Power Design

INTEGRATING EMBEDDED SYSTEMS (ANALOGUE PART)

RICHARD POWRIE

Power Design Introduction

- We need special power circuitry to:
  - Regulate
  - Control
- We need to know exactly how much power is needed by the circuit, and what our source of power is.
- Sources:
  - Mains - must convert the AC mains into DC at the desired voltage.
  - Battery - regulate or convert voltage to the right level.

- *These notes are developed with reference to content from Samuel Ginsberg's EEE3090F 2018 notes.*

AC Mains Supply

- Mains in South Africa is 230VRMS AC
- To use with a DC circuit, it must be:
  - Transformed
  - Rectified
  - Smoothed
  - Regulated

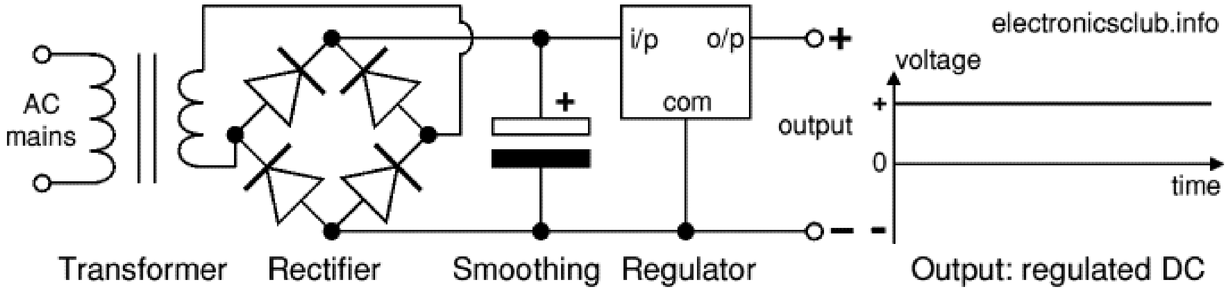


Image from https://electronicsclub.info/powersupplies.htm

AC Mains Supply: Transformer

- Transform
  - The peak voltage level of AC mains is too high
  - Needs to be stepped down to a closer level to prevent damage of equipment
  - If no transformer is used, the resulting DC voltage would be 325V ($230V \times \sqrt{2}$). This assumes no voltage drop over the rectifying diodes, which there is.
  - If you want 12VDC, then you need to step it down by a factor of 27.

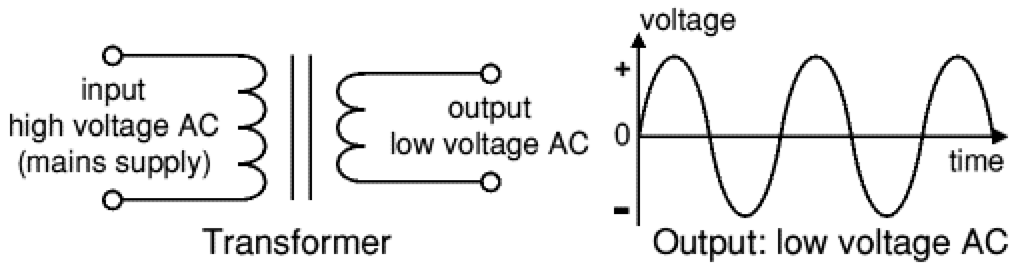


Image from https://electronicsclub.info/powersupplies.htm

Warning Note

MAINS CAN BE LETHAL!

WHEN WORKING WITH MAINS, BE CAREFUL!

TAKE PRECAUTIONS WHEN DEALING WITH THESE SUPPLIES.

AC Mains Supply: Rectify

- Transform
- Rectify
  - Using a clever configuration of diodes, the current can be routed so that the output current is always in the same direction
  - No longer positive and negative voltage on output
  - The 0.7V drop across the diodes means the output peak will be 1.4V lower than the input to the rectifier circuit. The waveform travels through two diodes.

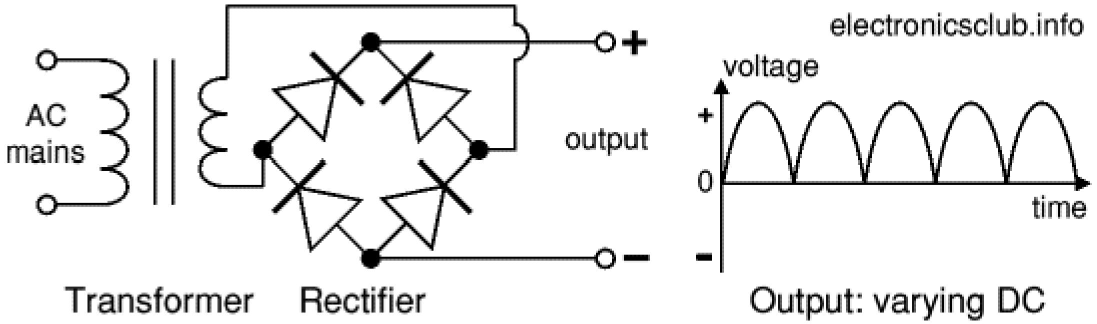


Image from https://electronicsclub.info/powersupplies.htm

AC Mains Supply: Smooth

- Transform
- Rectify
- Smoothing
  - The output voltage can be made more constant using a capacitor. The capacitor keeps the voltage higher for longer until the waveform returns to a peak again
  - The ripple present is fine for some DC circuits, but most are too sensitive to this changing supply
  - The voltage may change if mains fluctuates (which happens a lot!), so this voltage isn't safe to plug your circuit into yet

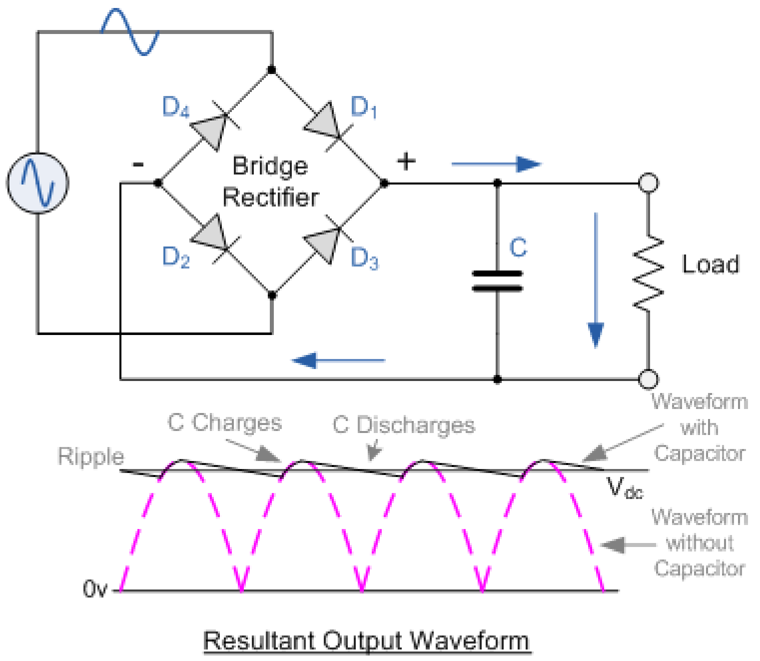


Image from electronics.stackexchange.com

AC Mains Supply: Regulate

- Transform
- Rectify
- Smoothing
- Regulator
  - Regulates the unstable DC supply voltage to produce a constant output

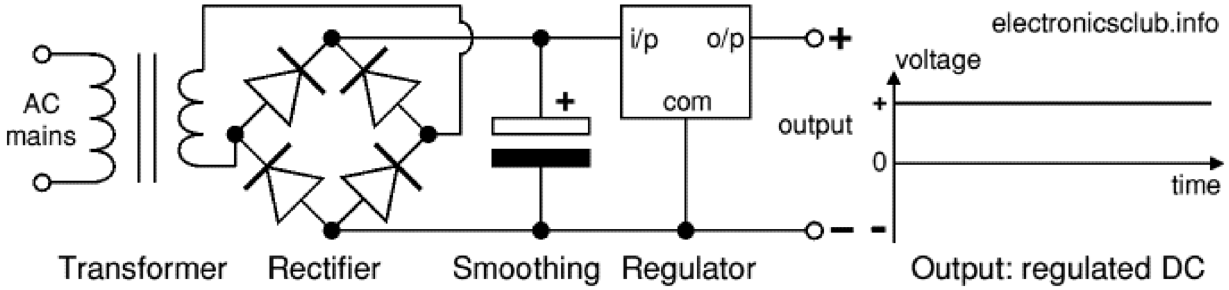


Image from https://electronicsclub.info/powersupplies.htm

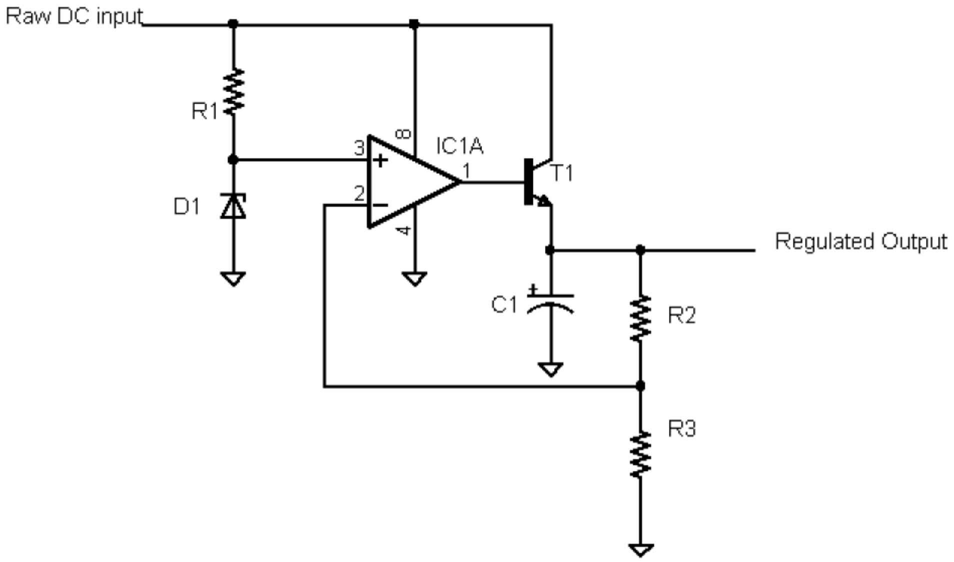
Linear Voltage Regulator

Linear Voltage Regulators

- Regulates a supply voltage to a stable voltage
- Step down only
- Regulating the voltage ensures:
  - Stable and constant voltage (smooth)
  - Predictable voltage
  - Suitable for all electronic circuits (no damaged components from the AC ripple or supply fluctuations)
- Very effective at removing (filtering) ripple from supply voltage

Voltage Regulator Circuits: Regulator with controllable voltage

- Most regulators have a control loop where the output is compared to some reference voltage.
- D1 is a Zener diode, which sets a stable reference voltage
- R2/R3 feedback the output to the op-amp
- If V_{out} is too large, the op-amp decreases its output so that the pass transistor T1 reduces the output voltage.
- If V_{out} drops due to loading, the op-amp will see a difference and raise the voltage.
- It regulates for changes in the input as well.



Voltage regulator with controllable output voltage *(Ginsberg, 2018)*

Voltage Regulator Circuits: Regulator with controllable voltage

Assuming D1 is a 5.6V Zener diode, and Vbe is 0.7V for T1, what resistor values R2 and R3 do you need to get a 10V output? The supply voltage is 12V.

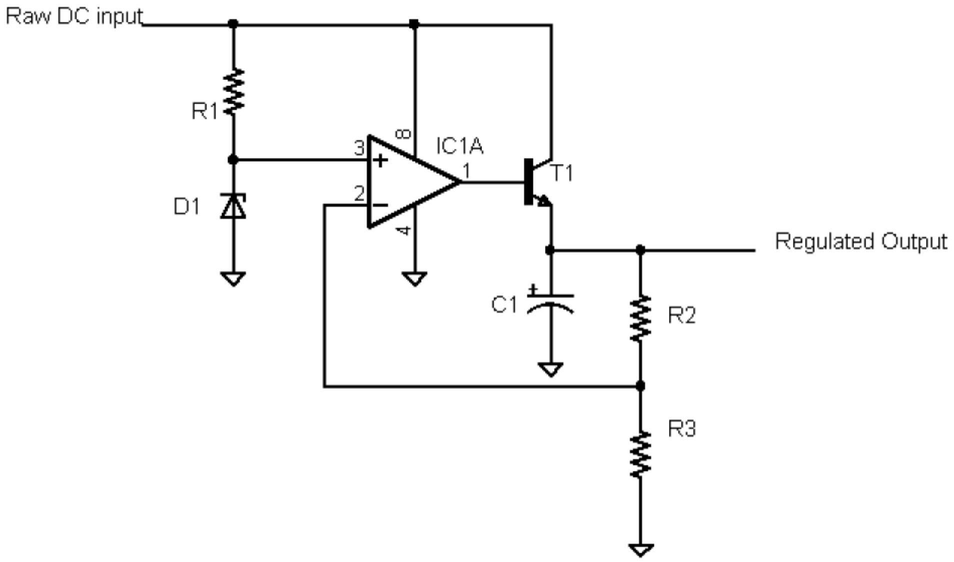
$$V_D = V_+ = V_- = 5.6V = V_{out} \times \frac{R_3}{R_2 + R_3}$$

$$\frac{10V}{6.6V} = \frac{R_3}{R_2 + R_3} \Rightarrow \frac{10}{5.6} = \frac{R_2}{R_3} + 1$$

$$R_2 = \left(\frac{10}{5.6} - 1\right) R_3$$

Let $R_3 = 1.5k\Omega, R_2 = 1178\Omega \approx 1.2k\Omega$

$$V_{out} = V_D \times \left(\frac{R_2}{R_3} + 1\right) = 5.6 \times \left(\frac{1.2}{1.5} + 1\right) = 10.08V$$



Voltage regulator with controllable output voltage *(Ginsberg, 2018)*

Voltage Regulator Circuits: Power Supply Protection Circuitry

- Power supplies need to protect against short circuits and over-loading
  - Over-current protection
  - Over-voltage protection (electronics-notes.com)
- The images shown so far did not include this, but most common voltage regulator chips come with these inbuilt to protect your circuitry
- They employ methods such as current sensing, fold-back current limiting, and for over-voltage protection often Crowbar circuits are used.
- How they work:
  - Overcurrent – When current drawn is too high, current is limited and voltage is dropped as load tries to draw more (example, short-circuit)
  - Overvoltage – When the supply voltage causes the output to exceed a threshold the output voltage drops (typically to 1V). You normally have to reset the system. This protects your expensive circuitry from supply faults.

Linear Voltage Regulators

- The difference between input and output voltage is dropped over the pass transistor.
- Think $P = V \times I$
- Higher supply means more voltage over your regulator
- Even a small load current draw can mean a high power dissipation in the regulator
  - Example: 24V supply, 5V regulator, 70mA load.
  - $P = V \times I = 5 \times 0.07 = 0.35W$ right? This is only your load's power
  - Your regulator is dissipating $P = V \times I = (24 - 5) \times 0.07 = 1.33W$!

Voltage Regulator Chips: Efficiency

- $\eta = \frac{P_{out}}{P_{in}}$
- $P_{out} = V_{out} I_{out}$
- $P_{in} = V_{in} I_{in}$
- $\eta = \frac{V_{out} I_{out}}{V_{in} I_{in}}$
- Linear regulators are highly inefficient. Example:
  - 10V supply, 5V regulator, output current of 10A, quiescent current of 5mA
  - $\eta = \frac{5V \times 10A}{10V \times 10.005A} = 0.5$

Voltage Regulator Chips: Heatsinks!!!

- Voltage regulators are inefficient, so can often get quite hot.
- To prevent overheating, a heatsink should be employed.
  - If you want to find out more, a good article to read is found here.
- Prevent overheating
  - Use a supply voltage as close as reasonable to regulated output
  - Reduces how much power the regulator must dissipate

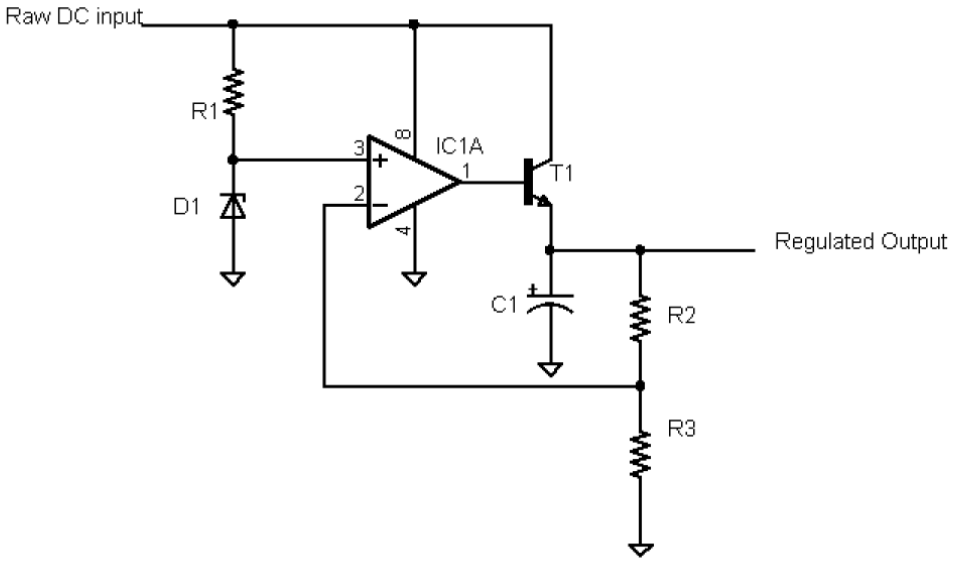
Various heatsinks (images from RS components)

Voltage Regulator Circuits: Headroom (or Dropout)

- The minimum voltage required across the regulator to maintain the output voltage.
- The op-amp can't provide the current and voltage needed to saturate the transistor.
- This means that Vce always has some voltage over it (typically 2V or more).
- Input voltage must be equal to

$$V_{in} = V_{out} + V_{headroom}$$

- If the supply (or the supply's ripple) is lower than the desired output plus headroom, the output will drop



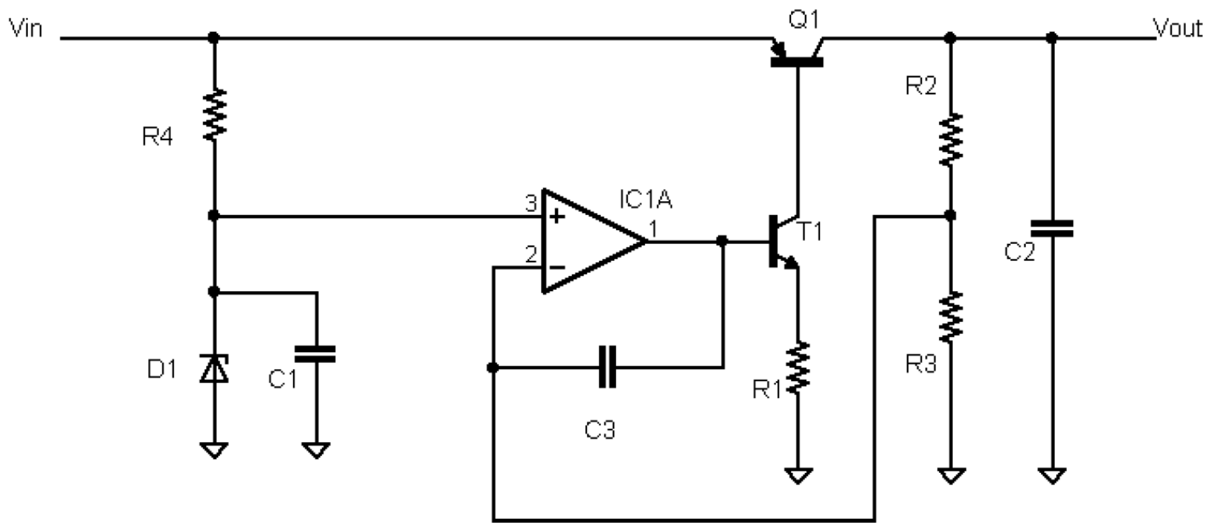
Voltage regulator with controllable output voltage *(Ginsberg, 2018)*

Linear Regulators: Pros and Cons

- Advantages:
  - Low cost
  - Good control
  - Low noise
  - Low emissions
  - Good transient response
- Disadvantages:
  - Headroom is large, can cause problems
  - Poor performance in standby
  - Low efficiency for large input/output difference

Voltage Regulator Circuits: Low Dropout Regulator

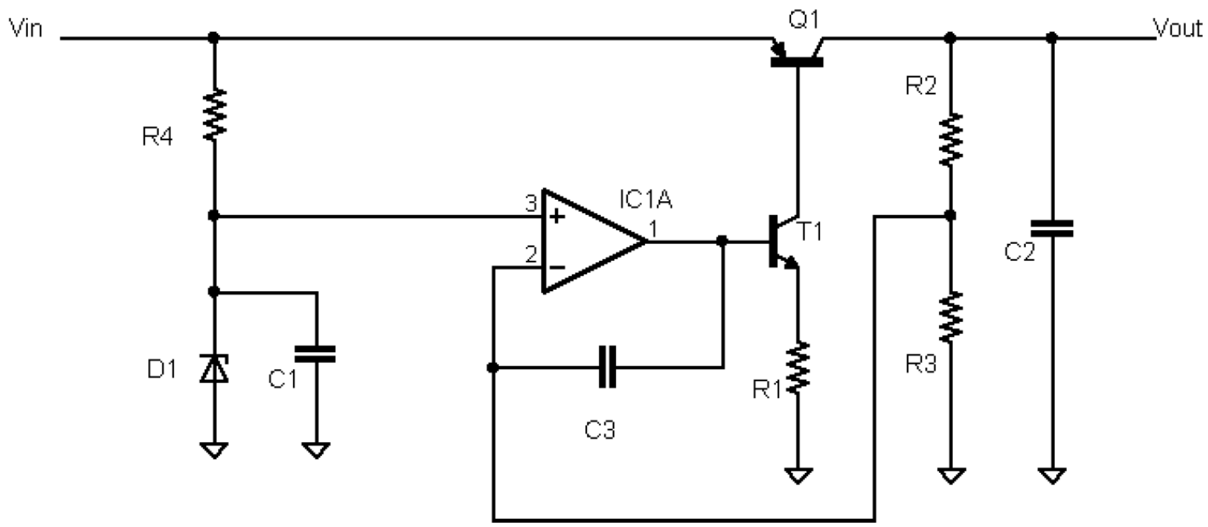
- By adding Q1 and R1 as shown, we can ensure that Q1 enters saturation if Vin is too low
- Q1 becomes the pass element, and T1 amplifies the op-amps signal which can force Q1 into saturation.
- Saturation means Q1's Vce is very low
  - Headroom (dropout) is thus very low
  - Vin can be closer to Vout before regulation stops



Low Dropout regulator *(Ginsberg, 2018)*

Voltage Regulator Circuits: Low Dropout Regulator

- As before, the op-amp adjusts its output as required to correct the output.
    - Increase in the base drive in T1
    - Collector current in T1 also increases, which increases the base drive in Q1.
    - This turns on Q1 (the Pass Element) more fully, which increases the output voltage.
    - In this way the op-amp can use T1 to amplify its output, not needing to approach the supply voltage in order to cause Q1 to saturate.
    - This reduces the large headroom.



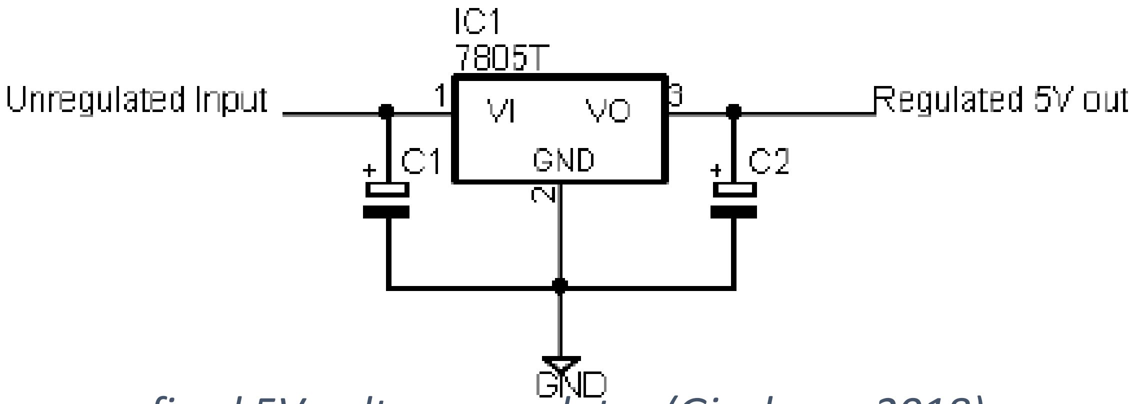
Low Dropout regulator *(Ginsberg, 2018)*

Voltage Regulator Chips

- Many premade voltage regulator chips available
- Types:
  - Fixed voltage regulators
  - Adjustable voltage regulators
  - Low dropout regulators

Voltage Regulator Chips: Fixed Voltage Regulators

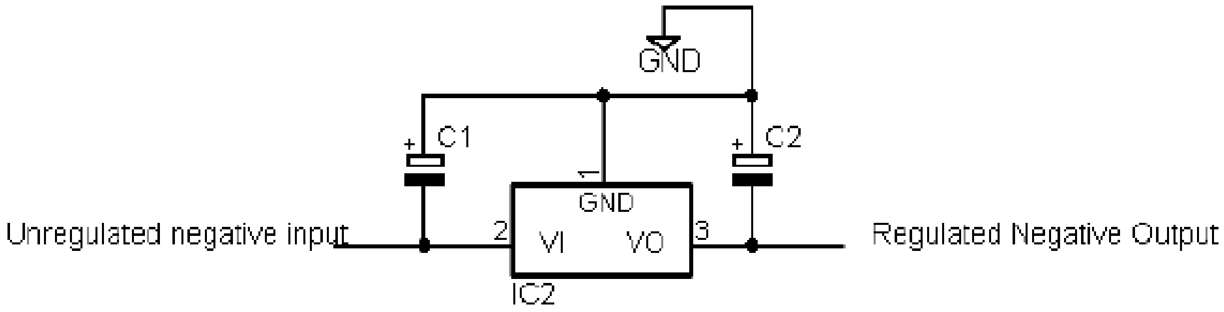
- Fixed output voltage
- Common ones labelled as 78xx (xx states the output voltage)
  - 7805 is a 5V regulator
- Capacitors C1 and C2 reduce high frequency noise from inputs and outputs. Always include these capacitors.



fixed 5V voltage regulator (Ginsberg, 2018)

Voltage Regulator Chips: Fixed Voltage Regulators

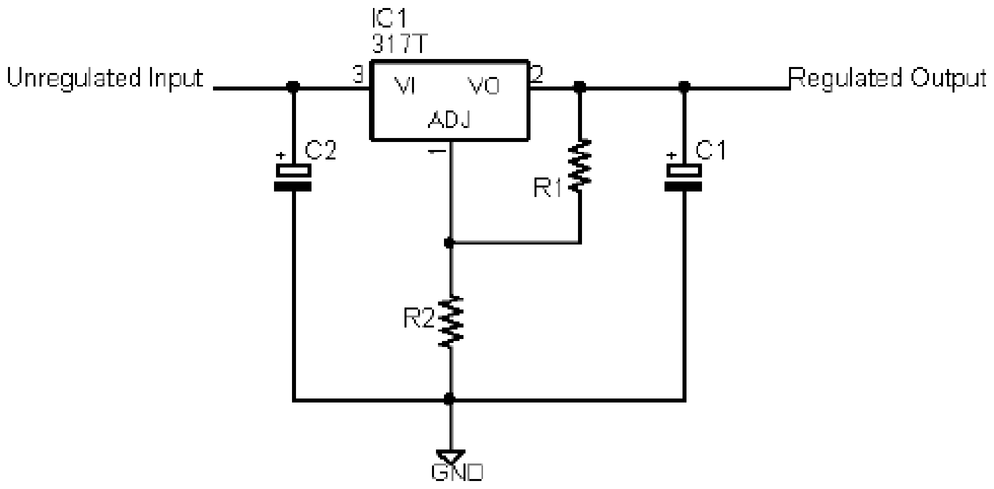
- You also get negative voltage regulators
- Labelled as 79xx
  - 7905 is -5V



Negative voltage regulator (Ginsberg, 2018)

Voltage Regulator Chips: Adjustable Voltage Regulators

- External resistors to set the output voltage.
- Most common are the LM317 (positive) and LM337 (negative).

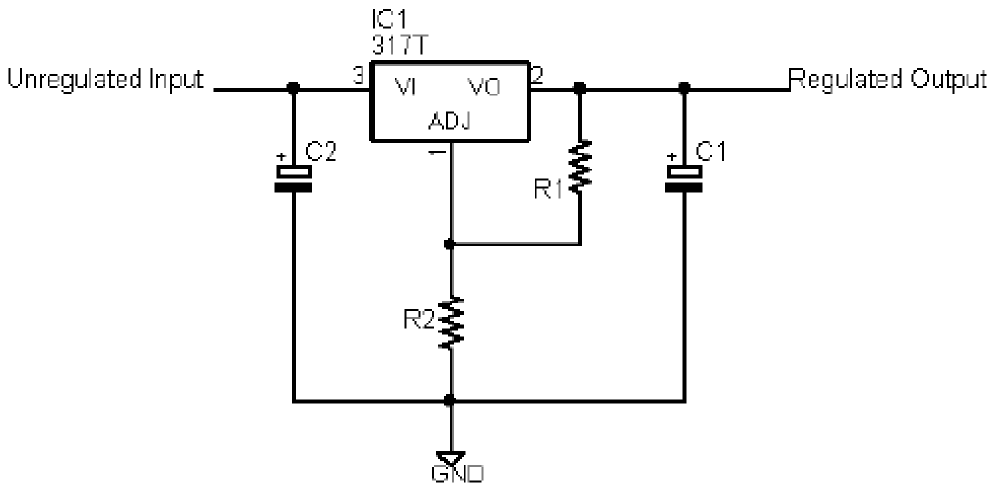


Adjustable voltage regulator (Ginsberg, 2018)

Voltage Regulator Chips: Adjustable Voltage Regulators

- How it works:
  - 1.25V drop across R1.
  - minimal current flows into pin ADJ, typically $50\mu A$
  - The current through R1 also flows through R2 so the output voltage is thus set by the resistors in series.
  - Set R1 = 200-330Ω
  - Select R2 according to:

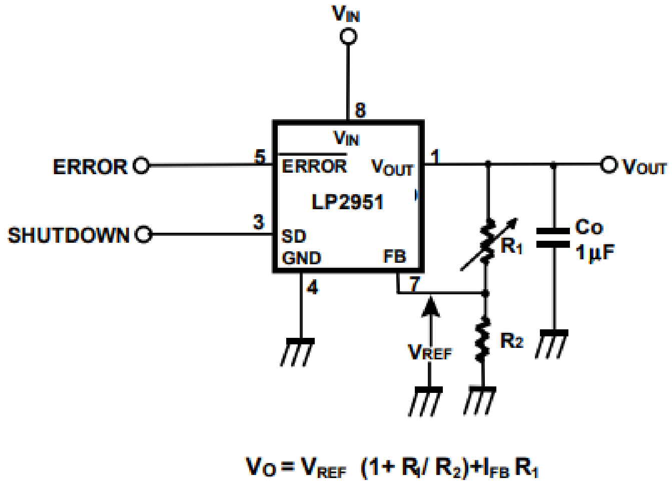
$$V_{out} = 1.25V\left(1 + \frac{R_2}{R_1}\right) + I_{adj}R_2$$



Adjustable voltage regulator (Ginsberg, 2018)

Voltage Regulator Chips:
Low Dropout Regulators (LDO)

- LDO chips
- Most common is LP2951
  - Best used with batteries
  - Error output used to indicate when batteries running flat
  - Shutdown input used to switch off regulator
  - Other operation similar to adjustable regulator
  - The headroom (dropout) for this chip is 0.6V in the worst case.



Application of LDO LP2951 regulator

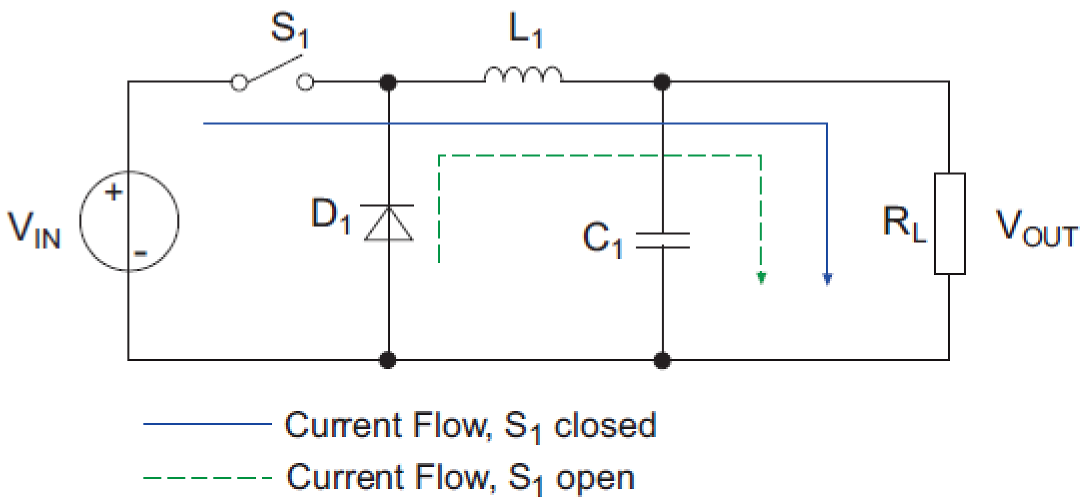
Buck Converters

Switching Regulators

- The regulators looked at till now were linear.
- Buck converters are in a class called switching regulators. The different topologies are:
  - Buck converters – steps down voltage
  - Boost converters – steps up voltage
  - Buck-Boost converters – steps up or down voltage
  - Etc.
- We will only investigate the Buck converters as an introduction. The principles of operation are similar, and all you need to know is what the output does in relation to the input (step-up or -down)

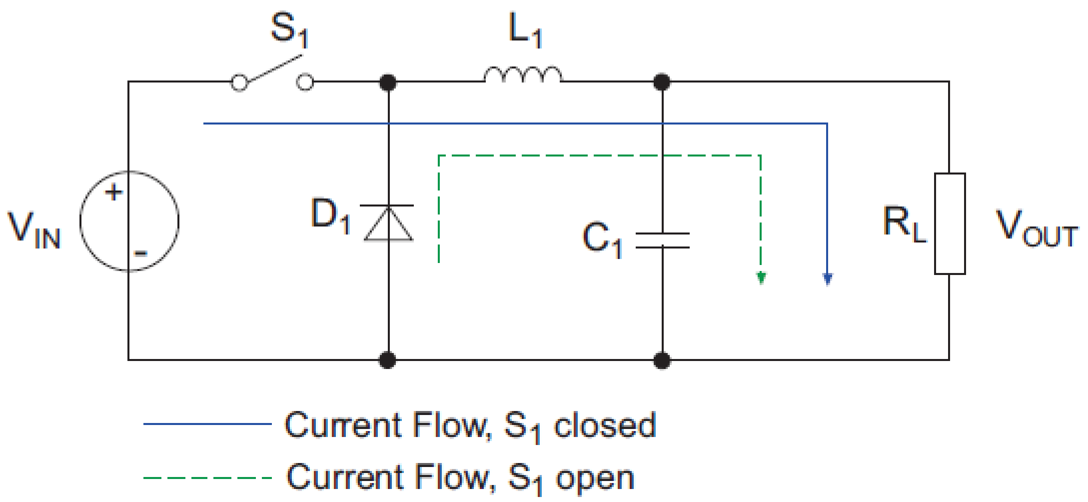
Buck Converters

- Some content for this section is taken from Book of Knowledge by Steve Roberts
- In the diagram used, a switch is depicted, but this represents whatever transistor may be used.
- The circuit below is a basic Buck Converter



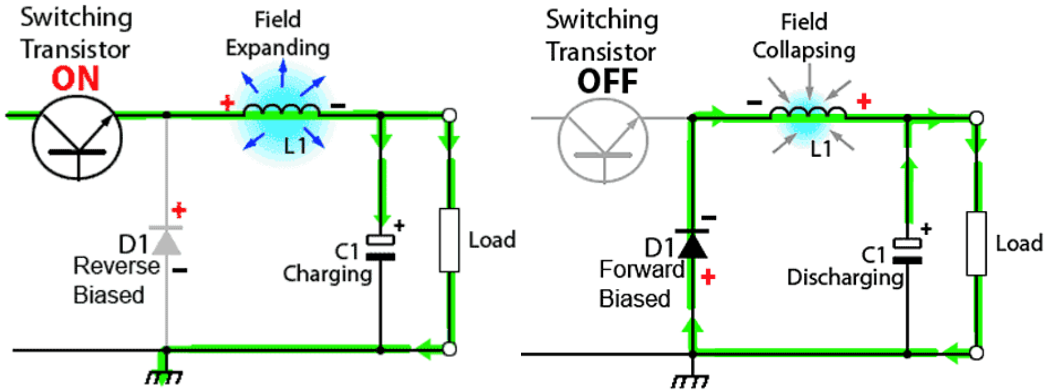
Buck Converters

- The Buck converter works by delivering packets of energy to the load circuit by switching S1 using PWM.
- The energy is “averaged out” using an inductor and capacitor

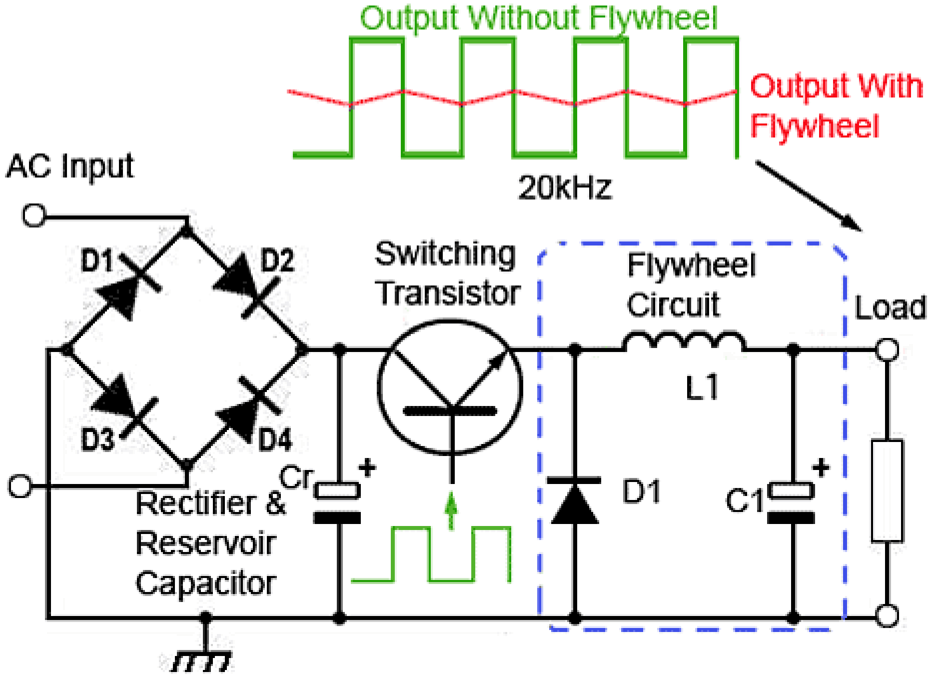


Flywheel Circuit

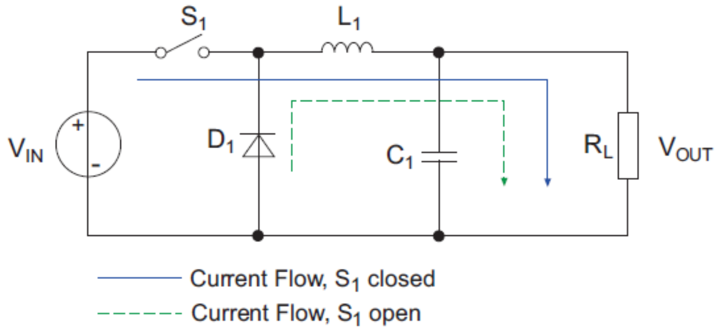
- The inductor, capacitor and diode



- The inductor and capacitor charge up and discharge into the load, just like a flywheel
- Much more efficient
  - Only deliver the energy that is needed



https://learnabout-electronics.org/PSU/psu31.php

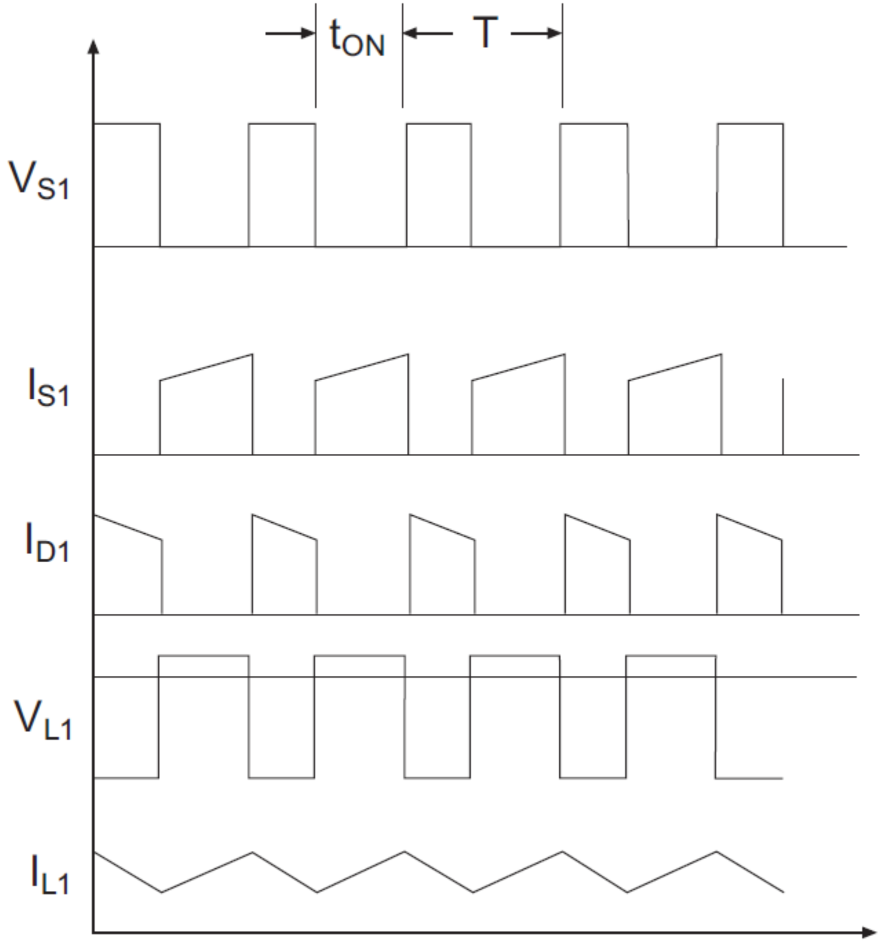


Transfer Function

$$Energy_{in} = (V_{in} - V_{out})t_{on}$$
$$Energy_{out} = V_{out}t_{off} = V_{out}(T - t_{on})$$

- We assume 100% efficiency

$$Energy_{in} \approx Energy_{out}$$
$$(V_{in} - V_{out})t_{on} \approx V_{out}(T - t_{on})$$
$$V_{in}t_{on} \approx V_{out}T$$
$$\frac{V_{out}}{V_{in}} \approx \frac{t_{on}}{T}$$

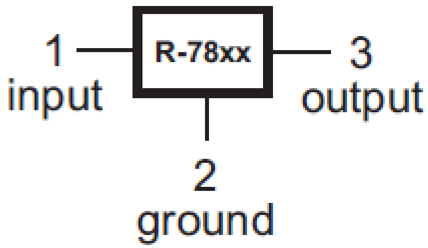


Buck Converter Features

- Advantages
  - Very high efficiencies (>97%)
  - Vout can be anywhere from Vref to Vin
  - Differences between Vin and Vout can be large (unlike linear converter)
  - No load power consumption is negligible
  - Very high switching frequencies possible
    - Higher frequency means smaller inductors and capacitors needed.
    - Compact design
- Disadvantages
  - Output has a larger ripple than linear regulators
  - Much more expensive

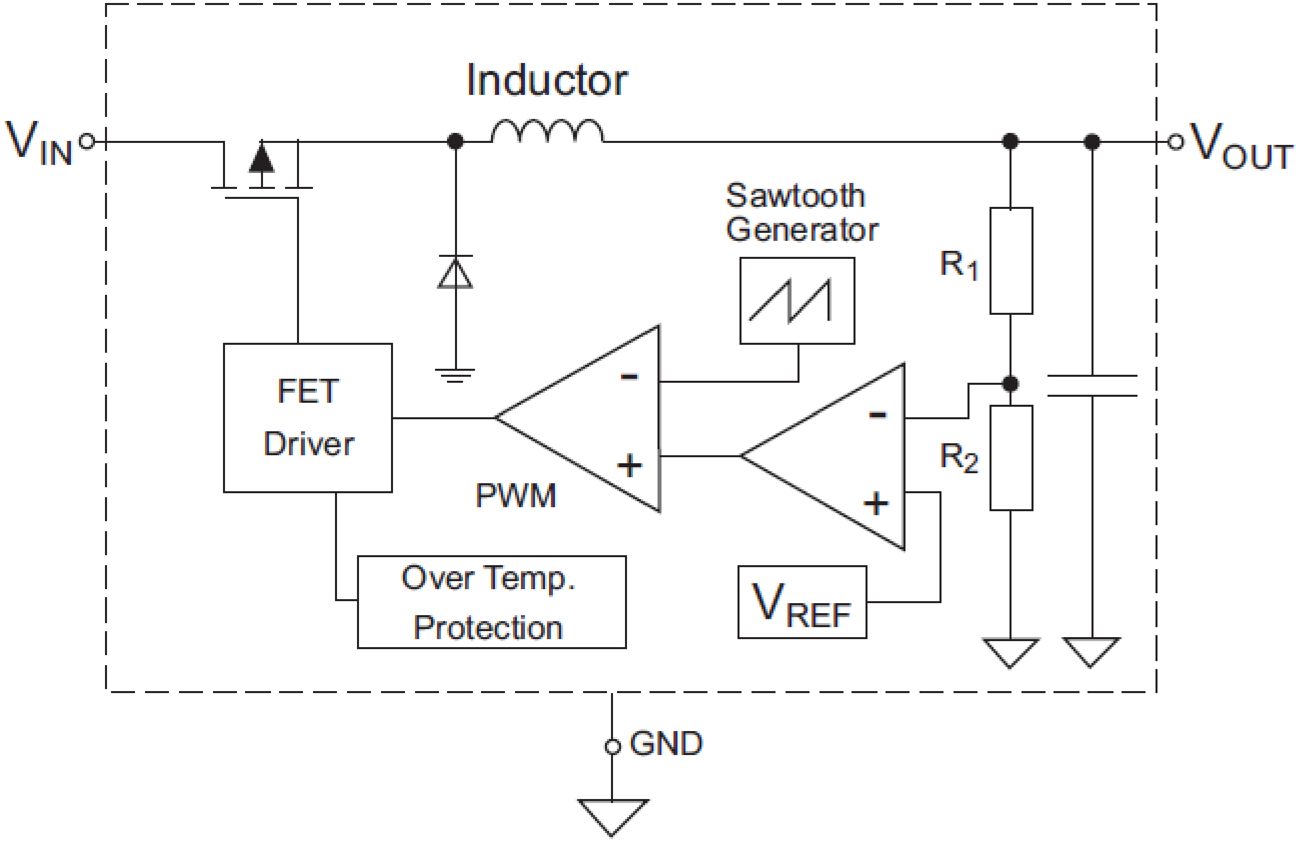
R-78xx Series

- A pin-compatible regulator for the 78xx linear regulators is the R-78xx Buck regulators
- Efficiency 97%
- Input voltages 72Vdc
- Quiescent consumption 20nA (turned off)



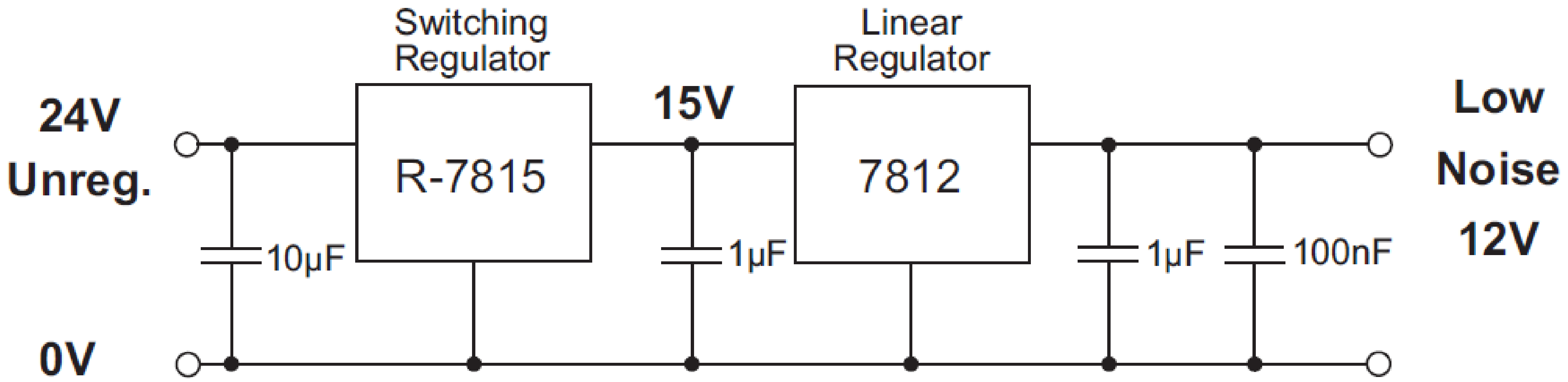
R-78xx Series: Feedback

- All switching converters need a feedback loop to control the switching PWM
- The R-78xx series block diagram shows this feedback through R1/R2
- Vref is the reference voltage desired, and it adjusts the output accordingly.
  - Similar to the linear regulator



Switching and Linear Converters

- If you have a large supply voltage but need to drop it down to a very stable (low ripple) output, you can cascade the two converters



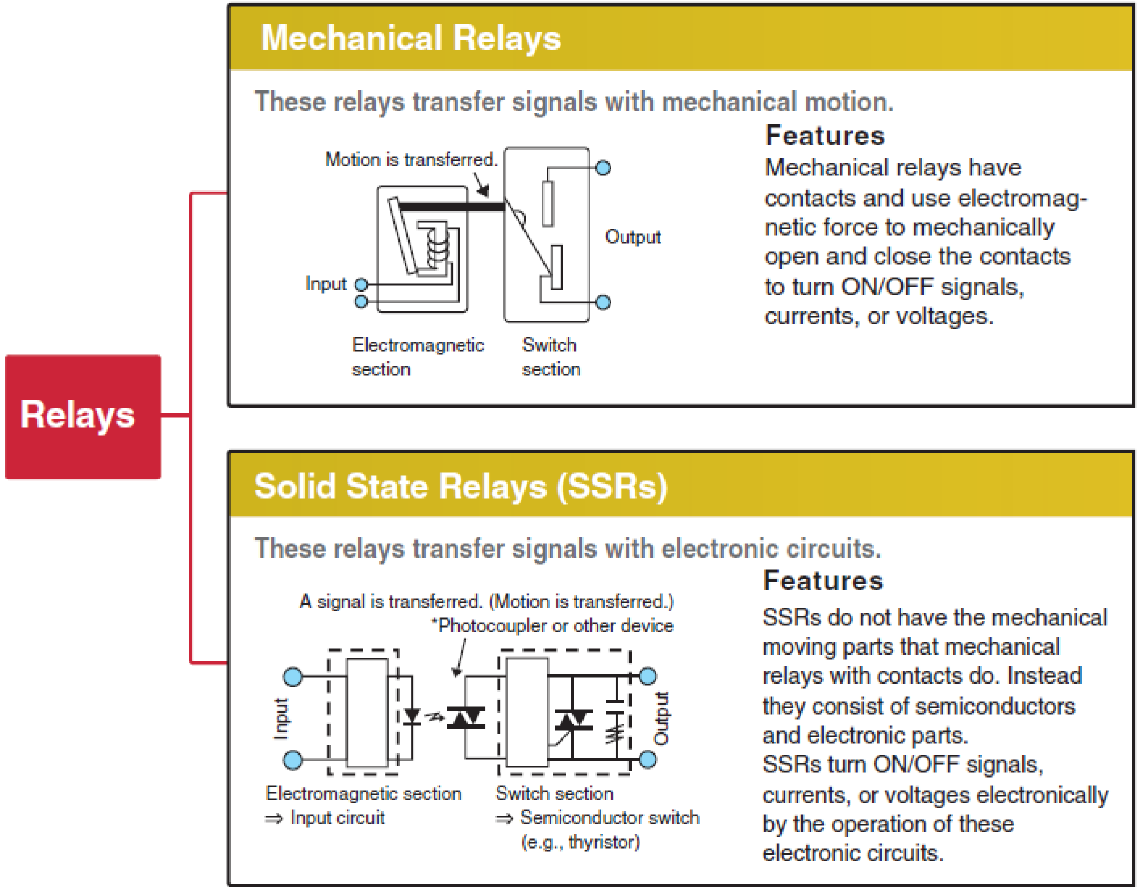
- Combines the efficiency of the Buck and the low ripple of the linear regulators.
  - Output efficiency >76% compared to <50% with just linear regulator

Relays

Relay Introduction

- A relay is a switch that allows a low power circuit to turn on a higher power circuit.
- There are two main types:
  - Electromagnetic mechanical relay (EMR),
  - Solid State Relay (SSR).

Relay Introduction



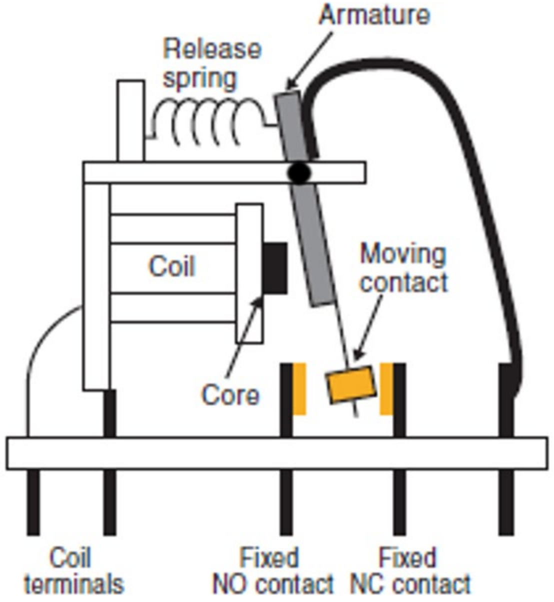
Relay Applications

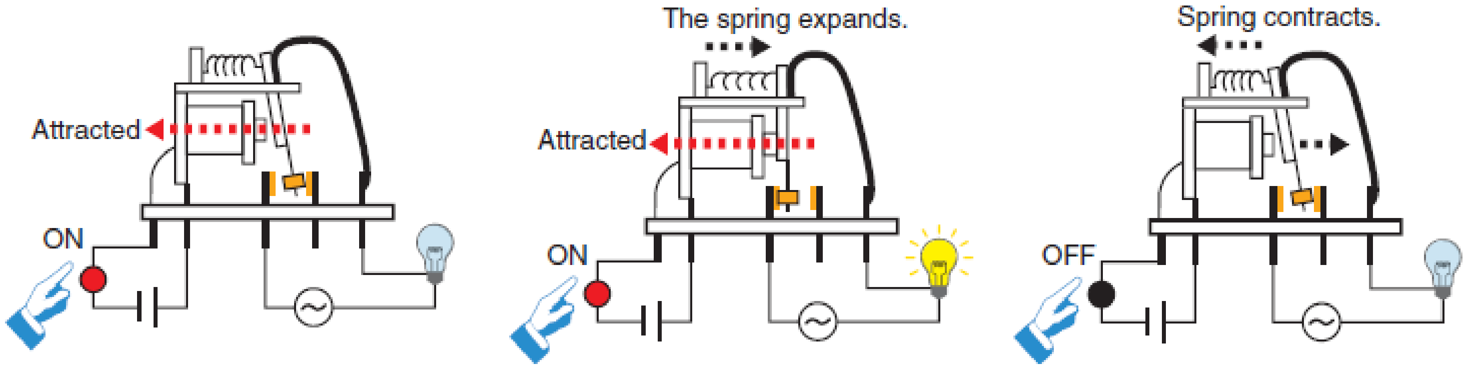
- Home electrical appliances
- Industry machinery
- Plants
- Scientific equipment
- Automatic vending machines
- Communications and measurement equipment
- OA devices



Mechanical Relays

- Many sub-categories of mechanical relays
- Uses an electromagnetic coil to move an arm such that it makes or breaks conduction with a contact.





Mechanical Relay Characteristics

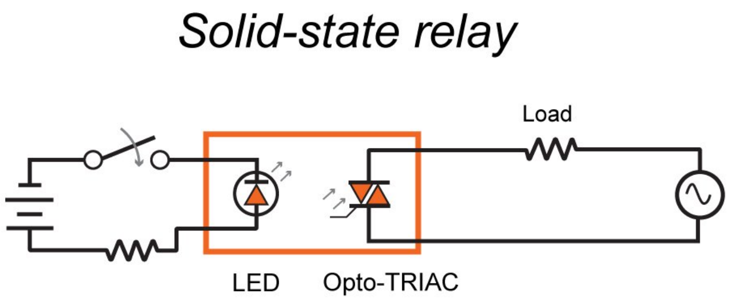
- Complete electrical isolation
  - between the controlling circuit and the driven circuit
  - Controlling can be DC while driven circuit can be AC
- Pick-up
  - The power required to initially move the arm into the active position
- Hold
  - The power required to keep the arm in the active position
- Both pick-up and hold mean that you are losing power while the circuit is active

Mechanical Relay Disadvantages

- Limited contact life
- Bulky and take up room
- Slow switching speeds
- Contact bounce (it can take 15ms to switch and settle without the contact bouncing off repeatedly)
- EMI noise
- There is power lost in the coil

Solid State Relays (SSRs)

- Operate in a similar way to EMRs
- Use semiconductor technology to perform switching function instead of mechanical motion



- Electrical isolation achieved using an optocoupler (shown in orange)
  - LED used to activate a TRIAC
  - TRIACs are similar to transistors, except they don't have a linear region and aren't good for amplification etc
  - A DC signal can drive an AC current through a TRIAC

Solid State Relays (SSRs)

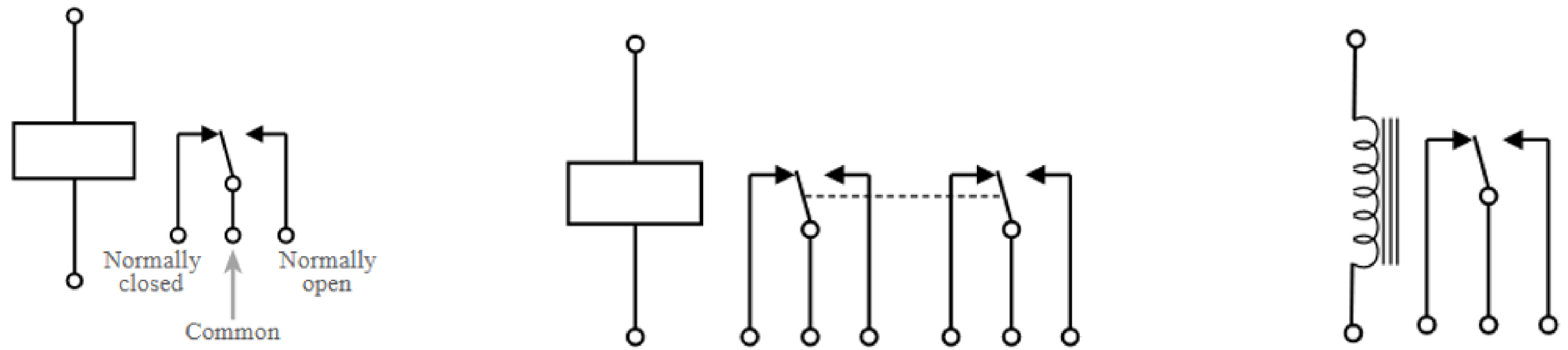
- Advantages:
    - Faster
    - Less space
    - No wear on contacts so less maintenance
    - No switching noise from a coil
    - Electrical isolation of circuits
- Disadvantages:
    - Really expensive for the higher power versions
    - Need large heatsinks for the higher power versions

Solid State Relays (SSRs)

- Preferred for lower power, while EMRs used for higher power
  - Because of cost and excess heat
- SSRs can be used for either AC, DC or AC/DC operation.
  - You will need to select your SSR according to your requirements.

Relay Control Circuits

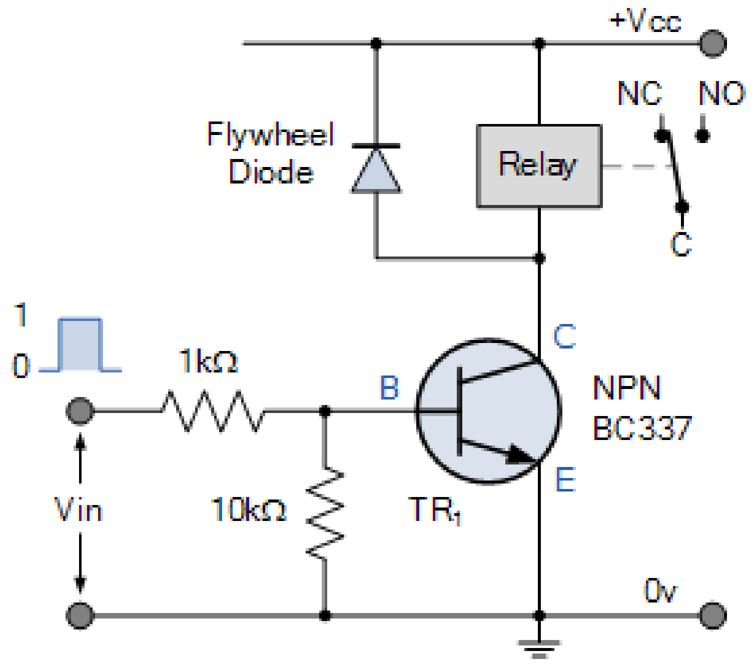
- Many types of control circuits, which you can research here
- Relay (EMR and SSR) circuit symbols



A (basic relay) B (multiple switch) C (older style)

Relay Control Circuits: NPN Relay Switch Circuit

- An NPN used as a switch to operate the relay's coil.
- NPN provides current amplification for microcontroller
- Flywheel diode
  - This is for a mechanical relay, which is essentially an inductor.
  - If the transistor turns off suddenly, the change of current in the inductor will produce a voltage spike which can damage the relay and transistor.
  - Always place a flywheel diode (if you're using a DC supply, AC needs other circuitry) to allow a path for current flow to prevent damage



Relay Control Circuits: Emitter Follower Relay Switch Circuit

- Similar to the NPN, only difference is that the relay is placed on the emitter of the NPN
- There are various other control circuits, using:
  - Darlingtons
  - PNP circuits
  - PNP collector circuits
  - MOSFET circuits
  - Logic or microcontroller controlled circuits