UNIVERSITY OF WOLLONGONG IN DUBAI

ECTE250

ENGINEERING DESIGN AND MANAGEMENT 2

Winter 2025 / Spring 2025

Practical Electronics 1

References

Diagrams used in these lecture notes are artwork directly taken for teaching purposes from

- Sedra and Smith, “Microelectronics Circuits”, International Edition, Oxford University Press (available in library)

- Voltage Regulator Basics https://www.baldengineer.com/regulator-basics.html

- Paul Scherz and Dr Simon Monk “Practical Electronics for Inventors”, McGraw Hill, 2013/2016, 3rd/4th Edition (available in library)

Outline

- Diodes
- Zener diodes
- Limiting Circuits
- Clamping circuits
- Voltage regulator circuits
- PWM

The Ideal Diode

- Most Fundamental non-linear element
- Two terminal device

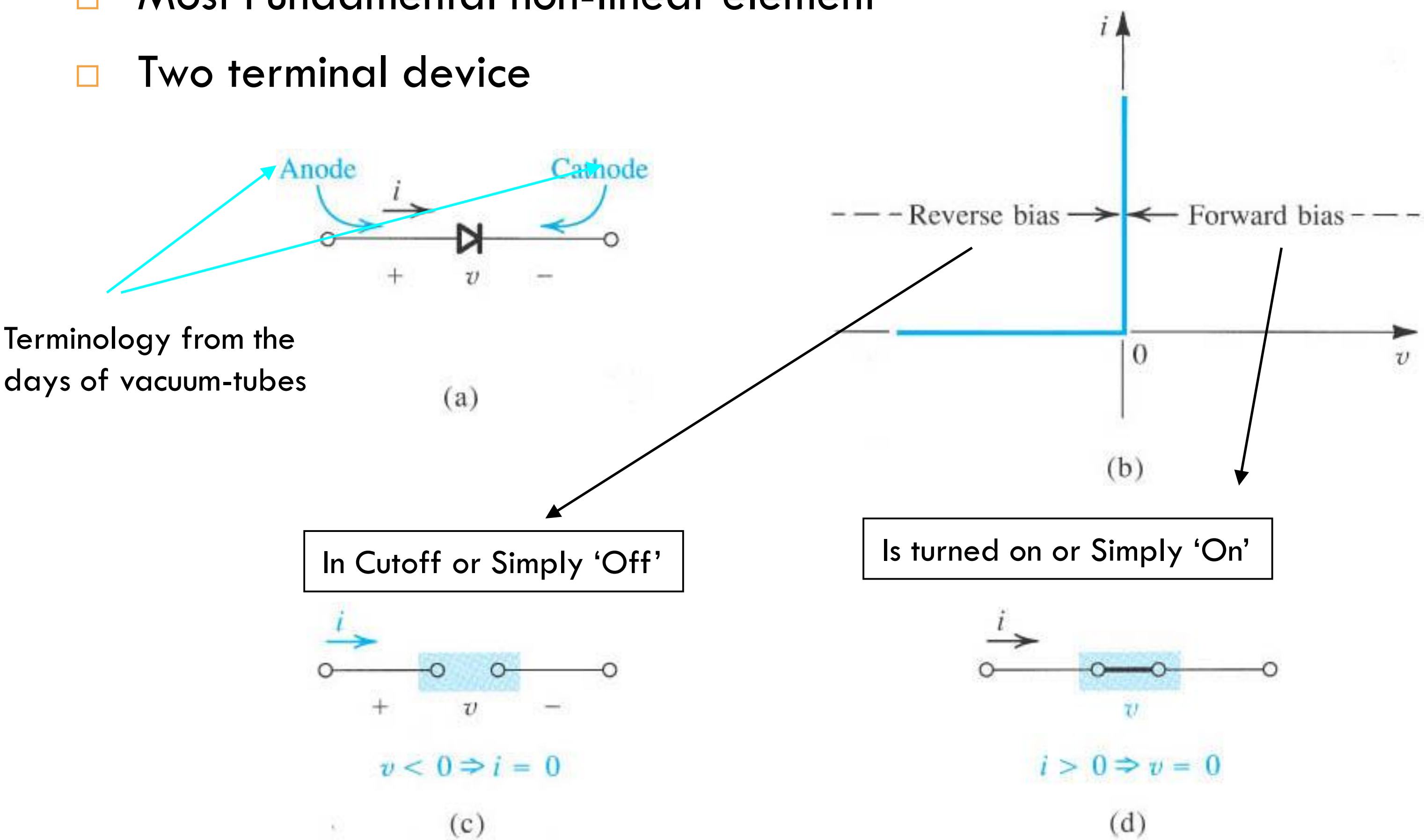

Figure 3.1 The ideal diode: **(a)** diode circuit symbol; **(b)** *i*–*v* characteristic; **(c)** equivalent circuit in the reverse direction; **(d)** equivalent circuit in the forward direction. Source: Page 140 Sedra and Smith 5th Edition

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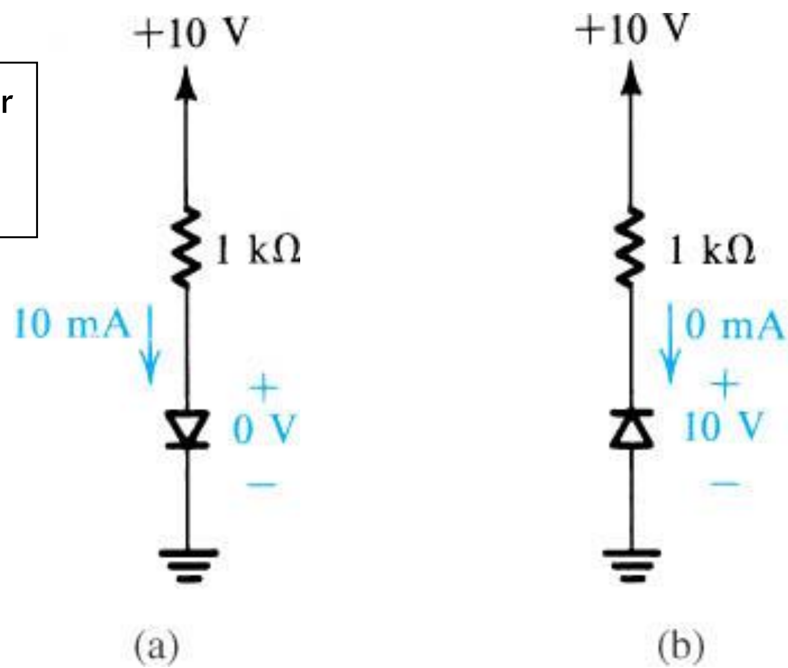
The Ideal Diode

Example

1k ohm resistor determines current



All 10 volts Appears Across the Reverse biased diode

Figure 3.2 The two modes of operation of ideal diodes and the use of an external circuit to limit the forward current **(a)** and the reverse voltage **(b)**. Source: Page 141 Sedra and Smith 5th Edition

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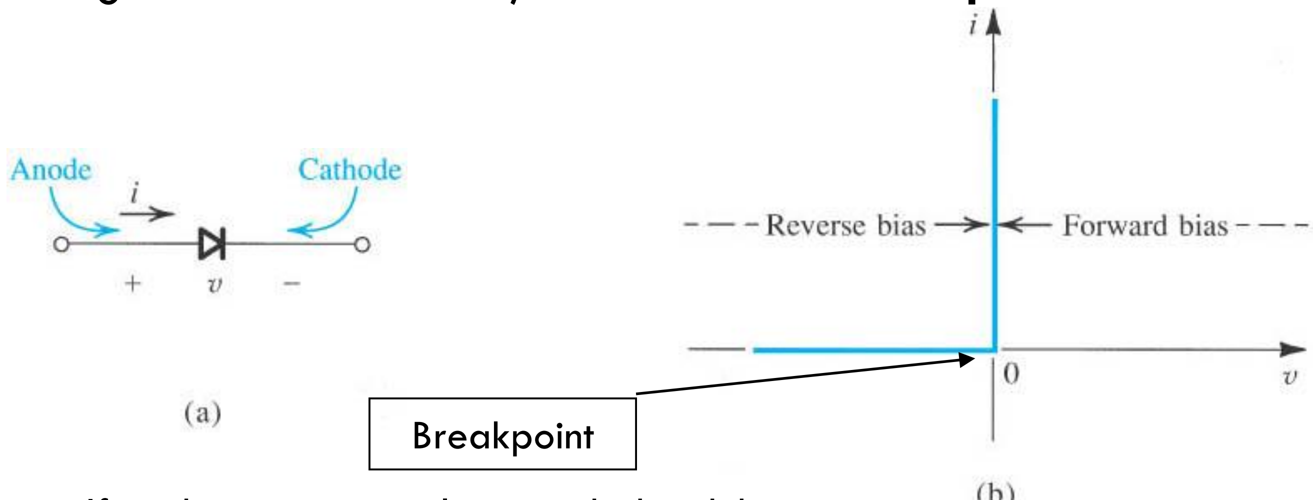
The Ideal Diode

- Ideal diode current versus voltage (i-v) curve is highly nonlinear
- But, because it consists of two orthogonal straight lines (i.e. operating lines are 90 degrees to each other) it can be said to be **piece-wise linear**



- Advantage: If we have a circuit element which exhibits a piece-wise or near piece-wise linear operation and we choose to operate this circuit in the piece-wise linear location / region (eg small signal equivalent circuit models we will see later) then we can treat the circuit as a linear circuit in our analysis – provided we do not allow our design to swing across breakpoints where the circuit switches from one segment of linear operation to another!

- Sometimes a circuit may not be piece-wise linear, like a diode, but if small enough signals are used it can be close enough for analysis.

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Circuits with Ideal Diodes

Diode Logic Gates: If 0V represents 0 (high) and +5V represents 1 (low) then:

- Circuit (a) will have 5V at v_y if any of v_a,v_b, v_c are +5V with any diode or all diodes in the 'on' state; it will be 0V at v_y (pulled down by resistor R) if all inputs are 0V and thus the diodes are all 'off' the logic **OR** function.
- Circuit (b) will have 0V at v_y if any of v_a,v_b, v_c are 0V with any diode then forward biased ('on' state) but if all of v_a,v_b, v_c are at +5V then the diodes will be 'off' and v_y will be +5V (pulled up by R) thus implementing a logic **AND** function

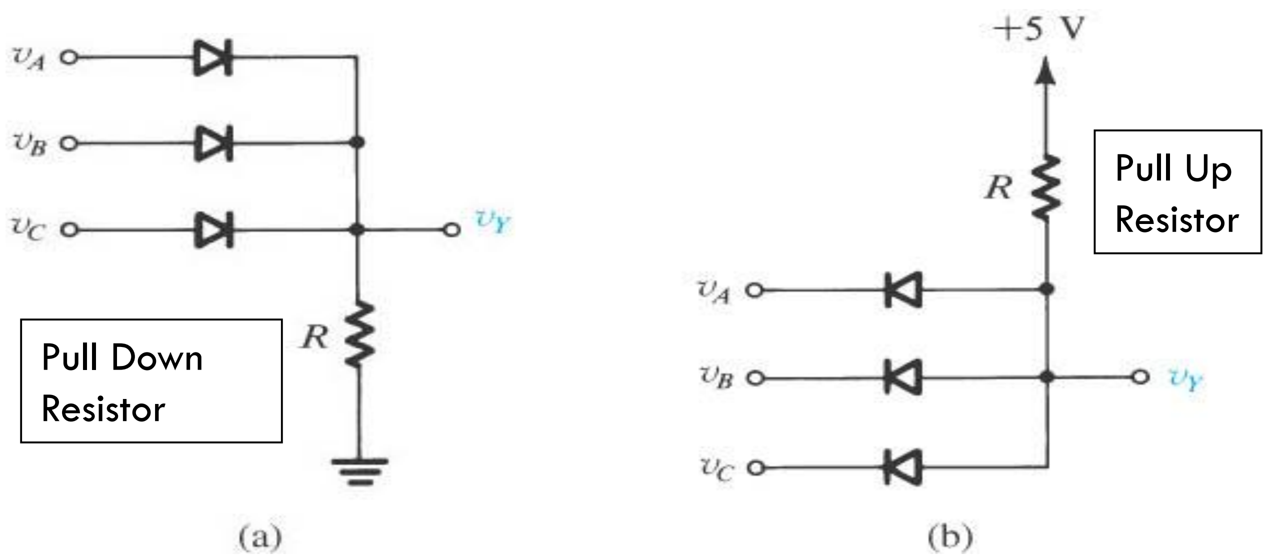

Figure 3.5 Diode logic gates: **(a)** OR gate; **(b)** AND gate (in a positive-logic system). Source: Page 144 Sedra and Smith 5th Edition

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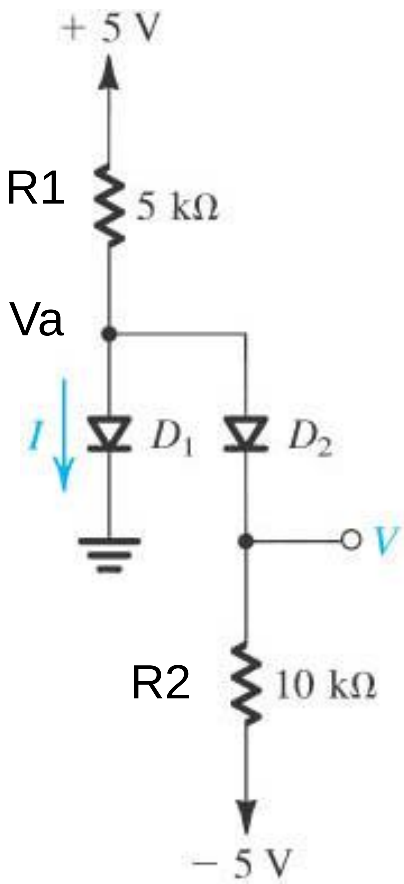
Circuits with Ideal Diodes



Q: For the circuit shown find the current I and the Voltage V. (problem 3.9a from Sedra and Smith)

Ans: We need to determine if D_1 , D_2 or both are conducting? So we should make plausible assumptions, proceed and then determine if these assumptions lead to a consistent solution.

So it seems plausible that both D_1 and D_2 are conducting.

If so then all 5V is dropped across the 5kohm resistor R1; resulting in current through R1=5/5k=1mA;

Also if D_2 is conducting V=0 volts and the current through R2 =(0-(-5))/10k=0.5mA

Which means that I=1mA-0.5mA=0.5mA

This seems to be a consistent solution

In fact if D_2 isn't conducting then the voltage Va must be less than -5V and D_1 must be on (for a current flow) but once D_1 is on then Va must be 0 volts (as D_1 is ideal and will have a 0 volt drop across it) so such a solution is not consistent;

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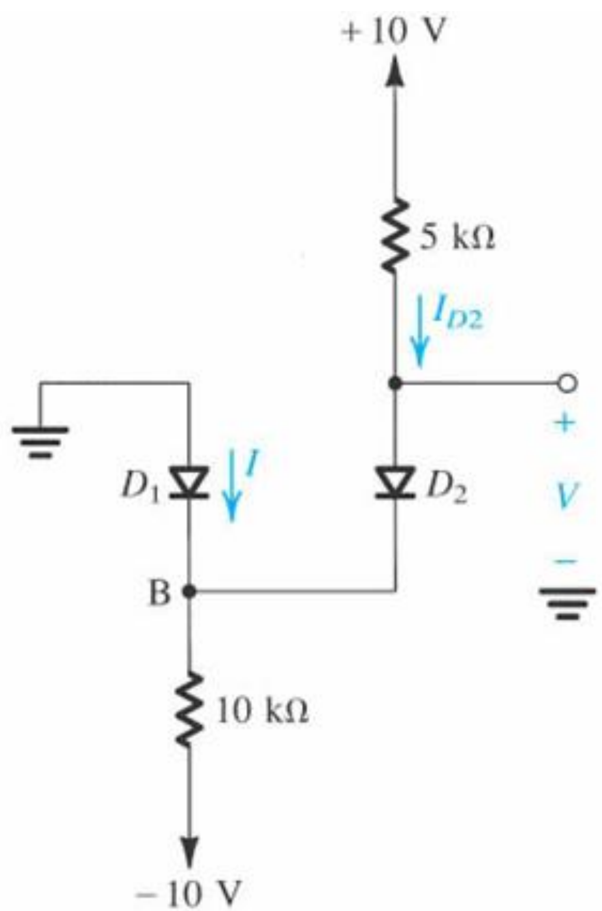
Circuits with Ideal Diodes



Now consider this circuit, once again lets assume that D_1 and D_2 are 'on' .
If this is so then V_B=0 and V=0

The current in D_2

$$I_{D2} = \frac{10V - 0V}{5K\Omega} = 2mA$$

Forming KCL (Kirchhoff's Current Law) nodal equation at node B gives:

$$I + 2mA = \frac{0V - (-10V)}{10K\Omega}$$

which results is an inconsistent current for *I* of -1mA!! So D_1 and D_2 cannot be both on!

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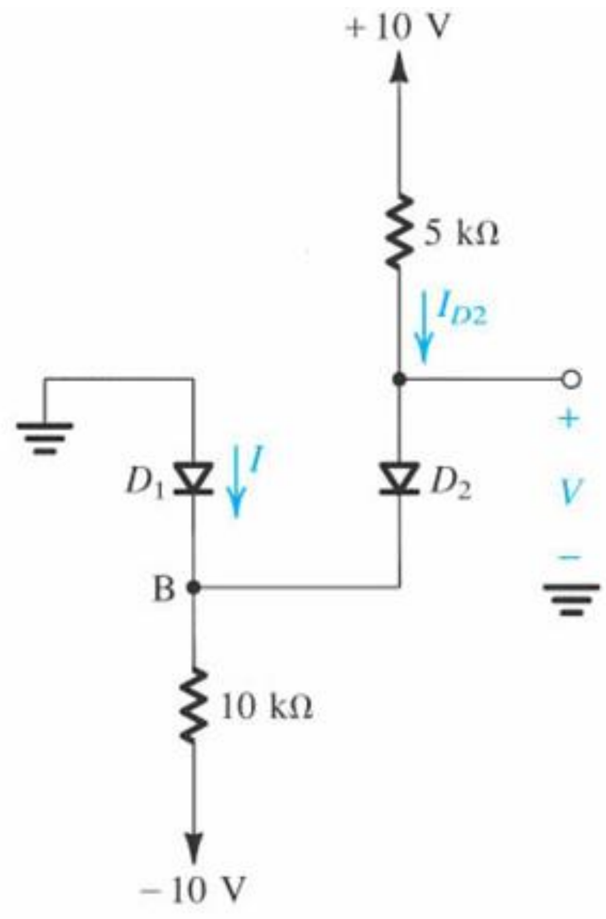
Circuits with Ideal Diodes



Now assume D_1 is 'off' and D_2 is 'on'

The current in D_2 is then:

$$I_{D2} = \frac{10V \ - (-10V)}{5K\Omega + 10K\Omega} = 1.33mA$$

and the voltage at node B is:

$$V_B = -10V + (10K\Omega * 1.33mA) = 3.3V$$

Which is consistent with D_1 being off and D_2 being on;

hence $V=V_B=3.3V$ and $I=0$ for this circuit

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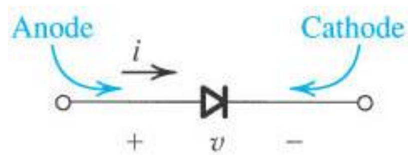
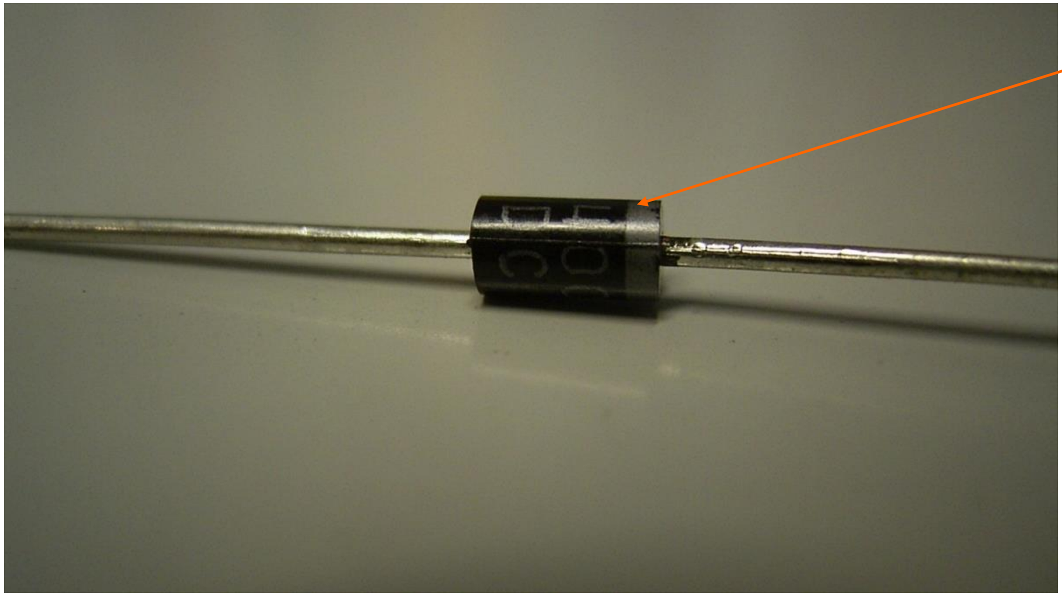
Real Diodes

- Diodes Marking
  - The Cathode (K) is usually marked with a silver bar/ring



Cathode



Real Diodes

- Silicon Junction Diodes
  - The current-voltage relationship of a typical silicon junction diode appears like this (e.g. 1N4007 from ECTE250 kits):

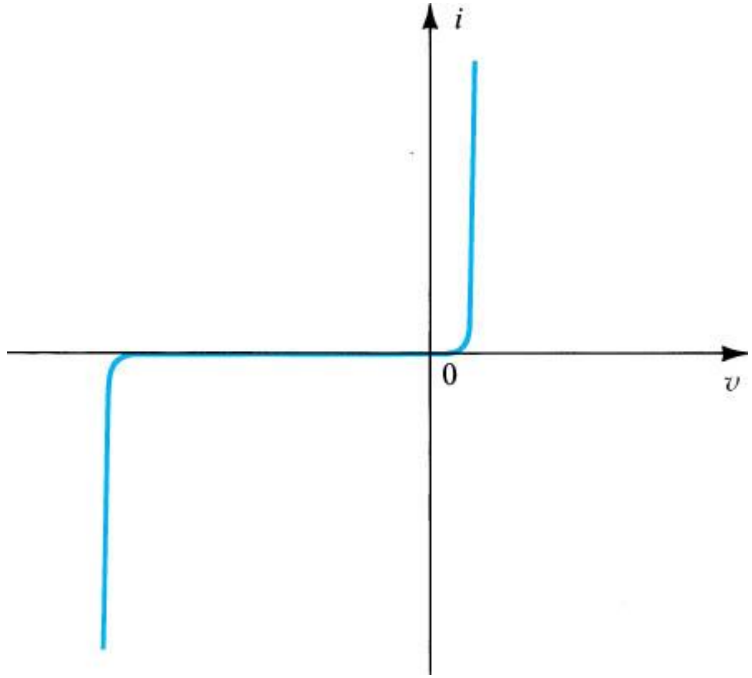


Figure 3.7 The *i*–*v* characteristic of a silicon junction diode.

Real Diodes

Silicon Junction Diode - Three distinct regions are:

- The **forward bias** region, determined by v>0
- The **reverse bias** region, determined by v<0
- The **breakdown** region, determined by $v<-V_{ZK}$

Note: below 0.5V the current is negligibly small
The voltage 0.5V is referred to as the **knee-voltage** or **cut-in voltage**

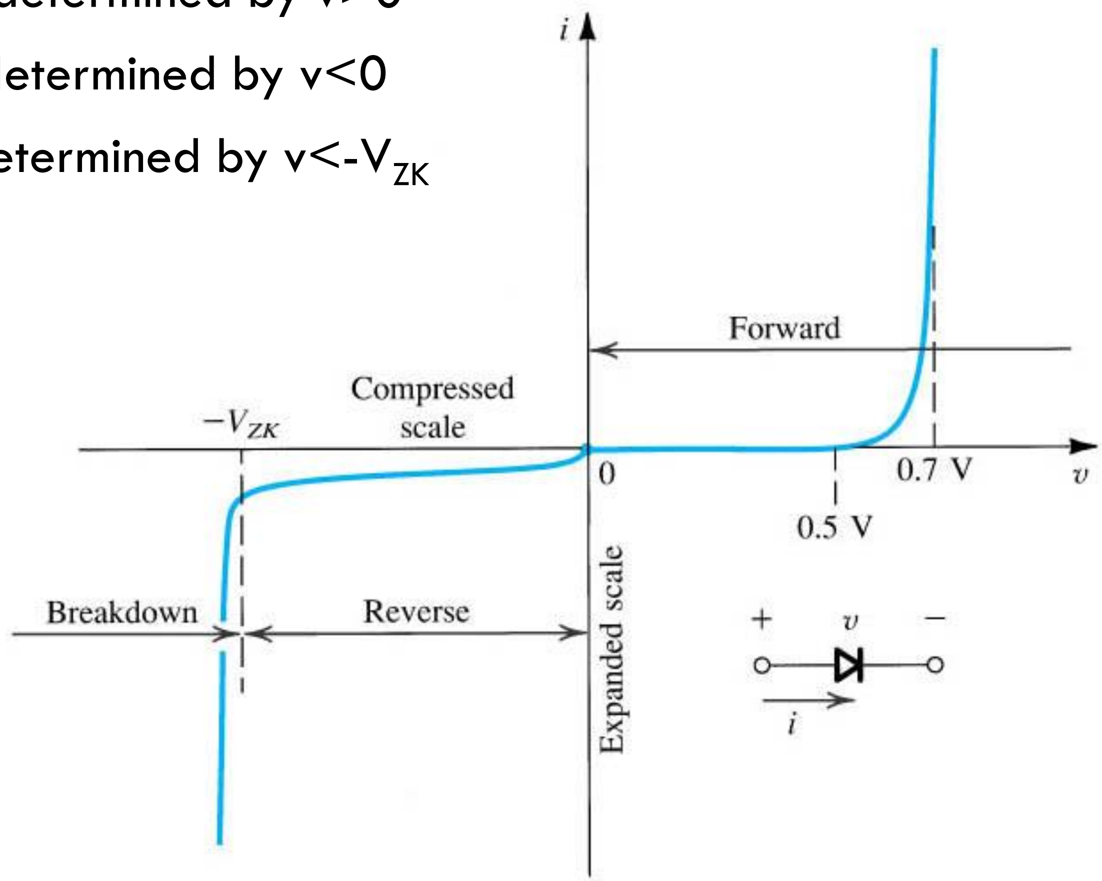


Figure 3.8 The diode *i*–*v* relationship with some scales expanded and others compressed in order to reveal details.

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Real Diodes

Silicon Junction Diode – Forward Bias Region (when v>0):

- i-v relationship closely approximated by

$$i = I_S\left(e^{v/nV_T} - 1\right)$$

  - I_s is usually called the **Saturation Current** (sometimes called the **Scale Current**)
  - For small signal diodes (low power) it has a value in the order of 10^{-15} Amps
  - Rule of thumb: for every 5 °C of temperature I_s doubles in value
  - *n* is the *ideality factor*, or *quality factor* or *emission coefficient.*

- V_T is called the **Thermal Voltage**
  - given by: $V_T = kT/q$
  - K = Boltzmann's constant = 1.38 x 10^{-23} Joules/Kelvin
  - T = the absolute temperature in Kelvin = 273 + $T_{Celsius}$
  - q = the magnitude of charge of an electron = 1.6 x 10^{-19} Coulomb

Real Diodes

Silicon Junction Diode – Forward Bias Region:

$$i = I_S\left(e^{v/nV_T} - 1\right)$$

- For V_T
  - At room temperature (20 °C) the value of V_T is 25.2mV
  - At 25 °C (typical for electronic equipment stored in a cabinet) it is 25.8mV
  - For simplicity we will use 25mV

- The constant *n* in equation
  - Has a value between 1 and 2 (function of material and physical structure of diode)
  - Normally assume n=1 (unless stated otherwise)

Real Diodes

Silicon Junction Diode – Forward Bias Region:

For the case where the current i >> I_s the approximation that can be used is:

$$i \cong I_S e^{v/nV_T}$$

Alternatively we can express this in logarithmic (natural-base e) form:

$$v \cong nV_T \ln\left(\frac{i}{I_S}\right)$$

Exponential i-v relationship holds over many decades of current – can be as much as a span of 7 decades ie a factor of 10^7 (this also applies to BJT's).

Real Diodes

Silicon Junction Diode – Forward Bias Region:

Using

$$i \cong I_S e^{V/nV_T}$$

And evaluating the current I_1 which related to a diode voltage V_1 we have:

$$I_1 = I \; e^{V_1 \; /nV_T}$$

And evaluating the current I_2 which related to a diode voltage V_2 we have:

$$I_2 = I \; e^{V_2 \; /nV_T}$$

Dividing the second equation by the first gives:

$$\frac{I_2}{I_1} = e^{(V_2 - V_1)/nV_T}$$

Real Diodes

Taking natural logarithms of both sides gives:

$$\ln\left(\frac{I_2}{I_1}\right) = \ln\left(e^{(V_2-V_1)/nV_T}\right)$$

$$\ln\left(\frac{I_2}{I_1}\right) = (V_2-V_1)/nV_T$$

which means that:

$$V_2 - V_1 = nV_T \ln\left(\frac{I_2}{I_1}\right)$$

Or we can get the results in terms of log10 by changing the base:

Since,

$$\log_a N = \frac{\log_b N}{\log_b a}$$

$$\therefore \ln\left(\frac{I_2}{I_1}\right) = \frac{\log_{10}\left(\frac{I_2}{I_1}\right)}{\log_{10} e}$$

where

$$\frac{1}{\log_{10}(e)} \cong 2.3$$

Which gives:

$$V_2 - V_1 = 2.3nV_T \log_{10}\left(\frac{I_2}{I_1}\right)$$

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Real Diodes

$$V_2 - V_1 = 2.3nV_T \log_{10}\left(\frac{I_2}{I_1}\right)$$

Simply stated, for a decade of change in current the diode voltage drop changes by $2.3nV_T$:

- About 60mV for n=1
- About 120mV for n=2

This suggests that diode *i*-*v* characteristics are best plotted on semi-log paper or scales using *v* as vertical & linear axis, and *i* as the horizontal and log scaled axis one will obtain a straight line with a slope of $2.3nV_T$ per decade of current.

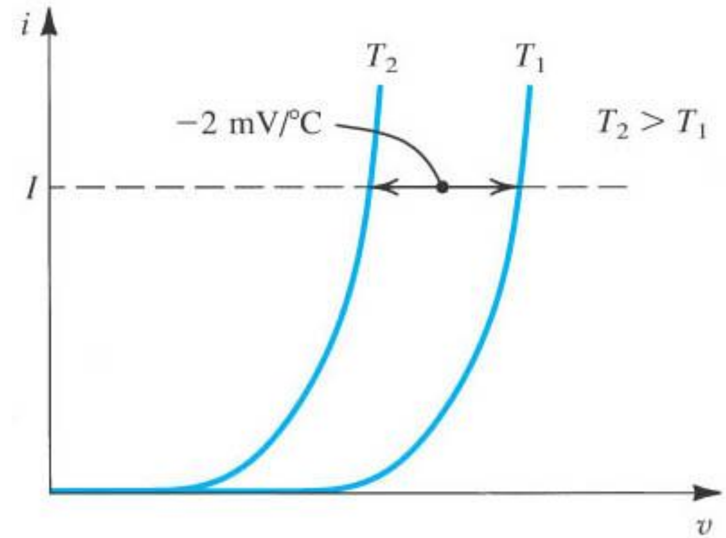
Not knowing 'n' circuit designers use the rule of $2.3nV_T$ being equal to 0.1 V i.e. a 0.1V/decade change.

Real Diodes

Silicon Junction Diode – Forward Bias Region:

- Note that diodes with different current ratings will experience a 0.7 V drop (used as a rule of thumb for a fully conducting diode which will be typically in the range of 0.5-0.8V drop- and the basis of the model we will most often employ for diodes) at different currents.
- Also, I_S and V_T are both temperature dependent which means forward i-v characteristic is also a function of temperature:

Figure 3.9 Illustrating the temperature dependence of the diode forward characteristic. At a constant current, the voltage drop decreases by approximately 2 mV for every 1°C increase in temperature. (pg 151 Sedra&Smith)
This characteristic has been exploited to produce electronic thermometers!



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Real Diodes

Silicon Junction Diode – Reverse Bias Region:

- From $i = I_S\left(e^{v/nV_T} - 1\right)$ (in theory), if v is negative and a few times larger than V_T then we can say that:

$$i \cong -I_S$$

- That is the current in the reverse direction is constant and equal in magnitude to the saturation current (this constancy is the origin of its name!)

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Real Diodes

- Real diodes exhibit currents that are still small but larger than I_S would indicate
  - E.g. a small signal diode has I_S about 10^{-14} to 10^{-15} Amps but the reverse current could be of the order of 1nA(10^{-9})
- There is also a tendency for the reverse current to increase in magnitude with the reverse voltage
- The reverse current is less sensitive to temperature changes doubling (rule of thumb) every 10 °C rise in temperature (see slide 17)
- We normally don't need to consider this in an analysis as currents are small compared to a forward biased current

Real Diodes

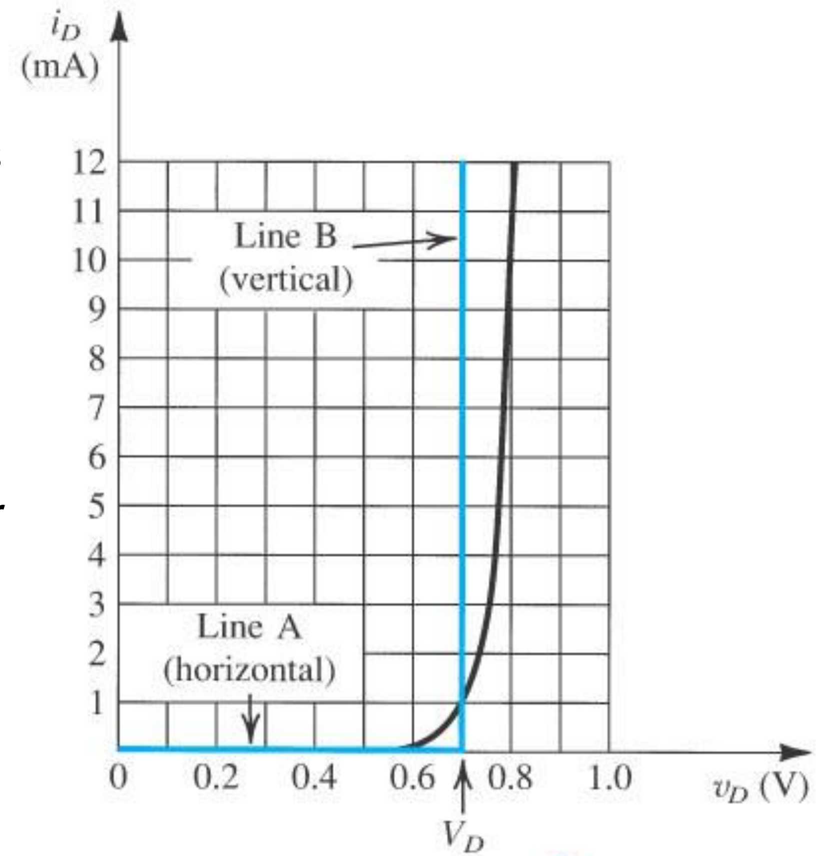
Silicon Junction Diode – Breakdown Region:

- Used in Zener diodes (diodes designed to be operated in the breakdown region).
- Once the reverse voltage exceeds a voltage called the breakdown voltage the diode will conduct in the reverse direction.
- Provided power dissipation is limited by the surrounding circuit topology to a safe level (refer to devices data sheet) the diode can be operated in the breakdown region – normally we only do this to Zener diodes in our designs.
- One application of the breakdown region is that of a voltage regulator as its i-v characteristic is almost vertical.

Practical Diode Model

Forward Bias – Constant Voltage Drop Model

- Simplest diode model
- Most often employed in quick calculations and at the initial phases of electronic design
- Uses a fixed forward bias diode drop of 0.7 V (usually) for silicon diodes
- It is clearly a form of the piecewise linear model where line B has infinite slope!
  $r_D = 0\Omega$
  $V_{D0} = 0.7$ V



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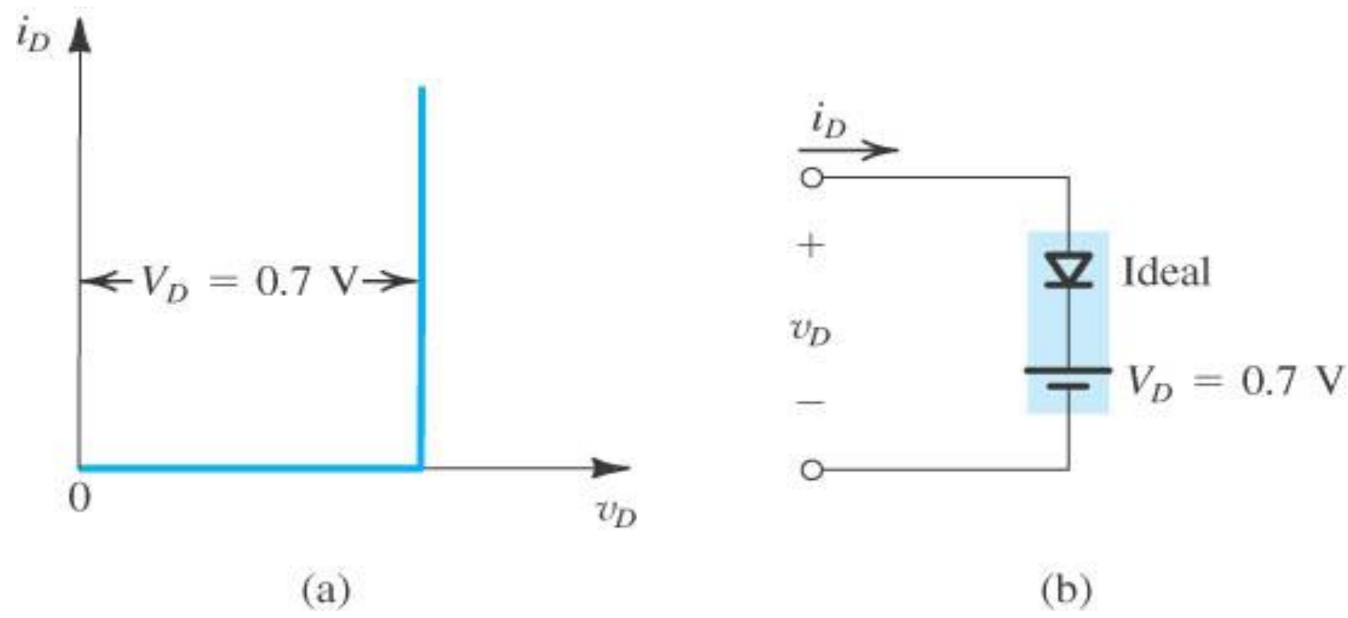
Practical Diode Model

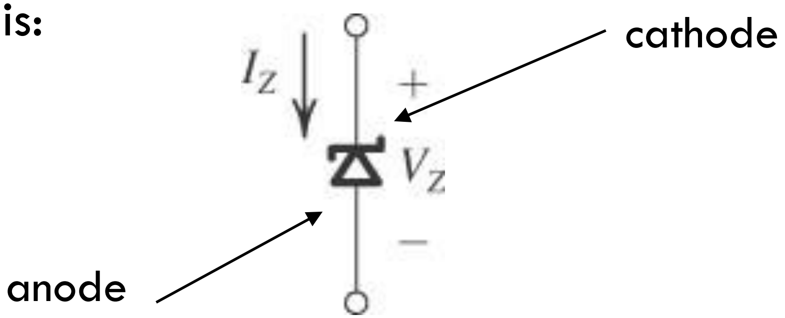
Forward Bias – Constant Voltage Drop Model

- The equivalent circuit of this model is



Zener Diodes

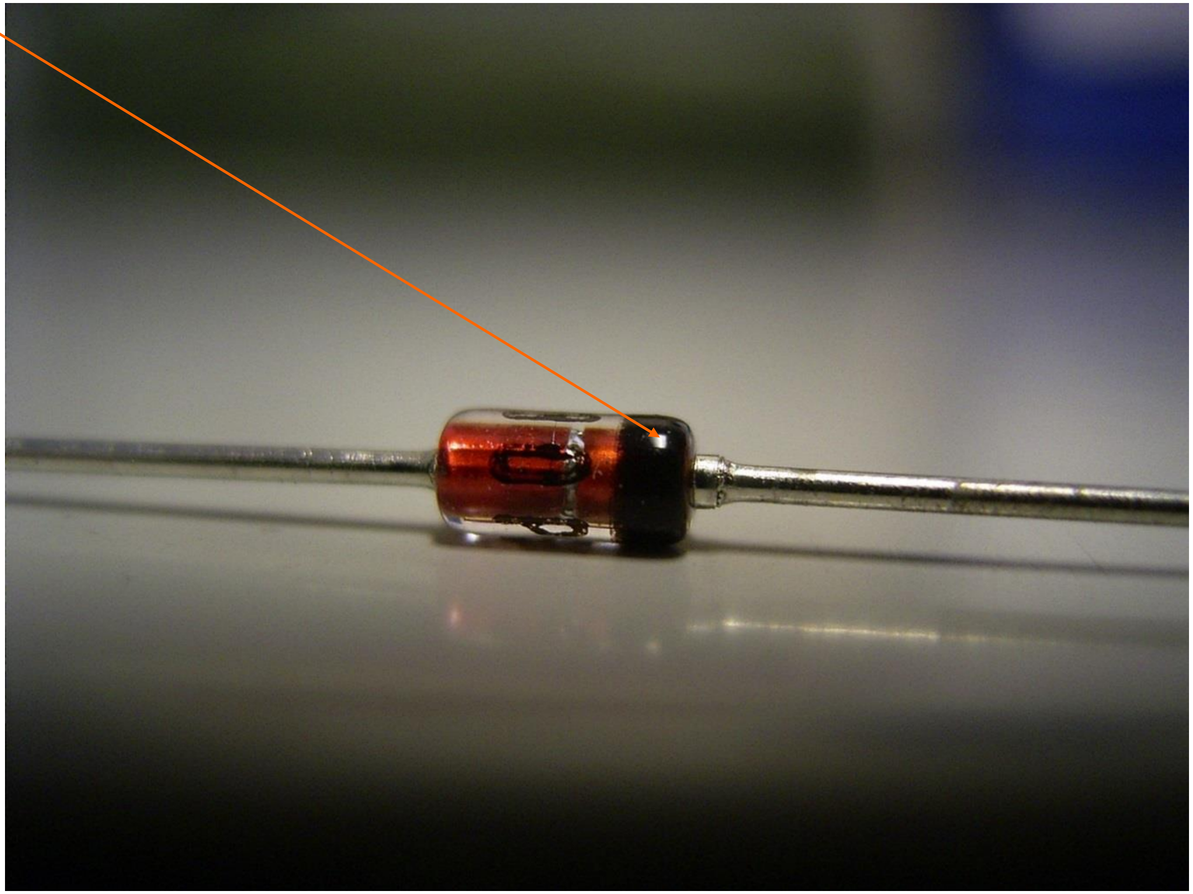
- Diodes designed to operate in the breakdown region (aka breakdown diodes)
- Have application in voltage regulators but now these have special purpose devices that do this (not as important as they once were)
- The circuit symbol of a Zener is:



- Normal applications of Zener diodes current flows into the cathode, and the cathode is +ve with respect to the anode which means that I_z and V_z have +ve values in this diagram

Zener Diodes

Cathode



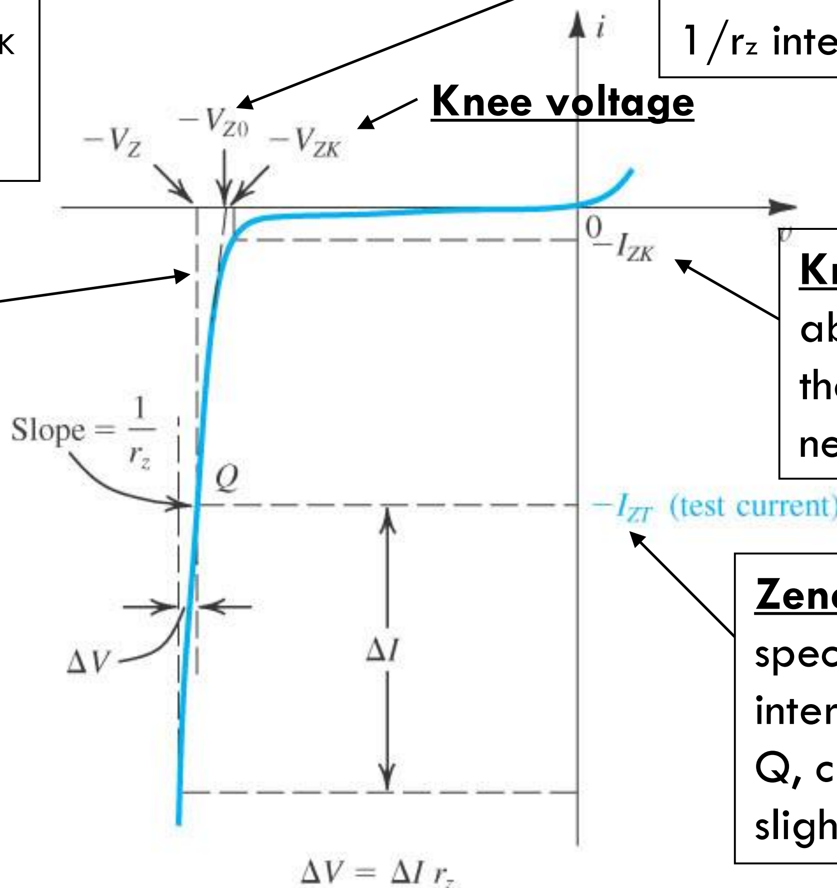
Zener Diodes

i-v characteristics of zener breakdown region:

Note that for V_{Z0} and V_{ZK} in practice their values are almost equal!

Point at which the line with slope $1/r_z$ intersects the voltage axes

Knee voltage



Good idea to avoid operation around knee as here the slope varies widely and hence the **incremental** (dynamic) resistance r_z (this is also specified in data sheets) will also vary widely

Knee current: for currents above this the zener current is nearly a straight line

Zener test current, specified in data sheet intersects with curve at Q, changes in i will cause slight changes in v

Zener Diodes Model

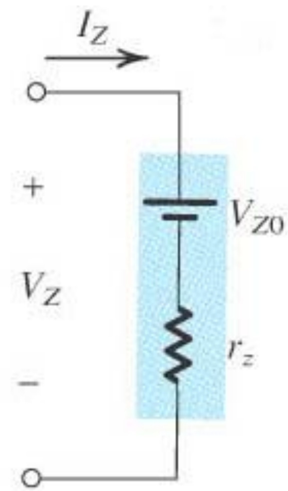
- Using the values from the breakdown curve as labeled, the Zener Voltage , V_Z, can be given as:

$$V_Z = V_{Z0} + r_z I_z$$

- which applies for $I_Z > I_{Zk}$ and $V_Z > V_{Z0}$ (the breakdown region where curve conducts nearly linearly); with r_z given by the inverse of the slope in the breakdown region at the operating point , Q and we know that:

$$\Delta V = r_z \Delta I$$

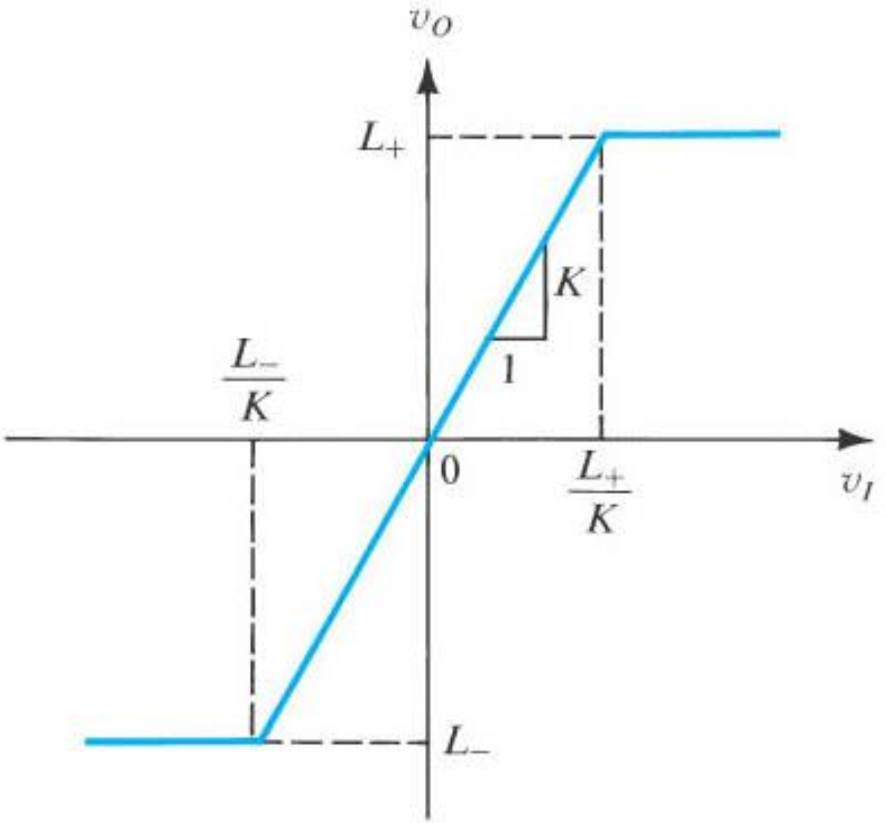
- So the equivalent circuit model is:



Limiting Circuits

Diodes can be used in a limiting circuit

A generic transfer function for a limiting circuit is:



$$v_o = K v_i$$

Circuits we will
look at have $K \leq 1$
And are known
as passive limiters

Figure 3.32 General transfer characteristic for a limiter circuit.pp. 185 Sedra & Smith

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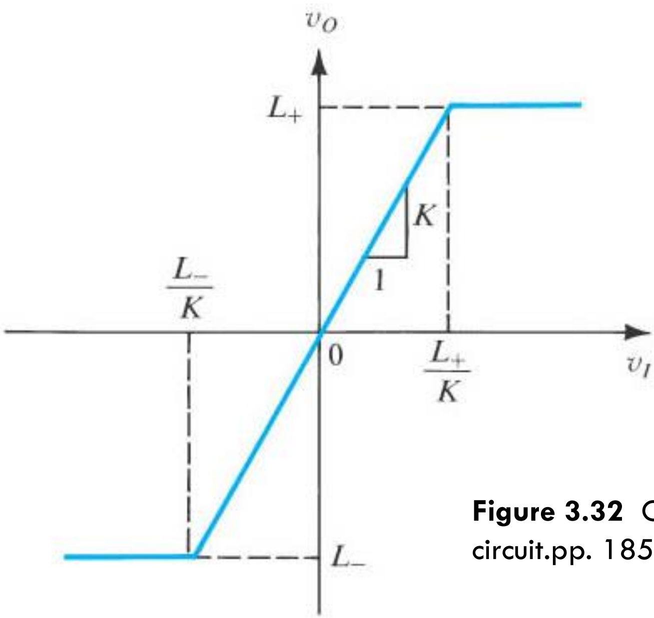
Limiting Circuits

- The transfer function depicted in Fig 3.32 describes a **double limiter** – where both positive and negative peaks are limited

- A **single limiter** only work on one side of the peaks (either negative or positive but not both)



$$v_o = K v_i$$

Figure 3.32 General transfer characteristic for a limiter circuit.pp. 185 Sedra & Smith

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Limiting Circuits

- Fig 3.33 shows the effect on a sinusoidal waveform passed into a double limiter – the peaks have been clipped (a non-linear function) and hence sometimes these circuits are called **clippers**

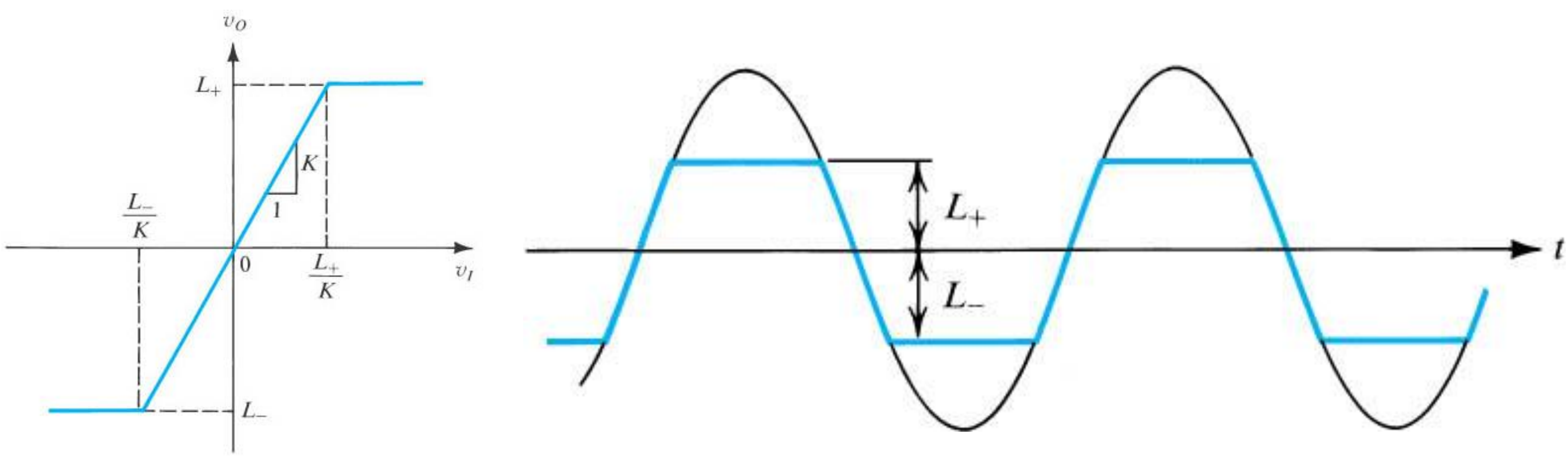
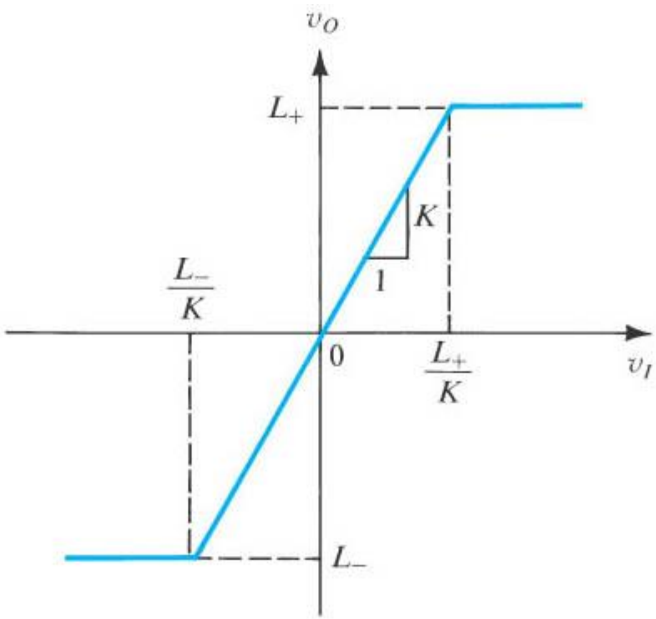


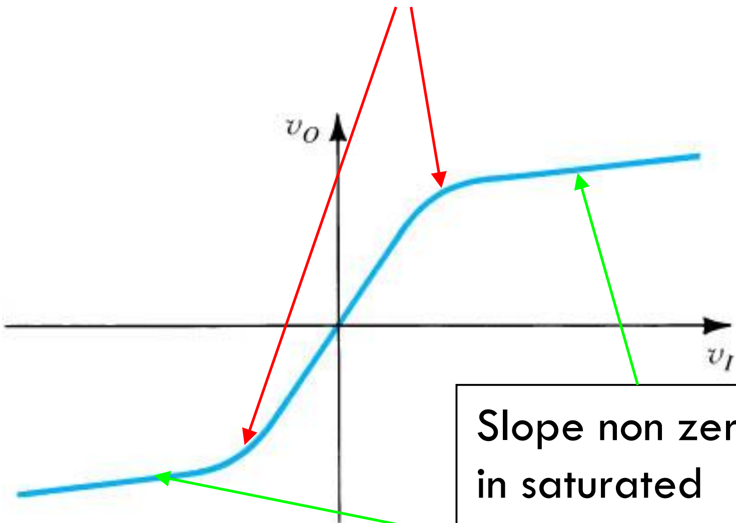
Figure 3.33 Applying a sine wave to a limiter can result in clipping off its two peaks.

Limiting Circuits



Hard Limiter characteristic

Smoother transition
between linear and saturated region



Slope non zero
in saturated
region

Figure 3.34 Soft limiting.S&Smith pg185

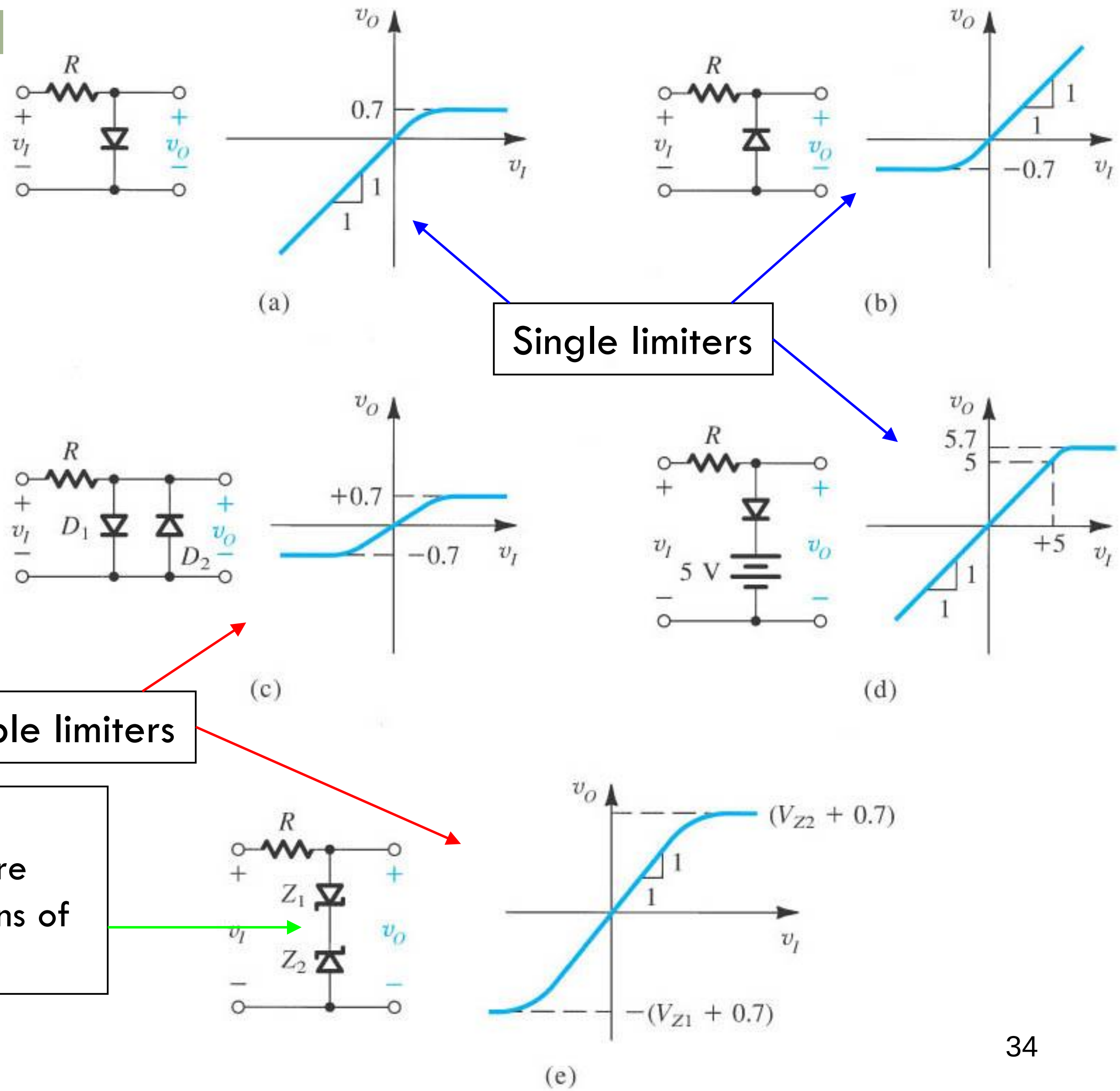
Soft Limiter characteristic

Limiting Circuits

Modeling diodes using the constant 0.7V diode model.

Some examples of limiting circuits.

Figure 3.35 A variety of basic limiting circuits.
Pg. 186 S&Smith



Special pairs of Zener diodes called **double-anode Zener** diodes are available commercially for applications of this type

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Clamping Circuits

- Peak detector (or peak rectifier) circuit

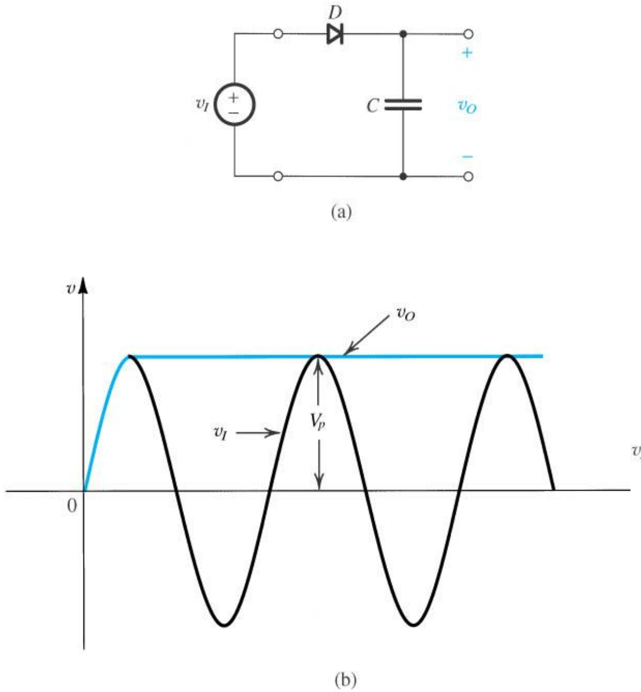
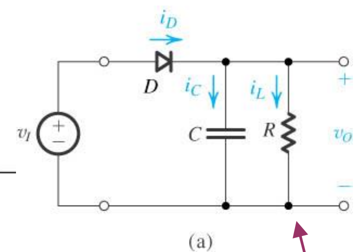


Figure 3.28 **(a)** A simple circuit used to illustrate the effect of a filter capacitor. **(b)** Input and output waveforms assuming an ideal diode. Note that the circuit provides a dc voltage equal to the peak of the input sine wave. The circuit is therefore known as a peak rectifier or a peak detector.



Load Resistor

Ripple voltage

$$V_r = \frac{V_p}{fCR}$$

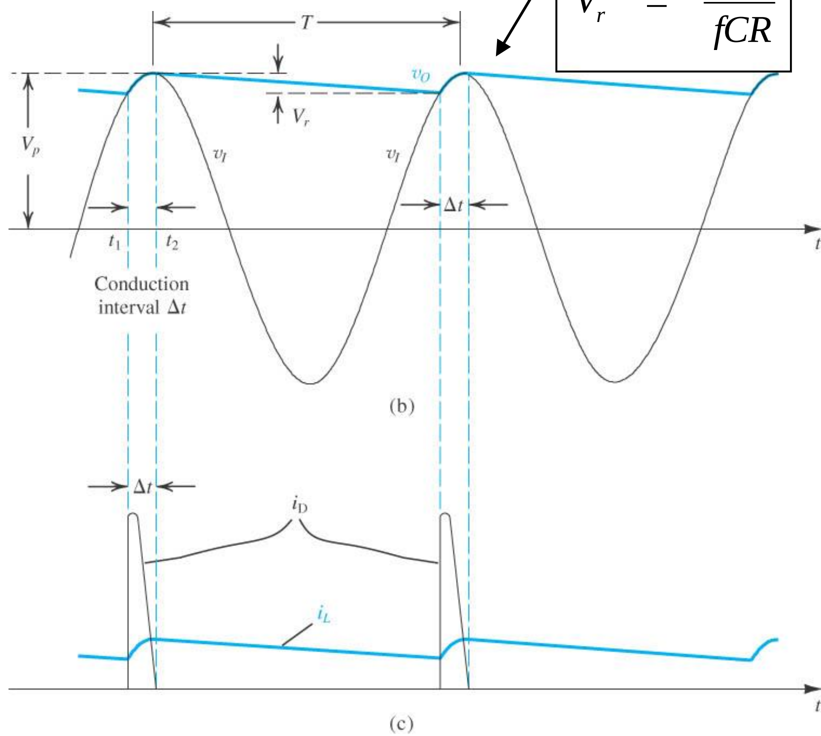
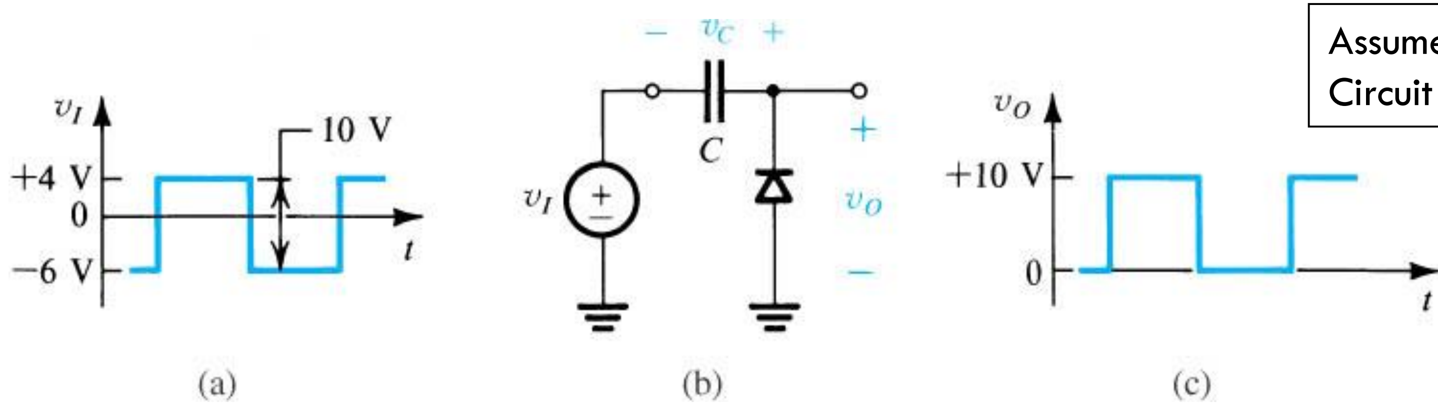


Figure 3.29 Voltage and current waveforms in the peak rectifier circuit with CR @ T. The diode is assumed ideal.

Clamping Circuits

- DC restorer (or clamped capacitor) circuit



Assume ideal Circuit elements!

Figure 3.36 The clamped capacitor or dc restorer with a square-wave input and no load. Pg. 188 S&Smith

Due to the polarity connection of the diode the capacitor in fig. (b) will charge to a voltage v_c with the polarity shown on the diagram (output pin positive) This voltage will have the magnitude of the most negative peak of the input Waveform – eventually the diode turns off and the capacitor retains the charge indefinitely.

Example: in fig.(a) the most negative voltage of the square wave input is -6V, while the voltage range is 10V, then v_c will charge to 6V; the output voltage (using KVL) is then the input voltage (v_i) plus the capacitor voltage (v_c) which gives the waveform at the output indicated by fig.(c) – the output has been shifted by v_c volts compared to the input waveform.

Clamping Circuits

- DC restorer (or clamped capacitor) circuit

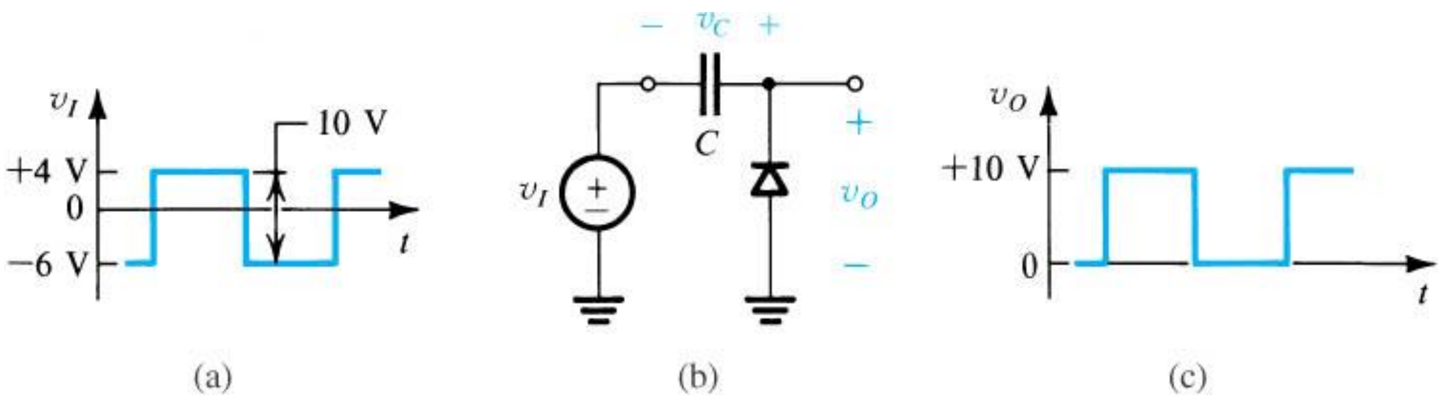


Figure 3.36 The clamped capacitor or dc restorer with a square-wave input and no load. Pg. 188 S&Smith

The diode (with shown polarity) prevents the output voltage from going below 0 V (ground) – done by conducting and charging up the capacitor –however the diode does not constrain the positive swing of vo hence the circuit has the effect of **clamping the lowest peak to 0V** hence its alternate name the clamped capacitor!

If we reverse the polarity then the highest peak will be clamped to 0V

If we pass a pulse or AC signal with a DC component through a capacitor coupling (or ac coupled system) then that signal will lose its DC component – we can use this circuit to restore a known DC component; a process known as DC restoration, hence the other name **DC restorer**.

Clamping Circuits

- DC restorer (or clamped capacitor) circuit

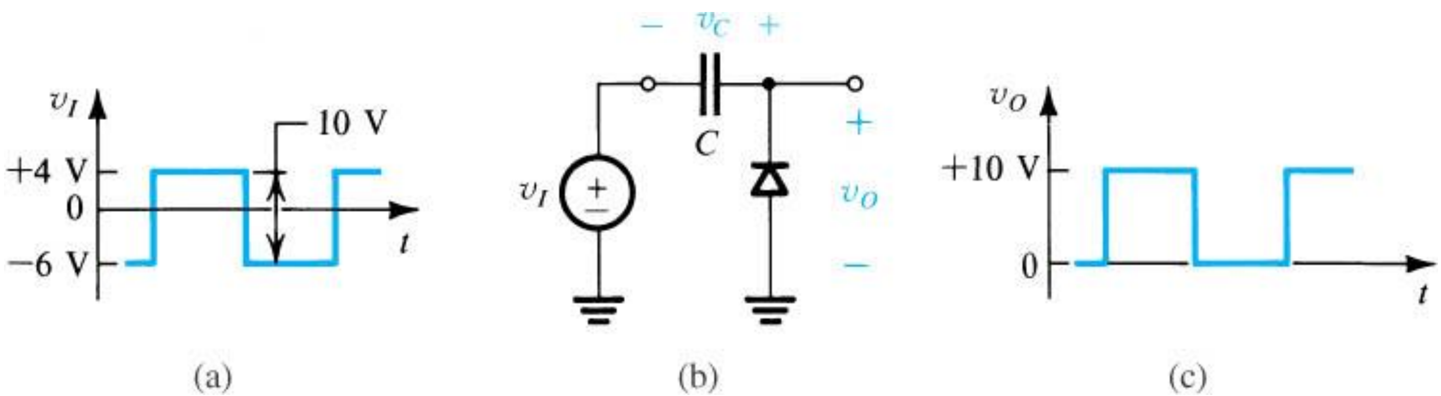


Figure 3.36 The clamped capacitor or dc restorer with a square-wave input and no load. Pg. 188 S&Smith

Applications:

- DC component or average value of a pulse waveform is a measure of duty cycle (which is the proportion of each cycle occupied by the pulse).
- Duty cycle can be modulated (with information) in a process called Pulse Width Modulation (PWM) ie pulse width is changed to convey different signal (data) conditions eg speed control using H-bridge for a small DC permanent magnet motor.
- The DC Restorer followed by a Single Time Constant (RC) low pass filter could be used to find the average value of the pulse train (or superimposed pulses).

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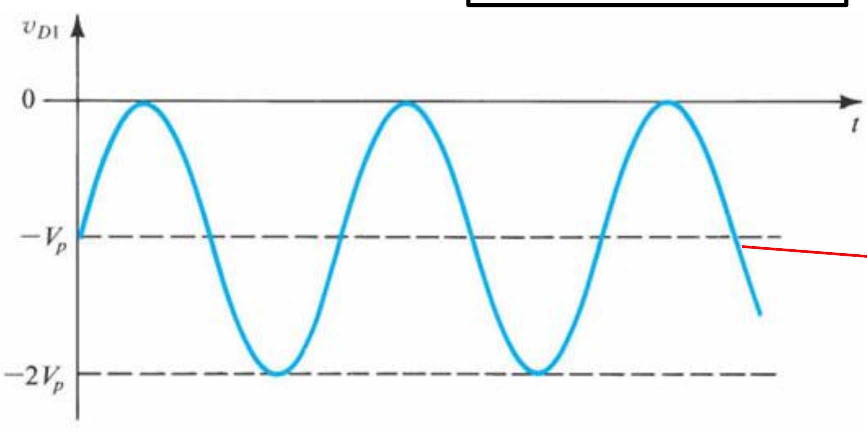
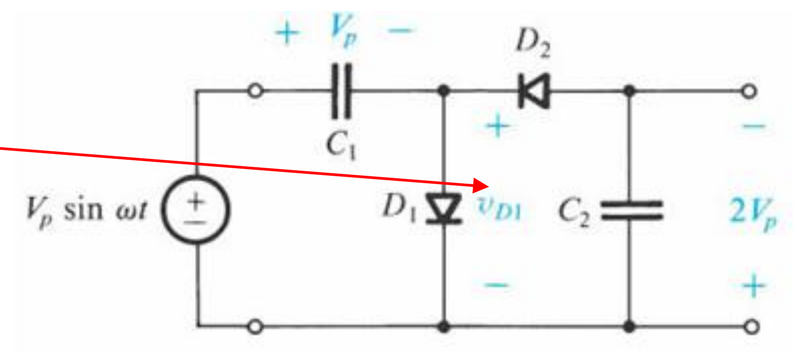
Voltage Doubler

- If we have a clamped capacitor (DC restorer) stage followed (cascaded) by a peak detector (peak rectifier) stage we can provide a DC output voltage that is twice the input voltages peak value:

Vin (sinusoid) → DC Restorer (clamping capacitor) → Peak Detector (peak Rectifier) → Vout (DC Voltage)



(b)



(a)

Voltage Regulator

- Each kit team has a 150mA Dual +/-15V DC power supply (mainly needed for op-amp circuits).

- Your design may, however, need to have stable voltages in your circuit at 5V or 3.3V.

- You could also use a linear voltage regulator.

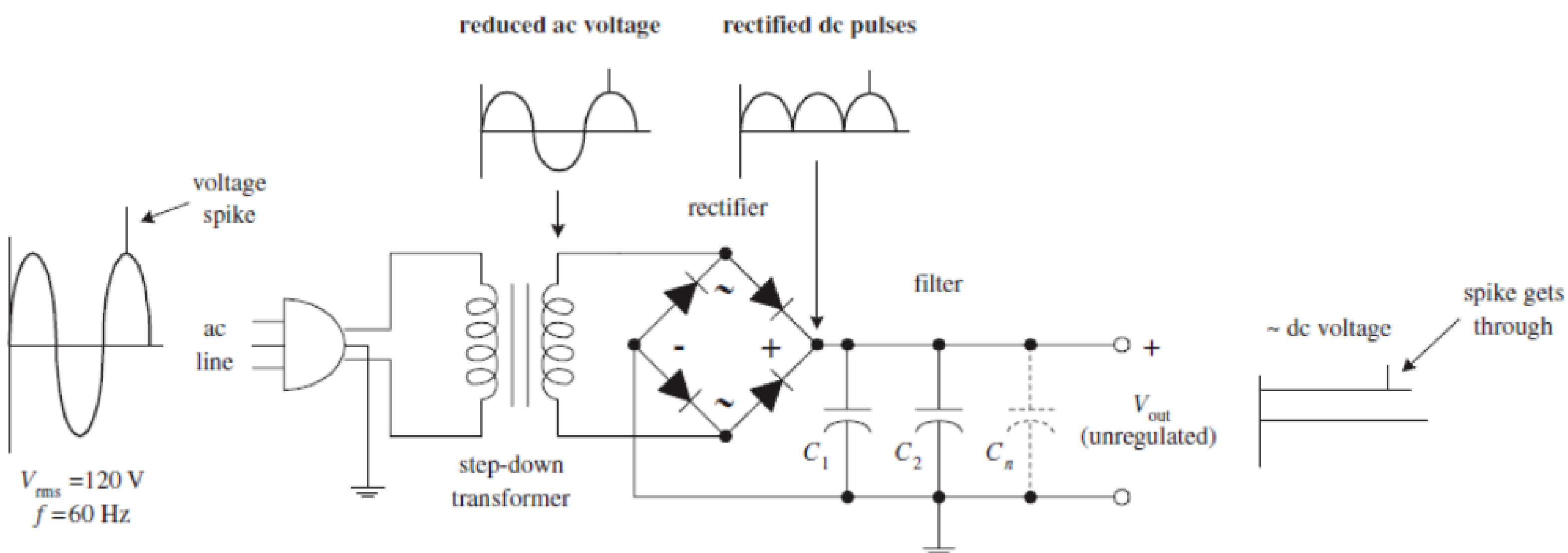
Voltage Regulator

- Circuits usually require a dc power supply that can maintain a fixed voltage while supplying enough current to drive a load.
- Batteries make good DC supplies, but their relatively small current capacities make them impractical for driving high-current and frequently used circuits.
- An alternative solution is to take a 240-V/120-V AC, 60-Hz / 50-Hz line voltage and convert it into a usable DC voltage
- So, as you may have seen in ECTE212, you might have a transformer and then use a full wave rectifier (using diodes) and an output capacitor to reduce ripple and produce a reasonably smooth DC output

Voltage Regulator

- However, if there is a inductive spike voltage on the input power source this flows through to the smooth DC output, it is hence unregulated

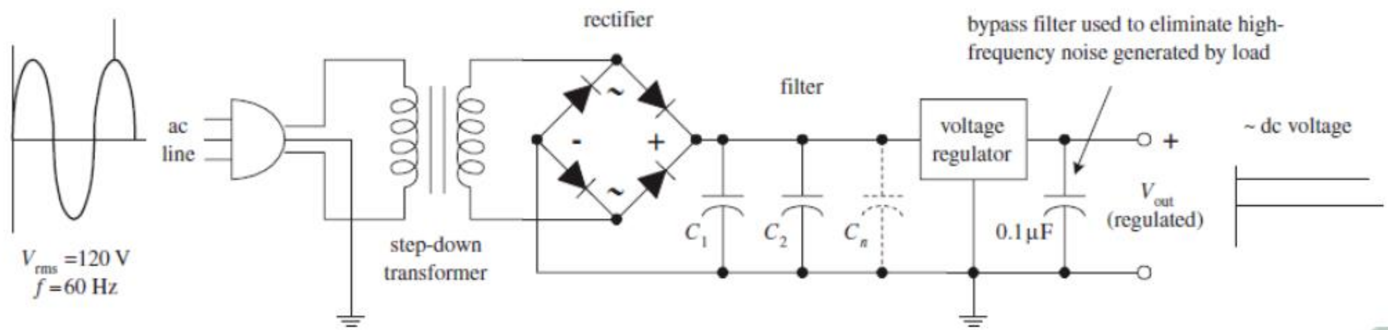
- A regulated supply will stop this spike before it gets to your circuit (provided the spike is not so large it destroys the regulated circuit as well, usually for a 7805 that's about 35 Volts)



Voltage Regulator

- Using an unregulated supply to run sensitive circuits (e.g., digital IC circuits) is a bad idea.
- The current spikes can lead to improper operating characteristics (e.g., false triggering, etc.) and may destroy the ICs in the process.
- An unregulated supply also has a problem maintaining a constant output voltage as the load resistance changes.
- If a highly resistive (low-current) load is replaced with a lower-resistance (high-current) load, the unregulated output voltage will drop (Ohm's law).

Voltage Regulator



- there is a special circuit that can be placed across the output of an unregulated supply to convert it into a regulated supply, i.e. a supply that eliminates the spikes and maintains a constant output voltage with load variations

- This special circuit is called a *voltage regulator.*

- A voltage regulator is designed to **automatically adjust** the amount of current flowing through a load, — so as to maintain a constant output voltage — by comparing the supply's dc output with a fixed or programmed internal reference voltage.

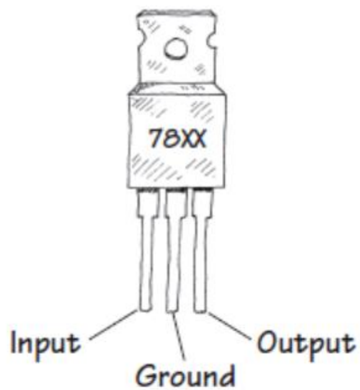
Voltage Regulator

- There are a number of different kinds of voltage-regulator ICs on the market today.

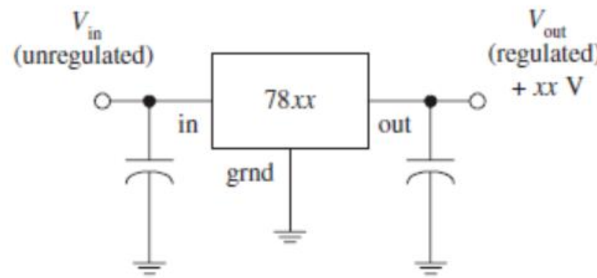
- Some of these devices are designed to output a fixed positive voltage, some are designed to output a fixed negative voltage, and others are designed to be adjustable.

Fixed Regulator ICs

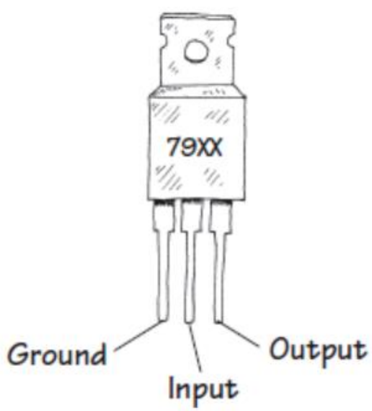
Positive voltage regulator



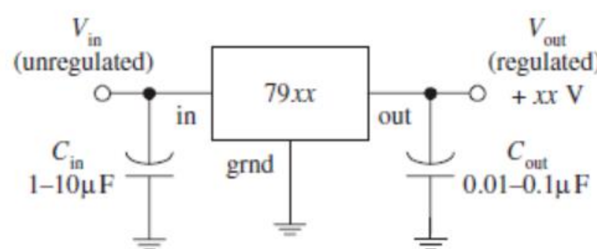
positive voltage regulator



Negative voltage regulator



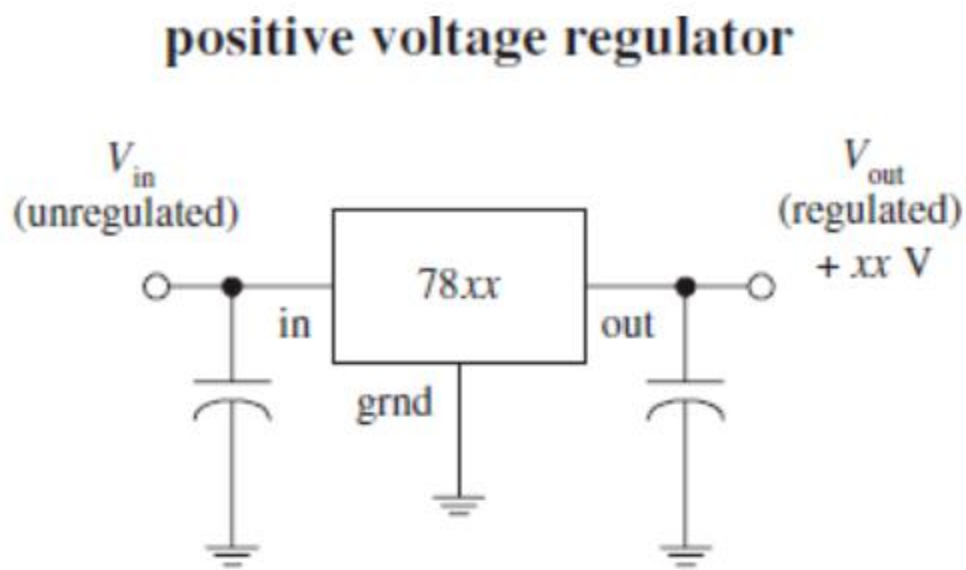
negative voltage regulator



Positive Voltage Regulator

- One popular line of regulators includes the three-terminal LM78xx series shown here. The "xx" digits represent the output voltage, e.g., 7805 (5 V), 7806 (6 V), 7808 (8 V), 7810 (10 V), 7812 (12 V), 7815 (15 V), 7818 (18 V), and 7824 (24 V). These devices can handle a maximum output current of 1.5 A if properly heat-sunk.

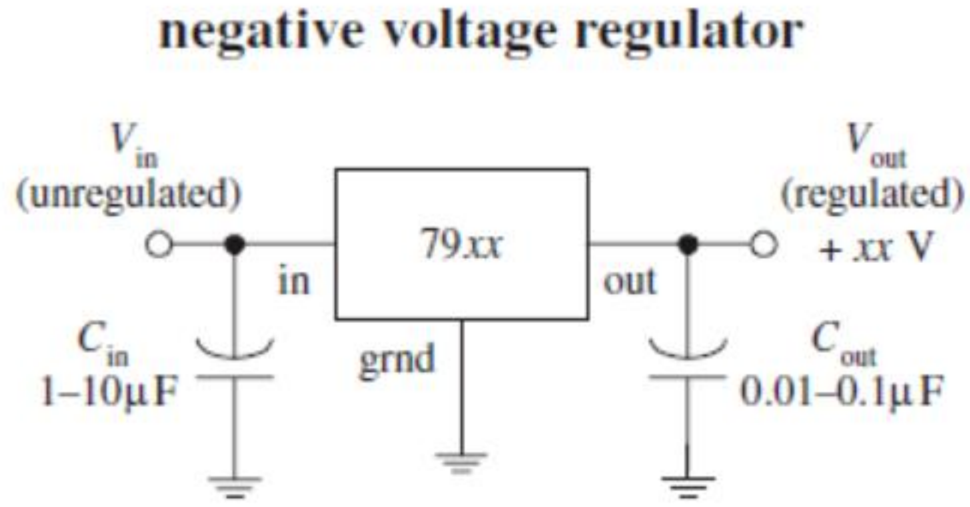
To remove unwanted input or output spikes/noise, capacitors can be attached to the regulator's input and output terminals, as shown in the figure:



Negative Voltage Regulator

- A popular series of negative voltage-regulator IC is the LM79xx regulators, where "xx" represent the negative output voltage. These devices can handle a maximum output current of 1.5 A.

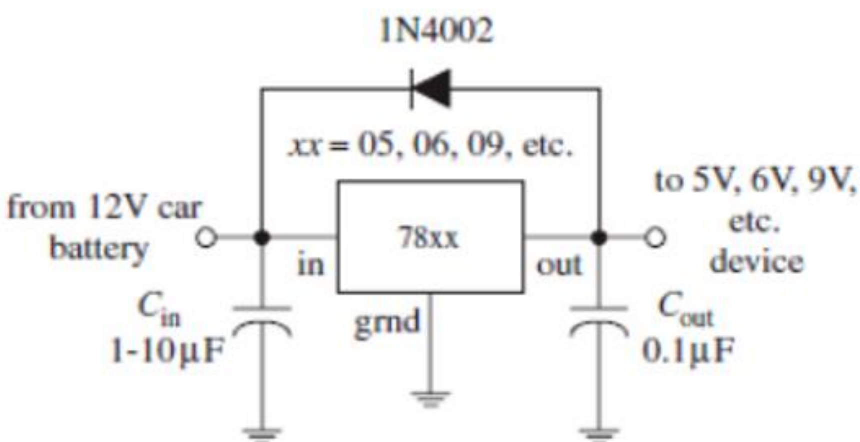
To remove unwanted input or output spikes/noise, capacitors can be attached to the regulator's input and output terminals, as shown in the figure:



Positive Voltage Regulator

- Use of a positive Voltage regulator in a car circuit
- The diode ensures that if a higher voltage occurs due to different discharge rates on the output side of the regulator compared to the input side, the resultant current will flow through the silicon diode rather than the 78xx IC regulator which could result in its failure!

Car battery voltage regulation



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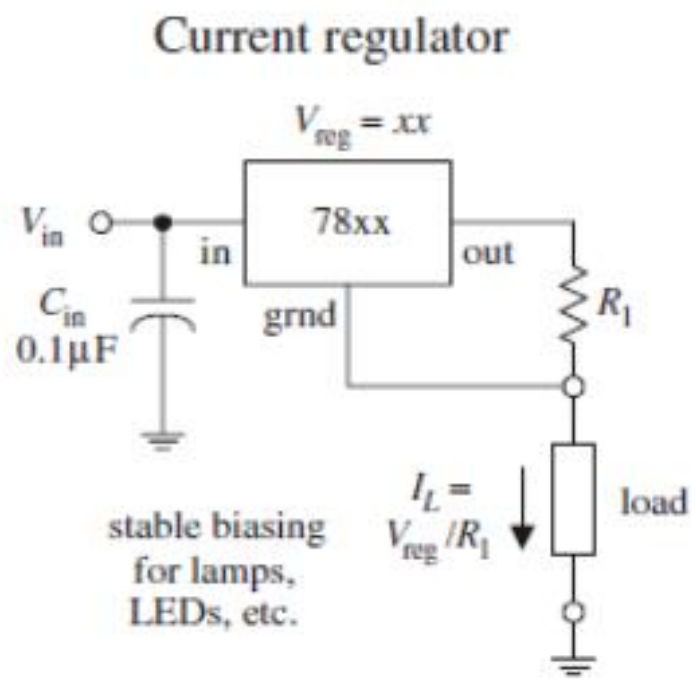
Positive Voltage Regulator

- This constant current regulator circuit is often used as a power supply for LEDs, especially the higher-power devices.



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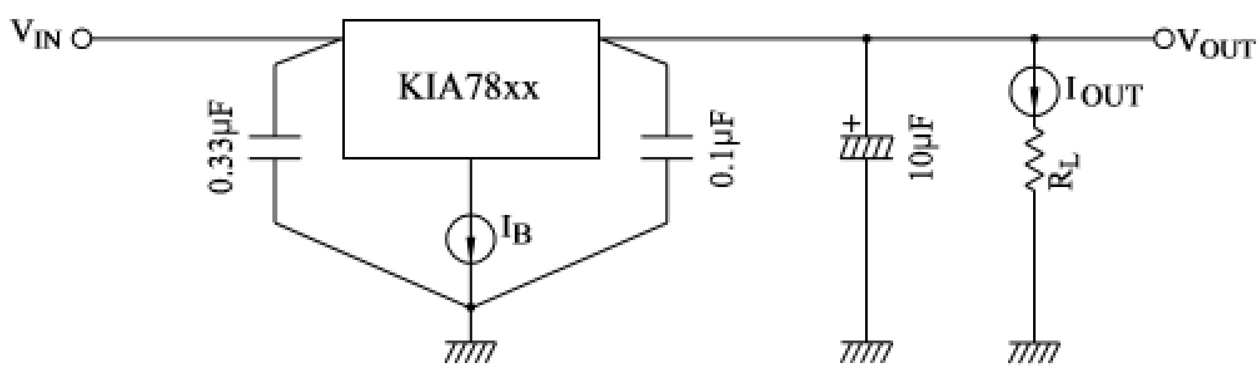
Voltage Regulators

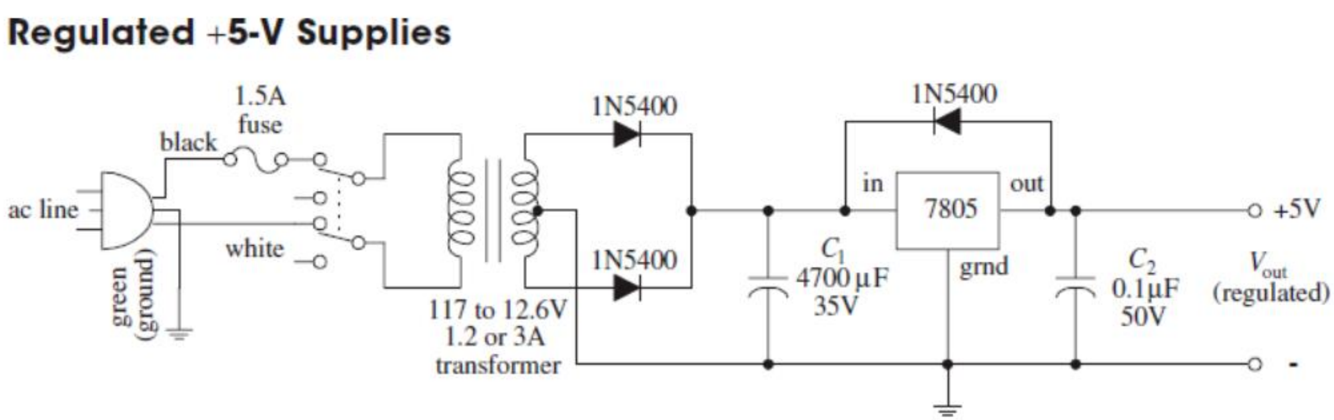
- You can use a 7805 Voltage regulator, for nominal 5V's out or the LM2936 for 3.3V's out in your project

- Using them is very simple and the data sheet shows the typical configuration using a 0.33μF capacitor on the input side and a 0.1μF capacitor on the output side in parallel with the load:

Fig. 1 Standard Test Circuit & Application Circuit



5V regulated power supply example



Circuit Explanation:

- This supply uses a centre-tapped transformer rated at 12.6 V at 1.2 to 3 A. The voltage after rectification resides at an 8.9-V peak pulse.
- The filter capacitor (C_1) smoothes the pulses, and the 7805 outputs a regulated +5 V.
- C_2 is placed across the output of the regulator to bypass high-frequency noise that might be generated by the load.
- The diode placed across the 7805 helps protect the regulator from damaging reverse-current surges generated by the load. Such surges may result when the power supply is turned off. For example, the capacitance across the output may discharge more slowly than the capacitance across the input. This would reverse-bias the regulator and could damage it in the process. The diode diverts the unwanted current away from the regulator.

Voltage Regulator

- Most of the time we have a higher voltage on the input than needed, e.g. 7 Volts on the input side to drive 5 Volts on the output. In this case a Low Drop Regulator (LDO) would be ideal, but it's not in the ECTE250 part list {its possible the 3.3V regulator is one LDO but that was not a criteria used in its selection}.

- For your project you have +15V DC outputs from our dual voltage DC supply (current limited to 150mA).

- So if we want 5V DC regulated we would put this through a Diode dropping the voltage down to 14.3V and then connect it to the voltage regulator input side

- This means we will have a voltage drop across the Voltage regulator of 14.3-5= 9.3Volts.

- If the device draws 10mA current this is a power of 93mW (P=VI) loosed in the voltage regulator circuit, and this is an issue with our circuits needing to minimise power usage

- So power usage is a draw back of using voltage regulators!

www.youtube.com/watch?app=desktop&v=OAoEWaGtQjs

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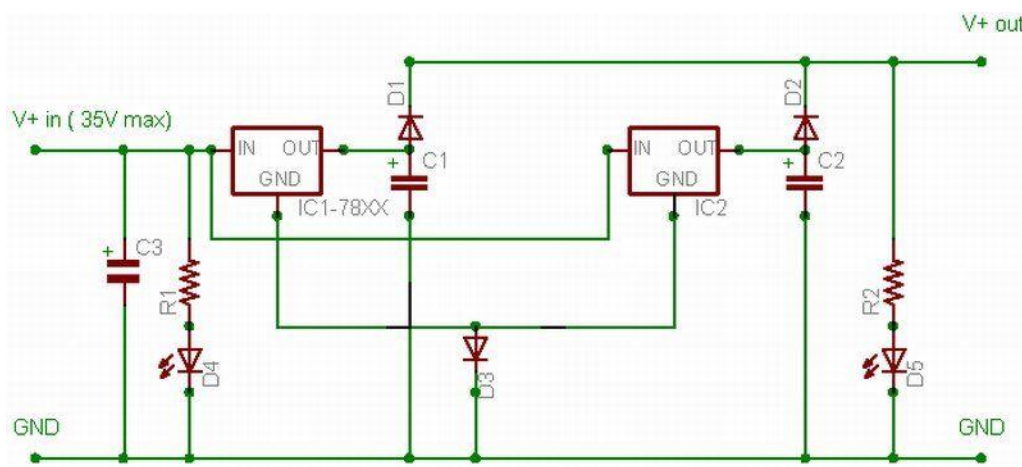
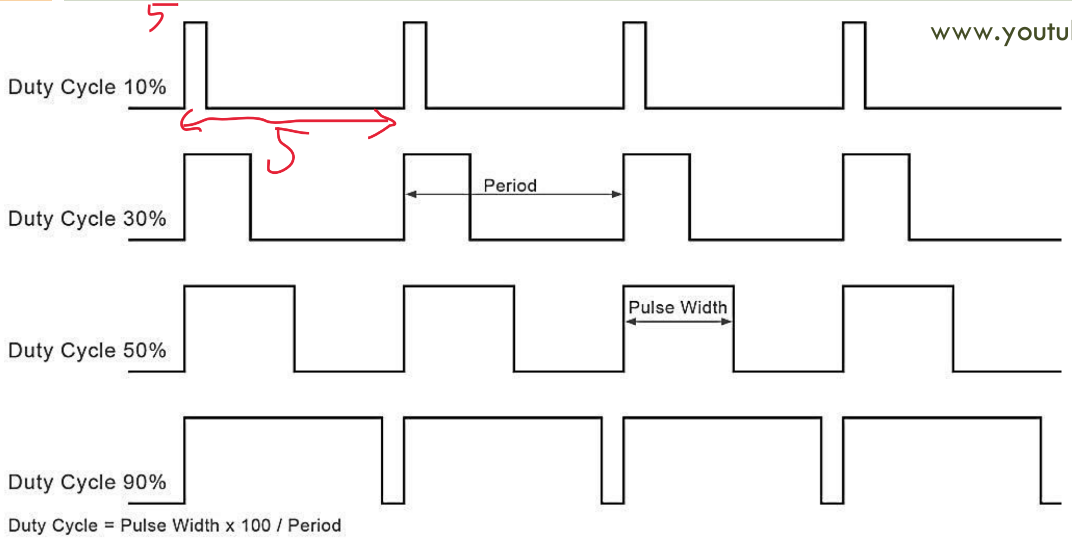
Multiple Voltage Regulators

- If the current supplied by a single 7805 is not sufficient (practical rule, assume a max of 1A at 5V output), you may need to use multiple.
- Use separate voltage regulators to feed different sub circuits of your design (preferred)
- DO NOT USE Voltage Regulators IN PARALLEL.
- Or use the following circuit



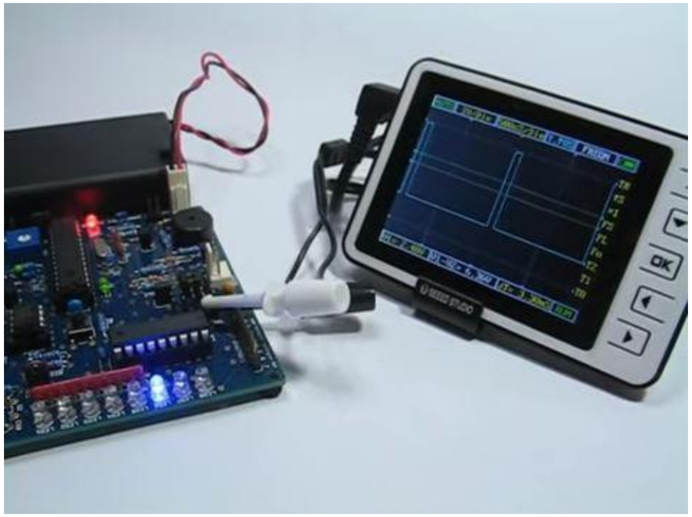
Pulse Width Modulation



www.youtube.com/watch?app=desktop&v=oU-WQVaHm4g

Applications:

- Signal generation
- Tone generation
- Motor control
- LED brightness control
- Analog voltage generator (LP)

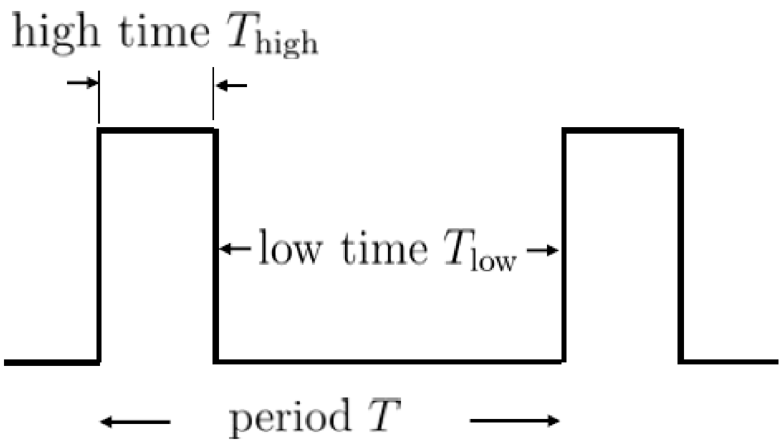


https://youtu.be/cITU3DiV3Bo

PWM Applications

- PWM signals are commonly used in embedded applications: motor control, sound alarm, and radio transmission.

- A PWM signal is a periodic, rectangular pulse. The period and the duty cycle can vary.



$$\text{mark space ratio} = \frac{T_{\text{high}}}{T_{\text{low}}}$$

$$\text{duty cycle} = \frac{T_{\text{high}}}{T}$$

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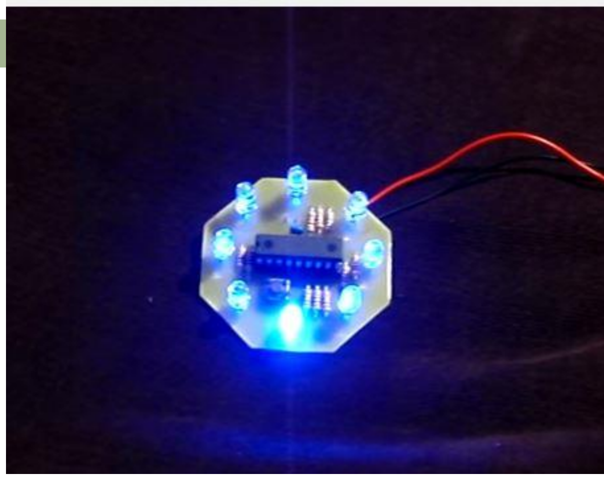
PWM to control LED luminosity



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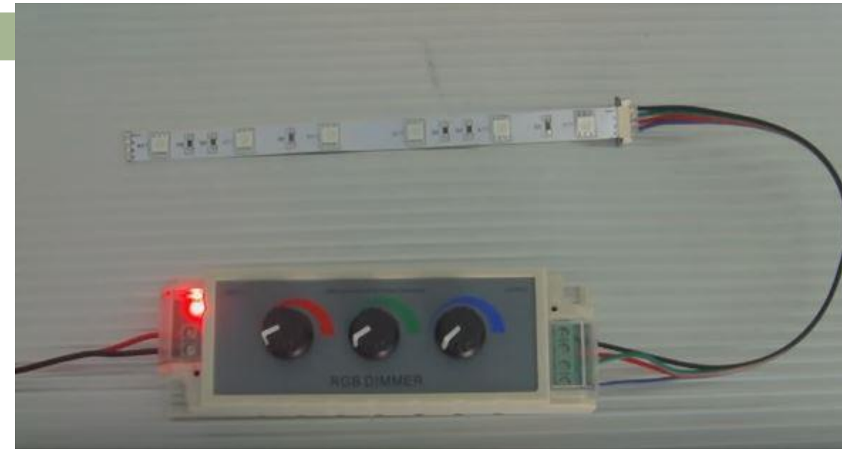

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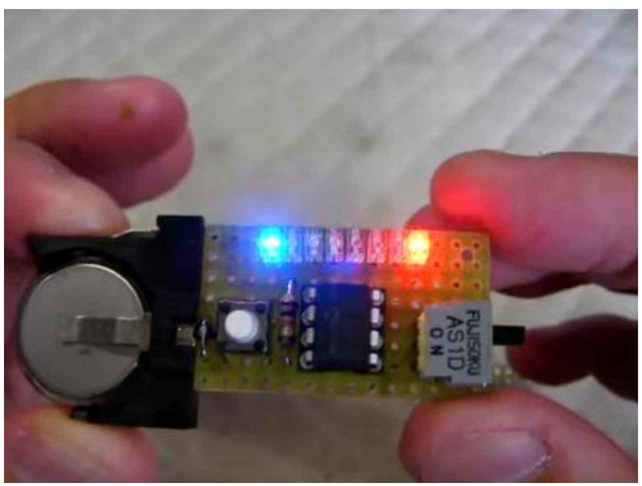

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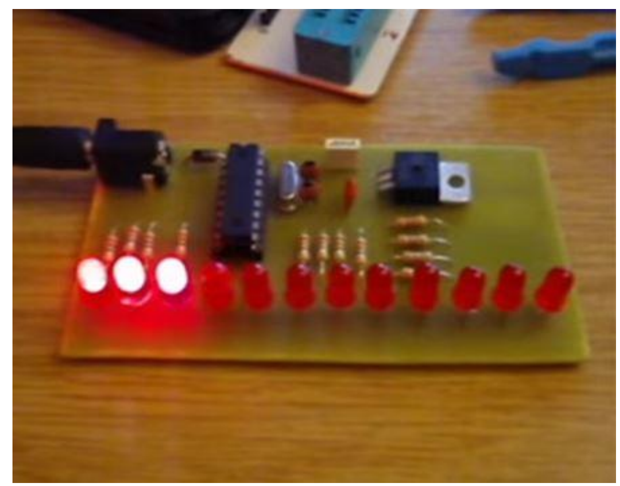


https://youtu.be/DHsjQSv8zMo

Digital to Analog Conversion using PWM

- Many microcontrollers (including the AVR on Arduino) do not feature DAC. I/O Pins can drive High (Vcc) or Low (GND) voltage levels only.

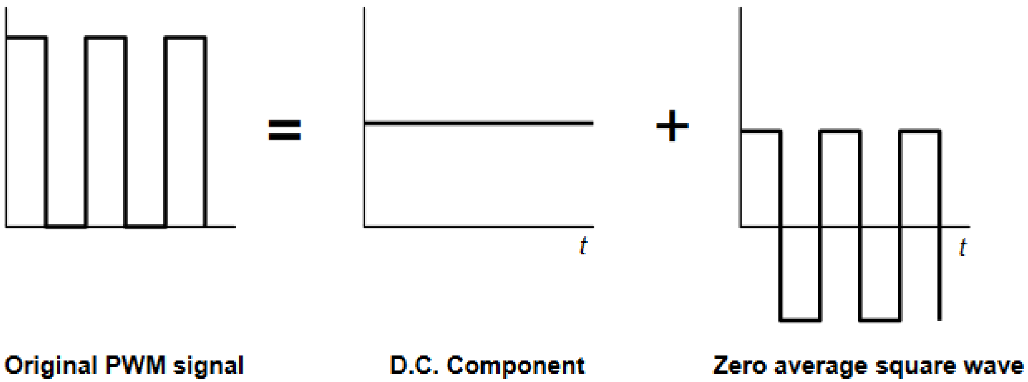
- Connect the any "~" pin of the Arduino (generating PWM signal) to an analog Low Pass filter (with low cutoff frequency), and use the arduino function "AnalogWrite(Pin, **Value**)", where value is in [0, 255] range. Value determines the duty cycle of the PWM signal.

- The frequency of the PWM signal on most Arduino pins is approximately 490 Hz. On the Uno and similar boards, pins 5 and 6 have a frequency of approximately 980 Hz.

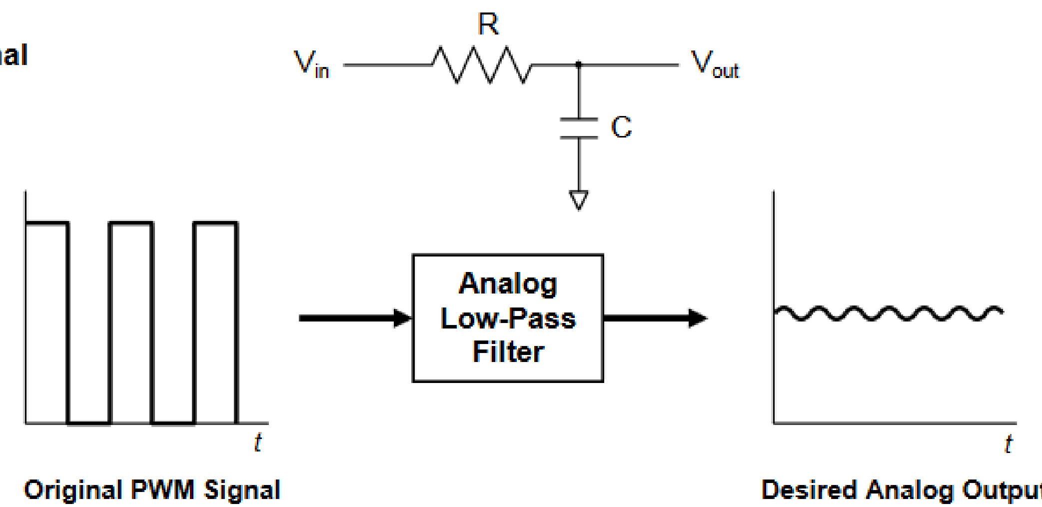
- If we filter (low pass) the PWM signal we get an "average" of the PWM signal, giving a DC value between Vcc and GND proportional to Value (and to the duty cycle of the PWM signal).

- PWM Frequency >> LP Cutoff Frequency
  - Lower LP Cutoff frequency = less ripple in DC out
  - Lower LP Cutoff frequency = lower response (higher settling time)

Digital to Analog Conversion using PWM

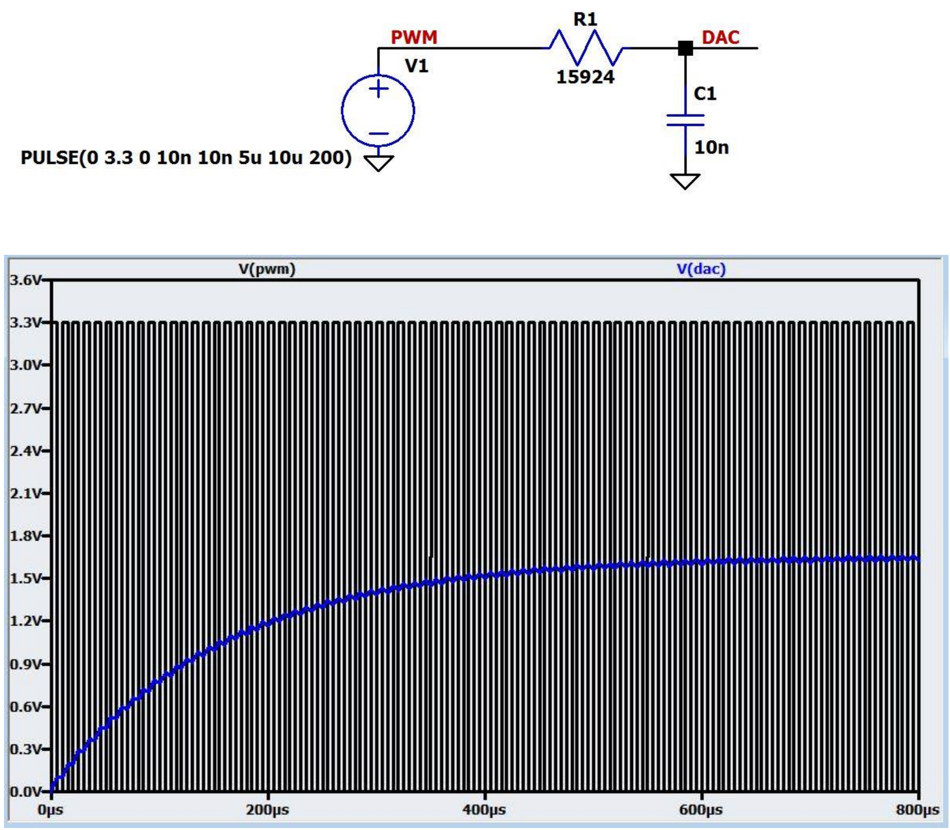


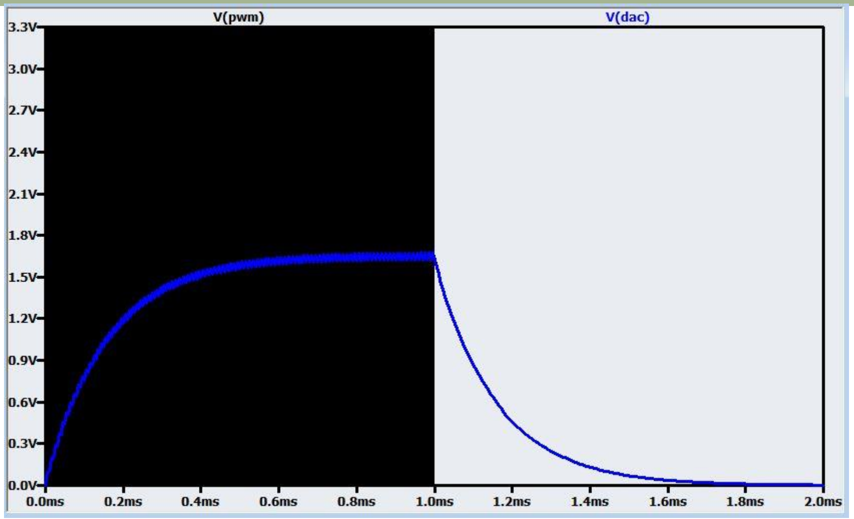
Decomposition of a PWM Signal

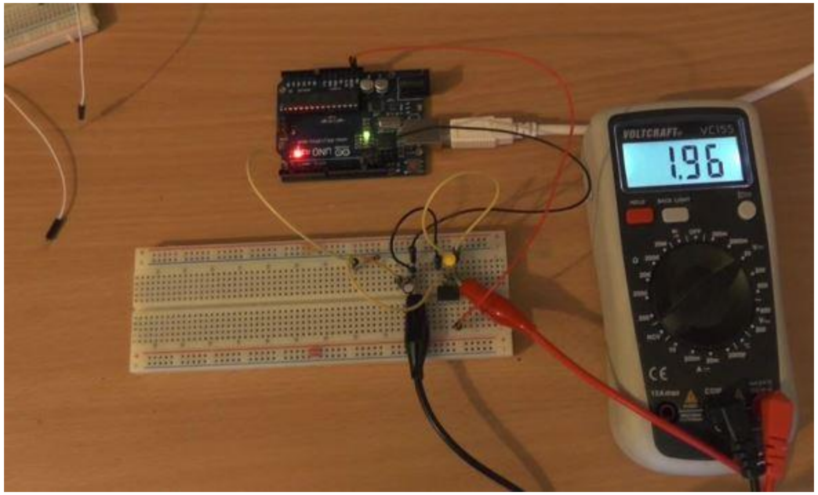


Analog Filtering of PWM Signal

Digital to Analog Conversion using PWM







https://youtu.be/oU-WQVaHm4g

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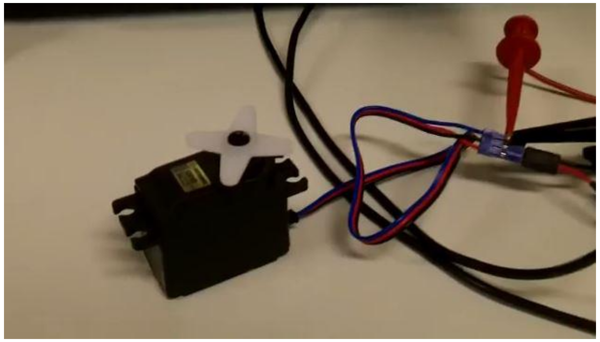
PWM Control of servo motor

- Servo motor S3003 (specs common to many other model)

- Three wires
  - Black: Ground
  - Red: DC supply between (4.8V, 6V)
  - White: PWM signal
- To keep the motor at a given angle, we send a PWM signal with a specific duty cycle.
- The frequency of the PWM signal is 50Hz (to generate this use the Arduino Servo Library)
- This motor have a rotation range of 180 (other have 360).
- To change the angle we change the duty cycle.



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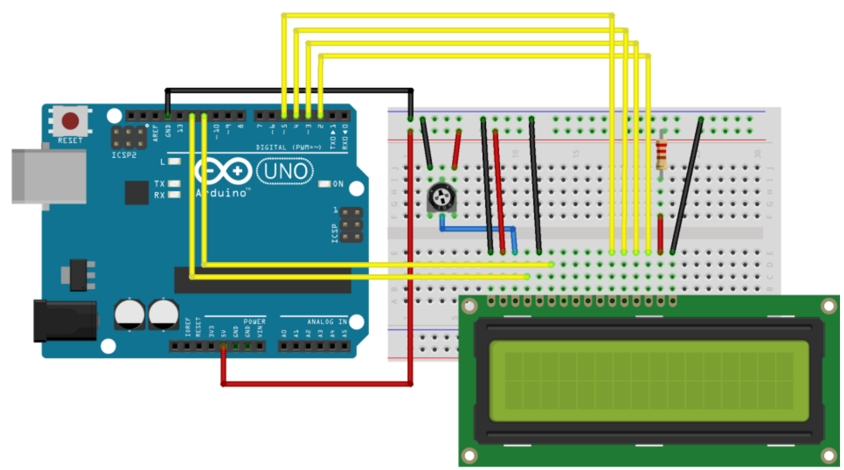
More on Arduino for your Project

- The Ethernet Shield uses digital pins 10, 11, 12, and 13.
- You used pins 12 and 11 with the LCD.
- The LCD can be interfaced using any I/O pin (including A0 to A5). The same does not apply to the Ethernet Shield with respire the SPI provided by pins 10 to 13.
- For instance to change pins 11 and 12 with A0 and A1 change

LiquidCrystal lcd(12, 11, 5, 4, 3, 2);

to

LiquidCrystal lcd(A1, A0, 5, 4, 3, 2);



More on Arduino

- If you run out of Arduino I/O Pins in your design consider to use
  - 74HC138 (3-to-8 demultiplexer): this can increase the number of output lines (only one at a time HIGH).
  - or 74HC151 (8 input multiplexer) for input lines.

Acknowledgement

- Peter Vial, UOW; Stefano Fasciani, Oslo University