Lecture 19

Batteries and OpAmp Solutions

Agenda

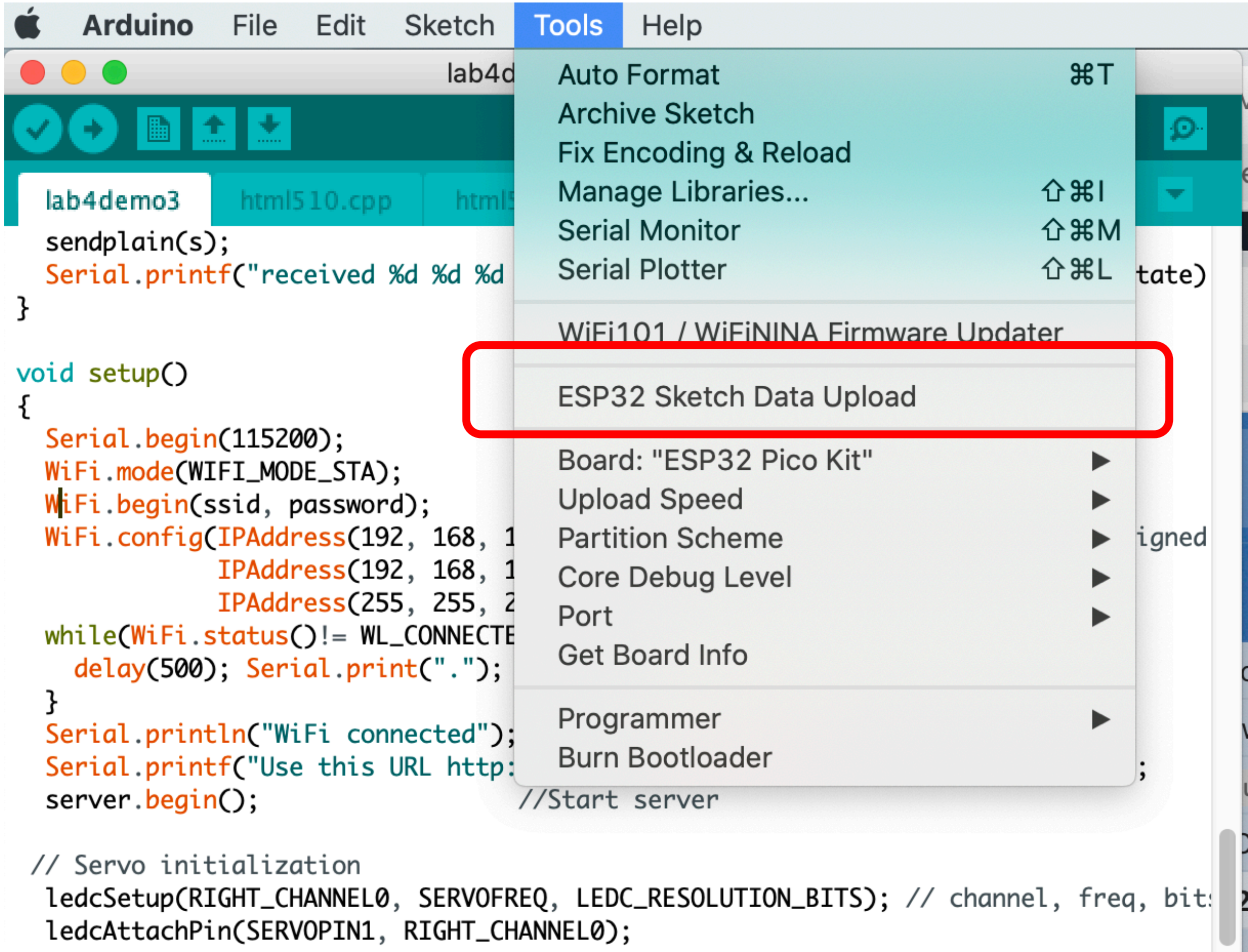
- Teaser on Final Project
- Battery overview
- LiPo Batteries
- High Gain OpAmp circuit solution

Misc. Stuff

- Oscope activity – only about ¼ people have done it. Don't forget. Also may be useful to help debug your robot
- Pass/Fail options - Passing this class requires:
  - Building a waldo that has partial functionality.
  - Building a mobile base that has partial functionality.
    - Check off rubric
- Cheating in this class.
  - Mis-representing work - e.g. if you submit work that is not yours.
  - The grading portion of the final project will include a check off of functionality. You will be asked questions as you demonstrate your robot – which if you built it and programmed it you should know how to answer.

Arduino stuff:

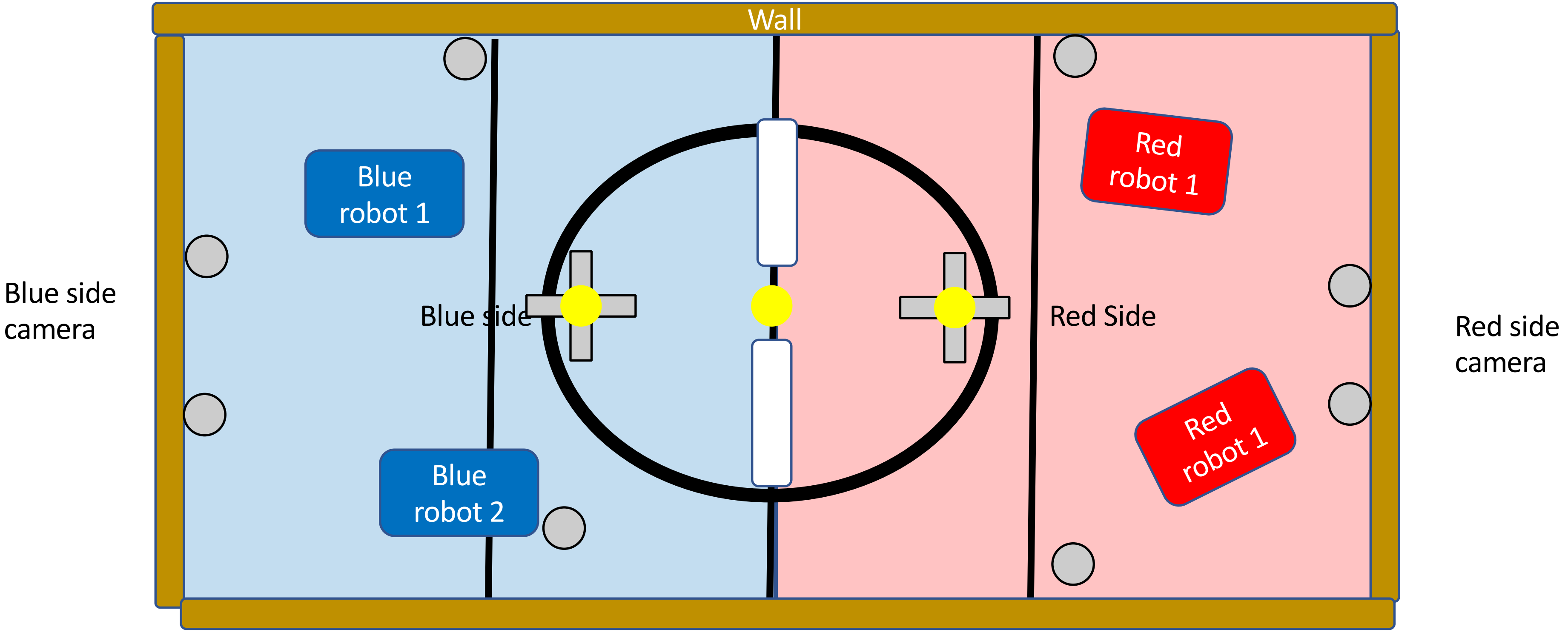
- Be sure you use 2.4GHz router
- If router consistently connects but URL does not, contact teaching staff.



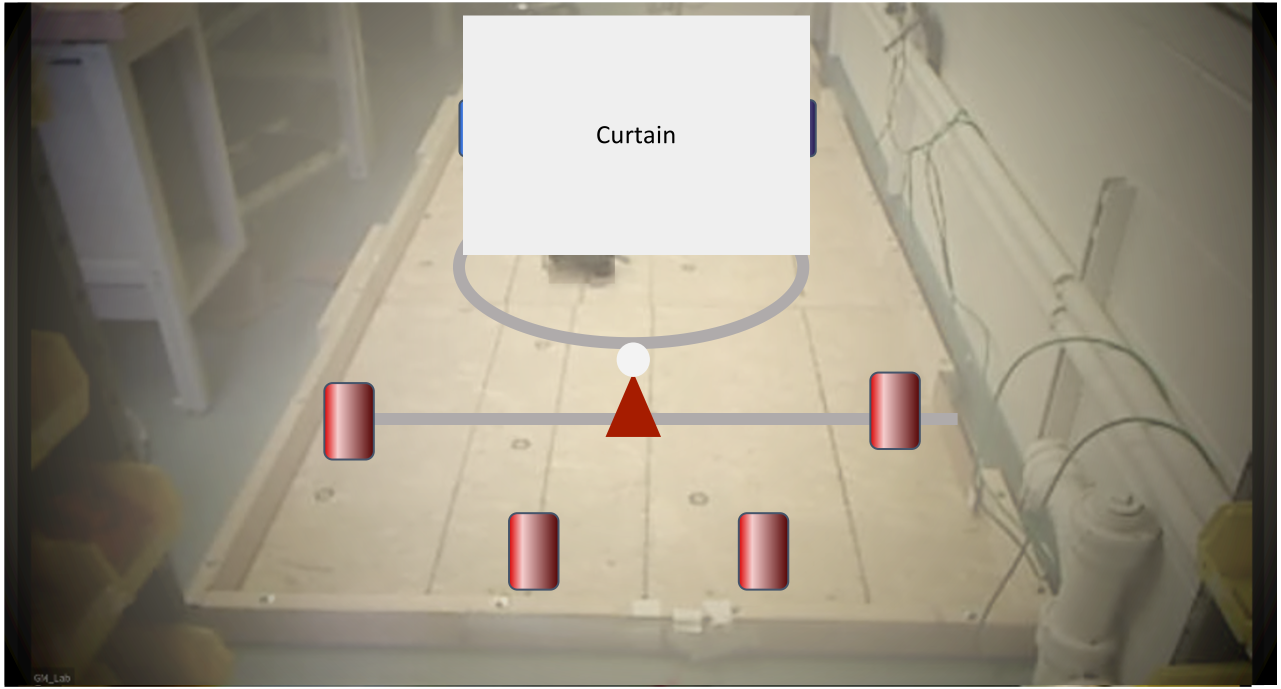
01

Final Project Game Teaser

Final Project Game: 2v2 games last 3 minutes



Limited Vision - to incentivize autonomy:



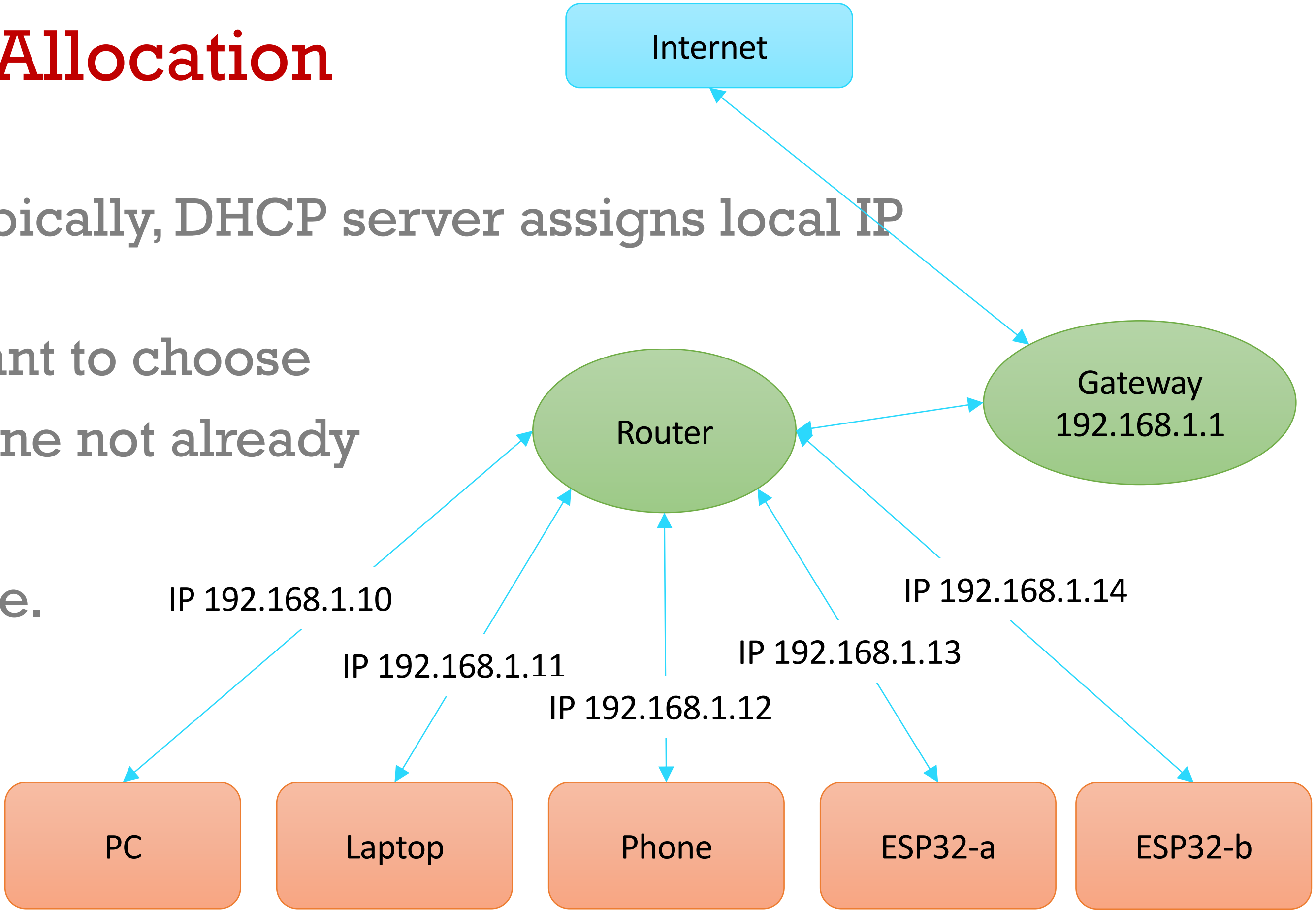
Tentative rules:

- Score for time your robot is in scoring zones on blind side
- Score for cans in scoring zones on your side at end of game.
- Lots of points if you bring opponents beacon over to your side

- Robots start 12"x12"x12"
- No intentional harming of other robots or field

IP Address Allocation

- On a network, typically, DHCP server assigns local IP addresses.
- In our case we want to choose our own. Ideally one not already taken…
- Slight risk at home.



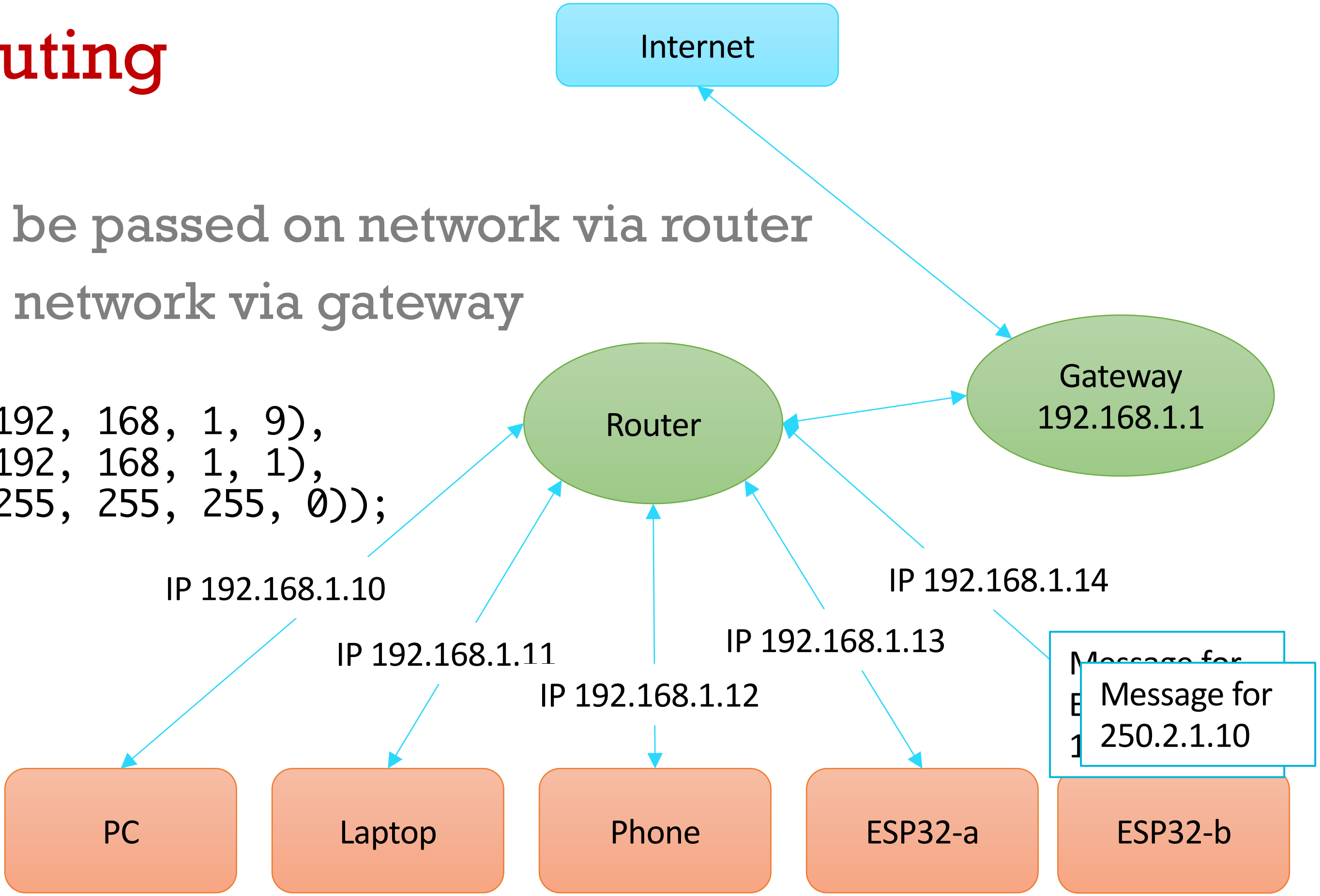
Message routing

- Messages can be passed on network via router
- Reach outside network via gateway

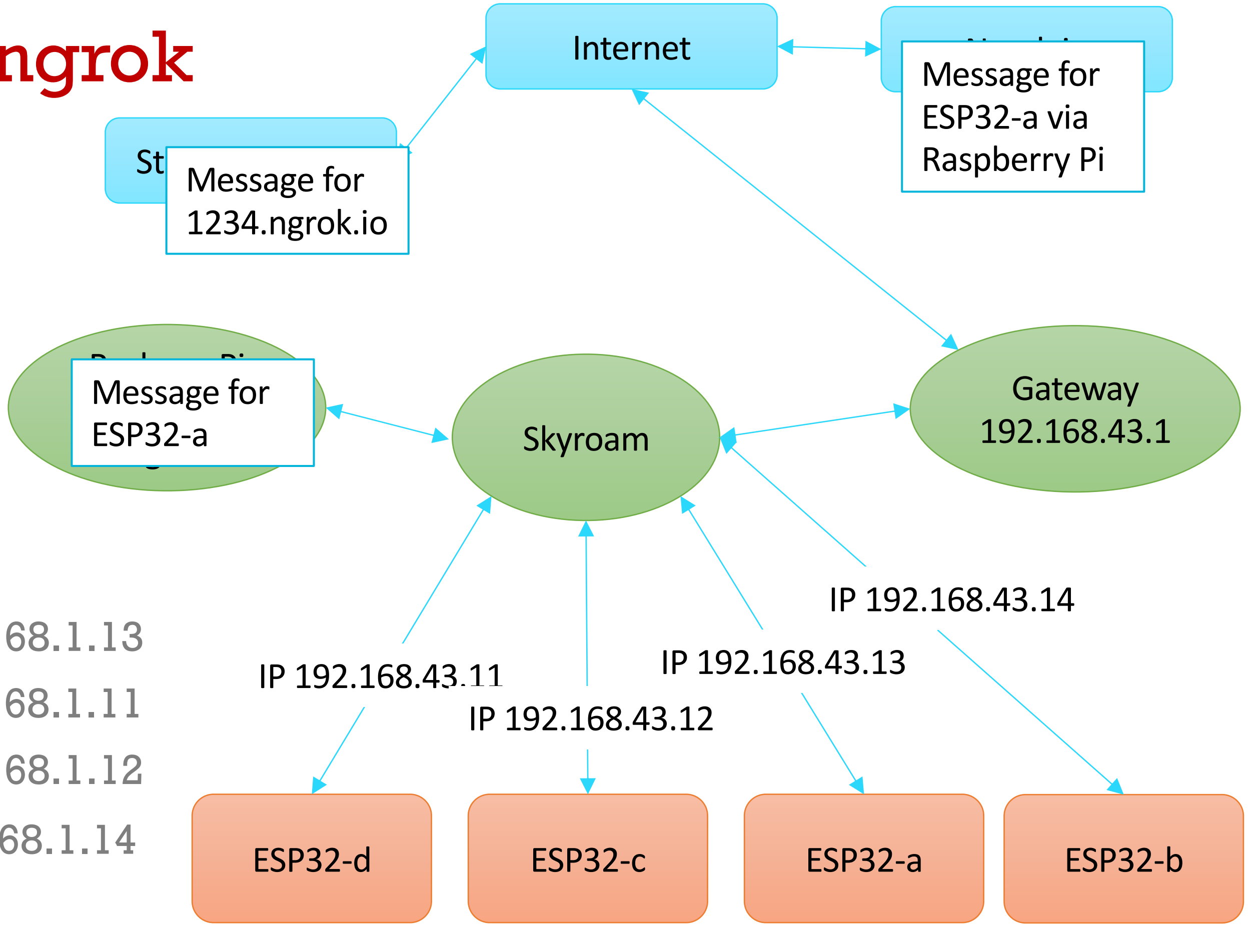
```
WiFi.config(IPAddress(192, 168, 1, 9),
            IPAddress(192, 168, 1, 1),
            IPAddress(255, 255, 255, 0));
```

Gateway

Subnet mask



Tunnelling w/ngrok



Ngrok forwarding

http://1234.ngrok.io -> 192.168.1.13

http://a523.ngrok.io -> 192.168.1.11

http://6435.ngrok.io -> 192.168.1.12

http://12fd.ngrok.io -> 192.168.1.14

02

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

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)

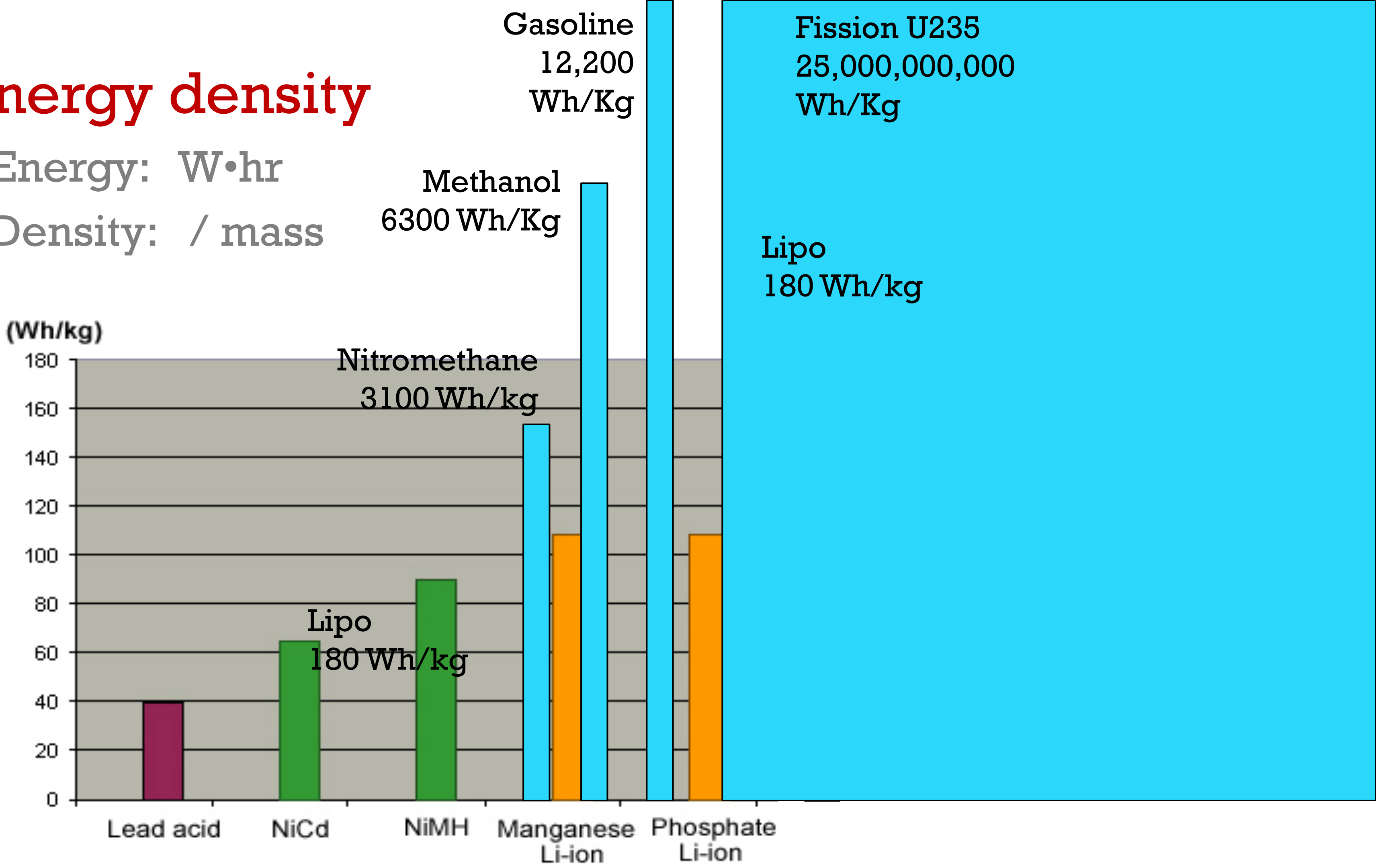
Q3: After sitting on a shelf for 3 years what is the voltage on a LiPo battery that started at 3.7V?

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?

Energy density

- Energy: W•hr
- Density: / mass



Battery Specifications

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

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.

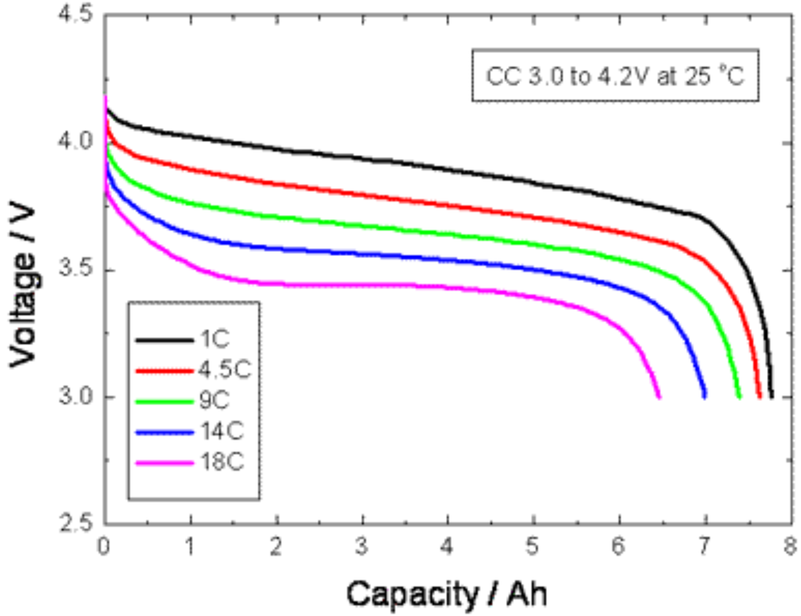


Chart for Lithium batteries

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 (V)	Rated Capacity[1] (mAh)	Rated Voltage Cut-off (V)	Rated Load (Ω)	Dimensions[2] Diameter (Max.) in. (mm)	Height (Max.) in. (mm)	Energy density [mWh/oz]	Weight (Avg.) oz. (g)	Cost [2017] $USD
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)

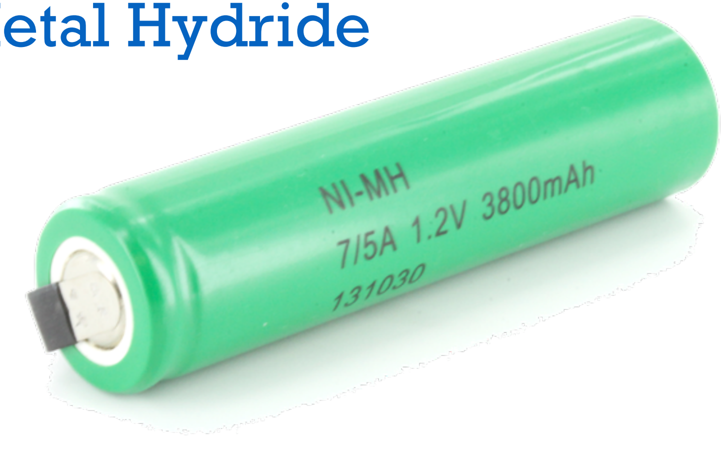
Nickel Cadmium

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.)
- Cell @ 3.7V nominal (3V-4.3V)
- Still changing technology
- Higher power density than NiCd, NiMH
- Shelf-life of ~3 yrs, loses 20%/yr (independent of use)
- Self-discharge 5%/month
- Maintains capacity with some discharge
- Dangerous if casing is damaged

Lithium Ion

LiPo

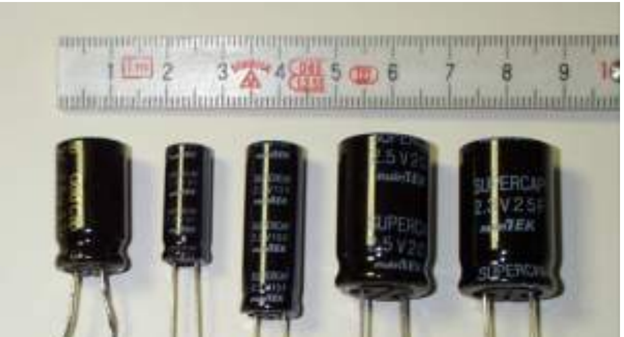
Lithium ion Polymer

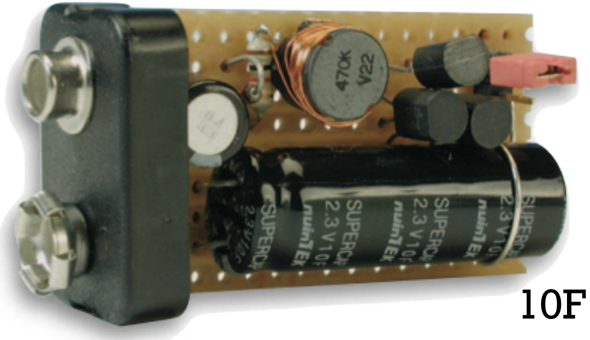
- **Highest power density** commercially available
- Cell @ 3.7V nominal (3V-4.3V)
- More easily conformable (typically prismatic), no casing required -> lighter
- Typically slower charge times,
- Low life cycle degradation rate
- Explosive w/water
- ***Easily causes fires!***

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)

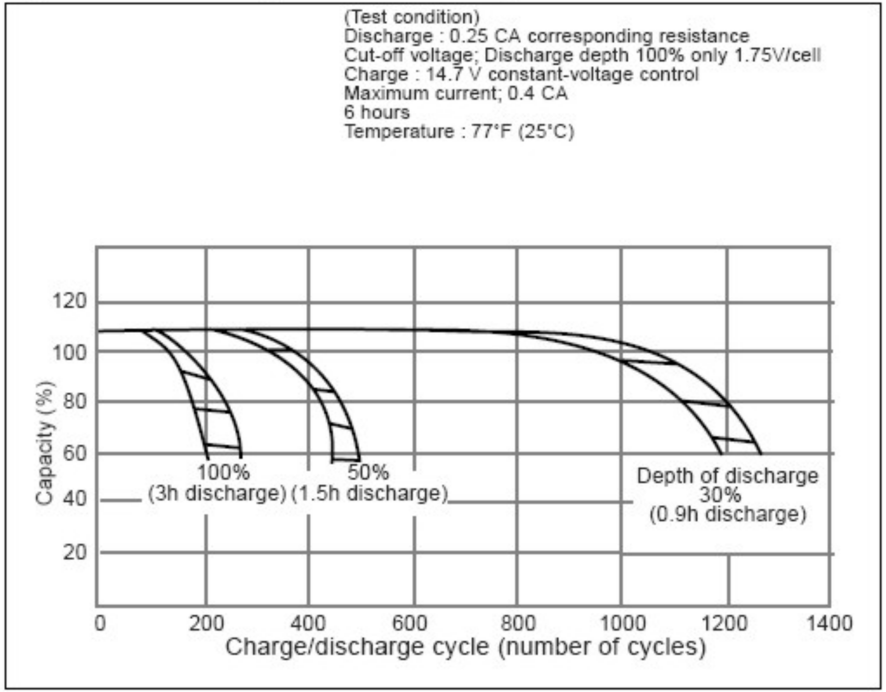
10F @ 2.3V

Battery Comparison Table

Type	NiCd	NiMH	SLA	Li-Ion	Li –poly	Reuse Alkaline	Supercap
Typ Energy Density (Wh/Kg)	50	75	30	150	175	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	.5	.8	.25	1	1	.05	10

Battery lifetime performance

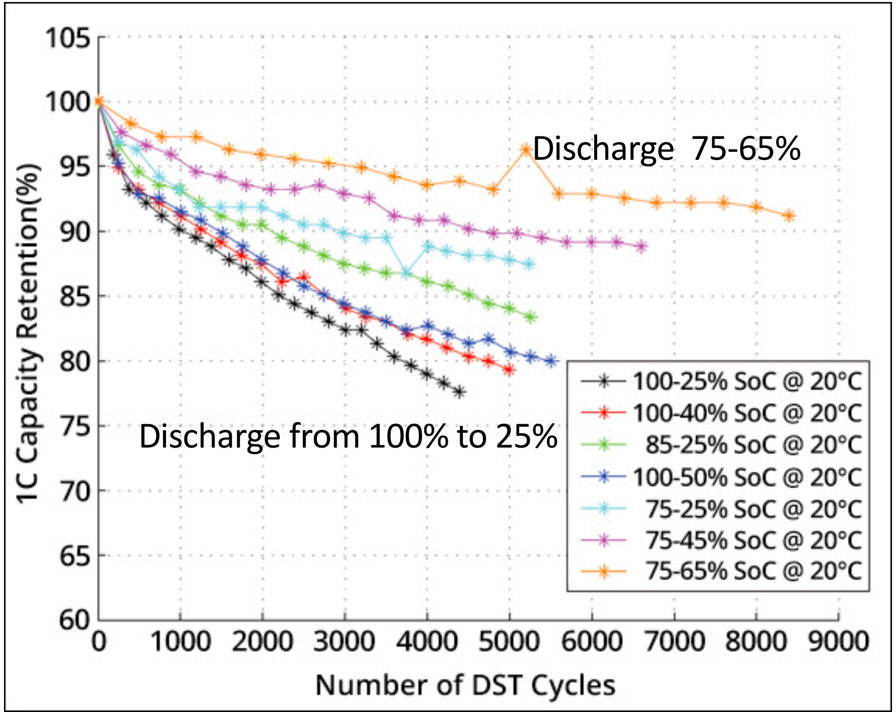
Cycle life vs. Depth of discharge



Deep discharge of SLA can reduce life time.

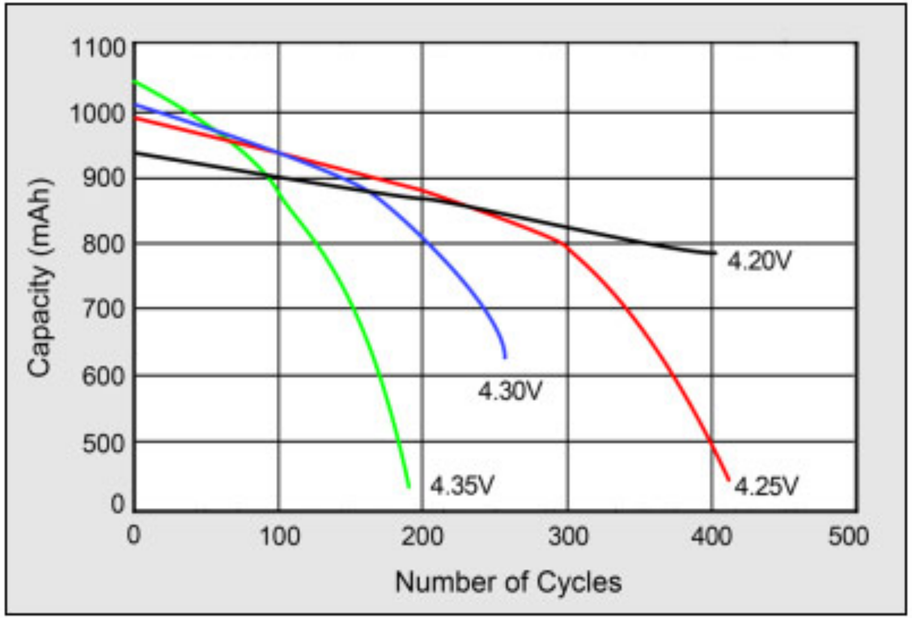
Number of cycles = f(depth)

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.
- More cycles lead to reduced capacity @ 3.9V



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?

03

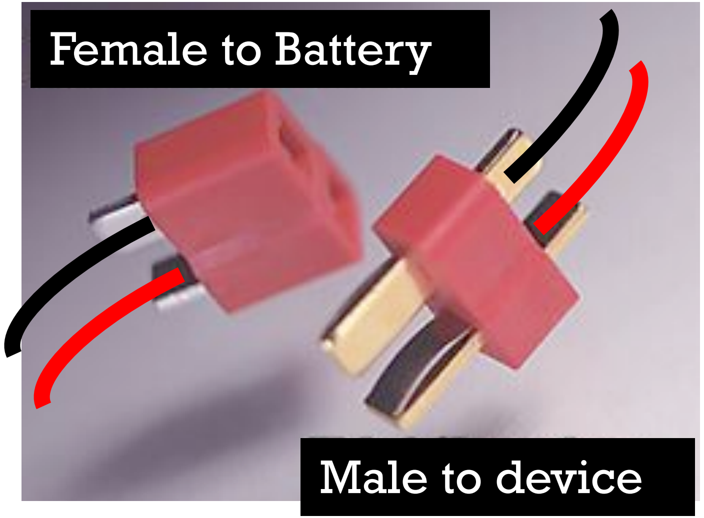
Lithium Polymer (LiPo) Battery recap

GMlab supplied LiPo (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

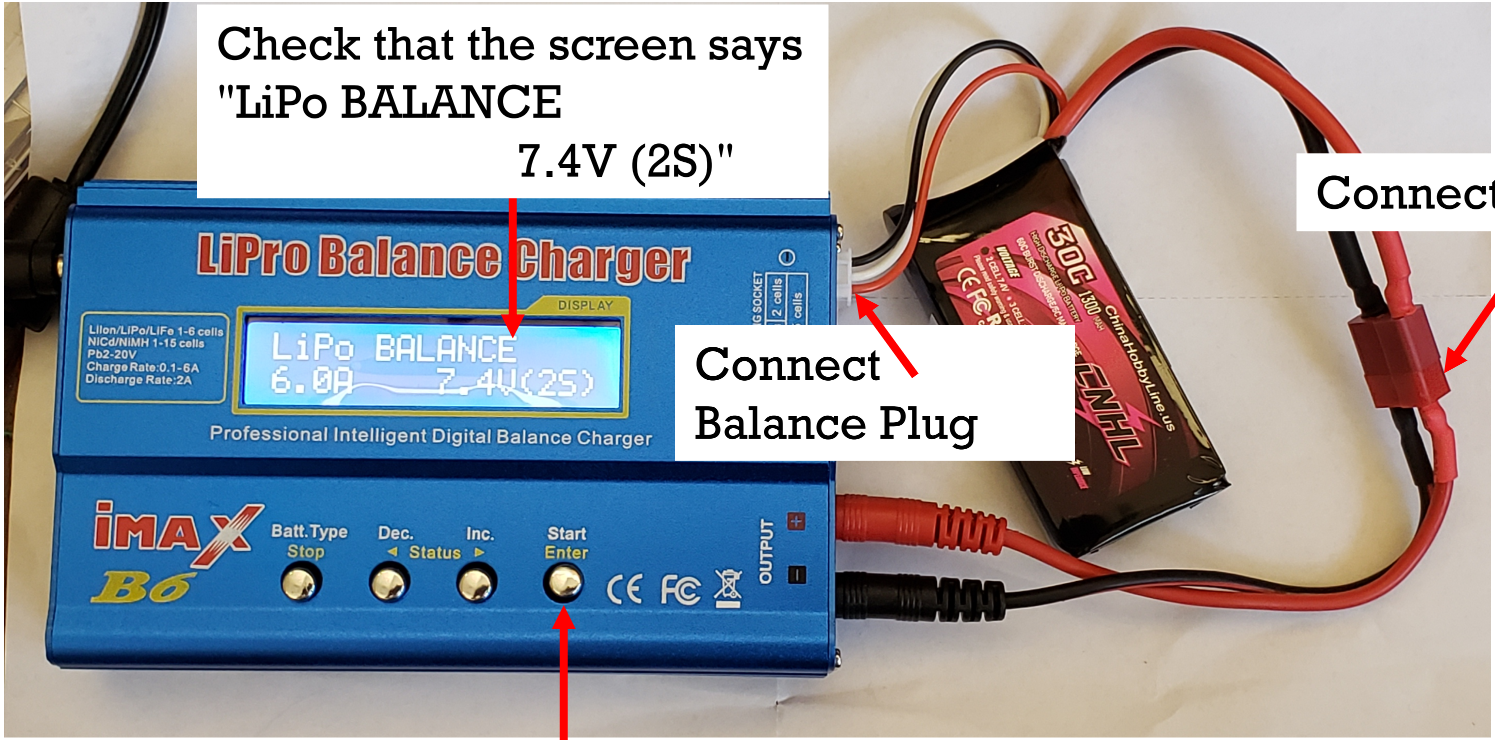
- When storing long term, set multi-cell lipos at 3.85V per cell
  - Most chargers have drain or storage modes to drain to proper level
  - Batteries stored at full voltage may become severly unbalanced.
  - Ideally store in cool dry place (e.g. fridge, but doesn't have to be)
- GMLab has Ammo cases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

Connect Balance 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

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/

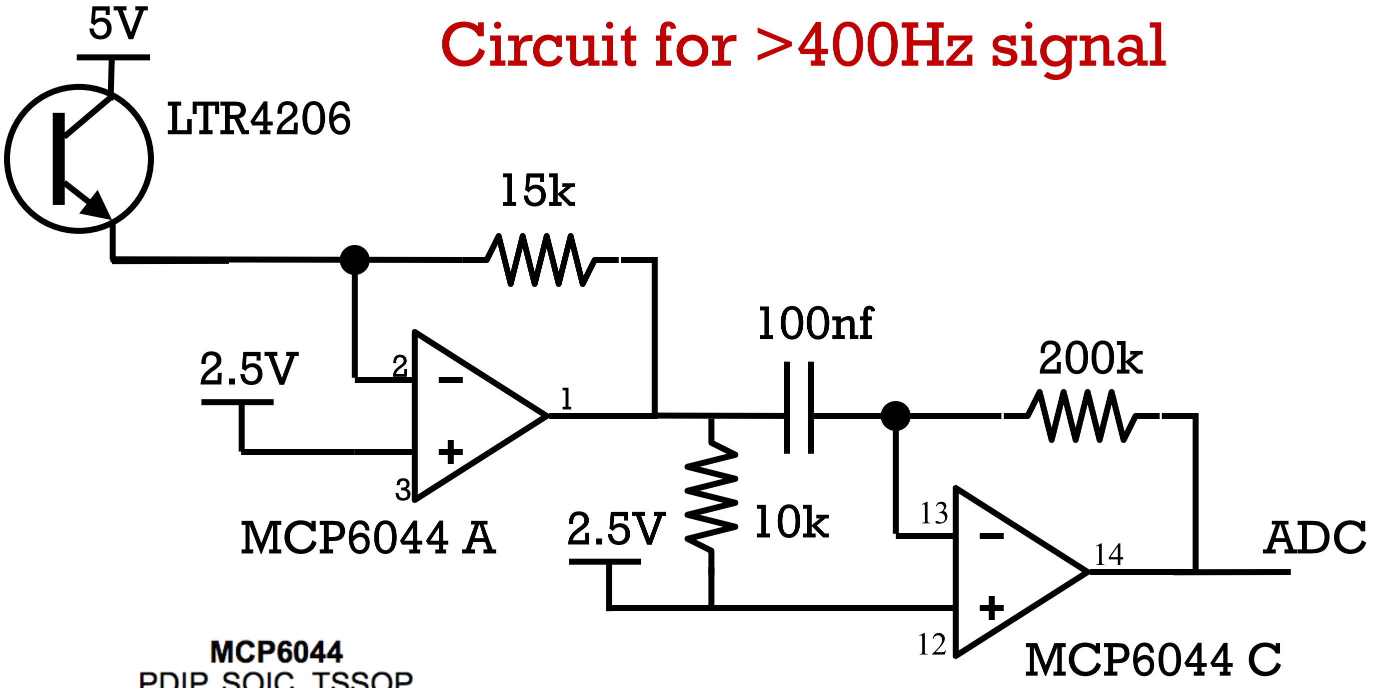
Summary

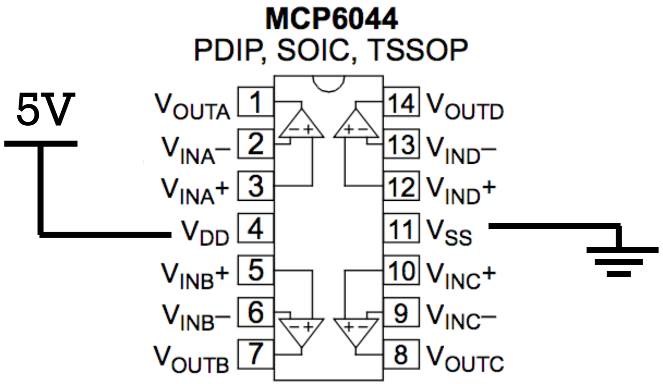
1. Lithium Polymer Batteries.
   A. 1 cell 3.7V (nominal), 2 cell 7.4V, 3 cell 11.1V etc.
   B. Full charge cell is 4.2V
   C. Empty is 3.0V (drain below this will damage cell!)
   D. Highest energy density commercially available technology
   E. Explode and create fires when exposed (e.g. moisture)
2. Sealed Lead Acid batteries
   A. Heavy (low energy density) but low cost
   B. Easy to charge
3. NiMH
   A. 1 cell is 1.2V nominal (1.5V full), 6 cell is 7.2V (9V full)
   B. Not as high density as Lip\Pos but close.
   C. Yim has 100s of 6 cell in his office

03

OpAmp High Gain Solution

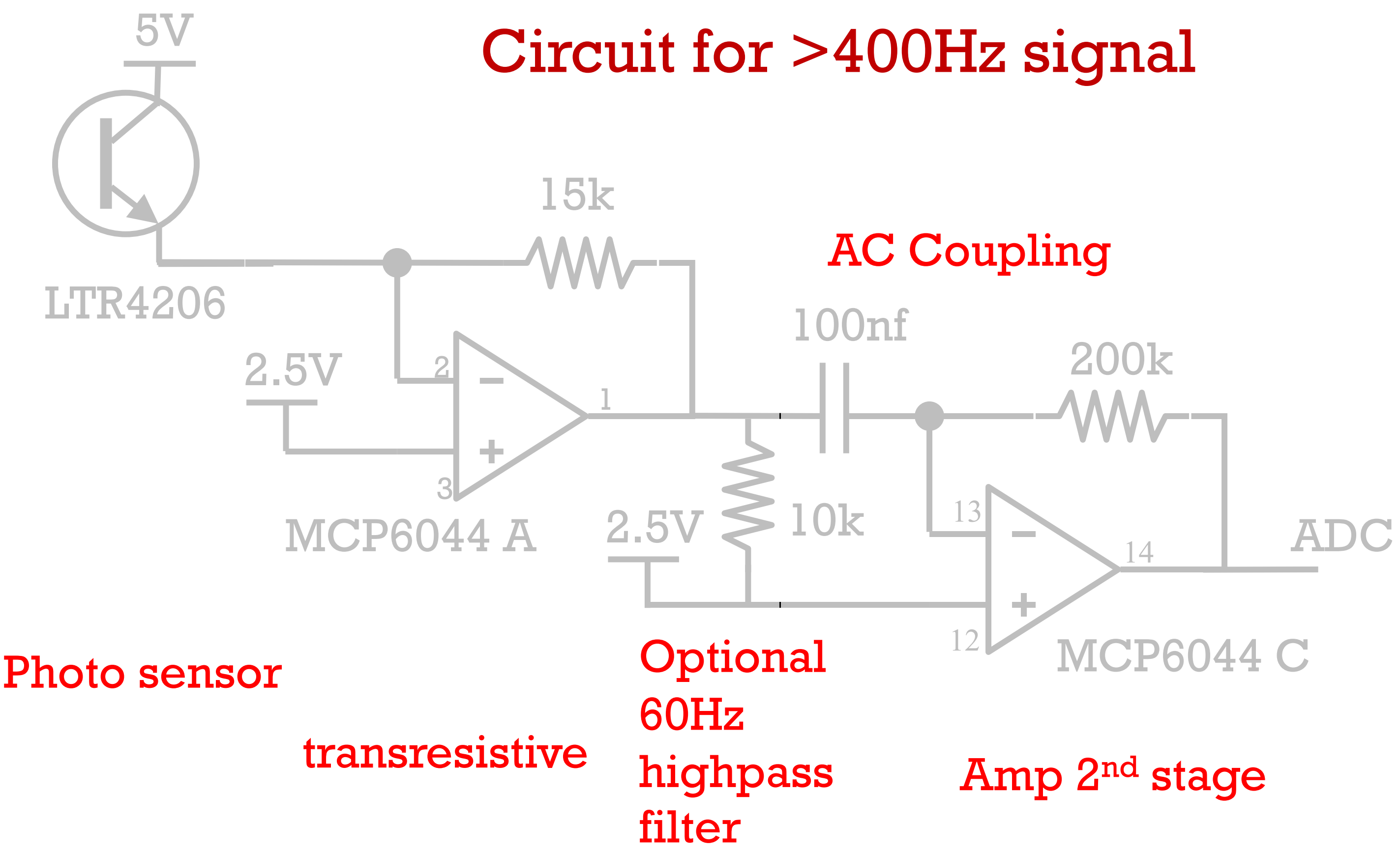
Circuit for >400Hz signal



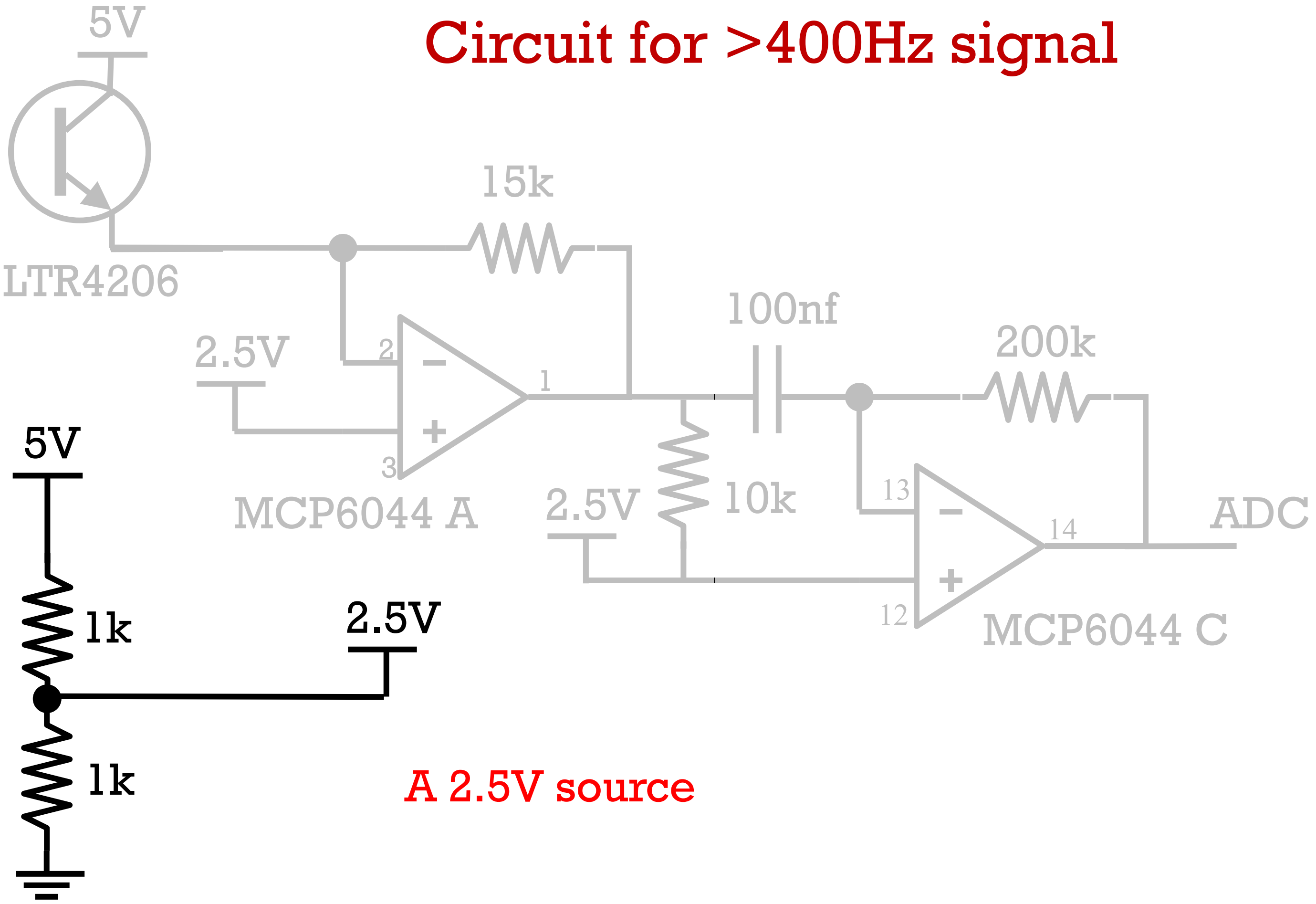


Available in GM lab.
Don't forget power and ground to the chip!

Circuit for >400Hz signal

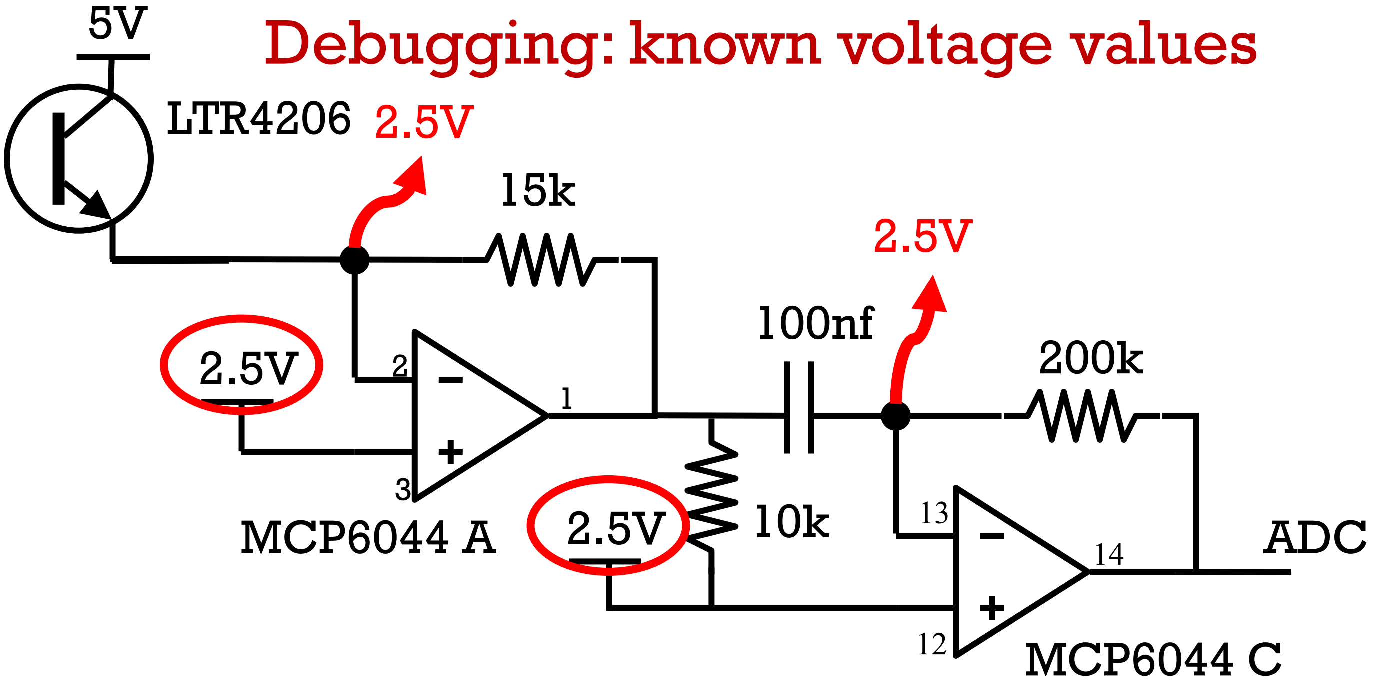


Circuit for >400Hz signal

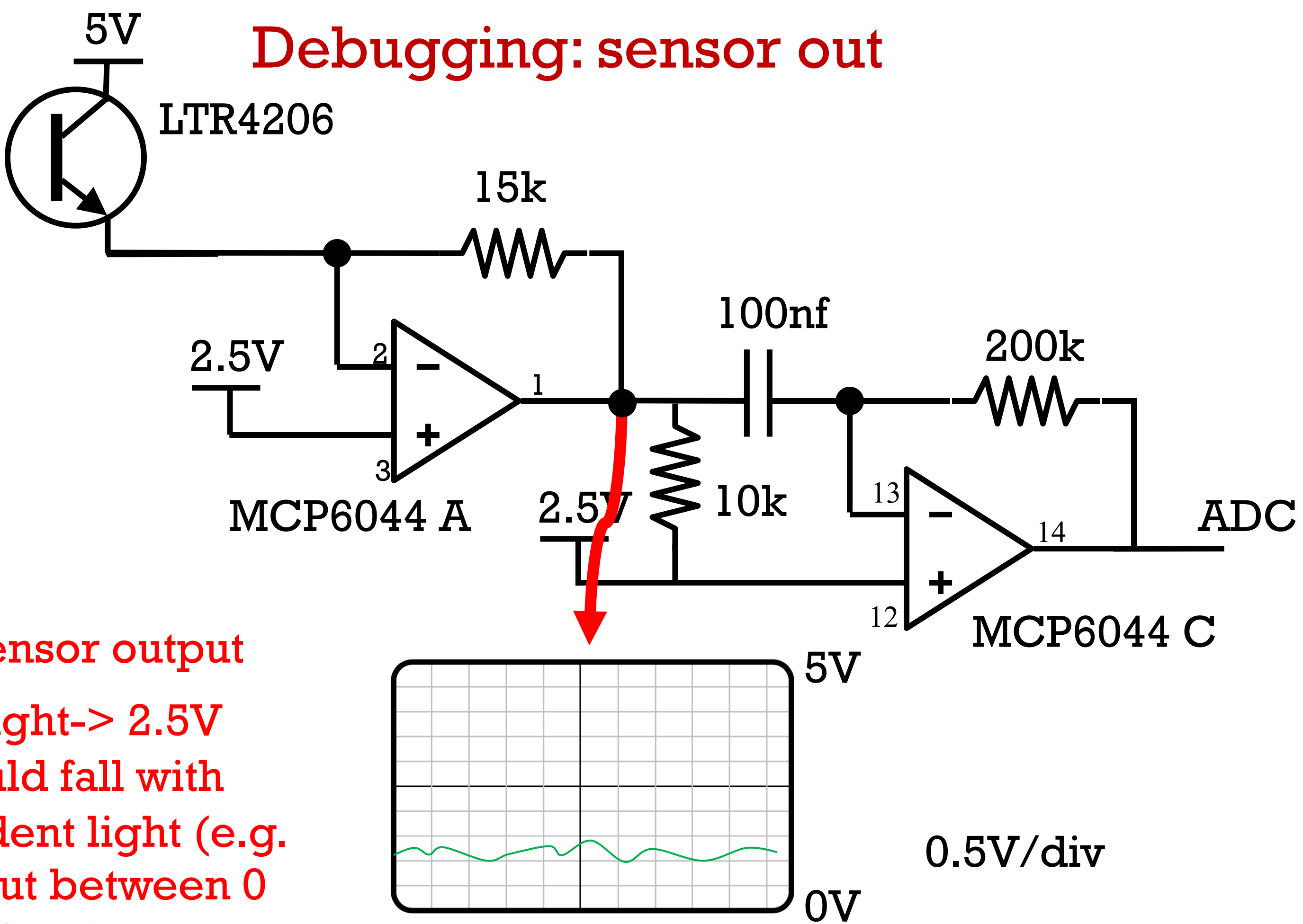


A 2.5V source

Debugging: known voltage values



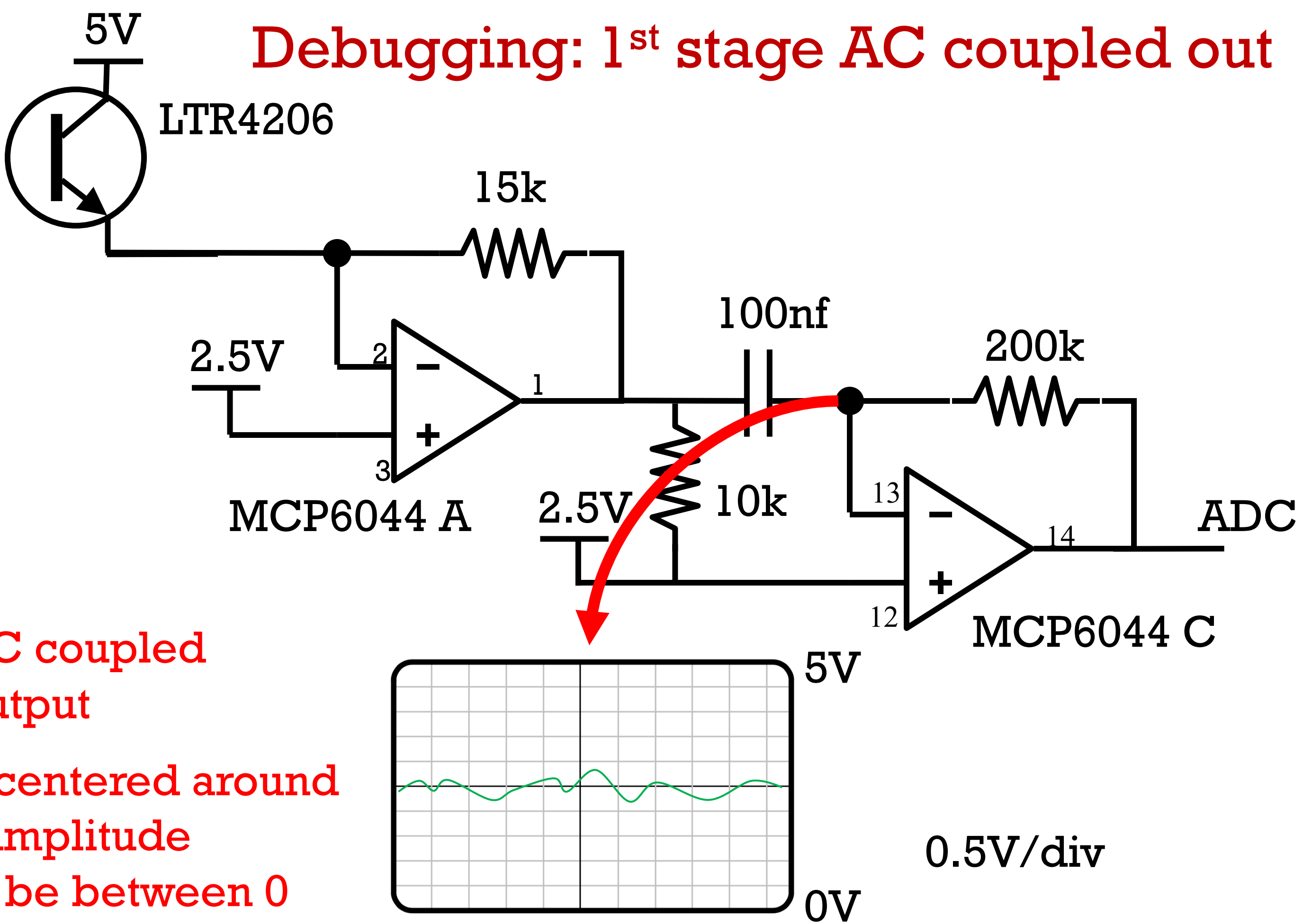
Debugging: sensor out



Sensor output

No light-> 2.5V
Should fall with incident light (e.g. output between 0 and 2.5V)

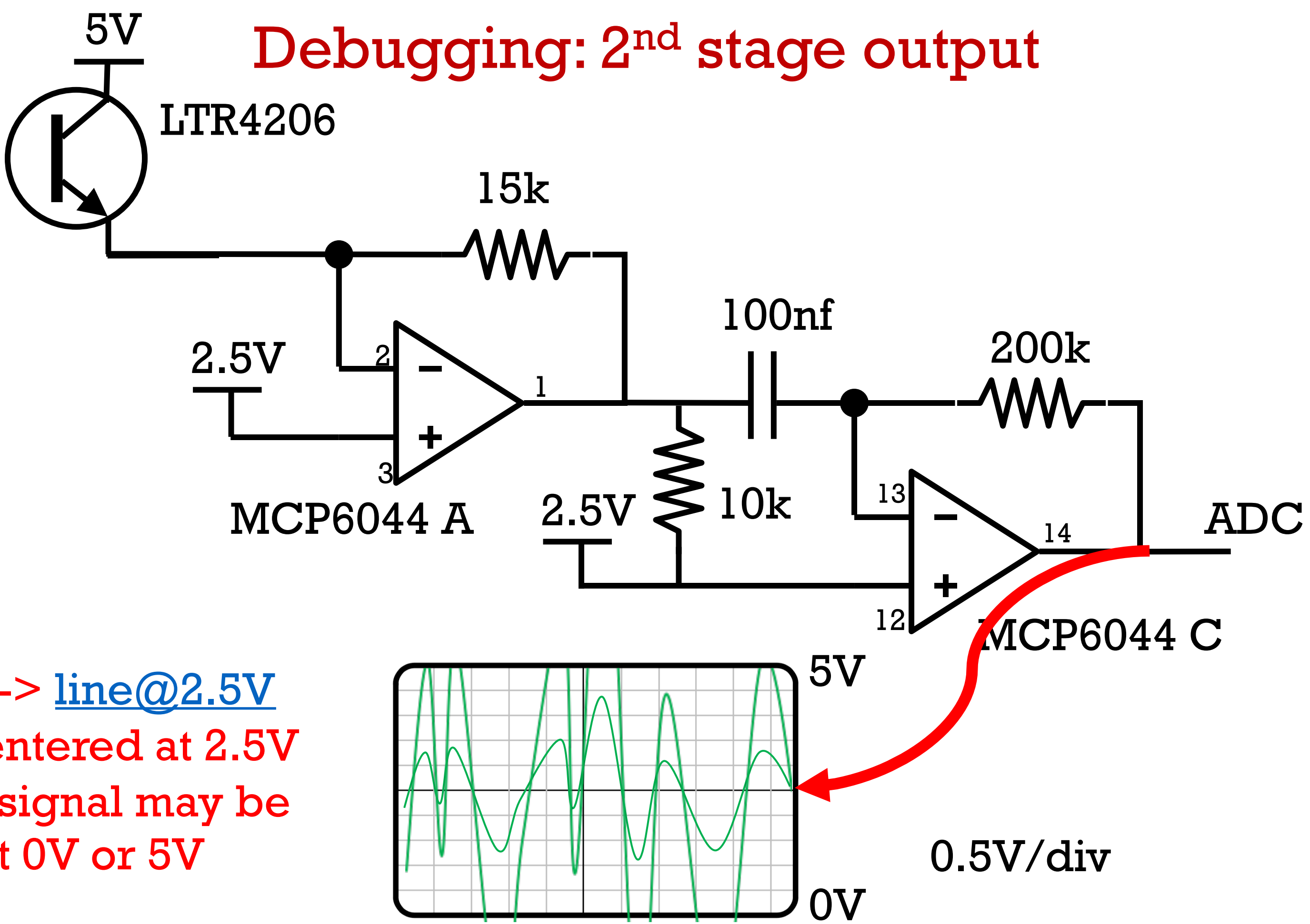
Debugging: 1st stage AC coupled out



AC coupled output

Signal centered around 2.5V. Amplitude should be between 0 and 5V

Debugging: 2nd stage output



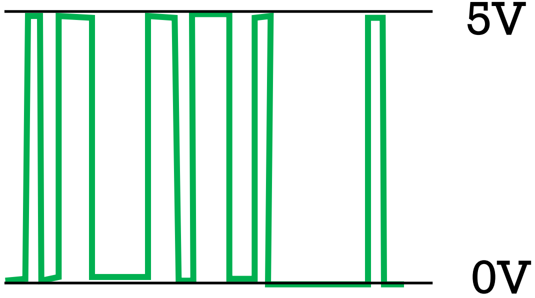
No signal-> line@2.5V
Ideally centered at 2.5V
But large signal may be clipped at 0V or 5V

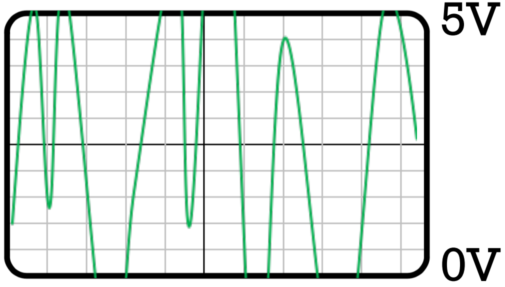
05

Digital freq detection example

Can we use waveforms that are rail-to-rail? No longer Analog

As gain gets very high, signal becomes rail to rail,





Can use a digital input pin (much faster than ADC)

- ~6KHz on ESP32 ADC
- ~300KHz digital

Maximum freq of MCP6044

Q6: What is approximately the max frequency the MCP6044 could generate for a 3.3V Logic?

AC ELECTRICAL CHARACTERISTICS

Electrical Characteristics: Unless otherwise indicated, V_{DD} = +1.4V to +5.5V, V_{SS} = GND, T_A = 25°C, $V_{CM} = V_{DD}/2$, $V_{OUT} \approx V_{DD}/2$, $V_L = V_{DD}/2$, R_L = 1 MΩ to V_L, and C_L = 60 pF (refer to Figure 1-2 and Figure 1-3).

Parameters	Sym	Min	Typ	Max	Units	Conditions
AC Response						
Gain Bandwidth Product	GBWP	—	14	—	kHz	
Slew Rate	SR	—	3.0	—	V/ms	
Phase Margin	PM	—	65	—	°	G = +1 V/V
Noise						
Input Voltage Noise	E_{ni}	—	5.0	—	μV_{P-P}	f = 0.1 Hz to 10 Hz
Input Voltage Noise Density	e_{ni}	—	170	—	nV/√Hz	f = 1 kHz
Input Current Noise Density	i_{ni}	—	0.6	—	fA/√Hz	f = 1 kHz

Comparators are much faster

Q7: What is approximately the max frequency the LM393 could generate for a 3.3V Logic?

ELECTRICAL CHARACTERISTICS (V_{CC} = 5.0 Vdc, $T_{low} \le T_A \le T_{high}$, unless otherwise noted.)

Characteristic	Symbol	LM293, LM393, LM393E			LM2903/E/V, NCV2903			Unit
		Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage (Note 4)	V_{IO}							mV
T_A = 25°C		–	±1.0	±5.0	–	±2.0	±7.0	
$T_{low} \le T_A \le T_{high}$		–	–	±9.0	–	±9.0	±15	
Voltage Gain $R_L \ge$ 15 kΩ, V_{CC} = 15 Vdc, T_A = 25°C	A_{VOL}	50	200	–	25	200	–	V/mV
Large Signal Response Time V_{in} = TTL Logic Swing, V_{ref} = 1.4 Vdc V_{RL} = 5.0 Vdc, R_L = 5.1 kΩ, T_A = 25°C	–	–	300	–	–	300	–	ns
Response Time (Note 7) V_{RL} = 5.0 Vdc, R_L = 5.1 kΩ, T_A = 25°C	t_{TLH}	–	1.3	–	–	1.5	–	µs

4. At output switch point, $V_O \simeq$ 1.4 Vdc, R_S = 0 Ω with V_{CC} from 5.0 Vdc to 30 Vdc, and over the full input common mode range (0 V to V_{CC} = –1.5 V).
5. Due to the PNP transistor inputs, bias current will flow out of the inputs. This current is essentially constant, independent of the output state, therefore, no loading changes will exist on the input lines.
6. Input common mode of either input should not be permitted to go more than 0.3 V negative of ground or minus supply. The upper limit of common mode range is V_{CC} –1.5 V.
7. Response time is specified with a 100 mV step and 5.0 mV of overdrive. With larger magnitudes of overdrive faster response times are obtainable.

Comparators switch faster with larger input signals.

Overdrive is how much over the threshold

Detection code: Approaches

To determine frequency of signal:

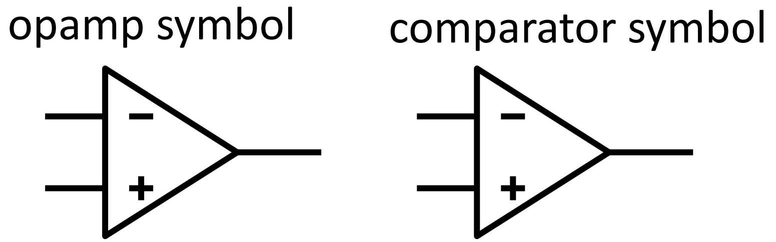
- Count rising edges
- Count peaks or troughs
- Count threshold crossings

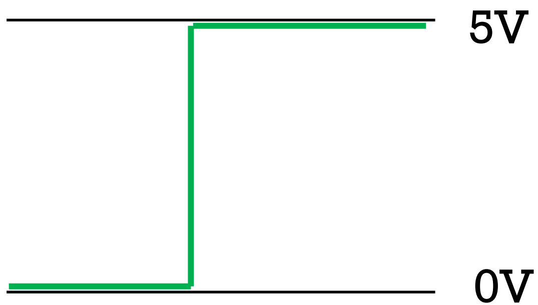
To check if frequency matches a desired signal:

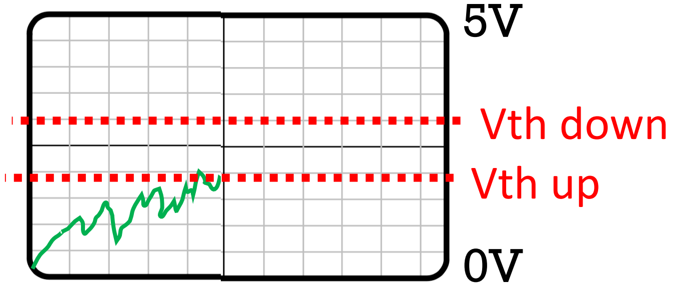
- Compare aligned data

Comparators

- High gain difference amp - Like an opamp
- Builtin hysteresis (two level directional threshold)
- Handles saturation better than opamps
- Logic level output
- LM393 and LM339 available in GM lab







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?

A: Understanding of Batteries

B: Understanding of example OpAmp circuit.

B: Excitement about Final Project