Power I

6.9000

Spring 2024

Things To Talk About

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

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

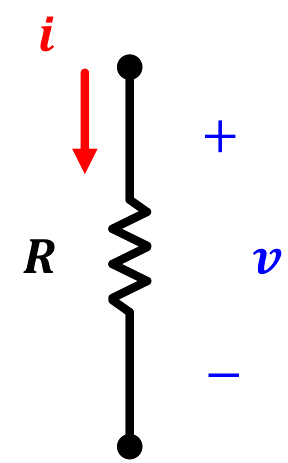
Lower Limit on Computation

- 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

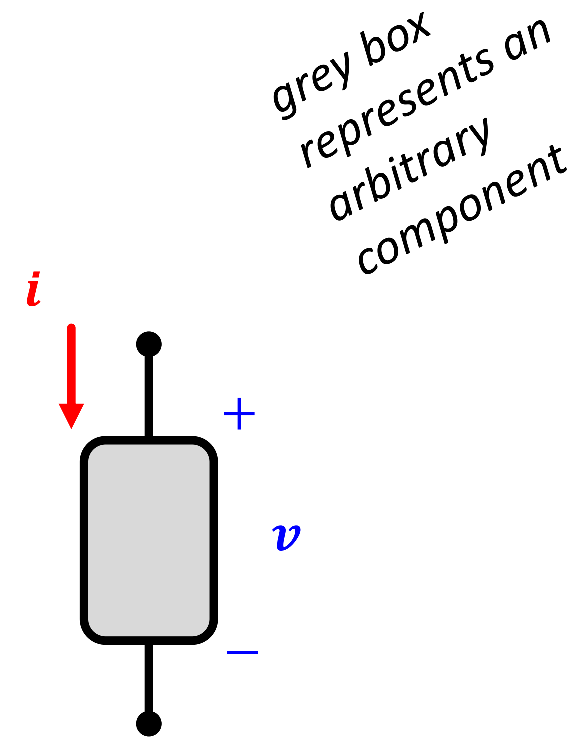


$$v = i \cdot R$$

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

$$p = v \cdot i$$

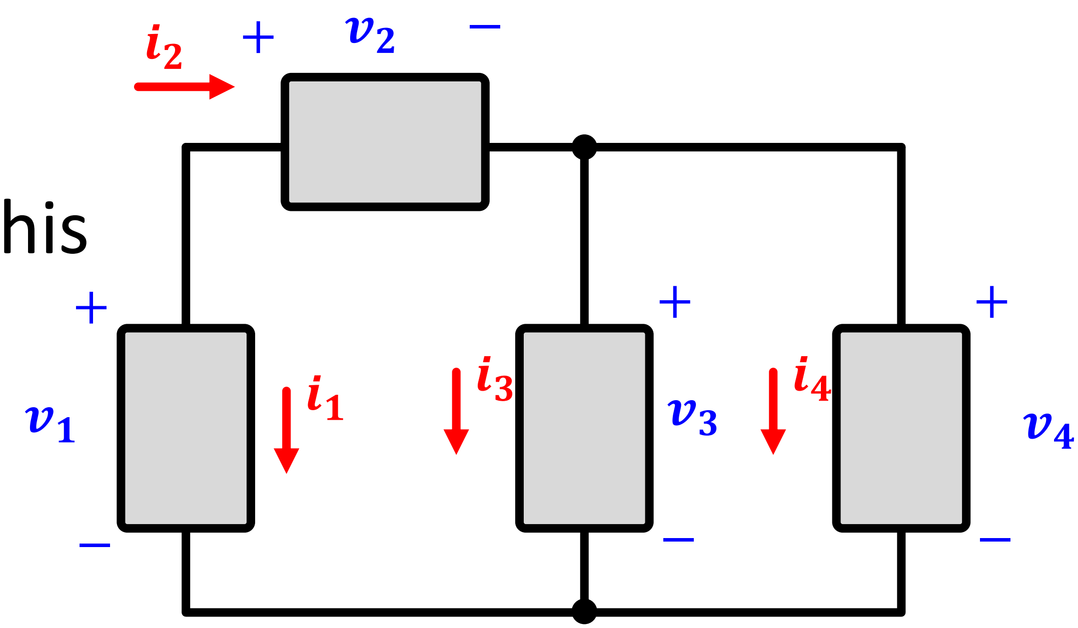


$$p = \frac{\text{Joule}}{\text{Coulomb}} \cdot \frac{\text{Coulomb}}{\text{sec}} = \frac{\text{Joule}}{\text{sec}} = \text{Watt}$$

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:

$$\mathbf{0} = \sum_{i=0}^{n} \boldsymbol{i}_{2} \cdot \boldsymbol{v}_{2}$$



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?

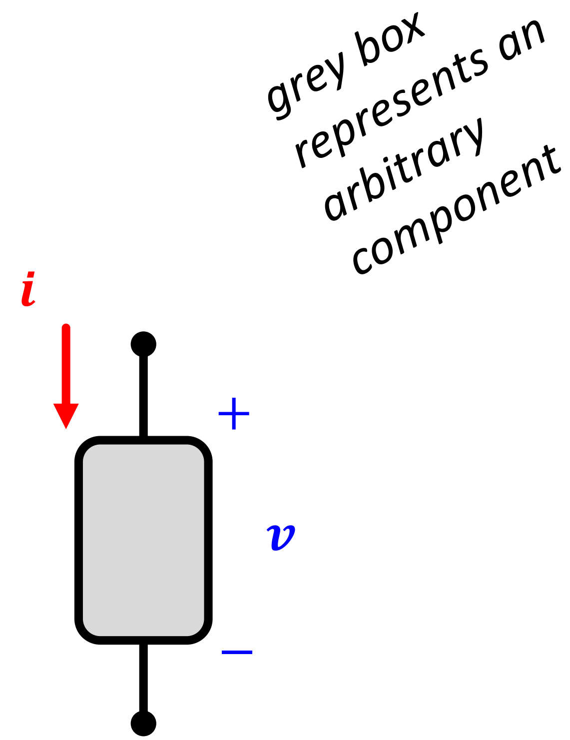
Power

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

$$p = v \cdot i$$

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

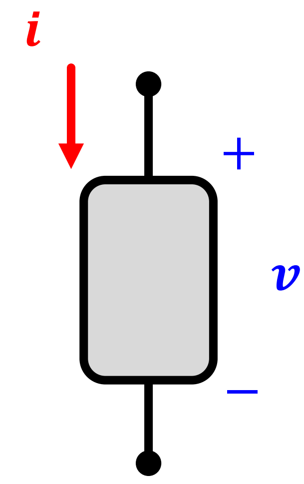
$$p = \frac{\text{Joule}}{\text{Coulomb}} \cdot \frac{\text{Coulomb}}{\text{sec}} = \frac{\text{Joule}}{\text{sec}} = \text{Watt}$$



Now Caveats

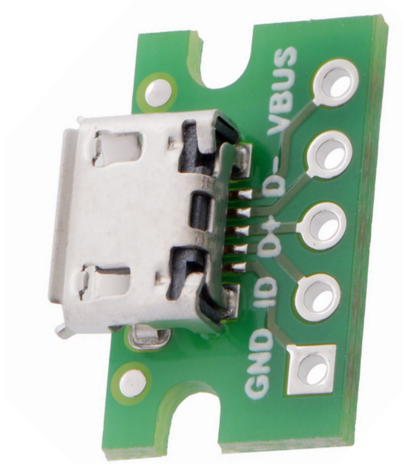
- The sign of power is great from a theory perspective and in deducing what devices are supplying/consuming power
- However in life, we usually know what components are supplying or consuming power *a priori*
- So generally power-supplying devices will have their currents documented and specified as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

$$p = v \cdot i$$

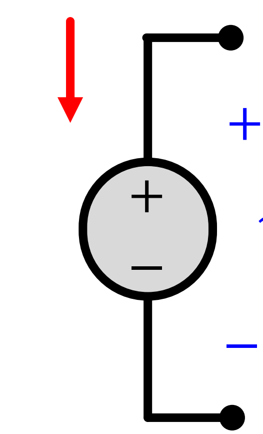


- If **p>0**, it **consumes** power
- If **p<0**, it **supplies** power

Example: MicroUSB Socket



$\approx$



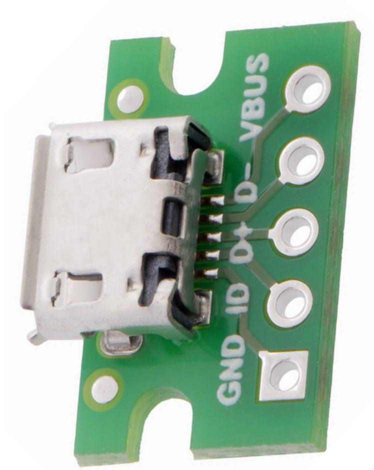
In Normal Operation:

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

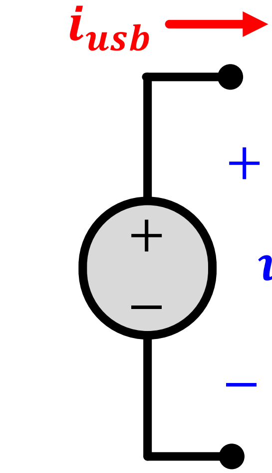
$$i_{usb} < 0\text{A}$$

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

$$p_{usb} < 0$$



$\approx$



In Normal Operation:

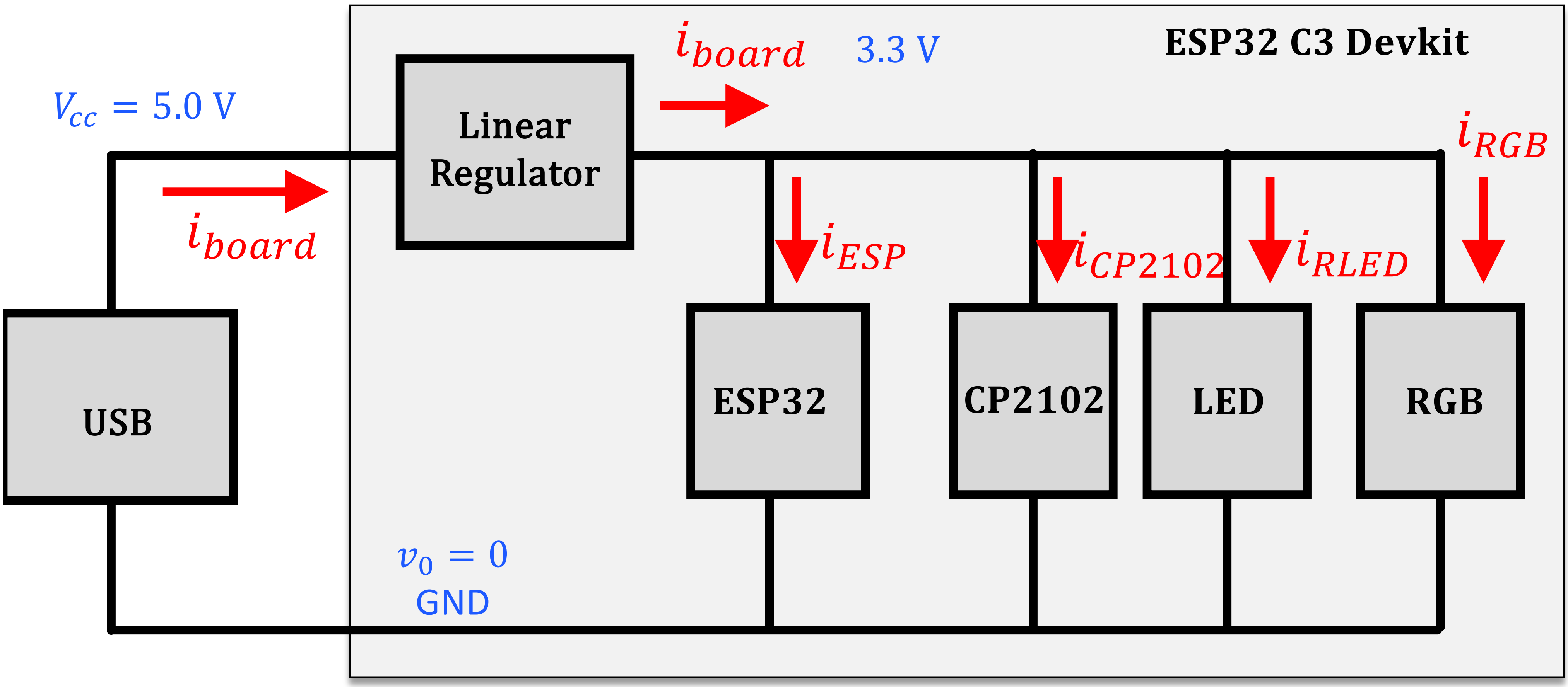
$$v_{usb} \approx 5\text{V}$$

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

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

$$“p_{usb}” > 0$$

Example: ESP32 C3 Board



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

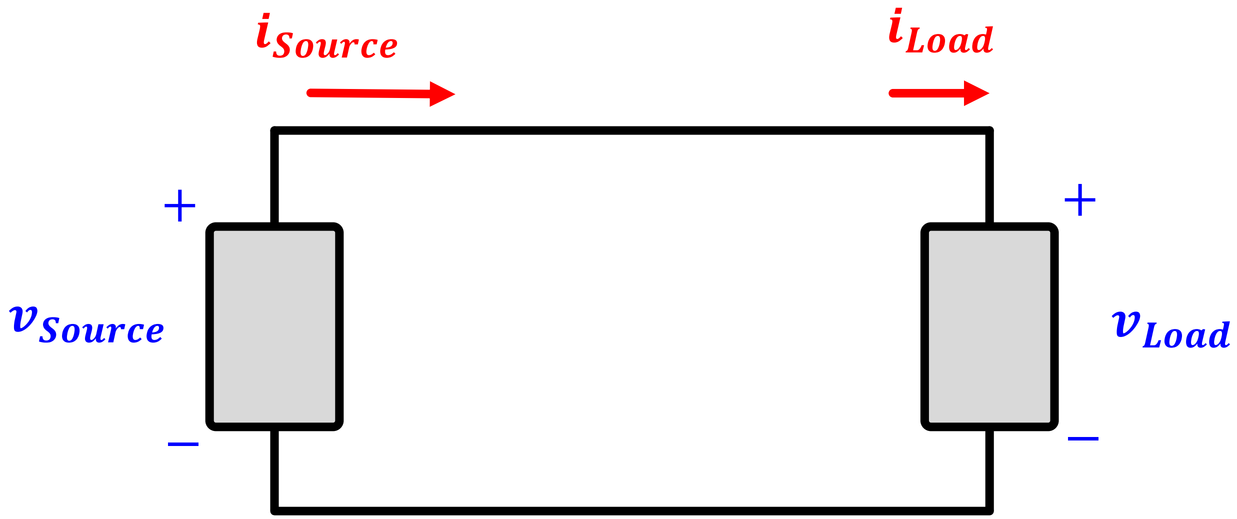
$i_{ESP} \approx 18.4\text{mA}^{*}$

*based on mode of operation

**if off

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

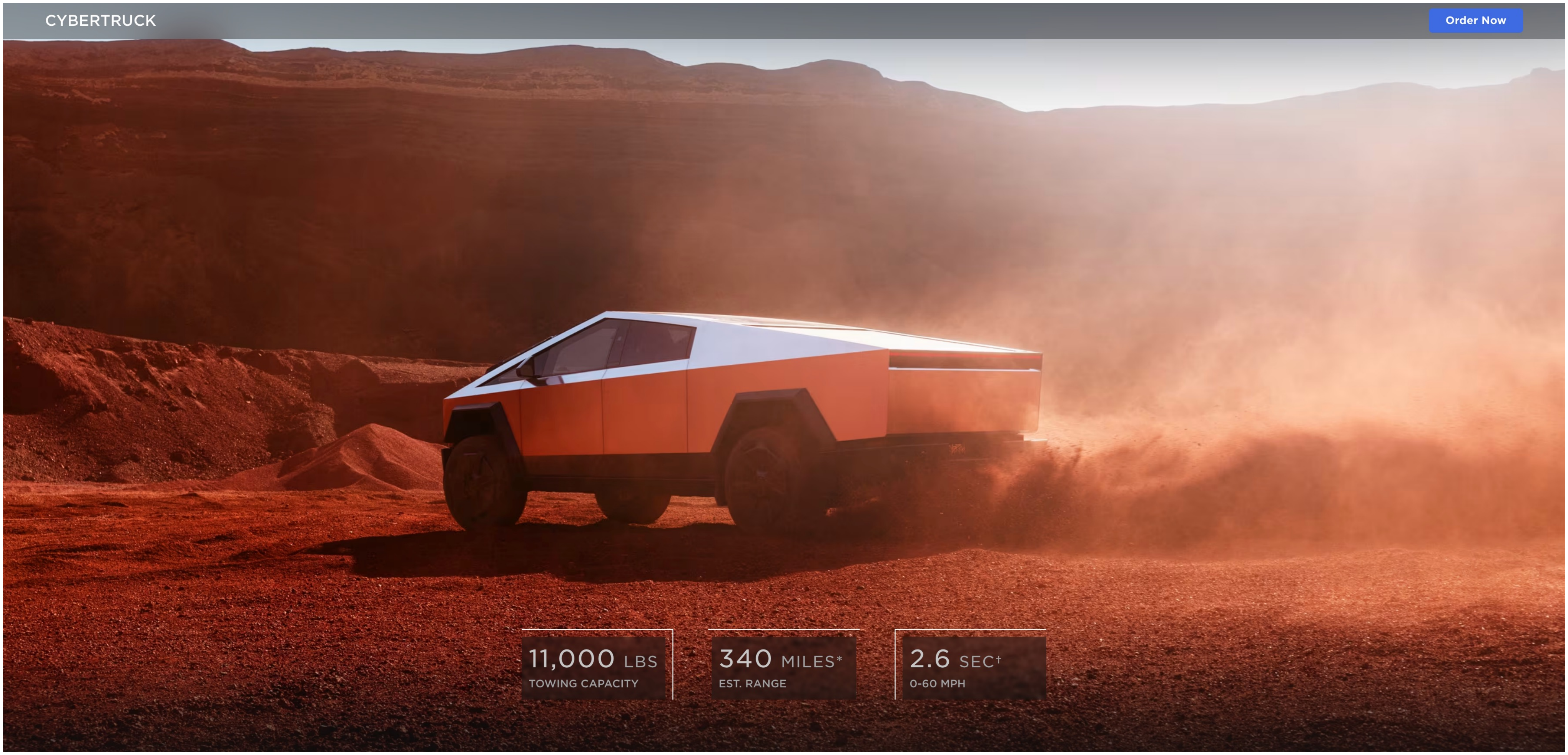
4.6 Current Consumption

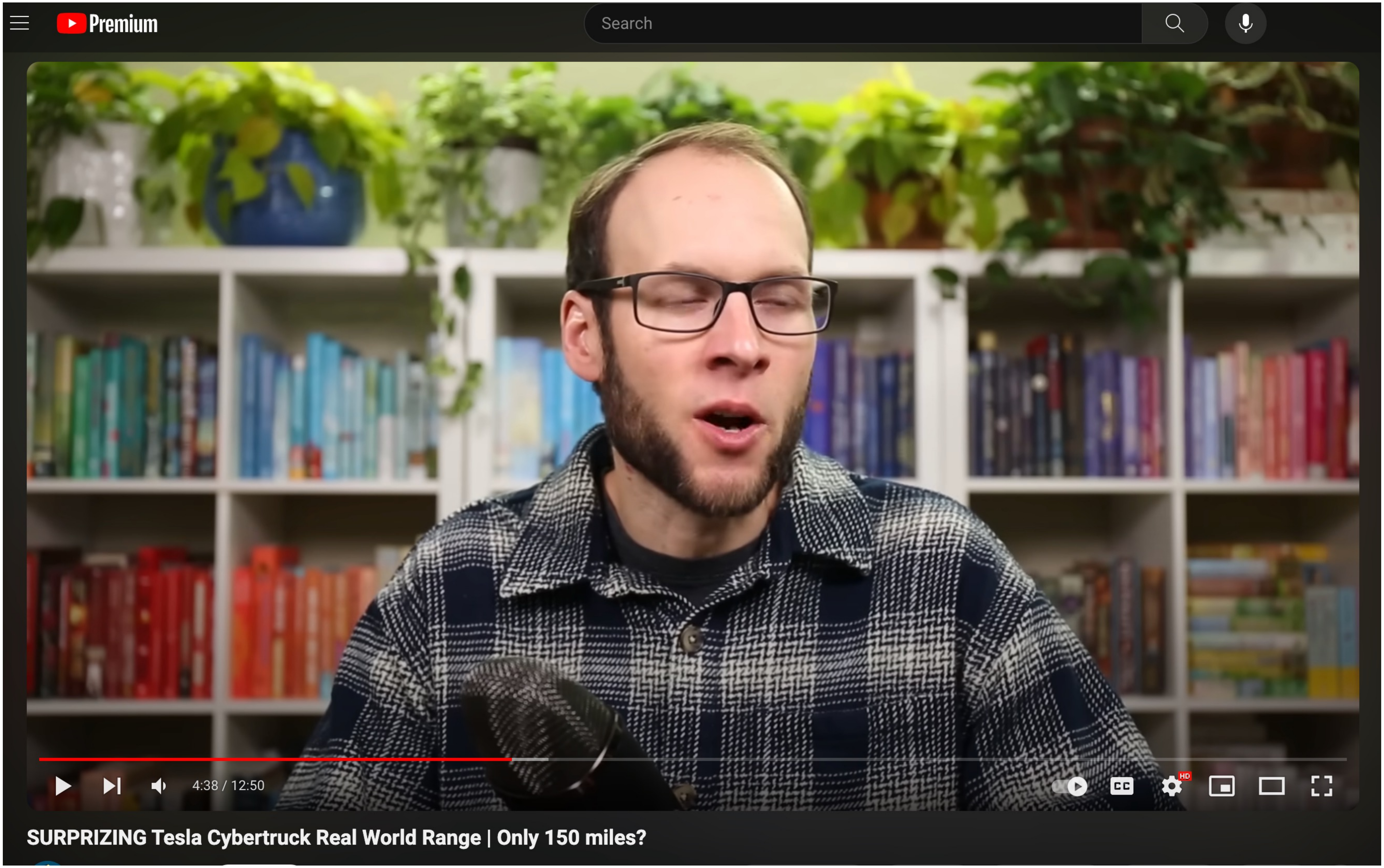
4.6.1 RF Current Consumption in Active Mode

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
Search
4:38 / 12:50
HD
SURPRIZING Tesla Cybertruck Real World Range | Only 150 miles?

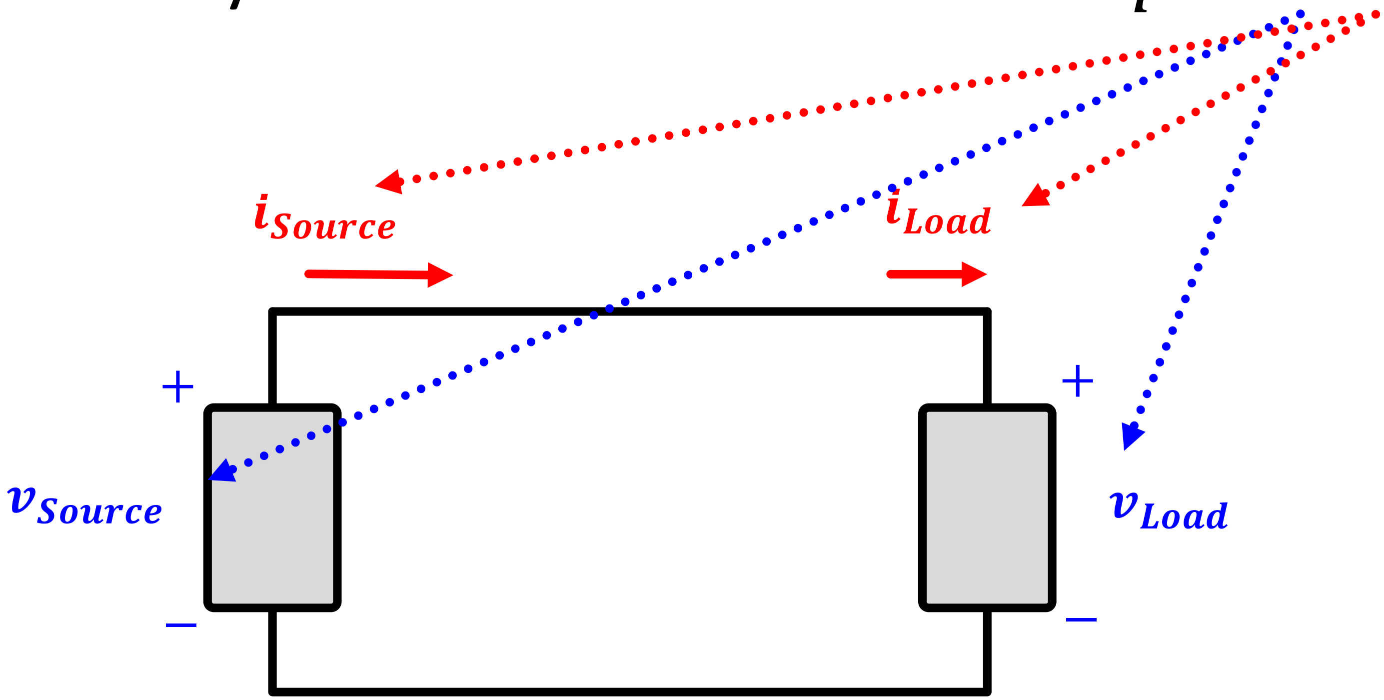
DataSheets

- Datasheets are somewhat based in fact, but they should always be viewed cautiously.
- They are propaganda in a sense.
- 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!

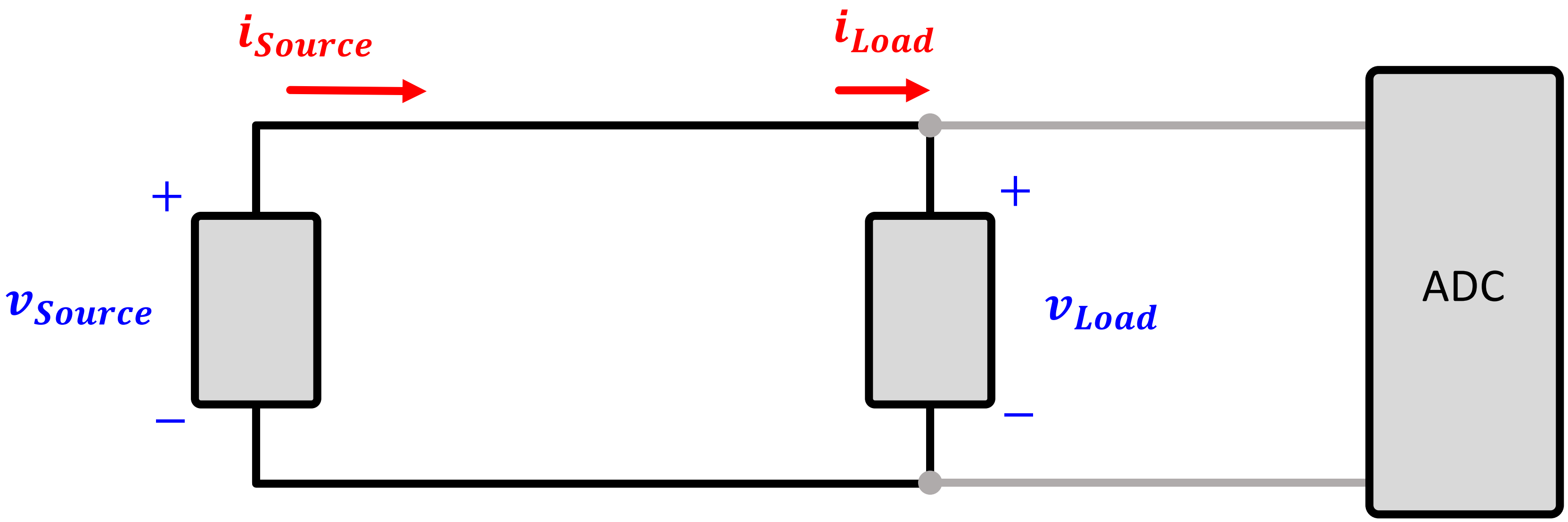
How Do You Measure Power?

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



How Do You Measure Voltage?

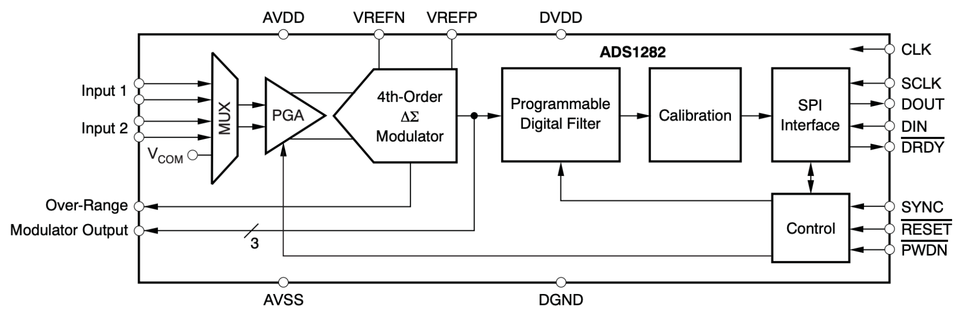
- This one is easy-ish. You can use a voltmeter or an Analog-to-digital converter and measure in parallel



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):

FUNCTIONAL BLOCK DIAGRAM

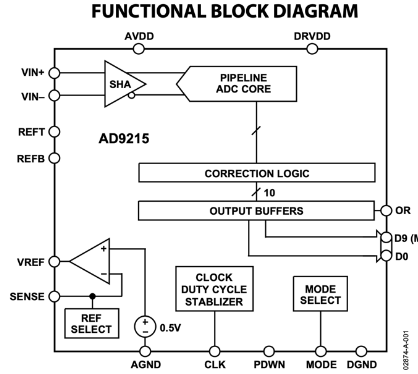
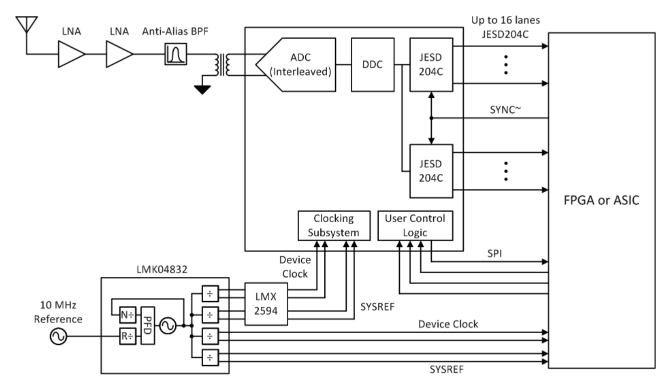


Figure 1.

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



How Do You Measure Current?

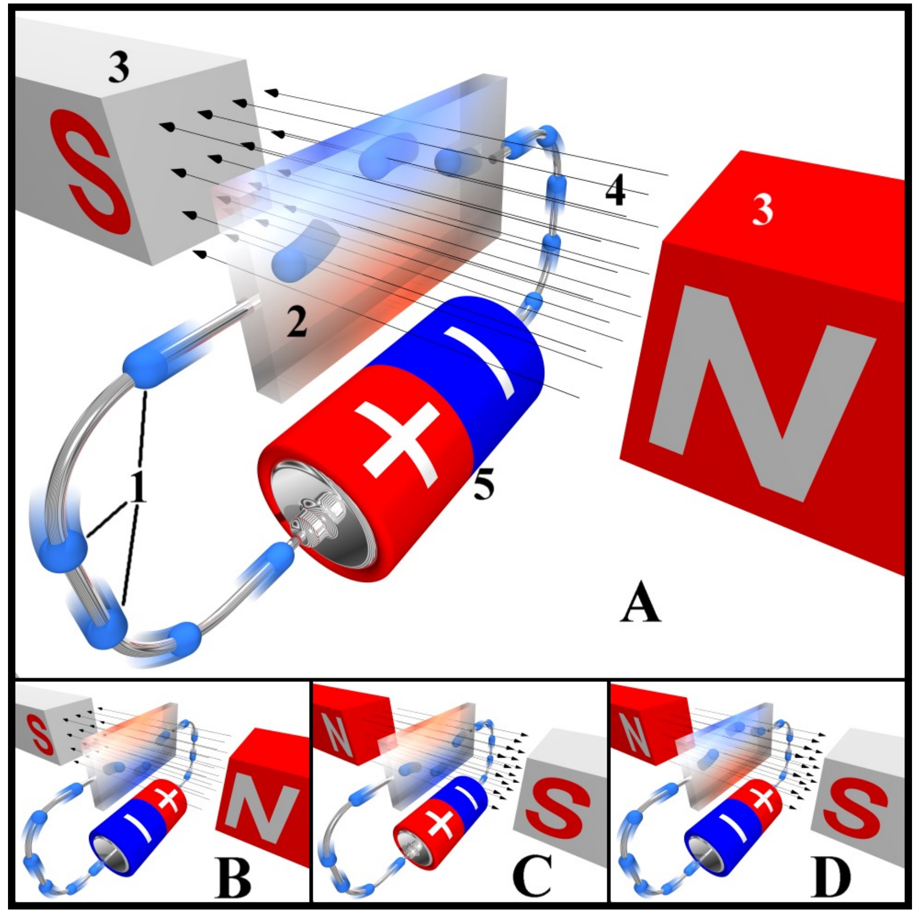
- Voltage is quite easy to measure. We have extremely sensitive voltage measurement devices out there.
- Current is actually a lot harder
- How to measure?

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

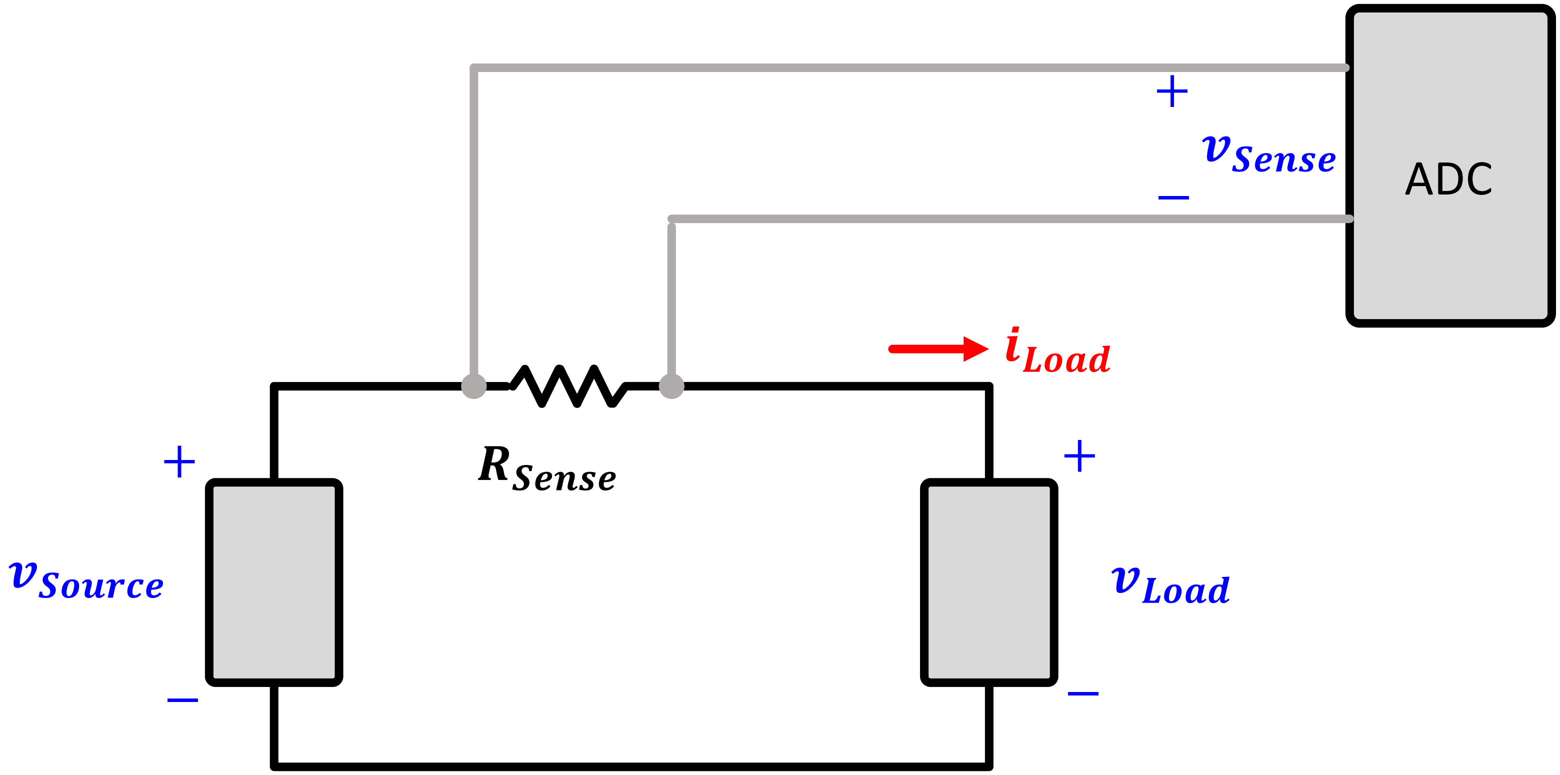
Both coils and Hall Effect Sensors

- Neither Ideal…

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 device could do this sort of behavior?
  - Take a current…
  - Reliably convert that current into a voltage…
  - ???

How Do You Measure Voltage?



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?

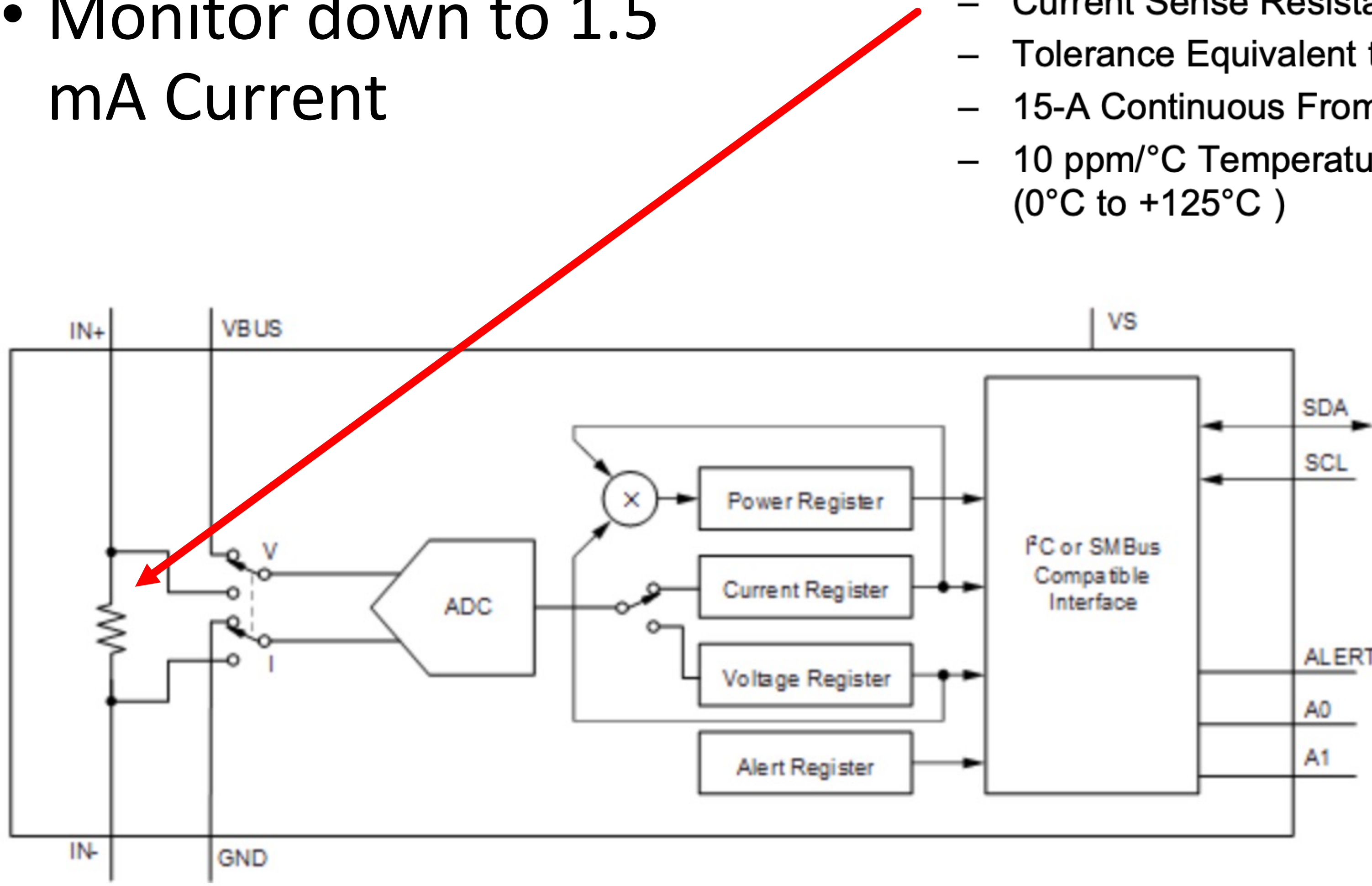
- You could build a circuit to do this! However for it to work with very low powers you'd really want:
  - Very high precision op amps
  - ADCs
  - Resistors!
- You could also buy some chips that do this all in one!

Texas Instruments' INA260 et al

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

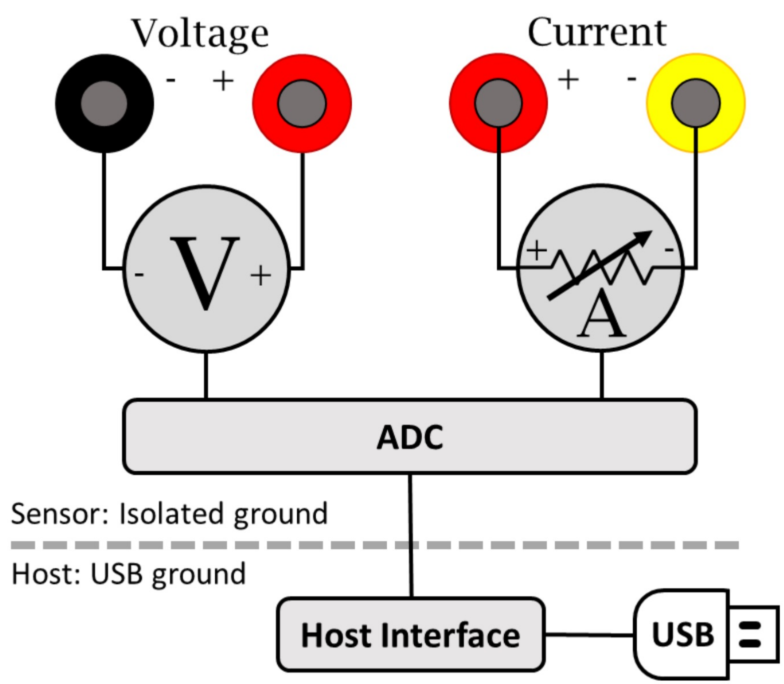
1 Features

- 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)



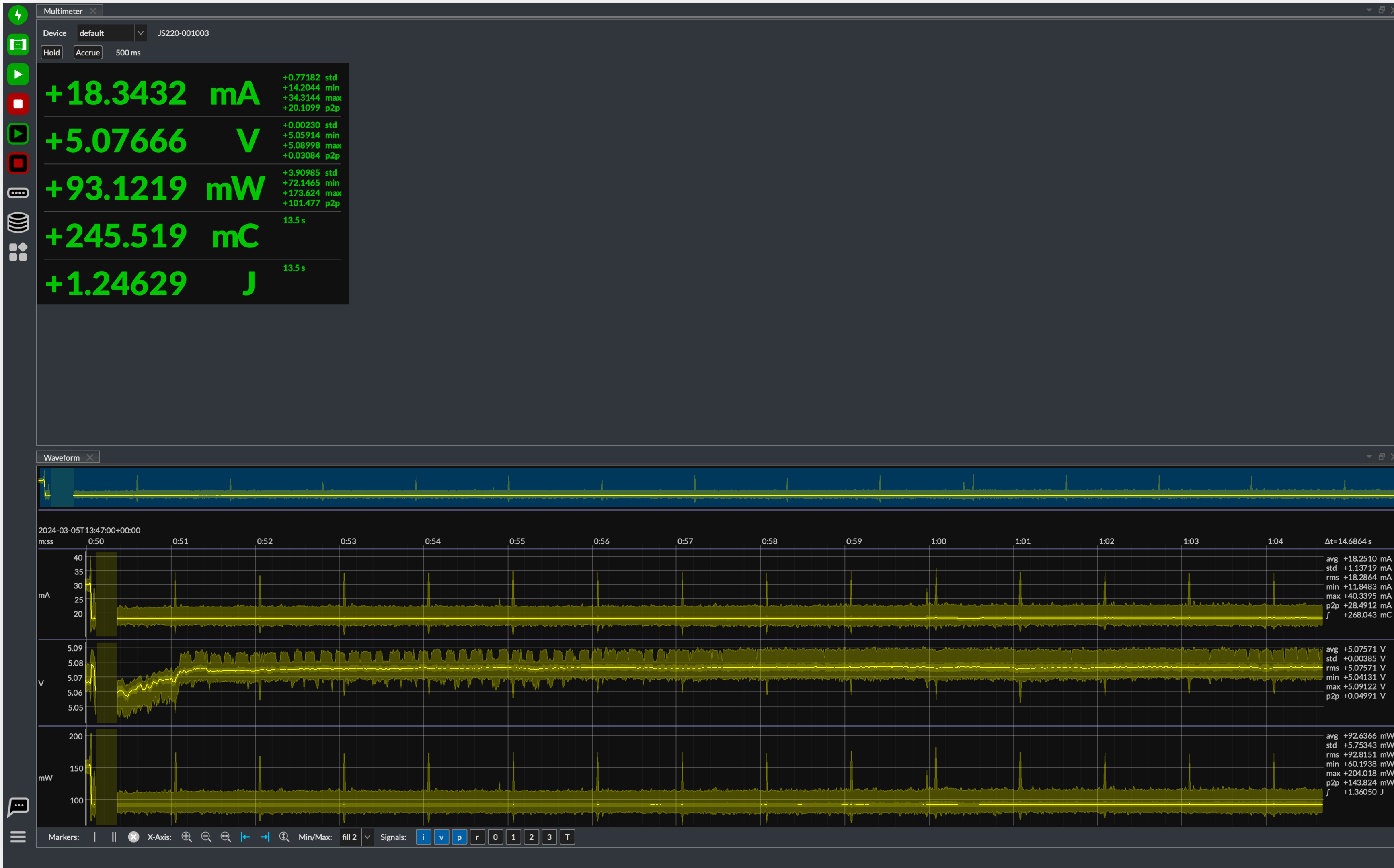
JouleScope

- Device we'll use in Lab 05 this week to measure our devices and which you'll need to use heavily to characterize your system



https://www.joulescope.com/

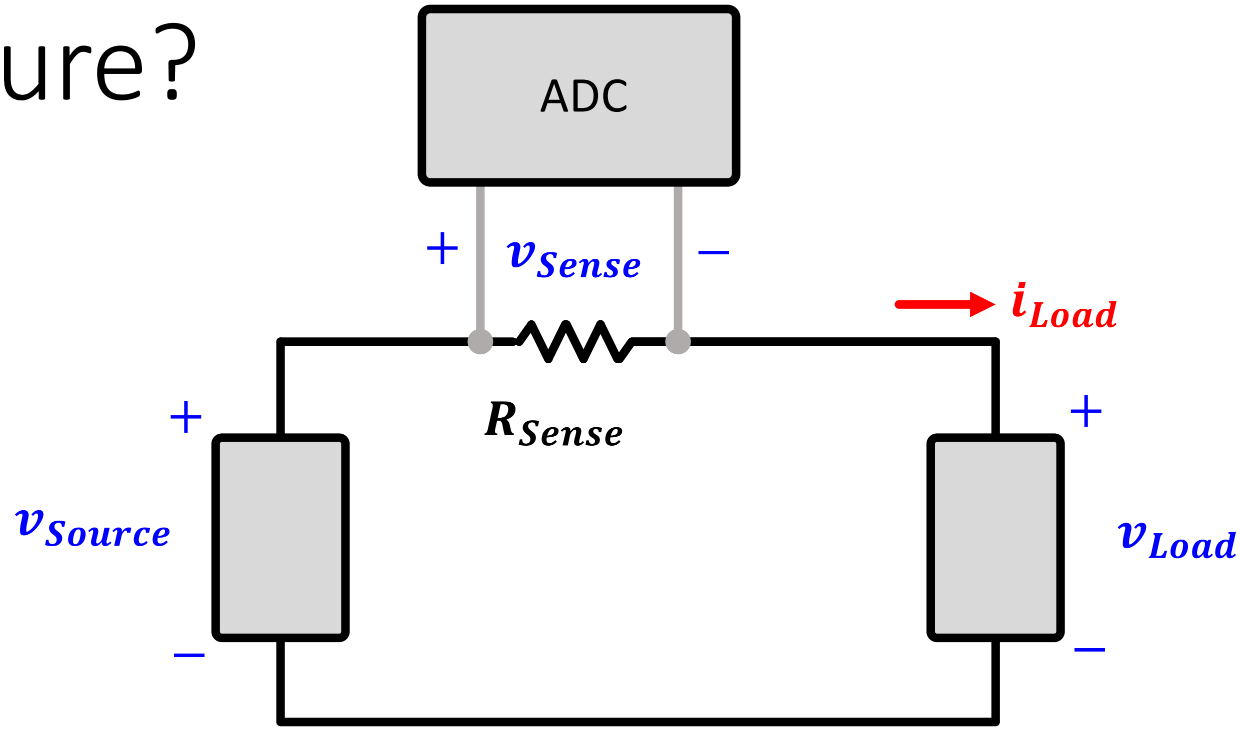
Very Nice Readout



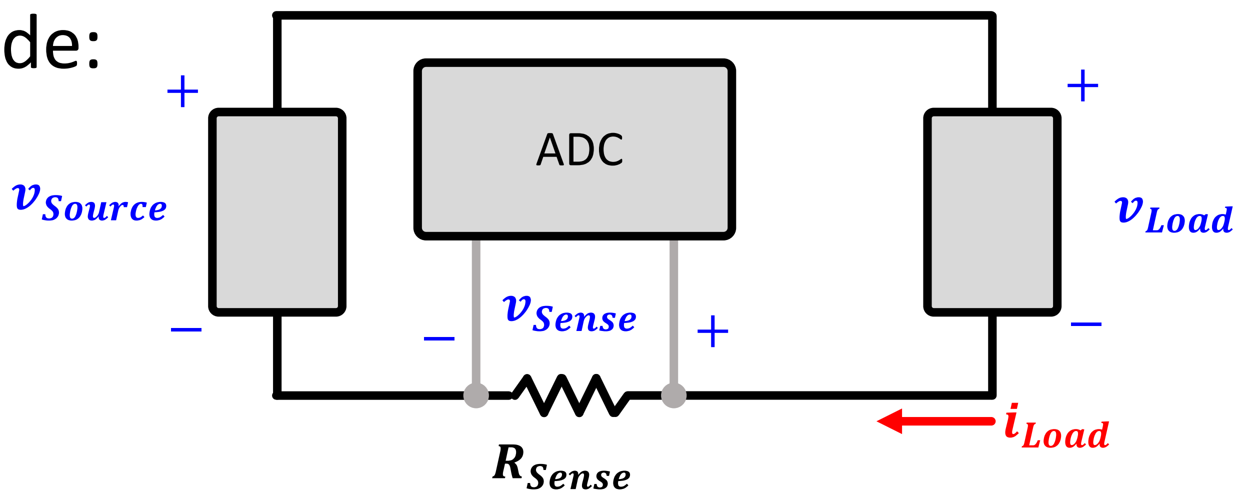
Application GUI…can readout and do all the stuff.

Where to Measure?

- High-Side:

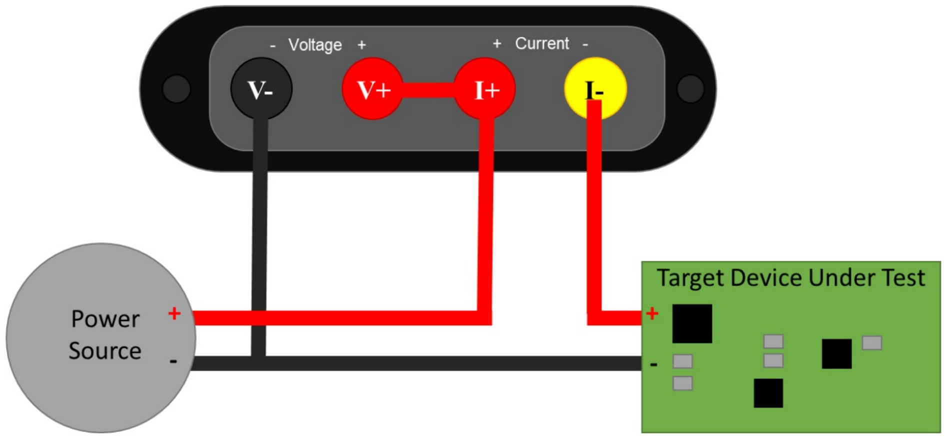


- Low-Side:

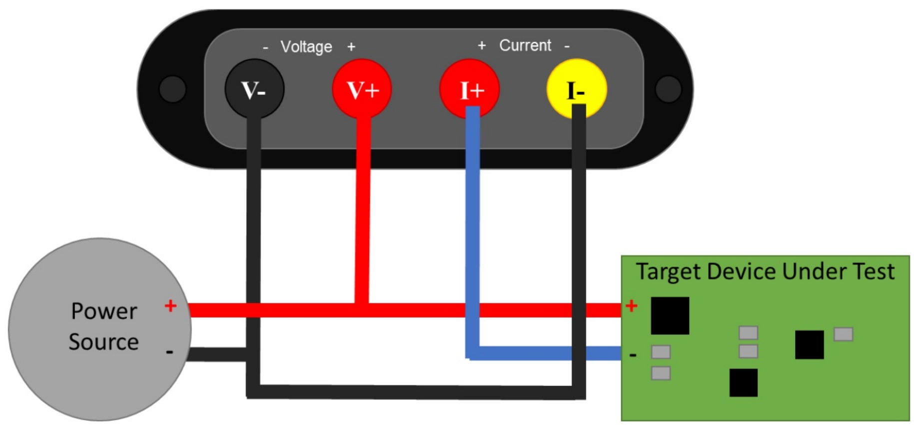


Joule Scope OK with That

- High-Side



- Low-Side



So in Lab 05 you'll use the Joulescope to measure…

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

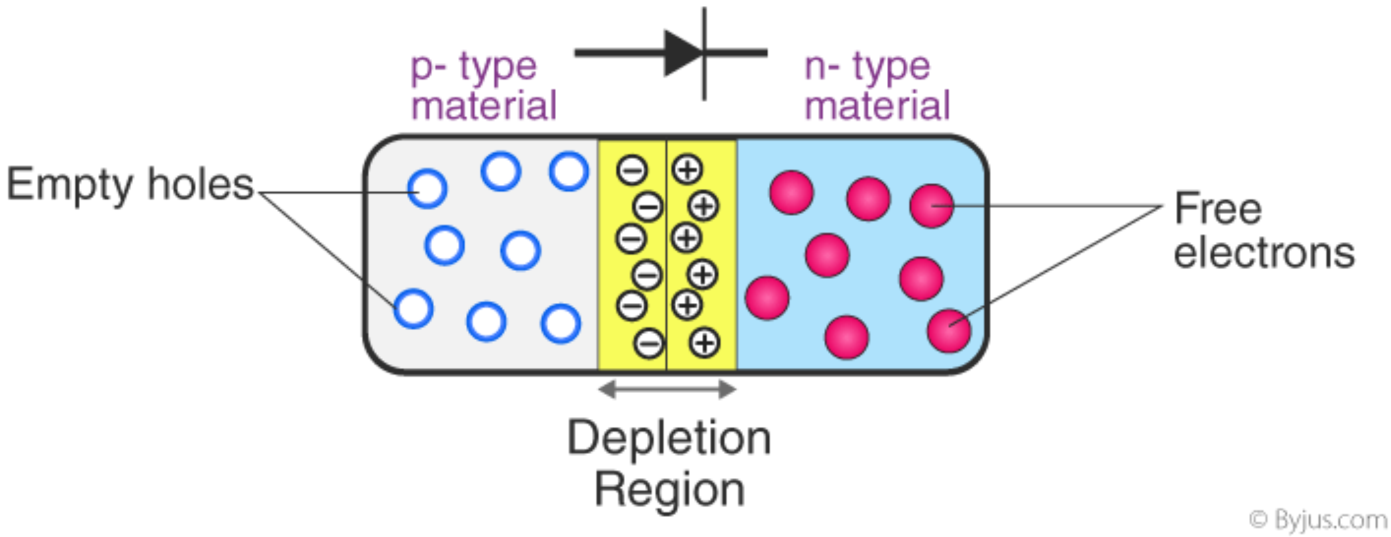
- And then for the project you will need to use this for characterizing your system in whole and in parts!

Solar Cell

- A Photovoltaic Cell

PN Junction

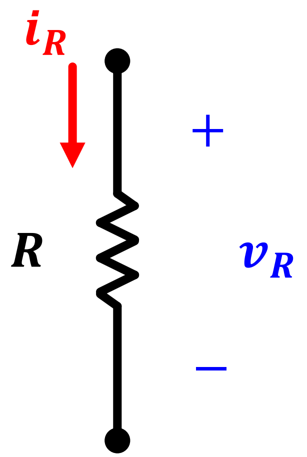
- A Solar cell is, interestingly, just a PN diode

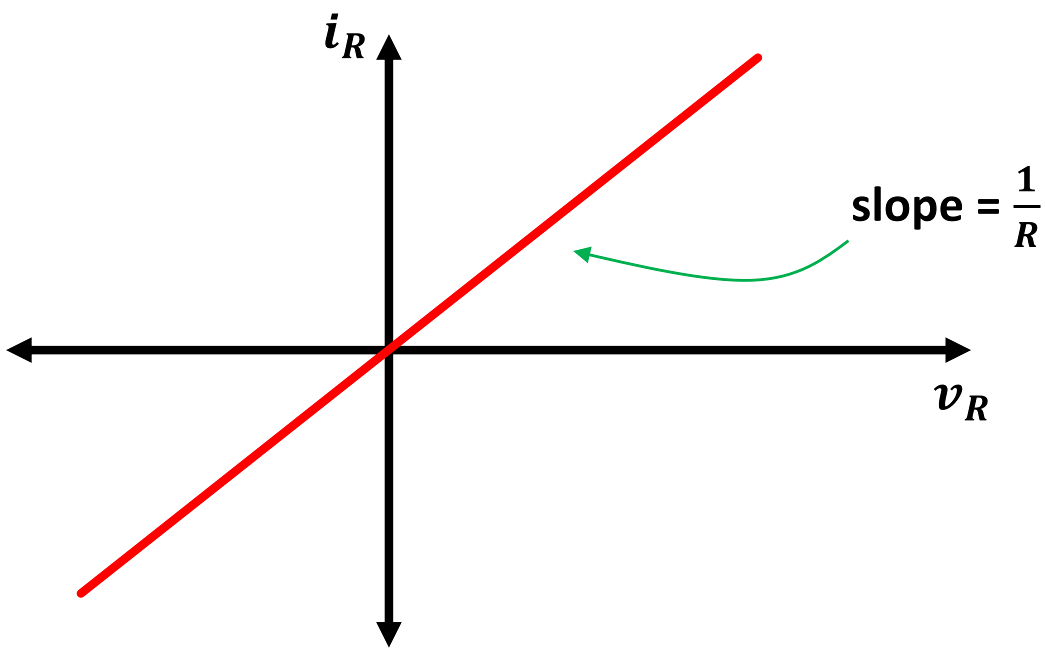


https://byjus.com/physics/p-n-junction/

What is the I-V relationship of a diode?

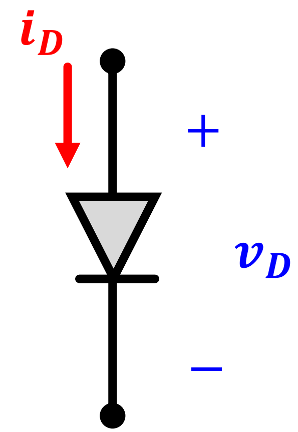
- A resistor, you'll remember is:

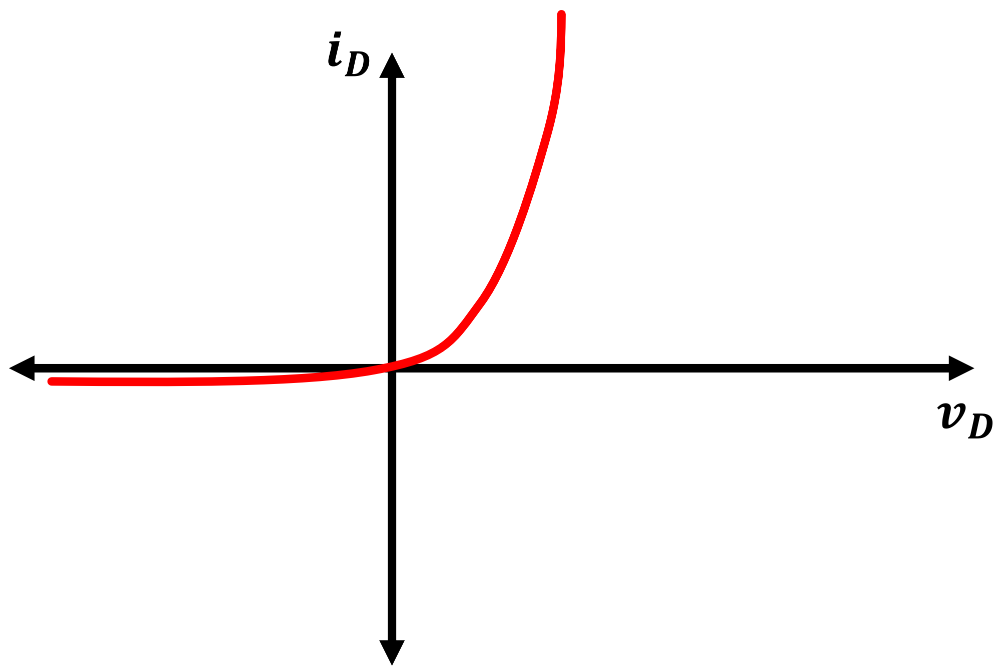




What is the I-V relationship of a diode?

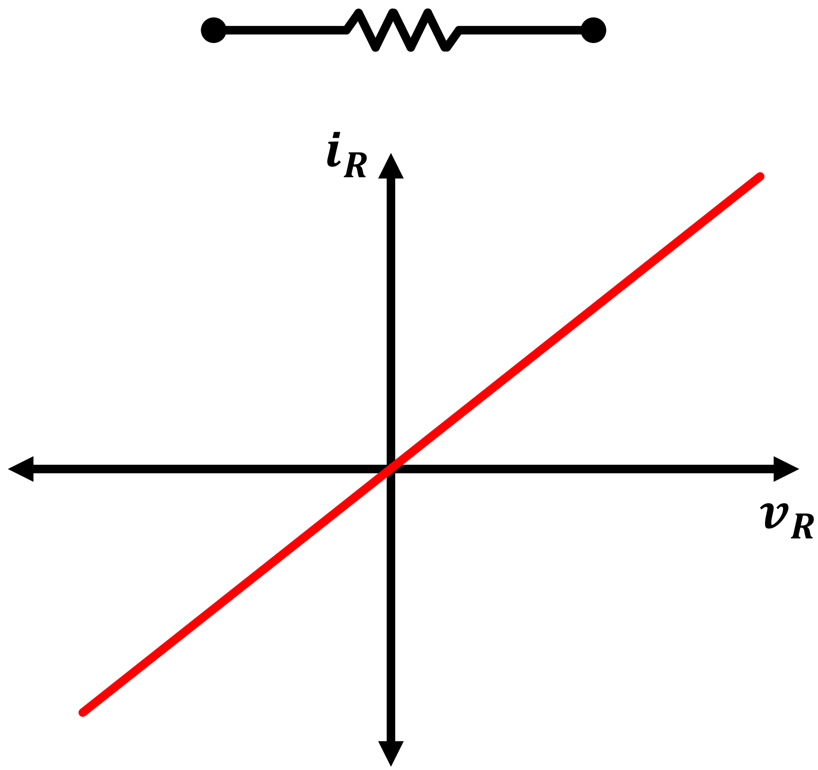
- Now a Diode

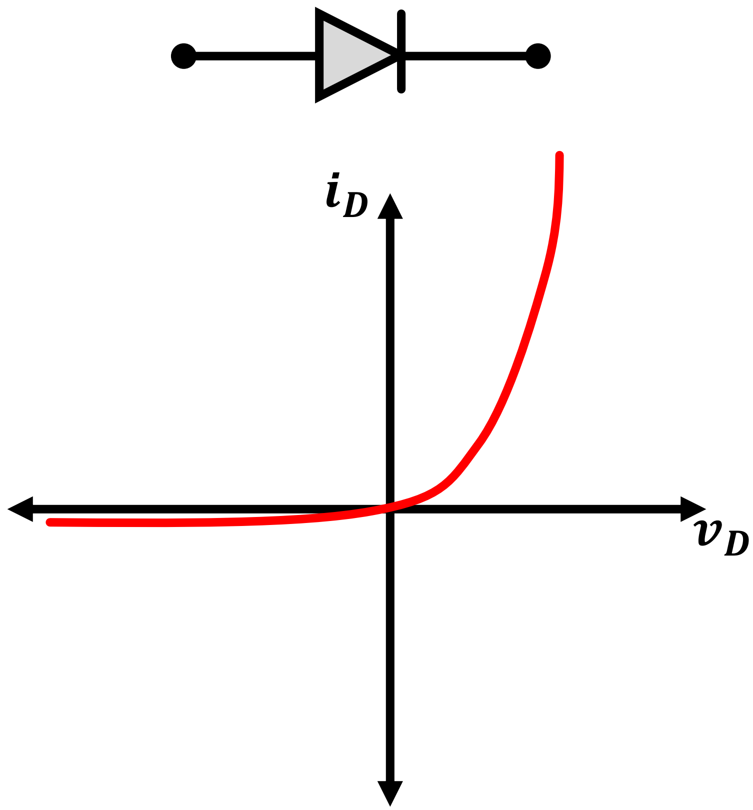




Interesting Feature to Notice

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





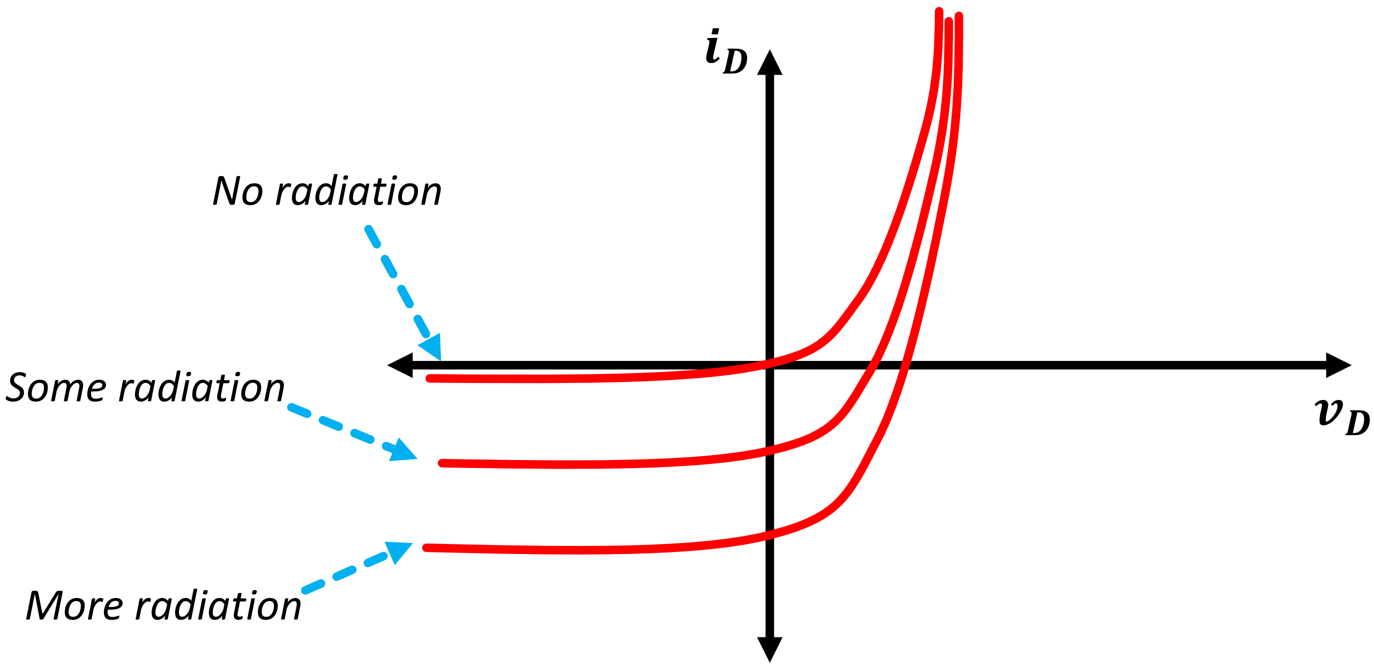
Quadrants

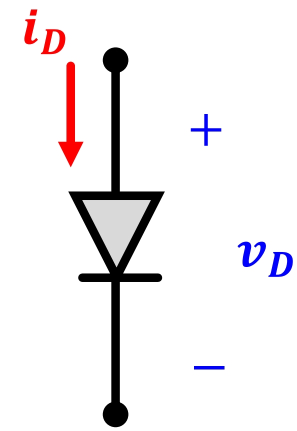
- Diodes and resistors (and all non-power-generating devices) will be stuck in quadrants I and III
- In those quadrants: $p = v \cdot i$
  - Quadrant I: $p = (+) \cdot (+) \rightarrow (+)$
  - Quadrant III: $p = (-) \cdot (-) \rightarrow (+)$
- This is really meaningful…why?

- 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

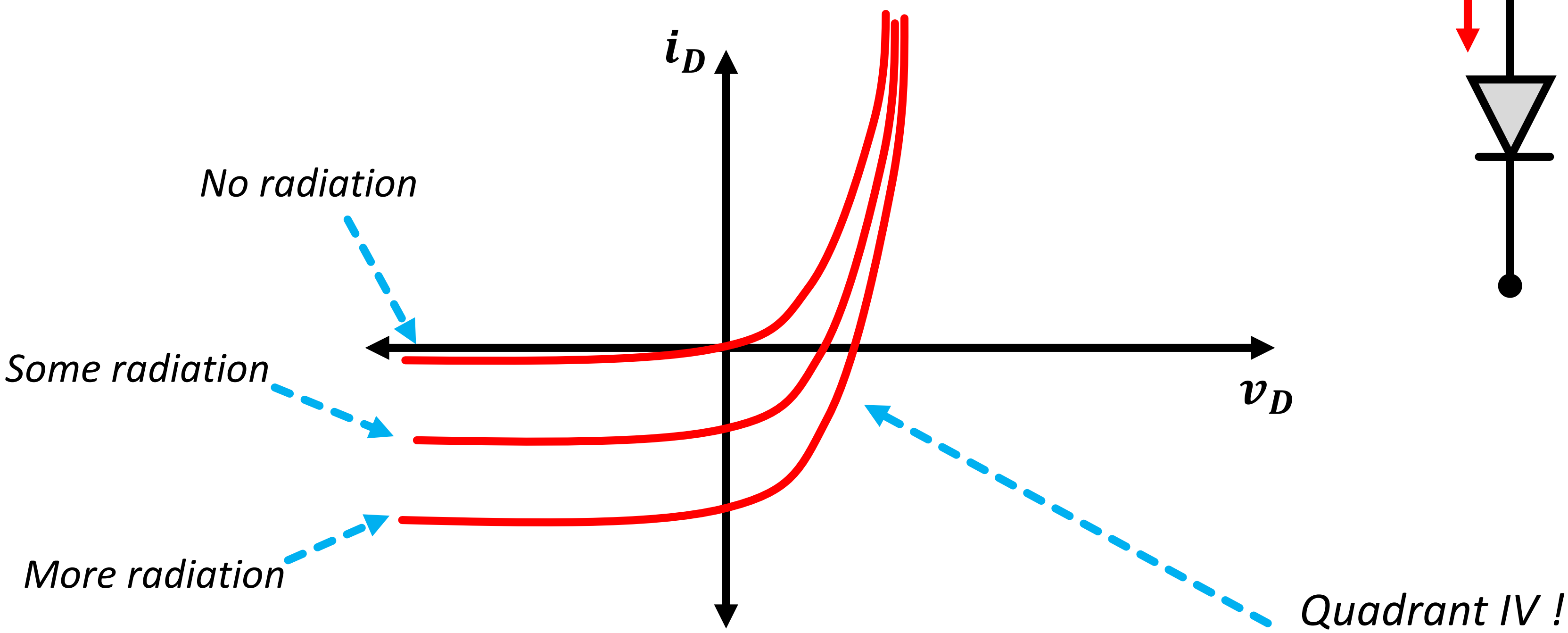




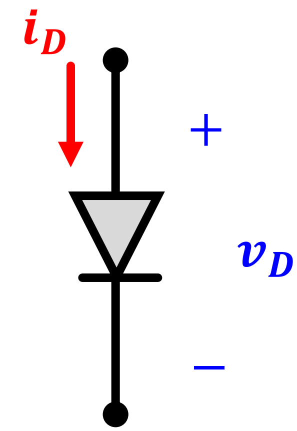
- What Do you Notice About these curves?

A PN junction exposed to radiation

- Light starts to shine on a PN junction



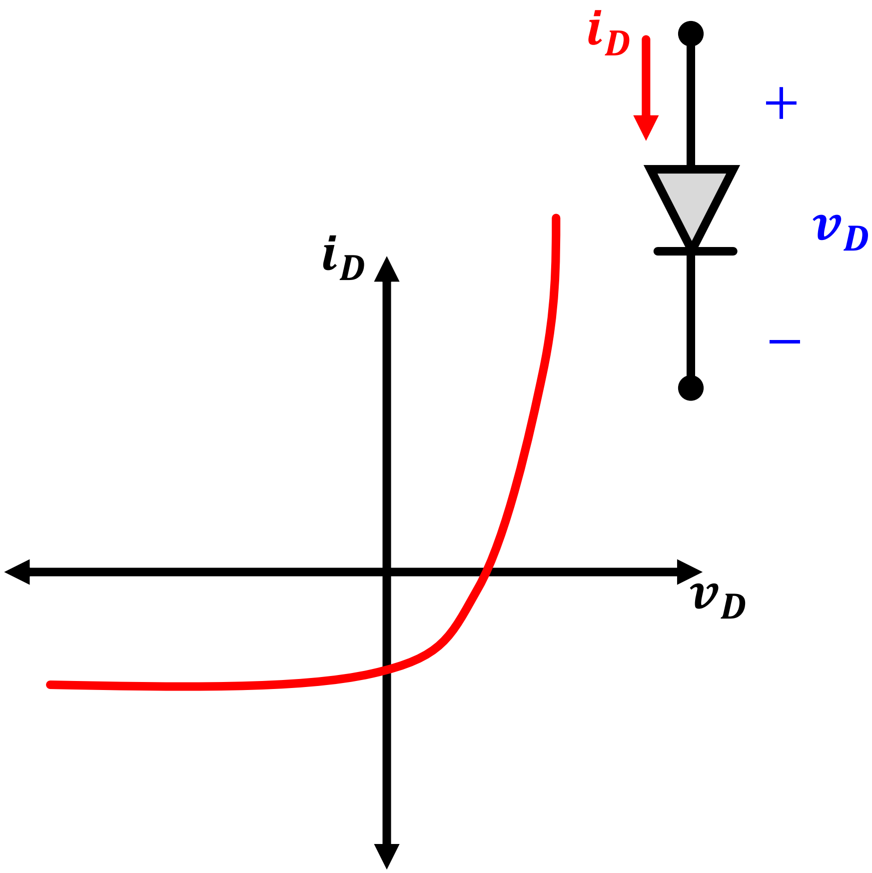
$$p = (-) \cdot (+)$$

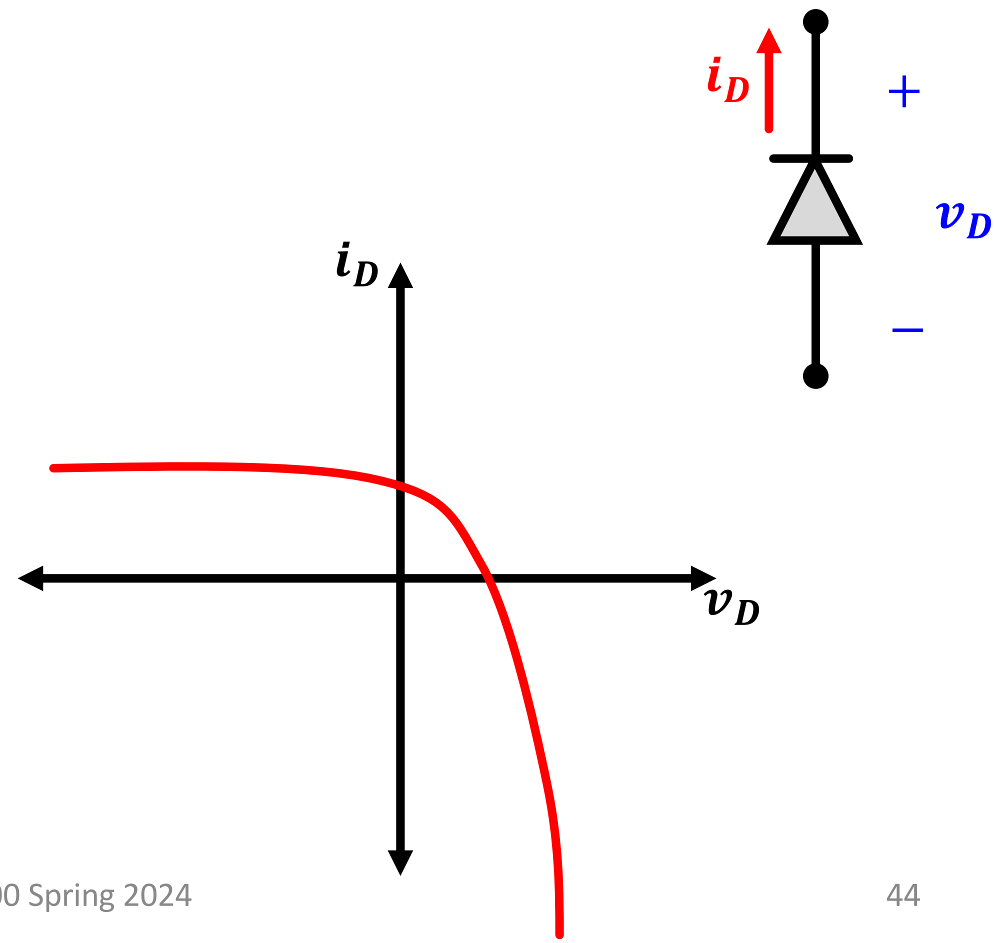


- What Do you Notice About these curves?

They Usually Flip Axes

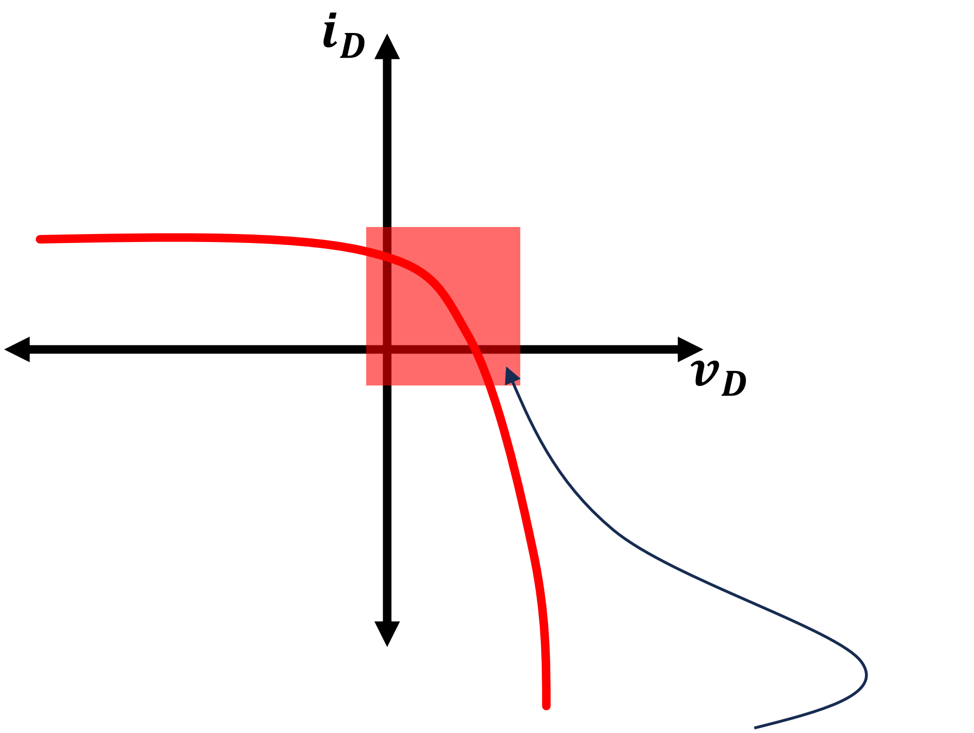
- When drawing Power-supply devices we usually flip the axes (as mentioned earlier!!!)



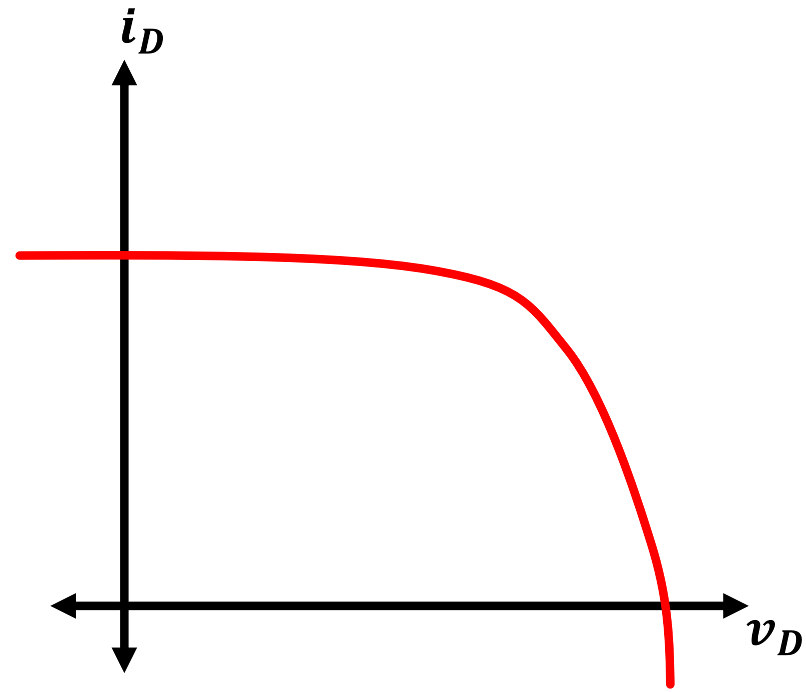


The I-V curve of a PV Cell

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

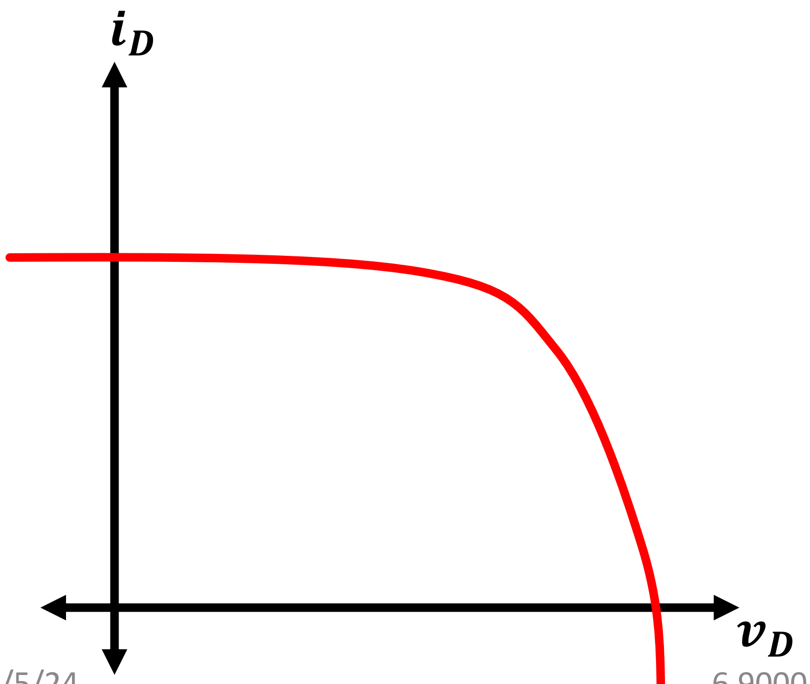


Zoooooooooooom in on this region!
Since that’s what we care about



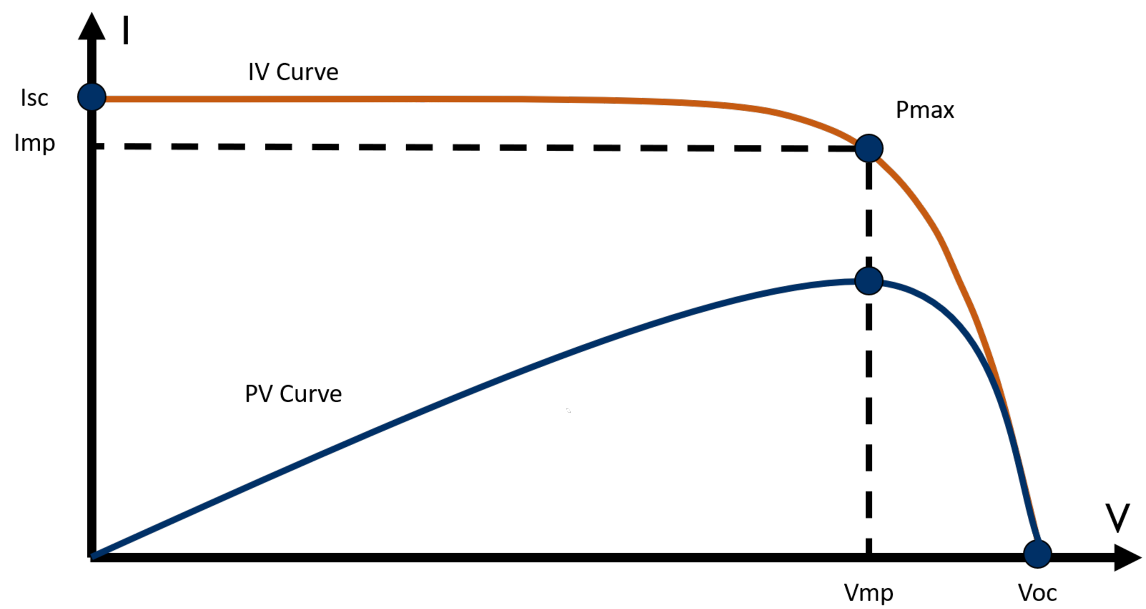
Operating a PV Cell

- A PV cell is *absolutely not* a voltage source or current source… it is a complex living thing with its own wants and needs as expressed through its I-V curve
- It will not give you the power you want in any 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.



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 an non-optimal efficiency.
- The question is

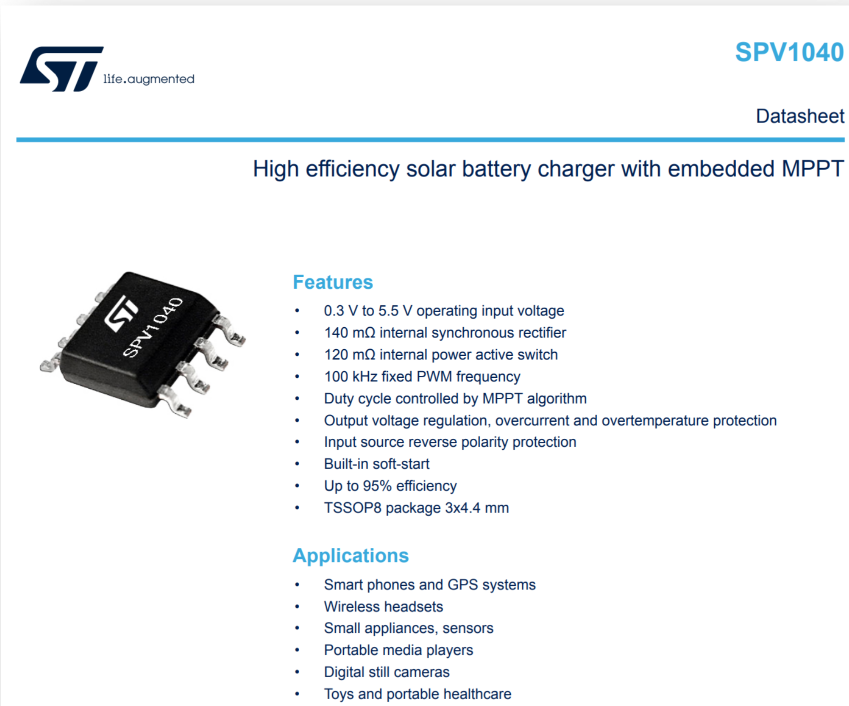


MPPT

- 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:



life.augmented

SPV1040

Datasheet

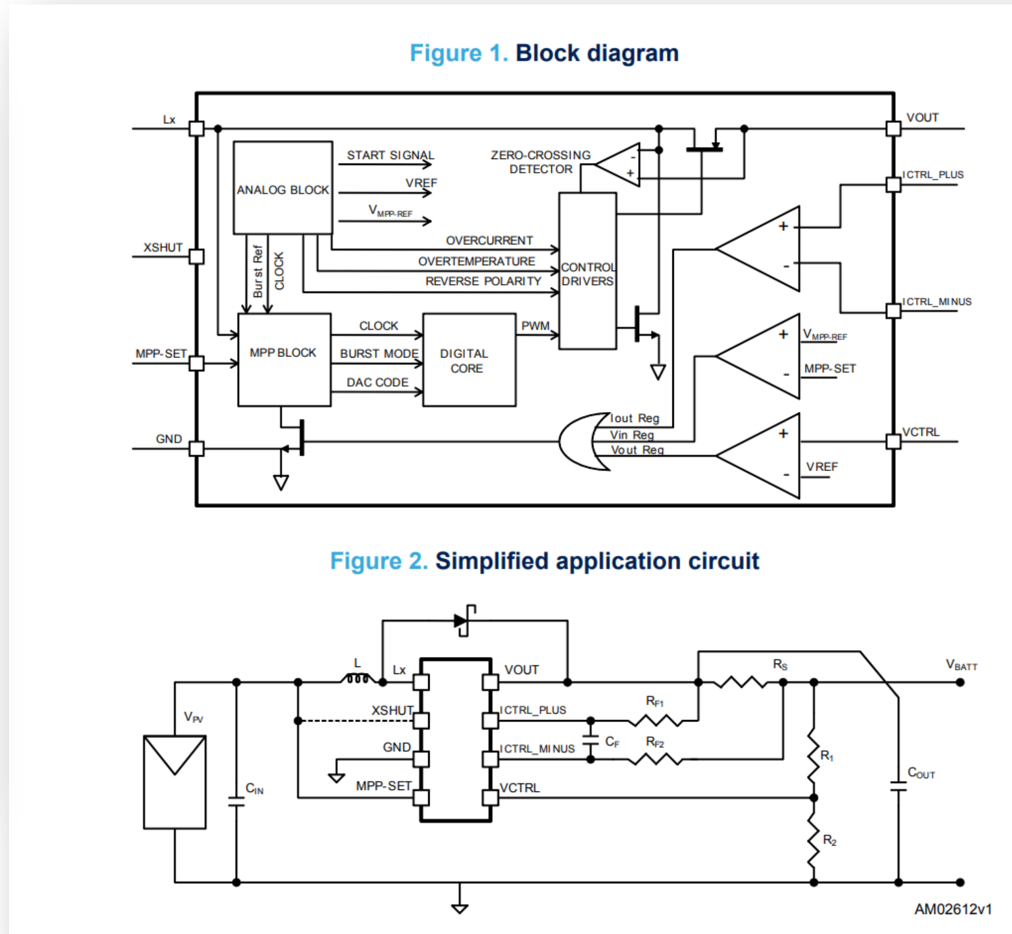
High efficiency solar battery charger with embedded MPPT

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



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 earlier in the semester 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

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

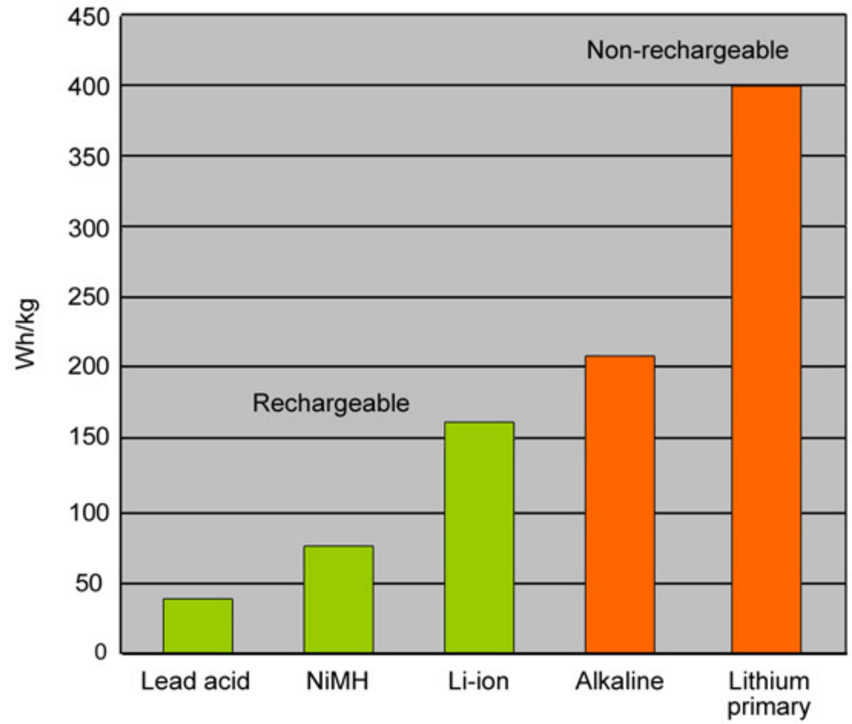
- We generally characterize batteries by:
  - The voltage they produce
  - Their capacity
- There are lots of caveats and additional characteristics, though:
  - Charge/discharge rate
  - Temperature Ratings
  - Instantaneous Current Ratings

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

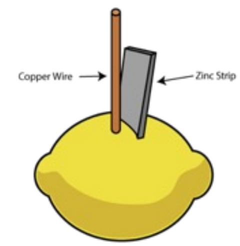
http://batteryuniversity.com/learn/article/primary_batteries

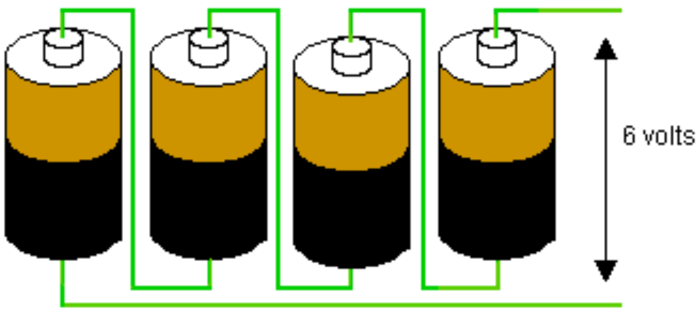
Battery Voltage

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

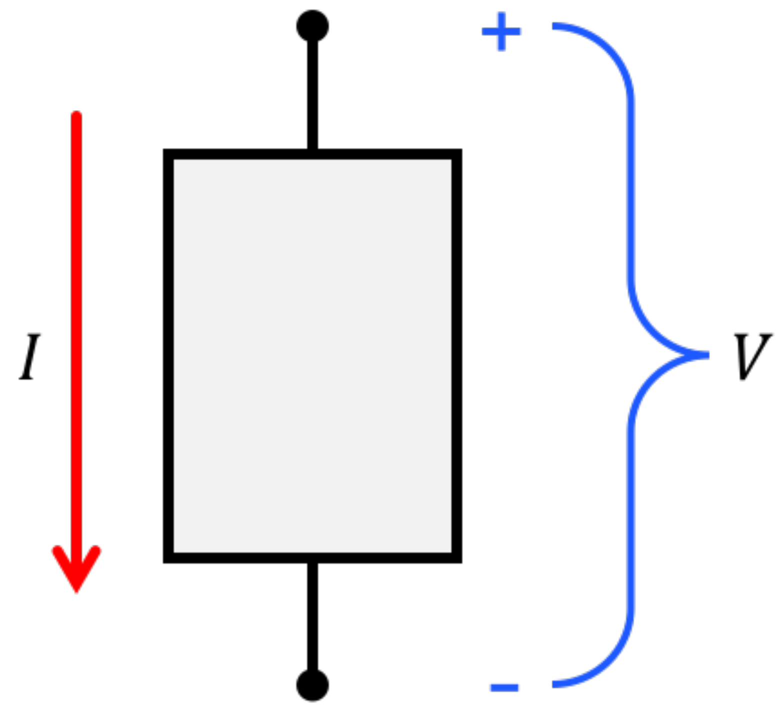
$$E(t) = \int_0^t P(\tau)d\tau$$

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

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

- If Voltage and Current are constant over time:

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



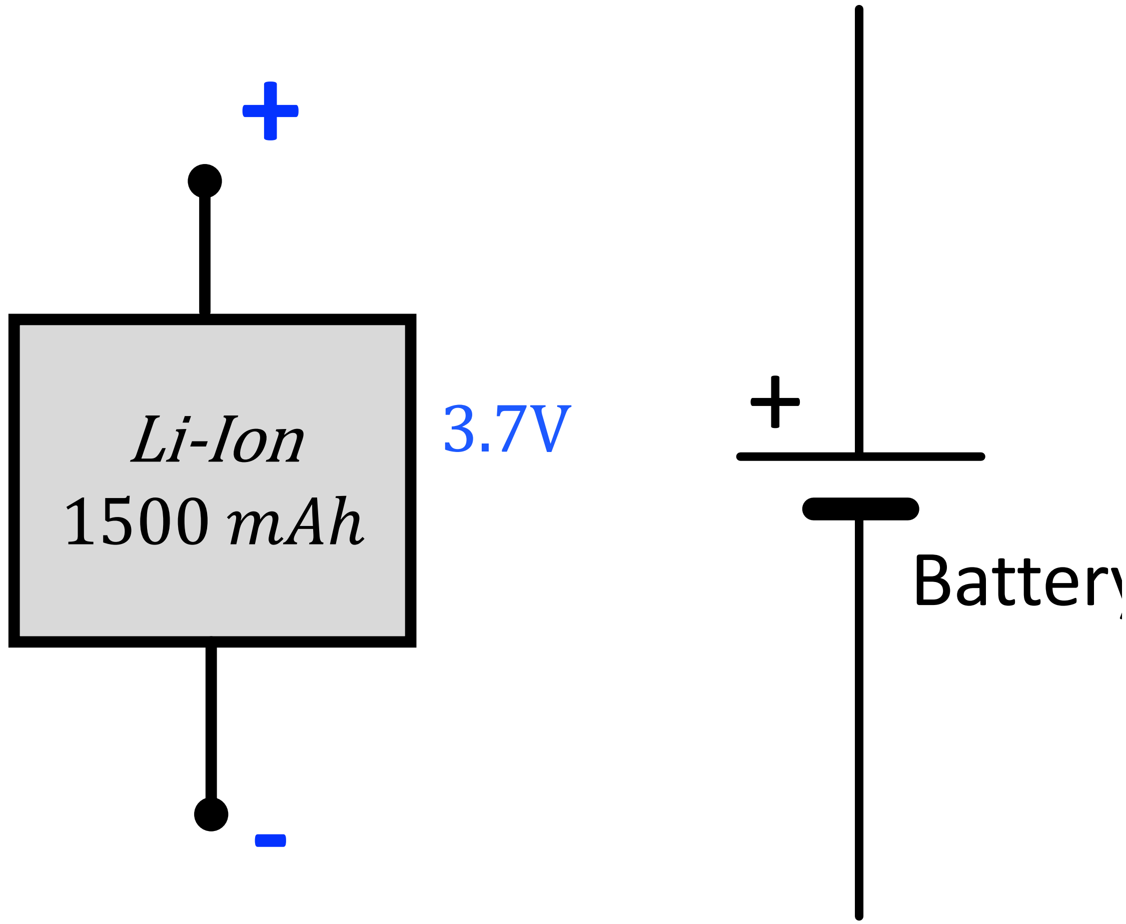
Our 6.9000 Battery
(1500 mAh @3.7V)
contains 20,000 Joules when fully charged

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

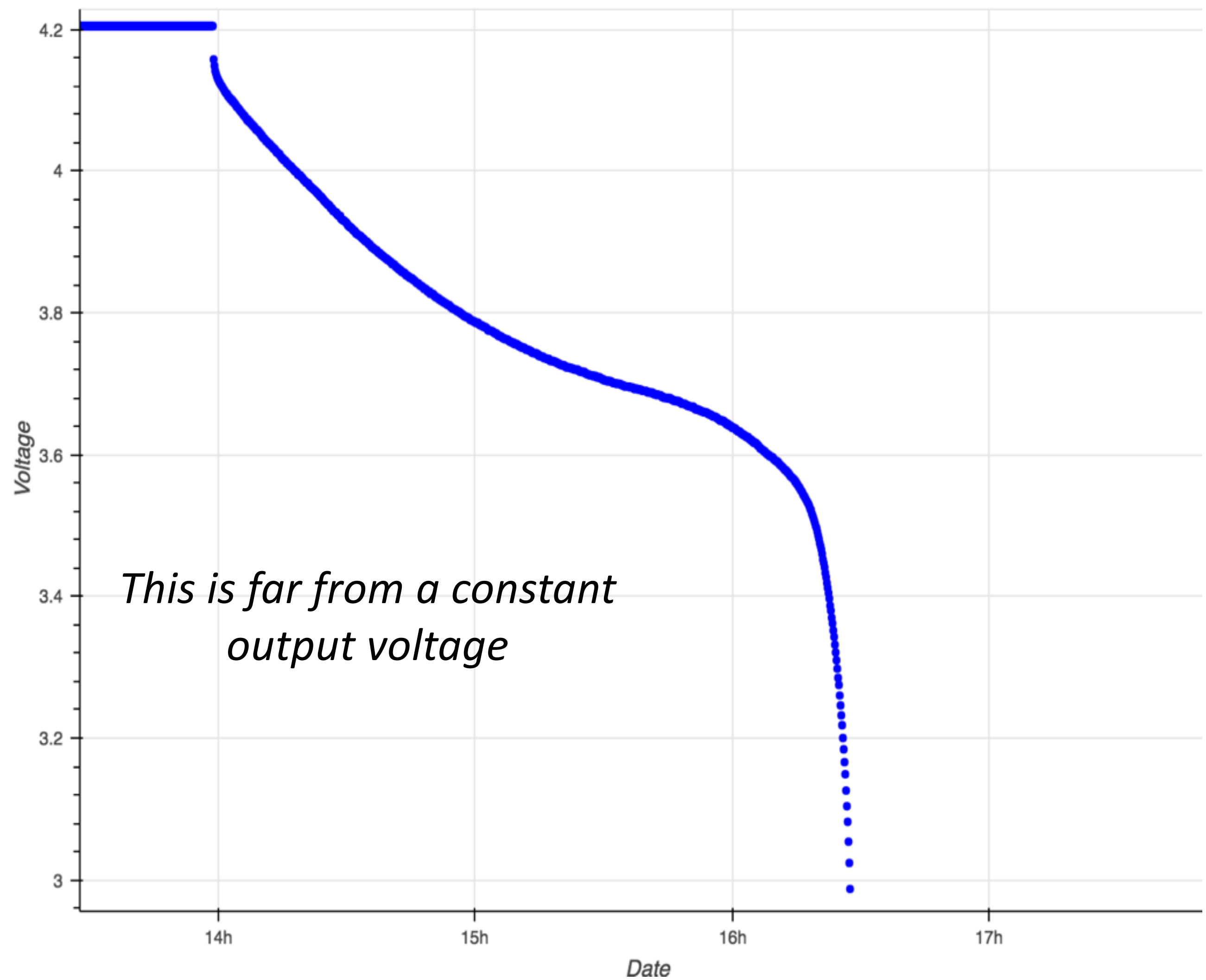
- This seems so nice and easy to think about…3.7 V when it is on, 0V when it is off
- But in real life it isn't so clean and nice…☹



Sometimes use one on the right too

Voltage of 350 mAh 3.7V battery

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

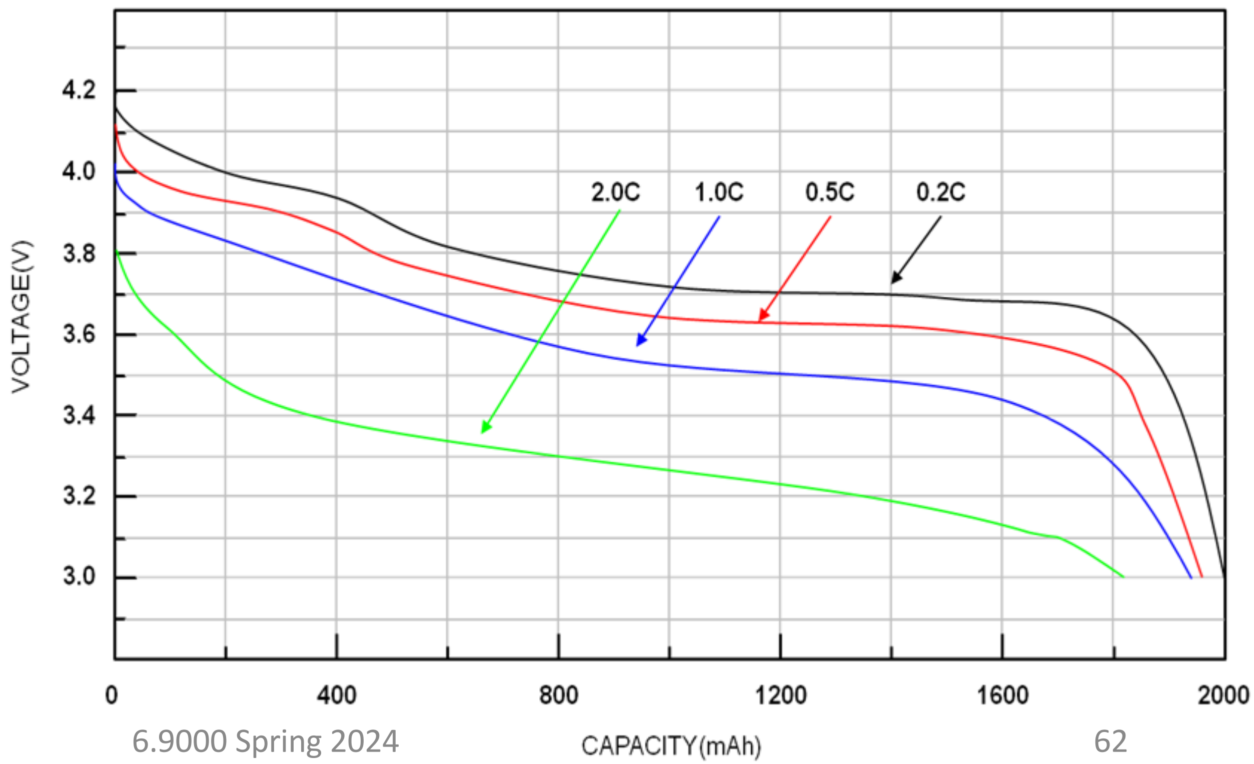


Changes over time ☹

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

Battery Voltage and System Voltage

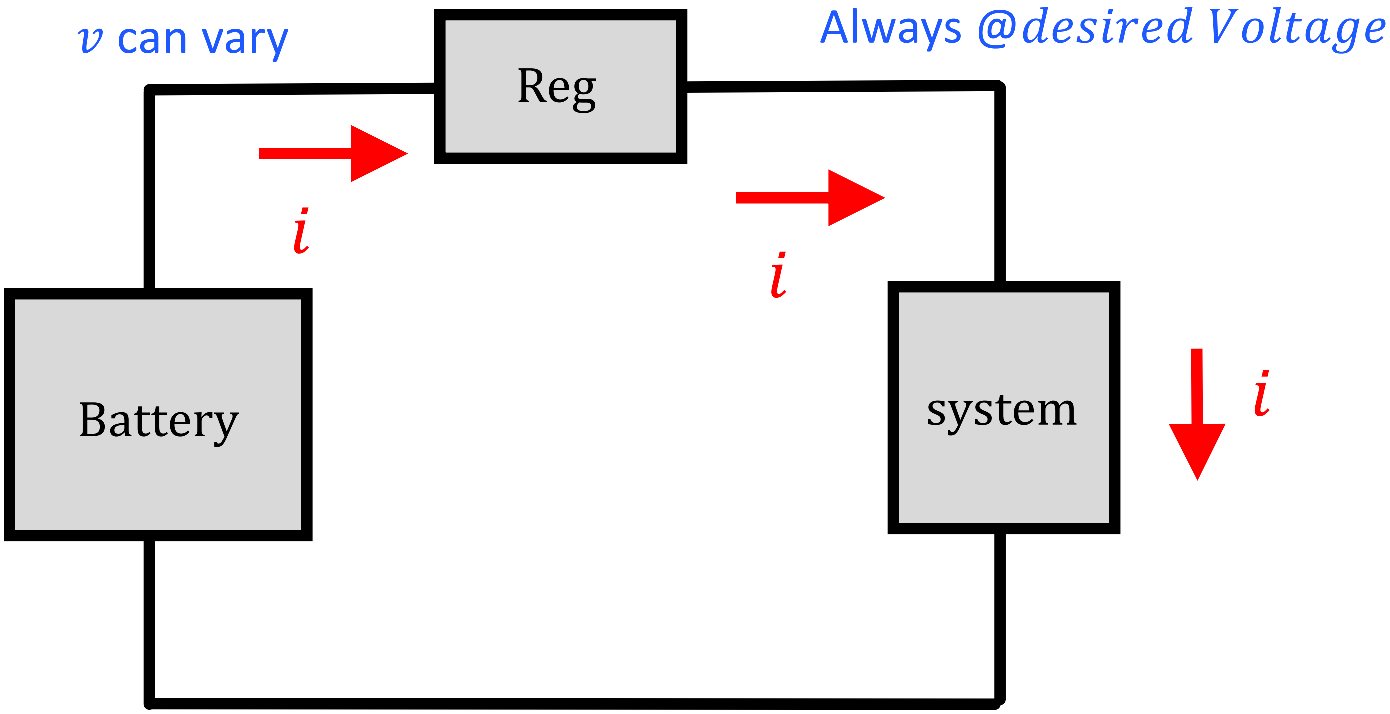
- As we use the battery, its voltage will vary
- Depending on how hard we use the battery, its voltage will also vary

- 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!

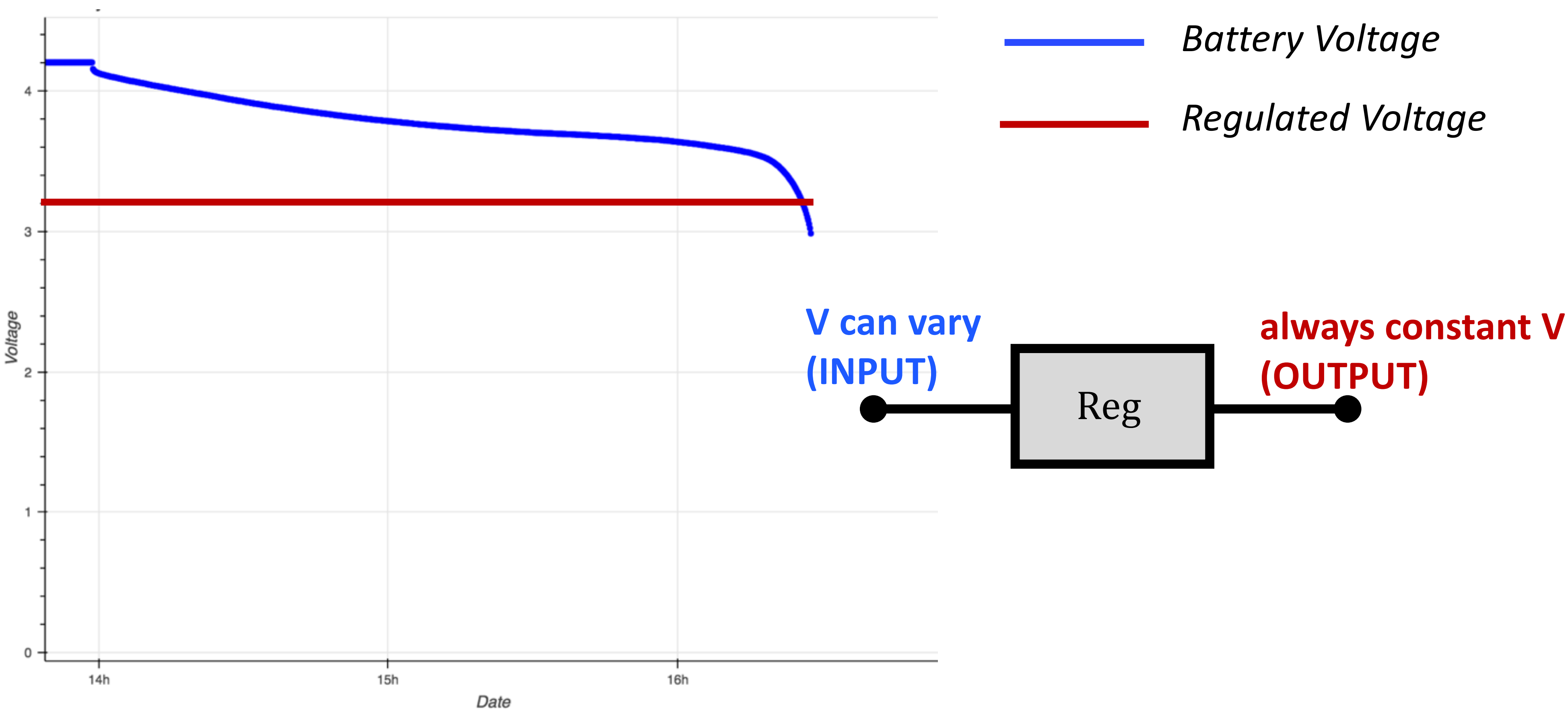
- Constant Current Device (KCL maintained)
- Can only regulate down in voltage



Could use this!

Stable Voltage

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



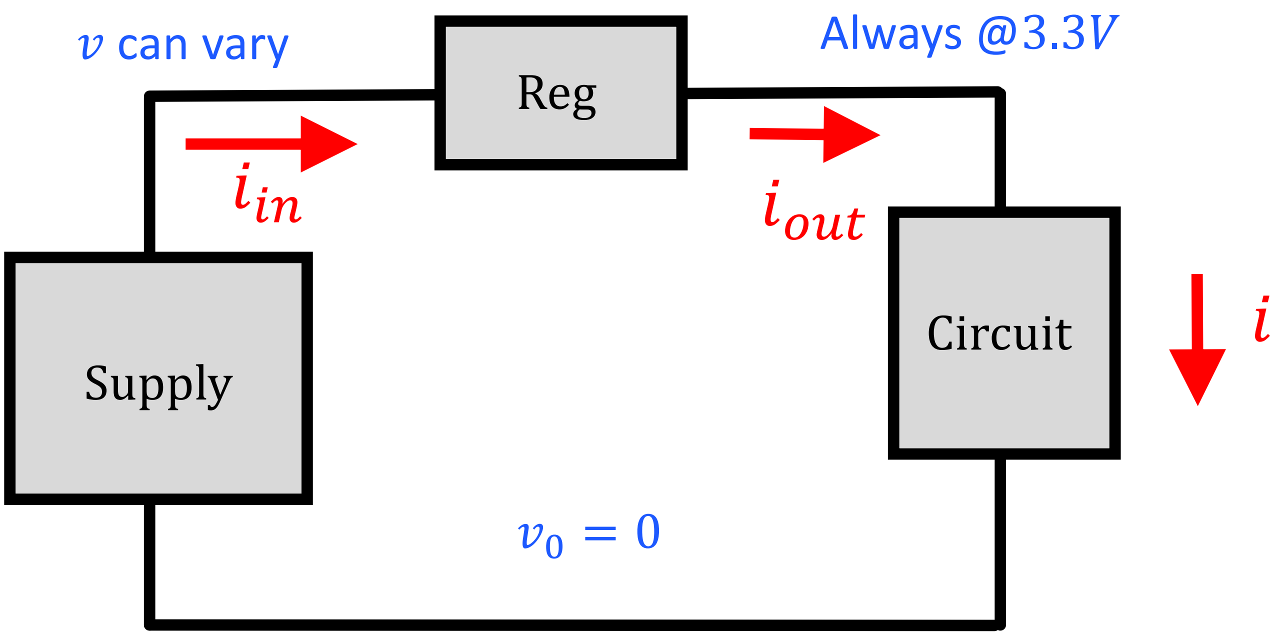
- Voltage Regulators can be used!

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

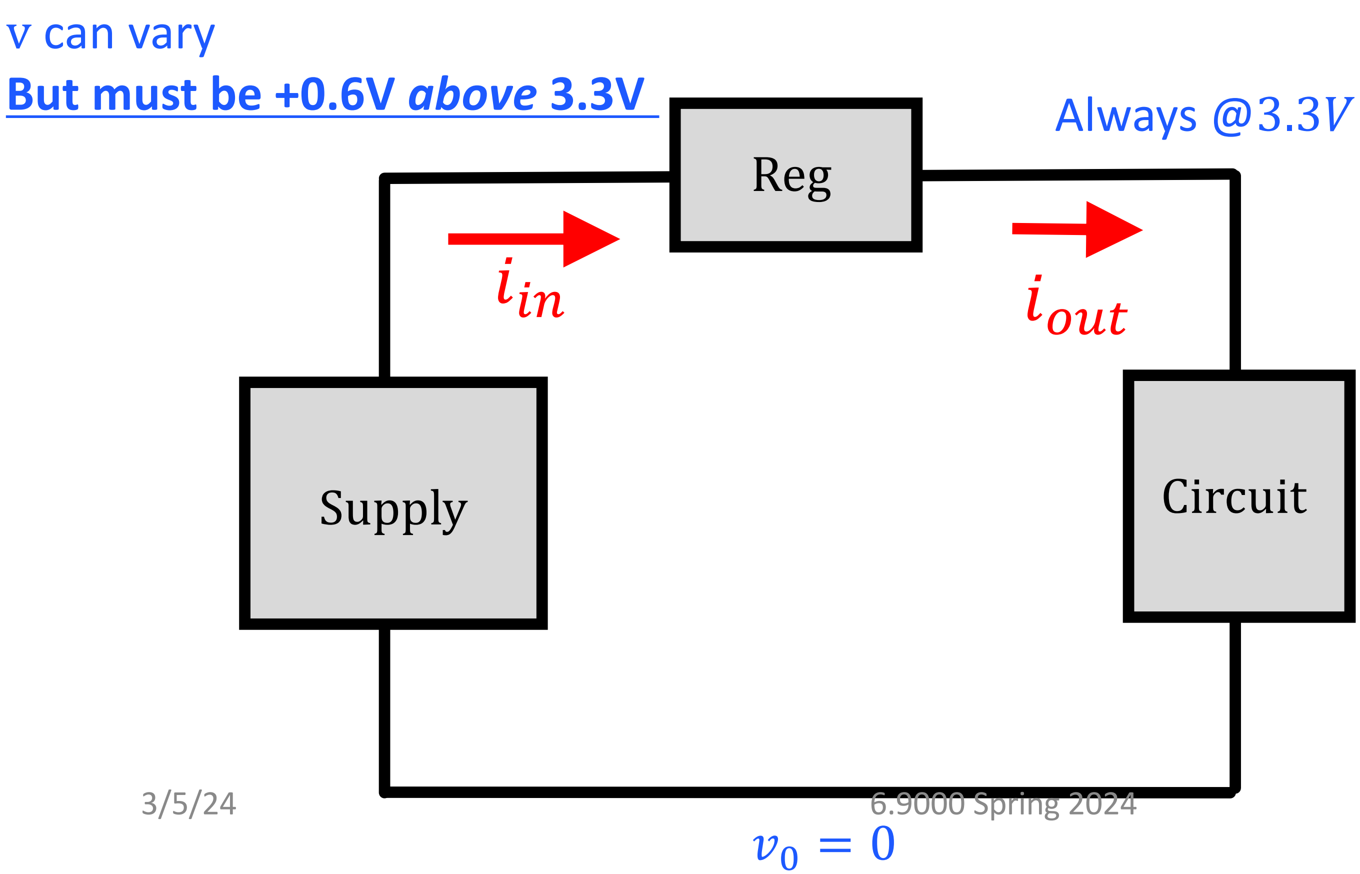


$i_{in} = i_{out} = i$

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:

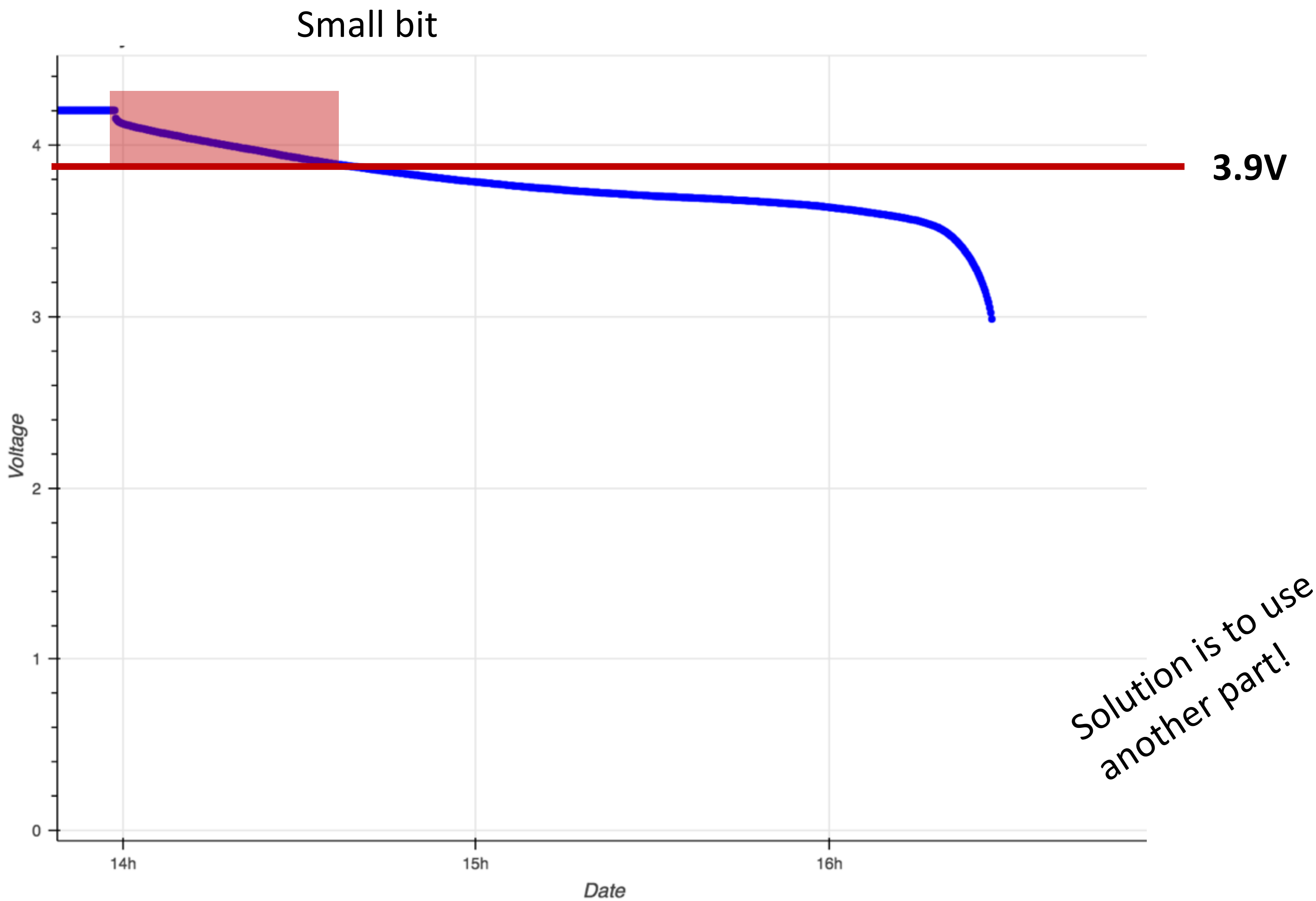


How low can our battery voltage go in this case?

3.9V…not good.

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

Most of Battery's Life is Unusable!

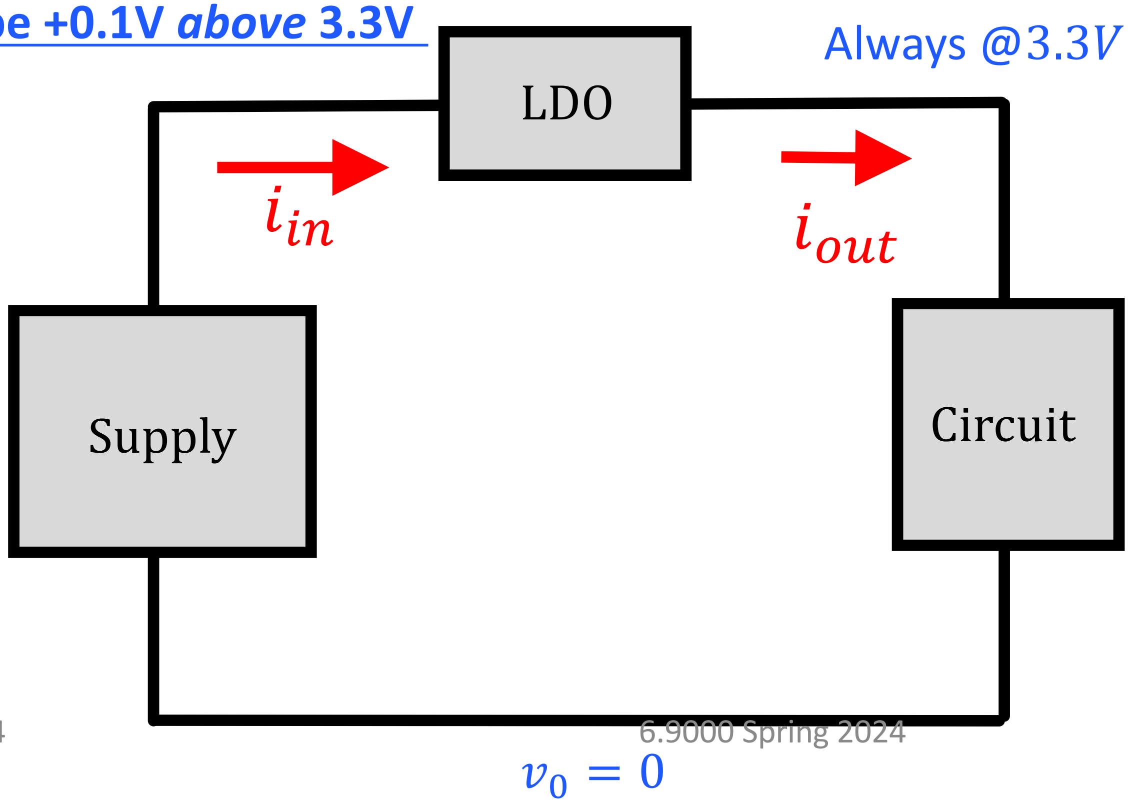


Problem #1 with Linear Regulators

- 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

v can vary

But must be +0.1V *above* 3.3V



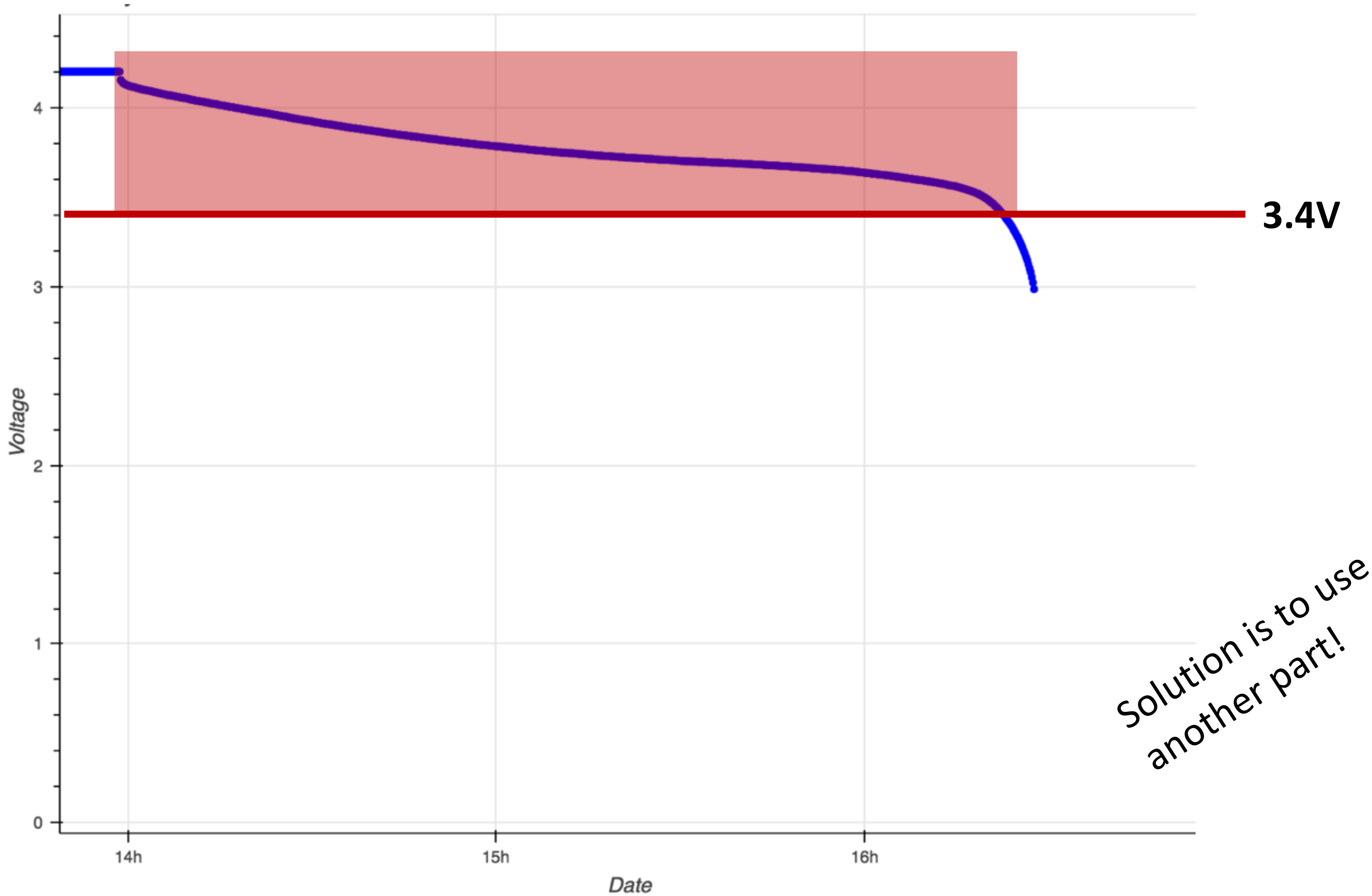
How low can our battery voltage go in this case?

3.9V…not good.

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

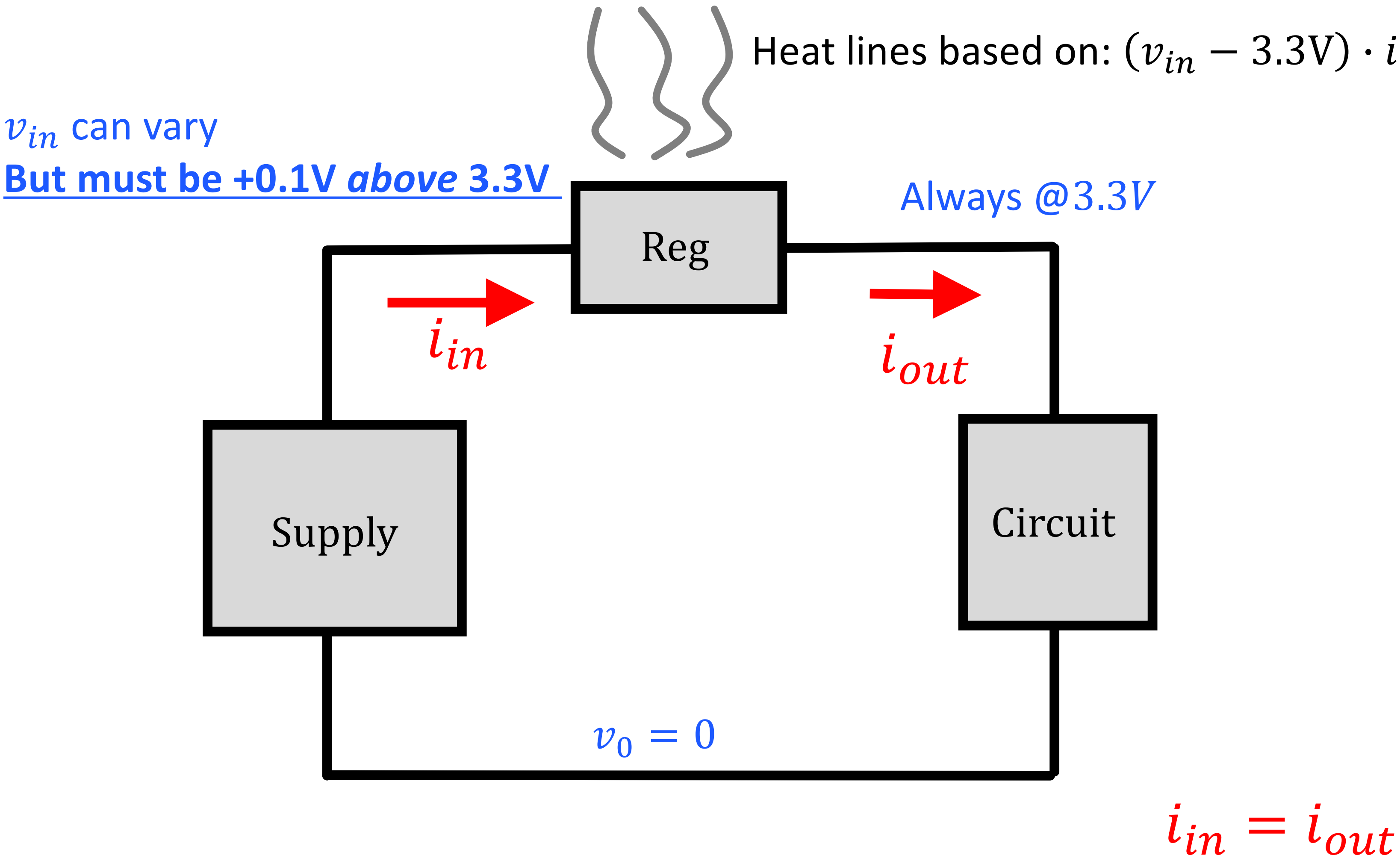
Using Most of Battery's Life!

Small bit



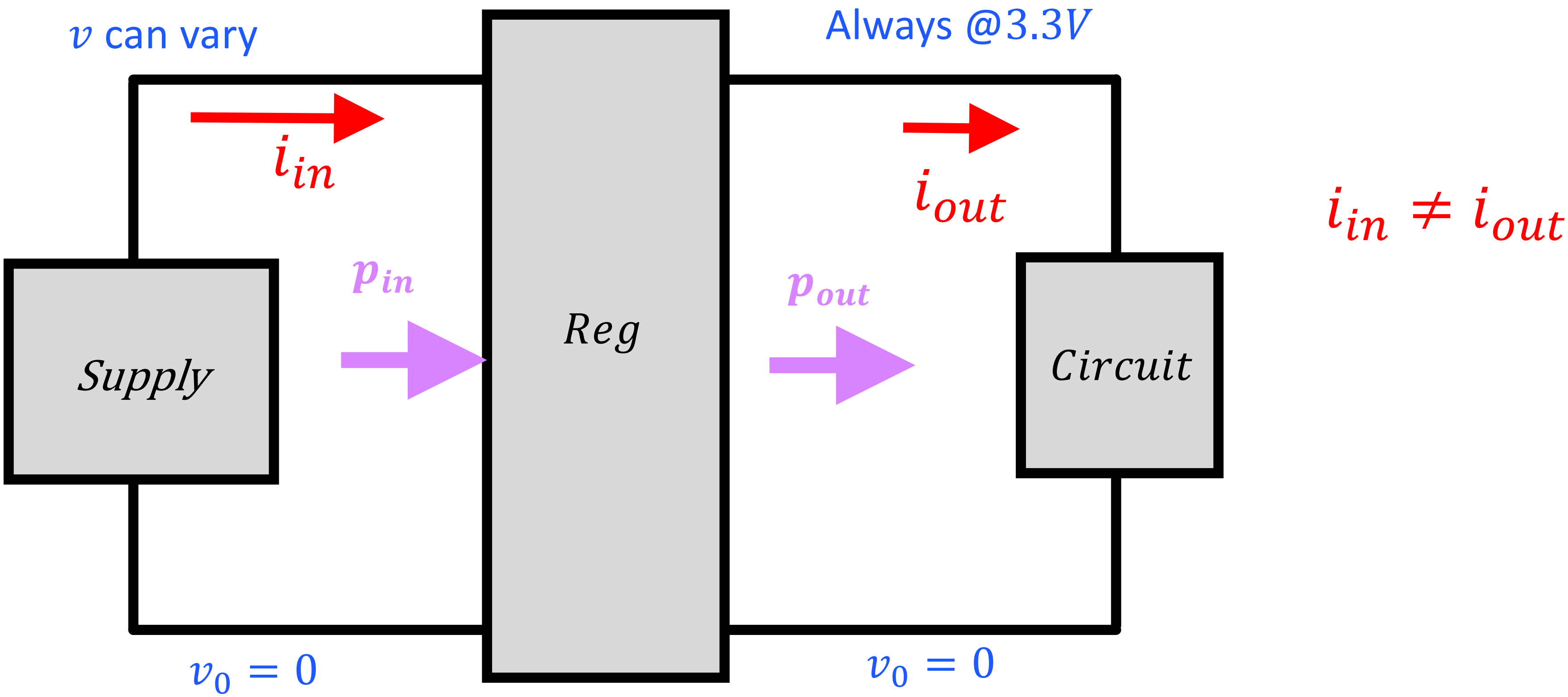
Problem #2 with Linear Regulators

- Regulate by throwing away excess energy



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



Switching Supply (non-linear device)

- Scaled Power Device ($p_{out} = \varepsilon \cdot p_{in}$)
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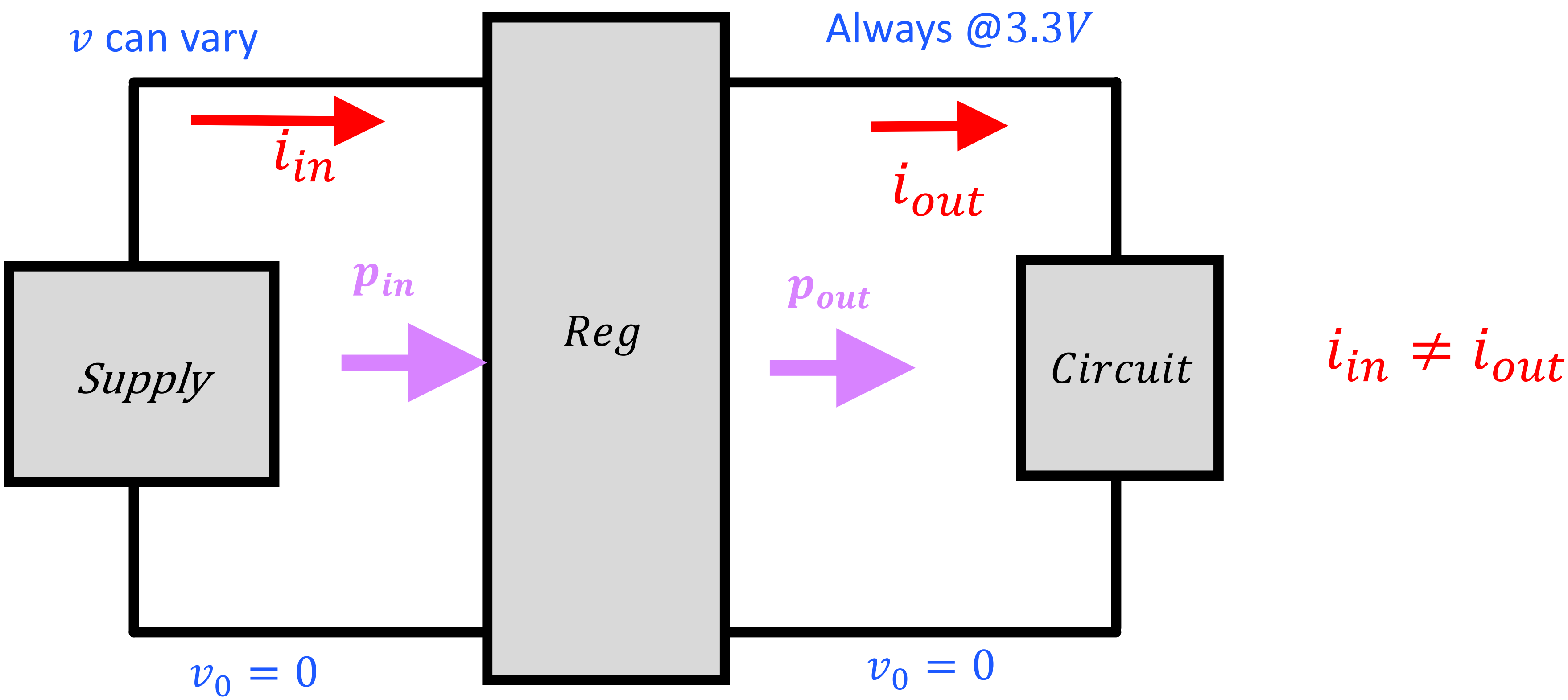
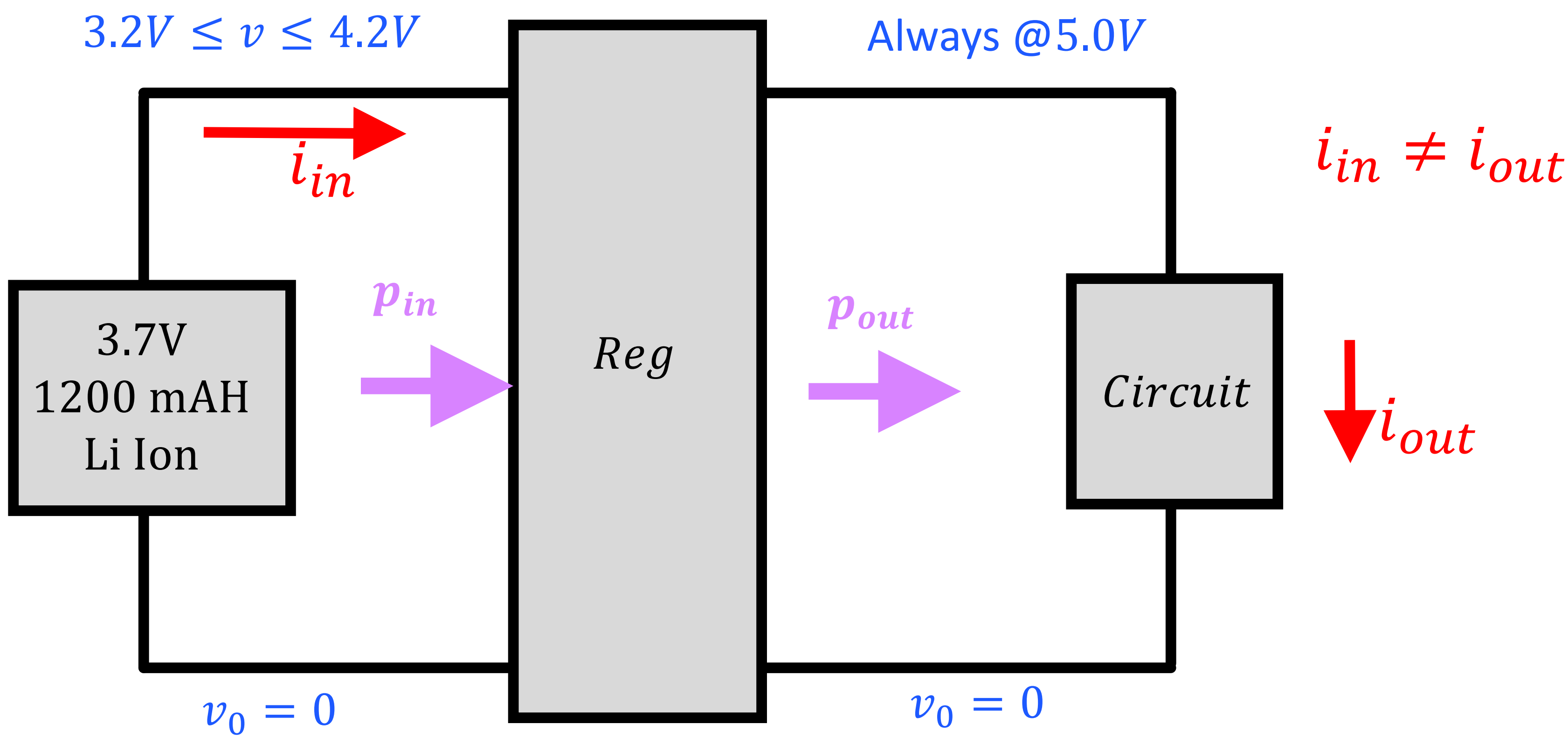


If $i_{out} = 50mA$, $i_{in} = 35mA$, and supply voltage is at $v = 5.0V$ what is the efficiency? (i.e. how much power is consumed by the circuit and not the regulator?)

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?)