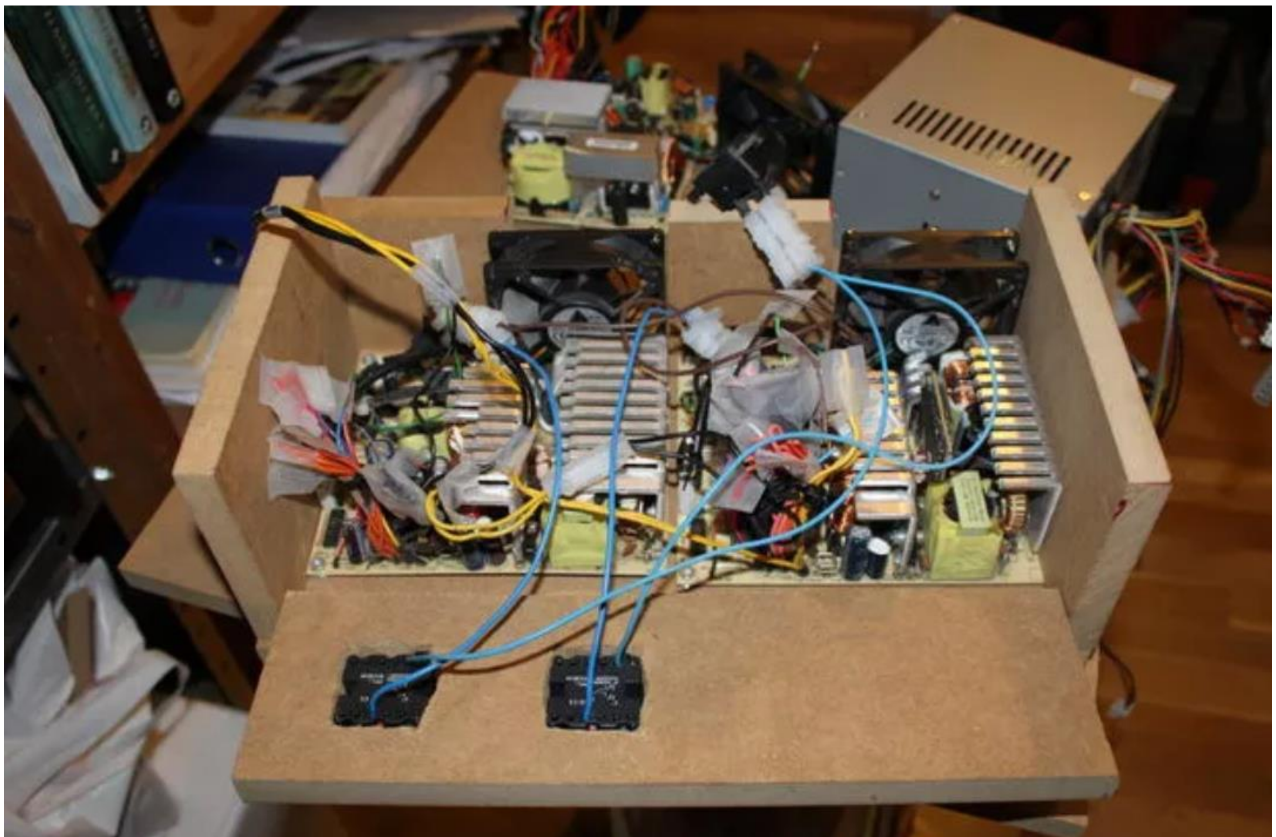
Power Supplies 101
DC-DC Converters

10-Feb-2018



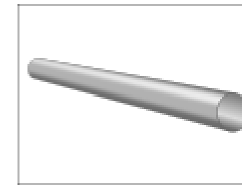
Tonight's Agenda

- Quick primer on circuit components and basic calculations
- Examples of unregulated linear supplies
- How regulated linear supplies work
- How switching supplies work
- Some notes on capacitors
- Cover related issues that you're likely to encounter

Quick circuit component primer

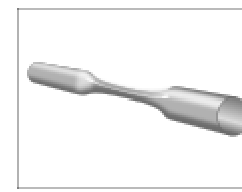
Wire – carries electrical current like a pipe carries water

Voltage – like the pressure of water in a pipe or air in a tire

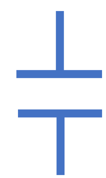


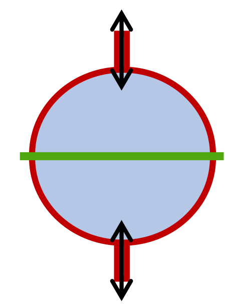
Current – the amount of water flowing through a specific cross section of the pipe

Resistor – resists the flow of current, like a constriction in a pipe

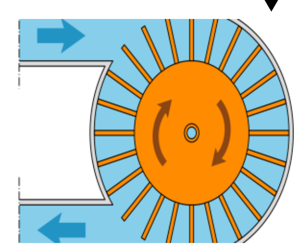


Capacitor – stores energy like a hydraulic accumulator





Inductor – stores energy like a heavy paddlewheel



Power supply math primer

Power (P, watts, W) = ***Voltage*** (volts, V) x ***Current*** (amps, A)

Power = 5V x 2A = 10W

Ohm's Law:

V = I x R

or: I = V / R

or: R = V / I

V = voltage, volts, V

I = current, amps, A

R = resistance, Ohms, Ω

Units:

1000 milli = 1.0

400mA = 0.4A

10mV = 0.01V

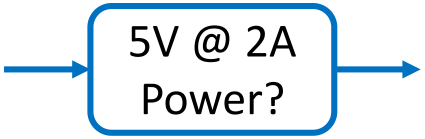
2000 mΩ = 2Ω

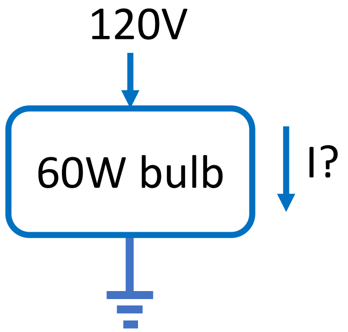
Examples

What is the power rating of a 5V, 2A power supply?

Power = Voltage x Current

5V x 2A = 10W





How much current does a 60W light bulb draw?

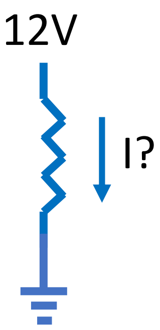
Current = Power / Voltage

60W / 120V = 0.5A

A 100Ω resistor is connected between a 12V supply and ground, how much current does it draw?

$I = V / R$

$= 12V / 100\Omega = 0.12A = 120mA$

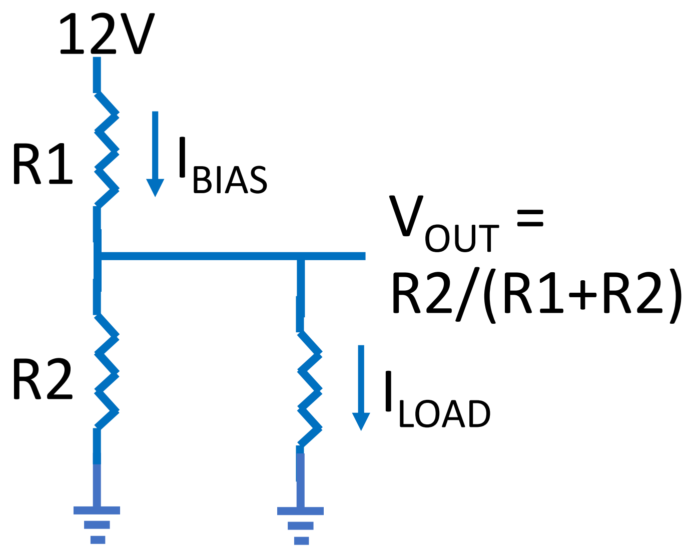


How much power does it dissipate?

Power = Voltage x Current

= 12V x 120mA = 1.44W

Simple Voltage Converter/Supply



Example: 12V to 5V, 10mA load

$R1 = 70\Omega$

$R2 = 50\Omega$

$I_{BIAS} = 100mA$

$V_{OUT,\ NO\ LOAD} = 5.0V$

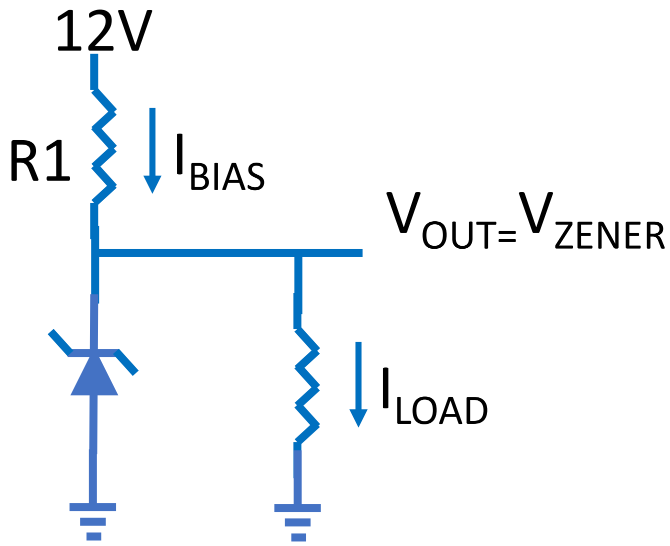
$V_{OUT,\ 10mA\ LOAD} = 4.7V$

Load regulation = 6%

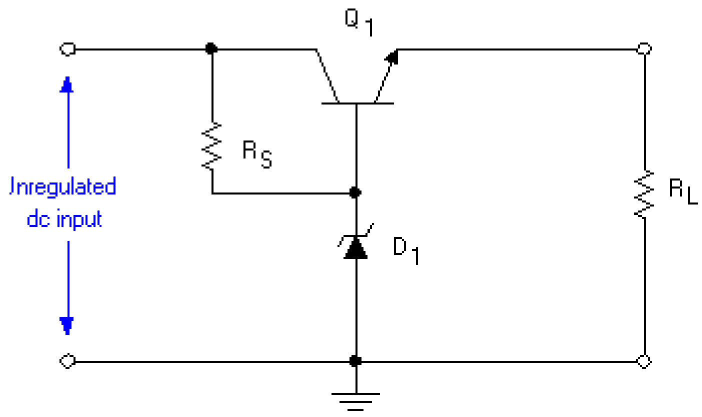
Efficiency = 9.6%

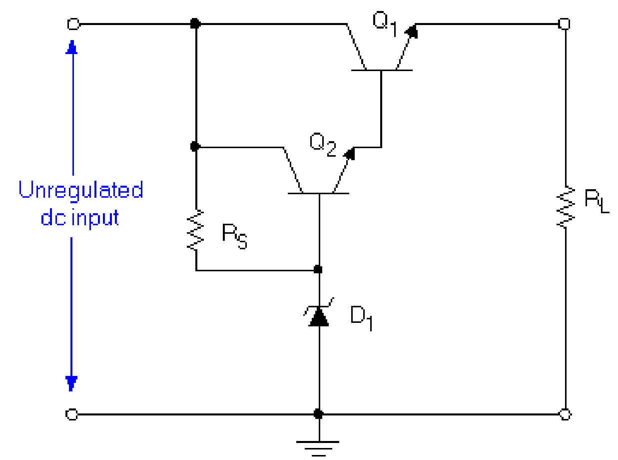
Zener Voltage Reference/Supply

Decent load regulation ~2-5%
Efficiency ~30%

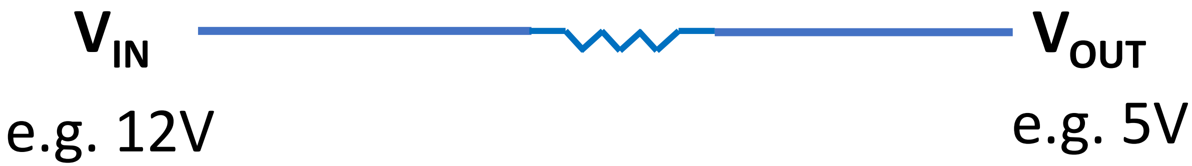


More unregulated supplies





How does a linear regulator work?



Resistor converts extra voltage into heat

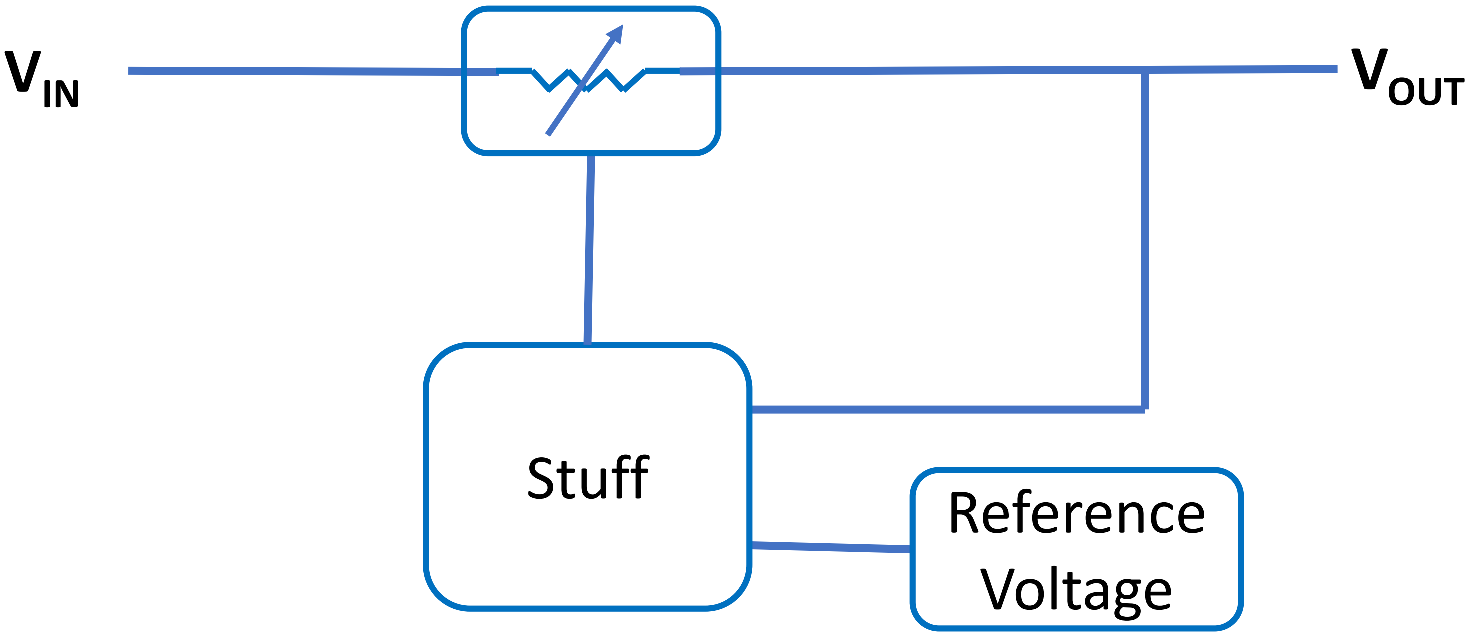
V_{OUT} will be less than V_{IN}

Efficiency = V_{OUT}/V_{IN}

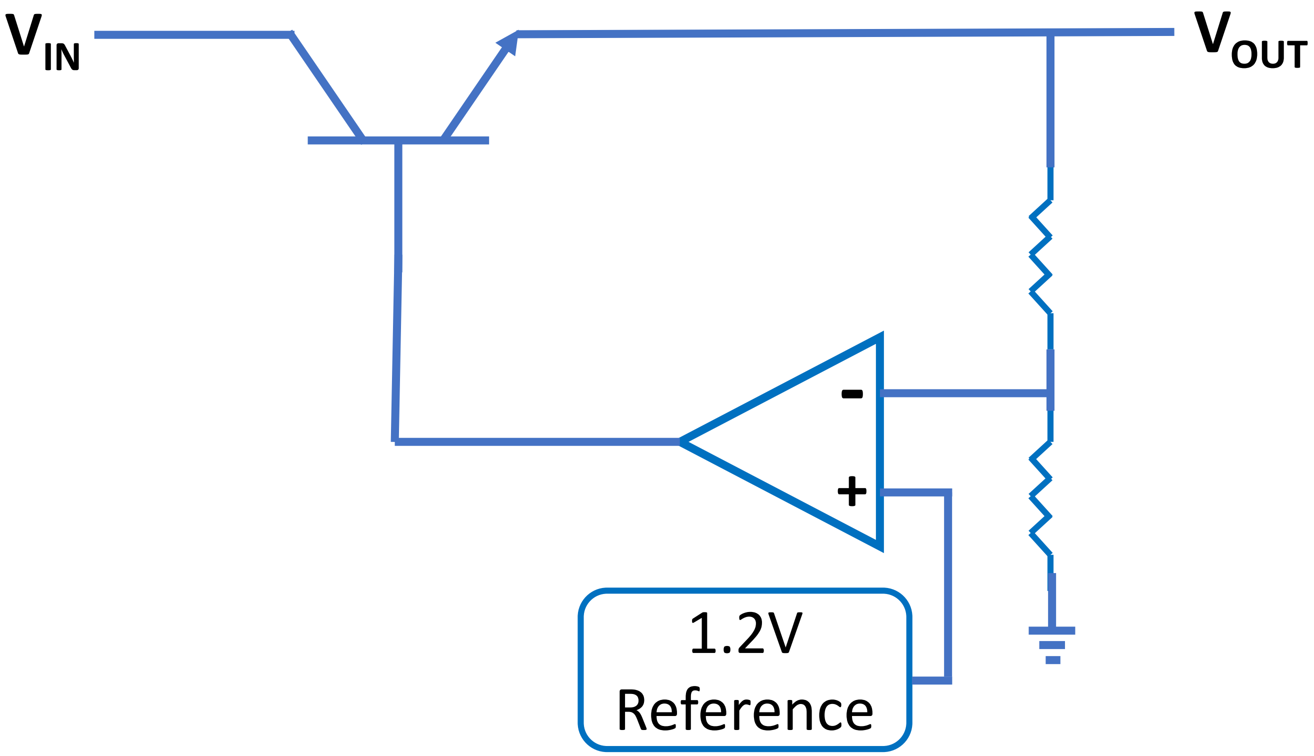
5V / 12V = 42%

3.3V / 5V = 66%

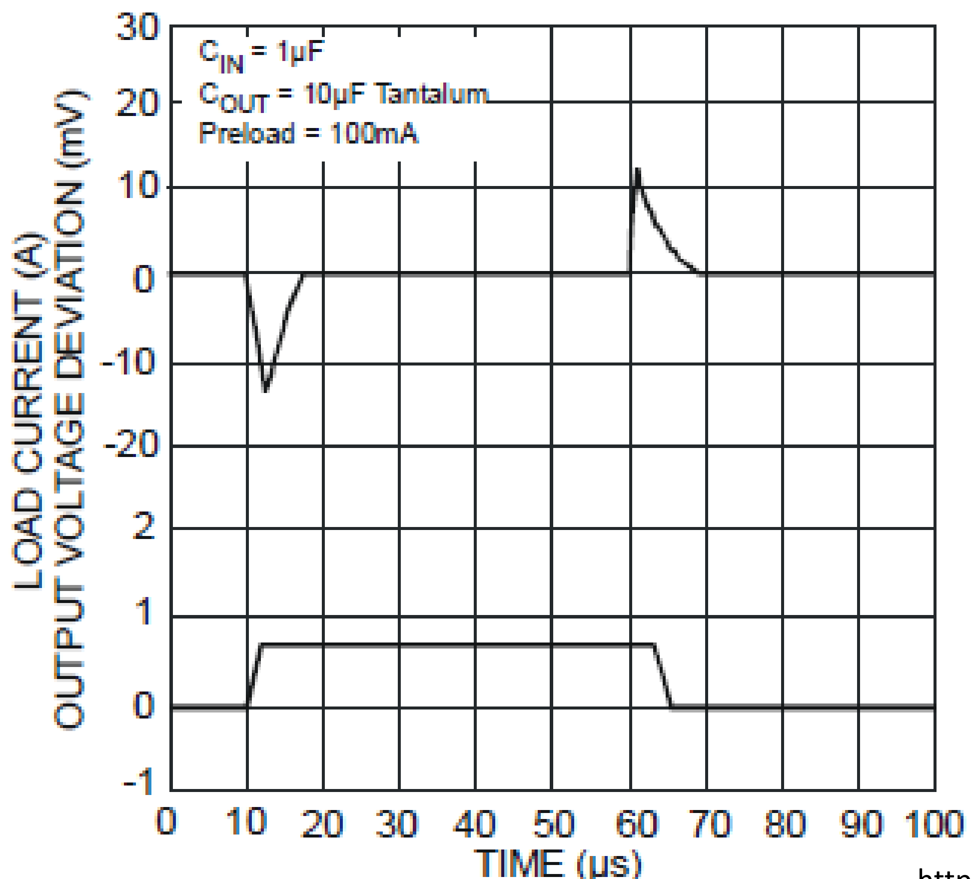
Add a control loop



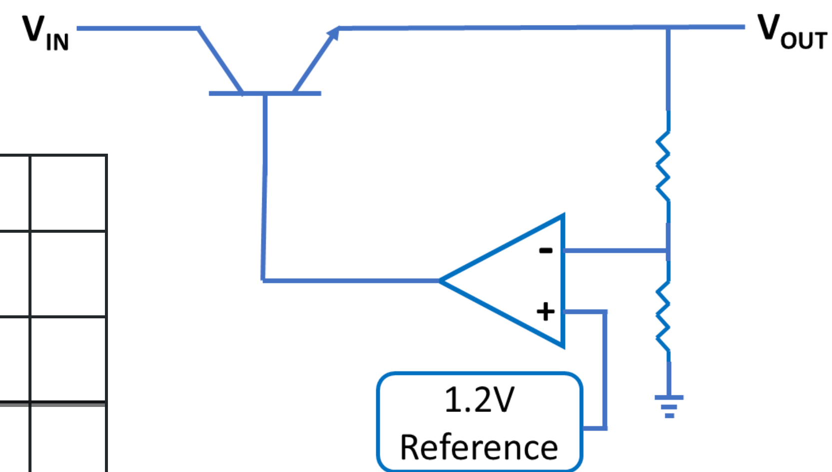
Make it more real



Linear regulator in action

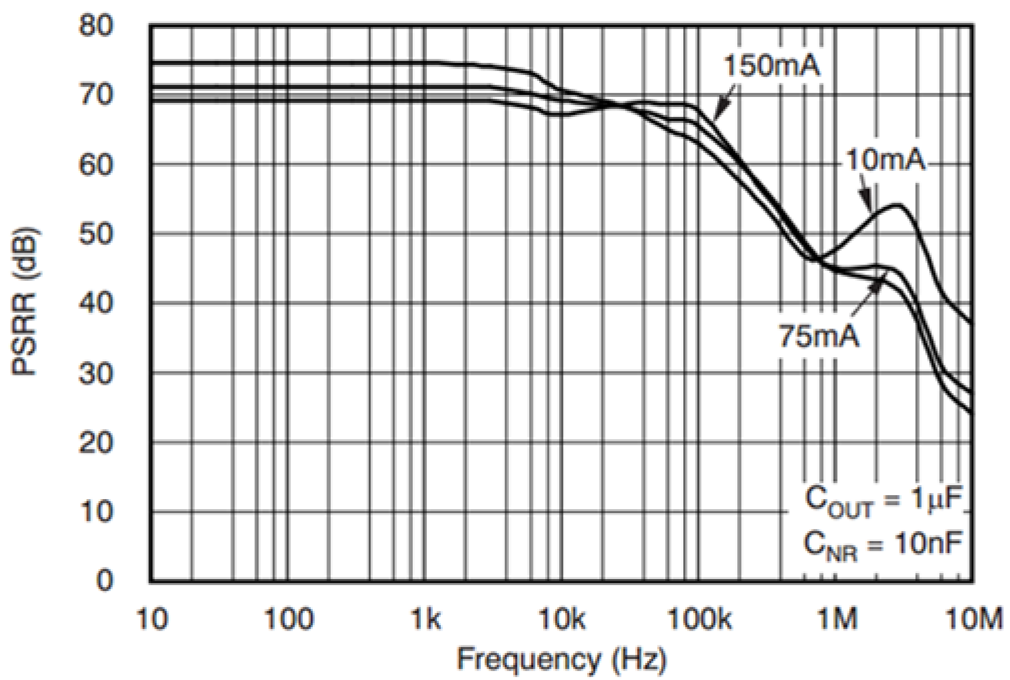


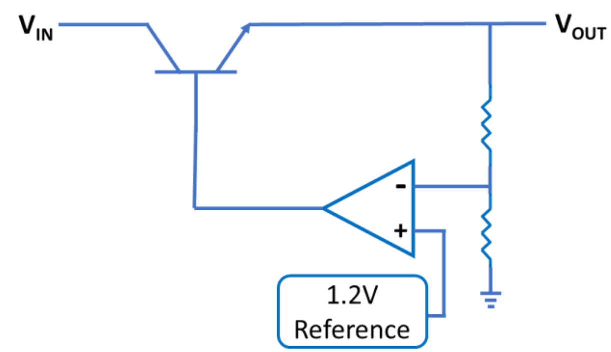
Load Transient Response



https://www.diodes.com/assets/Datasheets/AP1117.pdf

Power Supply Rejection





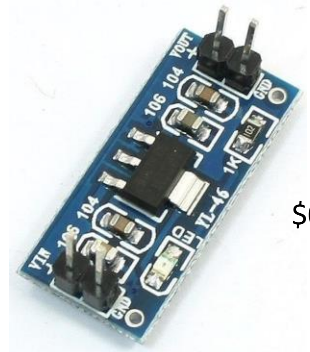
$$PSRR\ (dB) = 20\ log\ \frac{V_{ripple\ (in)}}{V_{ripple\ (out)}}$$

20dB = 1/10
40dB = 1/100
60dB = 1/1000
70dB = 1/3162 -> Vin ripple of 1V results in 0.3mV at Vout

https://e2e.ti.com/blogs_/b/powerhouse/archive/2017/03/03/ldo-basics-power-supply-rejection-ratio

Typical Hardware

$1.60

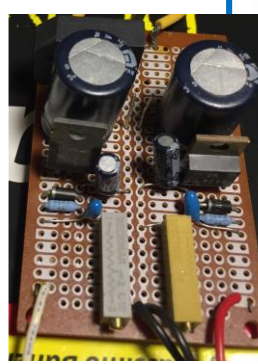


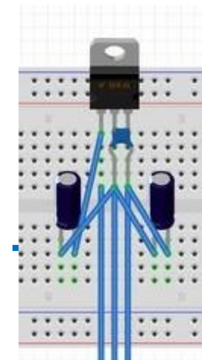
$0.99

$1.50

$1.70

@mikew



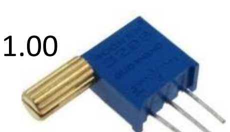


$0.50

$0.50-
$1.00

$0.05

$1.00



Workhorse linear regulators ICs

	V_{IN} Max	V_{OUT} Range	V_{DO} Dropout	Peak I_{OUT}
LM317	V_{OUT} + 40V	1.25V to 37V	3V	1.5A
LM1117	15V	1.25V to 13.8V	1.3V	1A
LM7812	35V	12.0V	2V	2.2A
LM7805	35V	5.0V	2V	2.4A
LM7833	36V	3.3V	2V	1.8A

These regulators are available from multiple manufacturers. Check the data sheet for the specific part you're looking at.

DC-DC Switching Supplies

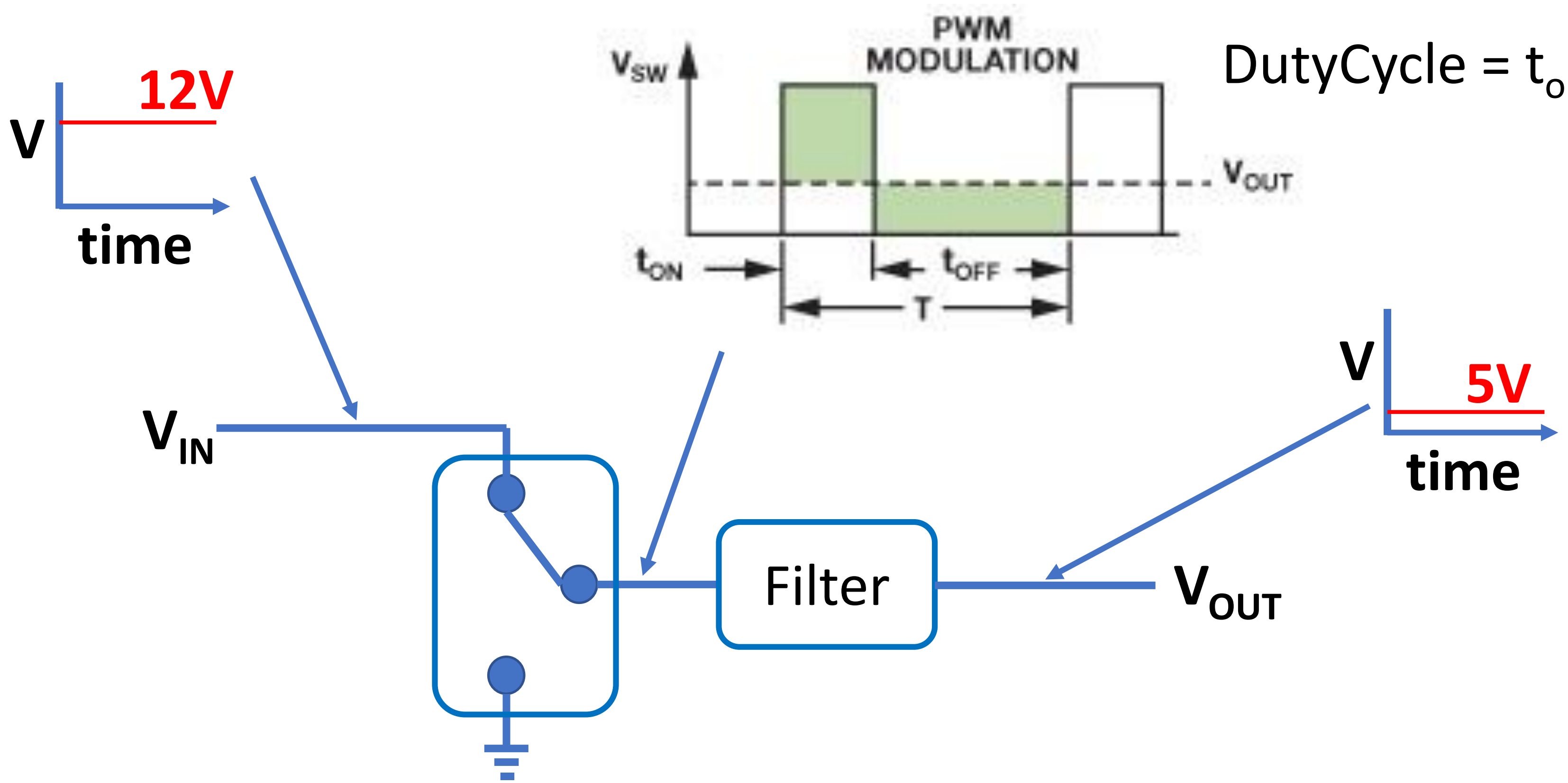
- Buck converter: $V_{OUT} < V_{IN}$
  - Very plentiful selection of products

- Boost converter: $V_{OUT} > V_{IN}$
  - Inductor-less Charge Pump, typically 10's of mA
  - Inductor based boost converter, any current

- Buck/Boost converter: V_{OUT} >= or <= V_{IN}
  - Useful in battery powered circuits where the battery voltage starts above the required voltage but ends below it
    - e.g. LED flashlight

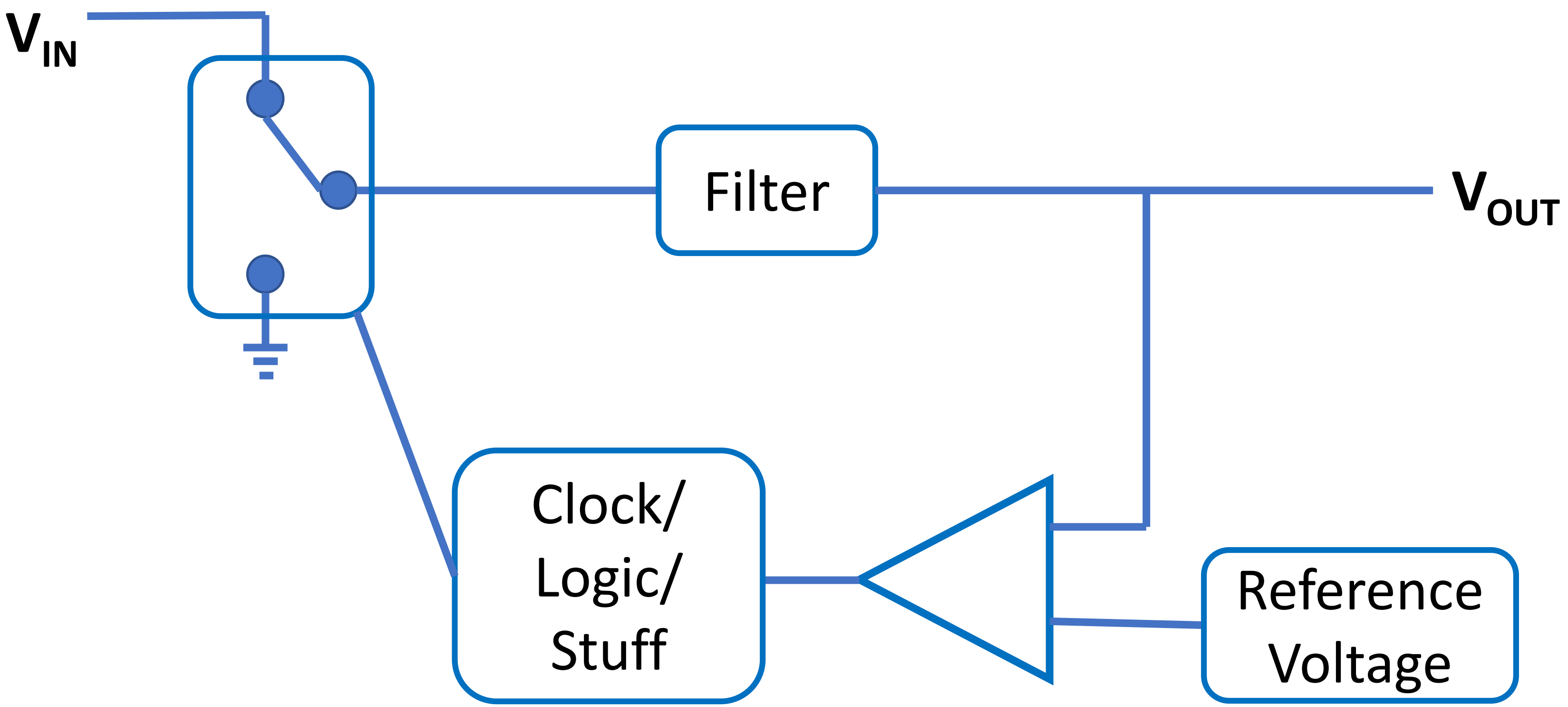
How does a buck regulator work?

$\text{DutyCycle} = t_{on}/T$

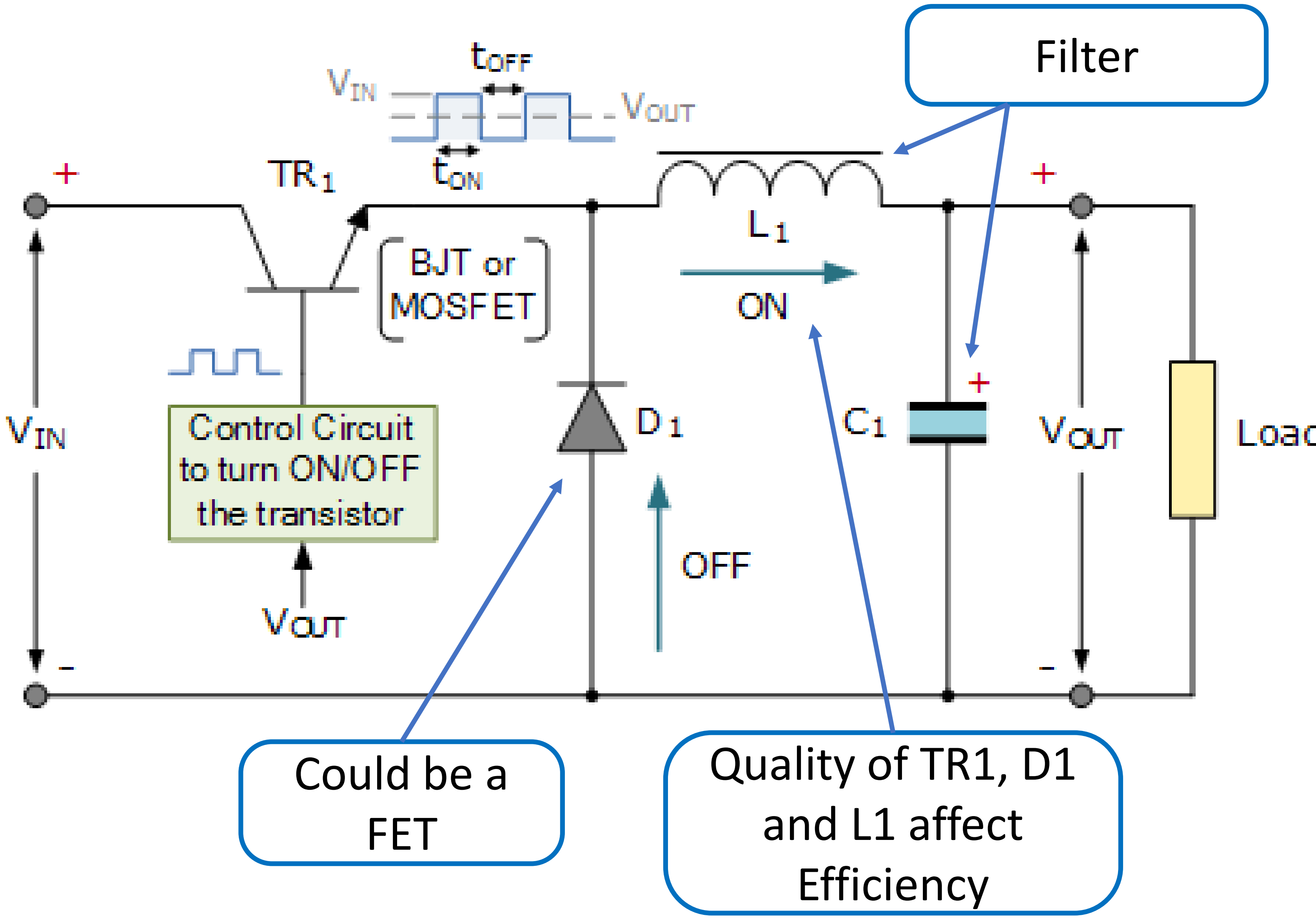


$V_{OUT} = V_{IN} \times \text{DutyCycle}$

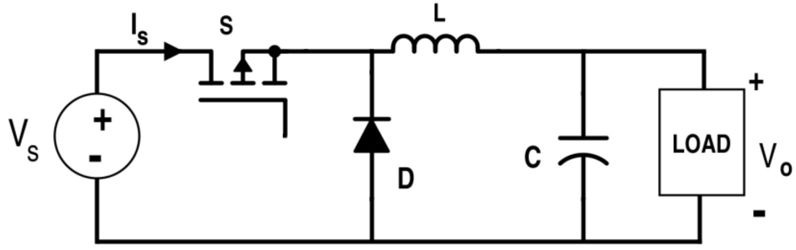
Add a control loop (regulation)



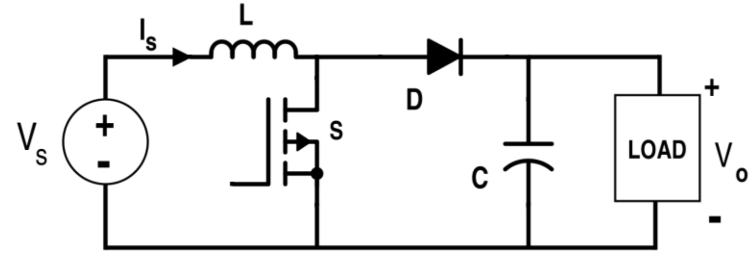
Make it more real



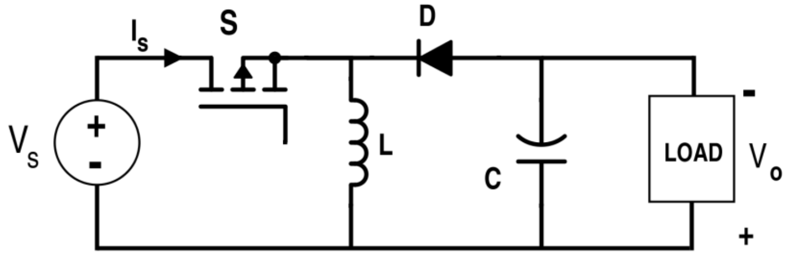
Buck, Boost, Buck/Boost



Buck Converter



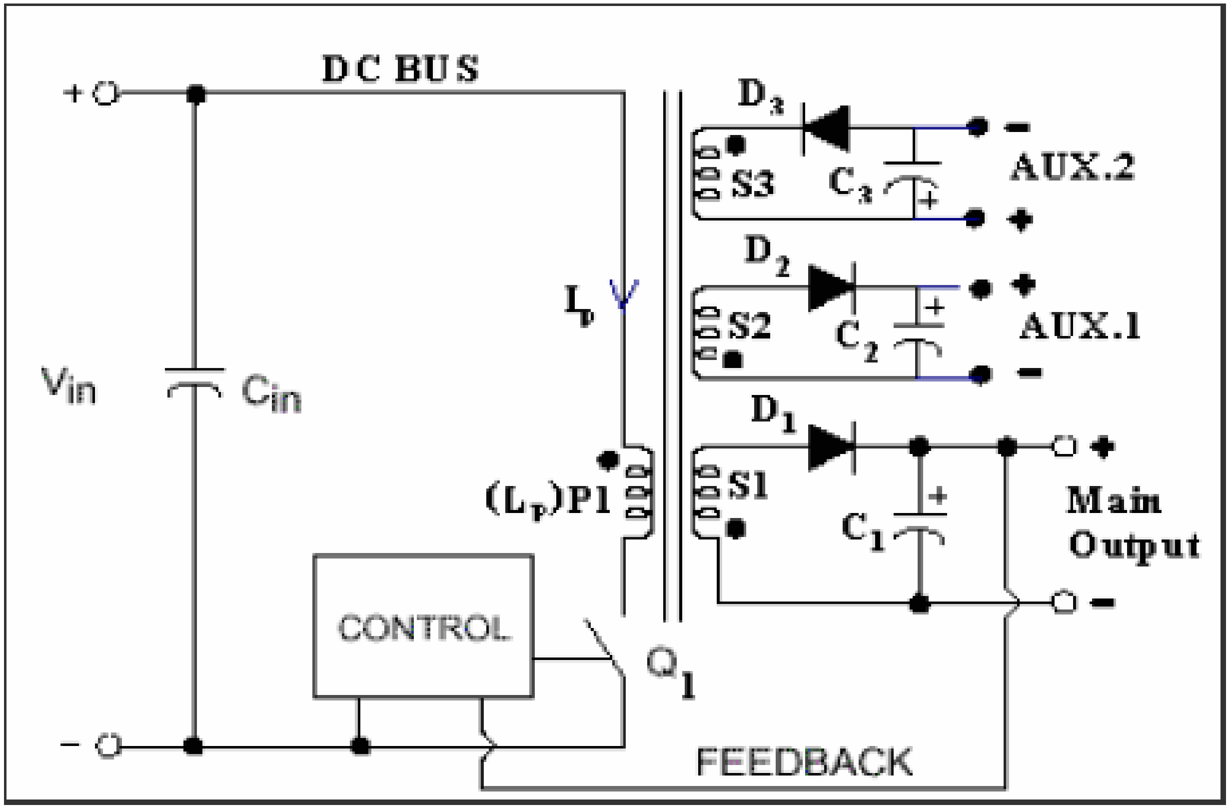
Boost Converter



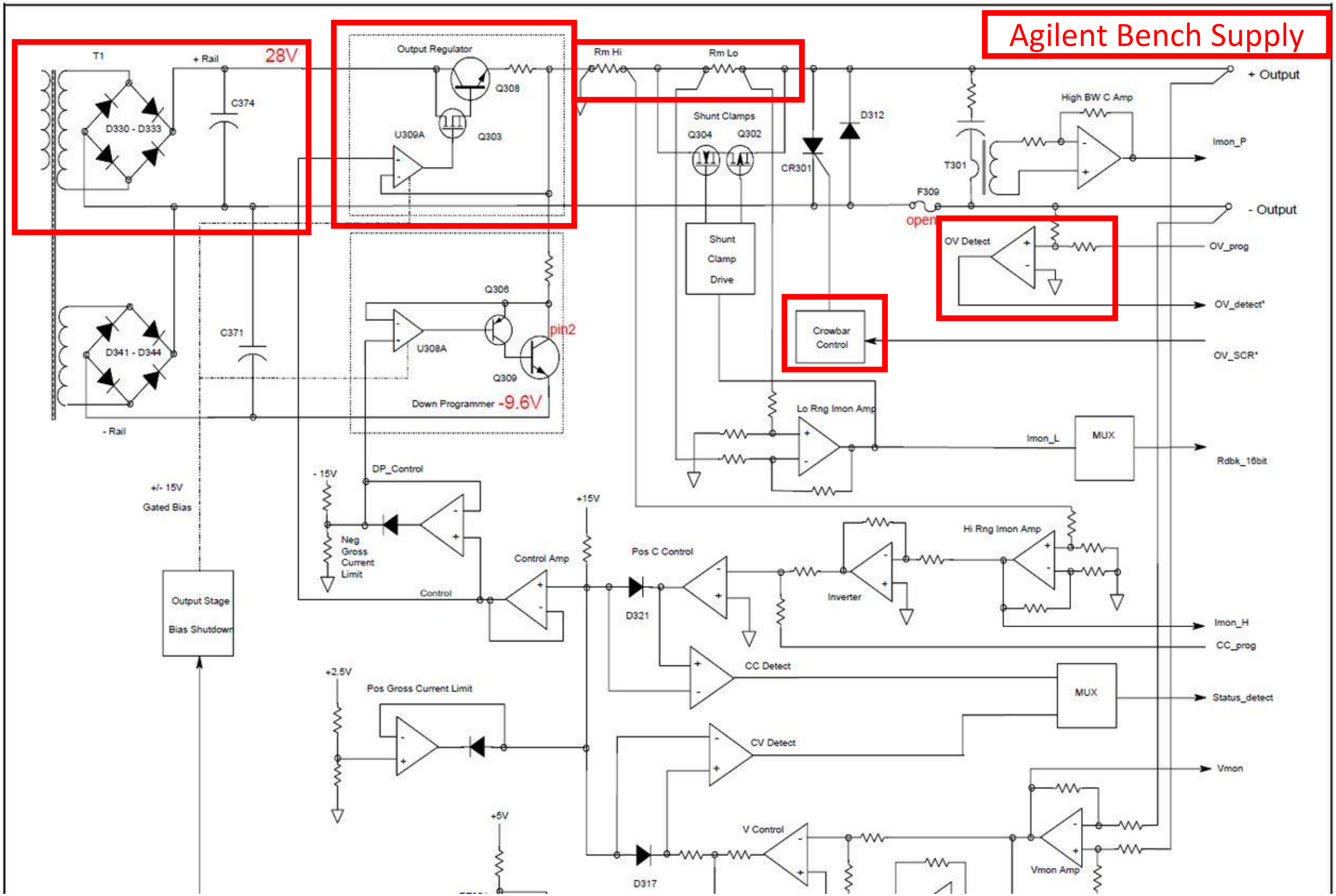
Buck-Boost Converter

Slight modifications in the schematic, operation is quite different from the earlier buck explanation

Flyback Converter



- Transformer is used in place of an inductor
- One or many outputs
- Feedback loop (regulation) based on one output or some weighted average of multiple outputs


Agilent Bench Supply
T1
+ Rail
28V
C374
D330 - D333
Output Regulator
Q308
Q303
U309A
Rm Hi
Rm Lo
Shunt Clamps
Q304
Q302
CR301
D312
F309
open
T301
High BW C Amp
+ Output
Imon_P
- Output
Shunt
Clamp
Drive
OV Detect
OV_prog
OV_detect*
Crowbar
Control
OV_SCR*
C371
D341 - D344
Q306
pin2
U308A
Q309
Down Programmer -9.6V
- Rail
Lo Rng Imon Amp
Imon_L
MUX
Rdbk_16bit
+/- 15V
Gated Bias
- 15V
DP_Control
Neg
Gross
Current
Limit
Control
Control Amp
+15V
Pos C Control
D321
Inverter
Hi Rng Imon Amp
Imon_H
CC_prog
Output Stage
Bias Shutdown
CC Detect
MUX
Status_detect
+2.5V
Pos Gross Current Limit
CV Detect
Vmon
+5V
V Control
Vmon Amp
D317

DC-DC linear vs switching supplies

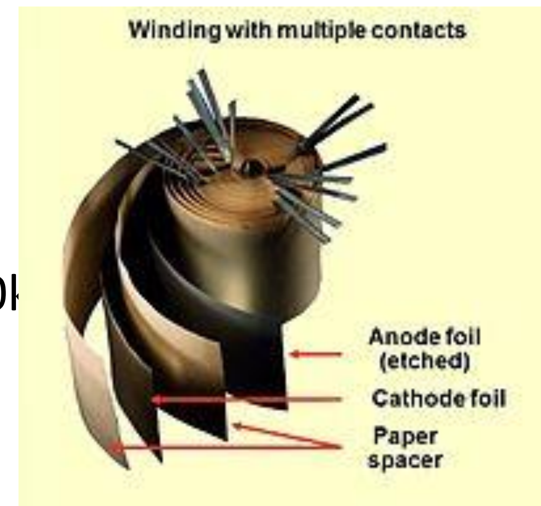
	Pros/Cons
Switching (Regulated)	• Easy to buy/use • Typically preferred over ~1A of output current • Typically overly-complicated for low power circuits (100's of mW)
Linear Regulators	• Easy to build, easy to buy • Easy to integrate onto proto boards • Becomes more difficult as P_{DISS} increases beyond a few watts • Off-the-shelf options above 1A are limited

About Capacitors

Capacitance value
Physical size
Lead configuration (axial, radial)
Voltage rating
Polarized
Equivalent Series Resistance (ESR)
Equivalent Series Inductance (ESL)
Appropriate frequency range

Electrolytic Capacitors

Electrolytic (Aluminum)
- Primarily used for bulk capacitance, up to 10,000’s of µF
- Lots of disadvantages:
  - Polarized (typically)
  - Need to check voltage rating, derate 20%
  - Physically large
  - High equivalent series resistance
  - High equivalent series inductance
  - Doesn’t look like a capacitor much above 100k

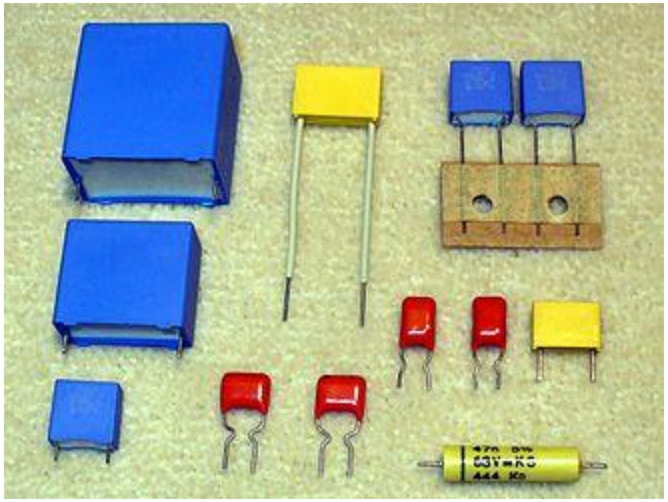


Electrolytic (solid tantalum)
- Similar to aluminum electrolytic except:
  - Smaller
  - Better (lower) ESR, ESL
  - Frequency response to ~500kHz, maybe 1MHz
- Derate voltage by 50%
- Overvoltage or wrong polarity can cause a fire

Ceramic Capacitors

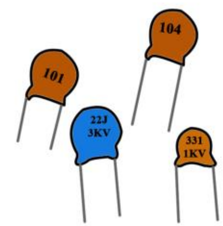
Film

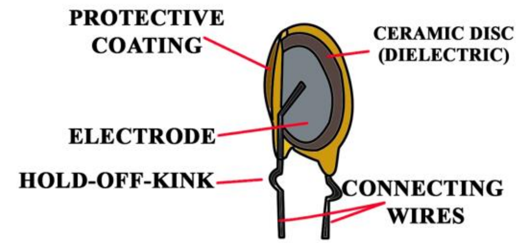
- Often thought of as an alternative to ceramics for audio
- Benefits:
    - Linear response
    - No microphonics
    - Slightly higher capacitance than ceramics
    - Good heat and vibration tolerance

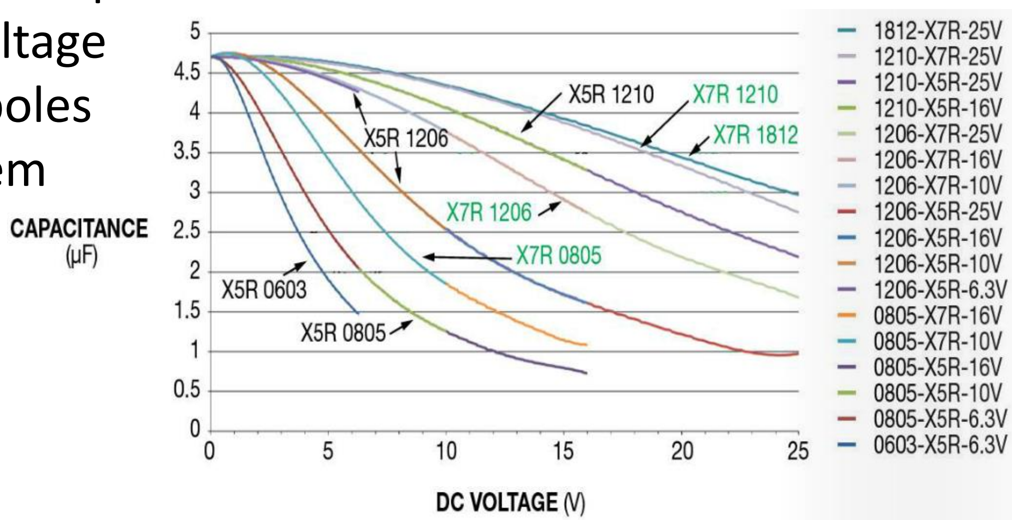


Film Capacitors

Ceramic
- Looks the most like an ideal capacitor
- Low capacitance value (1uF is a large
- Not polarized
- High voltage ratings (typ 100V)
- Very low equivalent series resistance
- Very low equivalent series inductance
- Frequency range, 10's or 100's of MHz
- Capacitance is highly voltage dependent
  - ~80% lower at rated voltage
  - Due to ferroelectric dipoles
  - Nonlinearity makes them less desirable in hifi audio
- Piezoelectric







Bypass caps, rules of thumb

Where to put them

- *Where power enters a board*
- *Near the V_{CC} pin of each IC*
- *Input and output of linear regulator ICs*

Values and types:

- *0.1uF ceramic is the workhorse for typical digital/analog*
- *Maybe add a 10µF or so where power enters the board*
- *AC rectifier circuits tend to use 1000's of uF*

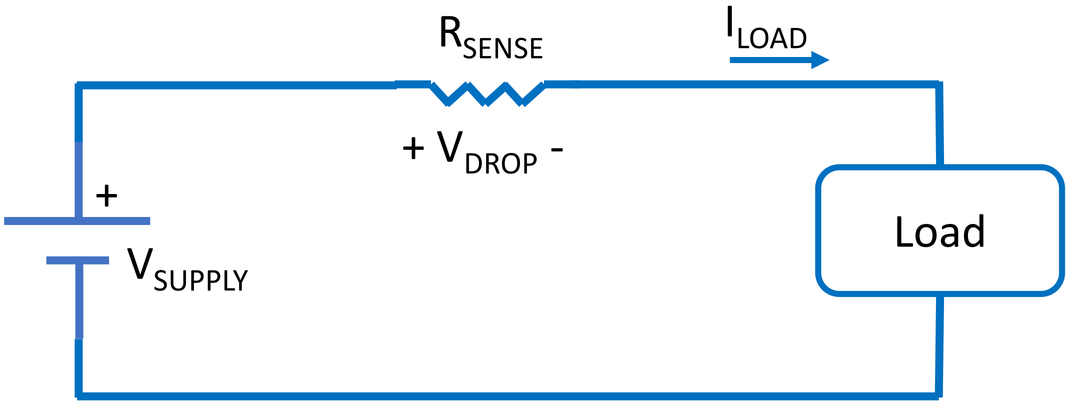
Larger bypass caps are needed with:

- *Larger current swings*
- *Lower frequency*
- *Power supply feed lengths get longer*

Star feed is better than daisy chain feed

Typical low current circuits -> 0.1uF ceramic cap every several inches

Measuring Current Draw of a Circuit



$$I_{LOAD} = V_{DROP} / R_{SENSE}$$

V_{DROP} should be large enough for a multimeter to measure it accurately but not so large that it affects the circuit being powered

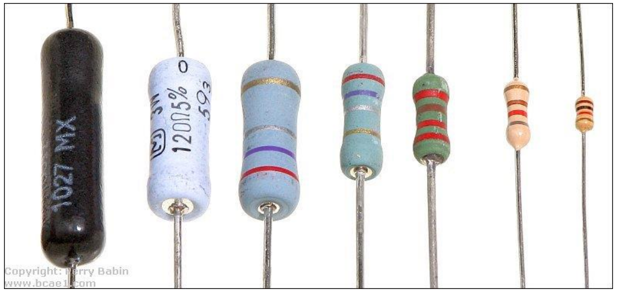
- $0.1V < V_{DROP} < V_{SUPPLY} / 10$

Check that resistor is rated for dissipated power

- If it's too hot to touch, measure fast
- $P_{DISS} = V_{DROP} \times I_{LOAD}$

3W 1W 1/4W

5W 2W 1/2W 1/8W



Determining if you'll run too hot

Build it, feel the device, if it's too hot to touch for 0.5 seconds, add a heat sink, choose a larger regulator or do something else about it

Or, rules of thumb->

Thermal Rules of thumb based on packaging

Package	R_{JA}	Max Power No Heat Sink	Accommodates Heat Sink?	Picture
TO-220	~20	~2-4W	Yes	
DDPAK	44	~1-1.5W	No	
SOT223	90	~0.5-0.7W	No	
SOT23	200	~0.25W	No	

Or, get your calculator out->

Calculate thermal limit for TO-220

absolute maximum ratings

Operating virtual junction temperature, T_J ... 150°C

40°C

PACKAGE	θ_{JA}
POWER-FLEX (KTE)	23°C/W
TO-220 (KC/KCS)	19°C/W

- $P_{DISS,MAX} = (T_{J,MAX} - T_{AMBIENT,MAX}) / (R_{JA})$
- $P_{DISS,MAX} = (110) / (19) = 5.8W$
- You need some margin on this. 3-4W might be OK

How much does a heat sink help?

PACKAGE	θ_{JC}	θ_{JA}
POWER-FLEX (KTE)	3°C/W	23°C/W
TO-220 (KC/KCS)	3°C/W	19°C/W

EV-T220-38E

Ohmite

Heat Sink Passive TO-220 Vertical Thru-Hole Aluminum 6063-T5 13°C/W

- $P_{DISS,MAX} = (T_{J,MAX} - T_{AMBIENT,MAX}) / (R_{JC} + R_{CA})$
- $P_{DISS,MAX} = (110) / (3+13) = 6.9W$ (compared to 5.8W bare)
- ~20% improvement, 4-5W

These numbers can be very rough:

- Air flow around part/heat sink
- Surface mount parts can be highly affected by PCB layout

Rules of thumb:

- ***TO-220 is good for 2-4W of power w/o heat sink, can be improved to 4-5W easily, significantly more requires very large heat sinks and/or fan cooling***
- ***SMT is good for 0.25W to 2.5W depending on part, package and PCB layout***

Appendix

A Quick Battery Primer

<u>Important battery terms:</u>

Voltage, e.g. 1.5V

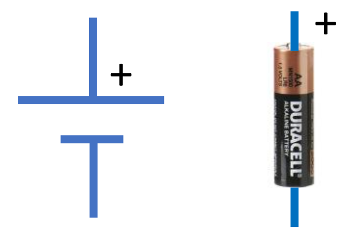
Voltage range, 0.9 to 1.5V

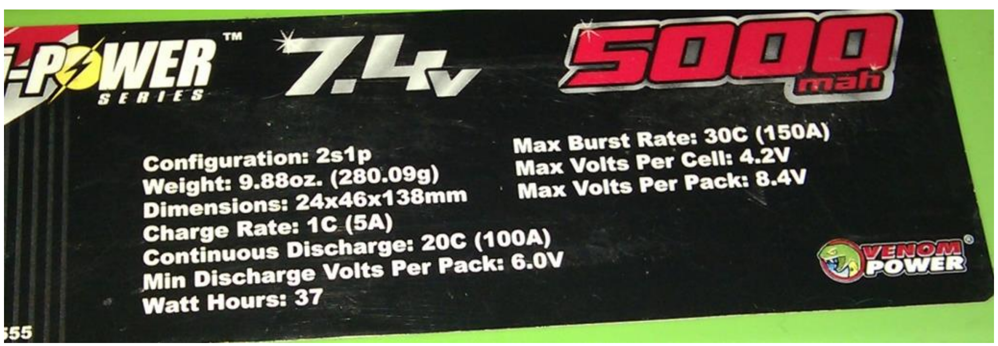
Capacity, e.g. 500mAh

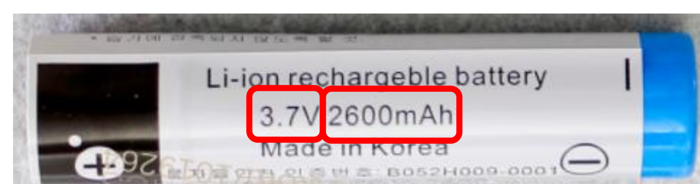
Discharge rate, e.g. 10C

High current applications - Killswitch

Proper schematic for a single cell







Series vs Parallel Batteries

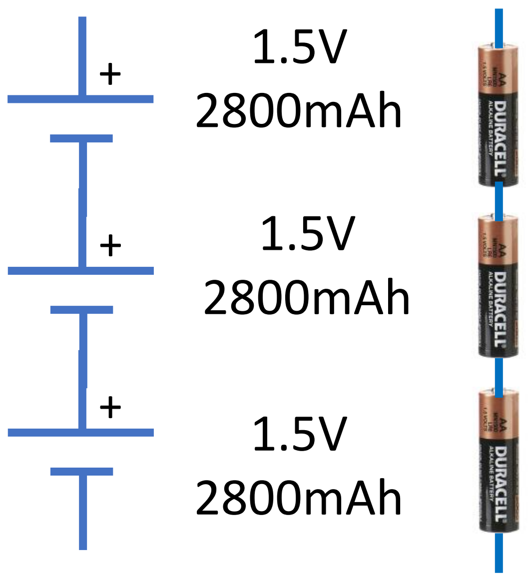
Batteries in series:

Multiply voltage, capacity stays the same

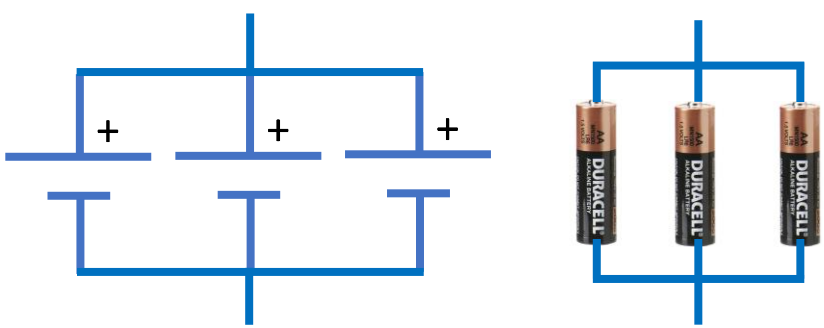
Batteries in parallel:

Multiply capacity, voltage stays the same

Series combination yields
4.5V @ 2800mAh



Parallel combination yields
1.5V @ 8400mAh

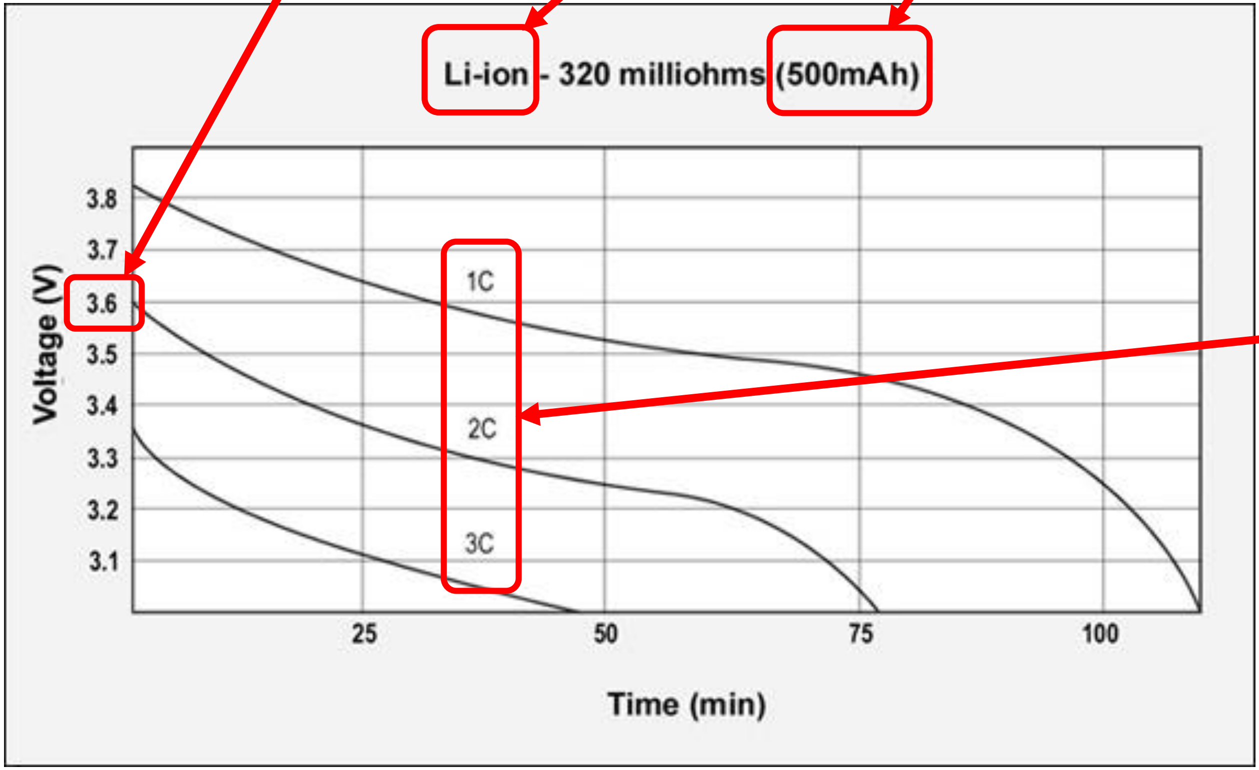


Battery discharge curve
This is the primary challenge

Rated as "3.6V"

Chemistry

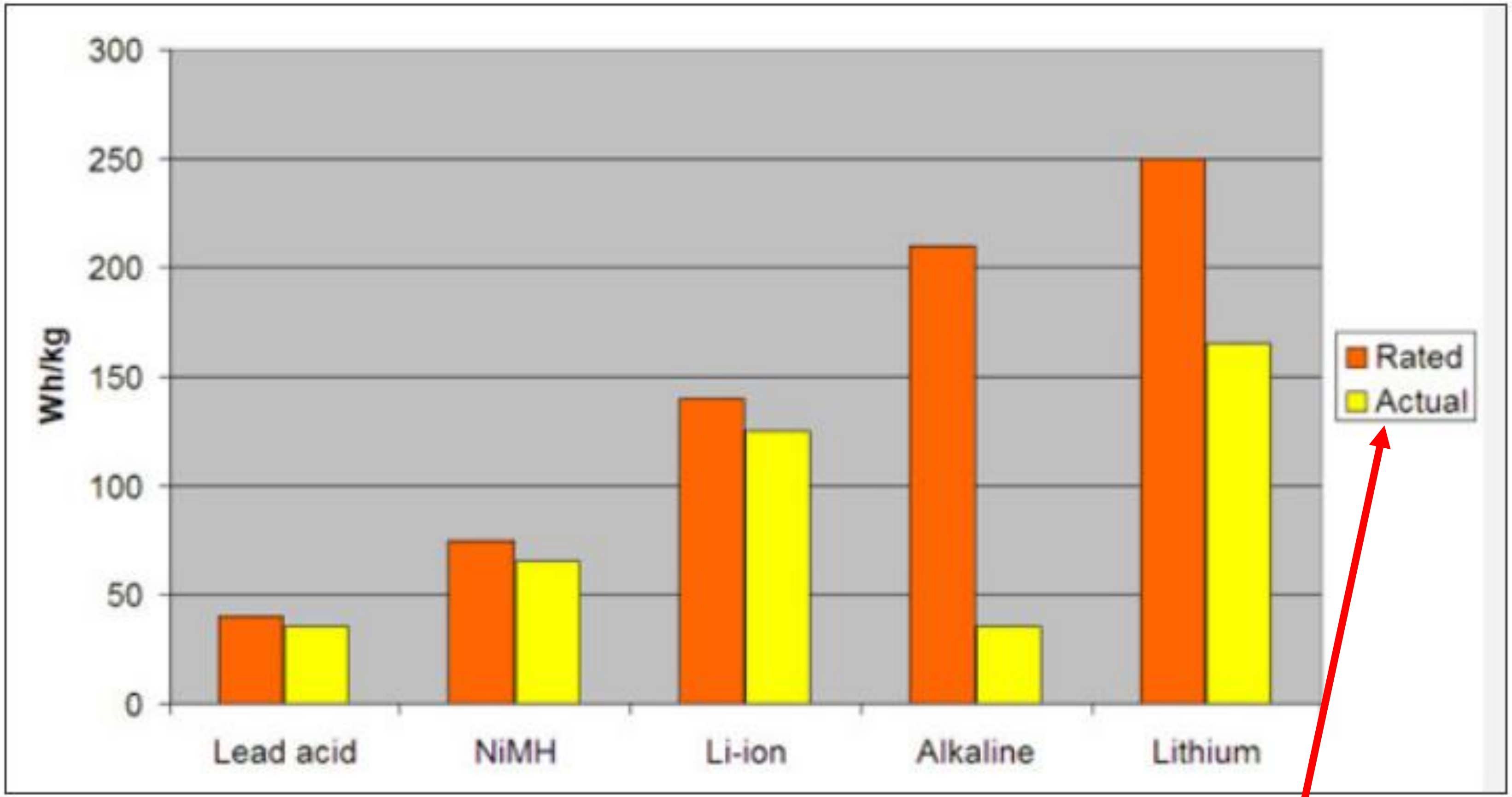
Capacity



Discharge rates

- ***1C = 500mA***
- ***2C = 1000mA***
- ***3C = 1500mA***

Battery Chemistry Comparison



Rated: low discharge current
Actual: 1C discharge current

http://batteryuniversity.com/learn/article/primary_batteries

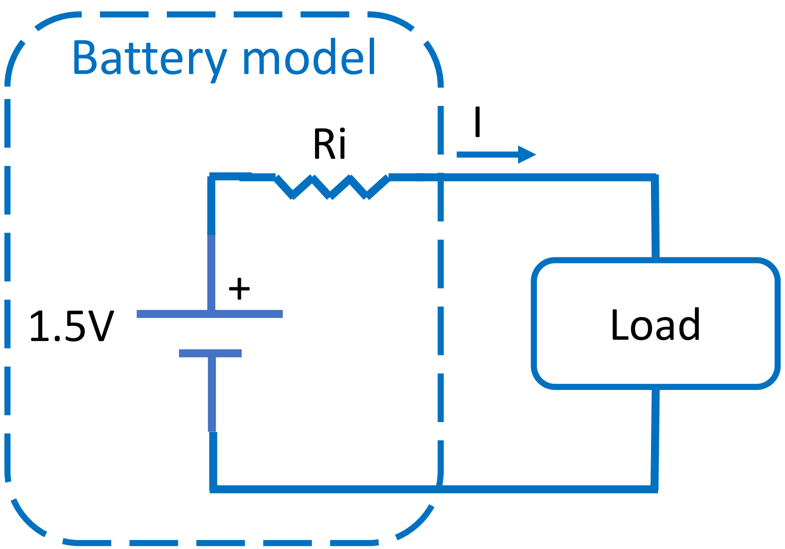
Battery internal resistance

Remember Ohm's law:

$V = I \times R$

Battery voltage depends on current

Might matter for higher current circuits



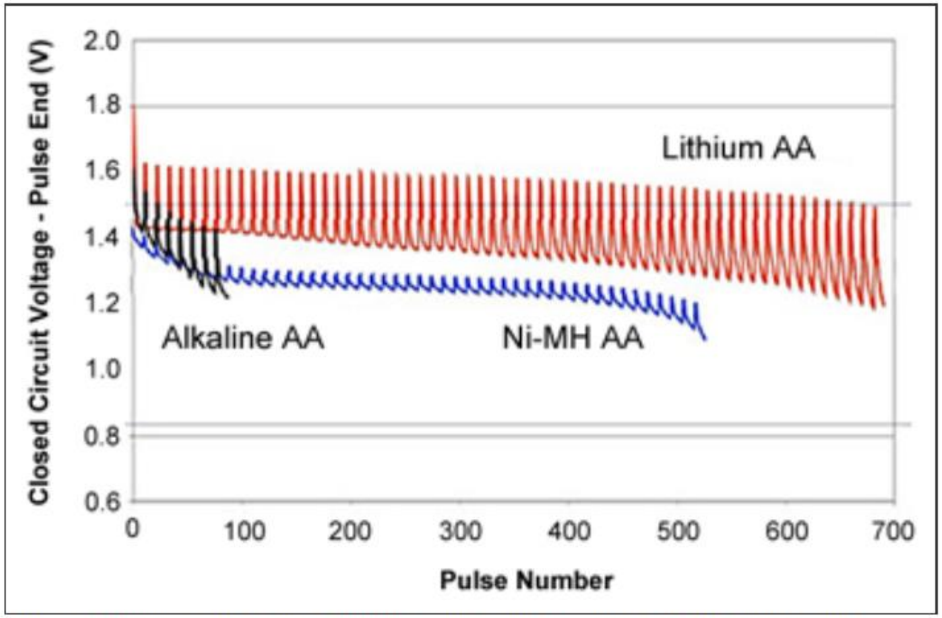


Figure 5: Number of shots a digital camera can take with alkaline NiMH and lithium.

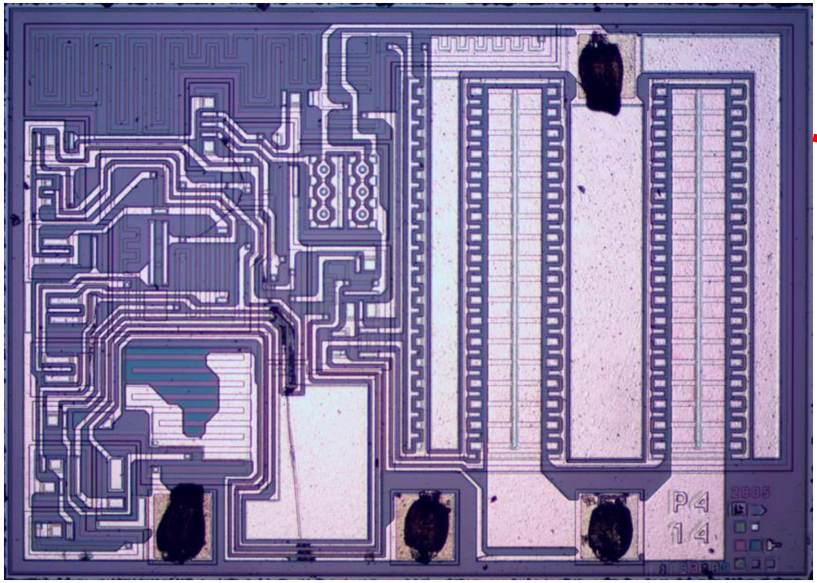
Powering off of Batteries

Options:

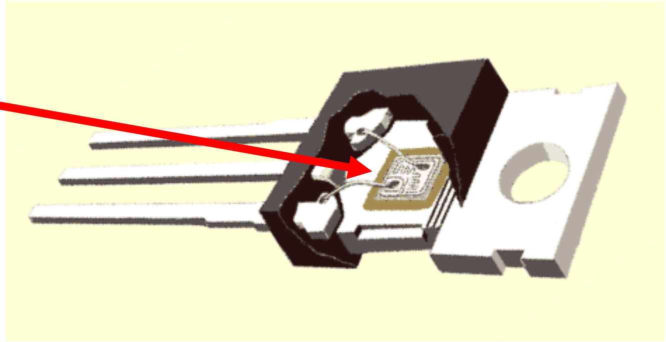
- Operate directly off battery if circuit allows
- Stack batteries and regulate down to desired voltage
- Buck-boost regulator if battery voltage range straddles desired voltage
- Low dropout linear regulators (e.g. 0.2V vs 1.0V) can significantly improve battery life

Battery Configuration	Voltage Range
3 alkaline cells	2.7V to 4.5V
4 alkaline cells	3.6V to 6.0V
9v cell	4.8V to 9.0V
3 NiCd cells	3.3V to 4.2V
NiMH	Similar to alkaline
1 Li+ (Li ion) cell	2.8V to 4.2V

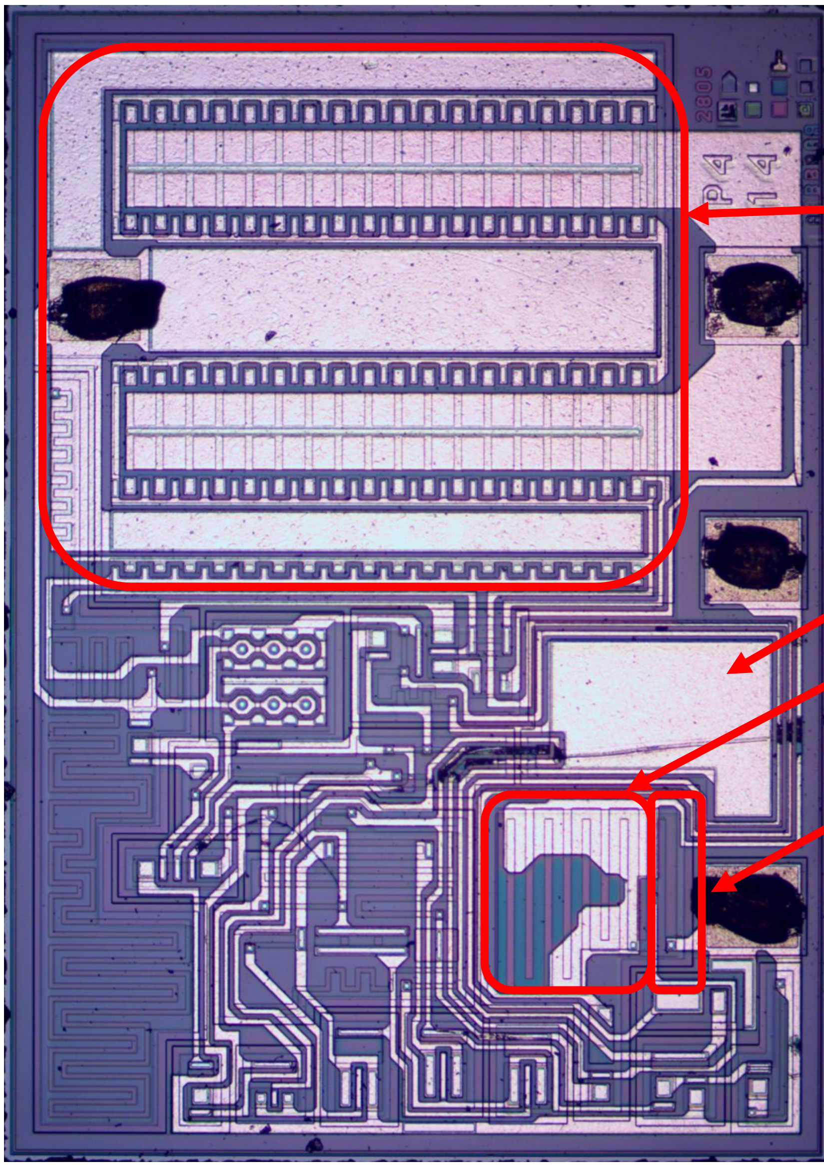
Thermal Management
First, a Fun Look Inside the LM7805

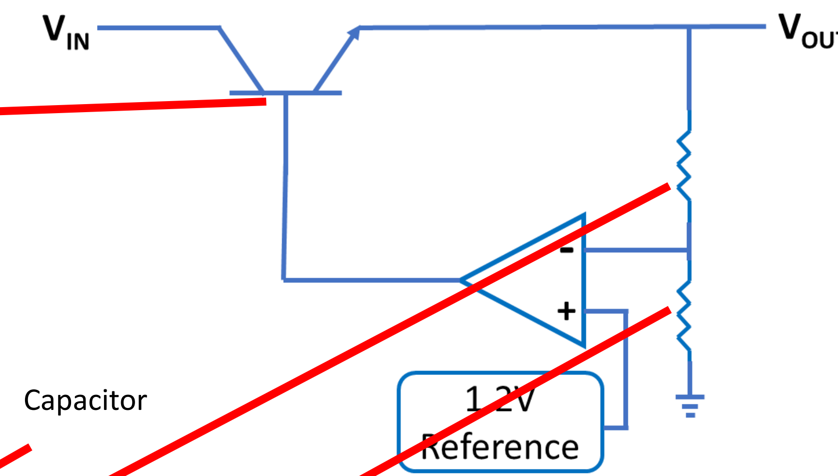


LM7805



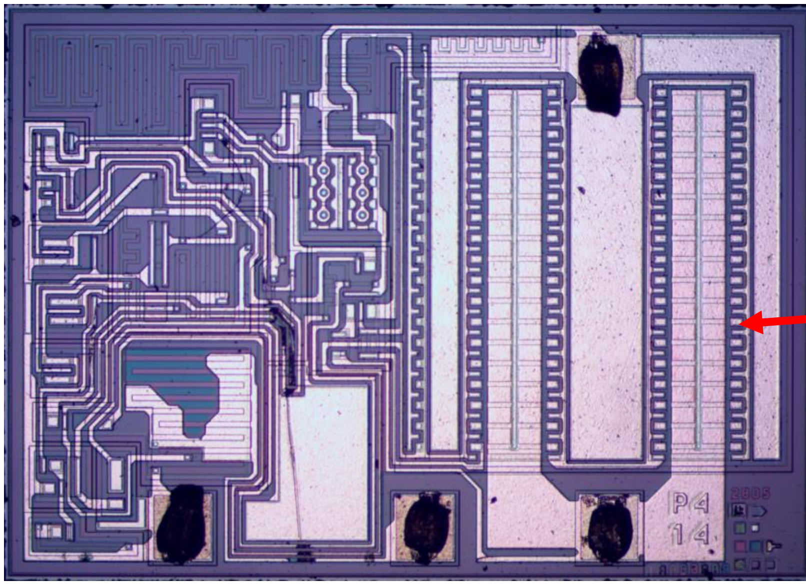
LM7805 Die



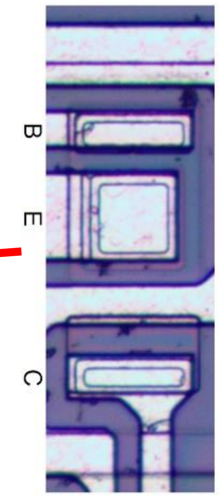


http://www.righto.com/2014/09/reverse-engineering-counterfeit-7805.html

Thermal Management
What are we protecting?



LM7805



Thermal management is about protecting this from overheating