Power I

6.9000

Spring 2025

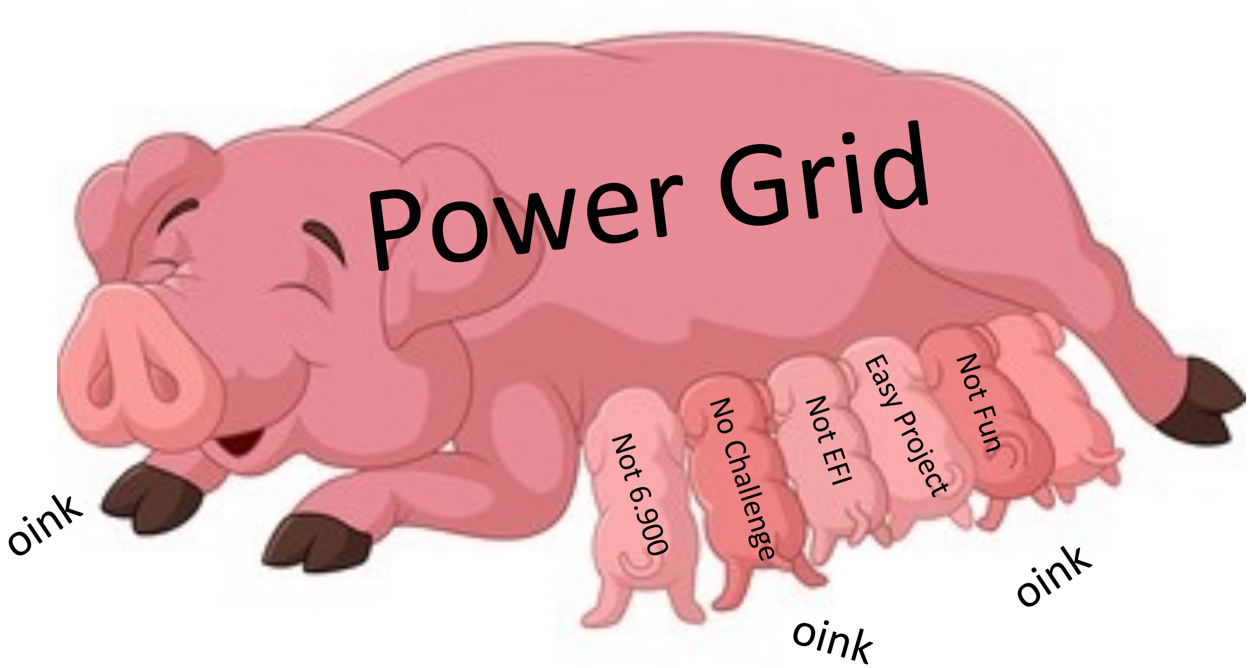
Things To Talk About

- What is power?
- Why do we use it?
- How do we make it?
- How to measure it?

- Why does it matter???

- Especially for us in 6.9000?

No Grid Connections



- Our sensors need to bring their power with them or harvest it from environment?
- Must be intimately aware of how we consume and produce and store energy

https://www.shutterstock.com/image-illustration/little-piglets-suckling-their-mother-253479343

All Computation Requires Power

- Power is related to energy
- All computation uses energy
- For a given computational technology…
  - The more computation you do, the more energy you use
  - The faster you do your computation, the more energy used per unit time, the more *power* your system uses
- We always want more computation and we want that computation faster, so we are constantly using more power…
- The implications of this can vary…

In Stationary Situations…

- (Such as desktop computer, server farms, stationary equipment connected to grid, etc…)
- The tendency to use more and more power means you'll:
    - Use more energy and therefore cost more to operate
    - May have to deal with waste heat disposal

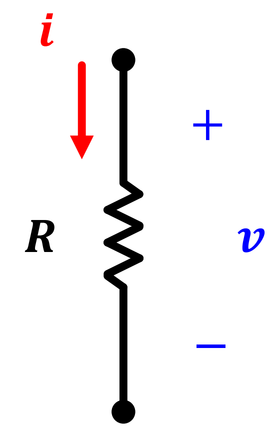
Lower Limit on Computation

- A little controversial…
- There is a lower limit: it takes about **3×10^{-21} Joules** to erase a bit no matter what
  - Called Landauer Limit
  - Experimentally shown in 2012 (Berut et al., Nature 2012)
- Intel 22nm process takes approximately
  - **100×10^{-15} Joules (estimate/approximation)**
- Between those two numbers are the inefficiencies and limitations of circuits
- People actively working on pushing towards that limit!...many people at MIT

https://spectrum.ieee.org/computing/hardware/landauer-limit-demonstrated
https://en.wikipedia.org/wiki/Landauer%27s_principle

Remember Ohm's Law Has a Sign

- We all know Ohm's Law, but we should make sure to remember that it has an orientation associated with it
- This orientation underlines the point that current naturally flows downward along the voltage gradient (from area of high potential to low potential)
- A resistor "consumes" power



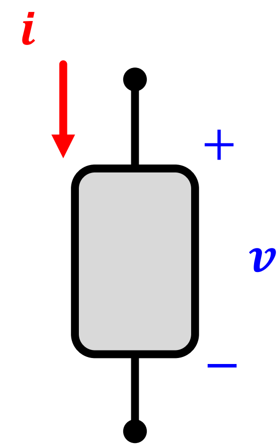
$$v = i \cdot R$$

Power

- Voltage: (Joule per Coulomb):
  - PE drop per unit charge
- Current: (Coulombs per sec):
  - Charge per unit time
- Power consumed:
  - Product of Voltage **across** and Current **through** a device

$$p = v \cdot i$$

grey box represents an arbitrary component

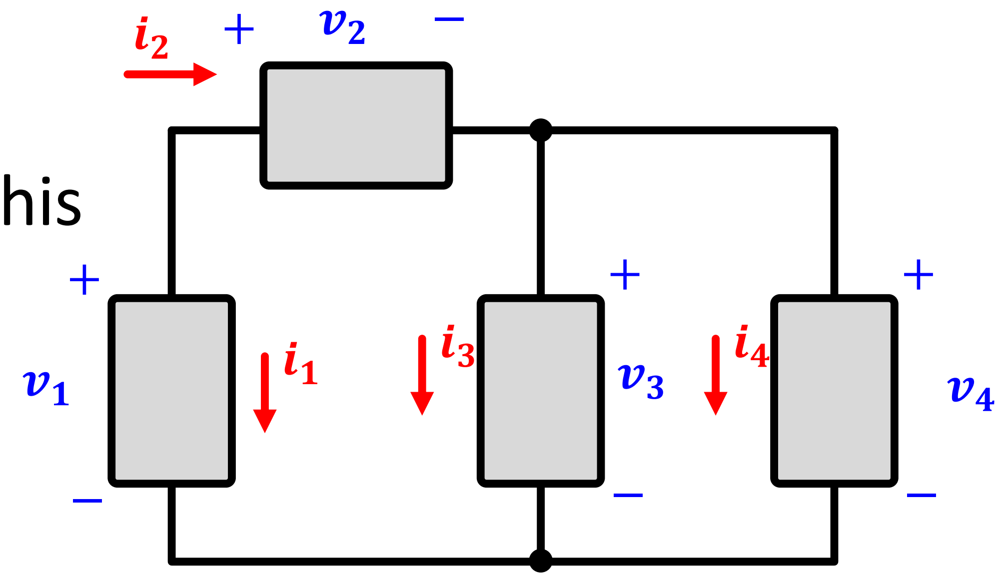


$$p = \frac{\text{Joule}}{\text{Coulomb}} \cdot \frac{\text{Coulomb}}{\text{sec}} = \frac{\text{Joule}}{\text{sec}} = \text{Watt}$$

Tellegen's Theorem

- In any circuit, the sum of all component powers must be 0 (you have to keep signs consistent for each component)
- For a circuit with $\boldsymbol{n}$ components you'd have this equation:

$$\mathbf{0} = \sum_{i=0}^{n} i_2 \cdot v_2$$



https://en.wikipedia.org/wiki/Tellegen%27s_theorem

Implications…

- If $\mathbf{0} = \sum_{i=0}^{n} \boldsymbol{i_2} \cdot \boldsymbol{v_2}$ and we know that some components will have positive power (resistor for example), does that mean that some components will have negative power?

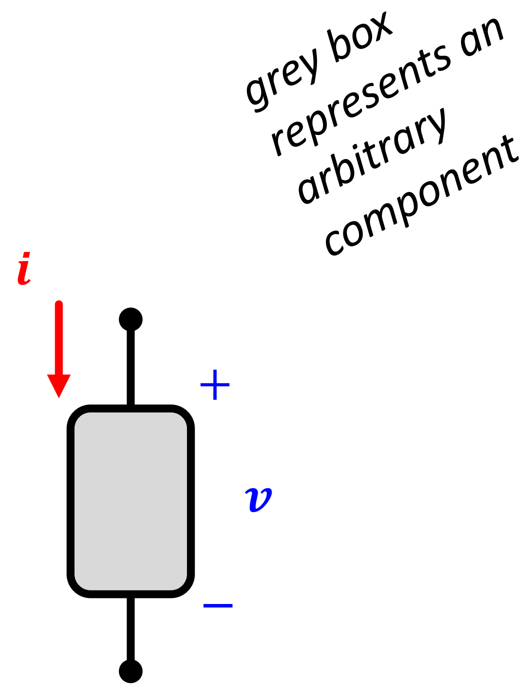
- Yes…what does that mean?

Power

- Voltage: (Joule per Coulomb):
  - PE drop per unit charge
- Current: (Coulombs per sec):
  - Charge per unit time
- Power consumed:
  - Product of Voltage **<u>across</u>** and Current **<u>through</u>** a device

$$p = v \cdot i$$

- If **p>0**, it **consumes** power
- If **p<0**, it **supplies** power

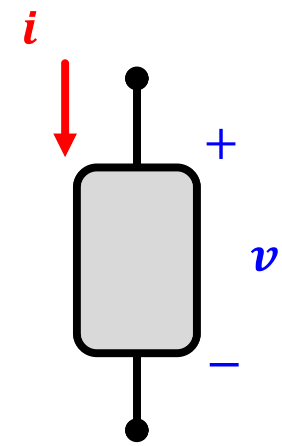


$$p = \frac{\text{Joule}}{\text{Coulomb}} \cdot \frac{\text{Coulomb}}{\text{sec}} = \frac{\text{Joule}}{\text{sec}} = \text{Watt}$$

Caveats

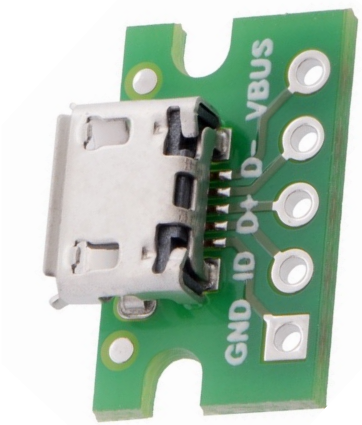
- The sign of power is great from a theory perspective and in deducing what devices are supplying/consuming power
- However in life, we usually know what components are supplying or consuming power *a priori*
- So generally power-supplying devices will have their currents documented and specified as going from the output of their + terminal!!!!

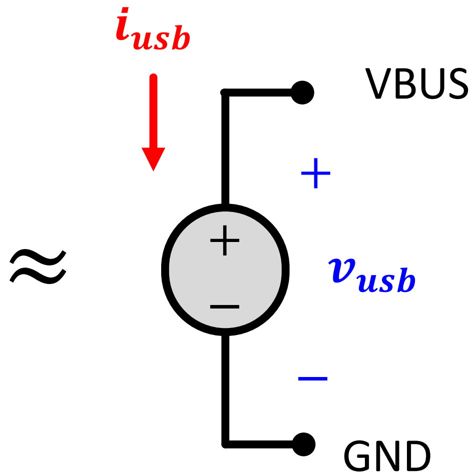
$$p = v \cdot i$$



- If **p>0**, it **consumes** power
- If **p<0**, it **supplies** power

Example: MicroUSB Socket





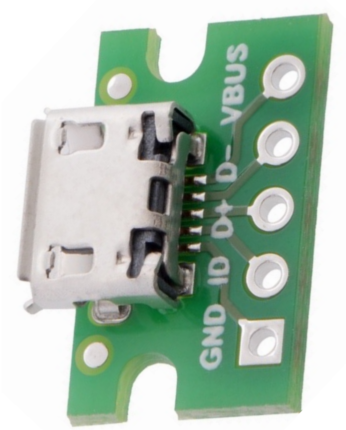
In Normal Operation:

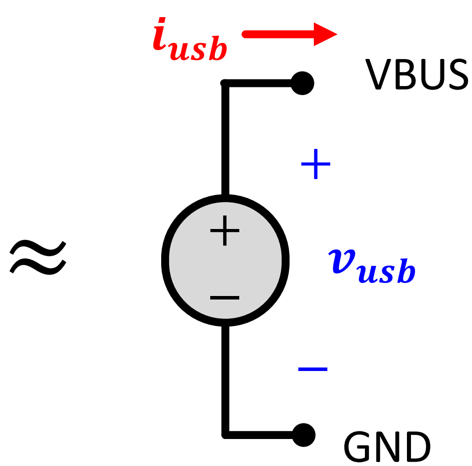
$$v_{usb} \approx 5\text{V}$$

$$i_{usb} < 0\text{A}$$

For example: $i_{usb} = -100\text{mA}$

$$p_{usb} < 0$$





In Normal Operation:

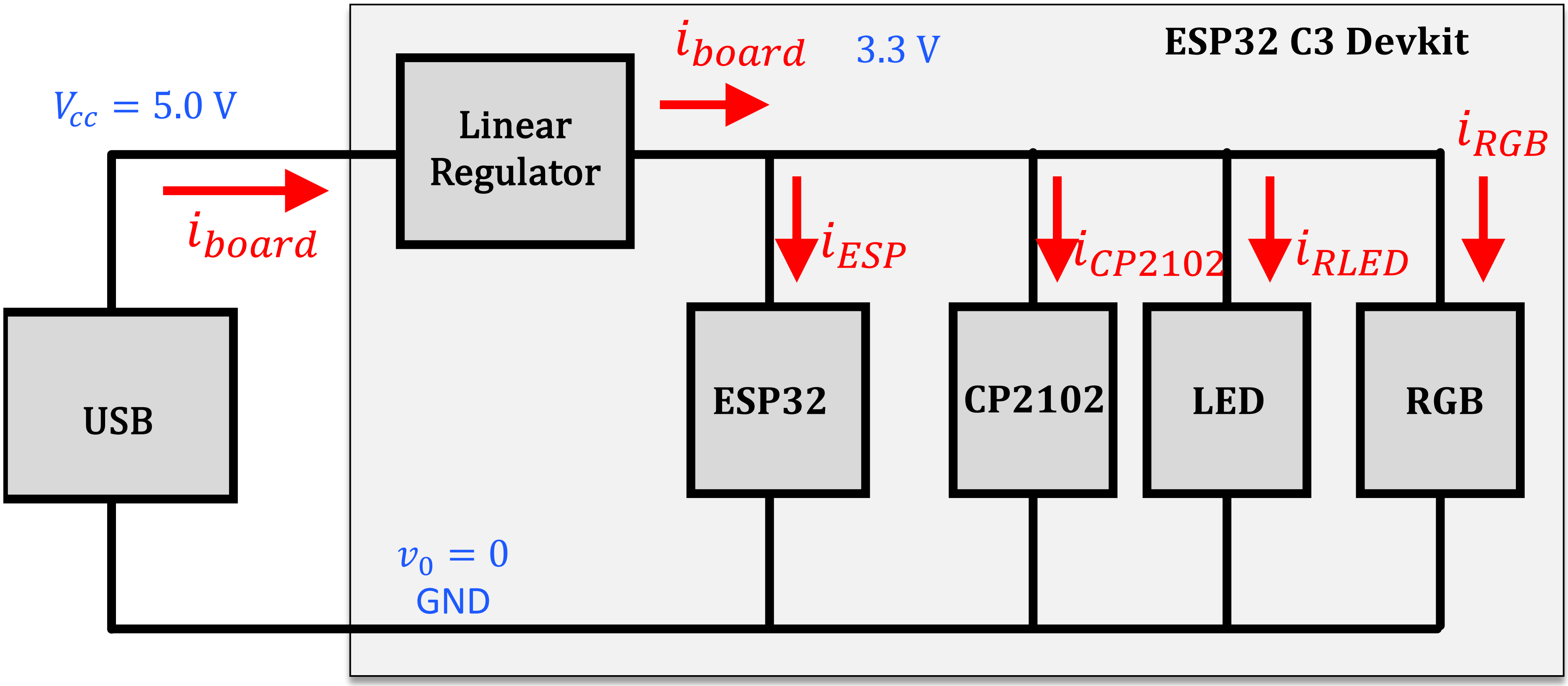
$$v_{usb} \approx 5\text{V}$$

$$i_{usb} > 0\text{A}$$

For example: $i_{usb} = 100\text{mA}$

$$\text{“}p_{usb}\text{”} > 0$$

Example: ESP32 C3 Board



$i_{RLED} \approx 0.5\text{mA}$ $\quad i_{CP2102} \approx 0.9\text{mA}$ $\quad i_{RGB} \approx 0^{**}$

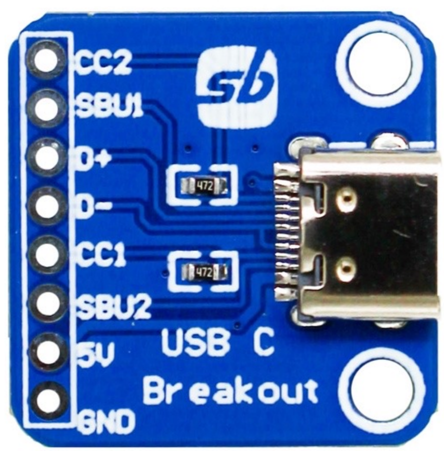
$i_{ESP} \approx 18.4\text{mA}^{*}$

*based on mode of operation

**if off

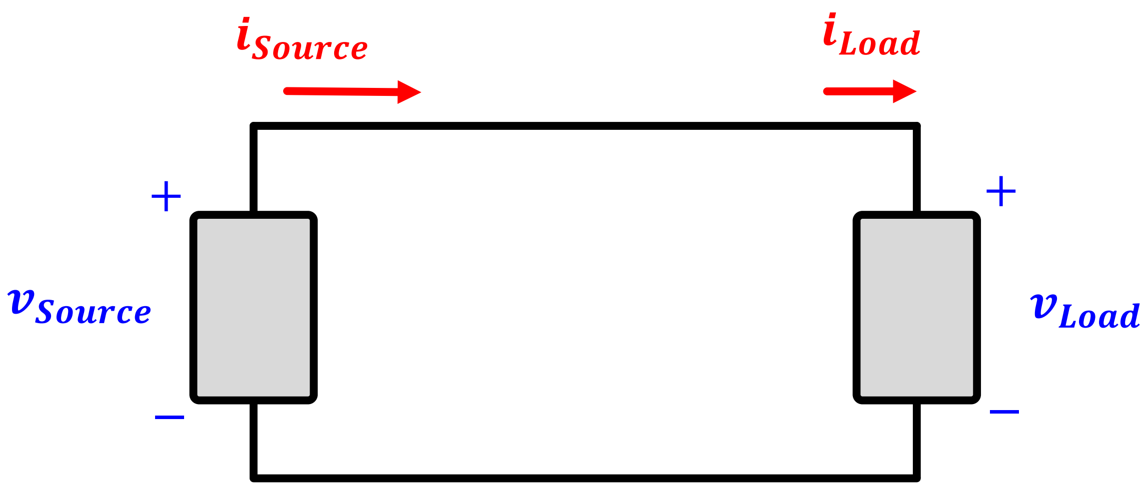
USB C Connector

- With USB C came the appearance of some addition of the Charge Control (CC) pins.
- These are means of specifying what voltage and current level you want...
- Don’t worry too much about them for now



How Do You Measure Power?

- Is a Complicated Question



DataSheets

- You should always refer to datasheets
- For example, the ESP32C3 datasheet reports the following:

4.6.2 Current Consumption in Other Modes

Table 4-8. Current Consumption in Modem-sleep Mode

Mode	CPU Frequency (MHz)	Description	Typ: All Peripherals Clocks Disabled (mA)	Typ: All Peripherals Clocks Enabled (mA)[1]
Modem-sleep[2,3]	160	CPU is running	23	28
		CPU is idle	16	21
	80	CPU is running	17	22
		CPU is idle	13	18

[1] In practice, the current consumption might be different depending on which peripherals are enabled.
[2] In Modem-sleep mode, Wi-Fi is clock gated.
[3] In Modem-sleep mode, the consumption might be higher when accessing flash. For a flash rated at 80 Mbit/s, in SPI 2-line mode the consumption is 10 mA.

Table 4-9. Current Consumption in Low-Power Modes

Mode	Description	Typ (μA)
Light-sleep	VDD_SPI and Wi-Fi are powered down, and all GPIOs are high-impedance	130
Deep-sleep	RTC timer + RTC memory	5
Power off	CHIP_EN is set to low level, the chip is powered off	1

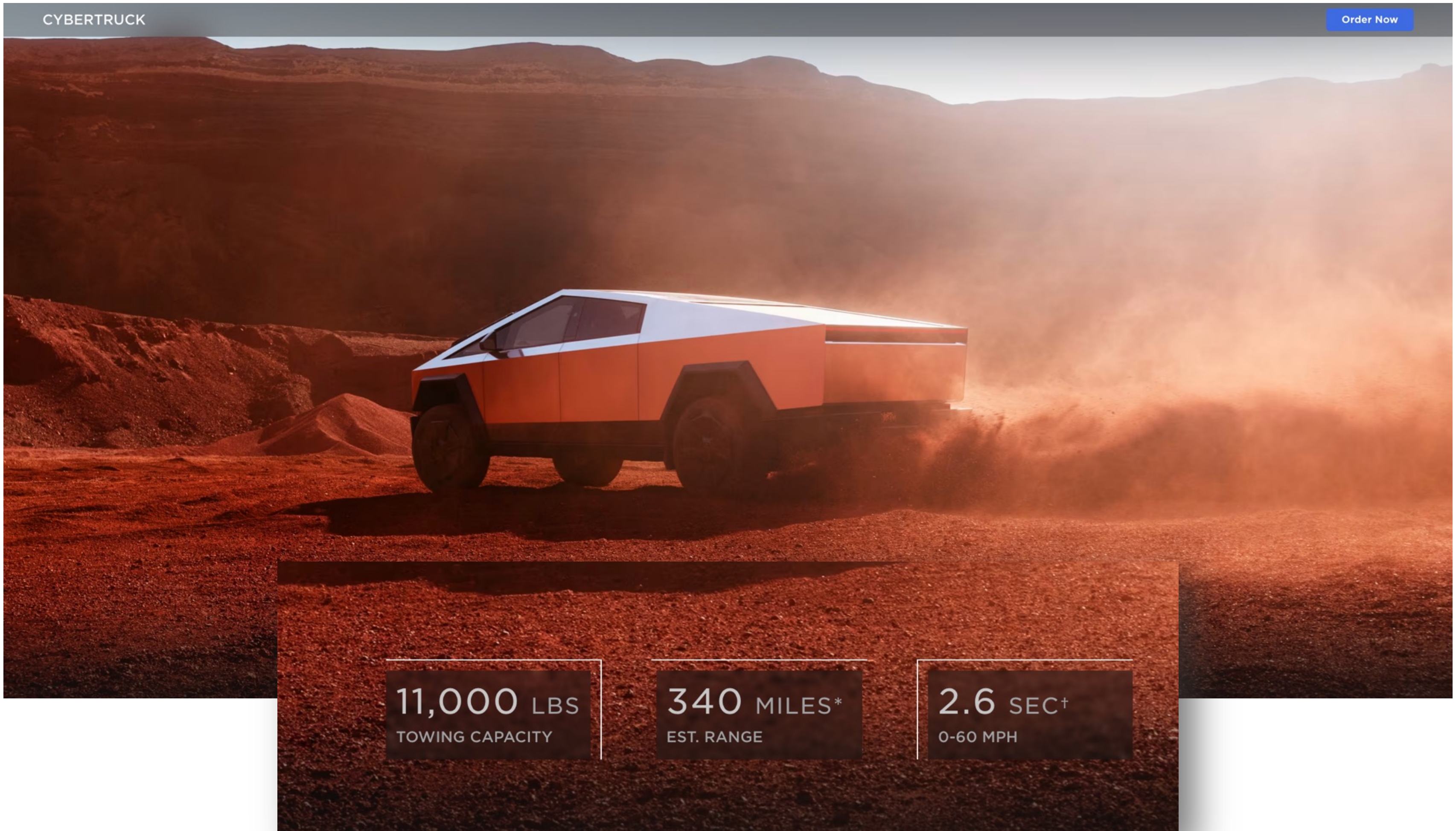
4.6 Current Consumption

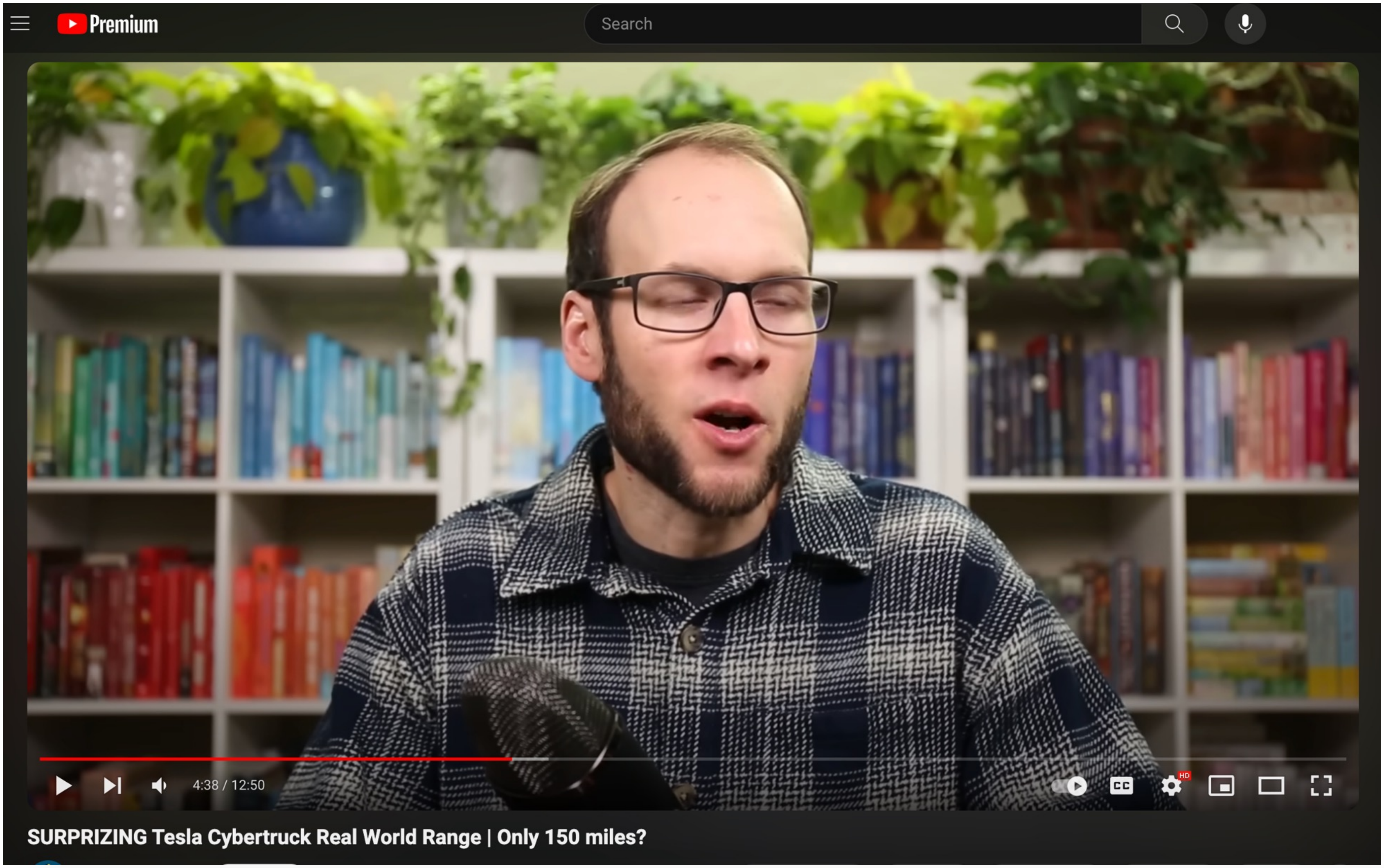
4.6.1 RF Current Consumption in Active Mode

The current consumption measurements are taken with a 3.3 V supply at 25 °C of ambient temperature at the RF port. All transmitters' measurements are based on a 100% duty cycle.

Table 4-7. Wi-Fi Current Consumption Depending on RF Modes

Work Mode[1]		Description	Peak (mA)
Active (RF working)	TX	802.11b, 1 Mbps, @21 dBm	335
		802.11g, 54 Mbps, @19 dBm	285
		802.11n, HT20, MCS7, @18.5 dBm	276
		802.11n, HT40, MCS7, @18.5 dBm	278
	RX	802.11b/g/n, HT20	84
		802.11n, HT40	87


CYBERTRUCK
Order Now
11,000 LBS
TOWING CAPACITY
340 MILES*
EST. RANGE
2.6 SEC†
0-60 MPH


Premium
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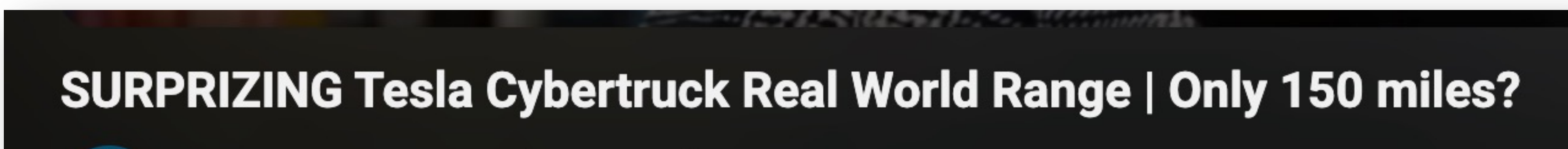
SURPRIZING Tesla Cybertruck Real World Range | Only 150 miles?


SURPRIZING Tesla Cybertruck Real World Range | Only 150 miles?

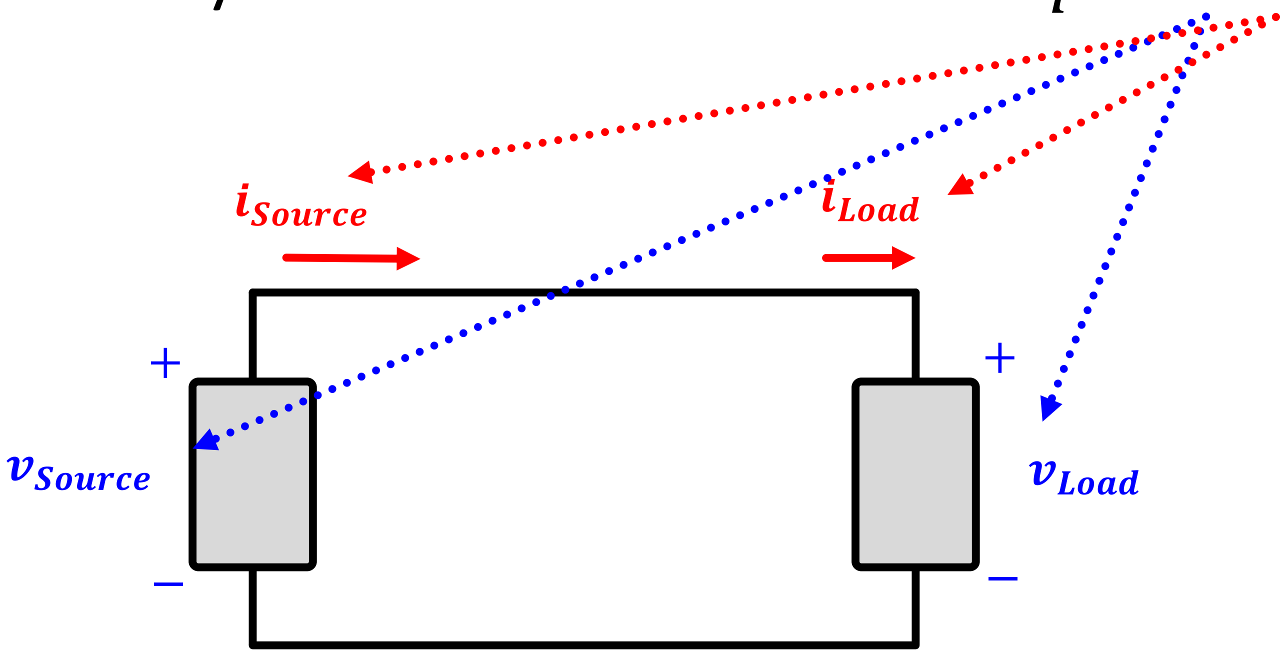
DataSheets

- Datasheets are somewhat based in fact, but they should always be viewed cautiously.
- They are to a certain extent propaganda.
- Also many devices are so so so so complicated, it can often be difficult to suss out exactly what they mean when a number is reported
- Power is also an extremely complicated field. You can have models for every part but they can all impact one another in real life so any extrapolation needs to be used cautiously.

- No alternative for *in vivo* measurements!

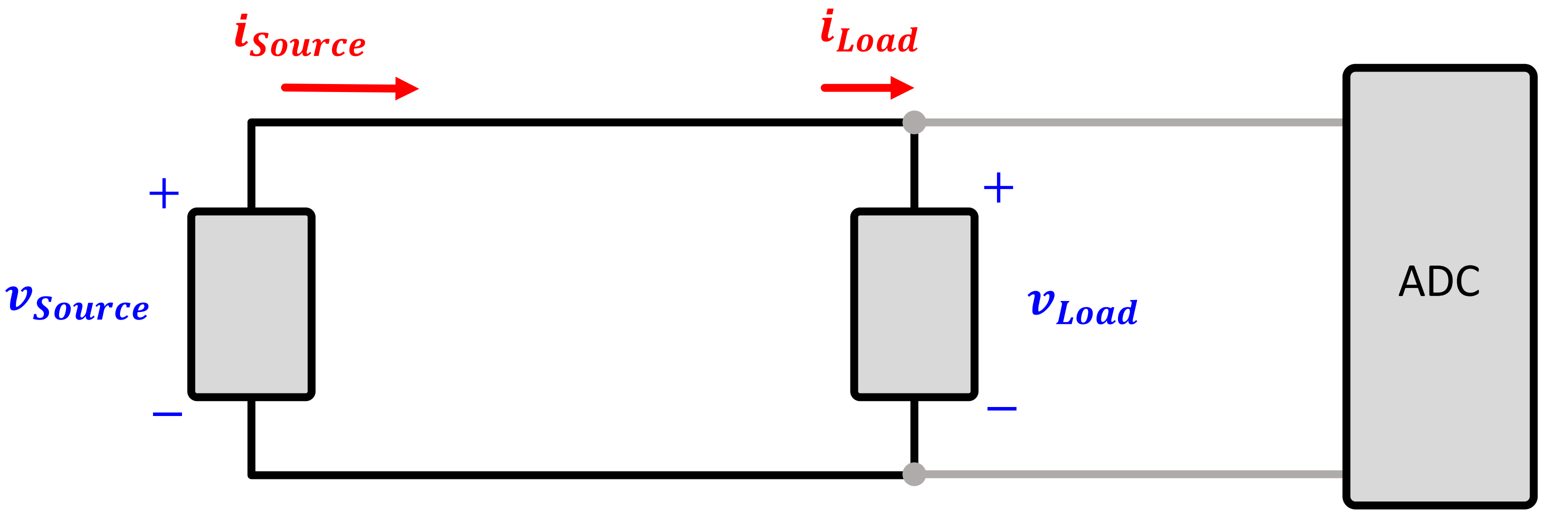
How Do You Measure Power?

- Is a Complicated Question
- Electrically we need to do determine: $p = v \cdot i$



How Do You Measure Voltage?

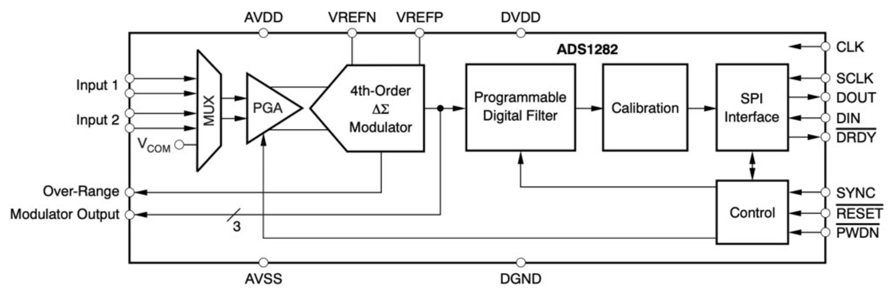
- This one is easy-ish. You can use a voltmeter or an Analog-to-digital converter and measure in parallel



Tons of great ADCs out there

- Tons of fantastic, robust technologies exist at various price points

Texas Instruments' ADS1282 31 bit ADC, capable of 4ksamp/sec ($20):



Analog Devices' AD9215 10 bit ADC, capable of 105MSamp/sec ($20):

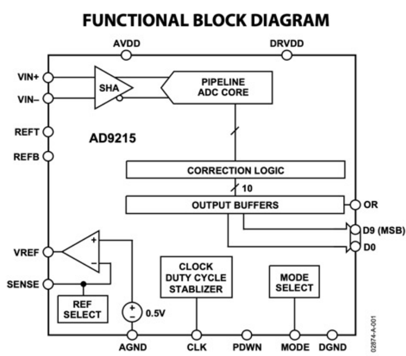
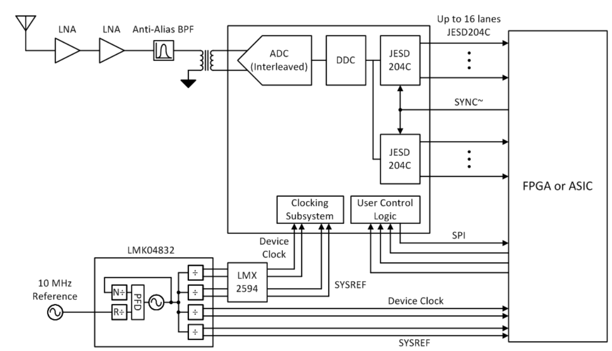


Figure 1.

Texas Instruments' radiation-hardened ADC12DJ5200 12 bit ADC, capable of 10.5Gsamp/sec ($30,000):



How Do You Measure Current?

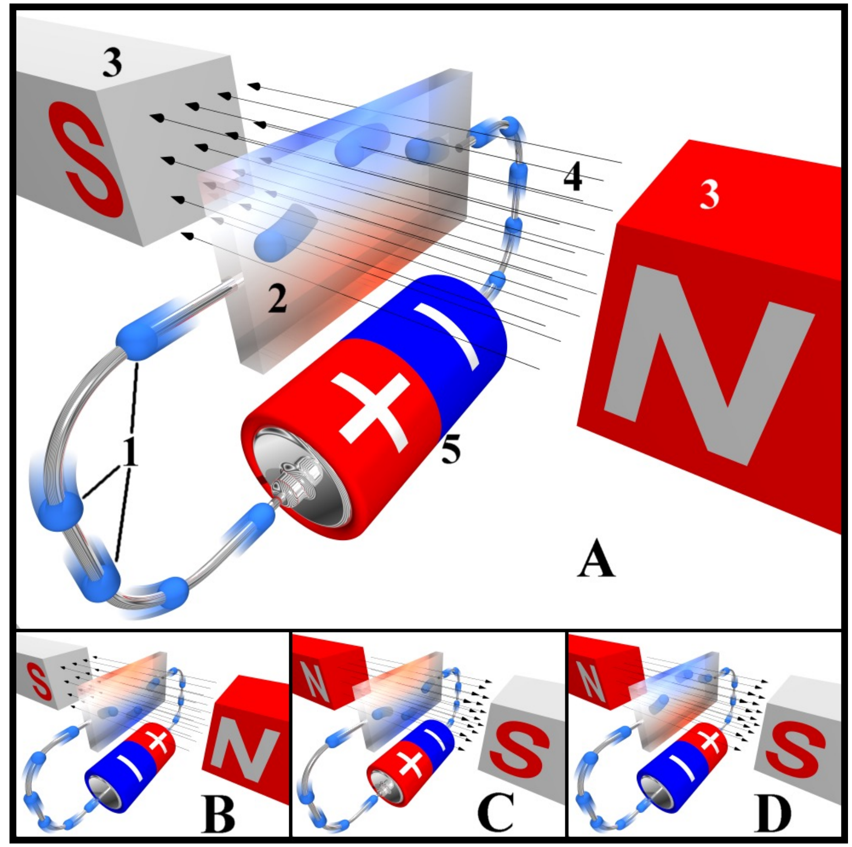
- Voltage is quite easy to measure. We have extremely sensitive voltage measurement devices out there.
- Current is actually a lot harder
- How to measure?

Coils

- Historical way to measure current is with a coil of some form
- Current induces magnetic field, this would make some sort of change
- Hard to interface to other systems

Hall Effect Sensors

- Similar idea to coils
- Expose a flow of current to a magnetic field
- The charge carriers will drift in the magnetic field due to the Hall Effect
- This drift will result in a measurable voltage…from that back out the current



https://en.wikipedia.org/wiki/Hall_effect

Both Coils and Hall Effect Sensors

- Neither Ideal for embedded systems.

- Coils and Hall Effect sensors really need current up into the mA or 10's of mA to get decent numbers/resolution. So in a lot of higher-power situations, these can help with power measurement.

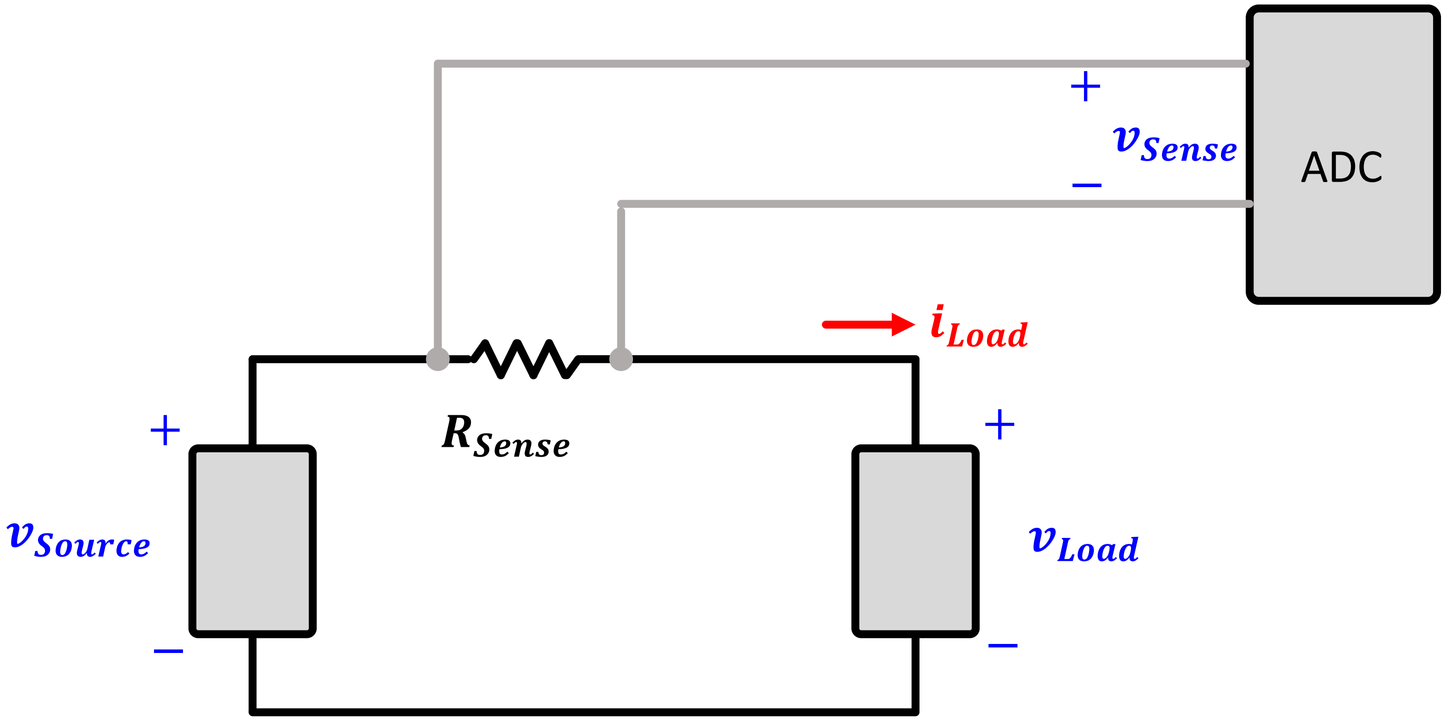
- In embedded systems, we need lower range and improved resolution!

Use a Current-to-Voltage Converter

- We have good ADC's!
- What if we could have a device convert the current into a voltage! Then we could measure it!
- What type of magical device could do this sort of behavior?
  - Take a current…
  - Reliably convert that current into a voltage…
  - Perhaps in a linear fashion???
  - ???

How Do You Measure Voltage?

- Solution:



Characteristics of this Resistor?

- Value is known to a high precision

- Small? Pros/Cons? What is Small?

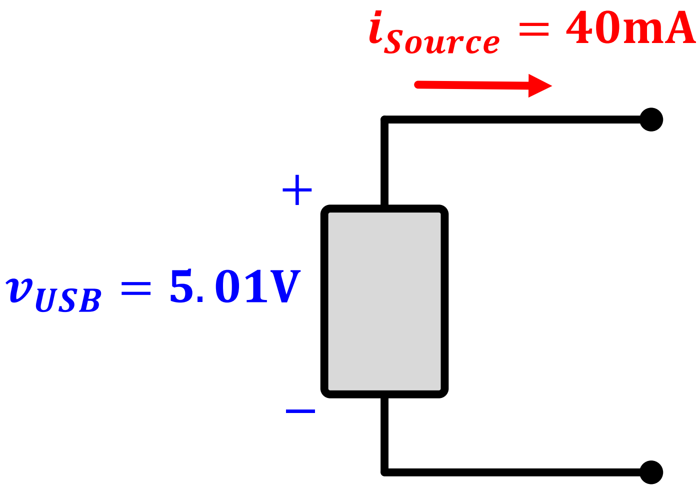
- Large? Pros/Cons? What is Large?

How Could You Do This IRL?

- You could build a circuit to do this! However for it to work with very low powers you'd really want:
  - Very high precision op amps
  - ADCs
  - Resistors!

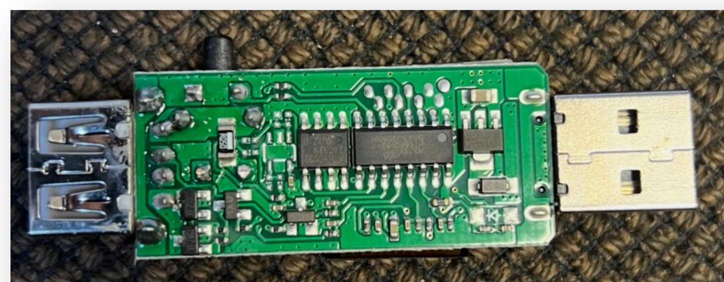
USB “Safety” Tester

- They make these power meters you can get for USB ports



USB “Safety” Tester

- Crack it open...

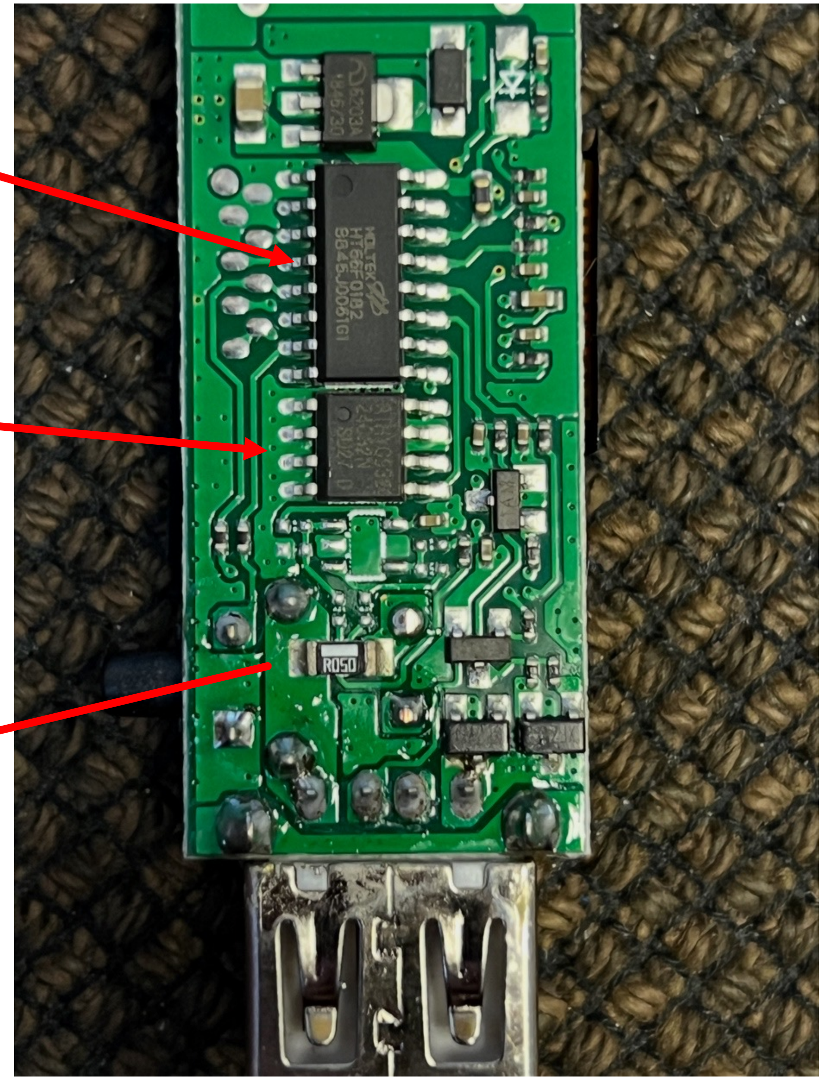


Operation

Simple 8 bit Holtek microcontroller with built-in ADC...drives OLED, does math, makes measurements

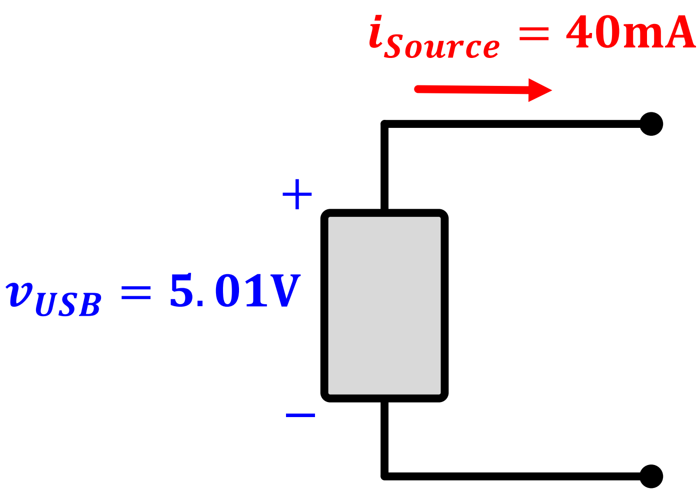
Some sort of instrumentation amplifier I think...part number intentionally or unintentionally hard to read

50 mOhm sense resistor



Limited Resolution

- Resolution on this is only in 10's of mA



Resistor Choice....

- The Bigger the resistor, the better your current resolution, but the more you disturb your system...so you want better amplifiers/ADCs, less noise
- You could build a circuit to do this! However for it to work with very low powers you'd really want:
  - Very high precision op amps
  - ADCs
  - Resistors!
- You could also buy some chips that do this all in one!

Texas Instruments' INA260

- Chip (costs few buckos)
- Monitor down to 1.5 mA Current

1 Features

- Precision Integrated Shunt Resistor:
  - Current Sense Resistance: 2 mΩ
  - Tolerance Equivalent to 0.1%
  - 15-A Continuous From –40°C to +85°C
  - 10 ppm/°C Temperature Coefficient (0°C to +125°C)

TEXAS INSTRUMENTS

INA260

SBOS656C – JULY 2016 – REVISED DECEMBER 2016

INA260

Precision Digital Current and Power Monitor With Low-Drift, Precision Integrated Shunt

PRECISION INTEGRATED SHUNT

Texas Instruments' INA260 et al

- Chip (costs few buckos)
- Monitor down to 1.5 mA Current

1 Features

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9.2 Typical Application

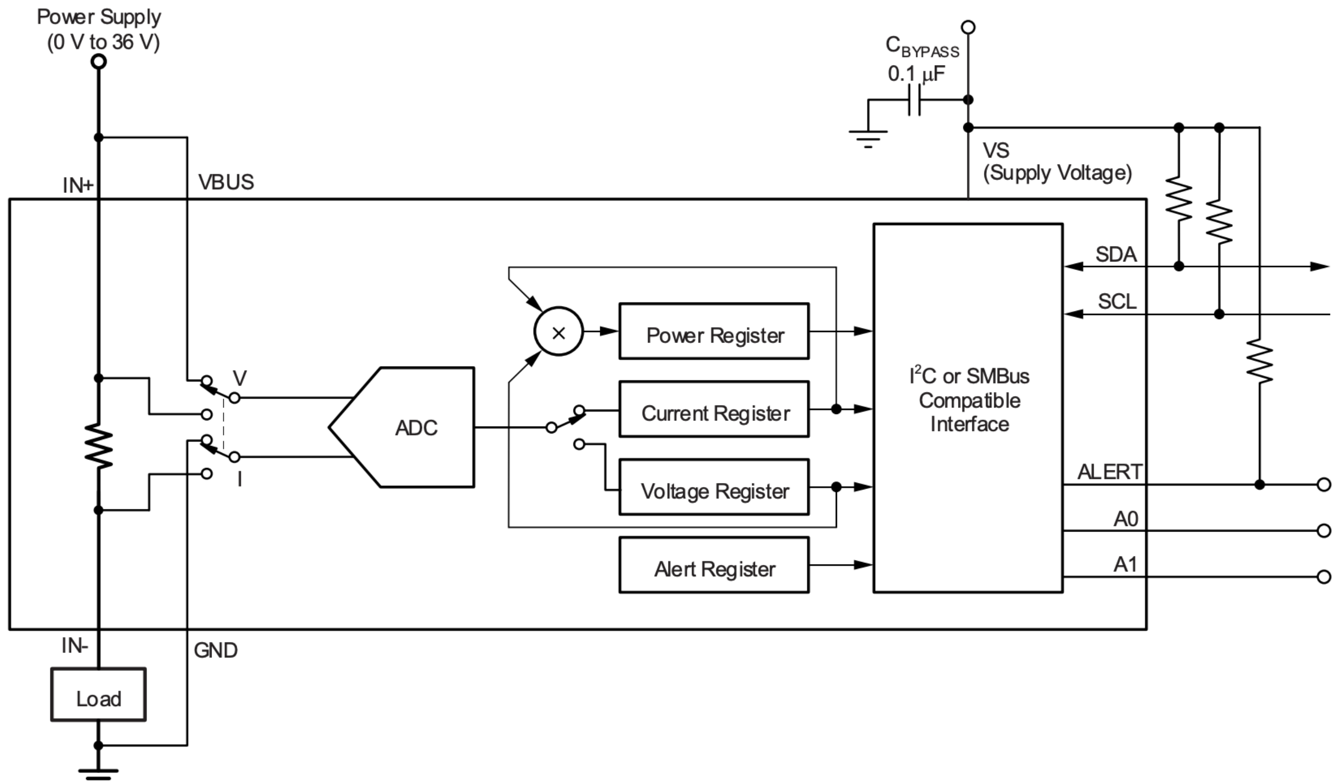


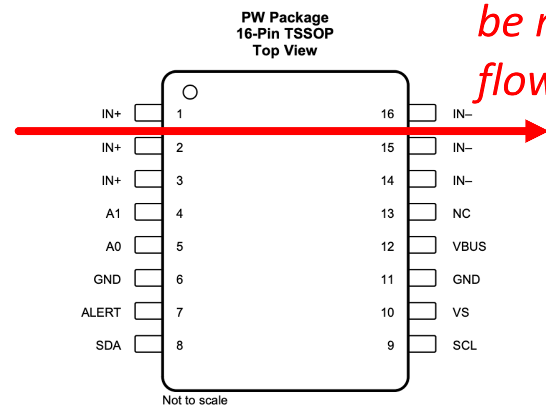
Figure 38. Typical Circuit Configuration, INA260

Pinout

- Prioritize low-resistance electrical path for signal we're measuring!
    - Minimizes parasitic resistance
    - Minimizes heating (which can result in thermal noise)!

Path through which current to be measured flows

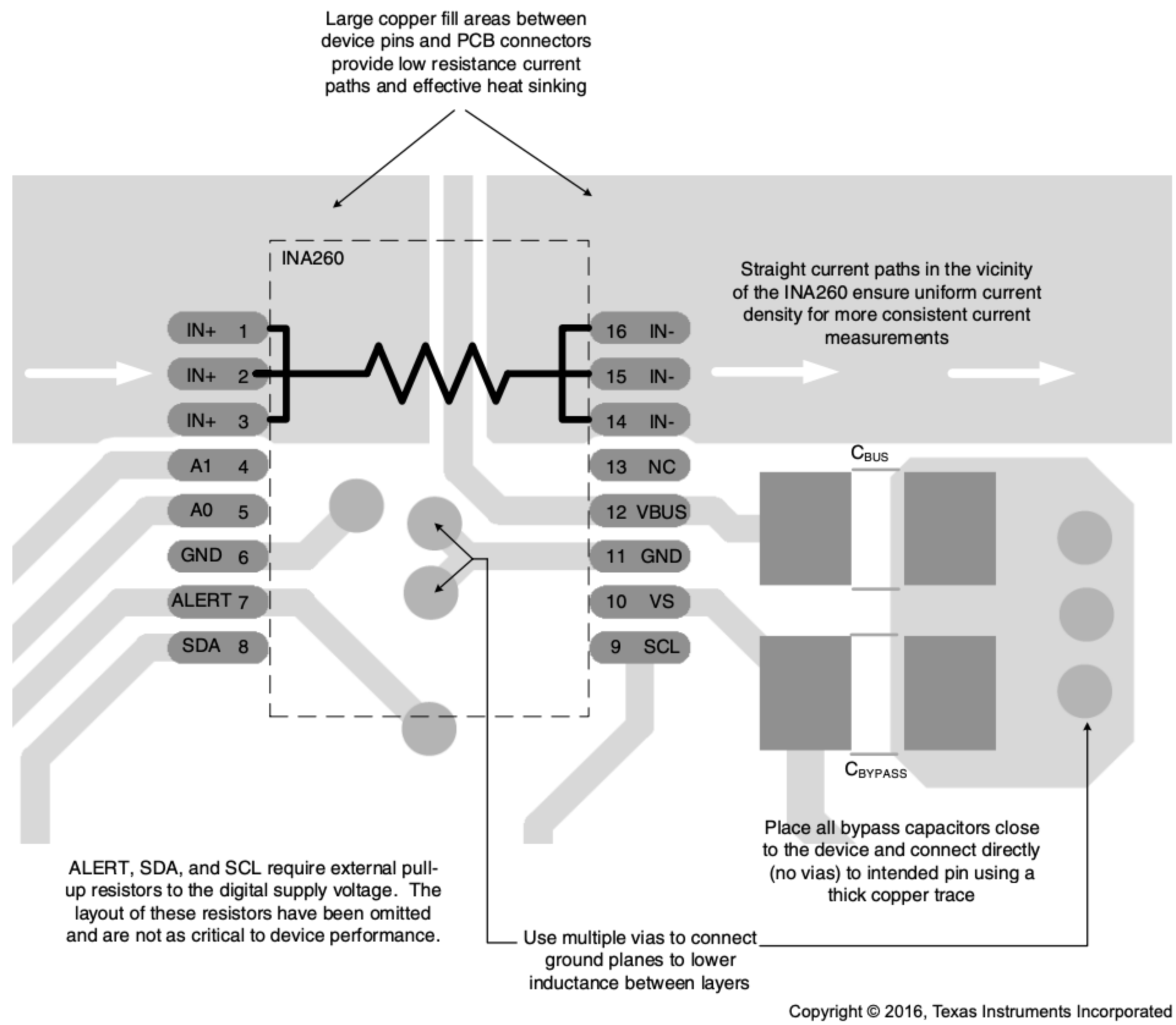
6 Pin Configuration and Functions



Pin Functions

PIN		I/O	DESCRIPTION
NAME	NO.		
A0	5	Digital input	Address pin. Connect to GND, SCL, SDA, or VS. Table 2 shows pin settings and corresponding addresses.
A1	4	Digital input	Address pin. Connect to GND, SCL, SDA, or VS. Table 2 shows pin settings and corresponding addresses.
ALERT	7	Digital output	Multi-functional alert, open-drain output.
GND	6, 11	Analog	Ground pin for both analog and digital circuits.
IN+	1, 2, 3	Analog input	Connect to supply for high side current sensing or to load ground for low side sensing.
IN–	14, 15, 16	Analog input	Connect to load for high side current sensing or to board ground for low side sensing.
NC	13	—	No internal connection. Can be grounded or left floating.
SCL	9	Digital input	Serial bus clock line input.
SDA	8	Digital I/O	Serial bus data line, open-drain input/output.
VBUS	12	Analog input	Bus voltage monitor input.
VS	10	Analog	Power supply input, connect a 2.7 V to 5.5 V supply to this pin.

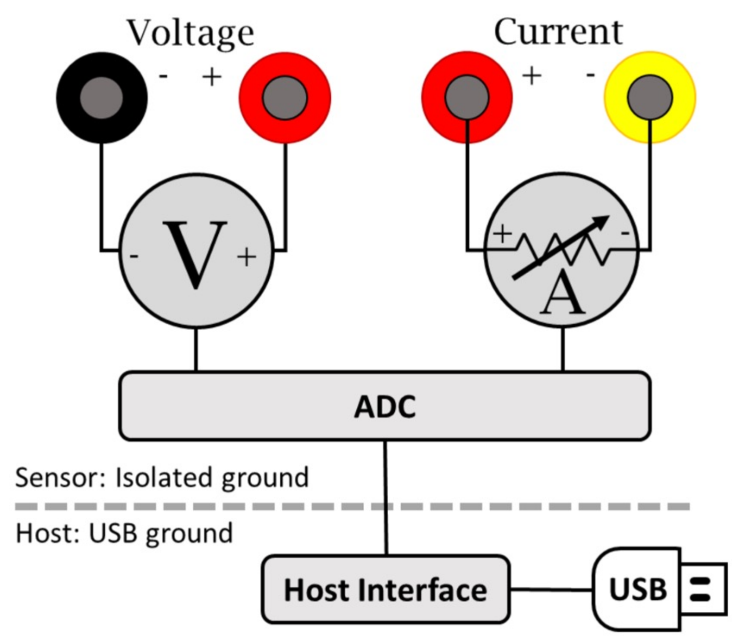
11.2 Layout Example



NOTE: Connect the VBUS pin to the power supply rail

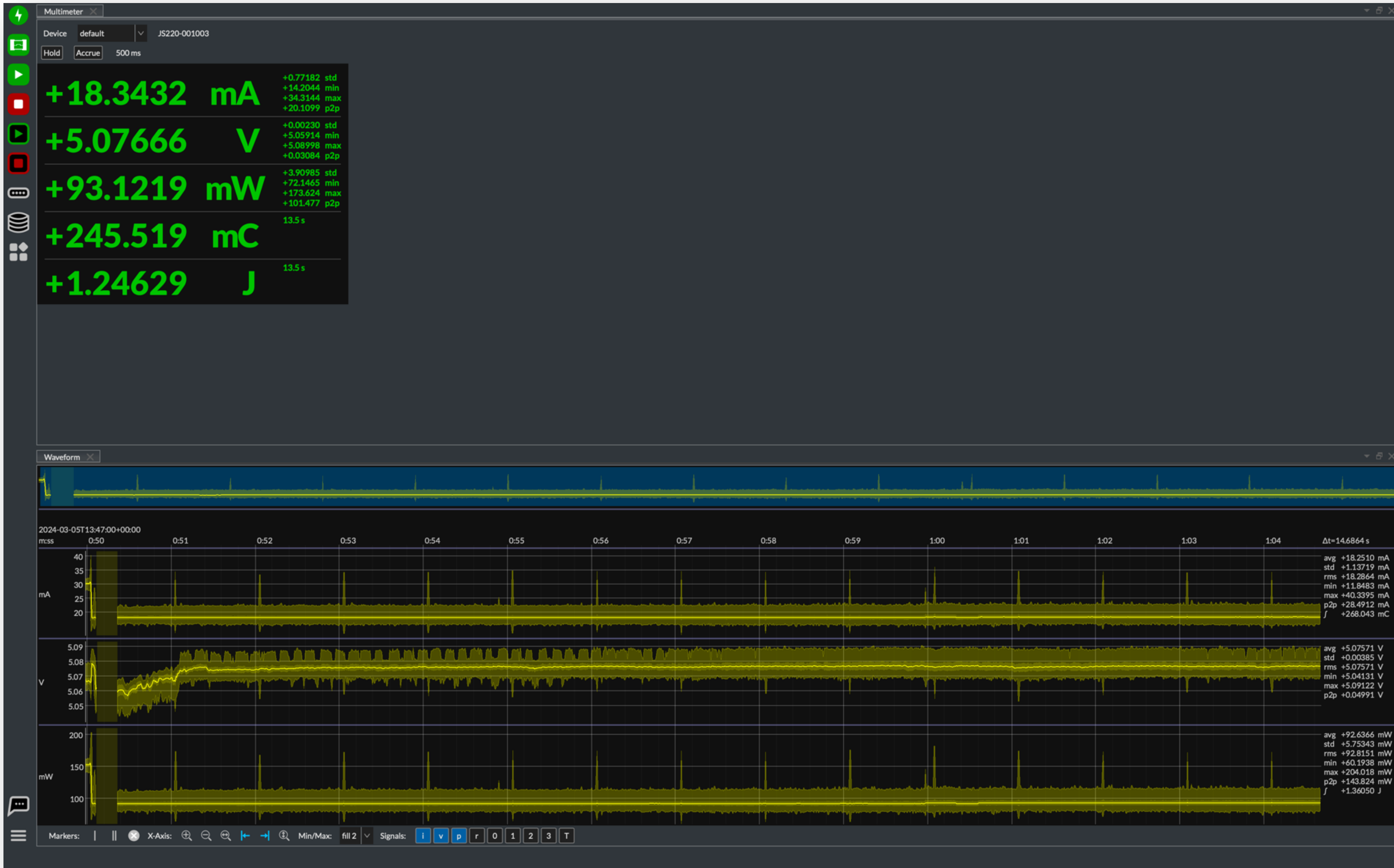
JouleScope

- Device we'll use in Lab 05 (I think?) soon to measure our devices and which you'll need to use heavily to characterize your system



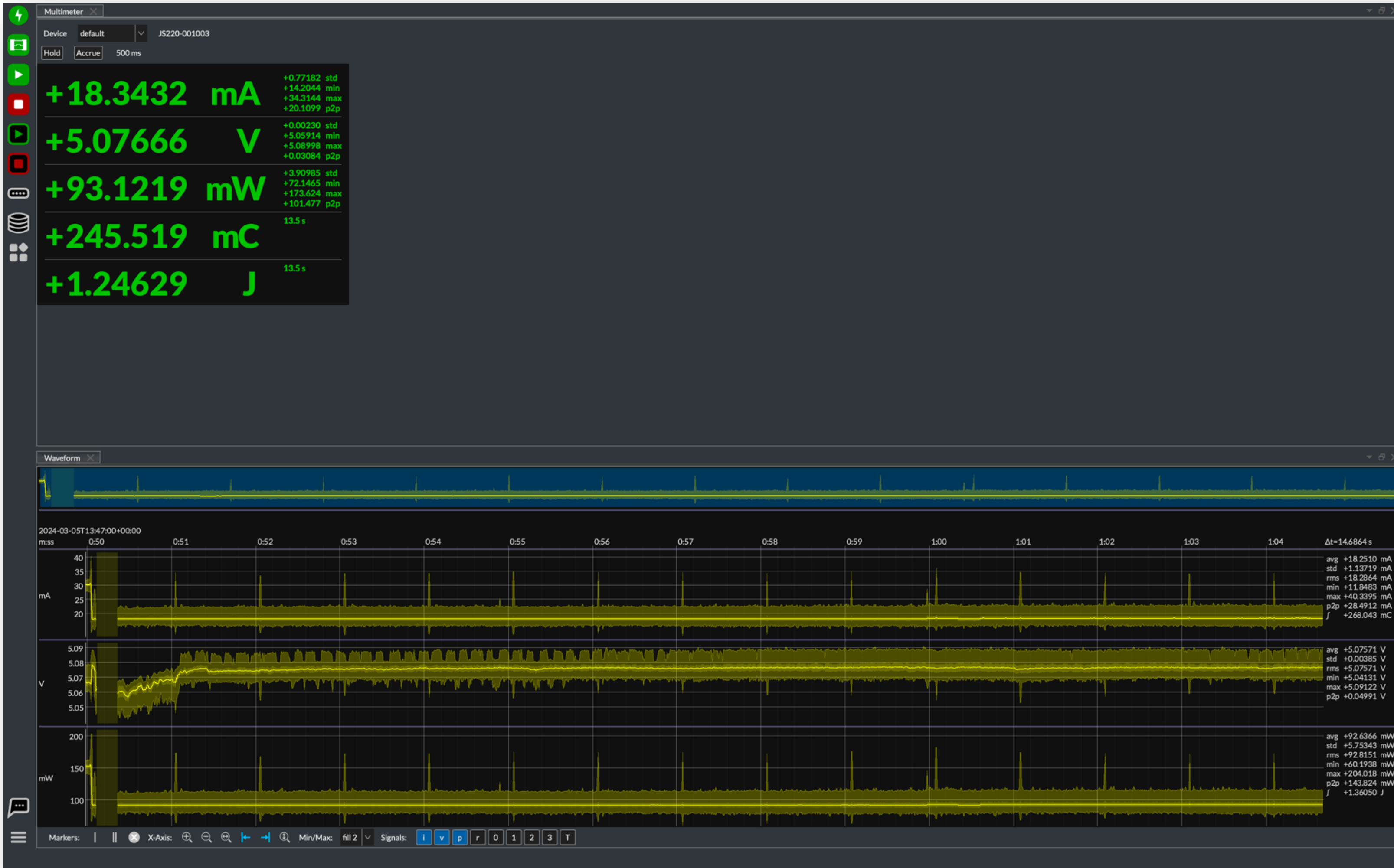
https://www.joulescope.com/

Very Nice Readout



Application GUI…can readout and do all the stuff.

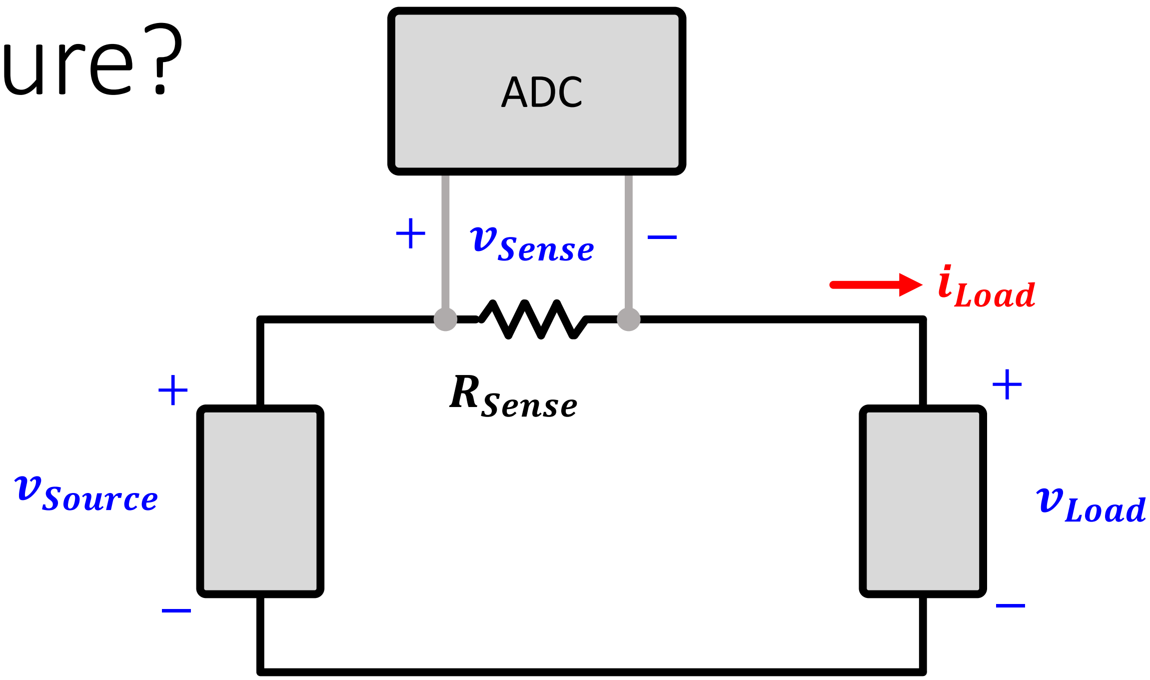
High Resolution in V, I , and P and in time!



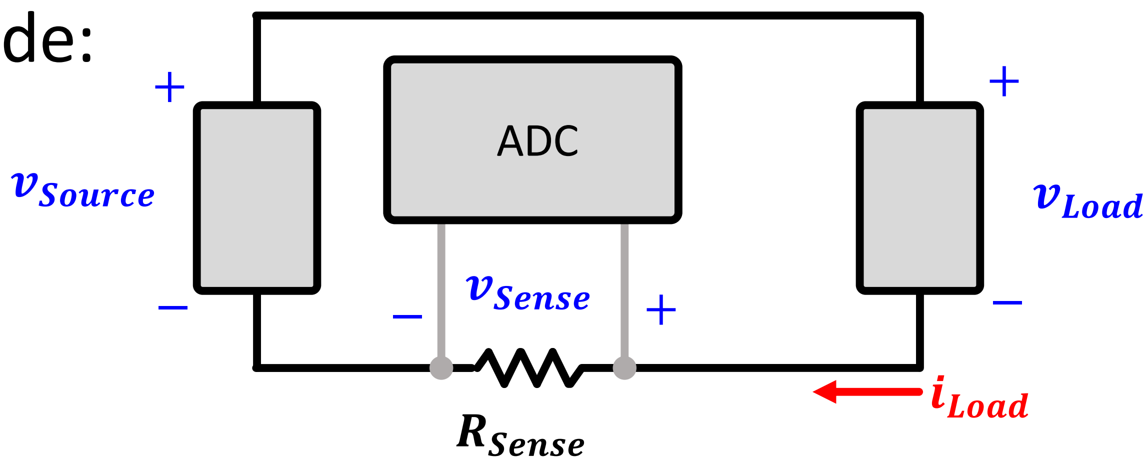
Application GUI…can readout and do all the stuff.

Where to Measure?

- High-Side:

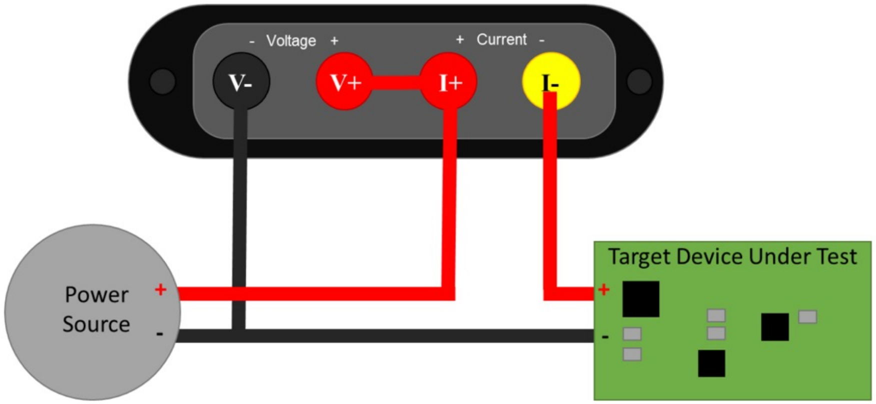


- Low-Side:

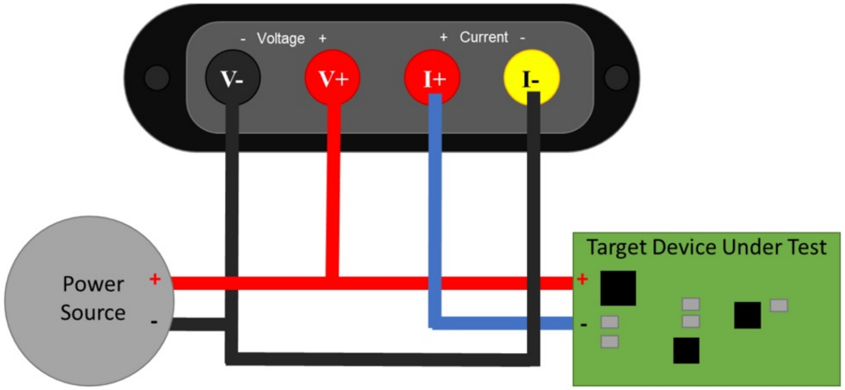


Joule Scope OK with That

- High-Side



- Low-Side



So in Upcoming Lab you'll use the Joulescope to measure…

- Regular LED resistor
- ESP32 Flashing LED
- ESP32 in different modes of operation
- Behavior/Output of Photovoltaic Cell…

- And then for the project you will need to use this for characterizing your system in whole and in parts!

On Project...What Will Be Using Power?

- Technically everything...but there will be some particularly problematic devices...

- Sensors?

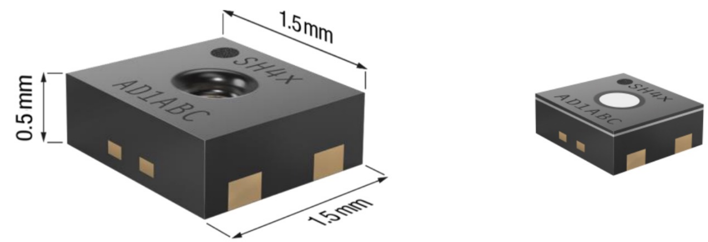
Temperature and Humidity Sensors

- Depending on what you pick... These can be pretty tame.

SENSIRION

Datasheet – SHT4x

4th Gen. Relative Humidity and Temperature Sensor



Highlights

- Accuracies ΔRH = ±1.0 %RH, ΔT = ±0.1 °C
- VDD = 1.08 V ... 3.6 V
- Avg. current: 0.4 µA, Idle current: 80 nA
- I2C FM+, CRC checksum, multip. I2C addr.
- Patented protection options [1], PTFE membrane and removable protective cover
- Operating range: 0 ... 100 %RH, −40...125 °C
- Fully functional in a condensing environment
- Power heater, true NIST-traceability
- JEDEC JESD47 qualification
- Sensor-specific calibration certificate acc. to ISO 17025: 2017, 3-point temp. calibration

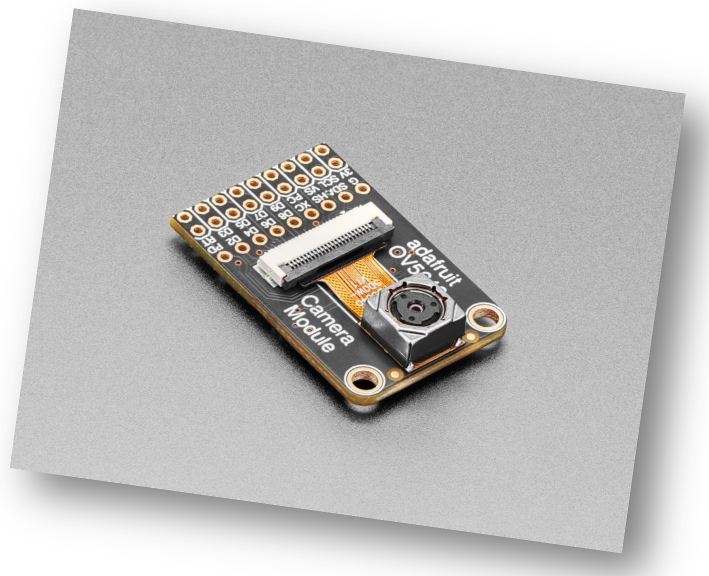
this is so small it is wild

Camera

CV AI Train AI Model 95% Accuracy AI

- These can use a lot of power

ML Train



Model CV ML AI

Camera

CV

AI

Train

AI

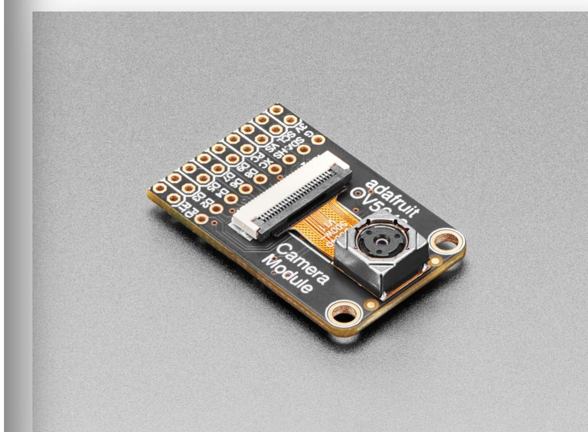
Model

95% Accuracy

8.3 DC characteristics

table 8-3 DC characteristics (-30°C < T_J < 70°C) (sheet 1 of 2)

symbol	parameter	min	typ	max	unit
power supply					
V_{DD-A}	supply voltage (analog)	2.6	2.8	3.0	V
V_{DD-D}[a]	supply voltage (digital core)	1.425	1.5	1.575	V
V_{DD-IO}	supply voltage (digital I/O)	1.71	1.8	3.0	V
internal DVDD short to DVDD, DVP output, AVDD = 2.8V, DOVDD = 2.8V					
I_{DD-A}	operating current 2592 x 1944 @ 15 fps JPG		30	40	mA
I_{DD-DO}			110	140	mA
I_{DD-A}	operating current 1080p @ 30 fps JPG		30	40	mA
I_{DD-DO}			100	130	mA
I_{DD-A}	operating current 720p @ 60 fps		32	42	mA
I_{DD-DO}			100	42	mA
I_{DD-A}	operating current 720 @ 30 fps YUV		32	40	mA
I_{DD-DO}			58	72	mA
I_{DD-A}	operating current VGA @ 30 fps		30	40	mA
I_{DD-DO}			58	72	mA

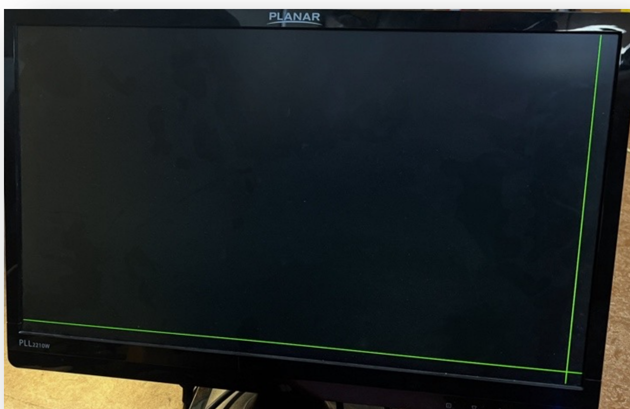


AI

Exact Same Device, just change data

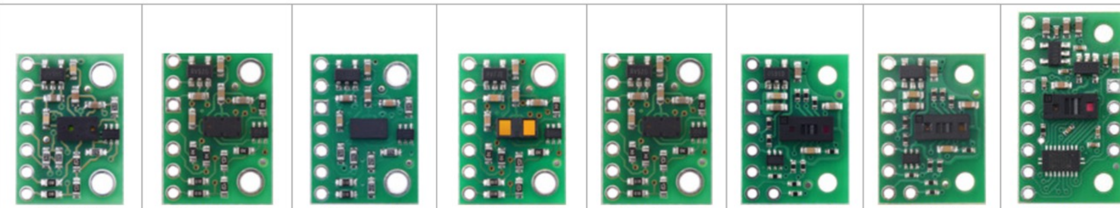
<u>OV5640 Camera Running and Exposed:</u>

<u>OV5640 Camera Running and Covered:</u>



*Achieve a ~30% drop in power consumed by camera and FPGA based off of the *type* of data transferred through the system*

Time-of-Flight Sensors

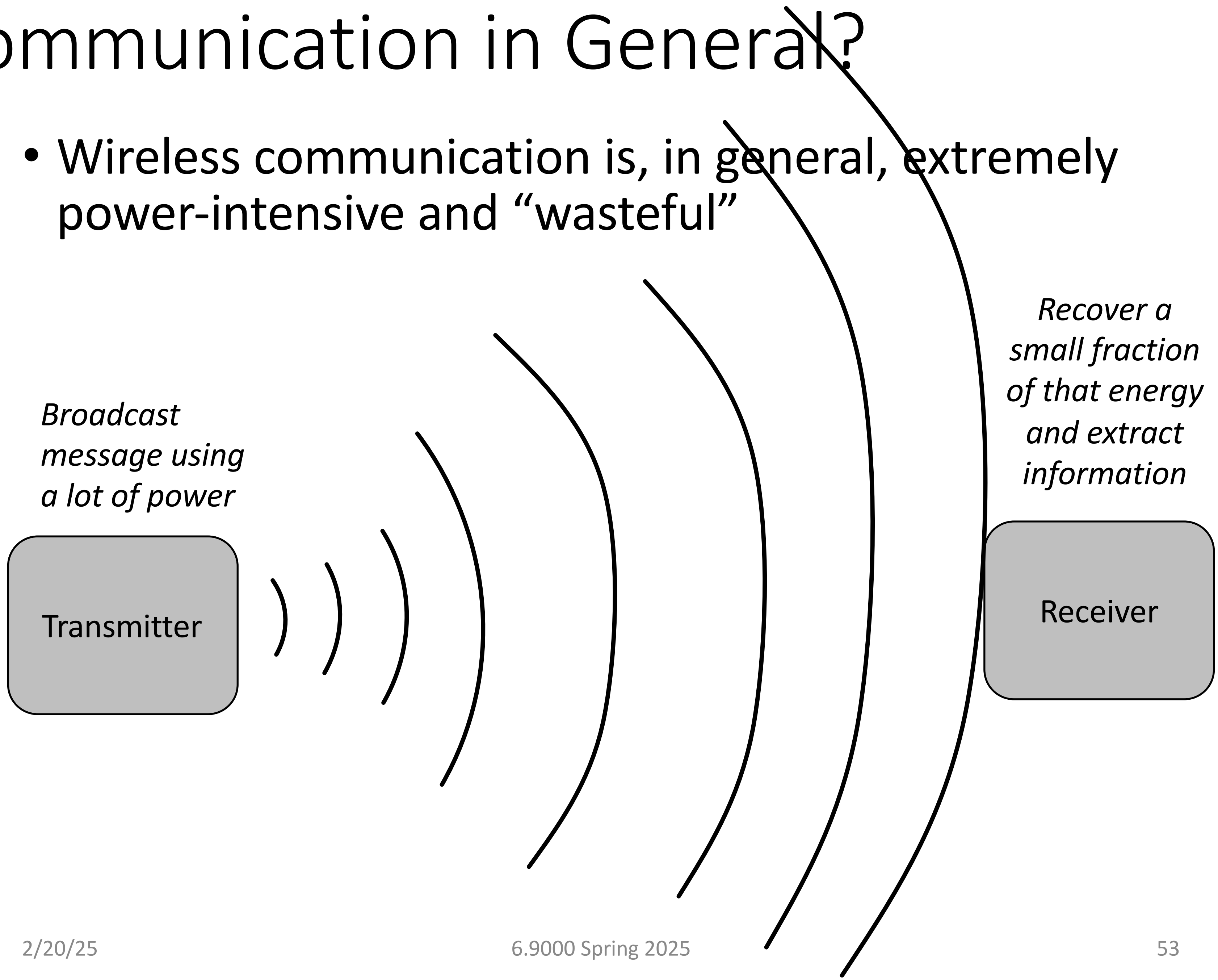


	VL6180X carrier	VL53L4CD carrier	VL53L0X carrier	VL53L1X carrier	VL53L3CX carrier	VL53L5CX carrier	VL53L7CX carrier	VL53L8CX carrier
Maximum range: (1)	60 cm	120 cm	200 cm	400 cm	500 cm	400 cm	350 cm	400 cm
Minimum range:	~10 mm	1 mm	~30 mm	40 mm	10 mm	20 mm		
Field of view:	25°	18°	25°	15° to 27° diagonal, programmable	25°	65° diagonal, up to 8×8 zones	90° diagonal, up to 8×8 zones	65° diagonal, up to 8×8 zones
Other features:	ambient light sensing, low memory footprint(2)	low memory footprint(2), ultra-low power mode	low memory footprint(2)	low memory footprint(2), ultra-low power mode	multi-target detection, ultra-low power mode	multi-target detection	multi-target detection	multi-target detection, improved performance in ambient light
Maximum update rate:(1)	~150 Hz	100 Hz	50 Hz	100 Hz	125 Hz	60 Hz		
Operating voltage range:	2.6 V to 5.5 V					2.5 V to 5.5 V		3.2 V to 5.5 V
Regulator	2.8 V					3.3 V		1.8 V and 3.3 V
Typical active-ranging supply current:	25 mA	25 mA	20 mA	20 mA	20 mA	100 mA		
Peak supply current:	40 mA					150 mA		
Interface:	I²C							I²C, SPI
Dimensions:	0.5″ × 0.7″							0.5″ × 0.9″
1-piece price:	$13.49	$12.95	$14.95	$18.95	$16.95	$19.95	$19.95	$24.95

https://www.pololu.com/product/2490

Communication in General?

- Wireless communication is, in general, extremely power-intensive and "wasteful"

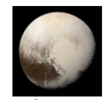


WiFi, for example…

- Energy recovered from wireless router to your computer is on the order of <1%
- The rest just gets bounced around and warms things up

Extreme Cases

- Wireless communication is, in general, extremely power-intensive and wasteful



Pluto

Earth

3.53 billion miles, 4.5 hours transit time for EM radiation

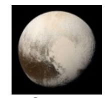
New Horizons Space Probe
Transmits 12 W signal back to Earth
On X-band (8.4 GHz)

By time/distance signal reaches earth
Strength is -220 dBm or about or about 10^{-22} mW

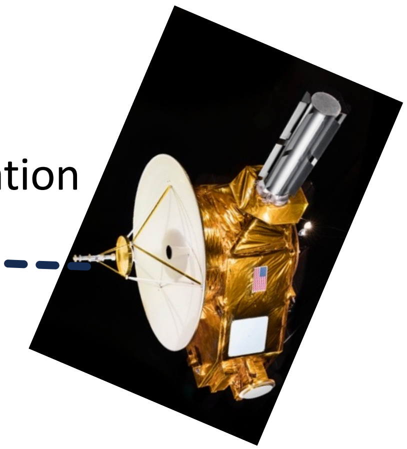
At that this distance, you’re actually below thermal noise levels

Extreme Cases

- Antennas help a lot here, but still not easy



Pluto



3.53 billion miles, 4.5 hours transit time for EM radiation

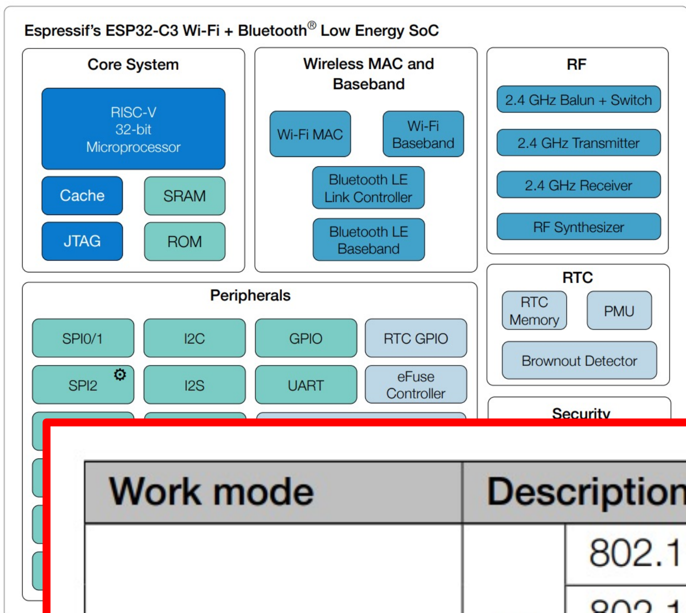
Earth

Use a 70 meter in diameter dish to harvest enough signal energy to get info out of it

Super directional antenna makes sure as much energy as possible gets focused to earth

ESP32 C3 Power Modes with Transmission

- There's about four of them power modes depending on who you talk to.



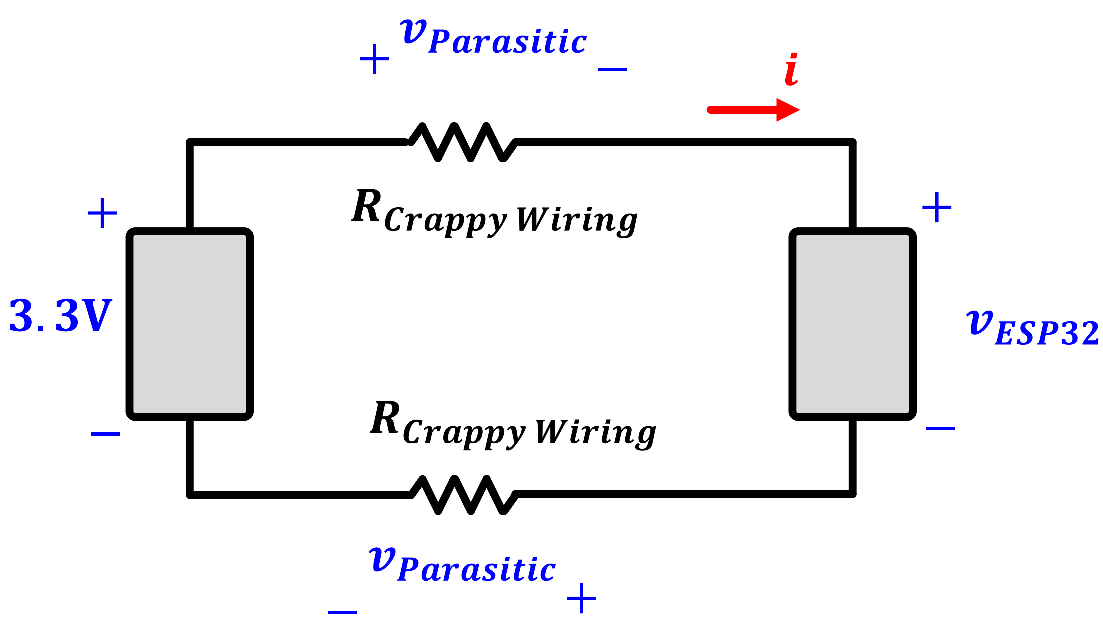
Work mode		Description	Peak (mA)
Active (RF working)	TX	802.11b, 1 Mbps, @20.5 dBm	345
		802.11g, 54 Mbps, @18 dBm	285
		802.11n, HT20, MCS7, @17.5 dBm	280
		802.11n, HT40, MCS7, @17 dBm	280
	RX	802.11b/g/n, HT20	82
		802.11n, HT40	84

Mode	CPU Frequency (MHz)	Description	Typ: All Peripherals Clocks Disabled (mA)	Typ: All Peripherals Clocks Enabled (mA)[1]
Modem-sleep[2,3]	160	CPU is idle	16	21
		CPU is running	23	28

Work mode		Description	Peak (mA)
Active (RF working)	TX	802.11b, 1 Mbps, @20.5 dBm	345
		802.11g, 54 Mbps, @18 dBm	285
		802.11n, HT20, MCS7, @17.5 dBm	280
		802.11n, HT40, MCS7, @17 dBm	280
	RX	802.11b/g/n, HT20	82
		802.11n, HT40	84

These Huge Current Spikes are also...

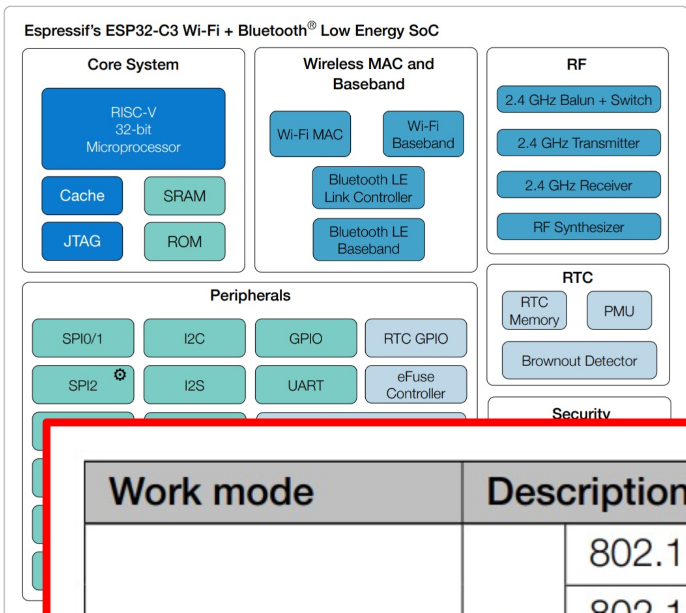
- Why a lot of you had issues with your ESP on startup or on connecting to WiFi



When i spikes on startup or WiFi negotiation parasitic drops develop and KVL tells us that v_{ESP32} *will dip...ESP32 freaks out and reboots*

Even if you have your parasitic losses under control…

- You still need to use all this power!



Work mode		Description	Peak (mA)
Active (RF working)	TX	802.11b, 1 Mbps, @20.5 dBm	345
		802.11g, 54 Mbps, @18 dBm	285
		802.11n, HT20, MCS7, @17.5 dBm	280
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	RX	802.11b/g/n, HT20	82
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Mode	CPU Frequency (MHz)	Description	Typ	
			All Peripherals Clocks Disabled (mA)	All Peripherals Clocks Enabled (mA)[1]
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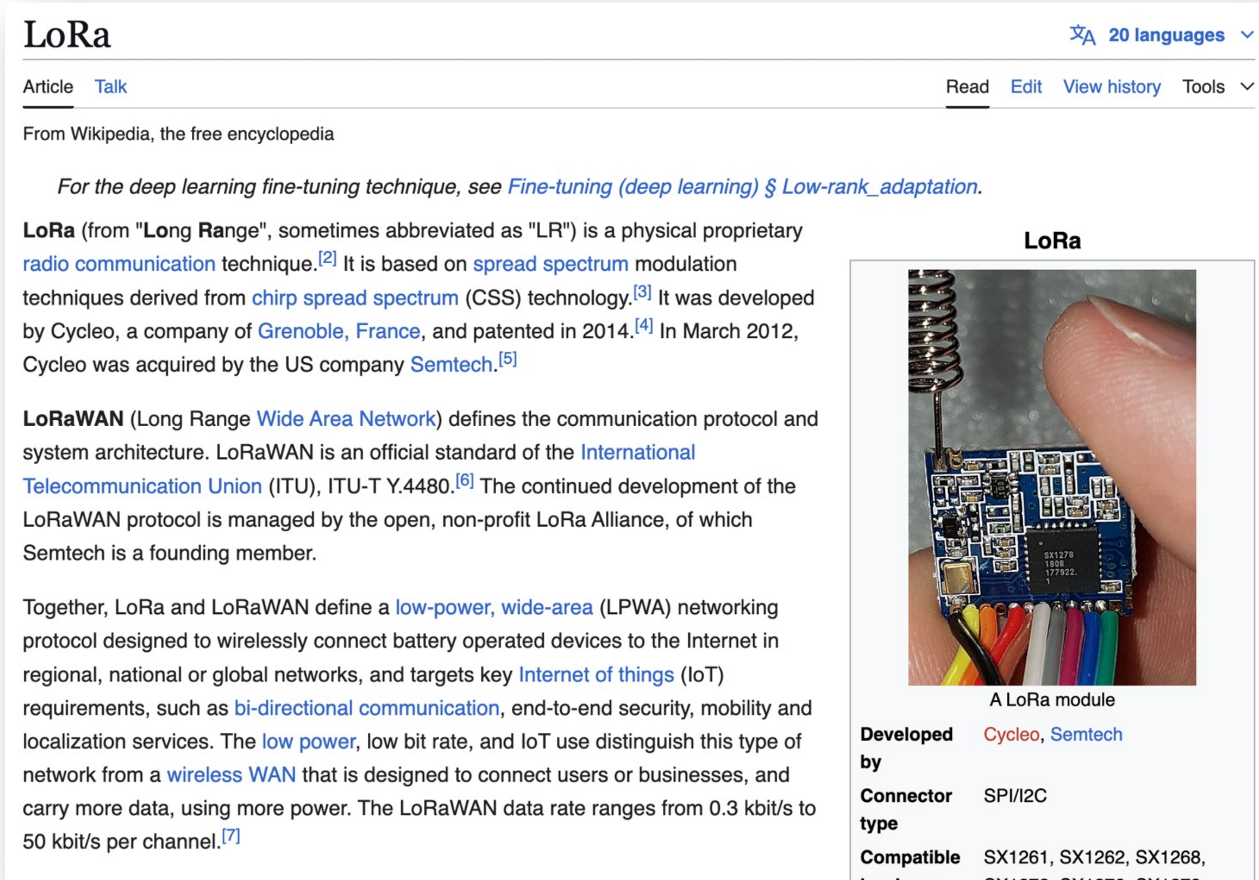
		802.11n, HT40, MCS7, @17 dBm	280
	RX	802.11b/g/n, HT20	82
		802.11n, HT40	84

LoRa?



LoRa

20 languages

Article Talk Read Edit View history Tools

From Wikipedia, the free encyclopedia

For the deep learning fine-tuning technique, see Fine-tuning (deep learning) § Low-rank_adaptation.

LoRa (from "**Lo**ng **Ra**nge", sometimes abbreviated as "LR") is a physical proprietary radio communication technique.[2] It is based on spread spectrum modulation techniques derived from chirp spread spectrum (CSS) technology.[3] It was developed by Cycleo, a company of Grenoble, France, and patented in 2014.[4] In March 2012, Cycleo was acquired by the US company Semtech.[5]

LoRaWAN (Long Range Wide Area Network) defines the communication protocol and system architecture. LoRaWAN is an official standard of the International Telecommunication Union (ITU), ITU-T Y.4480.[6] The continued development of the LoRaWAN protocol is managed by the open, non-profit LoRa Alliance, of which Semtech is a founding member.

Together, LoRa and LoRaWAN define a low-power, wide-area (LPWA) networking protocol designed to wirelessly connect battery operated devices to the Internet in regional, national or global networks, and targets key Internet of things (IoT) requirements, such as bi-directional communication, end-to-end security, mobility and localization services. The low power, low bit rate, and IoT use distinguish this type of network from a wireless WAN that is designed to connect users or businesses, and carry more data, using more power. The LoRaWAN data rate ranges from 0.3 kbit/s to 50 kbit/s per channel.[7]

LoRa

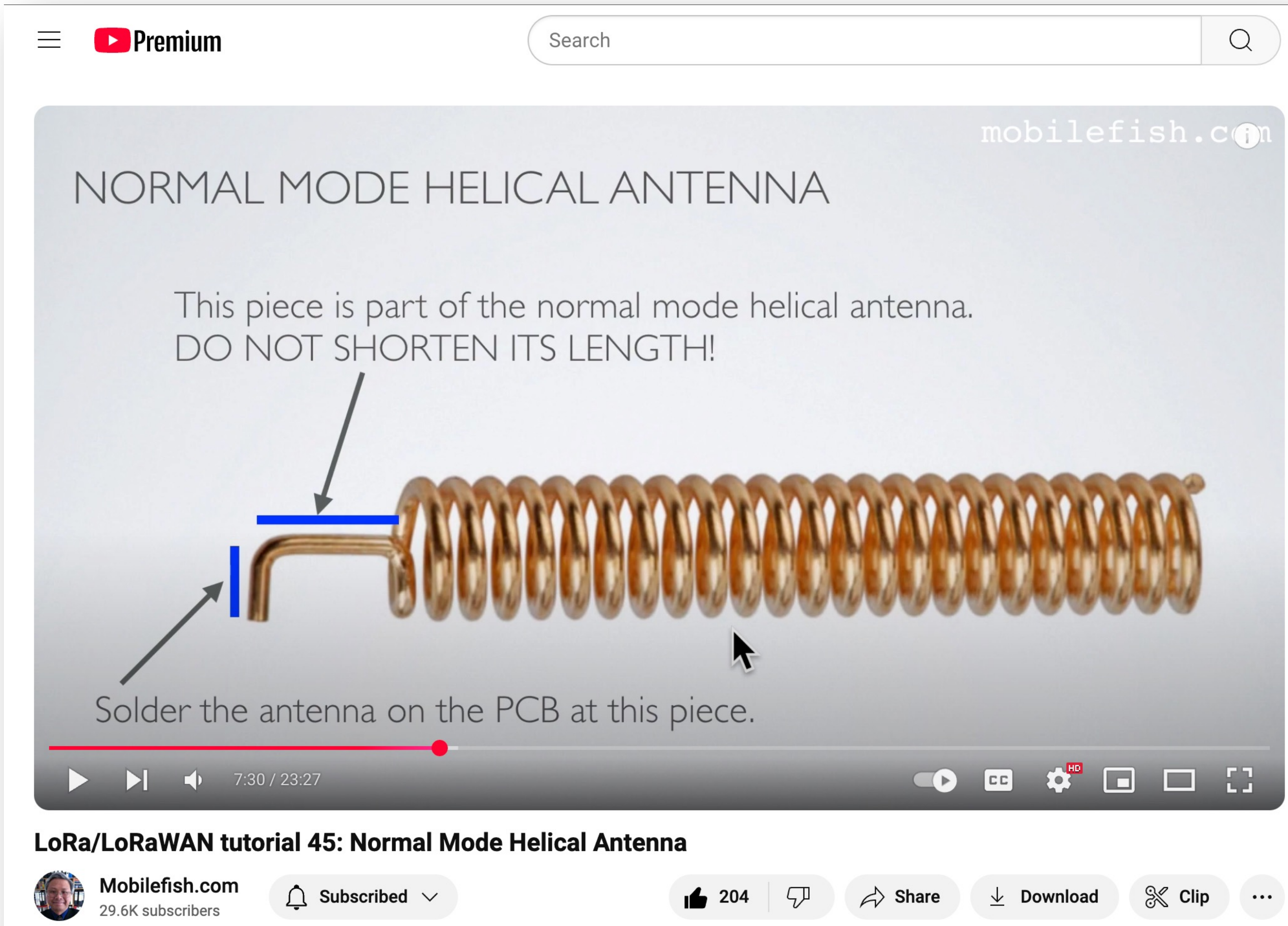
A LoRa module

Developed by	Cycleo, Semtech
Connector type	SPI/I2C
Compatible	SX1261, SX1262, SX1268,

- LoRa is "low power" in the relative sense...a lot of modules I was looking at still pull a serious amount of power.

LoRa

- A lot to optimize with LoRa to get the most out of it and to be efficient.
- Lots of great resources



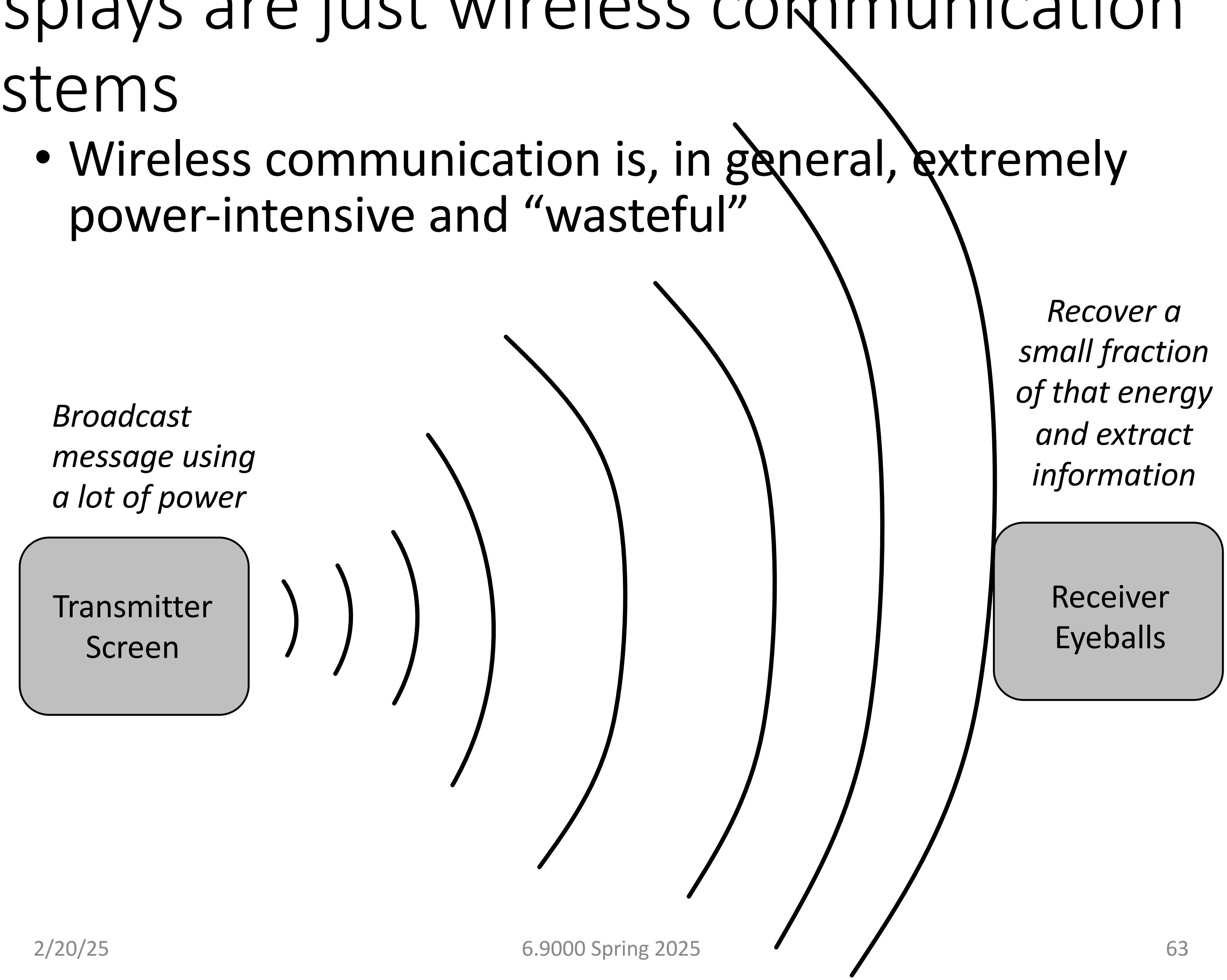
Displays?

- Some of the MITOS teams are looking at displays since community engagement is

- Those can use a lot of power!!!

Displays are just wireless communication systems

- Wireless communication is, in general, extremely power-intensive and “wasteful”



Different Types

- LCD? Uses a ton of power
- OLED uses decently less
- E-Ink uses waayy less but also sacrfices in other areas

- Gotta figure that out.

Computation in General

- We haven't even started talking about computation yet...do that next week
- That can use a ton of power

Take Take Take, Use Use Use

- What about Giving and/or Producing?
- Only talked about consuming power so far
- How can we produce power?

Solar Cell

- A good number of you teams, if not all, will likely determine solar energy is the way to generate energy

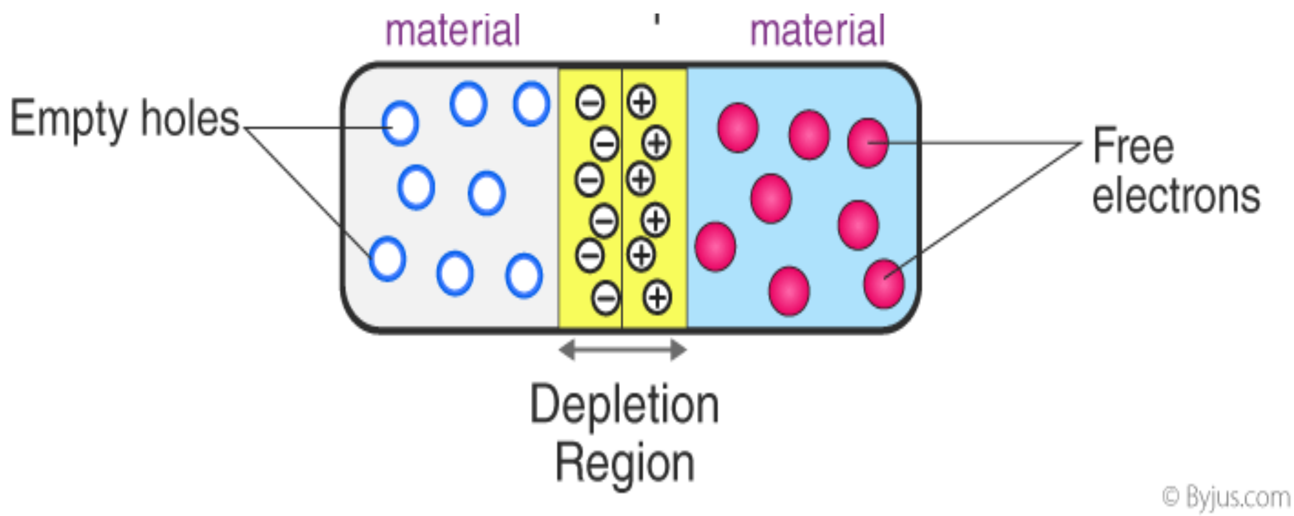
- Mature technology

- Relatively Cheap

- All Built Around the ”The Photovoltaic Cell”

PN Junction

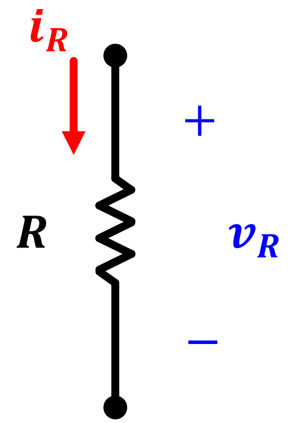
- A Solar cell is, interestingly, just a PN diode

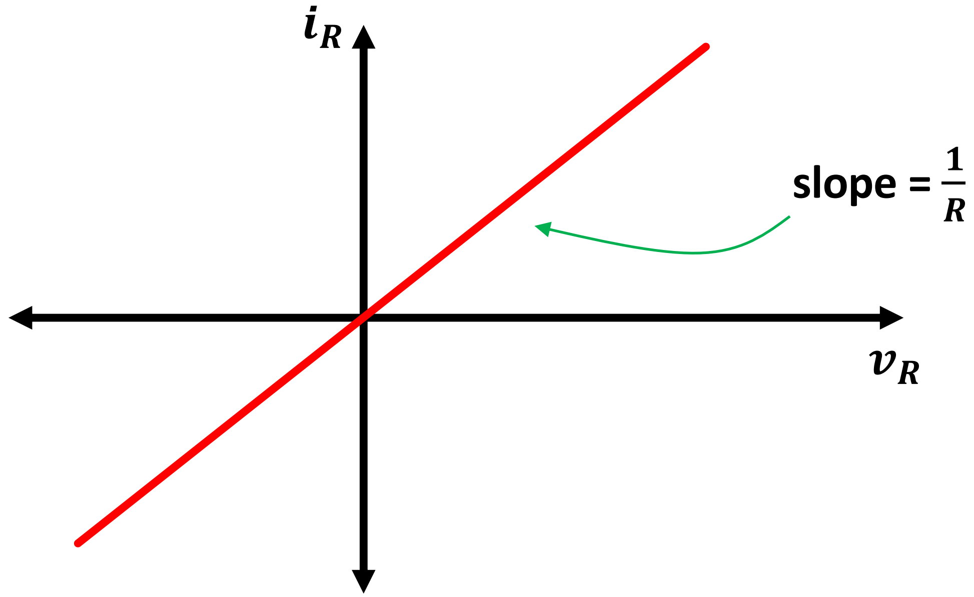


https://byjus.com/physics/p-n-junction/

What is the I-V relationship of a diode?

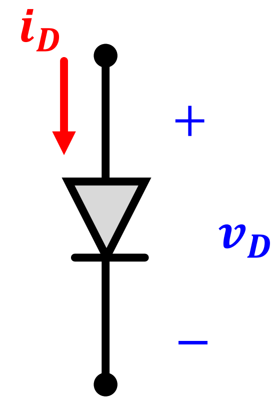
- A resistor, you'll remember is:

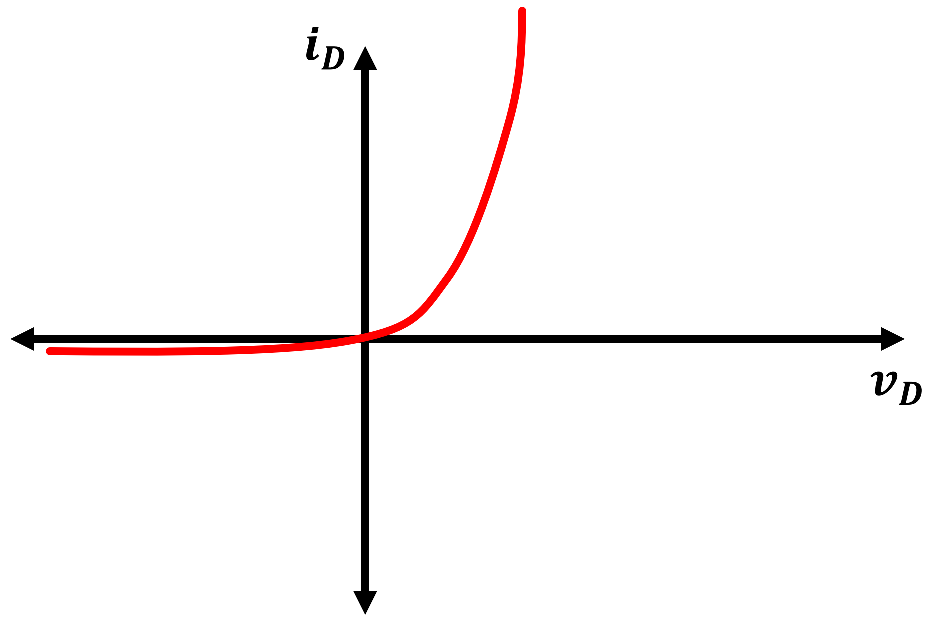




What is the I-V relationship of a diode?

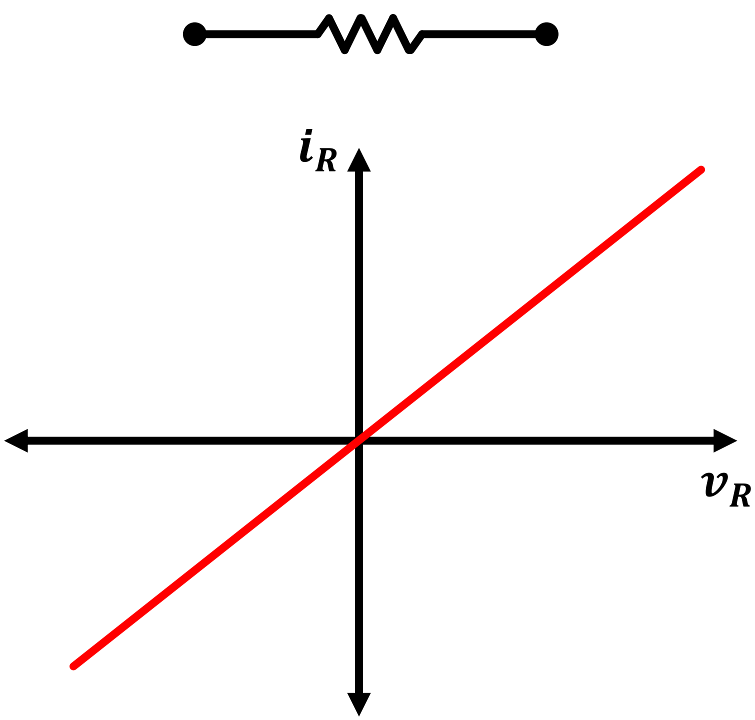
- Now a Diode

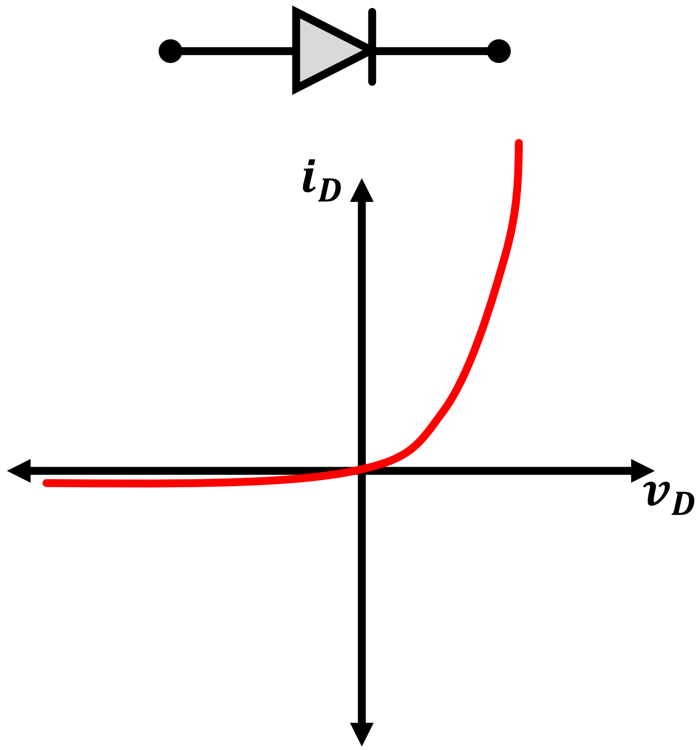




Interesting Feature to Notice

- What quadrants of the I-V space do these plots both live in?





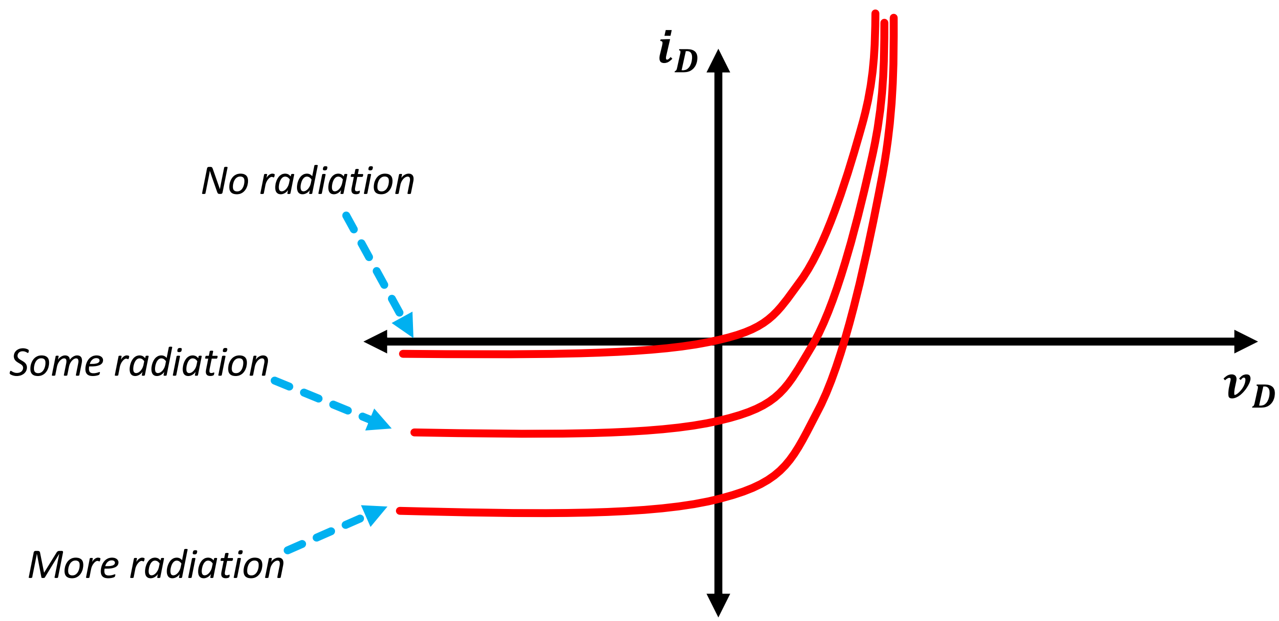
I-V Quadrants

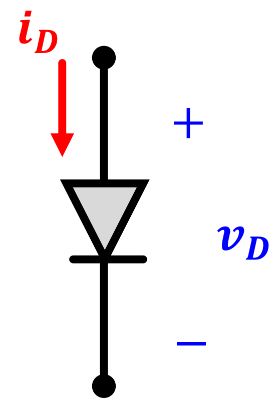
- Diodes and resistors (and all non-power-generating devices) will be stuck in quadrants I and III
- In those quadrants: $p = v \cdot i$
  - Quadrant I: $p = (+) \cdot (+) \rightarrow (+)$
  - Quadrant III: $p = (-) \cdot (-) \rightarrow (+)$
- This is really meaningful…why?

- To be supplying power you need to be in Quadrants II or IV:
  - Quadrant II: $p = (-) \cdot (+) \rightarrow (-)$
  - Quadrant IV: $p = (+) \cdot (-) \rightarrow (-)$

A PN junction exposed to radiation

- Light starts to shine on a PN junction

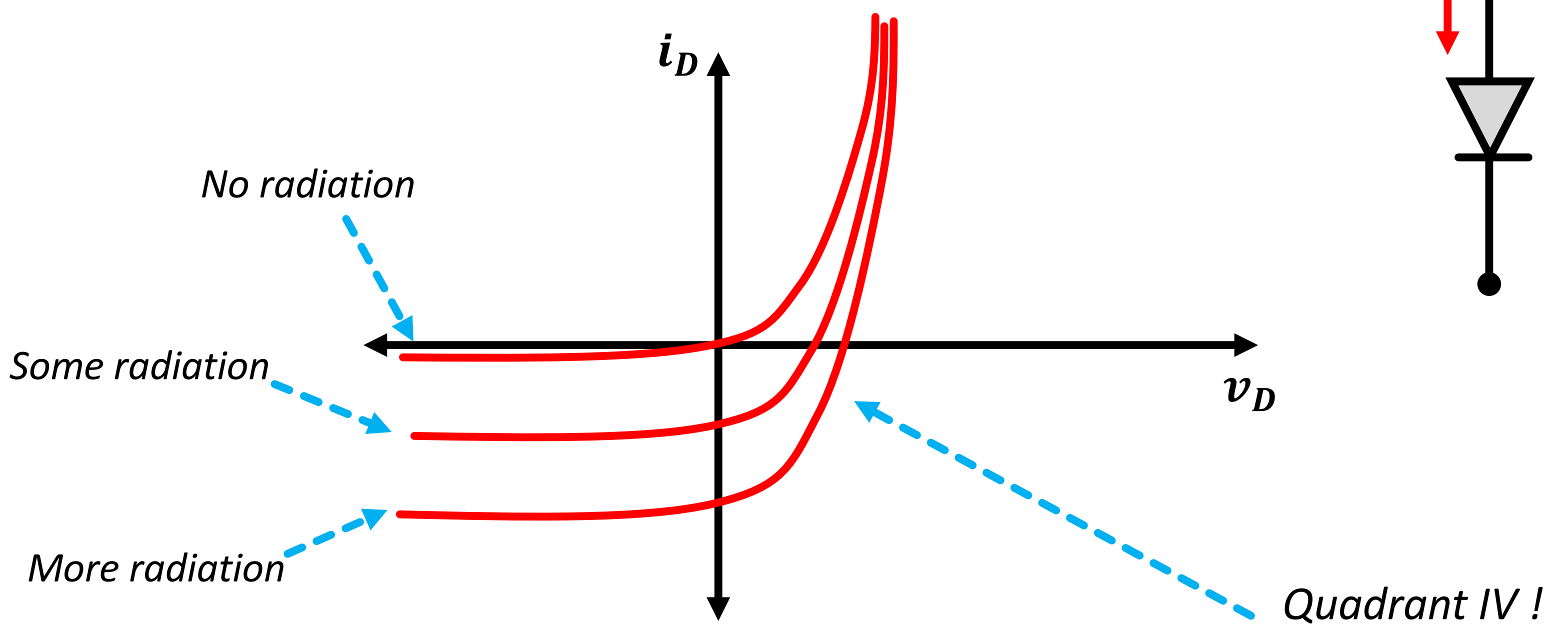


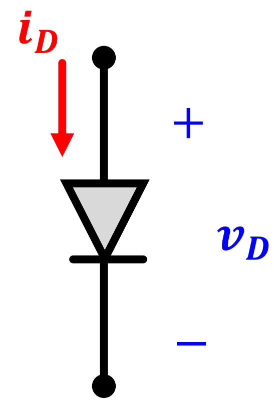


- What Do you Notice About these curves?

A PN junction exposed to radiation

- Light starts to shine on a PN junction



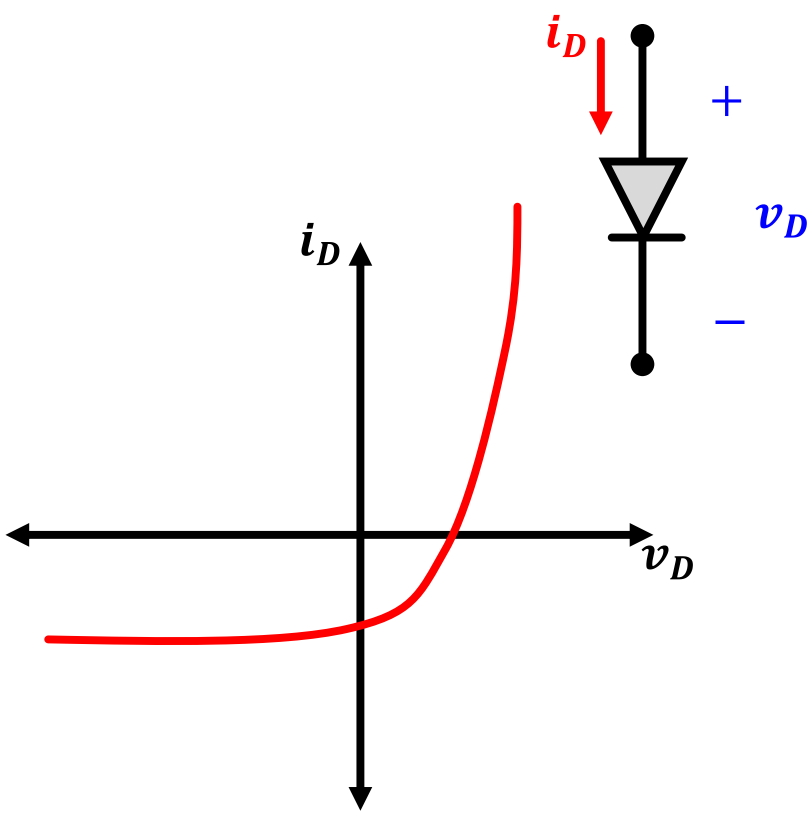


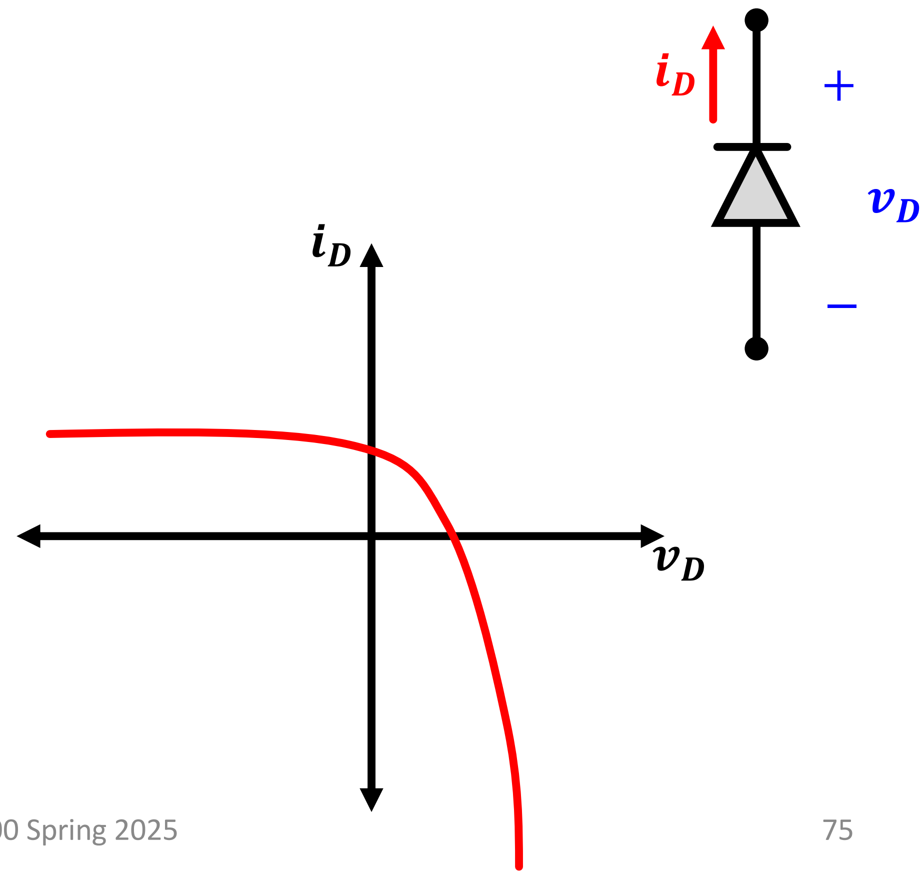
$p = (-) \cdot (+)$

- What Do you Notice About these curves?

They Usually Flip Axes

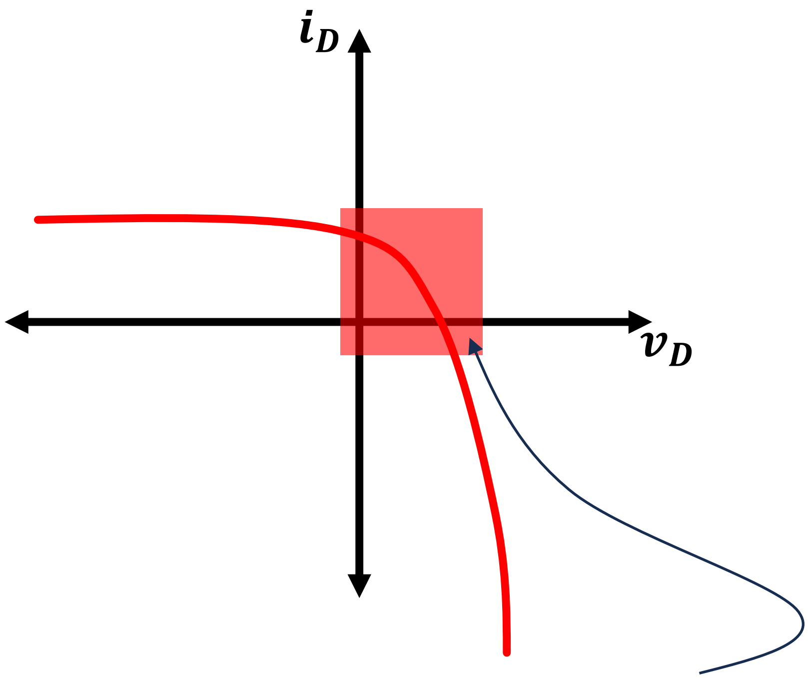
- When drawing Power-supply devices we usually flip the axes (as mentioned earlier!!!)



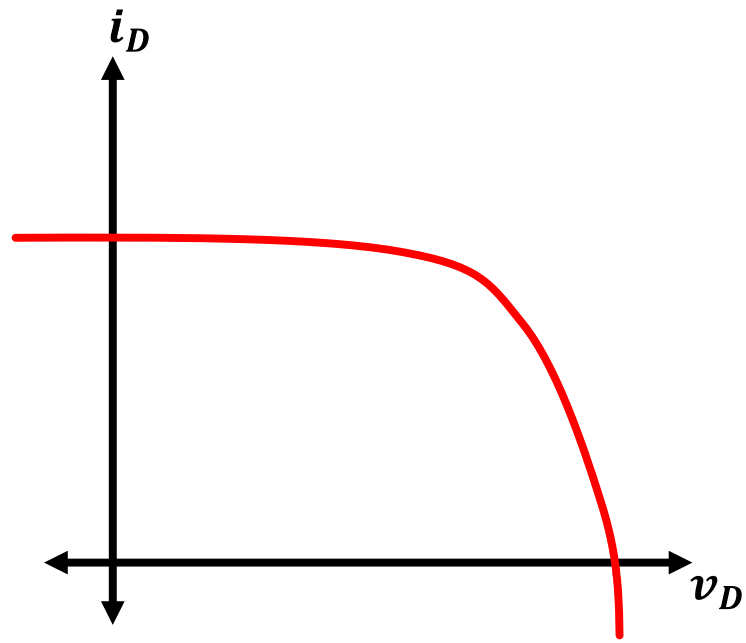


The I-V curve of a PV Cell

- If Power is the product of voltage and current, how much power can a PV cell provide?

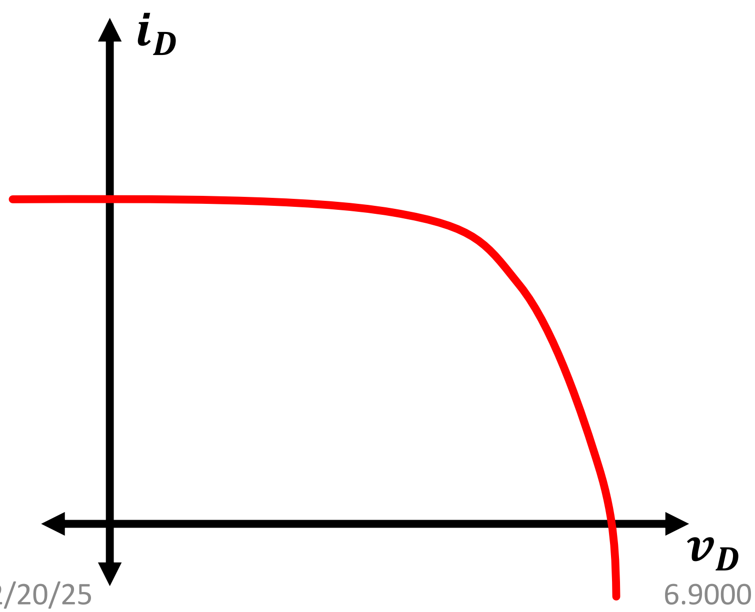


Zoooooooooooom in on this region!
Since that's what we care about



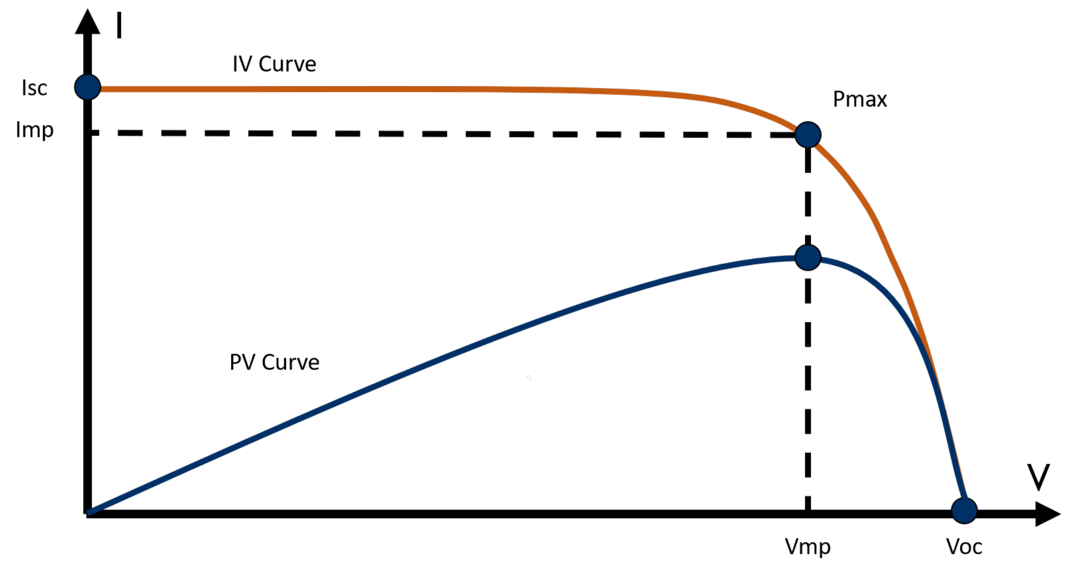
Operating a PV Cell

- A PV cell is *absolutely not* a voltage source or current source… it is a complex thing with its own wants and needs as expressed through its I-V curve
- It will not give you the power you want in the form *you* want. It will give you power in a form that it wants (certain I and V) and maybe that isn't what you want.
- But this is how relationships work



PV Curve

- Extracting the most power from a PV Cell requires using it at exactly one point on its I-V curve.
- Using it at anywhere else, will be a non-optimal efficiency.
- This is called the Maximum Power Point*

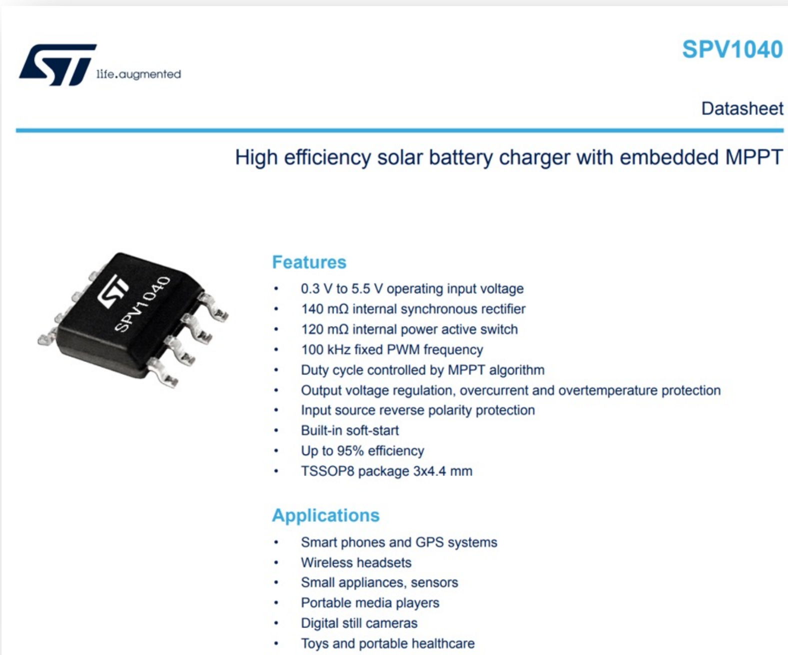


MPPT

- To get the most out of our PV cell, we need to be running it at its Maximum Power Point (MPP).
- Ideally we'd even want to to "track" that MPP. We'll call this MPP Tracking or MPPT

To MPPT or not to MPPT?

- It might sound like a no-brainer to do this. There are chips and things for this:


SPV1040

Datasheet

High efficiency solar battery charger with embedded MPPT

Features

- 0.3 V to 5.5 V operating input voltage
- 140 mΩ internal synchronous rectifier
- 120 mΩ internal power active switch
- 100 kHz fixed PWM frequency
- Duty cycle controlled by MPPT algorithm
- Output voltage regulation, overcurrent and overtemperature protection
- Input source reverse polarity protection
- Built-in soft-start
- Up to 95% efficiency
- TSSOP8 package 3x4.4 mm

Applications

- Smart phones and GPS systems
- Wireless headsets
- Small appliances, sensors
- Portable media players
- Digital still cameras
- Toys and portable healthcare

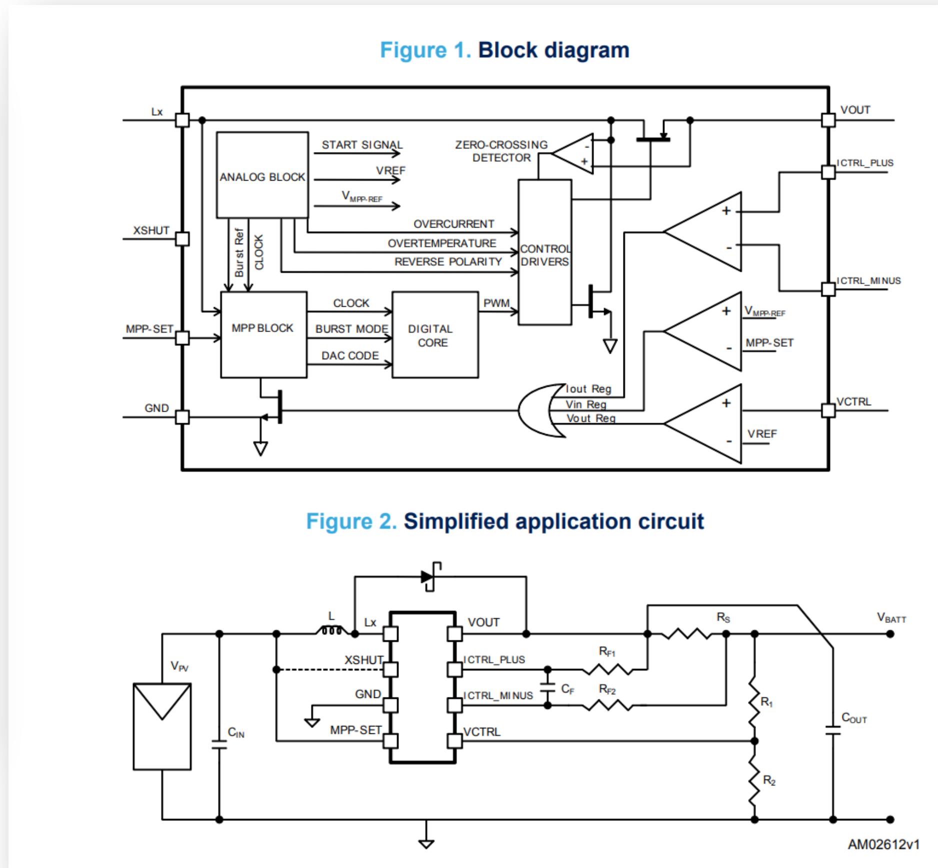


Figure 1. Block diagram

Figure 2. Simplified application circuit

To MPPT or not to MPPT?

- But these chips and their supporting circuitry cost money, and you may only be improving your operating efficiency by ~10 or 20% in doing so.
- You have to ask if this is worth it or not.
- Do you have lots of sun so you can use a PV cell inefficiently? Or are you just scavenging enough to breathe and so can’t afford to waste anything?
- Also what is the cost/benefit of just buying a larger cell (and continuing to use it at a similar efficiency) vs. using a smaller one more efficiently?
- There’s no single right answer so needs experimenting.

Adafruit Solar Charger Board

- The board we used last year in by Adafruit…
- Is not a MPPT board partially for cost.
- You should figure out whether or not this is the right way to go.

Batteries

Another Thing You need To Worry About

In a Mobile System

- Harvesting your energy from the environment will not be constant over the span of days or weeks. There will be good times and bad times as Led Zeppelin said.

- Batteries Provide a way to store energy in times of plenty and supply energy in the lean times.

- They are *like* bypass capacitors in this regard, though batteries have a much higher energy density and are generally much more stable and less lossy so perform this duty over much larger timescales

Batteries

- Primary solution and means of enabling mobile electronics
- Store energy chemically and then release it electrically

- Voltage sources with finite "life span" (finite total stored energy)

- Wide differences in:
  - Nominal voltage
  - Current capability
  - Energy capacity
  - Energy density (J/kg or J/m^3 or Wh/m^3)
  - Discharge characteristics
  - Renewable or one-time

Characterizing Batteries

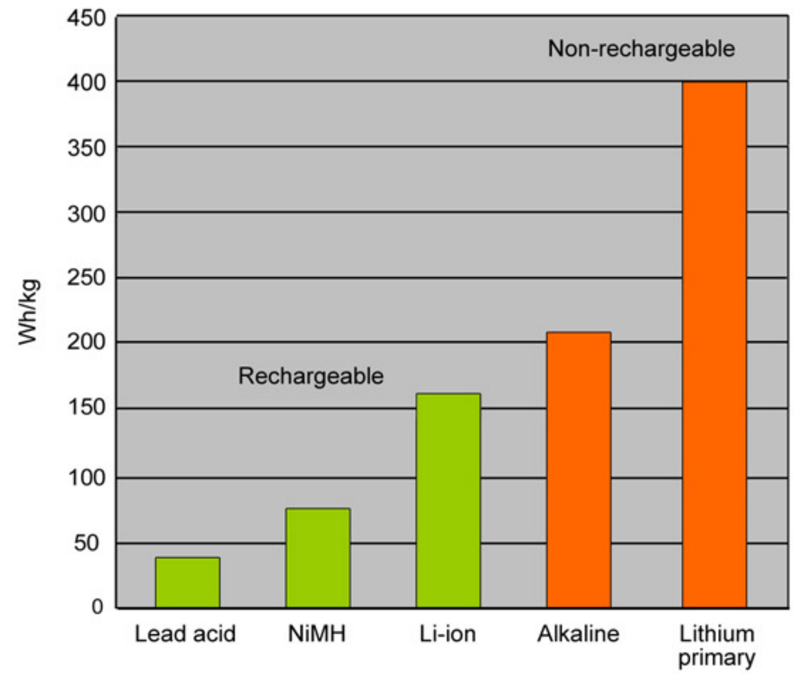
- We generally characterize batteries by:
  - The voltage they produce
  - Their capacity
- There are lots of caveats and additional characteristics, though:
  - Charge/discharge rate
  - Temperature Ratings
  - Instantaneous Current Ratings

Example:

All car batteries are 12V
But they can vary widely in capacity and
Cold-cranking amps, the number of amps it can deliver
When at 32 degrees Fahrenheit

Battery Chemistries

- Primary (non-rechargeable)
  - Alkaline
  - Lithium



- Secondary (rechargeable)
  - Li-Ion & Li-Poly
  - NiMH

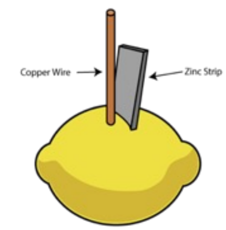
http://batteryuniversity.com/learn/article/primary_batteries

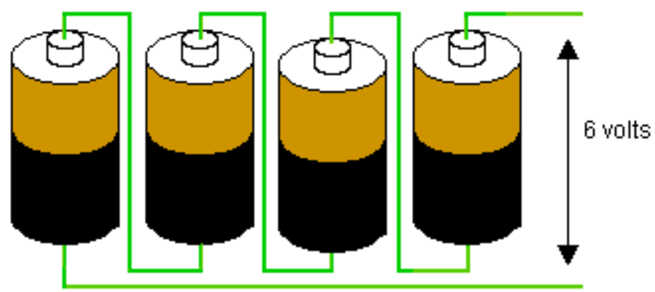
Battery Voltage

The voltage comes about from the material properties

- Depends on chemistry
- NiMH: 1.2 V
- Alkaline: 1.5 V
- Lemon (w. copper/zinc): 0.906V
- Lead-Acid: 2.10V
- Copper-zinc-lemon: 1.5V
- Lithium-manganese dioxide: 3.0 V
- Li-Ion and Li-Poly: ~3.7 V

- Can increase battery voltage by placing cells in series





Battery Capacity

- Measure it in **milliamp-Hours** (or Amp-Hours for bigger ones)
- If a battery is rated for 100 mAh it means it can deliver 100 mA of current at its specified voltage for one hour…or 50 mA at its specified voltage for two hours…or 10 mA at its specified voltage for 10 hours, etc… *

- Depends on chemistry and size
  - Li AA: 2500-3400 mAh
- CR2032 (coin cell)
  - ~200 mAh

- Lithium-Ion
  - Variety of sizes
  - iPhone 6: 1810 mAh
  - Apple watch: 205 mAh

Alkaline batteries

Battery type	Nominal voltage	Rated capacity
9V	9 volts	570mAh
AAA	1.5 volts	1,150mAh
AA	1.5 volts	2,870mAh
C	1.5 volts	7,800mAh
D	1.5 volts	17,000mAh

**approximately*

http://www.techradar.com/us/news/wearables/apple-watch-battery-size-mah-1291964

Capacity/Energy

- Integral of Power Consumed over time

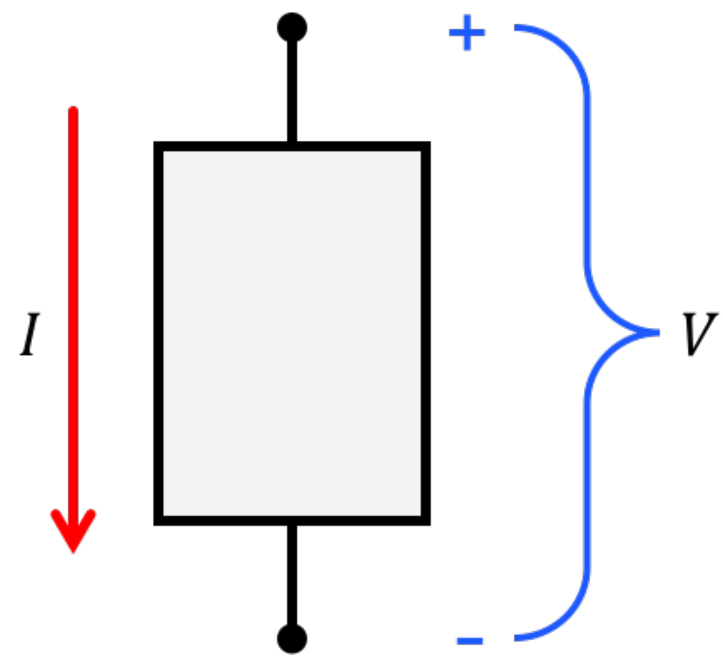
$$E(t) = \int_0^t P(\tau)d\tau$$

$$P(t) = V(t) \cdot I(t)$$

$$E(t) = \int_0^t V(\tau) \cdot I(\tau)d\tau$$

- If Voltage and Current are constant over time:

$$E = V \cdot I \cdot \Delta t$$

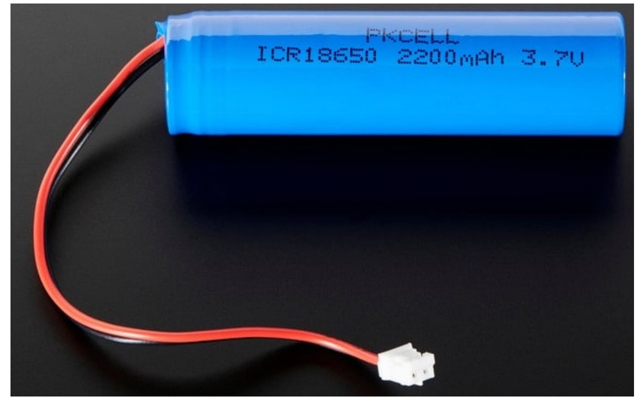


Our 6.900 Battery
(2200 mAh @~3.7V)
contains 20,000 Joules when fully charged

Batteries…

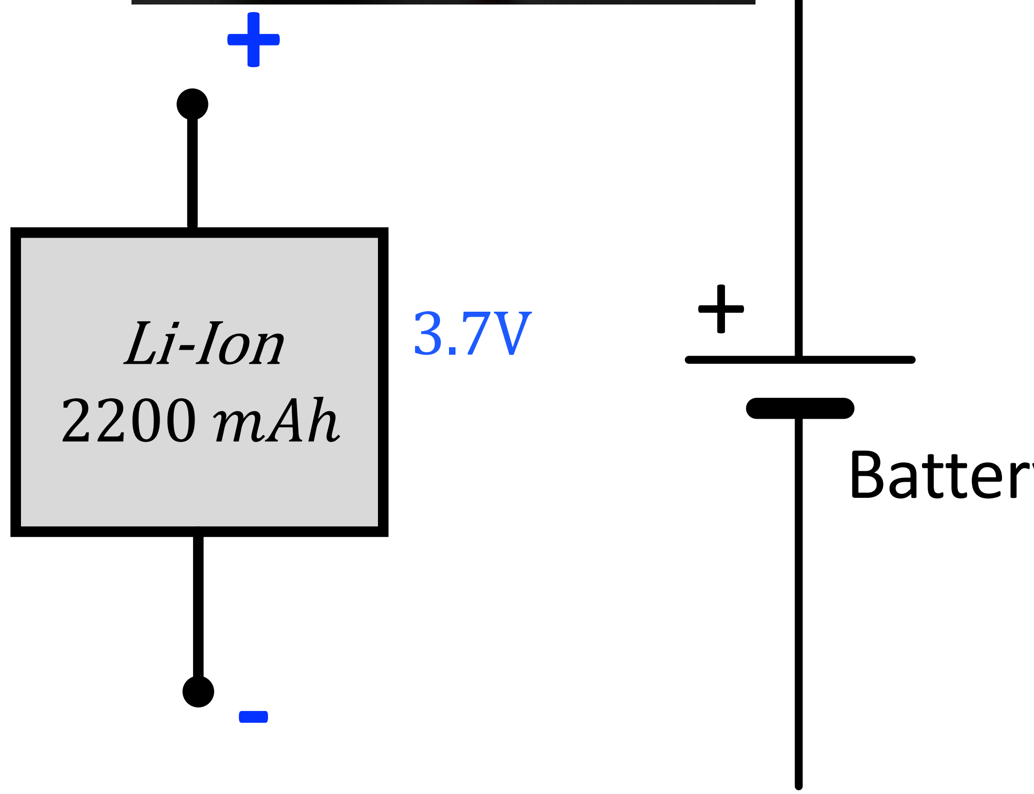
- For a given technology…
  - The bigger the battery, the more expensive
    - Motivation to size it properly
- Most batteries do need to get “used” otherwise they’ll degrade at certain rates.
- All batteries degrade over time.
- Lots of different chemistries even with the Lithium battery space.

Battery



- This seems so nice and easy to think about…3.7 V when it is on, 0V when it is off

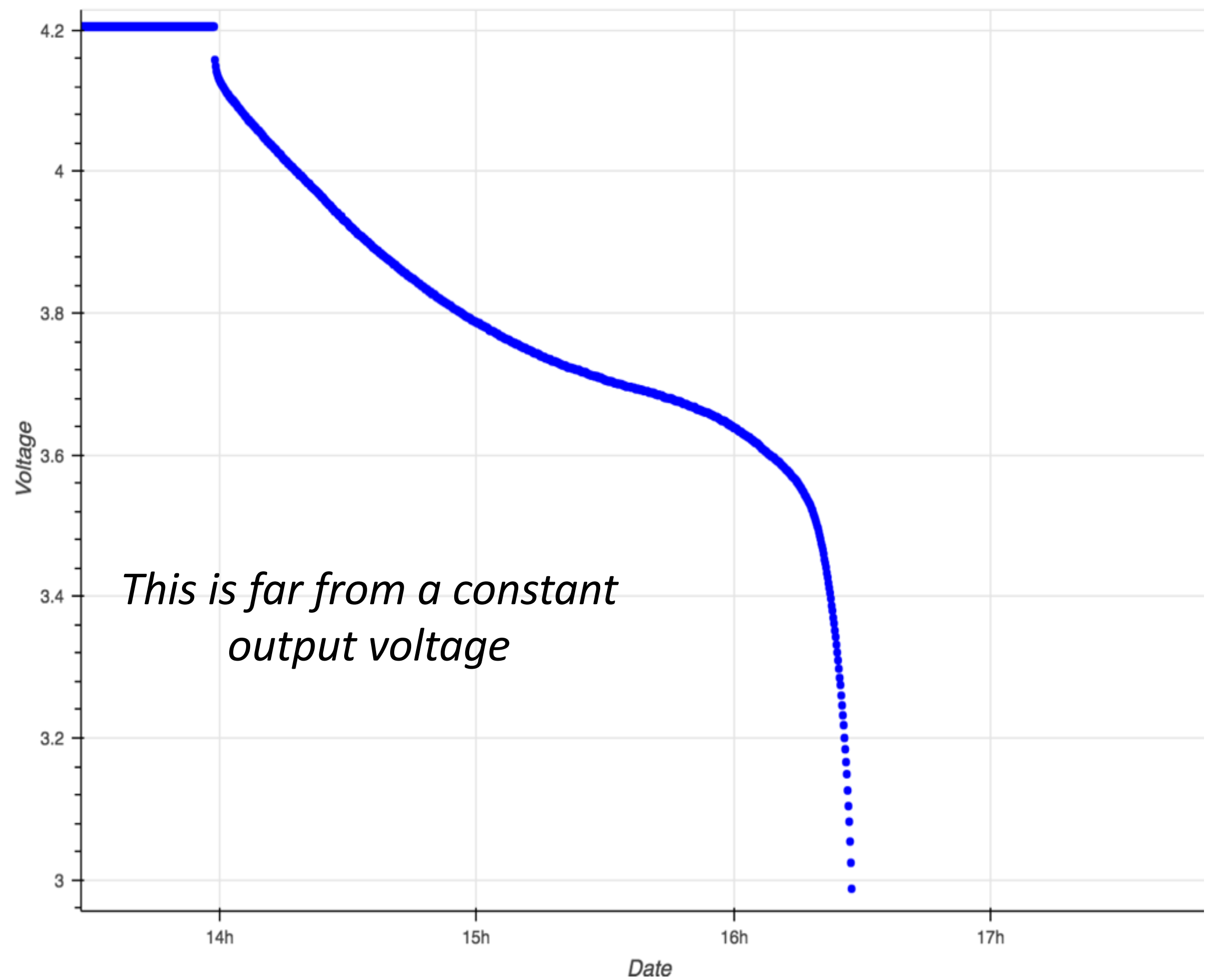
- But in real life it isn't so clean and nice…☹



Sometimes use one on the right too

Voltage of 350 mAh 3.7V battery

Discharge Curve:
(Voltage of battery over time, constant current draw)

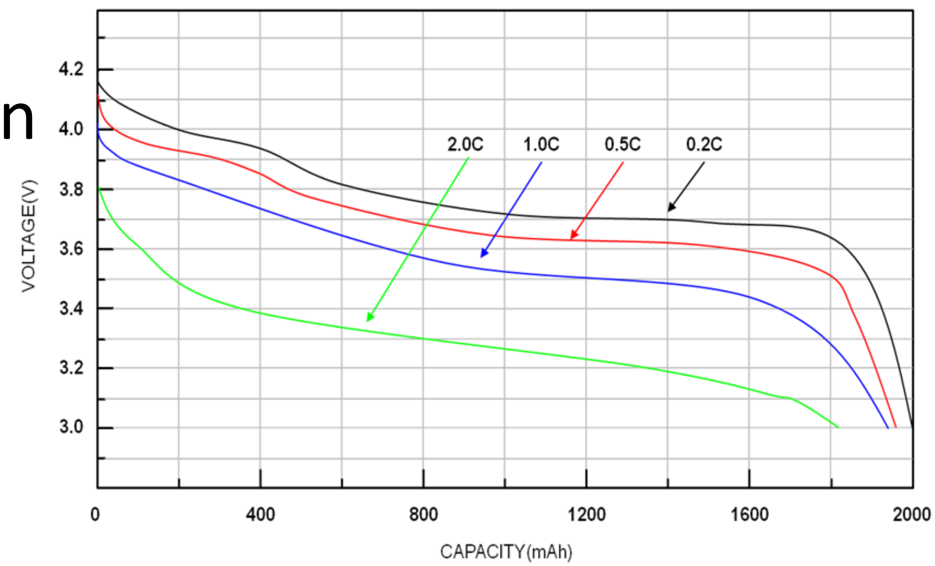


Changes over time ☹

Battery discharge curves

- Rated capacity depends on how quickly the cell is discharged
- Discharge (and charging) rates in units of “C”
  - 1C = discharge 1× capacity in 1 hr
  - 2C = discharge 2× capacity in 1 hr
  - Etc.
- Different battery types vary in max
  discharge current

2000 mAh cell



http://www.richtek.com/battery-management/en/designing-liion.html

Fuel Gauge Chips

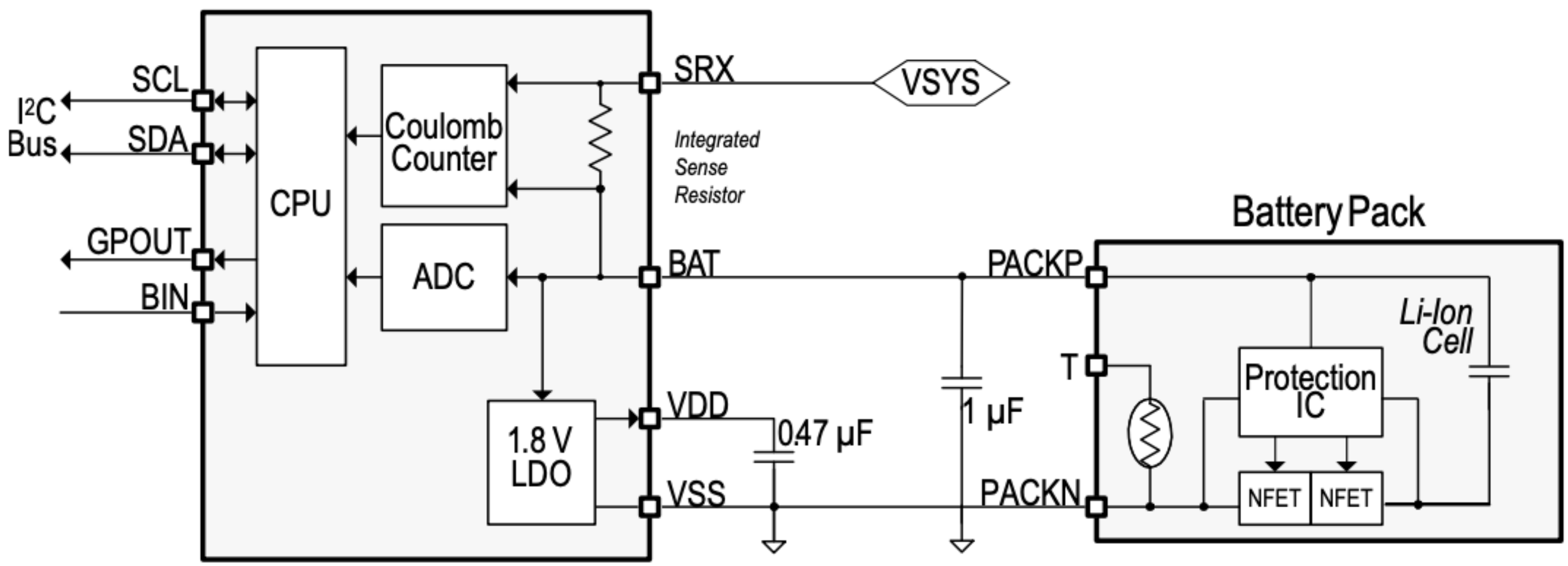
- The desire to know what your battery % is so great that companies have been producing “fuel gauge” chips in recent years to address this.

- These are quite complicated chips, often using proprietary algorithms to “learn” and estimate battery capacity based off of long-term voltage and/or current analysis of the battery

One example...

- Bq27421 by TI
- Monitors battery voltage and current and can report back over I2C an actual SOC (%) of battery!

Simplified Schematic



Has one of the worst datasheets

- The actual device ground is the center pin (B2). The C1 pin is floating internally and can be used as a bridge to connect the board ground plane to the device ground (B2).

11.2 Layout Example

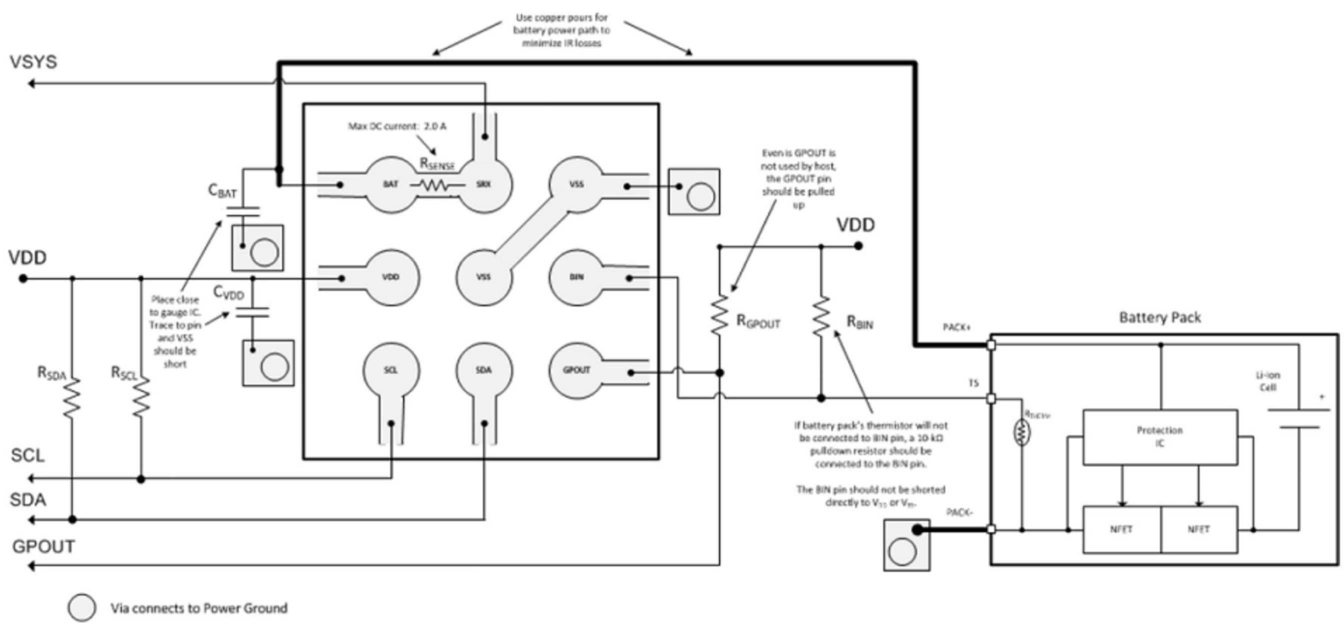
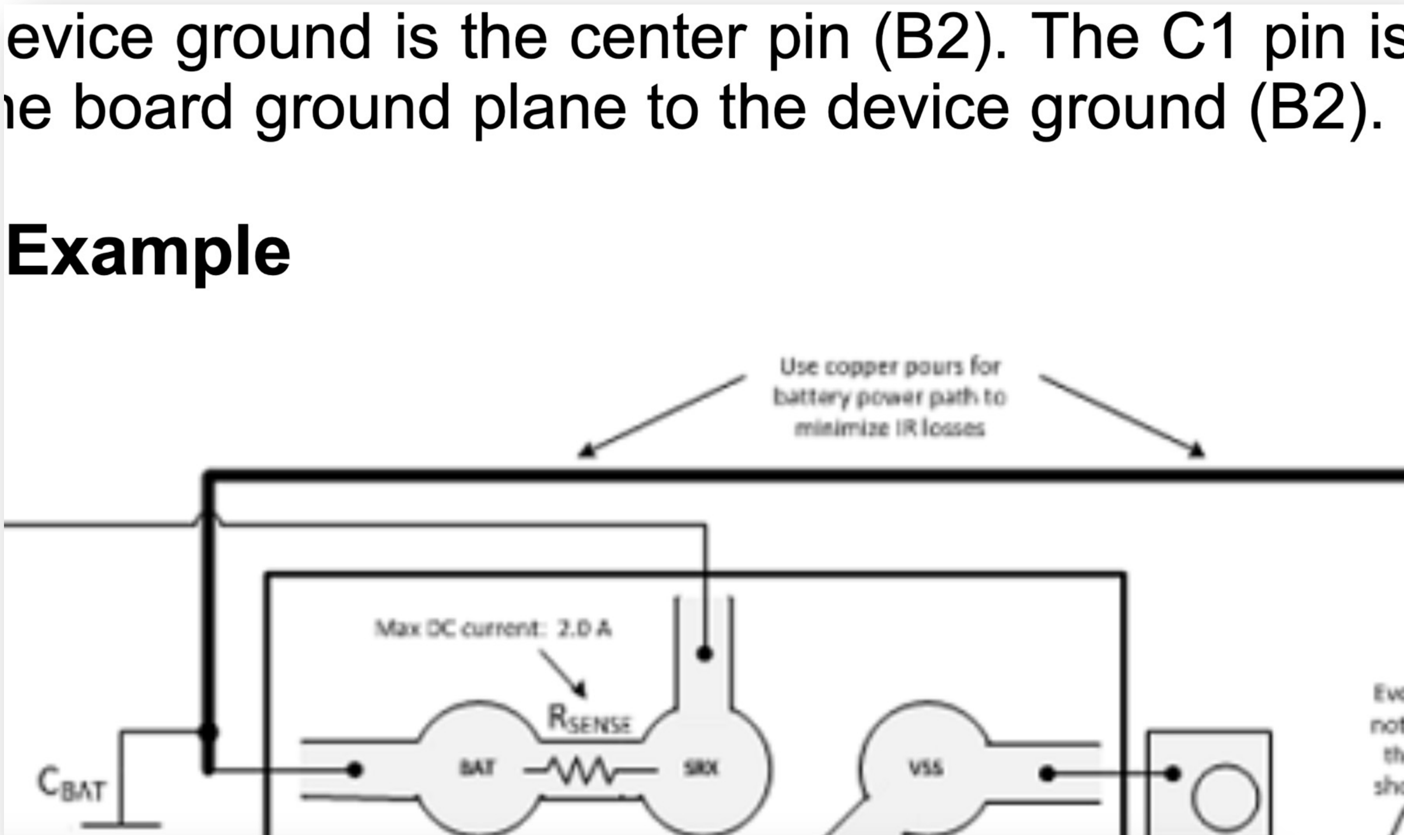


Figure 13. bq27421-G1 Board Layout Example

Actual resolution of their PDF datasheet



earch on Electrical Engineering...

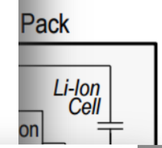
Mysterious Trace in Battery Fuel Gauge Datasheet

Asked 9 years, 3 months ago Modified 9 years, 3 months ago Viewed 513 times

0

I'm using a lipo battery in a project, and I want to include a sophisticated battery fuel gauge in my design. I have a battery input stage with a TI BQ24072 charge management IC and a linear down-regulator to 3.3v.

For the fuel gauge, I've chosen the TI BQ27421-g1 as I've had good luck with their battery charging IC. The typical application circuit is shown below:



That has to be the world's most confusing datasheet. Look at 10.2.2.3, which discusses the selection of an external sense resistor (unnecessary) connected to two pins that don't exist. I think the layout picture's completely misleading and you should not connect those pins. Just work from all the other schematics, etc. in the DS. – user1844 Nov 3, 2015 at 18:58

@WillDean I'm glad I'm not the only one confused by this thing. Usually TI does better than this with their datasheets. If this chip wasn ... one. – John M Nov 3, 2015 at 19

@WillDean I would go off the sche
Nov 3, 2015 at 19:01

The BAT pin should not be shorted to the SRX pin. The SRX pin goes to the system VSYS **and** the charging source. The charging source cannot be a raw USB+5v, that will kill the LiPo, it needs to be the +ve output of a LiPo charger. The BAT pin goes to the battery pack.

Figure 9 on page 20 is not meant to be a 'layout', it is a hybrid abomination which shows the footprint of the device, and a schematic of its connections. Unfortunately, the data sheet shows evidence of having been cobbled together hastily from a previous gas-gauge IC that used an external resistor. Section 10.2.2.3 discusses the selection of a suitable resistor. The tracking under the IC on figure 9 appears to show a trace between the BAT and SRX pins, which could be an alternative implementation of this resistor. This should not be there, and is obviously a hangover from the previous data sheet.

Have to "train"/"teach" chip about the battery

Theory and Implementation of Impedance Track™ Battery Fuel-Gauging Algorithm in bq20zxx Product Family

PMP Portable Power

Application Report

SLUA903–July 2018

Achieving The Successful Learning Cycle

Onyx Ahiakwo, Rushi Dalal, Steve Schnier

ABSTRACT

This paper discusses the steps necessary to complete the initial optimization cycle (also known as learning cycle) in order to ensure the accuracy and excellent performance of the gauge. A learning cycle is typically performed on a single representative battery pack during the development stage. The resulting values are then programmed into every pack during mass production as there should be minimal pack-to-pack variation for a well-controlled manufacturing process. The flash image extracted from a so-called "golden pack" during development is called the "golden file" and is used in mass production.

Maxim Have Some Too!

MAX17048/MAX17049 **3µA 1-Cell/2-Cell Fuel Gauge with ModelGauge**

General Description

The MAX1704
rent fuel gauge
and portable e
a single lithiur
cells in series.

Features and Benefits

Accurate Fuel Gauging Without Battery Characterization Using ModelGauge m5 EZ Algorithm

Aug 29 2019

Abstract

Battery Voltage and System Voltage

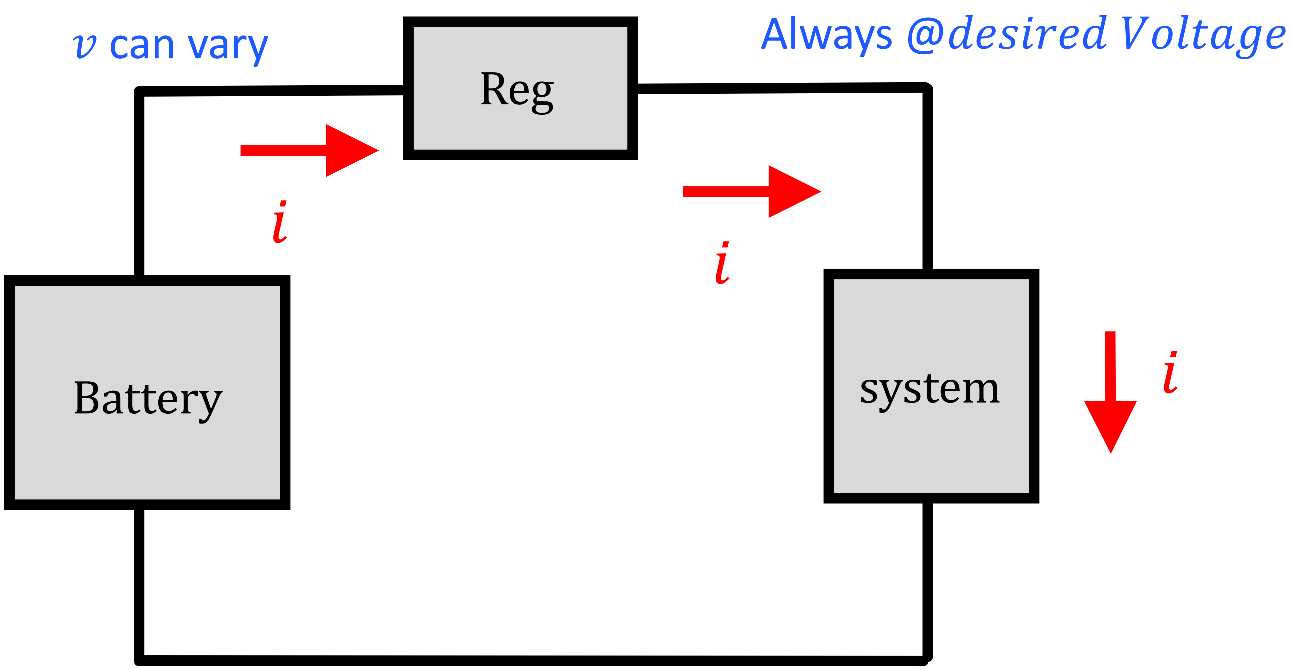
- As we use the battery, its voltage will vary
- Depending on how hard we use the battery, its voltage will also vary

- This is not good for microcontrollers and other parts. They need a steady voltage:
  - The ESP32 for example can only tolerate voltage fluctuations of ~1%...so it needs a near-ideal 3.3V supply

- Must regulate!!!

We already introduced the idea of a regulator!

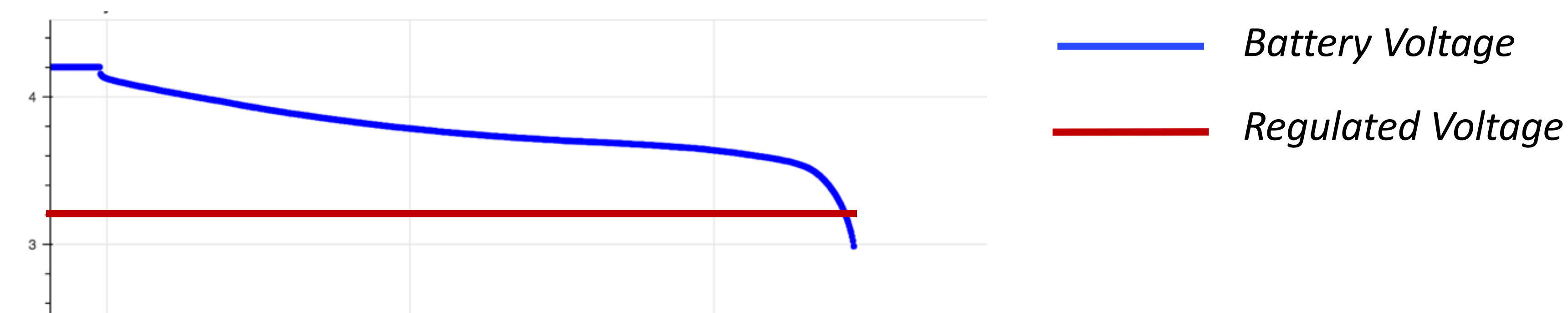
- Constant Current Device (KCL maintained)
- Can only regulate down in voltage

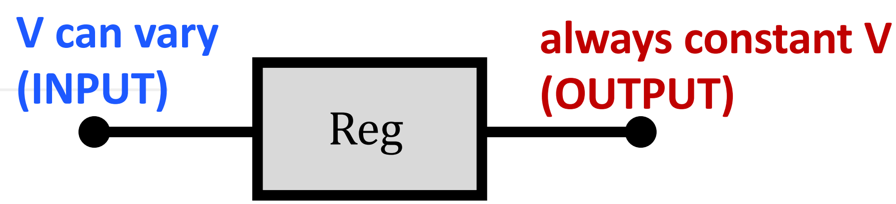


Could use this!

Stable Voltage

- Our Batteries provide us energy, but at a variable voltage





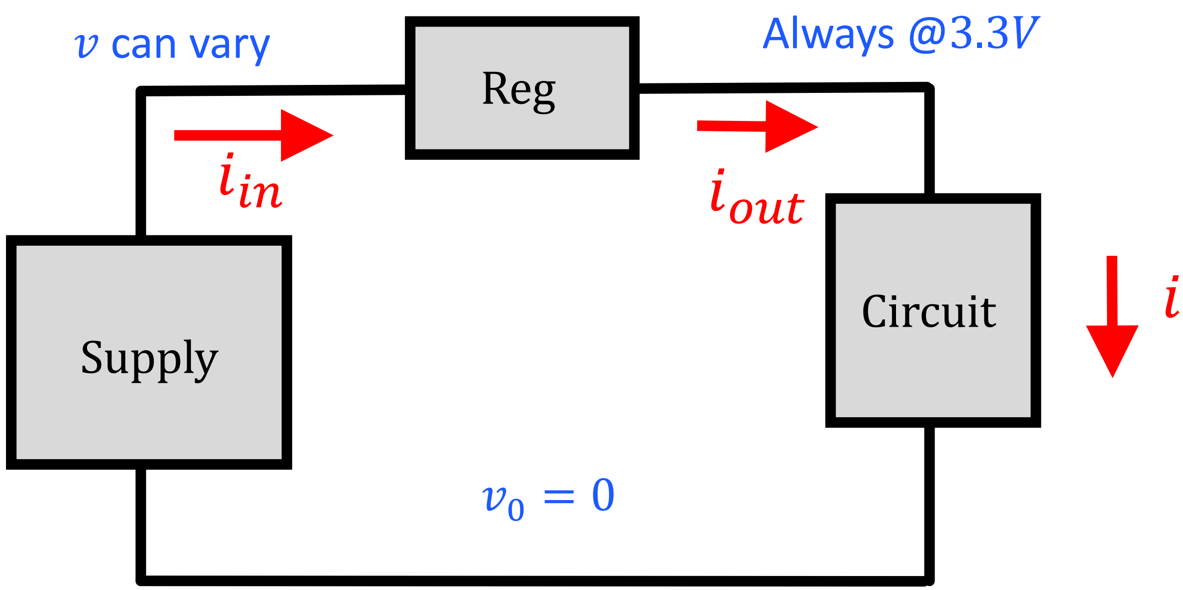
- Voltage Regulators can be used!

Power Regulators/Converters

- If battery voltage is higher than needed, must convert down
- If battery voltage is lower than needed, must convert up
- Two types of converters:
- **Linear (Traditional):**
  - Constant Current Device
  - Less efficient
  - Cheaper
  - Can only convert from higher voltage to lower voltage
- **Non-Linear (Switching Supply):**
  - Constant Power Device
  - More modern development
  - Generally more efficient
  - Usually not as cheap
  - Can convert up and down

Linear Regulator

- Constant Current Device (KCL maintained through them)
- Can only regulate down in voltage

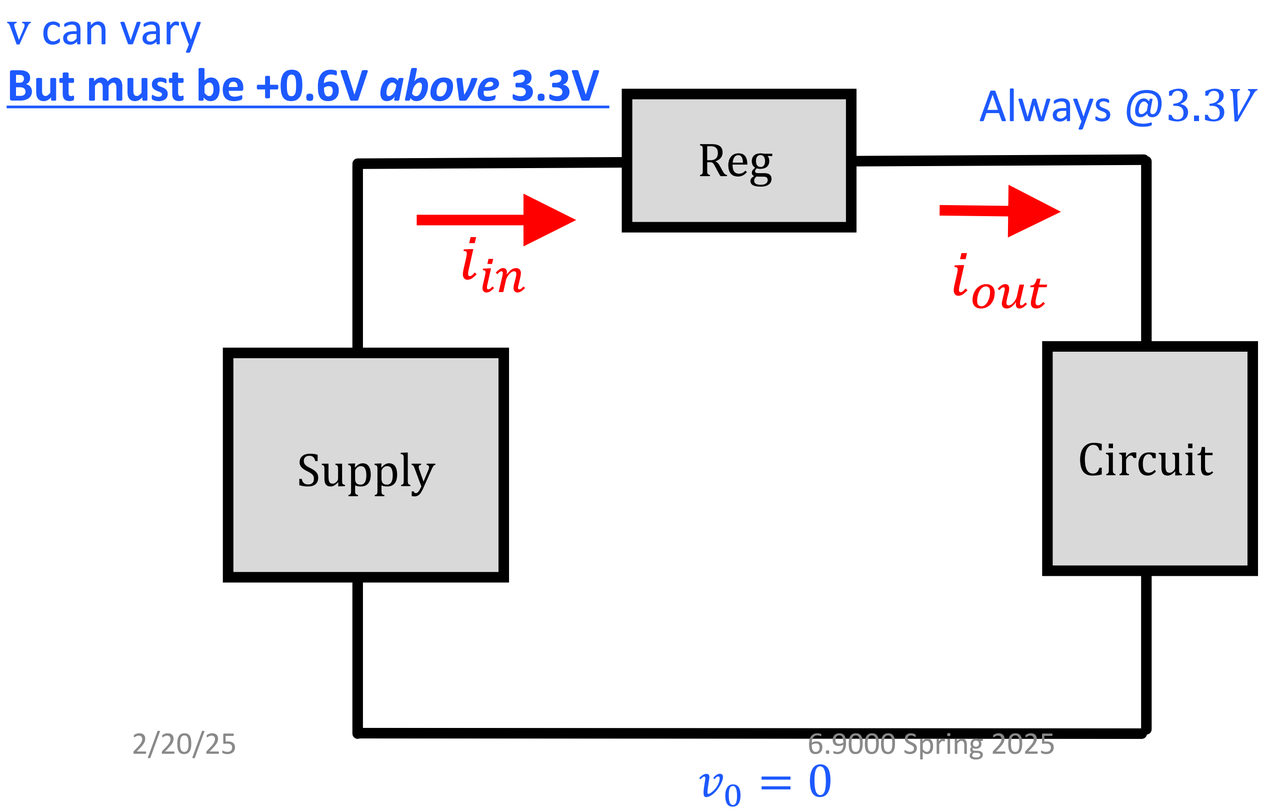


$i_{in} = i_{out} = i$

If $i = 50mA$ and supply voltage is at $v = 4.1\ V$ what is the efficiency of this system? (i.e. how much power is consumed by the circuit and not the regulator?)

Problem #1 with Linear Regulators

- If our Battery ranges from 3.2V to 4.2V in its output voltage we could mostly use a linear regulator…
- But in real life, cheap linear regulators need the input voltage to **be significantly higher** on the input than the output:

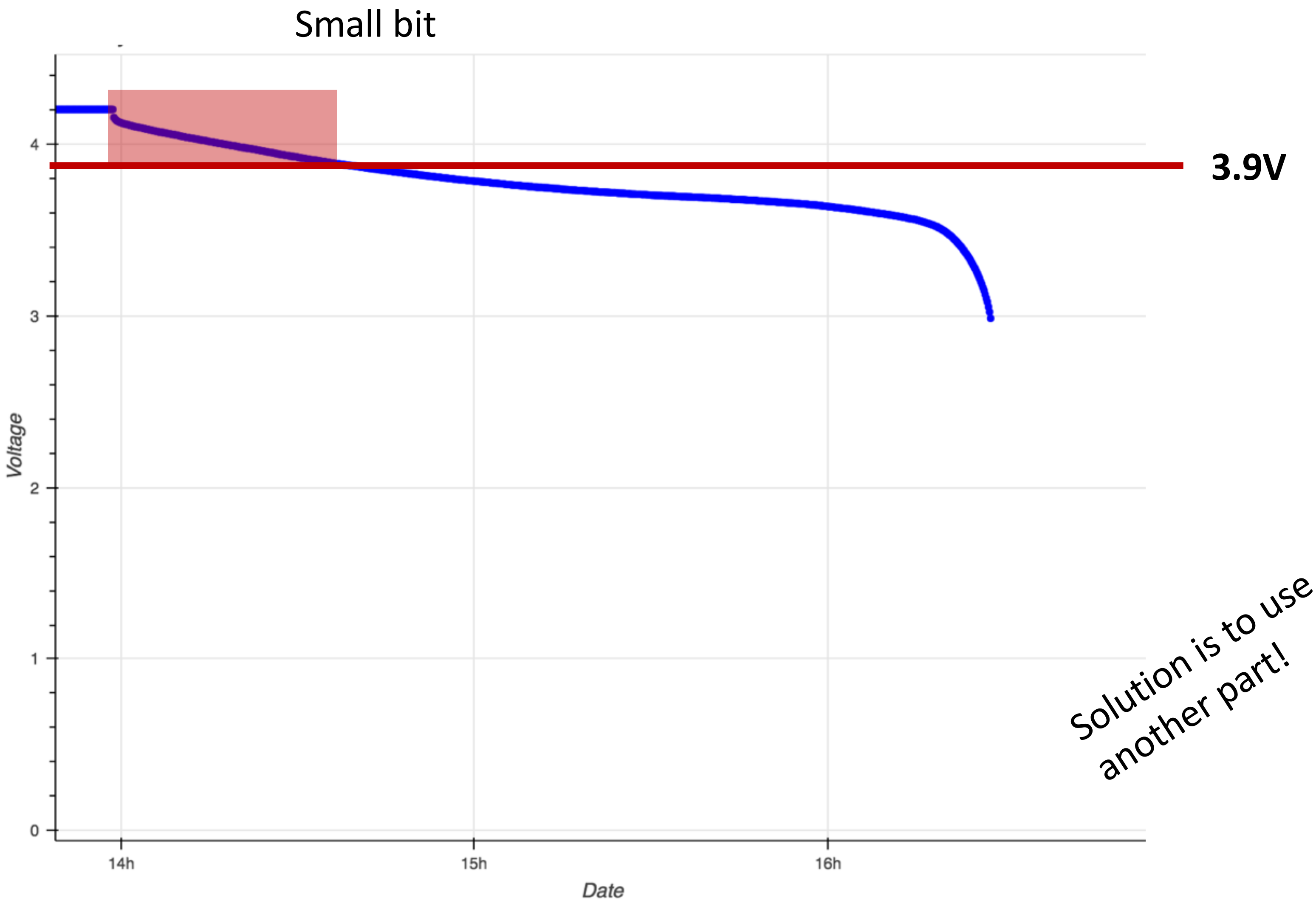


How low can our battery voltage go in this case?

3.9V…not good.

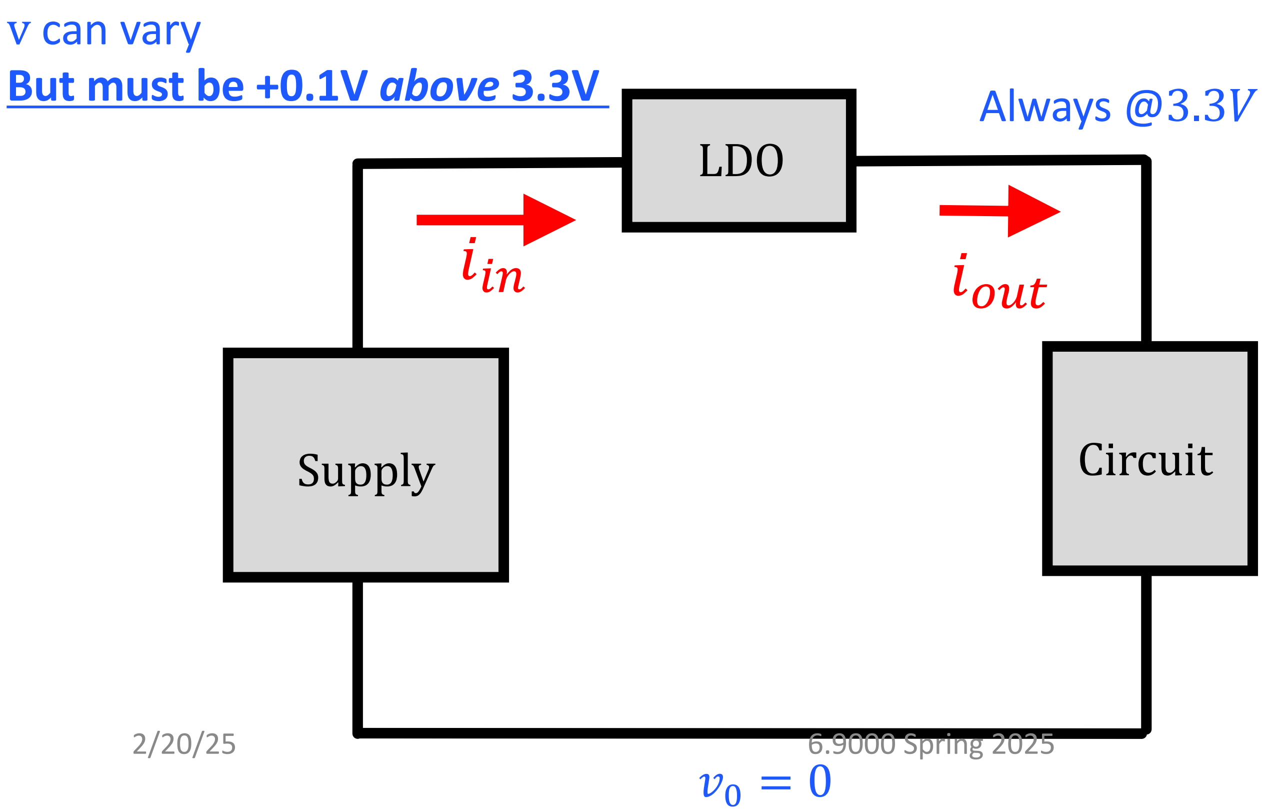
$$i_{in} = i_{out} = i$$

Most of Battery's Life is Unusable!



Problem #1 with Linear Regulators

- Can fix a bit using a Low Dropout Regulator (LDO)…a device that can regulate down to 3.3V from a much closer voltage (perhaps only 0.1V above

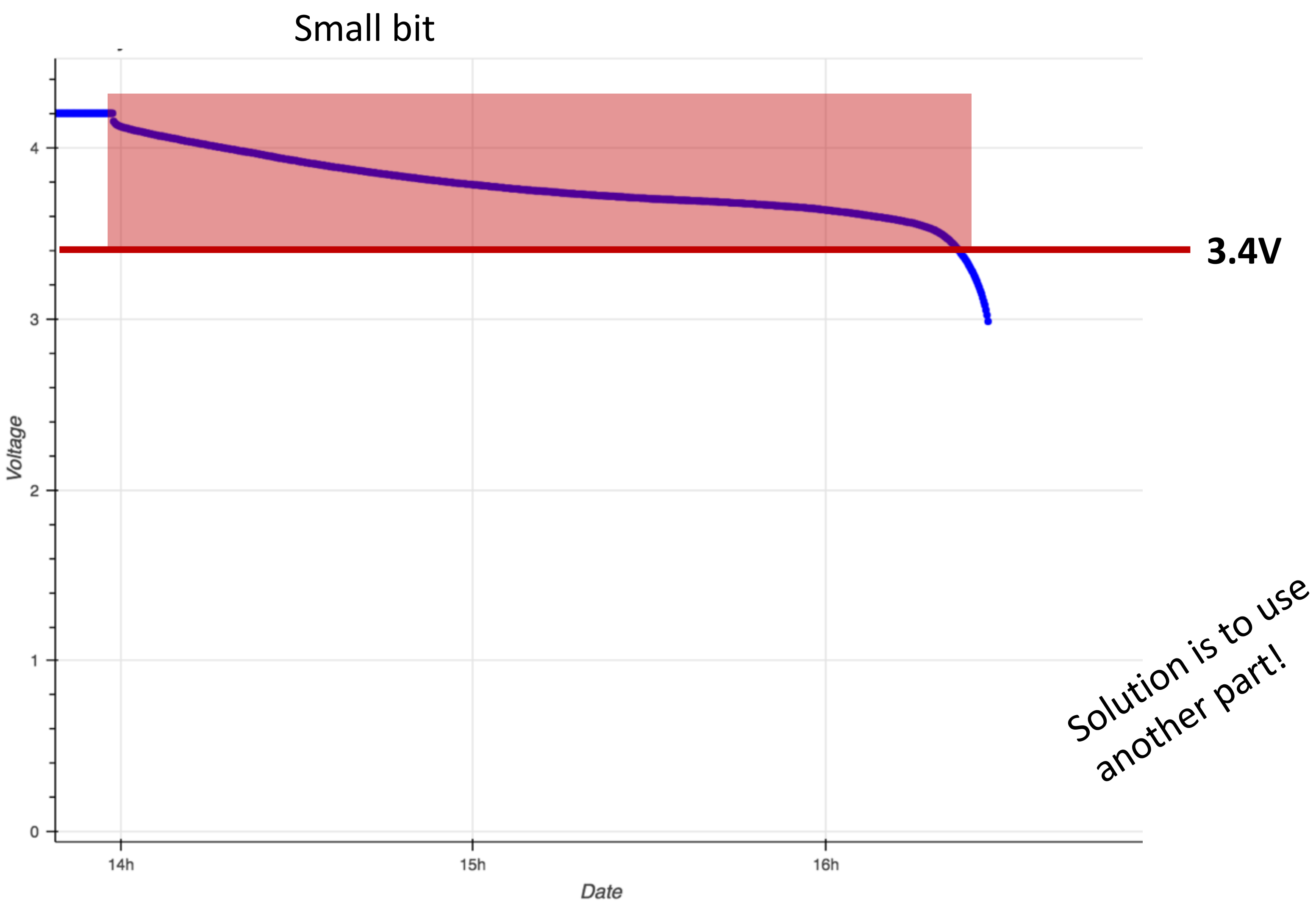


How low can our battery voltage go in this case?

3.9V…not good.

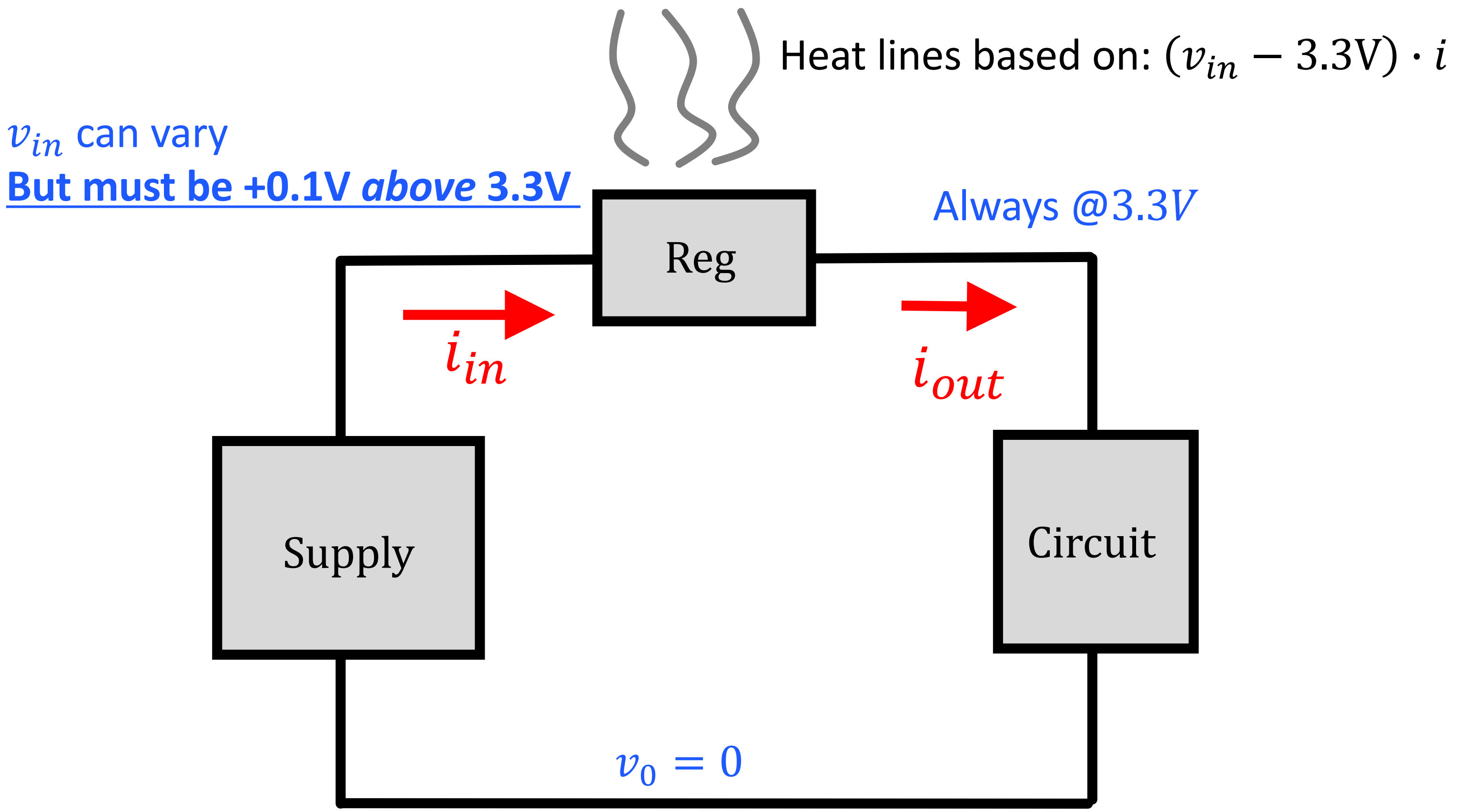
$i_{in} = i_{out} = i$

Using Most of Battery's Life!



Problem #2 with Linear Regulators

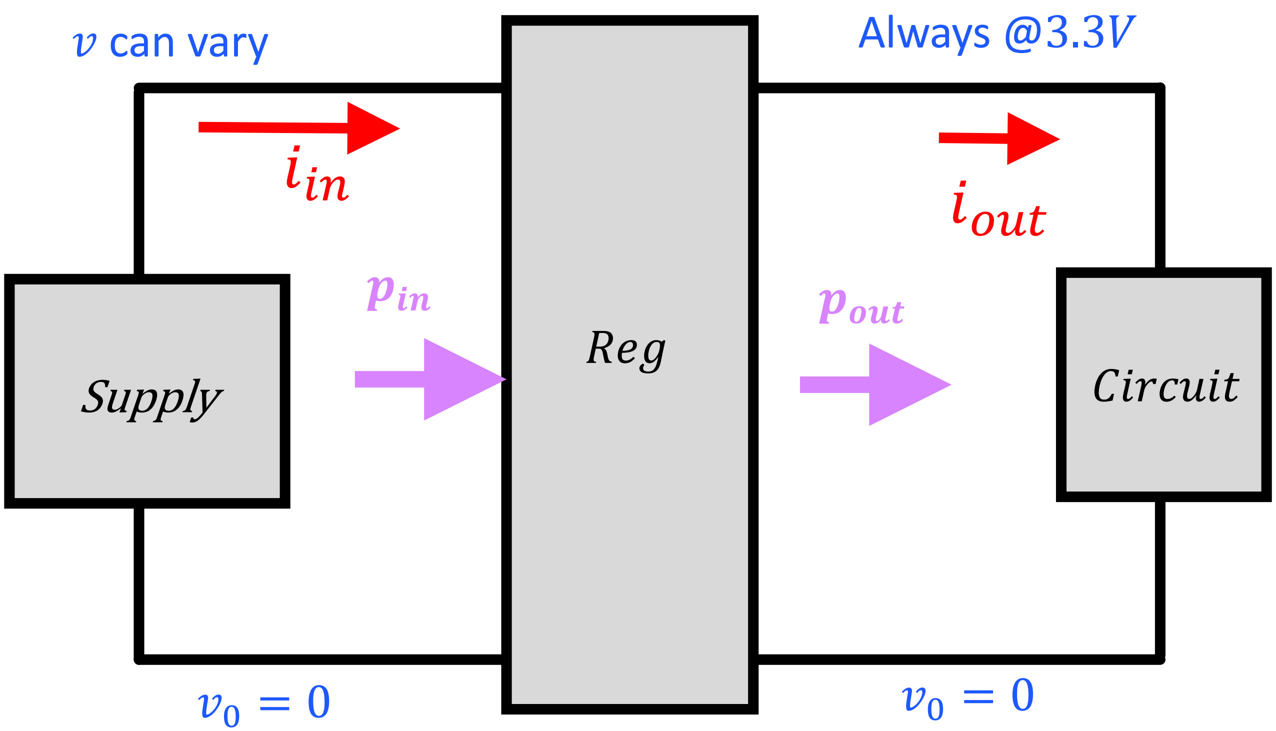
- Regulate by throwing away excess energy



$i_{in} = i_{out}$

Switching Supply (non-linear device)

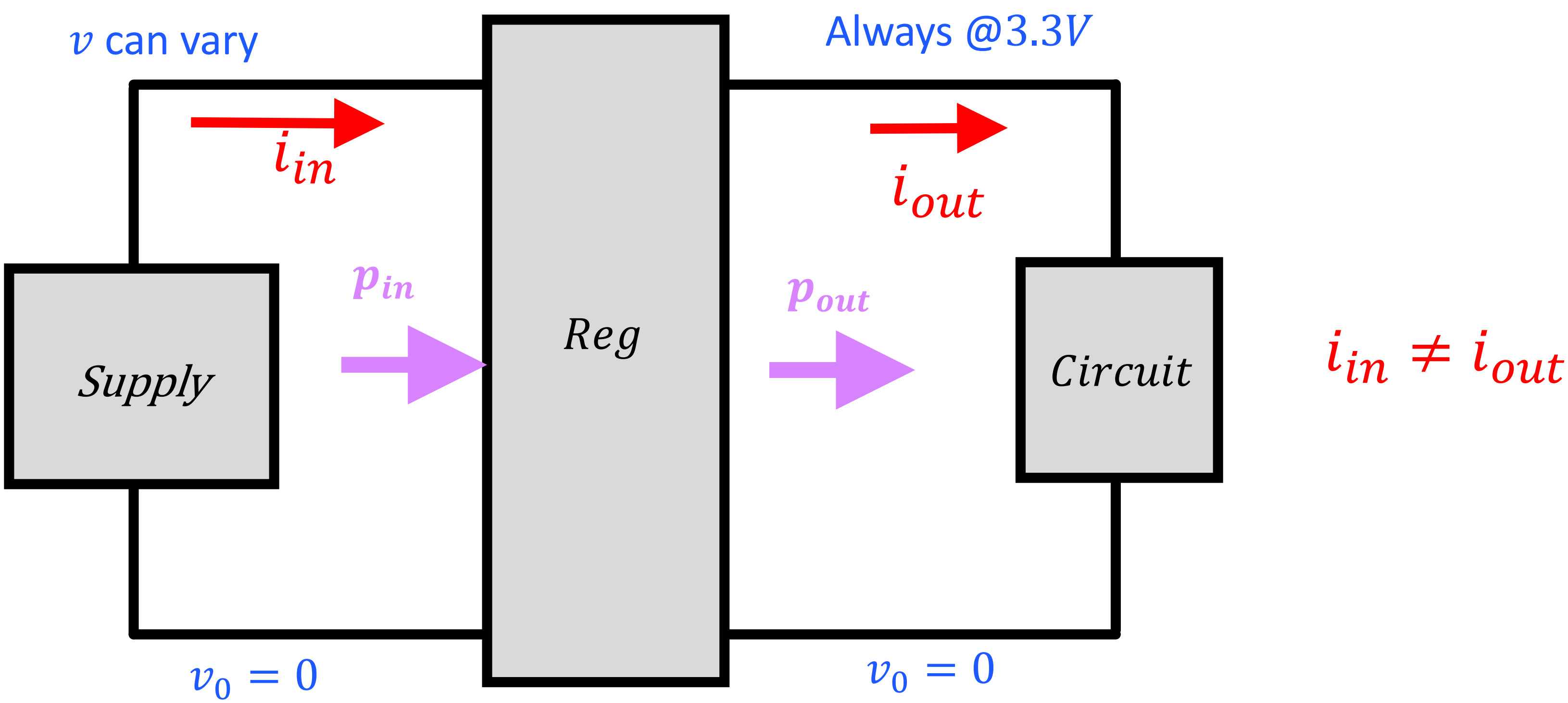
- Scaled Power Device ($p_{out} = \varepsilon \cdot p_{in}$)
  - ε is efficiency and $0 \leq \varepsilon \leq 1$
- KCL is NOT maintained through them



$i_{in} \neq i_{out}$

Switching Supply (non-linear device)

- Scaled Power Device ($p_{out} = \varepsilon \cdot p_{in}$)
  - ε is efficiency and $0 \leq \varepsilon \leq 1$

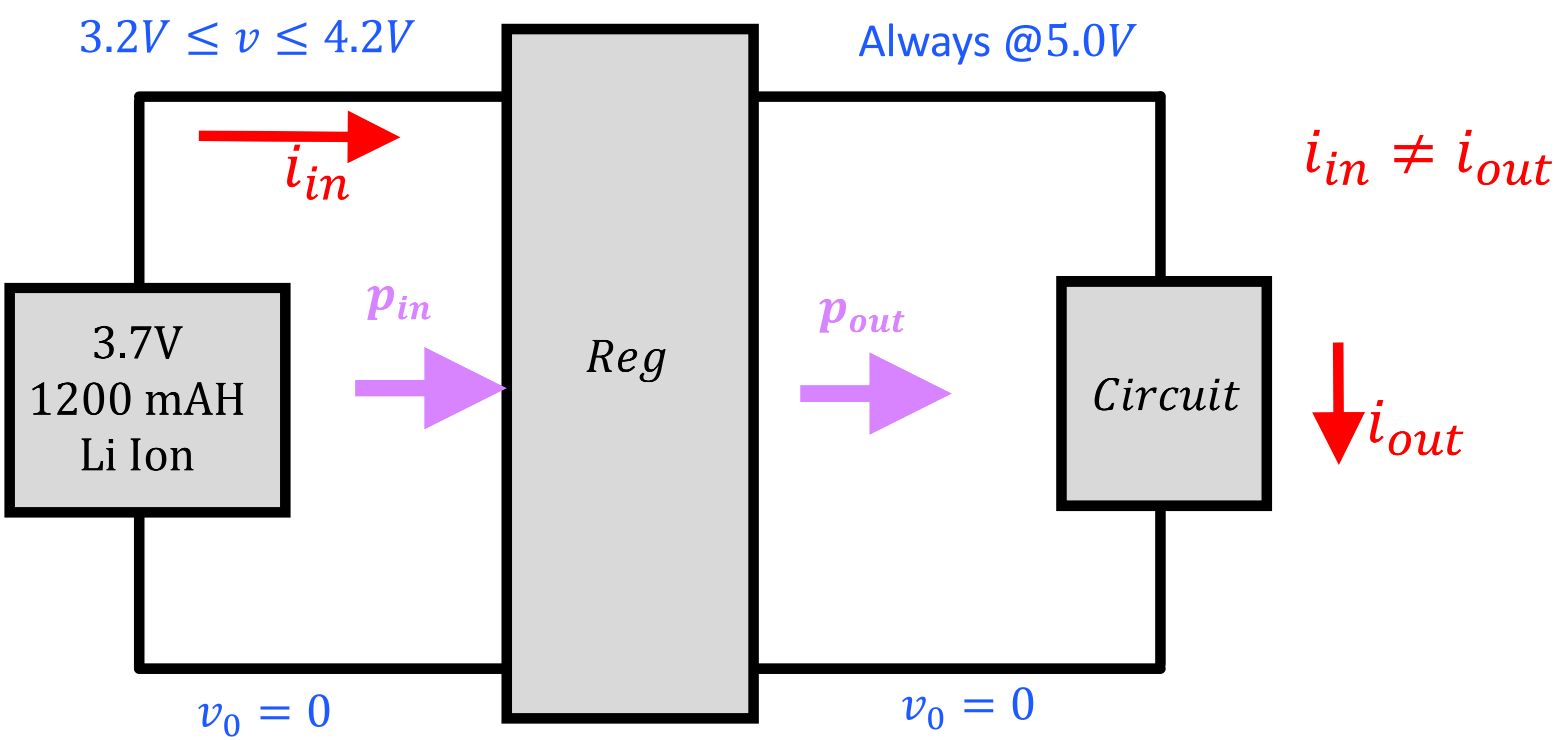


If $i_{out} = 50mA$, $i_{in} = 35mA$, and supply voltage is at $v = 5.0V$ what is the efficiency? (i.e. how much power is consumed by the circuit and not the regulator?)

Efficiency = $\frac{3.3V \cdot 50mA}{5.0V \cdot 35mA} \approx 94\%$

Switching Supply

- Switching Supplies can change voltage in two ways:
    - **increase (boost)**
    - **decrease (buck)**
- Linear regulators can't. They can only drop voltage



Issues

- In some power spaces, switching supplies are no-brainer decisions
- But they are:
  - More expensive
  - Can use more real estate on your board (complicate BOM)
  - Introduce more noise
- In “low-voltage” settings like your team project, the differences can be less drastic between linear and switching (is 90% vs. ~70% worth several extra dollars?)