Introductory Medical Device Prototyping

Analog Circuits Part 2 – Semiconductors

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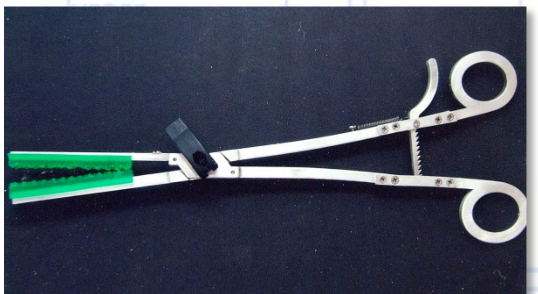
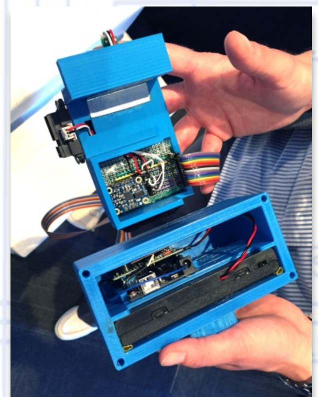
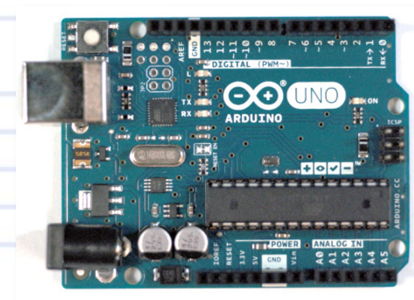
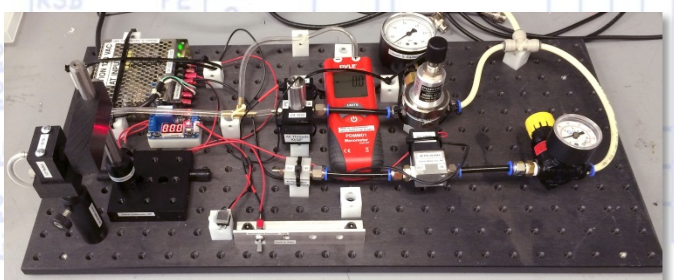
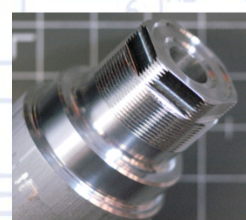










Concepts to be Covered

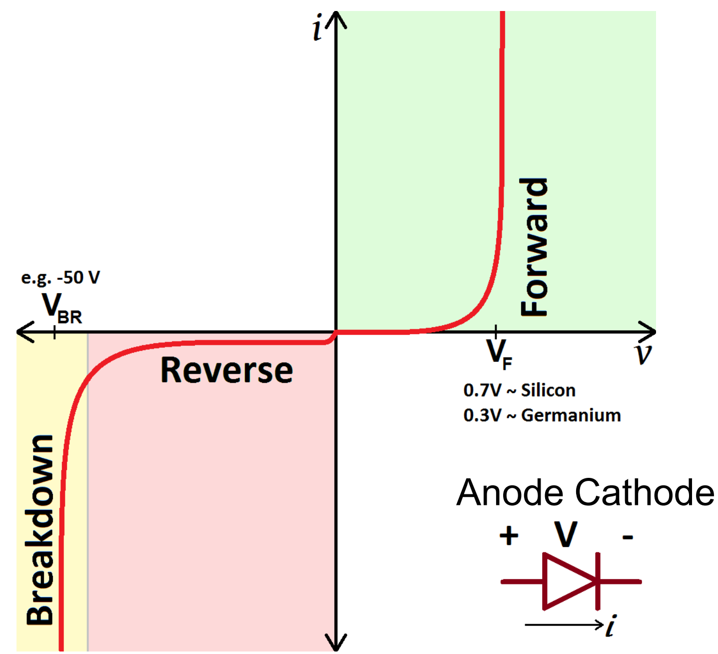
- Semiconductors
  - Diodes to Rectify Current
  - Zener Diodes for Voltage Reference
  - Voltage Regulators
  - Transistors as Switches
  - Common Emitter Bipolar Junction Transistor Amplifier

Diodes

- Diodes are semiconductor devices that rectify current – allowing flow in only one direction. The larger the current, the larger the diode.
- They may be used as switching devices, voltage-controlled capacitors (varactors) and voltage references (Zener diodes).
- Typically a 2-terminal device – an anode and cathode.
- Ideally resistance is zero in one direction, and infinite in the other.
- Diodes allow current to flow in only one direction and can therefore be used as simple solid state switches in AC circuits, being either open (not conducting) or closed (conducting).
- A bridge rectifier, consisting of 4 diodes can be used to convert AC into DC, and typically followed filtering capacitors and/or Zener diode.

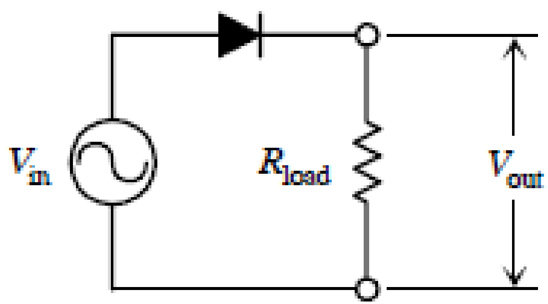
Diode Current to Voltage Relationship

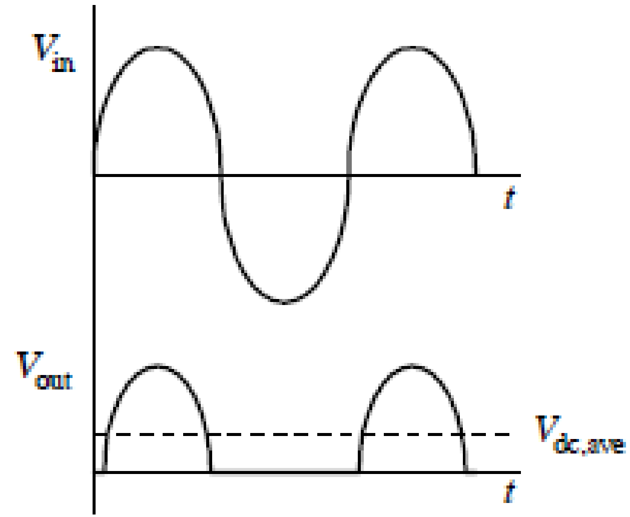
- Forward bias: Voltage across the diode is positive and flows.
- Reverse bias: This is the “off” mode of the diode, where the voltage is less than V_F but greater than $-V_{BR}$. In this mode current flow is mostly blocked,
- Breakdown: When the voltage applied across the diode is very large and negative, lots of current will be able to flow in the reverse direction, from cathode to anode



https://learn.sparkfun.com/tutorials/diodes/real-diode-characteristics

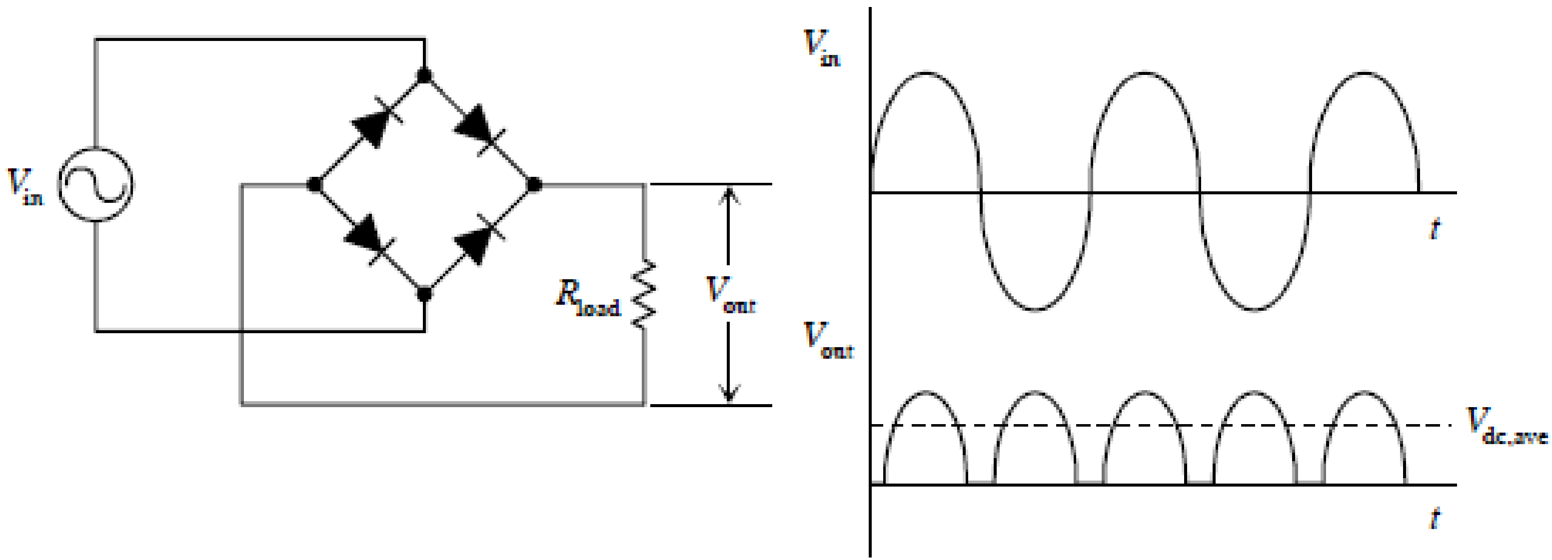
Half-Wave Rectifier





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

Full-Wave Bridge Rectifier



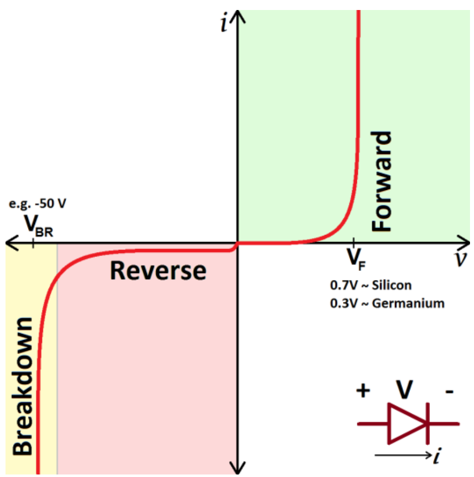
Scherz, P.& S. Monk. *Practical Electronics for Inventors*, McGraw Hill, New York, NY (2016).

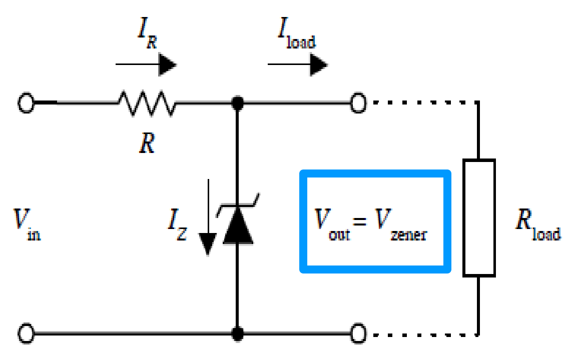
Zener Diode

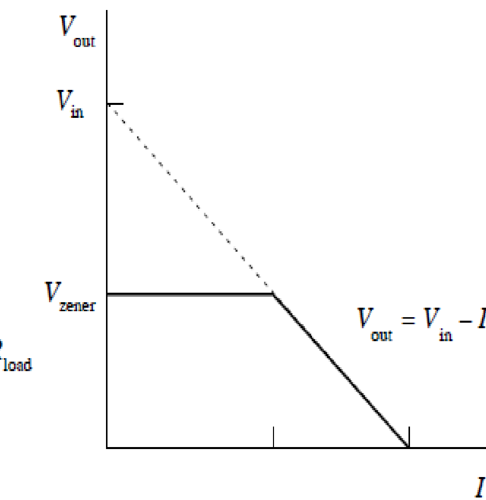
- A Zener diode is designed to operate in the reverse breakdown, or Zener region, beyond the peak inverse voltage rating of normal diodes.
  - This reverse breakdown voltage is called the Zener test voltage (V_{zt}), which can range between 2.4 V and 200 V.
- In the forward region, it starts conducting around 0.7 V, just like an ordinary silicon diode.
  - In the leakage region, between zero and breakdown, it has only a small reverse current.
  - The breakdown has a sharp knee, followed by an almost vertical increase in current.
- Zener diodes are used primarily for voltage regulation or voltage reference because they maintain constant output voltage despite changes in current.

Zener Diode Voltage Regulator…

1. $I_{load} = \frac{V_{in}}{R_{load}} \approx \frac{V_{Zener}}{R_{load}}$
2. $I_R = \frac{V_{in} - V_{out}}{R} \approx \frac{V_{on} - V_{Zener}}{R}$
3. $I_{Zener} = I_R - I_{load}$







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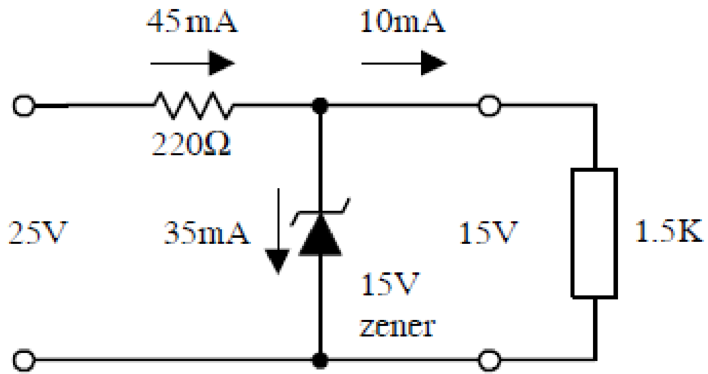
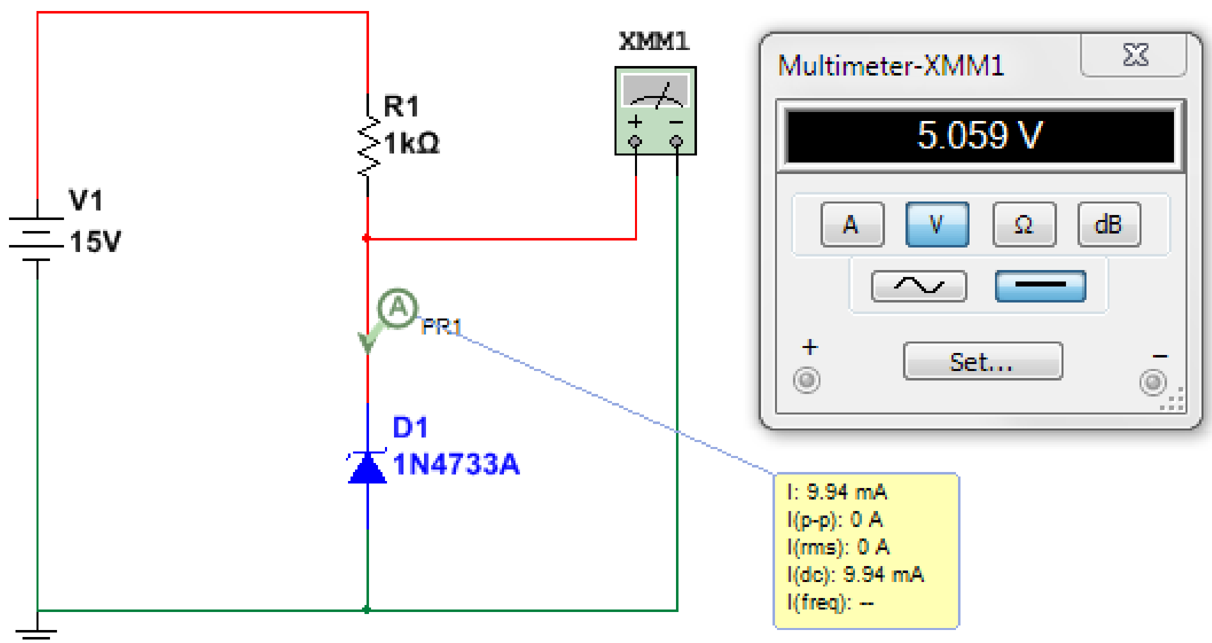
Zener Voltage Regulator Example…



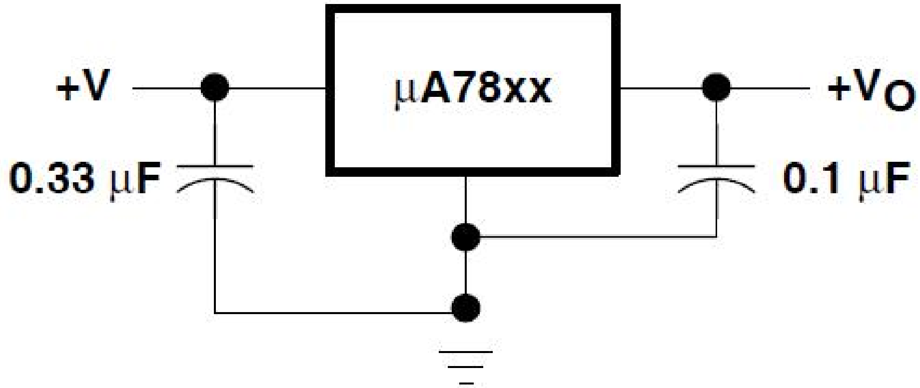
1. $I_{load} = \frac{15V}{1.5k} = 10mA$
2. $I_R = \frac{25\,V - 15\,V}{220\,\Omega} = 45mA$
3. $I_{Zener} = 45mA - 10mA = 35mA$

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

Zener Diode Simulation…



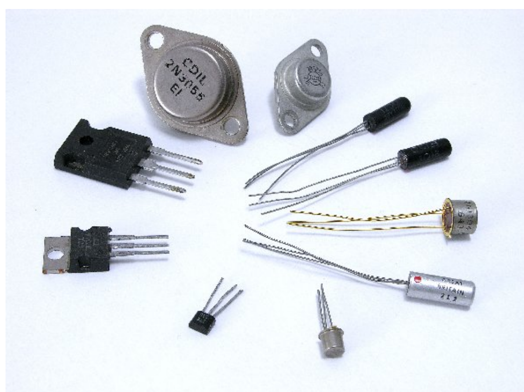
Voltage Regulators – 7800/7900 Series

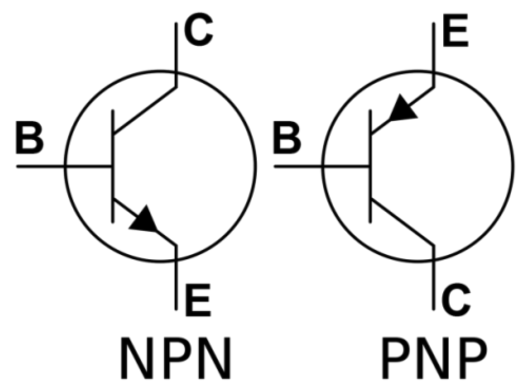


- Fixed voltage integrated voltage regulator.
- Three terminal regulation.
- Output current to 1.5A
- Internal thermal overload protection.
- High-power dissipation capability with heatsink tab.

Transistors

- Semiconductor devices that are used to *switch* or *amplify* a signal.
- They typically consist of three terminals. For an NPN or PNP bipolar junction transistor these are called the collector, base and emitter.
- They may ay be a discrete component, or through nanofabrication may number in the billions for a single CPU – e.g. 7.2 billion in Intel's 22-core chip.



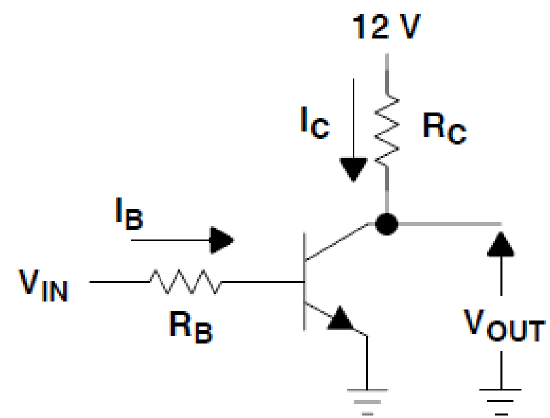


http://www.colorado.edu/physics/phys3330/phys3330_fa10/images/Transistors.JPG

Transistor as a Switch – On/Off

- Calculations for transistor saturation:
  - With sufficient base current, I_B through R_B, the transistor “switches on” or goes into *saturation*, and *sinks* the load current I_C (turning *off* the Vout),
  - When the transistor is off, output current is available through R_C.
  - Calculate the base and collector resistors to allow saturation, and a useful output voltage for this example with the following specifications:

1. V_{IN}= 12 V, V_{OUT} <0.4 V at I_{SINK}<10 mA (transistor *on*).
2. V_{IN} <0.05 V, V_{OUT} >10 V at I_{OUT} = 1 mA (transistor *off*).
3. The transistor current gain, β (beta) is 50, and equals I_C/I_B.



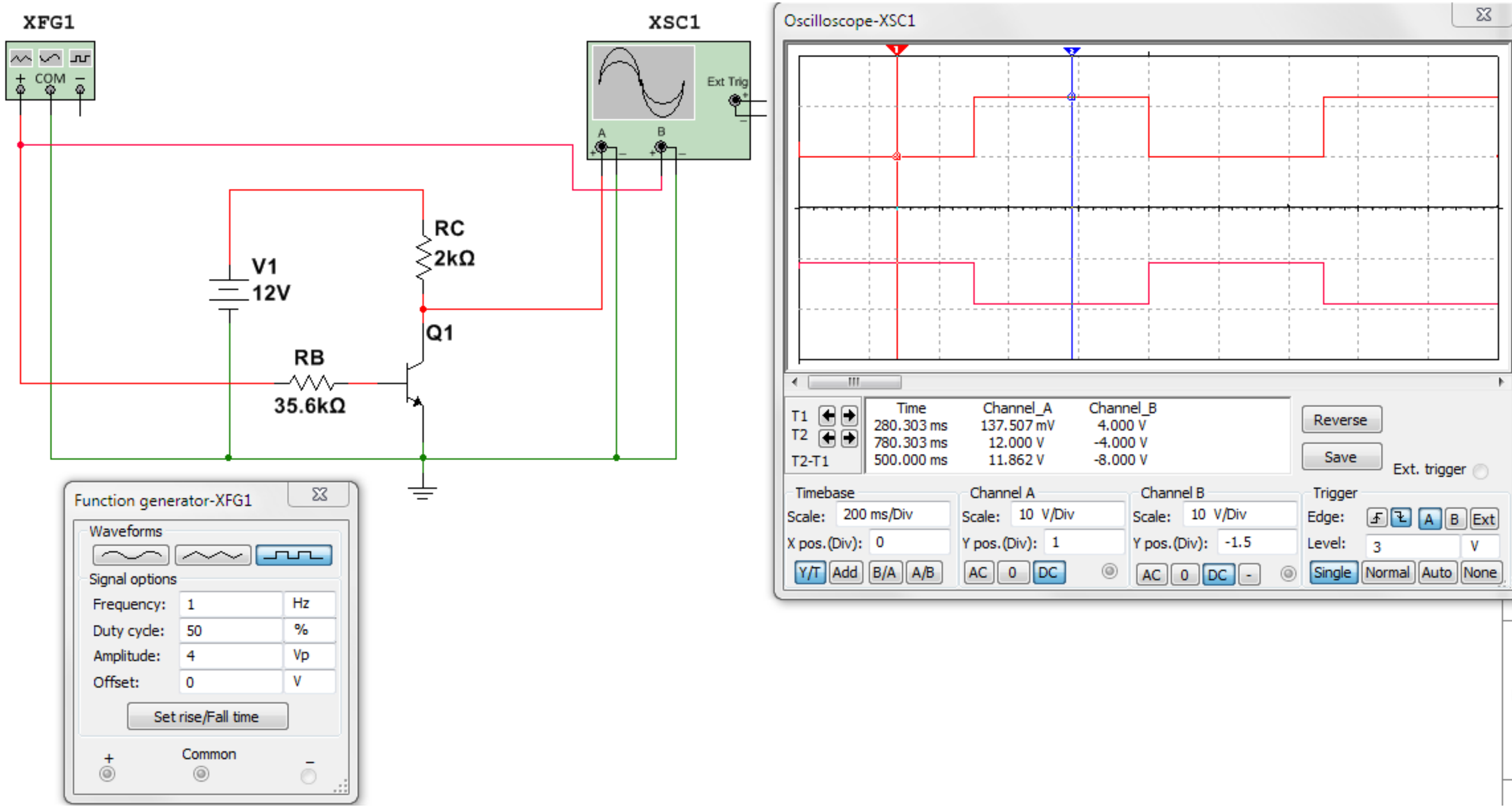
Mancini, R . *Op Amps for Everyone*, Texas Instruments, Dallas, TX (2002)

Calculating the Resistors and Current…

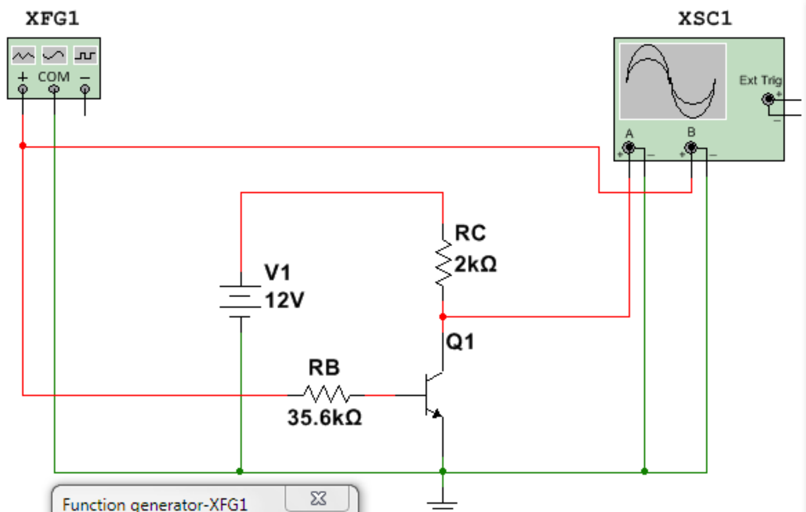
- When the transistor is *off*, 1 mA can be drawn out of the collector resistor without pulling the collector or output voltage to less than ten volts (circuit specification) *(V_{CE} is voltage from collector to emitter)*:
  - $R_C \leq \frac{V_{+12} - V_{Out}}{I_{Out}} = \frac{12-10}{.001} = 2k$
- When the transistor is *on*, the base resistor must be sized to enable the input signal to drive enough base current into the transistor to saturate it:
  - $I_C = \beta I_B = \frac{V_{+12} - V_{CE}}{R_C} + I_L \approx \frac{V_{+12}}{R_C} + I_L$ *(saturation plus sink current)*
  - $R_B \leq \frac{V_{In} - V_{BE}}{I_B}$ *(V_{BE} is voltage from base to emitter)*
  - $\therefore R_B \leq \frac{(V_{In} - V_{BE})\beta}{I_C} = \frac{(12-0.6)50\ V}{\left[\frac{12}{2}+10\right]mA} = 35.6k$
- When the transistor goes *on*, it sinks the load current.

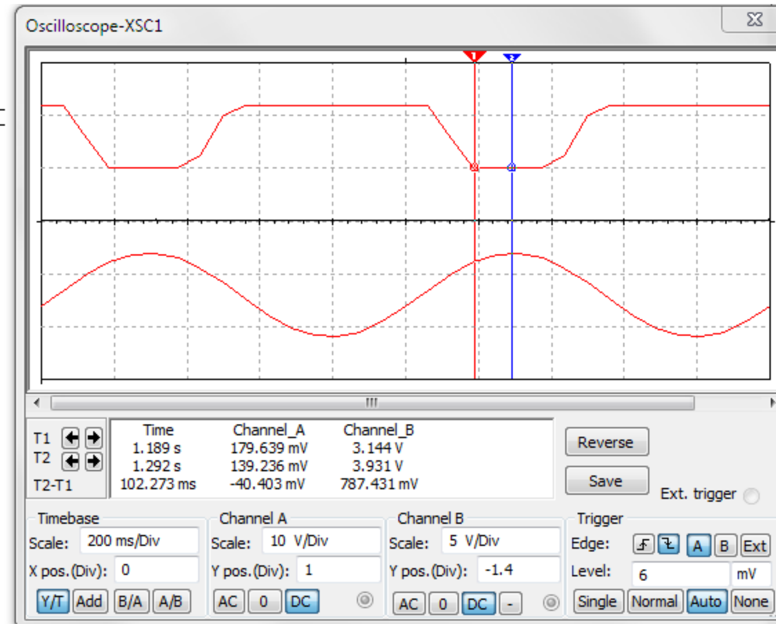
Mancini, R . *Op Amps for Everyone*, Texas Instruments, Dallas, TX (2002)

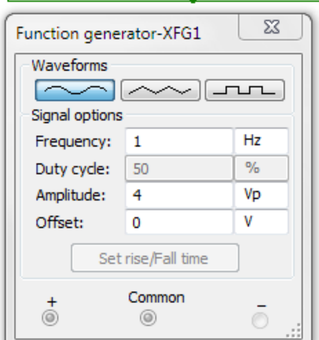
Transistor Switch Simulation…



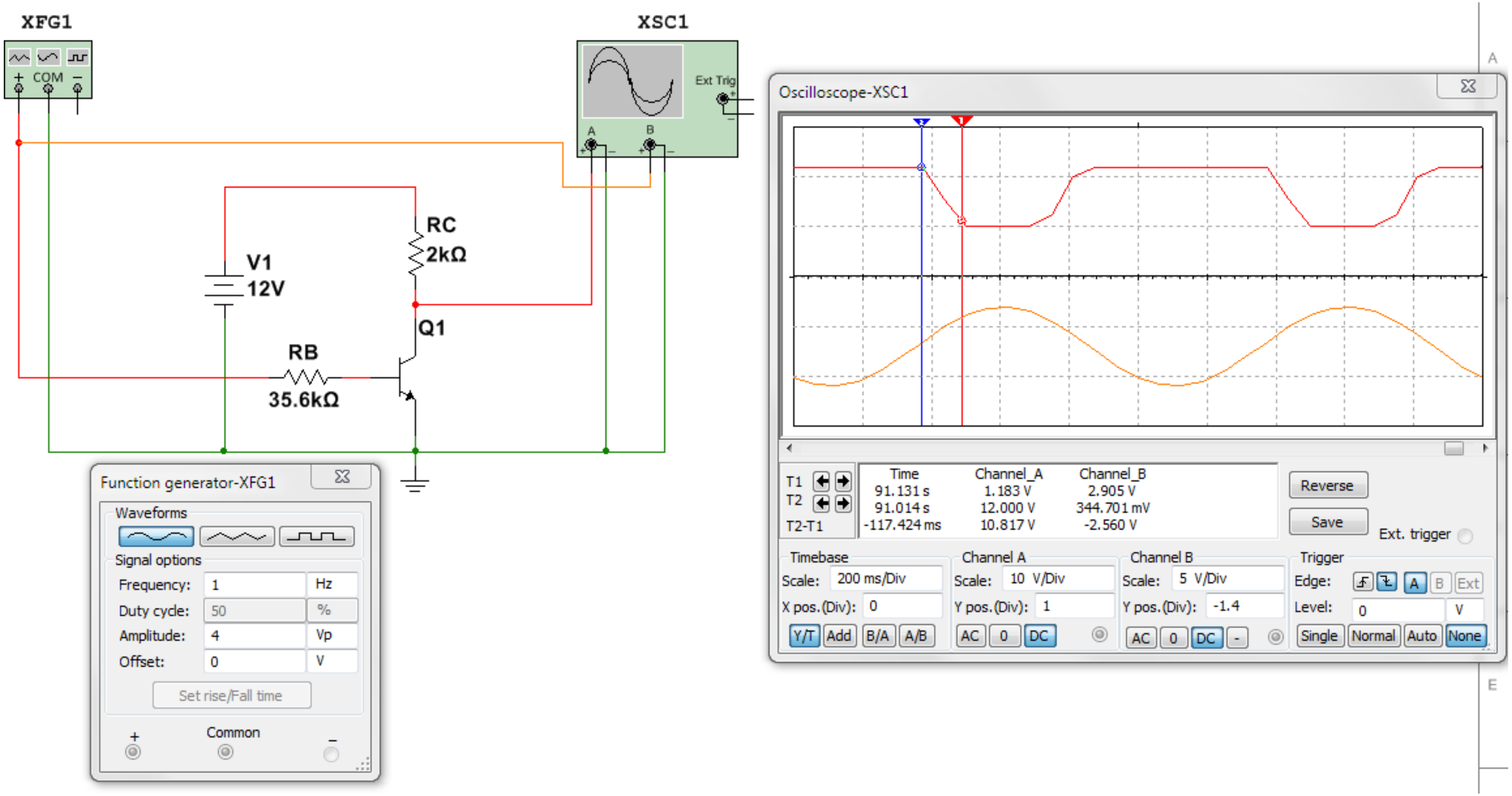
Saturation Voltage…







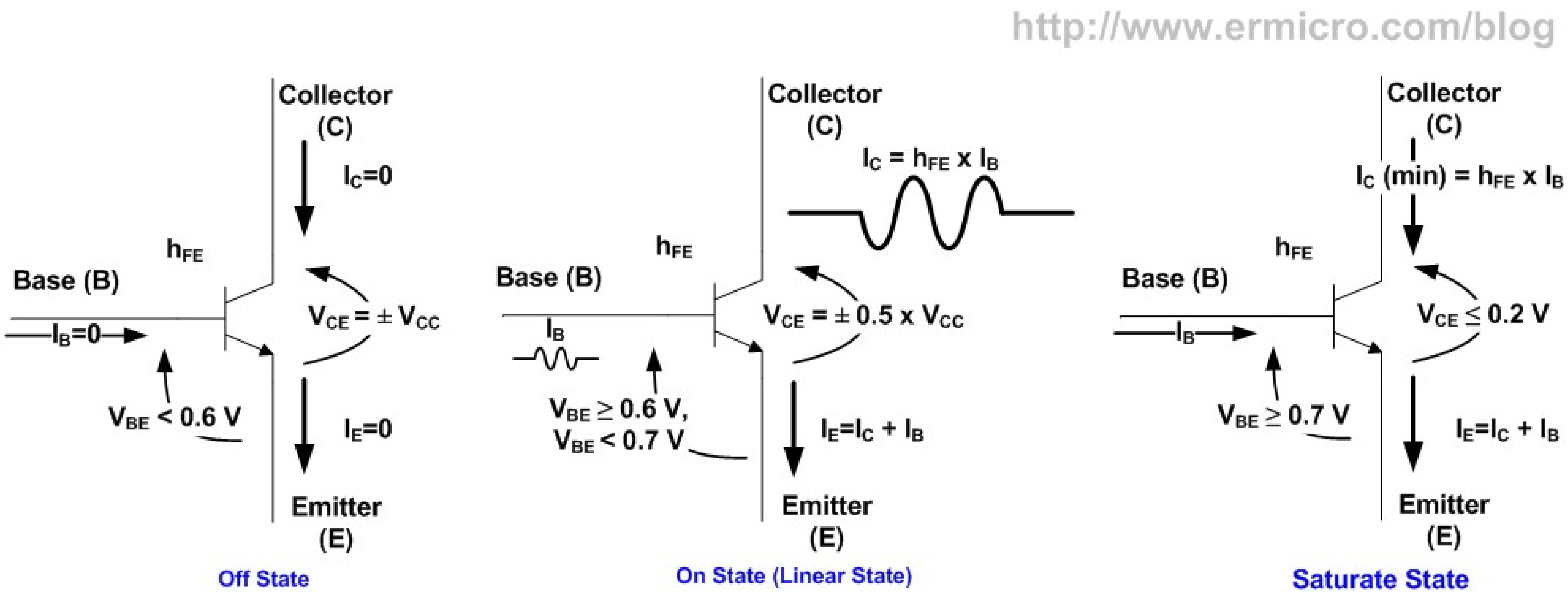
Linear Region…



Transistor as an Amplifier

- A transistor can be "off", "on" or in a "linear state" where I_B causes changes in I_C based on h_{FE}, the current gain factor:
  - $I_C = I_B \; x \; h_{FE}$
  - Useful for example, for a common emitter amplifier.
- In saturation, any changes in I_B will not cause changes in I_C.
- When "off", there is no base current applied.

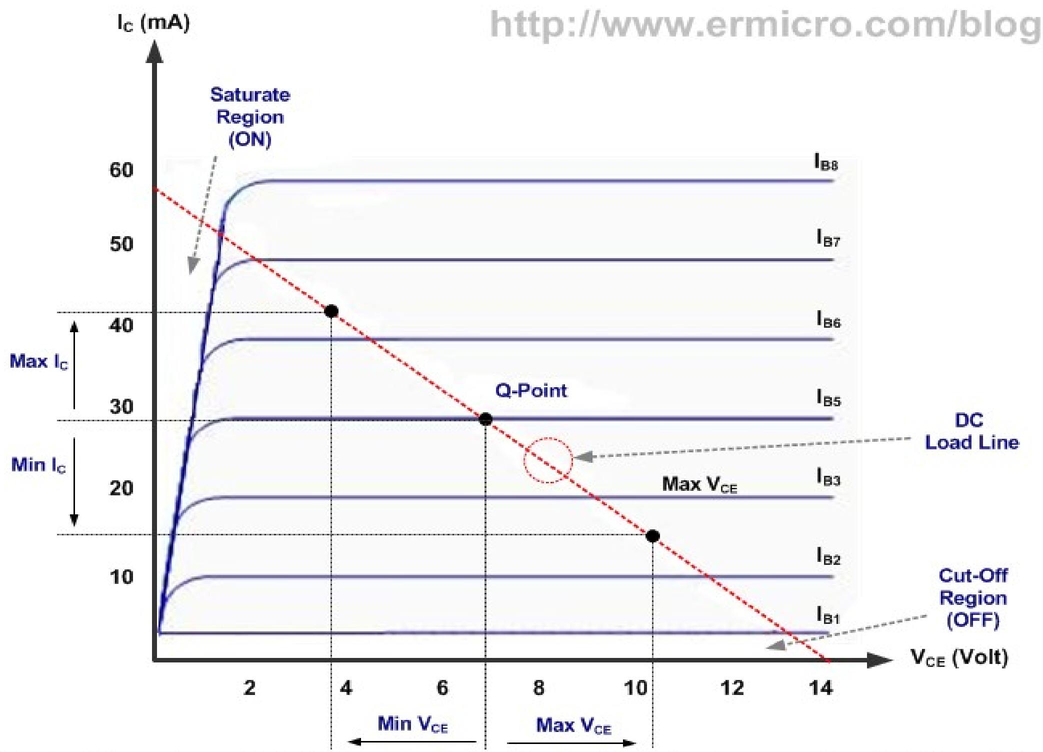
Transistor Operating State…



The Transistor Operating State

Image courtesy of www.ermicro.com/blog

Typical NPN Characteristic Curve…



Typical Transistor (NPN) Characteristic Curves for CE (Common Emitter) Amplifier

Curves relate the output collector current, (I_C) to the collector voltage, (V_{CE}) for different values of base current, (I_B).

Quiescent point - V_{CE} is set to allow the output voltage to swing positive and negative when amplifying an AC signal.

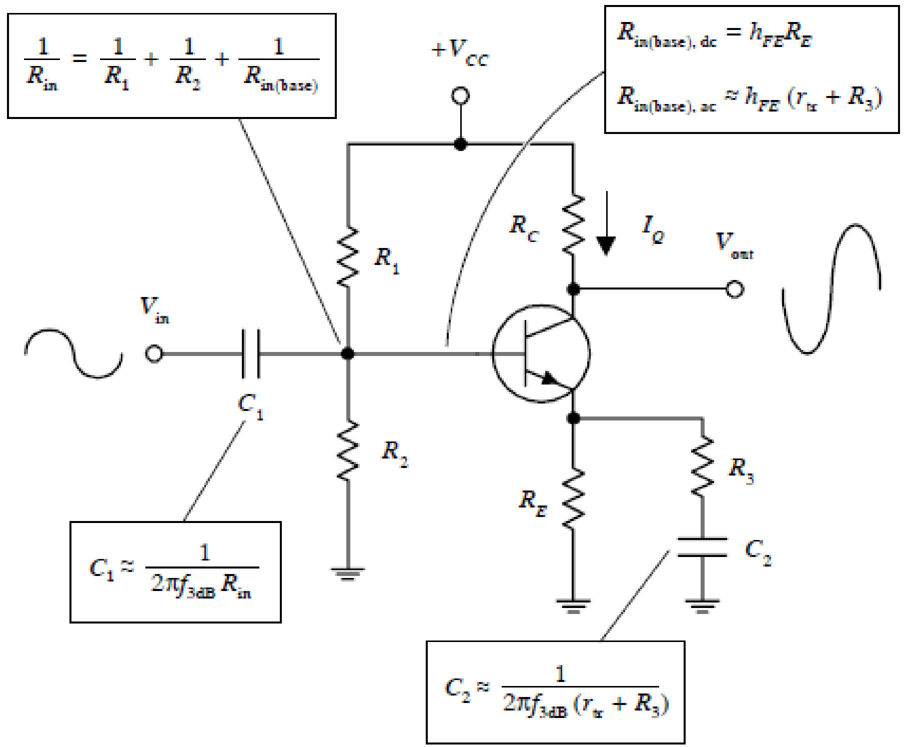
Image courtesy of www.ermicro.com/blog

Characteristic Curve Explained…

- These curves relate the output collector current, (I_C) to the collector voltage, (V_{CE}) for different values of base current, (I_B).
- A DC biasing voltage is applied to the base to allow it to operate in its linear region. The transistor is then operating half-way between its cutoff and saturation voltages.
- The DC load line shows all of the possible operating points when different base current values are applied.
- V_{CE} is set to allow the output voltage to swing positive and negative when amplifying an AC signal. This is referred to as setting the operating point or Quiescent point (Q-point).

Bipolar Junction Transistor Amplifier Example…

- Specifications:
  1. I_Q =1 mA (I_C)
  2. h_{FE} = 100 (Gain)
  3. V_{CC} = 20 V (Source)
  4. f_{3dB} = 100 Hz
  5. V_{BE} is 0.6 V
  6. Set V_{OUT} (or V_C) to 10 V
  7. Set V_E to 1 V



Common Emitter Amplifier

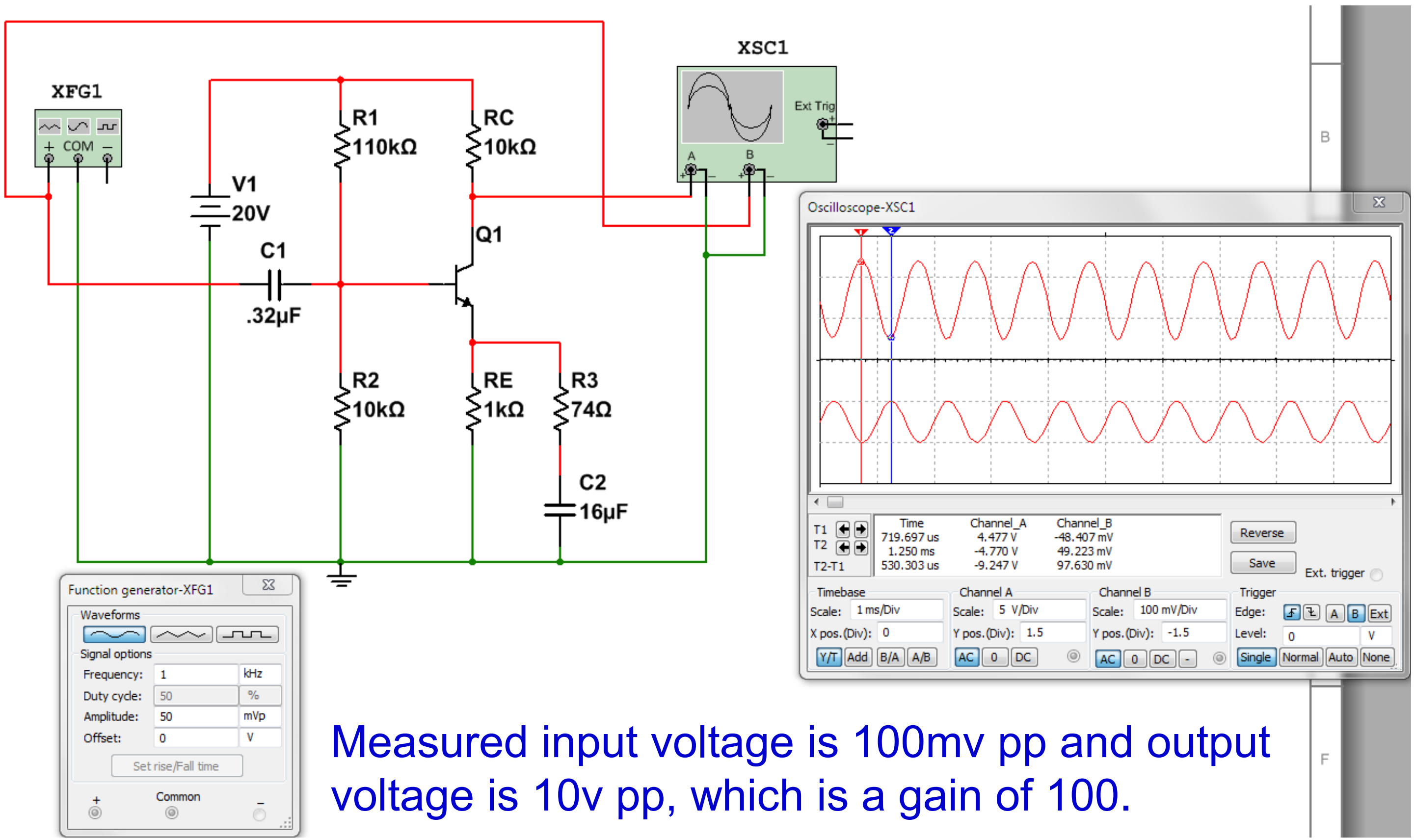
Scherz, P.& S. Monk. *Practical Electronics for Inventors*, McGraw Hill, New York, NY (2016).

Calculation of Resistors…

1. $R_c = \frac{V_c - V_{cc}}{I_c} = \frac{0.5V_{cc} - V_{cc}}{I_Q} = \frac{10\ V}{1\ mA} = 10k\ \Omega$
2. $R_E = \frac{V_E}{I_E} = \frac{1\ V}{1\ mA} = 1k\ \Omega$
3. $V_B = V_E + 0.6\ V = 1.6\ V$
4. $\frac{R_2}{R_1} = \frac{V_B}{V_{cc} - V_B} = \frac{1.6\ V}{20\ V - 1.6\ V} = \frac{1}{11.5},\ R_1 = 11.5R_2$
5. $\frac{R_1 R_2}{R_1 + R_2} \leq \frac{1}{10} R_{in(base),dc},\ R_{in(base),dc} = h_{FE} R_E$
   - $R_2 = 10k\ \Omega$
   - $R_1 = 115k\ \Omega$ (Substitute $110k\ \Omega$ which exists.)
6. R_3, C_1 and C_2 are based on gain and frequency.

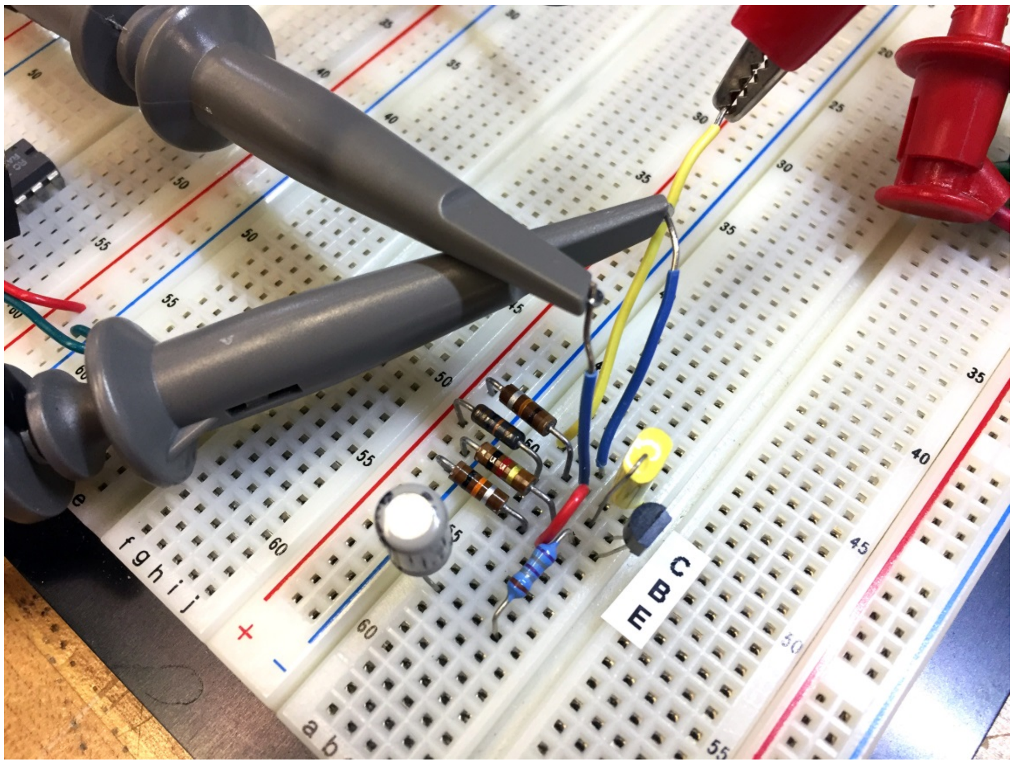
Scherz, P.& S. Monk. *Practical Electronics for Inventors*, McGraw Hill, New York, NY (2016).

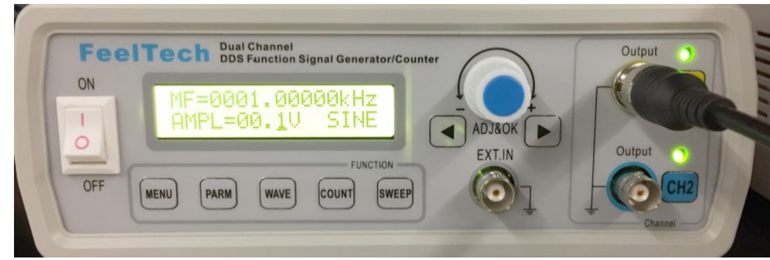
Simulation of the Amplifier…



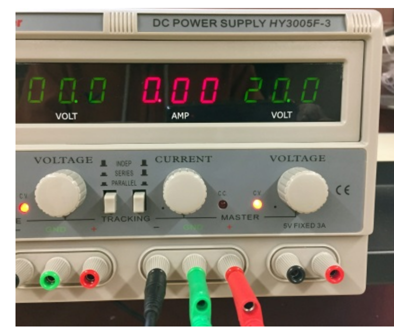
Measured input voltage is 100mv pp and output voltage is 10v pp, which is a gain of 100.

Amplifier on a Breadboard Example…



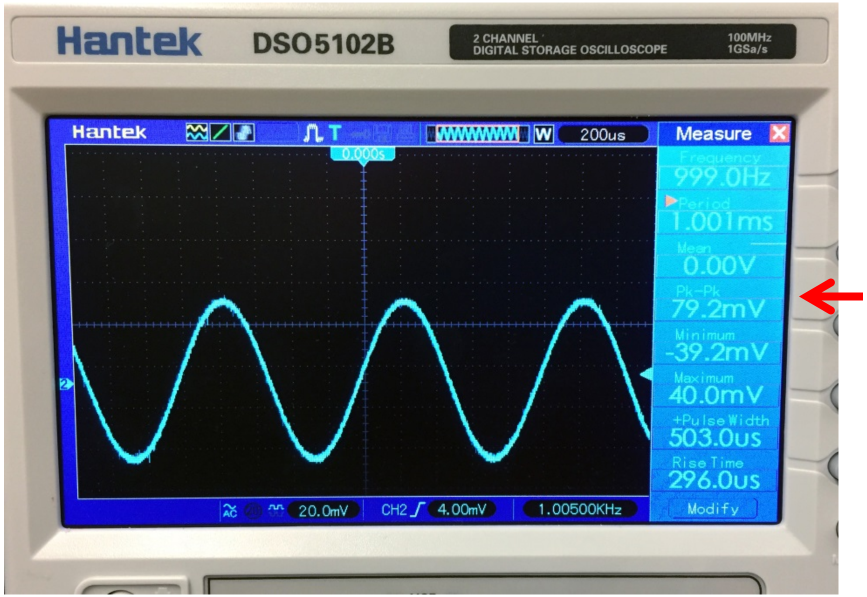


Function Generator set at 1 kHz, 0.1 V pp
(Actually measures 79.2 MV pp on oscilloscope)

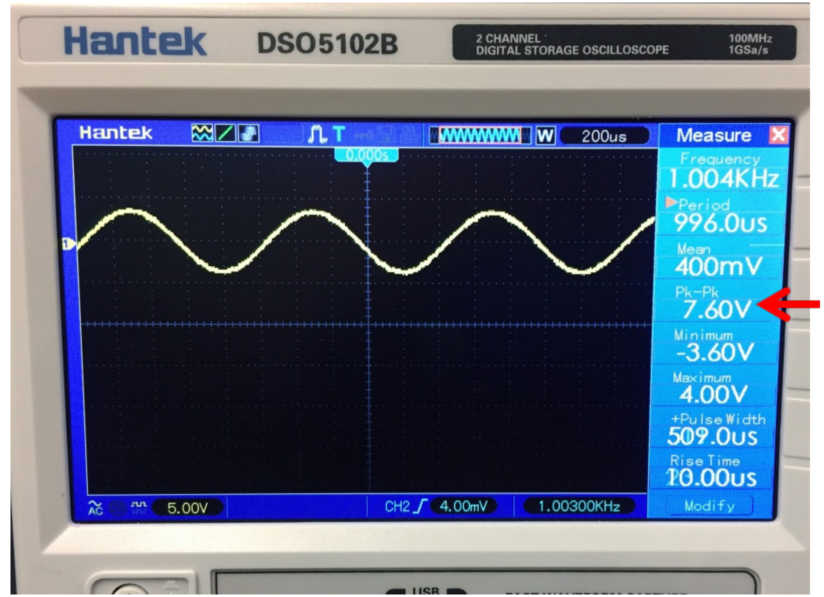


Power Supply set at 20 VDC

Voltage Gain…

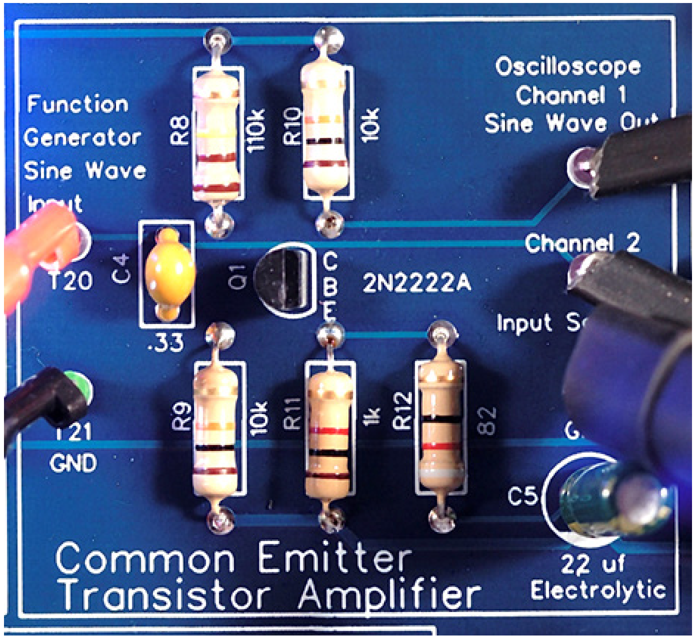


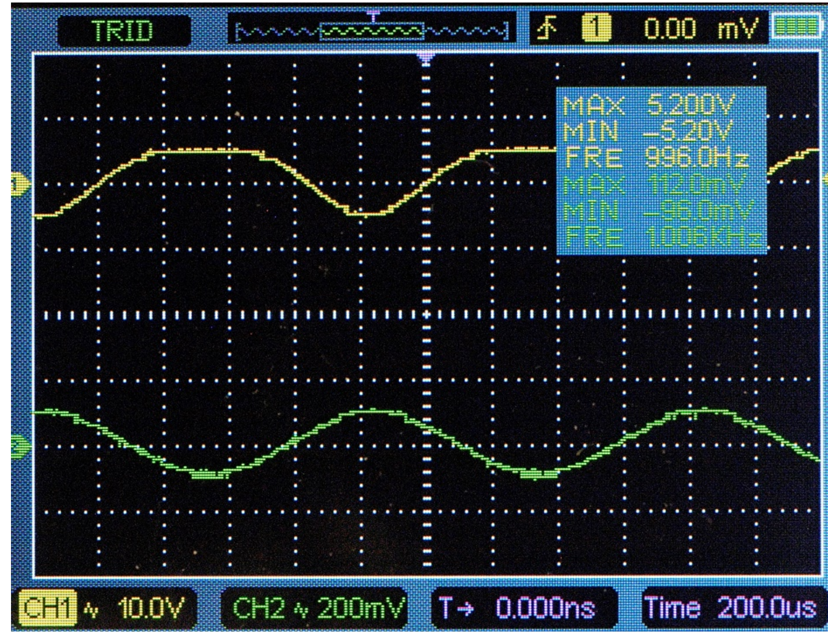
Amplifier Input 79.2 mV pp



Amplifier Output 7.6 V pp
Gain is 7.6/.079 = 96.2

Amplifier with the Trainer Board & Hantek 2D72…





- In this example, the input voltage measures 208 mVpp (.112 + .096), and the output voltage measures 10.4 Vpp (5.2 + 5.2).
- The gain is 10.4/.208 = 50

Summary

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