op-amp.

Marston, R., *Op-Amp Cookbook – Part 1*, Nuts & Volts Magazine, (July 2001)

Ideal vs Real Op Amp…



- **Rule 1**
  - For an ideal op amp, the open-loop voltage gain is infinite ($A_o = \infty$).
  - For a real op amp, the gain is a finite value, typically between 10^4 to 10^6.
- **Rule 2**
  - For an ideal op amp, the input impedance is infinite ($R_{in} = \infty$).
  - For a real op amp, the input impedance is finite, typically 10^6 (typical bipolar op amp) to 10^{12} Ω (typical JFET op amp).
  - The output impedance for an ideal op amp is zero ($R_{out} = 0$).
  - For a real op amp, *R*out is typically 75 to 300 Ω.
- **Rule 3**
  - The input terminals of an ideal op amp draw no current.
  - Typically within a pA (typical JFET op amp) to nA range (typical bipolar op amp).

Scherz, P. and S. Monk, *Practical Electronics for Inventors*, McGraw Hill, New York (2016)

Parameters Continued…

8. **CMRR (common mode rejection ratio)**
   - An op-amp produces an output proportional to the difference between the signals on its two input terminals.
   - *Ideally, it should give zero output if identical signals are applied to both inputs simultaneously*, i.e., in common mode. In practice, such signals do not entirely cancel out within the op-amp, and produce a small output signal.
   - The ability of an op-amp to reject common mode signals is usually expressed in terms of CMRR, i.e., the ratio of the op-amp's gain with differential signals versus the gain with common mode signals.
   - CMRR values of 90dB are typical of most op-amps.

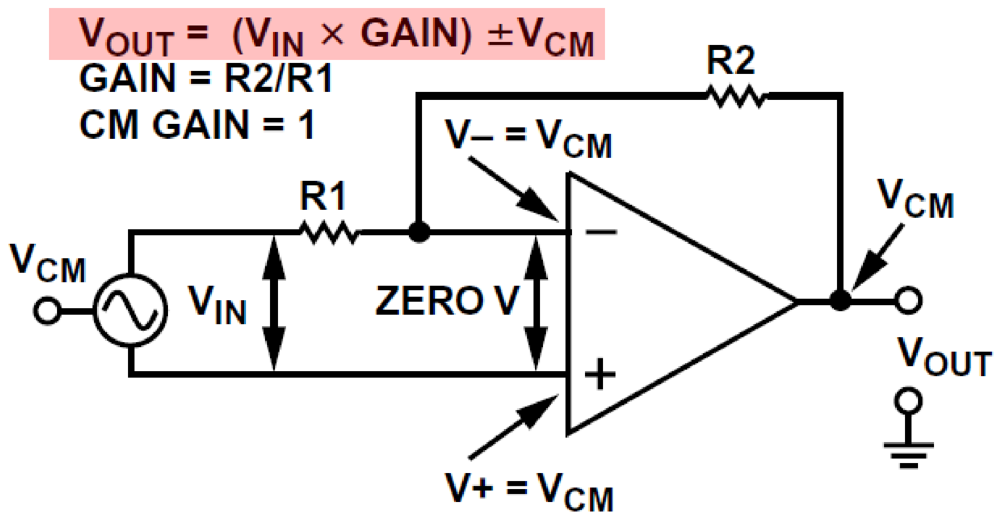
Marston, R., *Op-Amp Cookbook – Part 1*, Nuts & Volts Magazine, (July 2001)

CMRR & CMR…

- Mathematically, common-mode rejection can be represented as:
  - $CMRR = A_D \frac{V_{CM}}{V_{OUT}}$

  where:
    - A_D is the differential gain of the amplifier.
    - V_{CM} is the common-mode voltage present at the amplifier inputs.
    - V_{OUT} is the output voltage present when a common-mode input signal is applied to the amplifier.
- The term CMR is a logarithmic expression of the common-mode rejection ratio (CMRR).
  - $CMR = 20\, Log_{10} CMRR$

Common Mode Rejection Issue…



- An op amp operated in the typical inverting or noninverting amplifier configuration will process common-mode signals, passing them through to the output, but will not normally reject them.

Kitchin, C. and L. Counts, *A Designers Guide to Instrumentation Amplifiers,* 2nd ed., Analog Devices (2004)

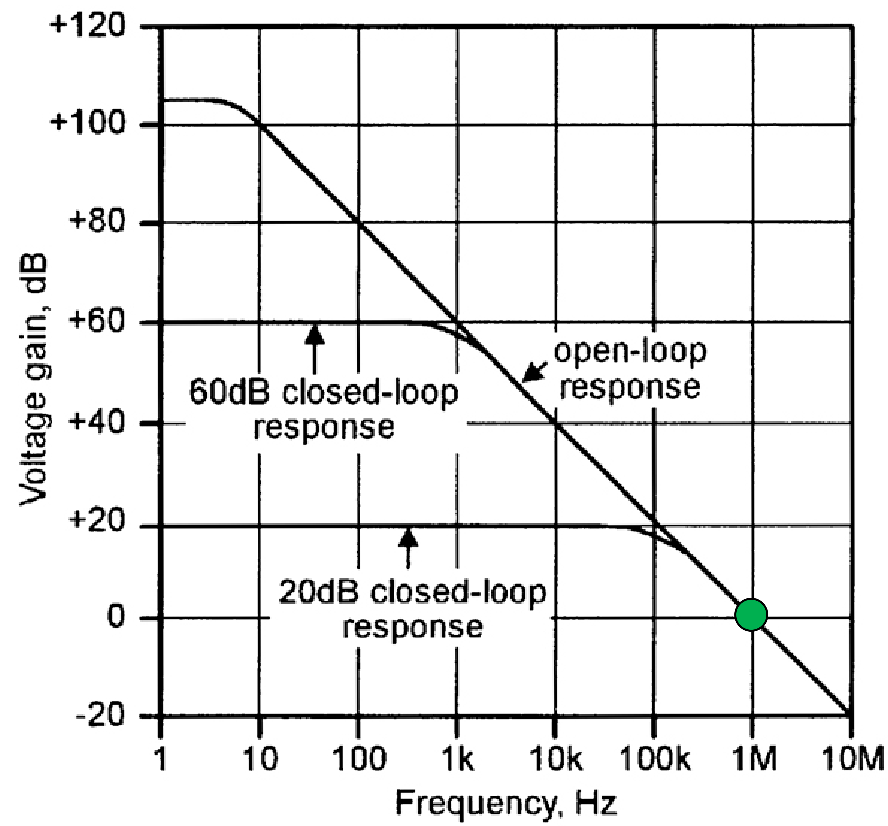
Parameters Continued…

9. **f_T (transition frequency)**
   - An op-amp typically gives a low-frequency voltage gain of about 100dB.
   - *The f_T is the frequency at which there is unity gain (0dB)*.
   - Open-loop frequency response is internally tailored so that the gain falls off at a rate of 6dB/octave (= 20dB/decade), eventually falling to unity.
   - For example, the 741 op-amp, has an f_T value of 1MHz and a low-frequency gain of 106dB.

Marston, R., *Op-Amp Cookbook – Part 1*, Nuts & Volts Magazine, (July 2001)

The 741 Op-Amp f_T = 1MHz…

- When the op-amp is used in a closed loop amplifier circuit, the circuit's bandwidth depends on the closed-loop gain.
- The circuit has a bandwidth of only 1kHz at a gain of 60dB, or 100kHz at a gain of 20dB.
- The f_T figure can thus be used to represent a gain-bandwidth product.



Marston, R., *Op-Amp Cookbook – Part 1*, Nuts & Volts Magazine, (July 2001)

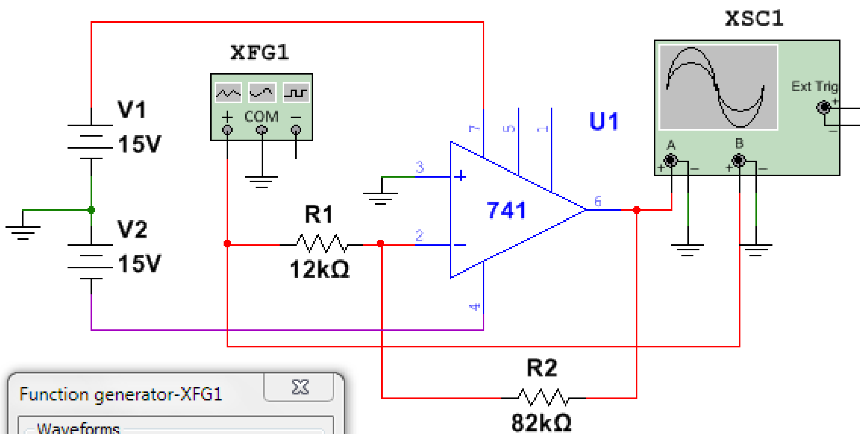
Parameters Continued…

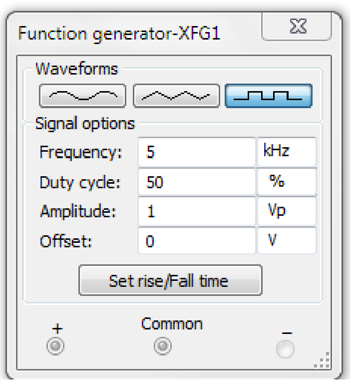
10. Slew rate

- The *maximum rate of change of voltage at the op-amp's output*.
- Slew rate is normally specified in terms of volts per microsecond.
- The LM741 op amp slew rate is .5V/µS at unity gain.
- One effect of slew rate limiting is to make a greater bandwidth available to small-amplitude output signals than to large-amplitude output signals.

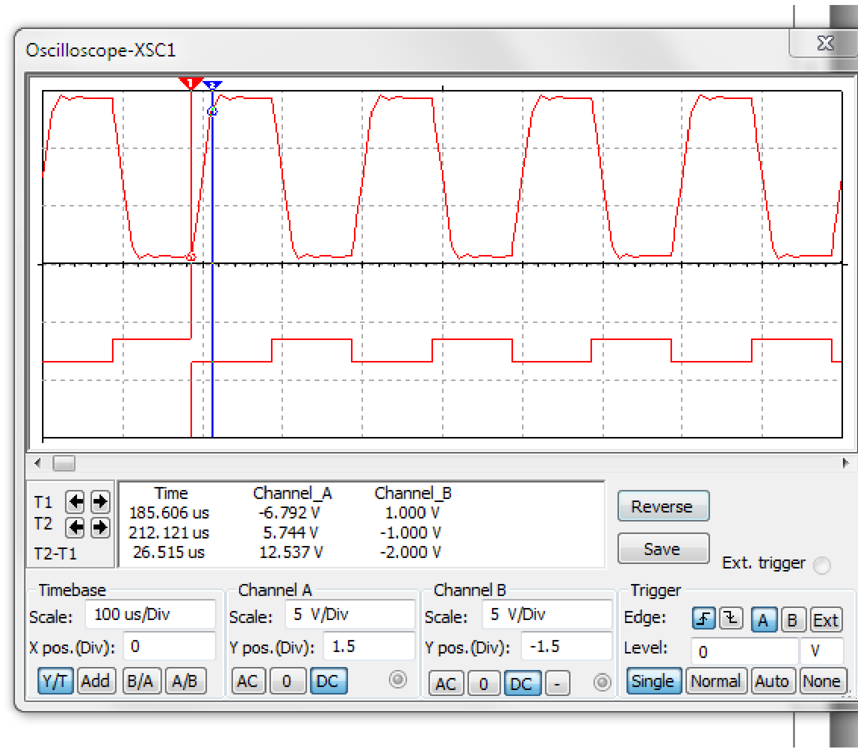
Marston, R., *Op-Amp Cookbook – Part 1*, Nuts & Volts Magazine, (July 2001)

Slew Rate Simulation…





Slew rate =V/uS =12.54/26.52=.47 V/uS
(time selected along most linear part)



Slew rate as determined by output of a square way input.

LM741 Data Sheet…

Electrical Characteristics

(V_{CC} = 15V, V_{EE} = - 15V. T_A = 25 °C, unless otherwise specified)

Parameter	Symbol	Conditions		LM741C/LM741I			Unit
				Min.	Typ.	Max.	
Input Offset Voltage	V_{IO}	$R_S \leq 10K\Omega$		-	2.0	6.0	mV
		$R_S \leq 50\Omega$		-	-	-	
Input Offset Voltage Adjustment Range	$V_{IO(R)}$	$V_{CC} = \pm 20V$		-	±15	-	mV
Input Offset Current	I_{IO}	-		-	20	200	nA
Input Bias Current	I_{BIAS}	-		-	80	500	nA
Input Resistance (Note1)	R_I	$V_{CC} = \pm 20V$		0.3	2.0	-	MΩ
Input Voltage Range	$V_{I(R)}$	-		±12	±13	-	V
Large Signal Voltage Gain	G_V	$R_L \geq 2K\Omega$	$V_{CC} = \pm 20V$, $V_{O(P-P)} = \pm 15V$	-	-	-	V/mV
			$V_{CC} = \pm 15V$, $V_{O(P-P)} = \pm 10V$	20	200	-	
Output Short Circuit Current	I_{SC}	-		-	25	-	mA
Output Voltage Swing	$V_{O(P-P)}$	$V_{CC} = \pm 20V$	$R_L \geq 10K\Omega$	-	-	-	V
			$R_L \geq 2K\Omega$	-	-	-	
		$V_{CC} = \pm 15V$	$R_L \geq 10K\Omega$	±12	±14	-	
			$R_L \geq 2K\Omega$	±10	±13	-	

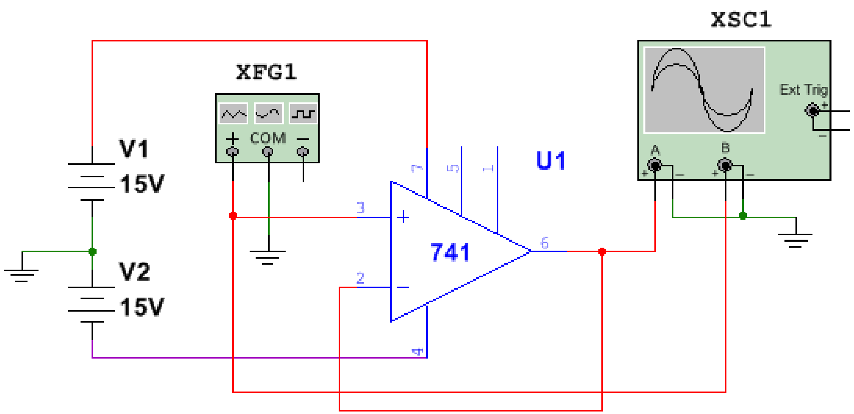
Fairchild Semiconductor, LM741 Single Operational Amplifier Datasheet, 2001.

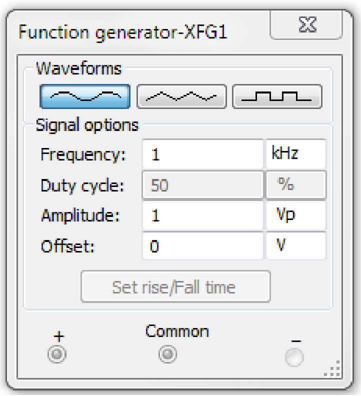
LM741…

Common Mode Rejection Ratio		CMRR	$R_S \le 10K\Omega$, $V_{CM} = \pm 12V$	70	90	-	dB
			$R_S \le 50\Omega$, $V_{CM} = \pm 12V$	-	-	-	
Power Supply Rejection Ratio		PSRR	$V_{CC} = \pm 15V$ to $V_{CC} = \pm 15V$ $R_S \le 50\Omega$	-	-	-	dB
			$V_{CC} = \pm 15V$ to $V_{CC} = \pm 15V$ $R_S \le 10K\Omega$	77	96	-	
Transient Response	Rise Time	T_R	Unity Gain	-	0.3	-	µs
	Overshoot	OS		-	10	-	%
Bandwidth		BW	-	-	-	-	MHz
Slew Rate		SR	Unity Gain	-	0.5	-	V/µs
Supply Current		I_{CC}	$R_L = \infty\Omega$	-	1.5	2.8	mA
Power Consumption		P_C	$V_{CC} = \pm 20V$	-	-	-	mW
			$V_{CC} = \pm 15V$	-	50	85	

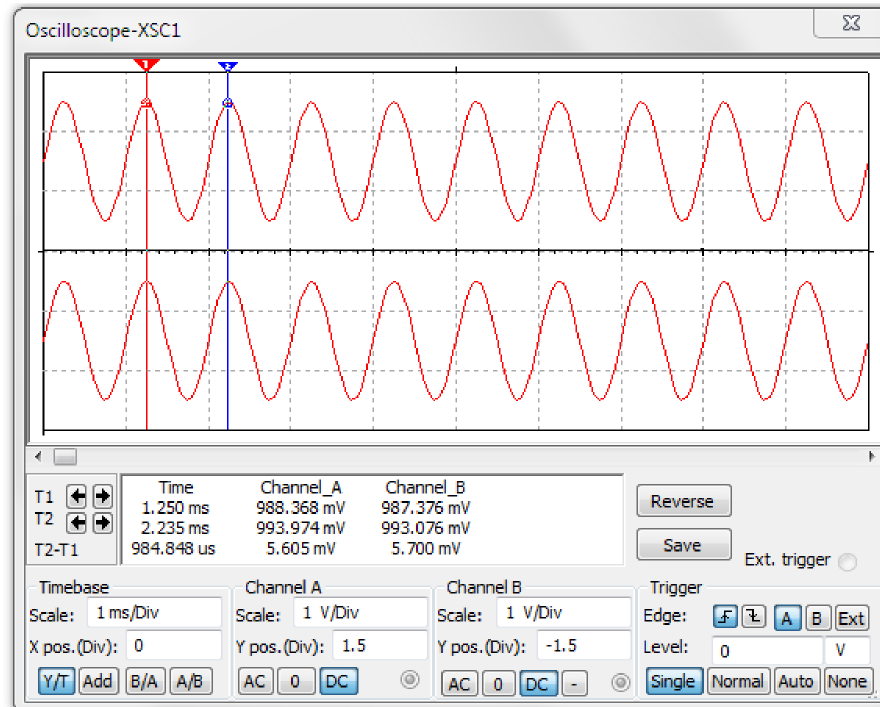
Fairchild Semiconductor, LM741 Single Operational Amplifier Datasheet, 2001.

Voltage Follower…

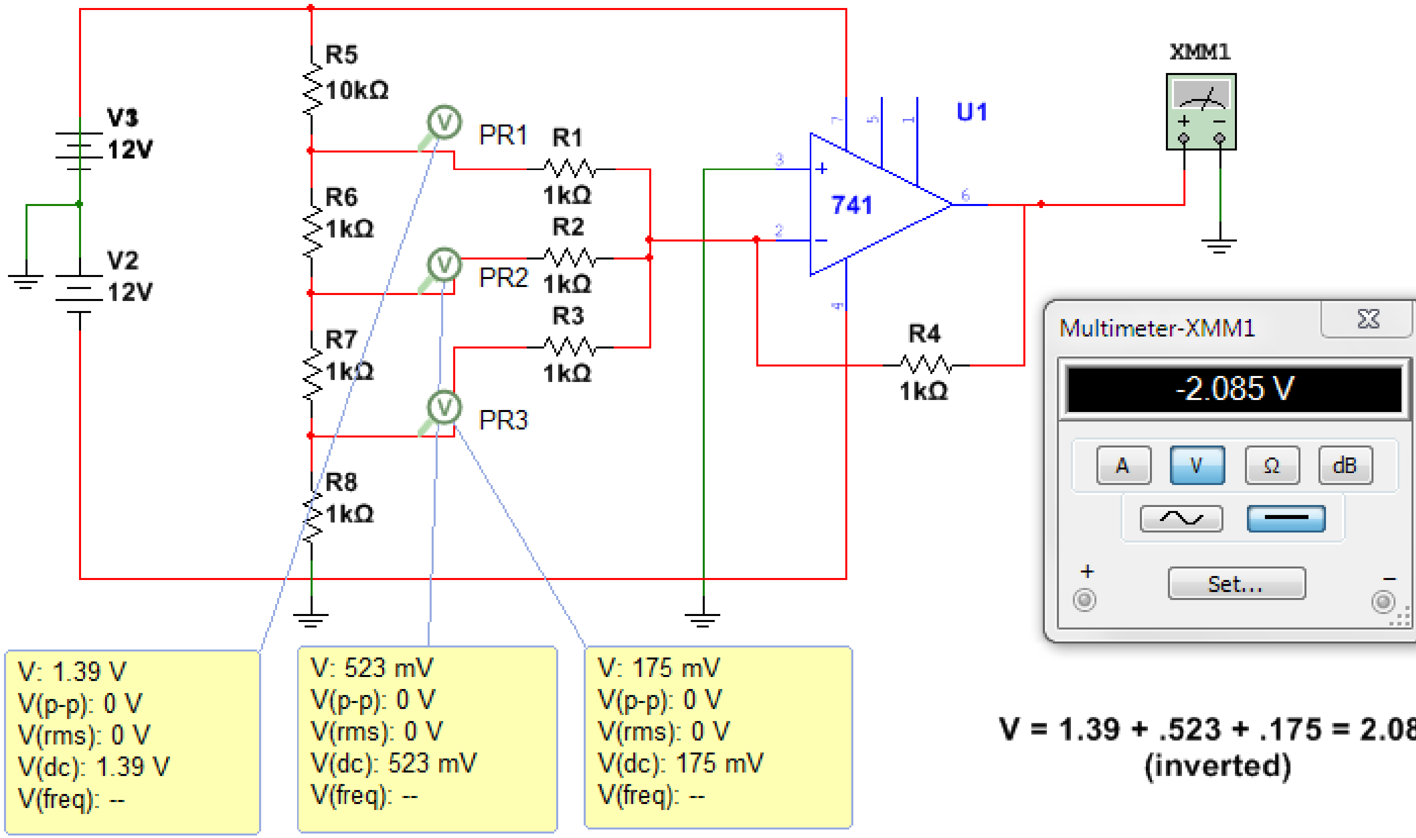




The gain is one. The input is very high and the output is very low impedance. This is useful for isolation.



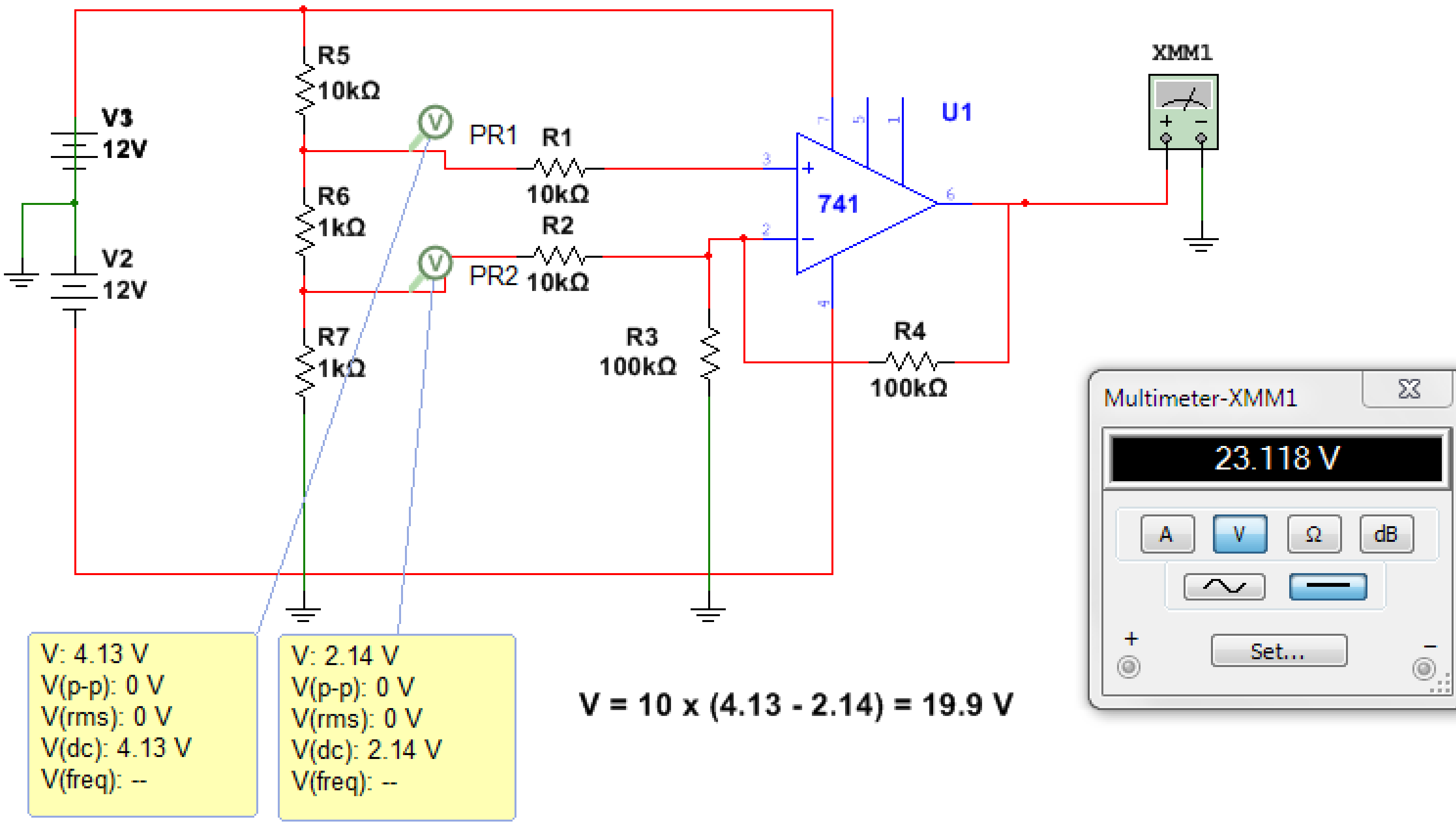
Summing Amplifier…



V = 1.39 + .523 + .175 = 2.088 (inverted)

See Summing Amplifier in Berlin, H.M., *Design of Op-Amp Circuits*, H.W. Sams, Carmel, IN (1977)

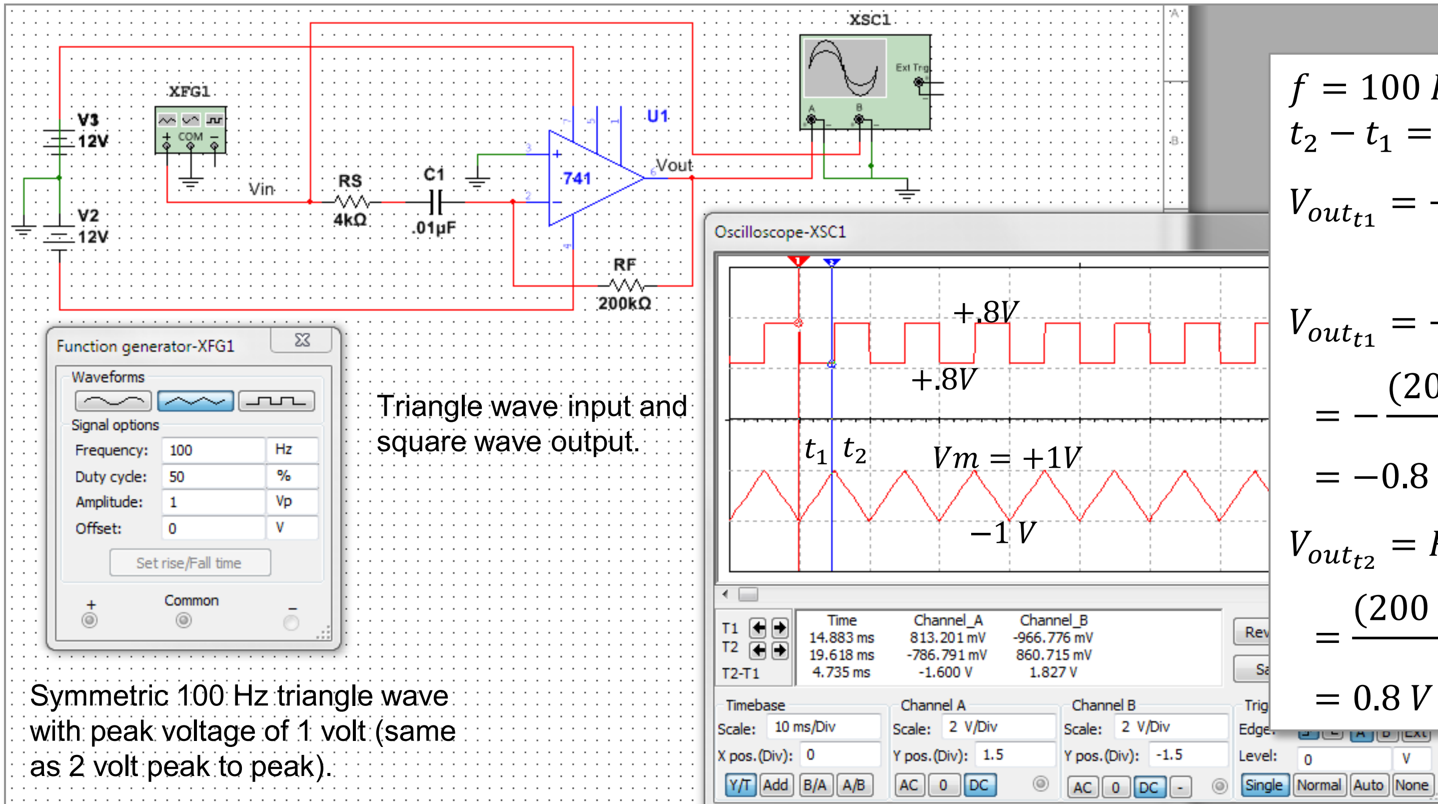
Difference Amplifier with Gain of 10…



V = 10 x (4.13 - 2.14) = 19.9 V

 See Difference Amplifier in Berlin, H.M., *Design of Op-Amp Circuits*, H.W. Sams, Carmel, IN (1977)

Differentiator…



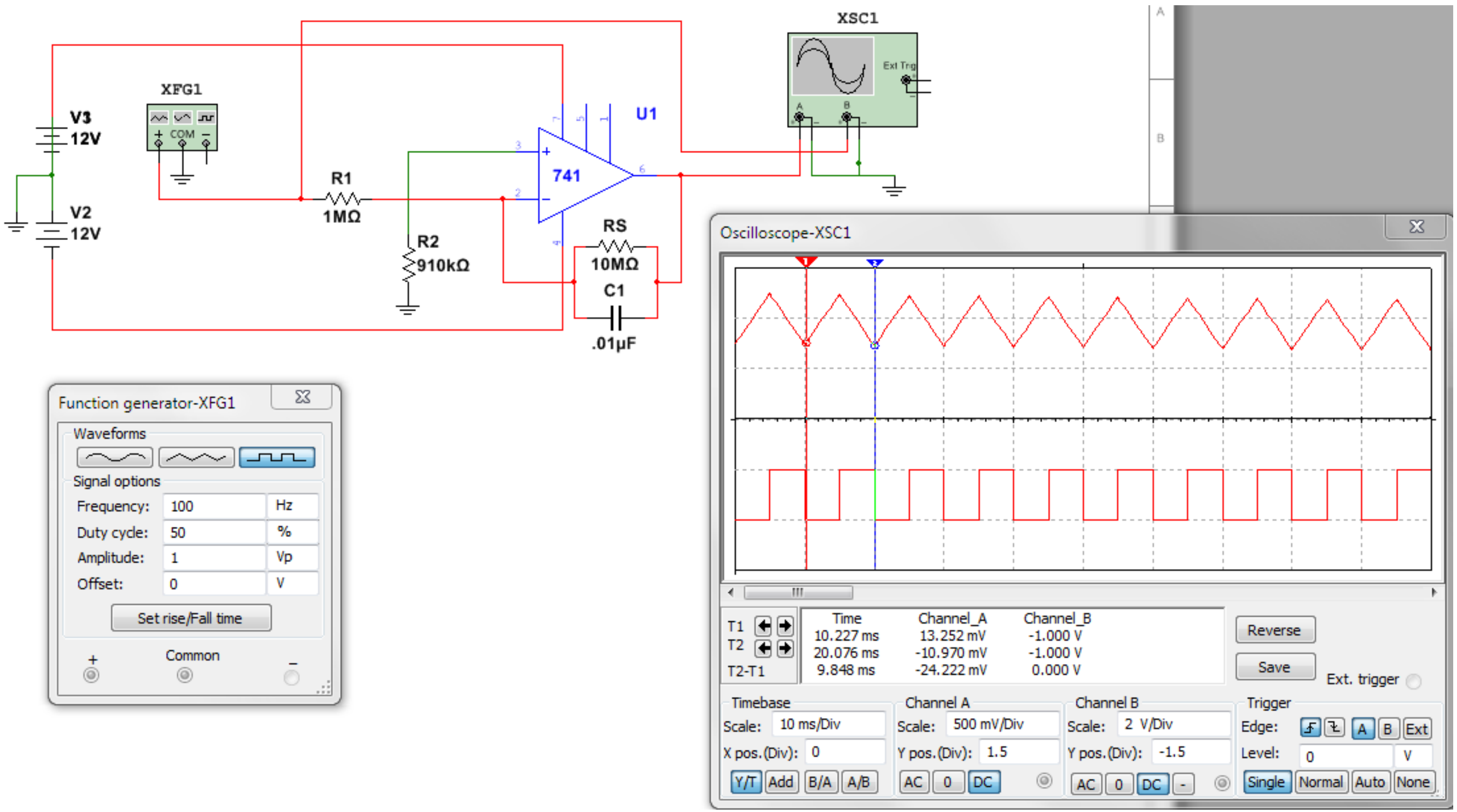
Triangle wave input and square wave output.

Symmetric 100 Hz triangle wave with peak voltage of 1 volt (same as 2 volt peak to peak).

$$f = 100\ Hz$$
$$t_2 - t_1 = 0.005\ S$$
$$V_{out_{t1}} = -R_F C_1 \frac{dV_{pp}}{dt}$$
$$V_{out_{t1}} = -R_F C_1 \frac{2V_m}{t_2 - t_1}$$
$$= -\frac{(200\ k\Omega)\ (0.01\ \mu F)\ (2)\ (1\ V)}{.005\ S}$$
$$= -0.8\ V$$
$$V_{out_{t2}} = R_F C_1 \frac{2V_m}{t_2 - t_1}$$
$$= \frac{(200\ k\Omega)\ (0.01\ \mu F)\ (2)\ (1\ V)}{.005\ S}$$
$$= 0.8\ V$$

 See Differentiator in Berlin, H.M., *Design of Op-Amp Circuits*, H.W. Sams, Carmel, IN (1977)

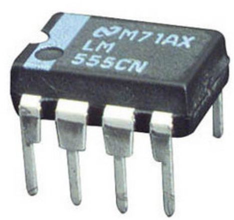
Integrator…

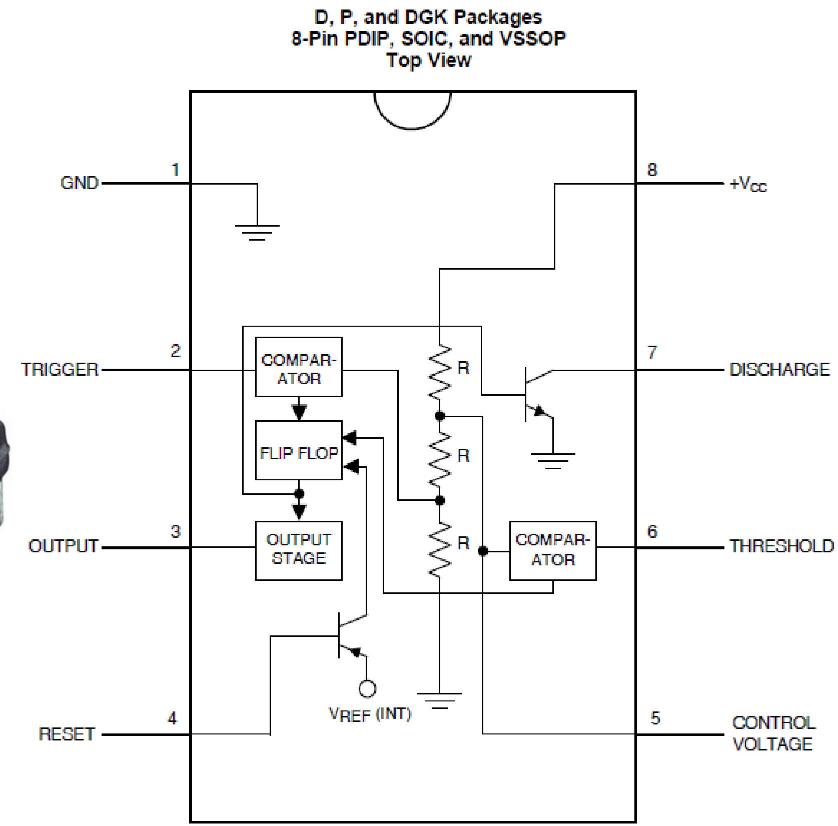


See Integrator in Berlin, H.M., *Design of Op-Amp Circuits*, H.W. Sams, Carmel, IN (1977)

LM555 Timer

- Features & Applications:
  - Precision Timing - µS to hours.
  - Pulse Generation – astable and monostable operation.
  - Output can sink 200 mA – TTL compatible.
  - Sequential Timing
  - Time Delay Generation
  - Pulse Width Modulation
  - Pulse Position Modulation
  - Linear Ramp Generator





LM555 Timer, Texas Instruments Datasheet, (2015)

Pinouts for the LM555 Timer…

1. Pin 1 (ground). IC ground.
2. Pin 2 (trigger). Input to comparator 2, which is used to set the flip-flop. When the voltage at pin 2 crosses from above to below $\frac{1}{3}V_{CC}$, the comparator switches to high, setting the flip-flop.
3. Pin 3 (output). The output of the 555 is driven by an inverting buffer capable of sinking or sourcing around 200 mA. The output voltage levels depend on the output current but are approximately $V_{out}(\text{high}) = V_{CC} - 1.5$ V and $V_{out}(\text{low}) = 0.1$ V.
4. Pin 4 (reset). Active-low reset, which forces $\bar{Q}$ high and pin 3 (output) low.
5. Pin 5 (control). Used to override the $\frac{2}{3}V_{CC}$ level, if needed, but is usually grounded via a 0.01-μ bypass capacitor (the capacitor helps eliminate V_{CC} supply noise). An external voltage applied here will set a new trigger voltage level.

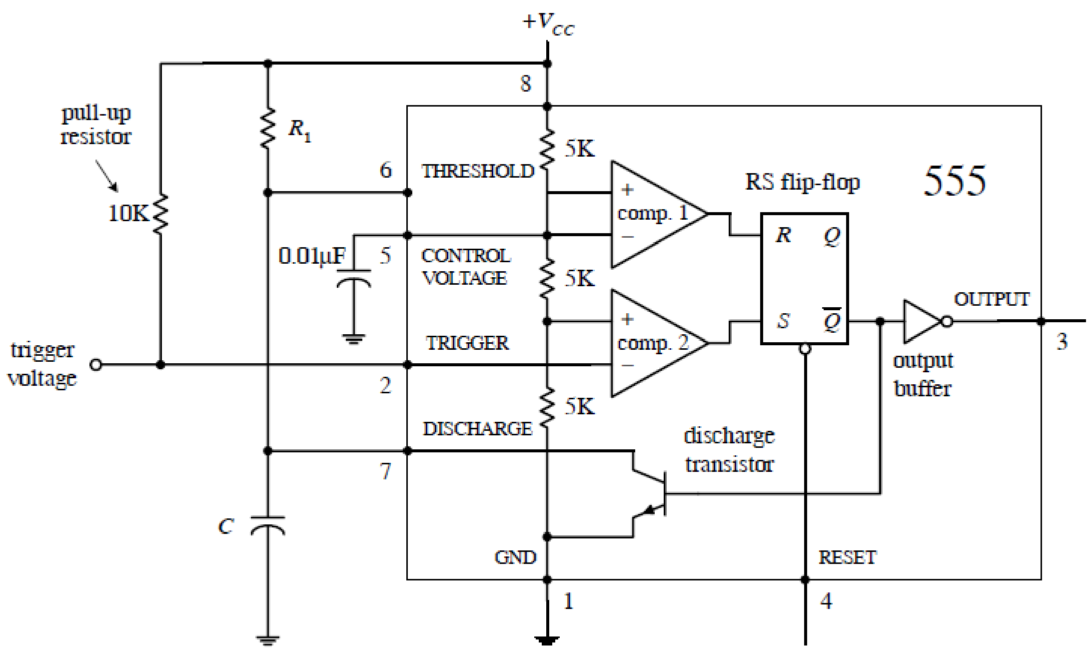
LM555 Timer, Texas Instruments Datasheet, (2015)

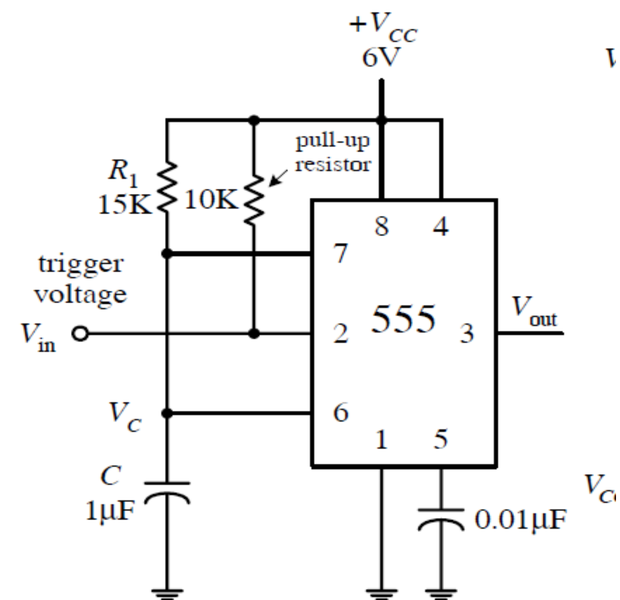
Pinouts…

6. Pin 6 (threshold). Input to the upper comparator, which is used to reset the flip-flop. When the voltage at pin 6 crosses from below to above *2⁄3VCC,* the comparator switches to a high, resetting the flip-flop.
7. Pin 7 (discharge). Connected to the open collector of the *npn* transistor. It is used to short pin 7 to ground when *Q* is high (pin 3 low). This causes the capacitor to discharge.
8. Pin 8 (Supply voltage VCC). Typically between 4.5 and 16 V for general-purpose TTL 555 timers. (For CMOS versions, the supply voltage may be as low as 1 V.)

LM555 Timer, Texas Instruments Datasheet, (2015)

Monostable Mode or "One Shot" Diagram…



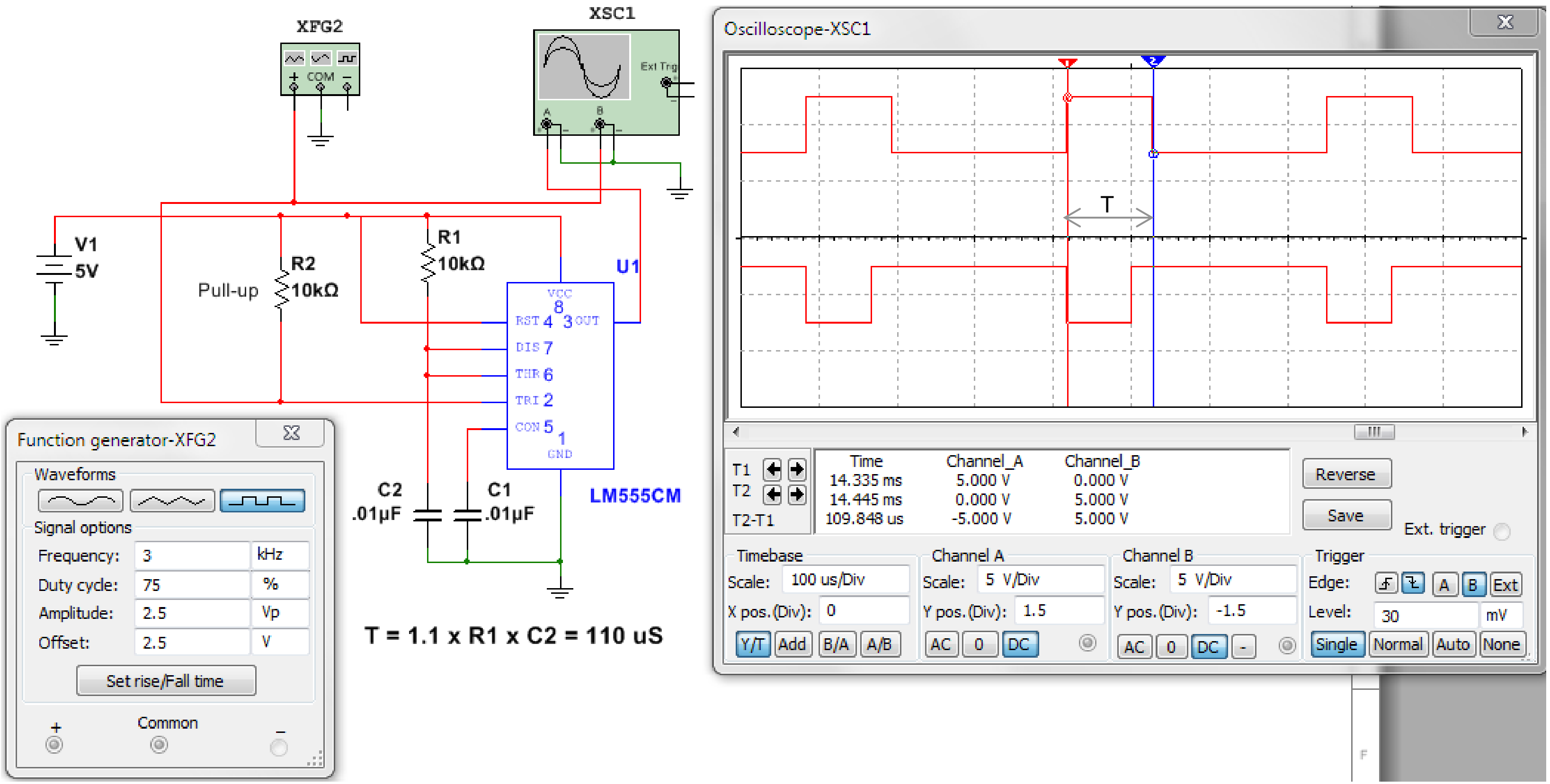


$t_{width} = 1.10\ R_1 C$

$t_{width} = 1.10\ (15K)(1\mu F) = 16.5ms$

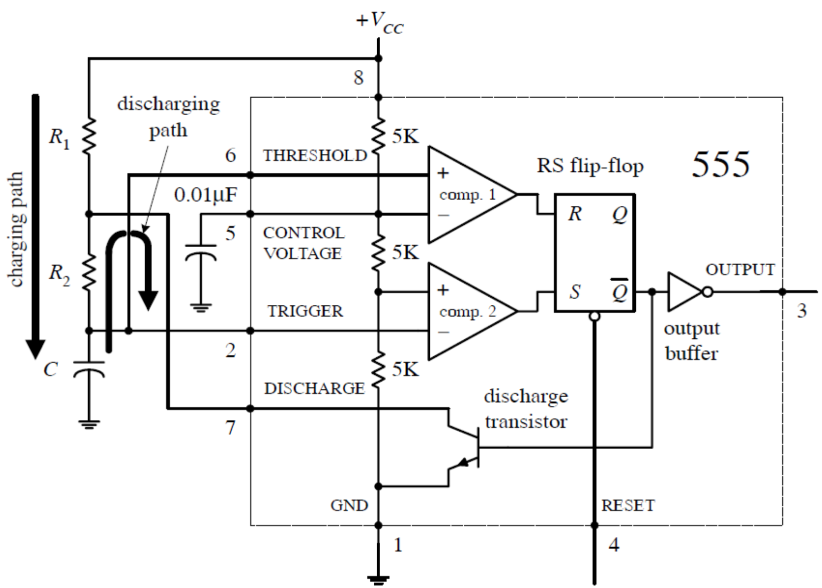
Scherz, P. and S. Monk, *Practical Electronics for Inventors*, McGraw Hill, New York (2016)

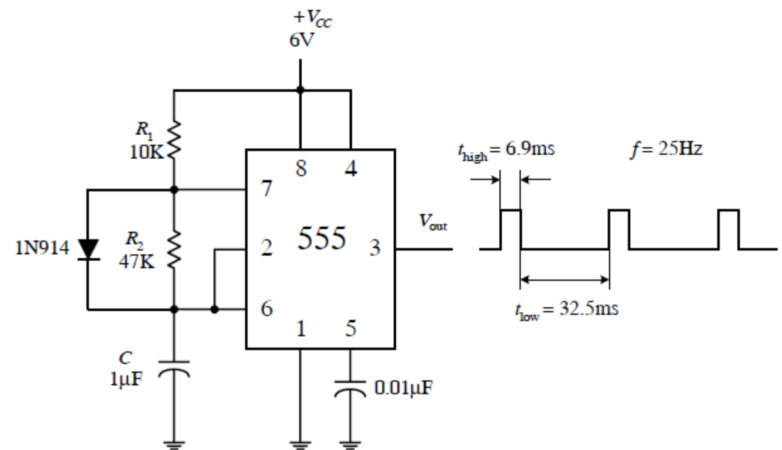
Monostable Mode or "One Shot" Simulation…



T = 1.1 x R1 x C2 = 110 uS

Astable Multivibrator or Oscillator…





$$t_{high} = 0.693 R_1 C_1 = 6.9\ mS$$

$$t_{low} = 0.693 R_2 C_1 = 32.5\ mS$$

$$f = \frac{1}{t_{high} + t_{low}} = 25\text{ Hz}$$

$$Duty\ Cycle = \frac{t_{high}}{t_{high} + t_{low}} = 0.18$$

Scherz, P. and S. Monk, *Practical Electronics for Inventors*, McGraw Hill, New York (2016)

“Astable Multivibrator”…

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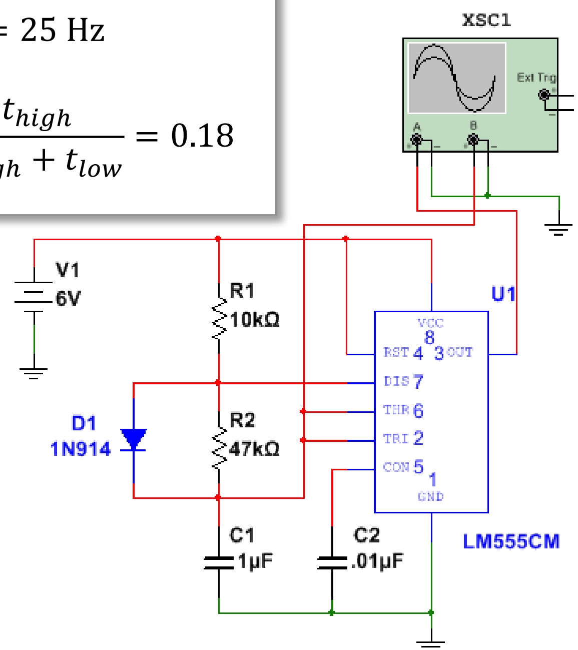
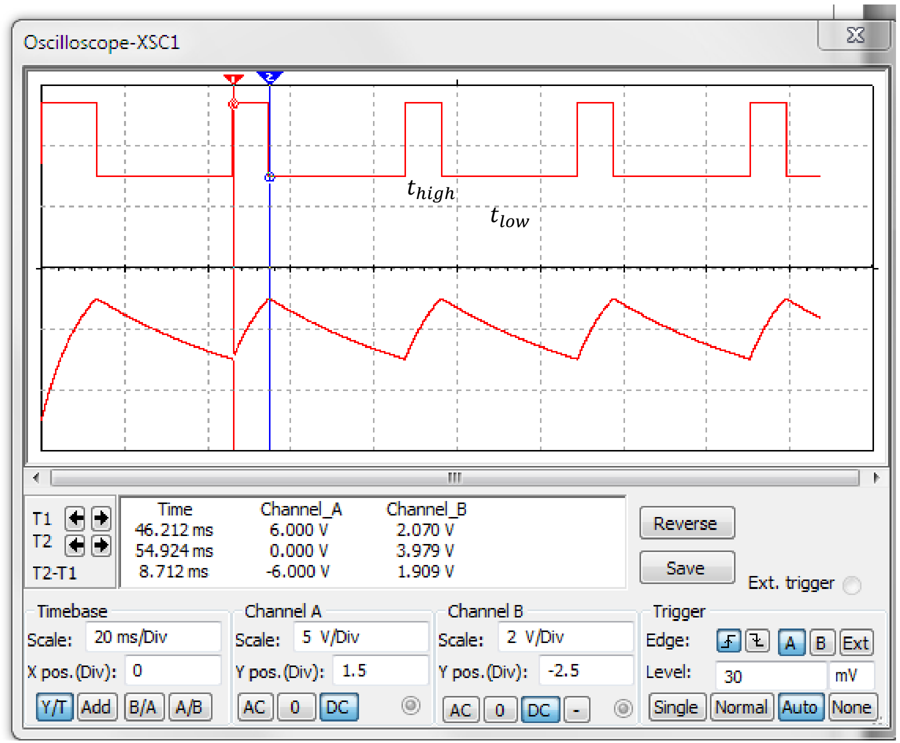
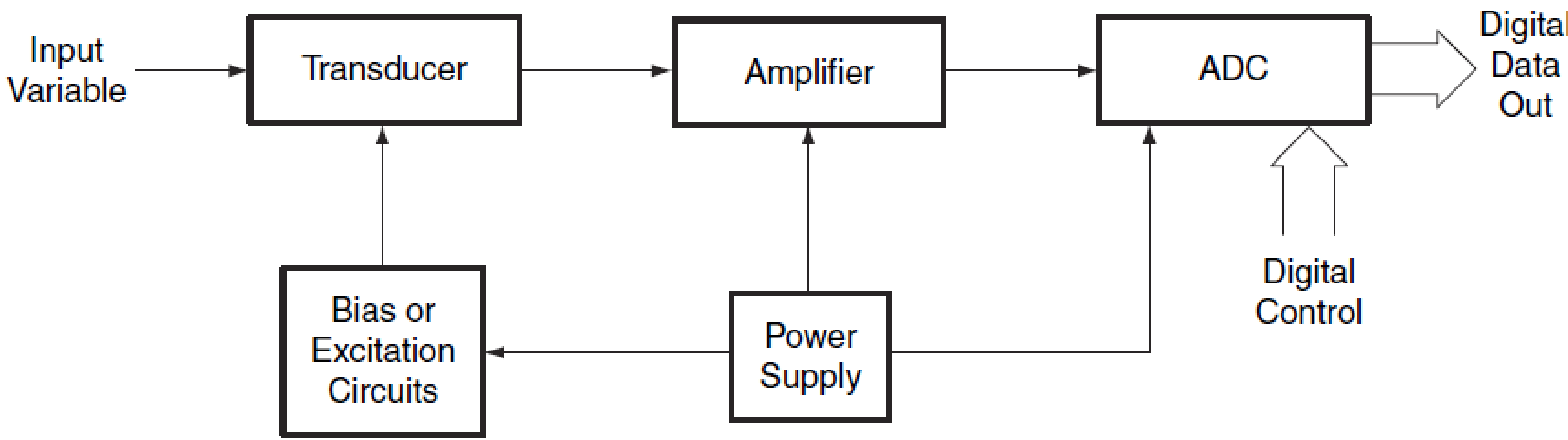




Summary

- Operational amplifiers.
  - Basics
  - Amplification
  - The 741 Op Amp
- LM555 timer
  - Monostable or “one shot”
  - Astable multivibrator (oscillator)
- Appendix - Applications
  - Transducers

Transducers

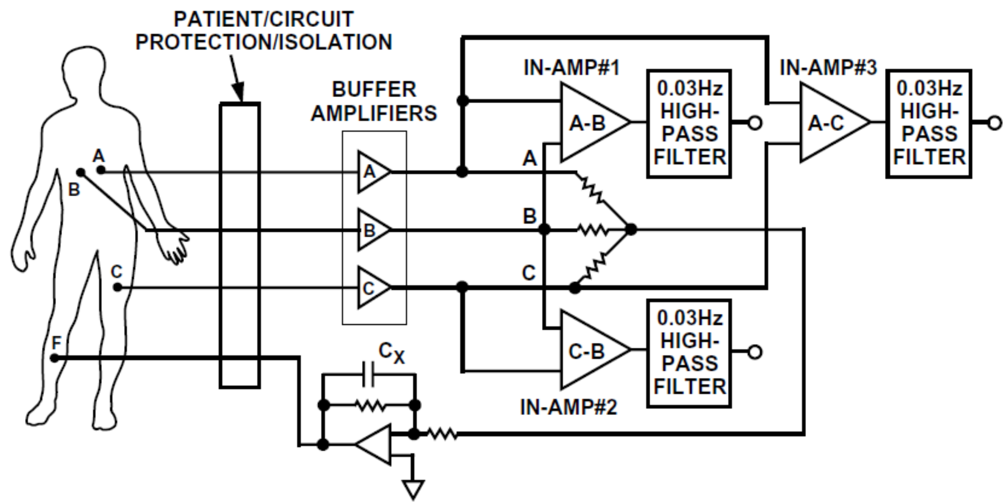


- A transducer converts data into an electrical signal.
- All transducers have *offset voltages or currents*, and they can be referenced to ground, either power supply rail, or some other voltage.
- The output of the transducer is an electrical signal representing the measured variable.
- The signal must be *amplified and filtered* so as to increase the signal to noise ratio.
- The analog to digital converter must have enough bits to obtain the *resolution* required by the accuracy specification.

Carter, B and Mancini B. *Op Amps for Everyone*, Newnes and TI, Burlington, MA (2009)

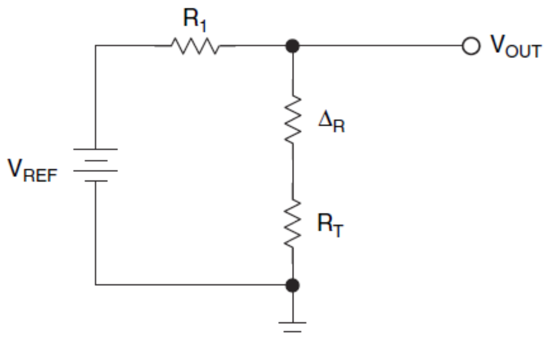
ECG Medical Monitor for example…

- Signal is 5 mV in a 60 Hz noisy environment, with a large DC component to offset.
- The buffer op amps are low noise, low input current FET op amps.
- The three resistors form a summing network to drive the force amplifier.
- Current is sent through the patient until the net sum output from the three buffer amplifiers is zero.
- The filters after the amplifiers remove the DC component.
- Note also some form of isolation to protect the patient.

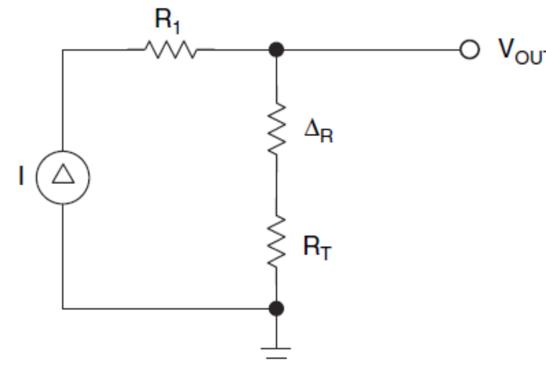


Kitchin, C. and L. Counts, *A Designers Guide to Instrumentation Amplifiers,* 2nd ed., Analog Devices (2004)

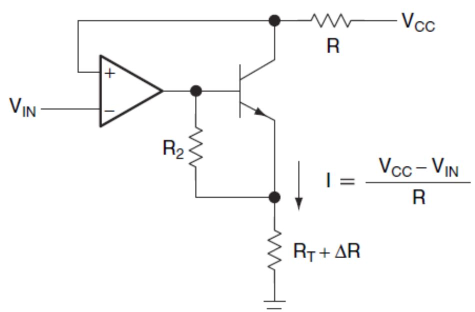
Resistive Transducers…



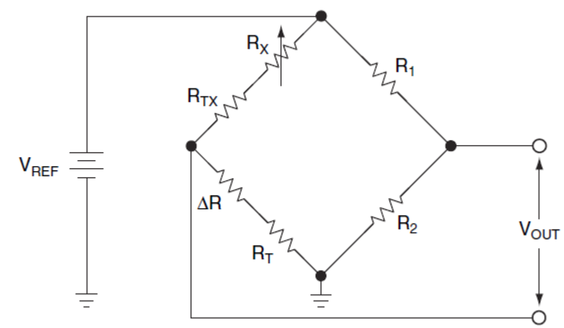
Voltage Divider for a Resistive Transducer



Current Source Excitation for a Resistive Transducer



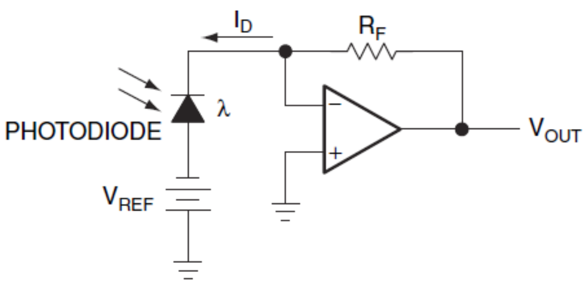
Precision Current Source



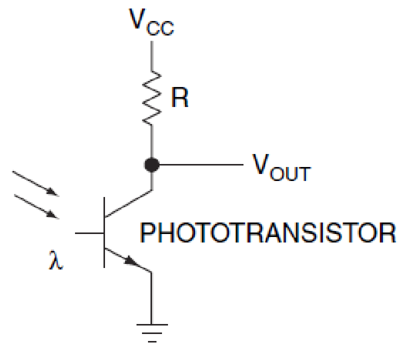
Wheatstone Bridge Circuit

Carter, B and Mancini B. *Op Amps for Everyone*, Newnes and TI, Burlington, MA (2009)

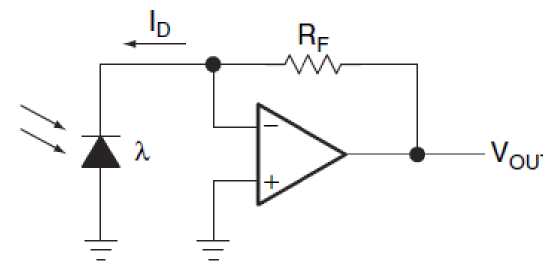
Optical Transducers…



Photodiode Amplifier



Phototransistor Amplifier



Photovoltaic Cell Amplifier

Carter, B and Mancini B. *Op Amps for Everyone*, Newnes and TI, Burlington, MA (2009)