Lecture 18

Batteries and Voltage Regulators

Agenda

- Battery overview
- LiPo Batteries (Safety)
- Voltage Regulators

Misc. Stuff

- Individuals not in Lab 4 teams will be assigned to teams Thursday morning by teaching staff.
- Router in GMLab
  - SSID: TP-Link_05AF
  - Password: 47543454
- USB chargers are typically LiPo or LiIon batteries. You can purchase small grey one for $8 for Lab 4 or final project.

5 Ah capacity
2Amp output max
Can power ESP32 or Teensy through USB
Can be recharged

https://www.amazon.com/SIXTHGU-Portable-Capacity-External-Indicator/dp/B08QHG1SWY/

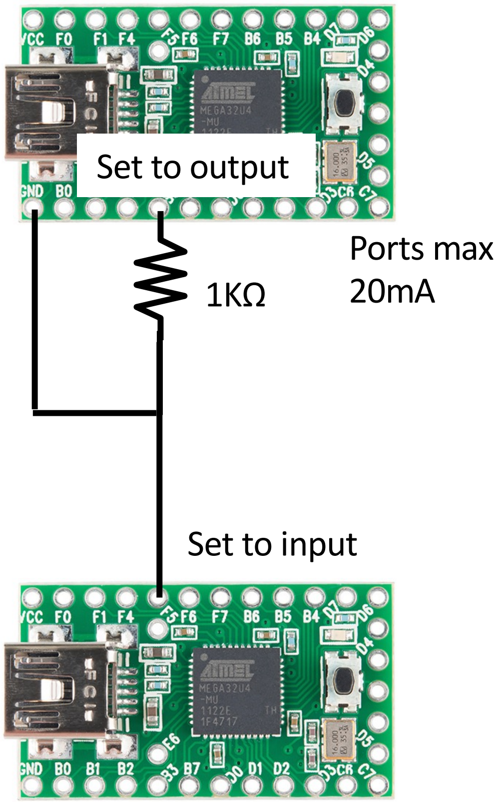
Current analysis confusion

A. What is the worst case current supplied by the power supply that has max current of 5A when set to 5V?

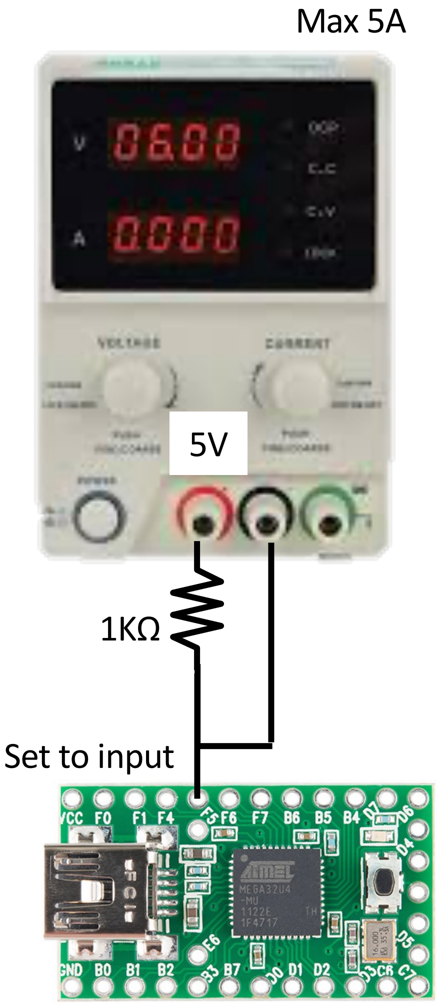
B. What is the worst case current going through the Teensy Port that has max output of 20mA?

"Current Limiting Resistor" may or may not set curret

B



A



01

Battery overview

Battery types (in this lecture)

Sealed
Lead
Acid

NiMH

NiCad, NiMH, Alkaline

Lithium polymer is now dominating the high density battery market

Super Capacitor
Ultra Capacitor

Lithium Ion
(18650 or packs)

Questions to answer as lecture proceeds

Q1: You open the hood of your parked car and find a 12V battery in good condition. What does your voltmeter read when you measure the battery?

Q2: What is the nominal voltage for NiMH and NiCad cells (which are the same)

Q3: After sitting on a shelf for 3 years how do you check if a LiPo is still good?

More Questions: Three scenarios

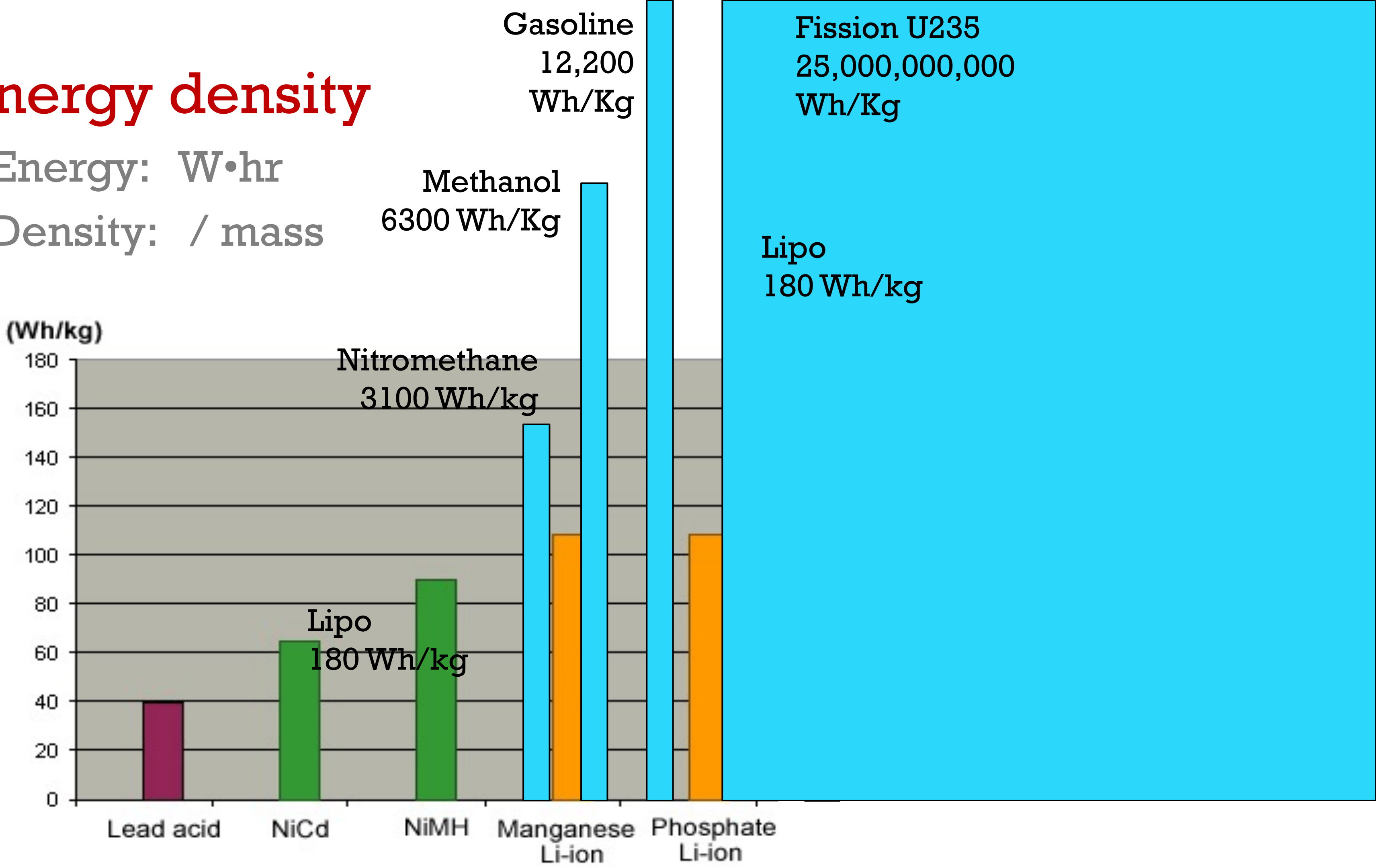
1. You have a project that automatically takes pictures of birds in Alaska. Size isn't a problem. The camera system sits there for 6 months with no maintenance. What kind of battery do you use?
2. DARPA has asked you to build a small flying robot – cost is no problem. What are good candidate battery technologies?
3. DARPA has changed their mind, they want the robot to swim. What now?

Important Battery Specifications

- **Cell Voltage** [Volts]
  - Battery implies multiple cell (single cell technically not a battery)
- **Capacity** [amp-hours]
- Constant **C Rating** [A/(Ah)] – current as a function of capacity
  - C Rating (discharge) / (Burst C Rating)
  - C Rating (charge)
- **Energy Density** [watt-hours/kg]= Battery V x Capacity / mass
- **Primary** (disposable) vs **Secondary** (rechargable)
- **Self-discharge**
- **Service Life**
- **Shelf-life**

Energy density

- Energy: W•hr
- Density: / mass



Discharge (drawing current from the battery)

- V typically drops as battery is drained.
- But rate of drop depends on discharge rate [A].

- 1 Amp hr capacity supplies
  - ~1 hour at 1 amp.
  - < 0.5 hour at 2 amps.

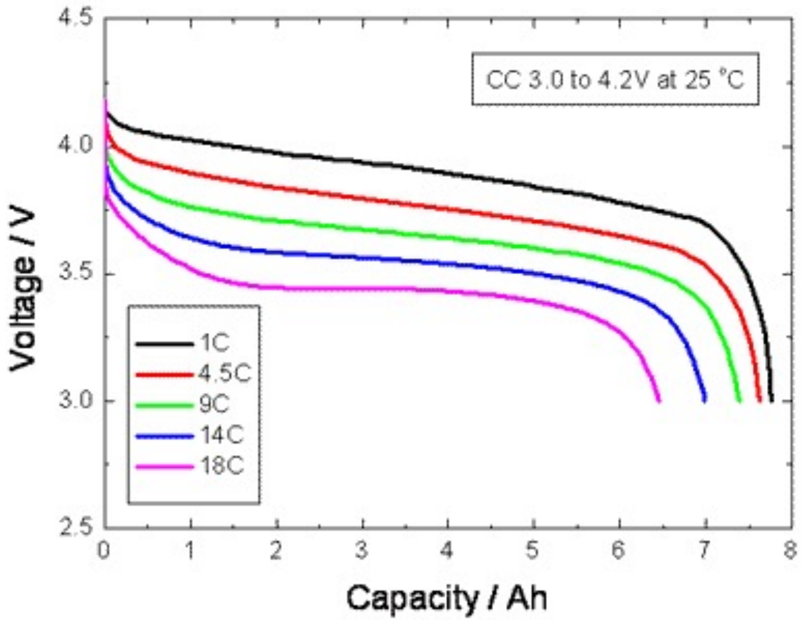


Chart for Lithium batteries

Exponent depends on battery type
E.g. 1.2 for gel cells

Follows Peukerts Law: $t = H\,(C/(IH))^{1.3}$
H =rated time [h], C=rated charge [Ah], I=actual discharge [A]

"Primary" batteries: Zinc-carbon and Alkaline

- Zinc-Carbon
  - Cheapest most common primary (non-rechargable) cell
  - Shelf life 2-3 years (Casing gets thinner from use and acidic wear – leaking of sticky ammonium chloride electrolyte paste)
  - Becoming obsolete… I couldn't find it on amazon but typically "batteries included" are these cheapo batteries
- Alkaline
  - Higher power density and longer shelf life 5-10 years

Primary (non-rechargable) Batteries

Alkaline Batteries

tion S

Size	Nominal Voltage	Rated Capacity[1]	Rated Voltage Cut-off	Rated Load	Dimensions[2] Diameter (Max.)	Height (Max.)	Energy density [mWh/oz]	Weight (Avg.)	Cost [2017] $USD
	(V)	(mAh)	(V)	(Ω)	in. (mm)	in. (mm)		oz. (g)	
D	1.5	17,000	0.8	39	1.346 (34.19)	2.421 (61.49)	5402	4.72 (135)	0.95
C	1.5	7,800	0.8	39	1.031 (26.19)	1.969 (50.01)	4178	2.28 (65)	0.88-1.00
AA	1.5	2,870	0.8	75	0.571 (14.50)	1.988 (50.50)	5125	0.84 (24)	0.25-0.55
AAA	1.5	1,150	0.8	75	0.413 (10.49)	1.752 (44.50)	4107	0.42 (12)	0.33-0.49
9V	9.0	570	4.8	620	-	1.909 (48.49)	3109	1.65 (45)	1.00-1.50

Lead Acid (wet cell, or SLA)

- 12V Wet Cell (e.g. car battery)
  - Liquid acid in an unsealed container
    - Must be kept upright
    - Vents O_2 and H_2 when overcharged.
  - Heavy, high capacity
  - Nominally 12.6V (6, 2.1V cells)
  - @ 12.0V ~10% left. @ 11.8V empty.
  - @<10.5V will damage battery
  - Simple charging (apply ~13.6V, not more than 14.4)
- SLA or Gel Cell (Gel Battery)
  - Same as wet but no upright constraints
  - *Easy to charge*

Sealed Lead Acid

NiCad (NiCd)

Nickel Cadmium

Toxic heavy metal

- Rechargeable, 1.2V cells
- Lower internal resistance –> high current
  - AA cells-> 18A, D cells-> 35A
- Mis-charging results
  - Overcharging O2 generated at cathode, needs venting and resealing (complex expensive)
  - Reverse charging, (charge past empty)
    - Cell is permanently damaged, may release H2 at anode
- 1000+ cycles before 50% capacity, (if used right)

NiMH

Nickel Metal Hydride

- Similar to NiCd (1.2V no cadmium)
- Higher capacity than NiCd
- Lower lifetime cycles than NiCd
- Not as good at high discharge rate
- Self-discharge 10% in 1 day then 10% per month. (compare to NiCad 10% per month, SLA 5% per month
- Mis-charging
  - Overcharging -> gas, heat generation, damages battery
  - Discharging -> reverse charge (past empty) will kill battery

Li Ion

- Very common rechargeable battery (cell phones, laptops etc.)
- Very common to find 18650 form factor --->
- Cell @ 3.7V nominal (3V-4.3V)
- Higher power density than NiCd, NiMH
- Higher energy density than NiCd, NiMH
- Shelf-life of ~3 yrs (likely <80% capacity)
  - If stored properly, see if battery holds charge
  - If less than 3V, properly dispose.
- Self-discharge 5% /month
- Maintains capacity with some discharge
- Dangerous if casing is damaged

Lithium Ion

LiPo

Lithium Polymer

- Highest power density commercially available
- Cell @ 3.7V nominal (3V-4.3V)
- More easily conformable (typically prismatic), no casing required -> lighter
- Typically slower charge times,
- Low life cycle degradation rate
- Shelf life similar to Li-Ion
- Damage to casing -> Explosive w/water,
- ***Easily causes fires!***

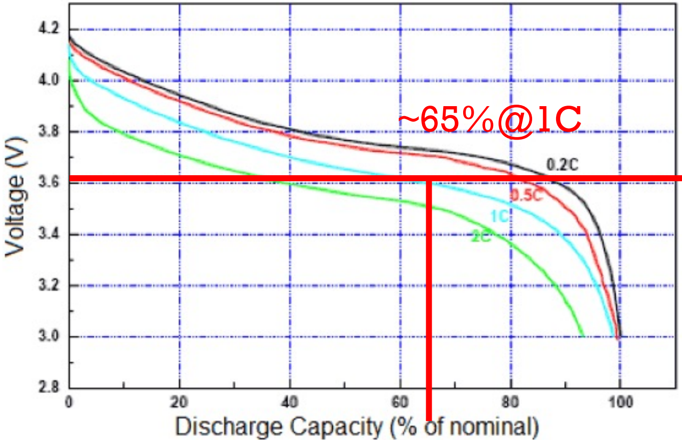
Lithium Ion vs Lithium Polymer (4S1P, 14.8V test)

Tom Stanton
https://www.youtube.com/watch?v=UB8fas6zBSE

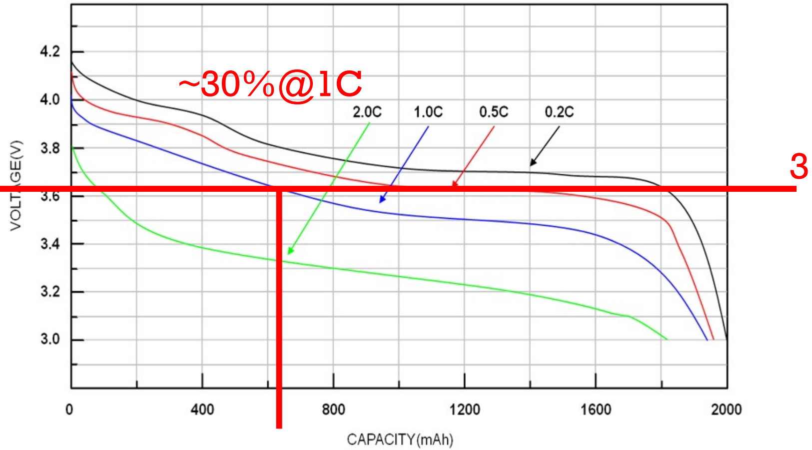
RC plane flight tests: avg draw 3A, peak 20A

- 4 cell pack LiIon (0.25Wh/g) has higher energy density than 4 cell pack LiPo(0.14Wh/g)
- LiIon has higher internal resistance (lower maxAmp C-rating) lower power dens. than LiPo
- LiIon can be run to lower voltage and recover than LiPo
- LiIon voltage drop for full charge will be larger than LiPo
- Final result: LiPo lasted longer from 16.8V to 14.8V than LiIon, but LiIon had more charge left (going to lower voltages).

Typical Lithium Polymer Discharge



Typical Lithium Ion Discharge



3.6V

Other Lithium Technologies

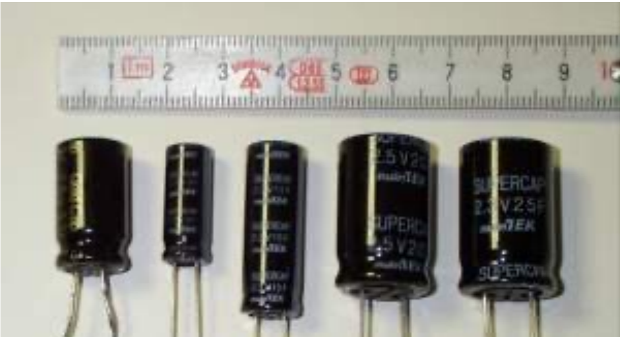
Likely direction for future 510 classes due to safety

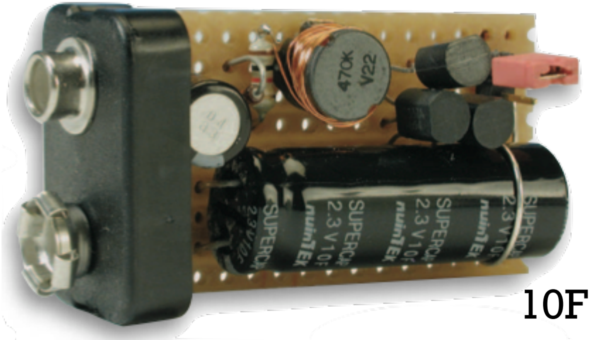
- Lithium Iron Phosphate (LiFePo4)
  - **Safest form** of Lithium (won't catch fire if punctured)
  - Better life cycle (4-5x than LiPo depending on usage)
  - Lower voltage and energy density (3.2V nominal, 3.6V @ full)
  - Flatter discharge curve (stays flat at ~3.0V)
  - Digikey sells 3.3Ah 3.2V cell for $10 each (~$1 per Wh same as LiPo)
- Lithium Titanate (LTO)
  - **Much faster charging** than LiPo (~10x faster)
  - Lower energy density (~60% of LiPo)
  - Digikey sells 40Ah 2.3V cell for $65 each (~.70 per Wh)

SuperCapacitors (ultracaps)

- Supercaps have ~3-15Wh/Kg (Normal Caps ~0.5Wh/kg)
- Can get 3-60F in ~small casing
- But at low voltage ~2.3V- 2.7V
  - F = A•s/V,
  - Ref: 9V has ~0.5 Ah capacity
- Practically infinite cycles
- Very high discharge current
- Self-discharge @ 50% in 30 days
- Hybrids are becoming the new thing.

Function	Supercapacitor	Lithium-ion (general)
Charge time	1–10 seconds	10–60 minutes
Cycle life	1 million or 30,000h	500 and higher
Cell voltage	2.3 to 2.75V	3.6 to 3.7V
Specific energy (Wh/kg)	5 (typical)	100–200
Specific power (W/kg)	Up to 10,000	1,000 to 3,000
Cost per Wh	$20(typical)	$2 (typical)
Service life (in vehicle)	10 to 15 years	5 to 10 years
Charge temperature	–40 to 65°C (–40 to 149°F)	0 to 45°C (32°to 113°F)
Discharge temperature	–40 to 65°C (–40 to 149°F)	–20 to 60°C (–4 to 140°F)





9V battery (internal switching regulator)

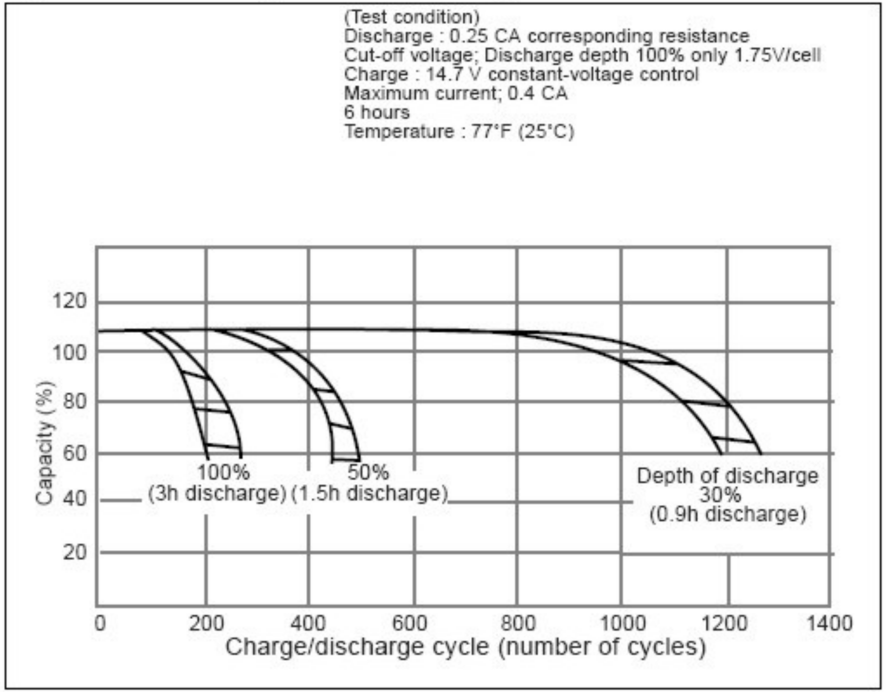
10F @ 2.3V

Battery Comparison Table

Type	NiCd	NiMH	SLA	Li-Ion	Li –poly	Reuse Alkaline	Supercap
Typ Energy Density (Wh/Kg)	50	75	30	150-265	185-220	80 (initial)	<15
Cycle Life, @ 100% (typical)	1500	500	200-300	300-500	150	10 – (65%)	Very high
Fast-Charge Time	1.5h	2-3h	8-15h	3-6h	8-15h	3-4h	Mins
Self-Discharge	Med.	high	v.low	low	low	lowest	v.high
Cell Voltage (nom.)	1.2V	1.2V	2V	3.6V	3.7V	1.5V	2.7max
Sp. Power (W/kg)	150	~500	180	1800	3000	50	10,000+
Relative cost / Ah	.6	.9	.3	1	1	.07	10

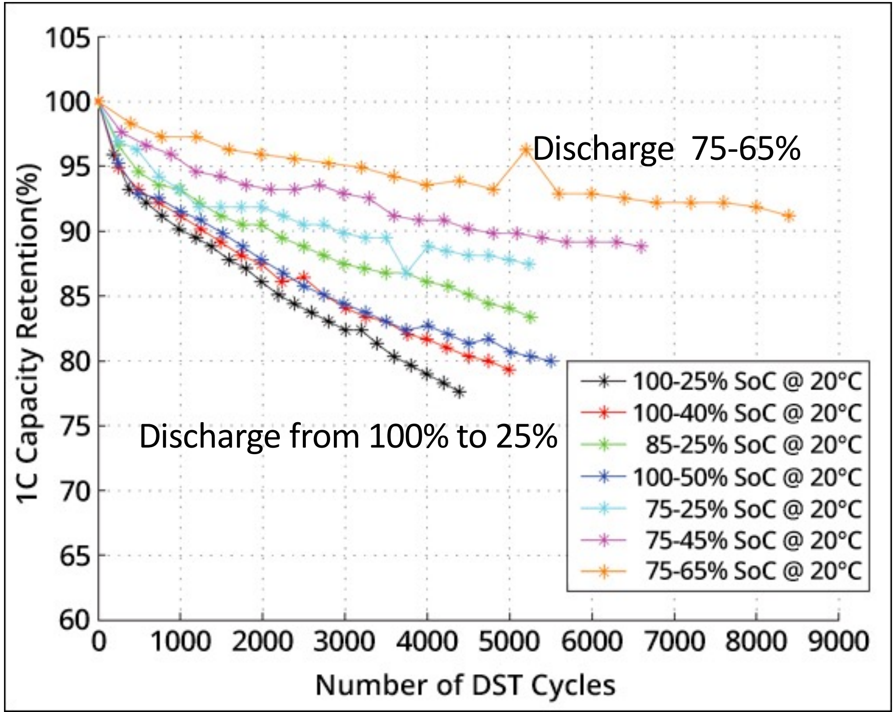
Battery lifetime performance

Cycle life vs. Depth of discharge



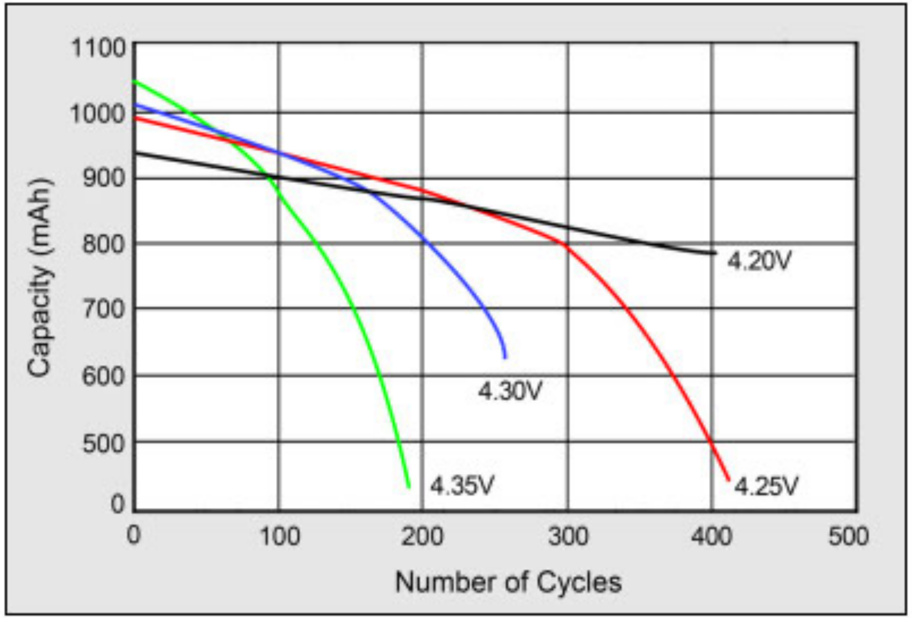
Deep discharge of SLA can reduce life time.
Number of cycles = f(depth)

Lithium ion also shows gradual capacity loss after discharge but depends on range



More on lifecycle

- Typical lithium chargers charge to 4.2V but you can go further.
- But rate of capacity loss @ 3.9V is faster.



Reminder: lipo nominal charge is 3.7V, complete discharge @ 3.0V

Temperature and life time

Battery Temperature	Permanent capacity loss when stored at 40% state-of-charge (recommended storage charge level)	Permanent capacity loss when stored at 100% state-of-charge (typical user charge level)
0°C	2% loss in 1 year; 98% remaining	6% loss in 1 year; 94% remaining
25°C	4% loss in 1 year; 96% remaining	20% loss in 1 year; 80% remaining
40°C	15% loss in 1 year; 85% remaining	35% loss in 1 year; 65% remaining
60°C	25% loss in 1 year 75%; remaining	40% loss in 3 months

Table 3: Permanent capacity loss of lithium-ion as a function of temperature and charge level. High charge levels and elevated temperatures hasten permanent capacity loss. Newer designs may show improved results.

- E.g. Running laptops hot and charging (@100%) will reduce life time.
- Wireless mat chargers often elevate temperatures

Q4 Three scenarios – answers?

1. You have a project that automatically takes pictures of birds in Alaska. Size isn't a problem. The camera system sits there for 6 months with no maintenance. What kind of battery do you use?
2. DARPA has asked you to build a small flying robot – cost is no problem. What are good candidate battery technologies?
3. DARPA has changed their mind, they want the robot to swim. What now?

Q5 Battery Summary Quiz:

Q5.1 Of the standard AA, AAA, D, C and 9V. 9V batteries are:

A. The least efficient
B. The most expensive
C. The most rectangular
D. All of the above

Q5.2 Why is a 3 cell LiPo battery (3.7V per cell nominal) not safe to power the Pico ESP32 (whose regulator takes from 4.6V to 12V)?

Q5.3 What happens to a LiPo battery when it is drained below 3.0V?

02

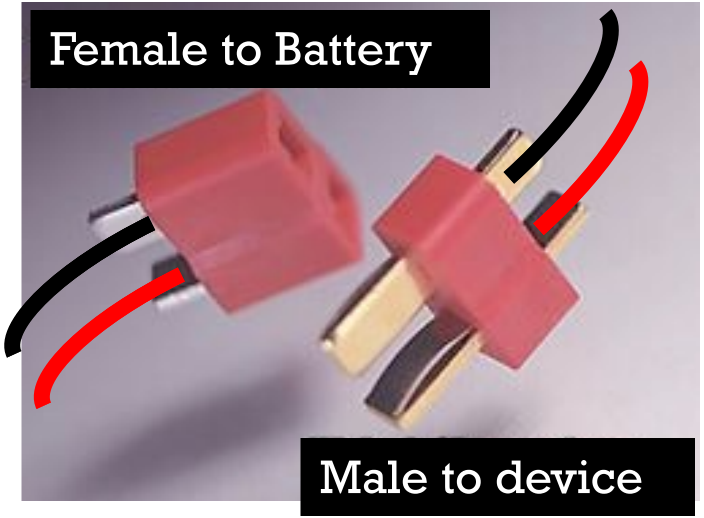
Lithium Polymer (LiPo) Battery recap

LiPo (some available for final project)

Specification	1300MAH 2S 7.4V 30C
Capacity	1300 mAh = 1300 milli Amp hour = 1.3Ah
Configuration Series/Parallel	2S1P = 2 series and 1 parallel
Voltage	7.4V = 2 x 3.7 cells in series
Discharge rating "C-Rating"	30C = can safely discharge @ 30 x 1.3A

Battery connectors

- Deans connector or Deans T-connectors
- LiPos connectors need to handle large currents
  - Deans can handle 60Amp continuous
- Careful soldering wires and melting plastic housing
- The positive (red) on the horizontal part of T, negative (black) on vertical.
- Don't forget heat shrink



Soldering video
https://www.youtube.com/watch?v=hmhKIaH3vH4

LiPo balancing batteries

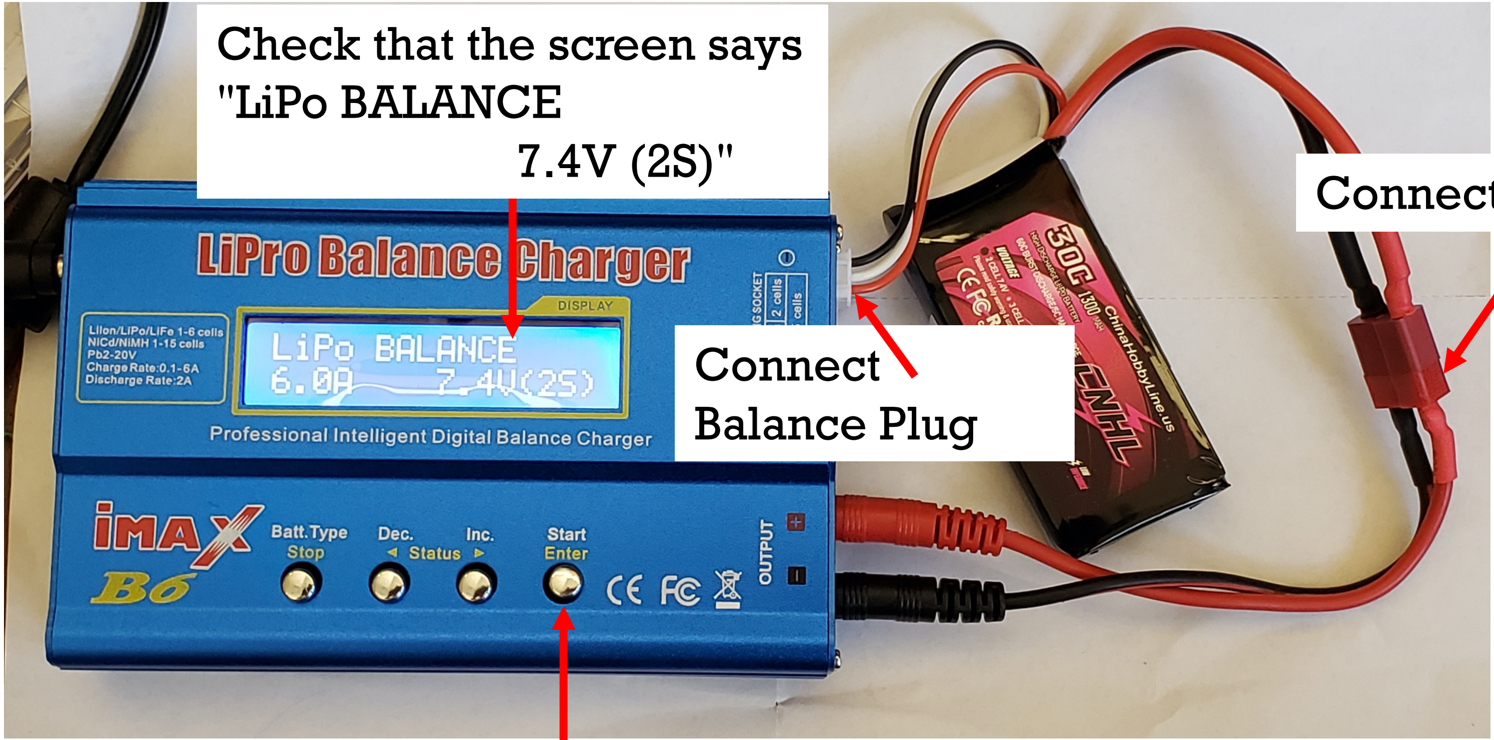
- Batteries implies multiple cells in series.
- Not all cells are exactly the same – even within one battery.
- Recharging multiple cells does not guarantee equal charging between cells.
- Imbalance more likely to occur after deeper discharge

- Low Voltage Alarms devices easily check

LiPo Safety

- When storing long term, set multi-cell lipos at 3.85V per cell
  - Most chargers have drain or storage modes to drain to proper level
  - Batteries stored at full voltage may become severly unbalanced.
  - Ideally store in cool dry place (e.g. fridge, but doesn't have to be)
- GMLab has Ammo cases filled with sand.
- Charge LiPo batteries INSIDE this case

Using the LiPo battery charger for 2S battery



Check that the screen says "LiPo BALANCE 7.4V (2S)"

Connect Balance Plug

Connect Deans plug

Press and hold "Start" button for 3 seconds

Using the LiPo battery charger for 2S battery

Confirm 2SER, press "Start" again

Using the LiPo battery charger for 2S battery

Put the battery in the firebag.

Put everthing in the ammo case.

Confirm that screen shows time is increasing...

Using the LiPo battery charger for 2S battery

Beeps when done
Also flashes :
FULL 0.0A

Put the battery in the firebag.

Put everything in the ammo case.

Lid can be open or closed.

In case of fire, close lid.
Call EOS 215-573-3333

03

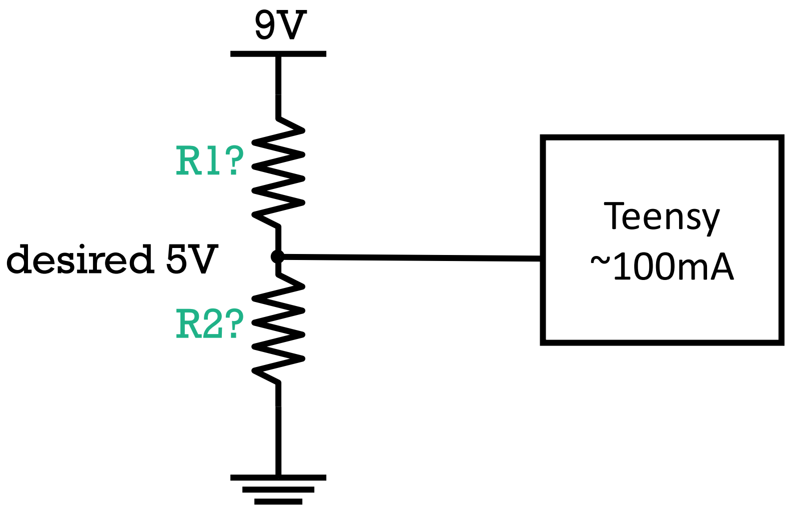
Voltage Regulators

Voltage Dividers as Voltage Source

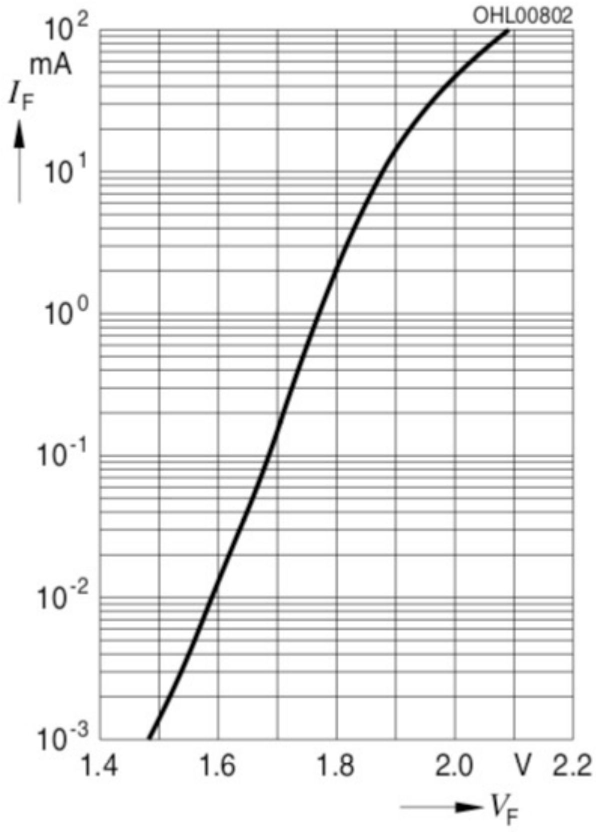
- You've got 9V battery and you need 5V to run a Teensy.
- Can you use a voltage divider to supply 5V?
- What resistors would you choose?

Q6: Which will result closest to 5v?

A. R1 = 4Ω , R2 =5Ω
B. R1 = 40Ω , R2 = 50Ω
C. R1 = 4kΩ , R2 = 5kΩ
D. they are all the same



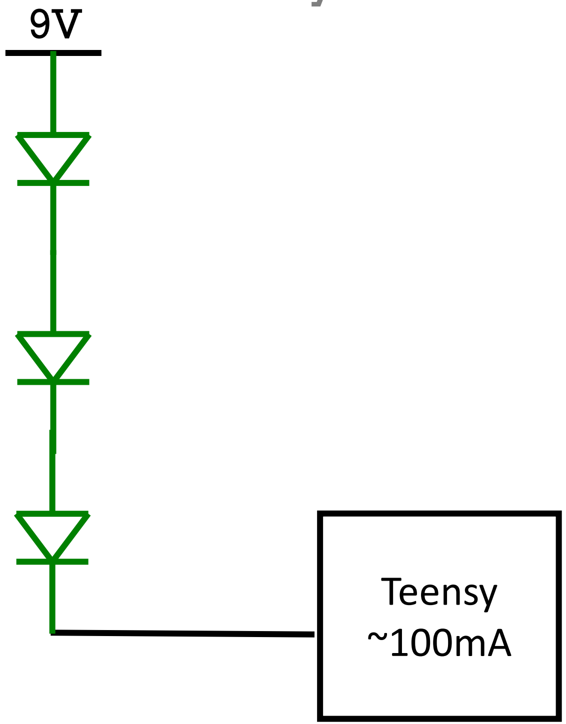
Voltage Diode Drop (Vf) to Supply Voltage



ry and you need 5V to run the Teensy.

le diode drops?

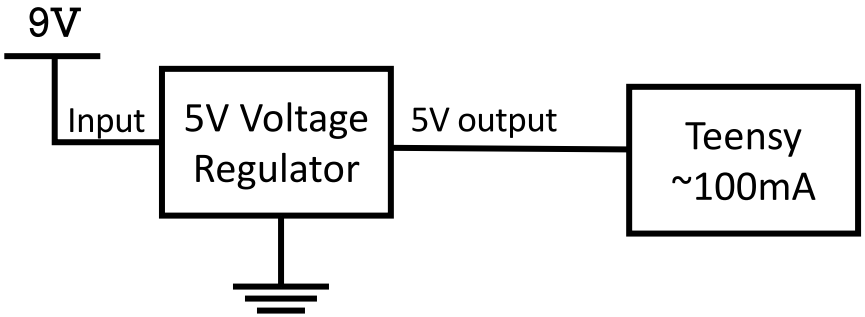
Q7: What issues do we have with using 3 LEDs with Vf = 1.4V?



Voltage Regulators

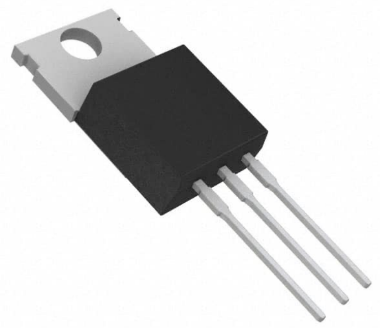
- You've got 9V battery and you need 5V to run a Teensy.

- Ideally use a voltage regulator
- They have voltage input range
- They have current limits
- Do NOT put them in parallel
  - They may fight each other and go unstable
  - If you need more current, find a different regulator.

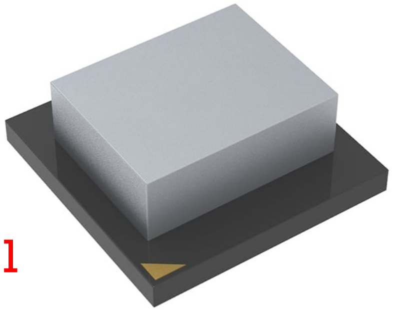


Voltage Regulators

- Linear Voltage Regulators
  - Cheap
  - Very inefficient
  - Easy to use
  - Available in ministore
  - Digikey: **MC7805CTG** 5V 1.5Aout, 7V to 35Vin $0.65



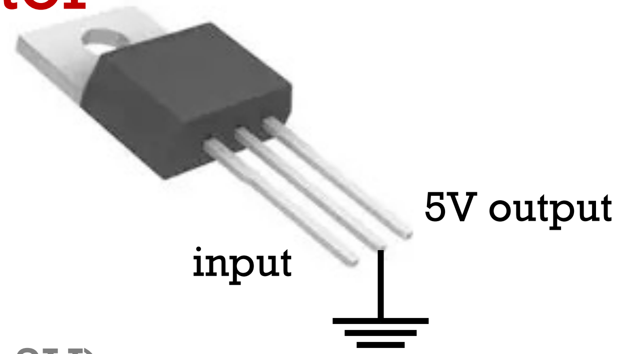
- DC-DC converters, Buck or Boost converter
  - Much more efficient
  - Has inductor coil (may create WiFi interference)
  - More expensive
  - Not available in ministore
  - Digikey: **MAXM17634AMG** 5V 2Aout, 4.5V to 36Vin $7.31

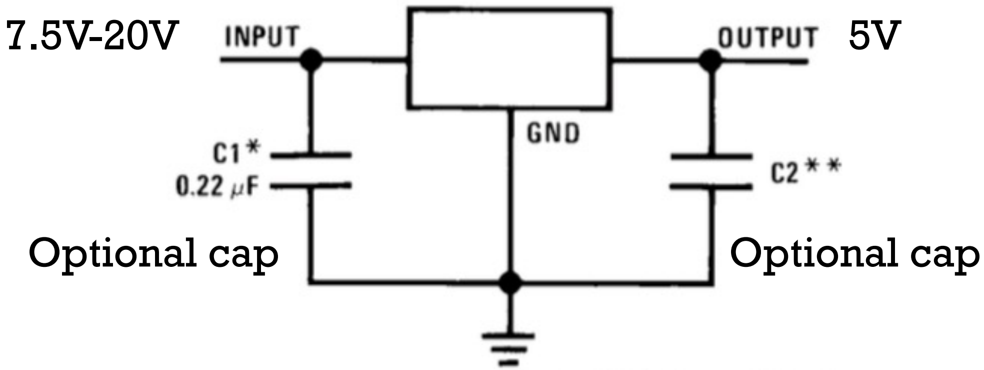


LM7805 5V linear voltage regulator

Standard (old), low cost, low performance

- Max output: 1.5A
- Input range: 7.5V to 20V (Dropout Voltage: 2V)
- Output usually: 5.0V
  but can vary 4.8 to 5.2V





LM7805

Listed as obsolete in Digikey,

Replacement **MC7805**

$0°C \le T_J \le 125°C$ unless otherwise specified[(1)]

	PARAMETER	TEST CONDITIONS		MIN	TYP	MAX	UNIT
V_O	Output voltage	$T_J = 25°C$, $5\ mA \le I_O \le 1\ A$		4.8	5	5.2	V
		$P_D \le 15\ W$, $5\ mA \le I_O \le 1\ A$, $7.5\ V \le V_{IN} \le 20\ V$		4.75		5.25	V
ΔV_O	Line regulation	$I_O = 500\ mA$	$T_J = 25°C$, $7V \le V_{IN} \le 25V$		3	50	mV
			Over temperature, $8V \le V_{IN} \le 20V$			50	mV
		$I_O \le 1\ A$	$T_J = 25°C$, $7.5V \le V_{IN} \le 20V$			50	mV
			Over temperature, $8V \le V_{IN} \le 12V$			25	mV
ΔV_O	Load regulation	$T_J = 25°C$	$5\ mA \le I_O \le 1.5\ A$		10	50	mV
			$250\ mA \le I_O \le 750\ mA$			25	mV
		Over temperature, $5\ mA \le I_O \le 1\ A$				50	mV
I_Q	Quiescent current	$I_O \le 1\ A$	$T_J = 25°C$			8	mA
			Over temperature			8.5	mA
ΔI_Q	Quiescent current change	$0°C \le T_J \le 125°C$, $5\ mA \le I_O \le 1\ A$			0.5		mA
		$7\ V \le V_{IN} \le 20\ V$	$T_J = 25°C$, $I_O \le 1\ A$			1	mA
			Over temperature, $I_O \le 500$ mA			1	mA
V_N	Output noise voltage	$T_A = 25°C$, $10\ Hz \le f \le 100\ kHz$			40		µV
$\frac{\Delta V_{IN}}{\Delta V_{OUT}}$	Ripple rejection	$f = 120\ Hz$, $8\ V \le V_{IN} \le 18\ V$	$T_J = 25°C$, $I_O \le 1\ A$	62	80		dB
			Over temperature, $I_O \le 500$ mA	62			dB
R_O	Dropout voltage	$T_J = 25°C$, $I_O = 1\ A$			2		V
	Output resistance	$f = 1\ kHz$			8		mΩ
	Short-circuit current	$T_J = 25°C$			2.1		A
	Peak output current	$T_J = 25°C$			2.4		A
	Average TC of V_{OUT}	Over temperature, $I_O = 5\ mA$			−0.6		mV/°C
V_{IN}	Input voltage required to maintain line regulation	$T_J = 25°C$, $I_O \le 1\ A$		7.5			V

Linear Voltage Regulator

- Regulate down by throwing away voltage by heat.
  - e.g. 10V regulated to 5V is 50% power efficient.
- V regulators get HOT! Especially w/more current or voltage
- LM7805 automatic shutdown at 125C

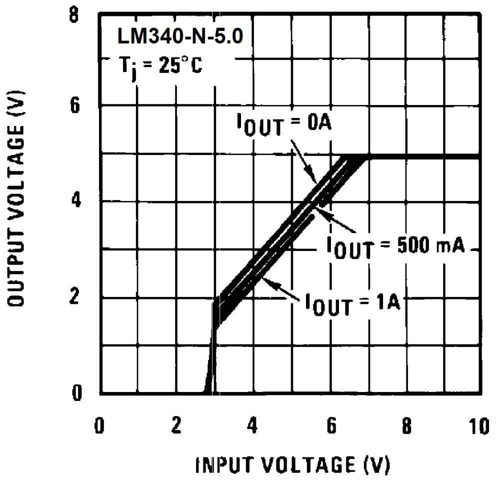
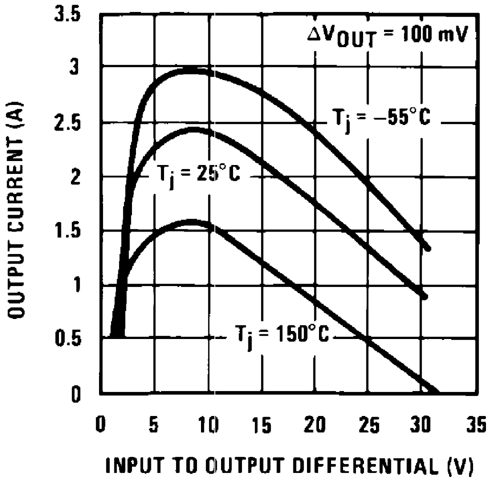
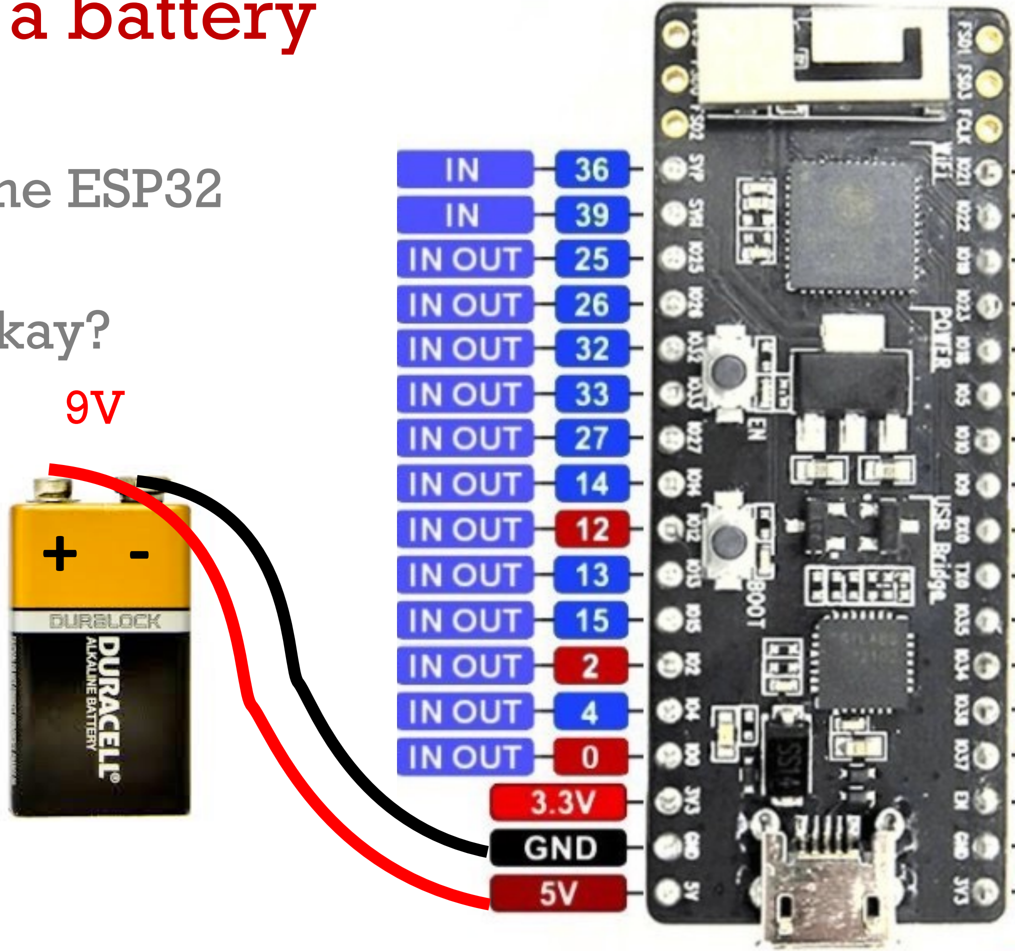


Figure 8. Dropout Characteristics



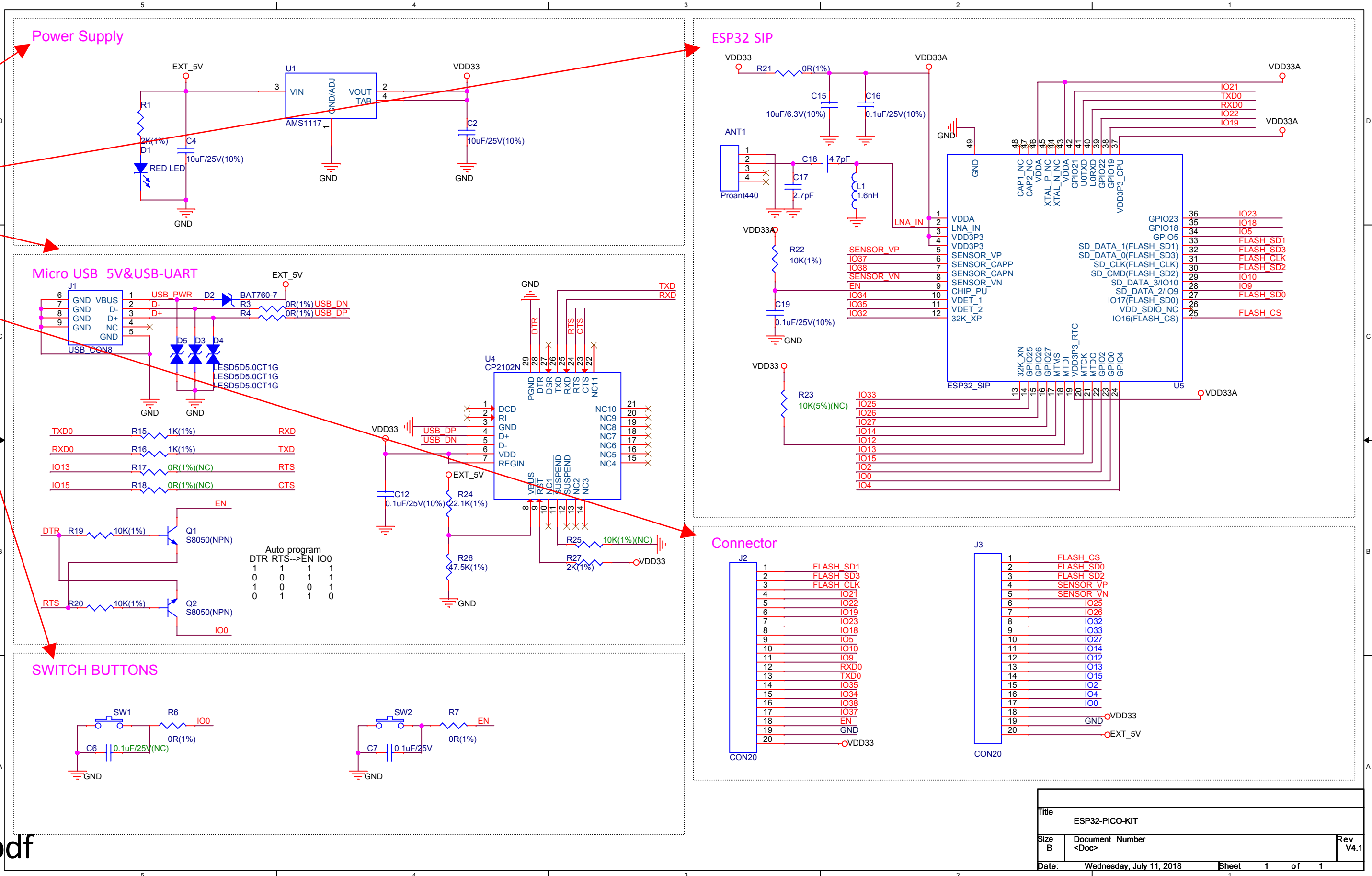
Powering boards with a battery

- Can we apply 9V to power the ESP32 PicoKit?
- How can we find out if it is okay?



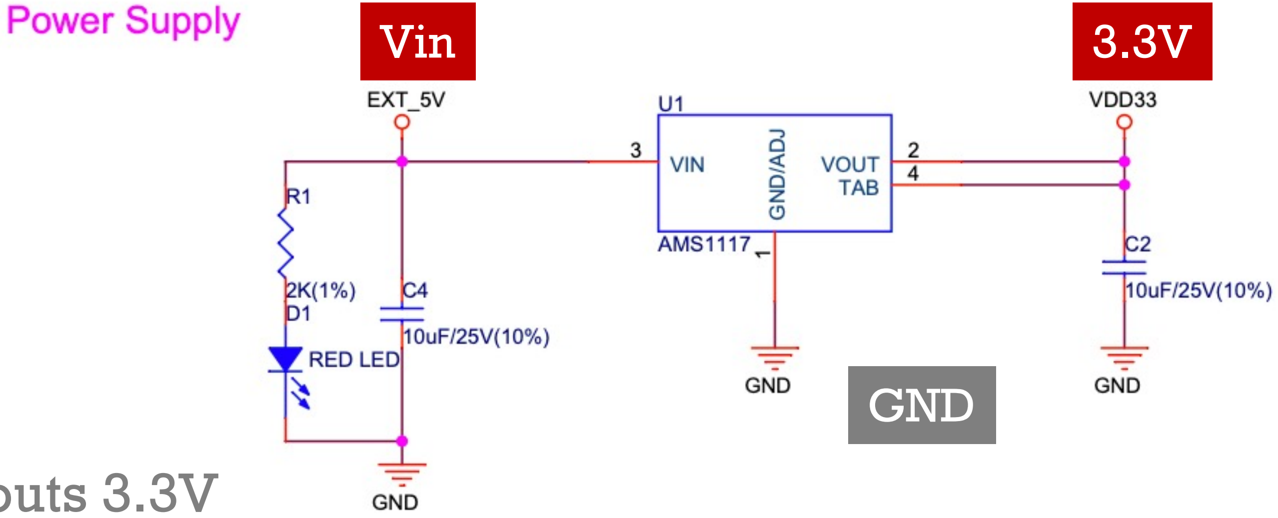
Q8: If we look at the board schematic what section(s) would likely tell us if we can use 9V?

A) Power Supply
B) ESP32 SIP
C) Micro USB 5V
D) Connector
E) Switch Buttons



On canvas:
esp32-piko-kit-v4.1_schematic.pdf

PicoKit Voltage Regulator: AMS1117

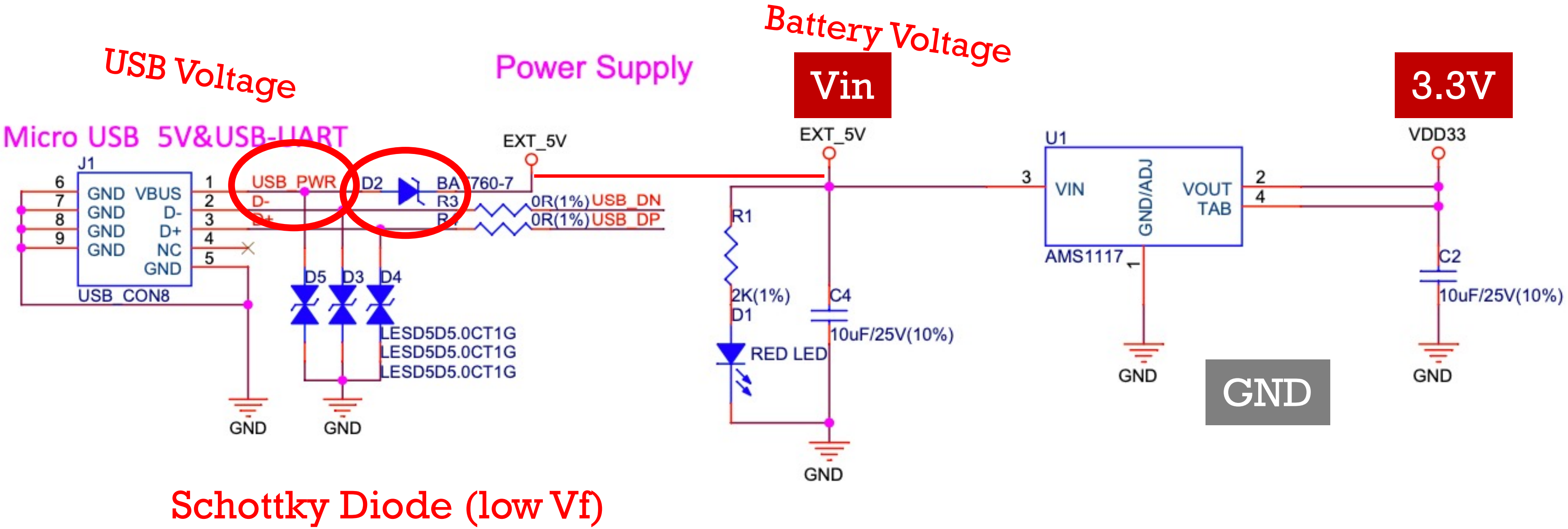


- AMS1117-3.3 outputs 3.3V
- Low Drop Out (LDO) means it can take closer to 3.3V as input
  - LDO is 1.1V@0mA to 1.3V@800mA
- Looking at datasheet: AMS1117 works with input:

  4.6V to 12V

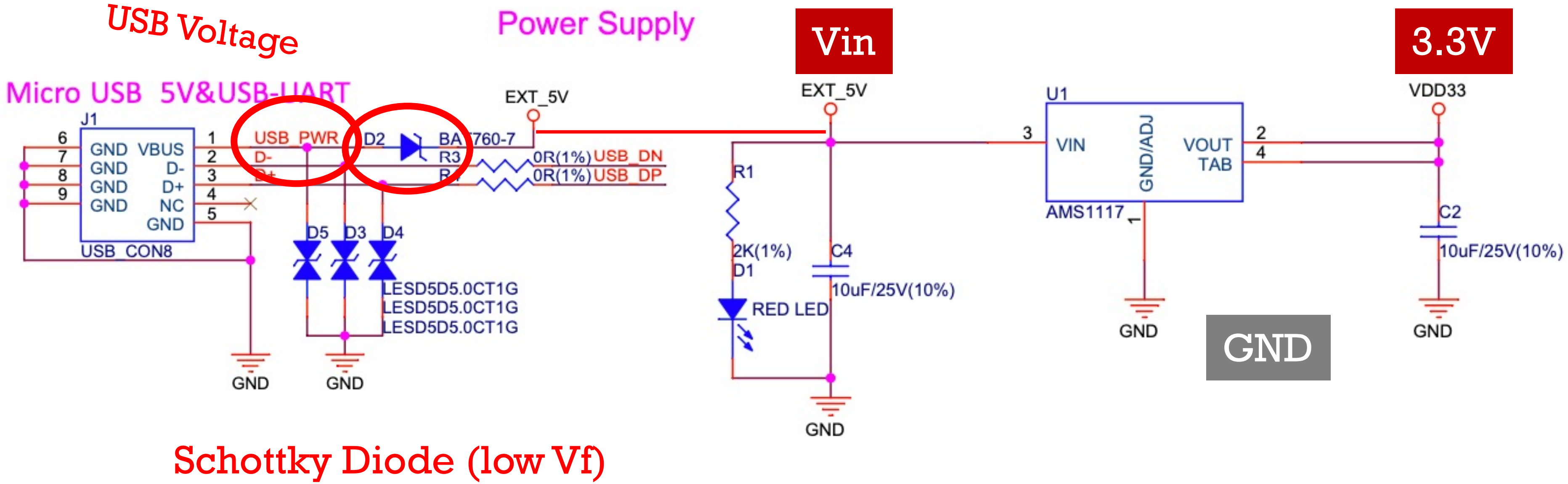
On canvas: esp32-piko-kit-v4.1_schematic.pdf

Q9: Is it okay to use both USB and battery at Vin?



On canvas: esp32-piko-kit-v4.1_schematic.pdf

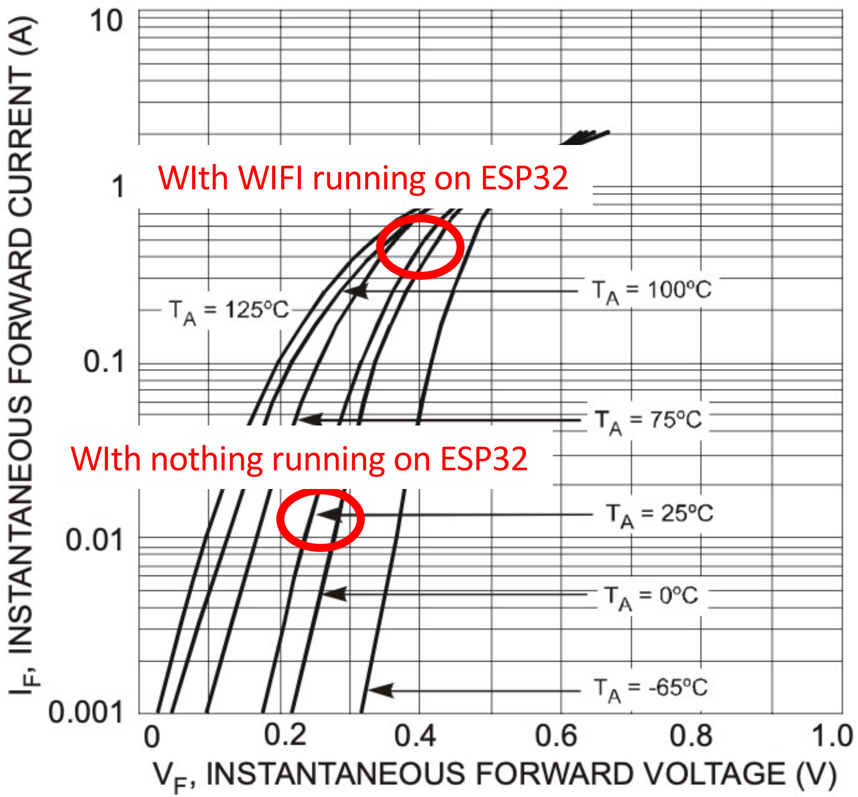
Q10 With USB power only, what will the voltage be at Vin?



On canvas: esp32-piko-kit-v4.1_schematic.pdf

Schottky Diodes (PICO uses BAT760-7)

- Advantage of schottky is low Vf, but varies with load and temp.



VF about 0.25V without WiFi
VF about 0.4V with WiFi

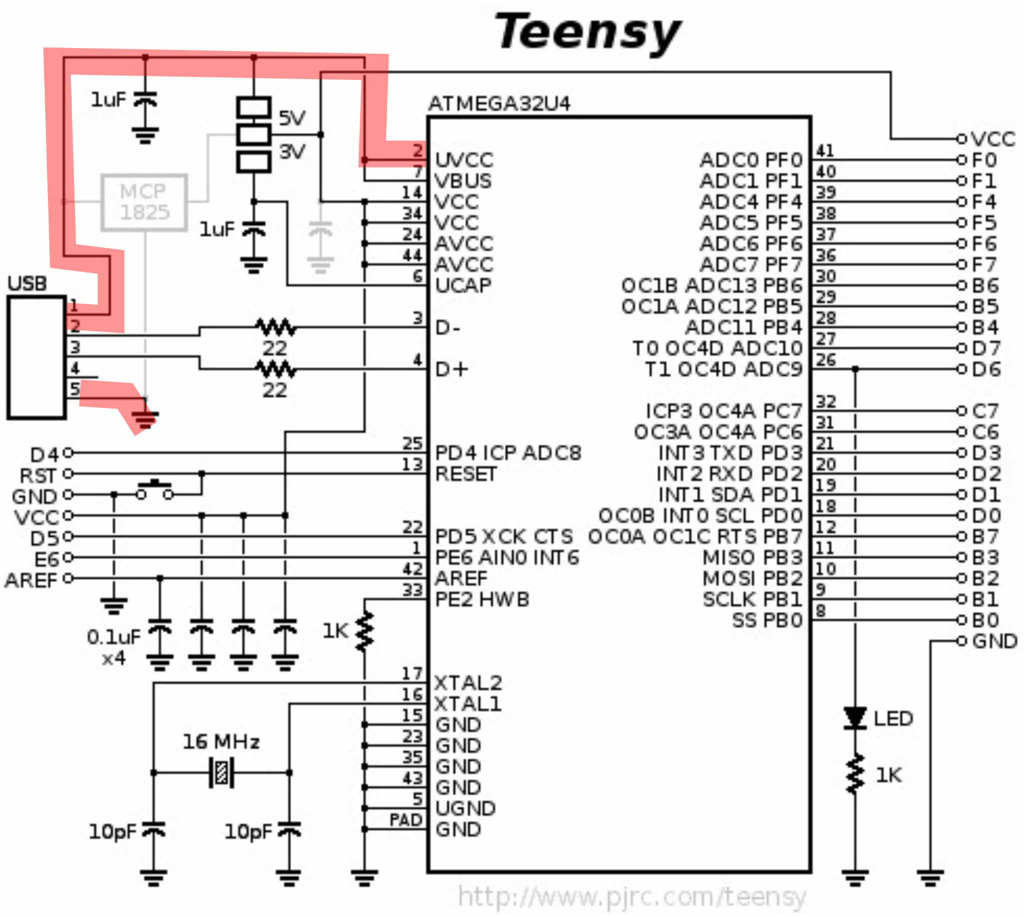
- Power from USB is nominally 5V
- Power at Vin = 5V – Vf
- Power required at AMS1117 > 4.6 worst case, though typically works at 4.4!=V

Solutions to borderline power issue:

- Simple thing, add external 5V to 12V supply to Vin line on PICO (e.g. external battery) or power supply.
- Replace BAT760-7 with lower Vf (I found some about 0.1V lower) – hard to desolder SMD diode – not recommended
- Replace AMS1117 with lower LDO, but major hassle to see if it fits right form factor of surface mount component – hard to desolder SMD diode – not recommended
- Bypass the Schottkey diode. Dangerous, but okay if you remember never to plug in USB when it is battery powered. - not recommended
  - Or bypass Schottkey and never run battery powered - also not recommended.

What about Teensy?

- USB 5V goes straight to VCC
- No protection, but ATmega32U4 has wide range of input.
- Current only limited by USB port, USB connector and traces on PCB



Random Useful Websites:

Basic Circuits

http://www.seattlerobotics.org/encoder/mar97/basics.html

Sensors

http://www.seattlerobotics.org/encoder/jul97/basics.html

Filters

http://mysite.du.edu/~etuttle/electron/elect15.htm

Batteries (more detail)

http://www.mpoweruk.com/index.htm

http://batteryuniversity.com/

Summary

- 9V batteries are convenient but VERY inefficient
- Lithium Polymer/Ion Batteries.
  - 1 cell 3.7V (nominal),   2 cell 7.4V,   3 cell 11.1V etc.
  - Full charge cell is 4.2V
  - Empty is 3.0V (drain below this will damage cell!)
  - Highest energy density commercially available technology
  - Explode and create fires when exposed (e.g. moisture)
- Linear voltage regulators get hot. Limited by current.
- You can supply upto 12V on PicoKit, Teensy can handle up to 5.5V.

In Chat Feedback and Q1,2,3

Q1: You open the hood of your parked car and find a 12V battery in good condition. What does your voltmeter read when you measure the battery?

Q2: What is the nominal voltage for NiMH and NiCad cells (which are the same)

Q3: After sitting on a shelf for 3 years what is the voltage on a LiPo battery that started at 3.7V?

Answer in Chat

Answer how you feel about each topic below with:

1. I don't understand this topic at all
2. I don't know now, but know what to do to get by
3. I understand some, but expect to get the rest later
4. I understand completely already

A. Difference between battery types
B. How to use LiPos safely
C. Using Voltage Regulators