

# Power Part I

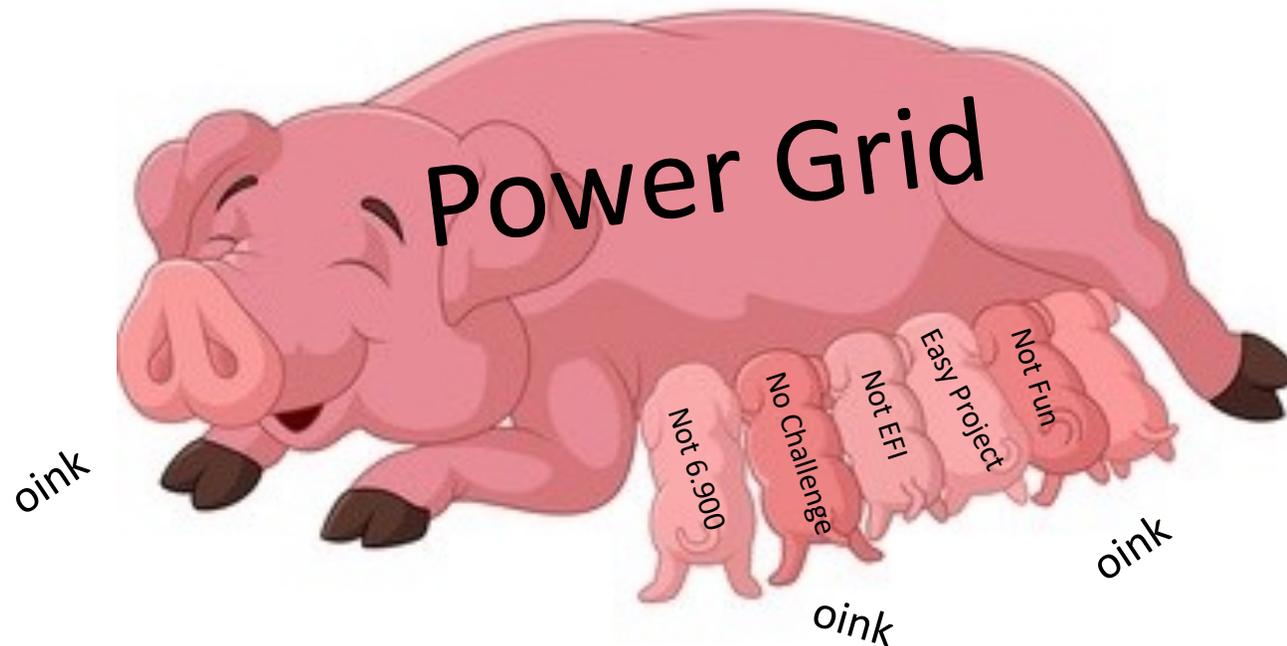
6.9000

Spring 2026

# 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?

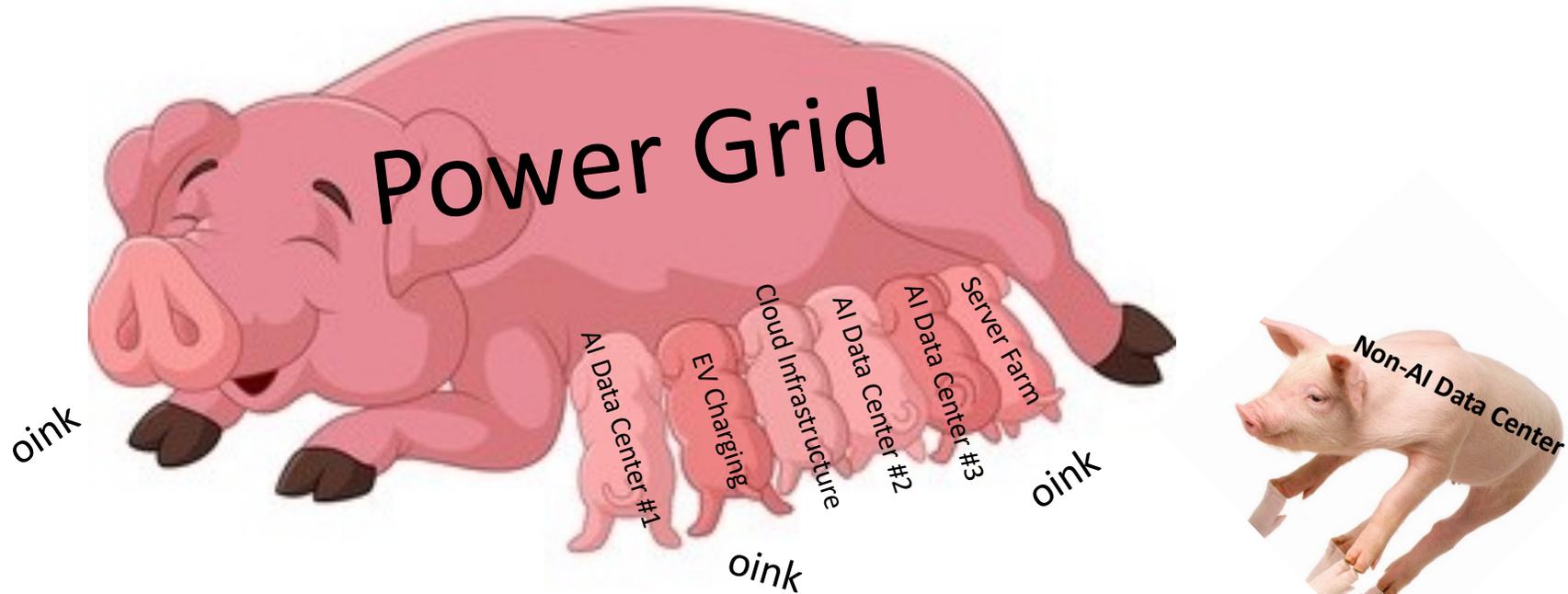
# No Grid Connections in 6.900



- Our systems need to bring their power with them AND/OR harvest it from environment
- Therefore...must be intimately aware of how we consume and produce and store energy



# And Even If Connected to Grid...



- Immense strain is being placed on the grid by recent developments in the field:
  - Electric Vehicle Charging infrastructure
  - Server/Compute Centers
  - And many more!

# 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
- Implications of this can vary

# Computation Energy Consumption

- Early computer ENIAC (~1945)...entire computer consumed about 150 kW of power
- Worked at an efficiency of around  $10^{-3}$  Joules per bit
- State-of-the-art processors are using around  $10^{-15}$  Joules per bit
- *Does not mean* gov't scale computers are currently using 150 nW of power...
- We “cancel out” every improvement in computing efficiency by just trying to do more computing.
- Modern data centers can consume over **100 MW** of power now.

# Lower Limit on Computation

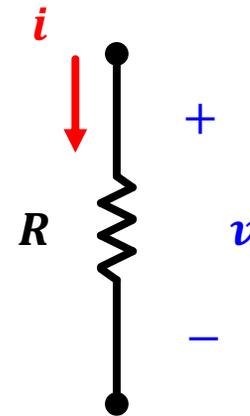
- There is nominally a lower limit: it takes about  $3 \times 10^{-21}$  Joules to erase a bit no matter what
  - Called Landauer Limit
  - Experimentally shown in 2012 (Berut et al., Nature 2012)
- State of art processors are using about  $1 \times 10^{-15}$  Joules-ish per bit flip
- Between those two numbers are the inefficiencies and limitations of circuits
- People actively working on pushing towards that limit!...many people at MIT.
- Doesn't mean future is "solved"...since we'll just end up trying to do more computation...so these concepts are relevant!!!

<https://spectrum.ieee.org/computing/hardware/landauer-limit-demonstrated>

[https://en.wikipedia.org/wiki/Landauer%27s\\_principle](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



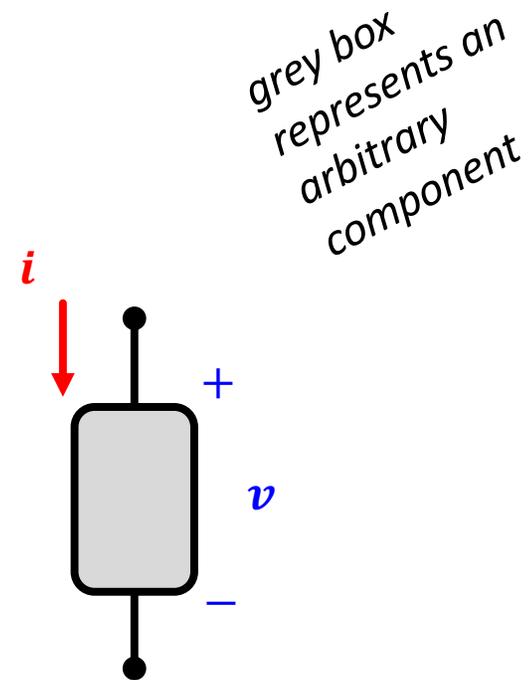
$$v = i \cdot R$$

# 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

$$p = v \cdot i$$

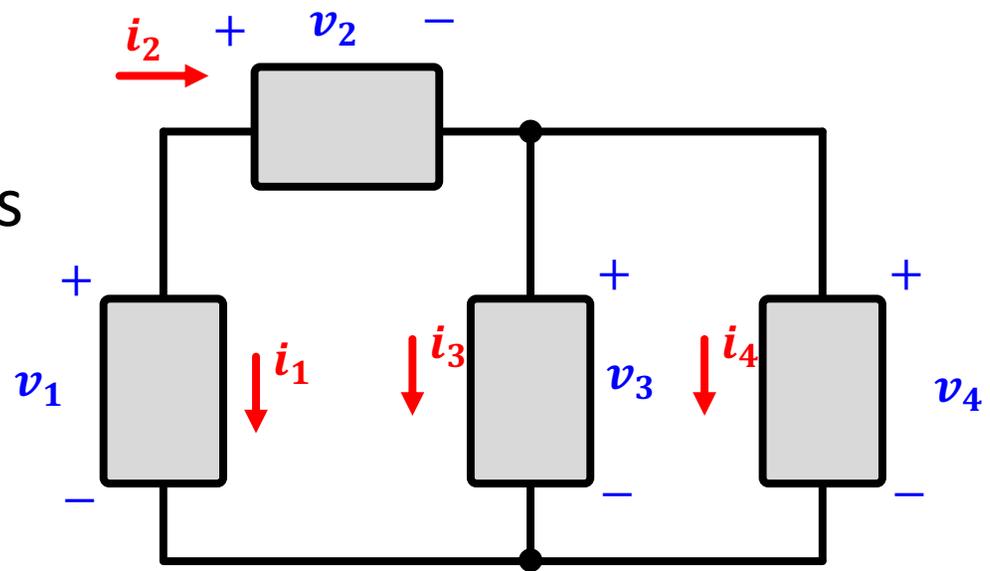
$$p = \frac{\text{Joule}}{\text{Coulomb}} \cdot \frac{\text{Coulomb}}{\text{sec}} = \frac{\text{Joule}}{\text{sec}} = \text{Watt}$$



# 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  $n$  components you have this equation:

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



[https://en.wikipedia.org/wiki/Tellegen%27s\\_theorem](https://en.wikipedia.org/wiki/Tellegen%27s_theorem)

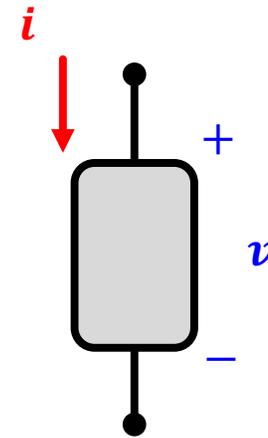
# Implications...

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

# Power **PASSIVE SIGN NOTATION**

- 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

$$p = v \cdot i$$

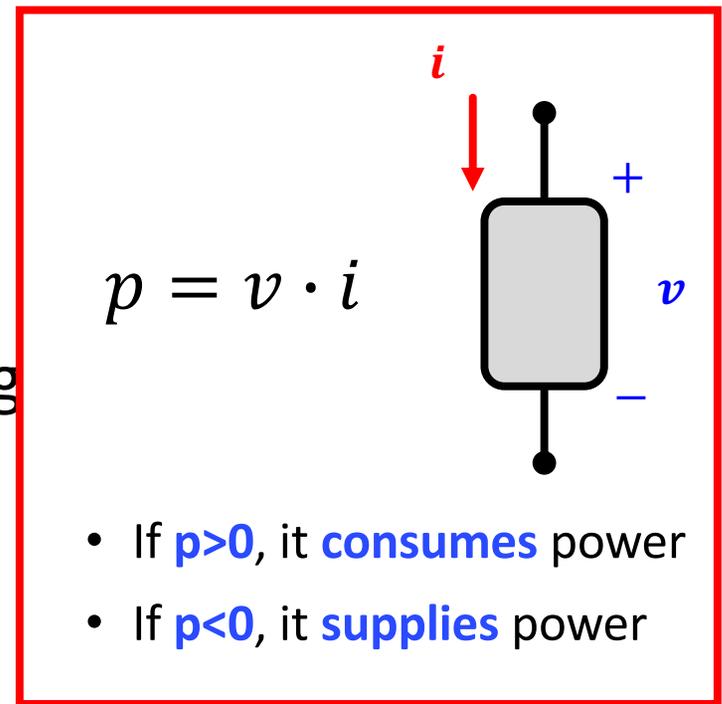


grey box  
represents an  
arbitrary  
component

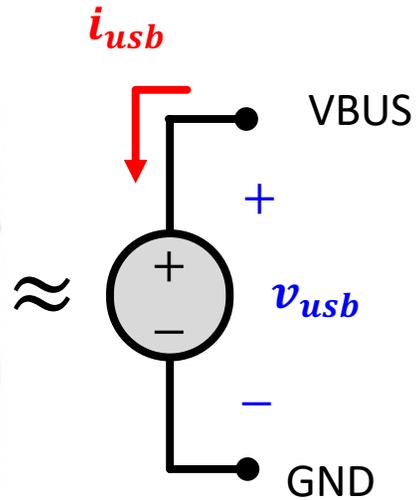
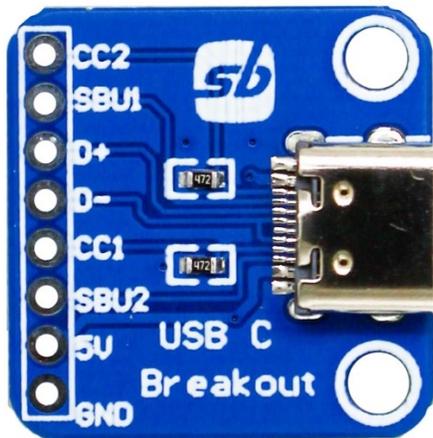
$$p = \frac{\text{Joule}}{\text{Coulomb}} \cdot \frac{\text{Coulomb}}{\text{sec}} = \frac{\text{Joule}}{\text{sec}} = \text{Watt}$$

# 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!!!!



# Example: USB-C Socket



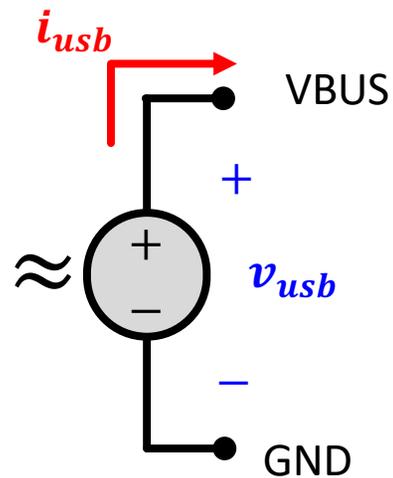
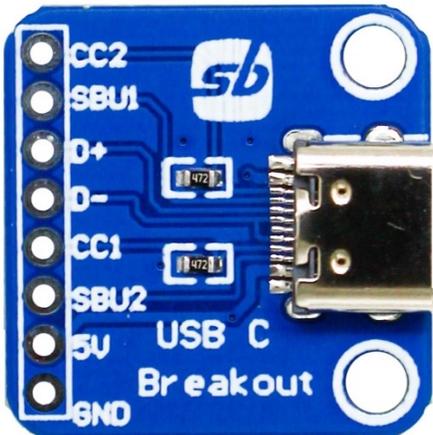
In Normal Operation:

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

$$i_{usb} < 0A$$

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

$$p_{usb} < 0$$



In Normal Operation:

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

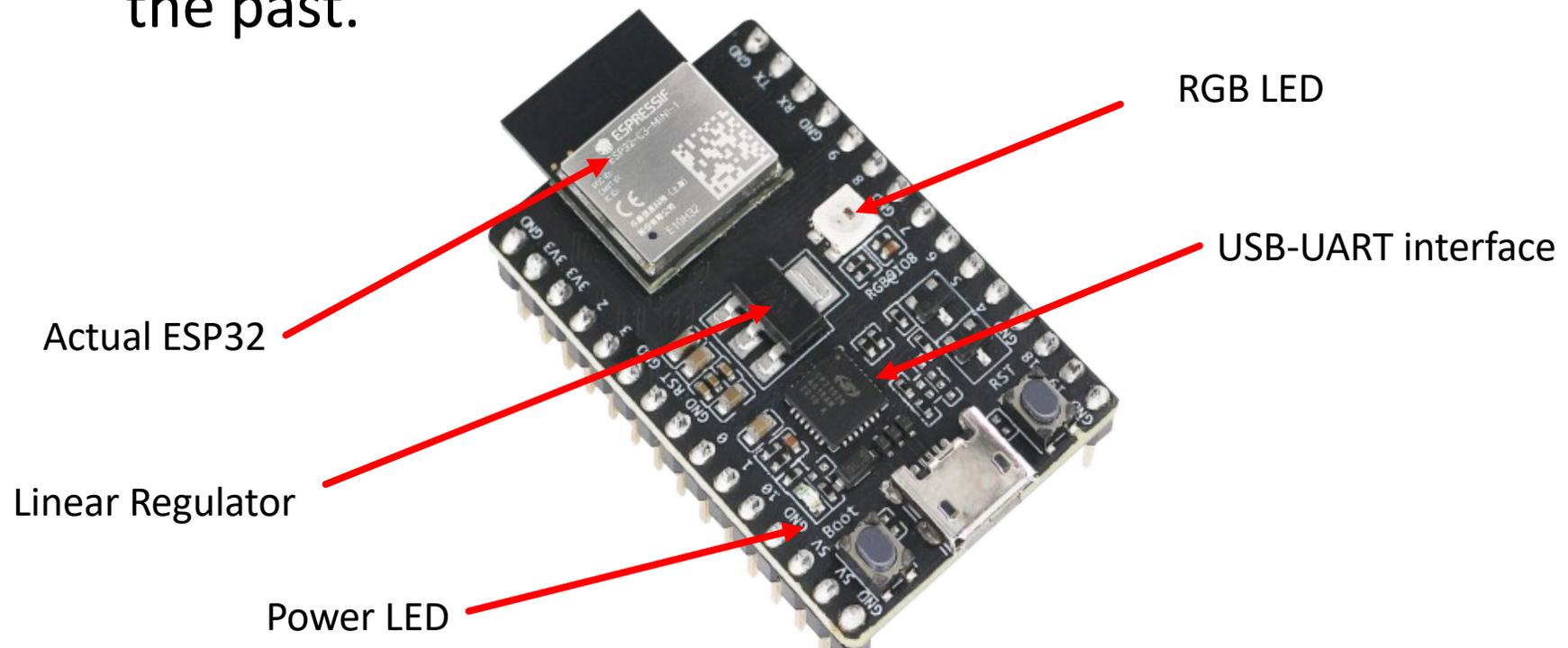
$$i_{usb} > 0A$$

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

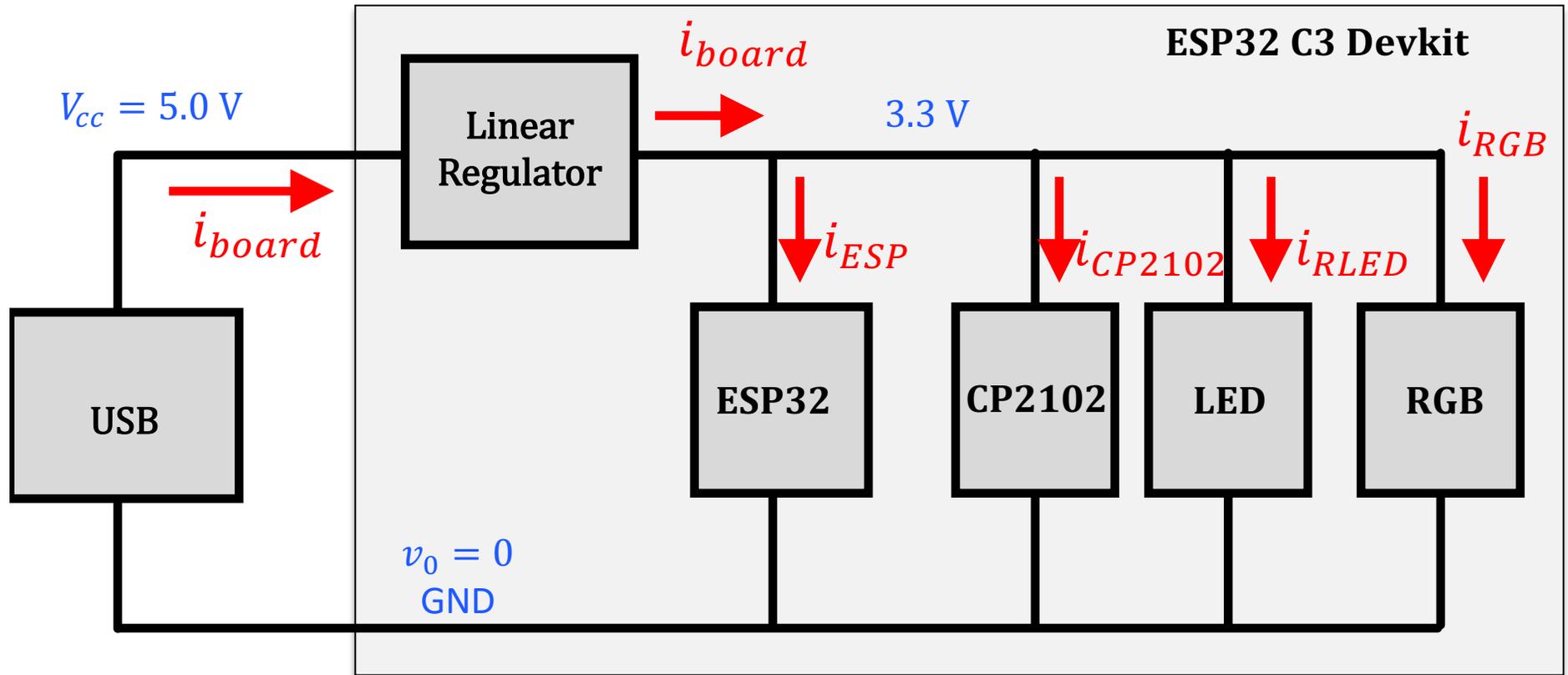
$$p_{usb} > 0$$

# ESP32 C3 Devkit M1

- This is the development board we've used in classes like 6.1903/4 and which we've even used in 6.900 in the past.



# Example: ESP32 C3 M1 Dev 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

# ESP32 C3 6.900 Board

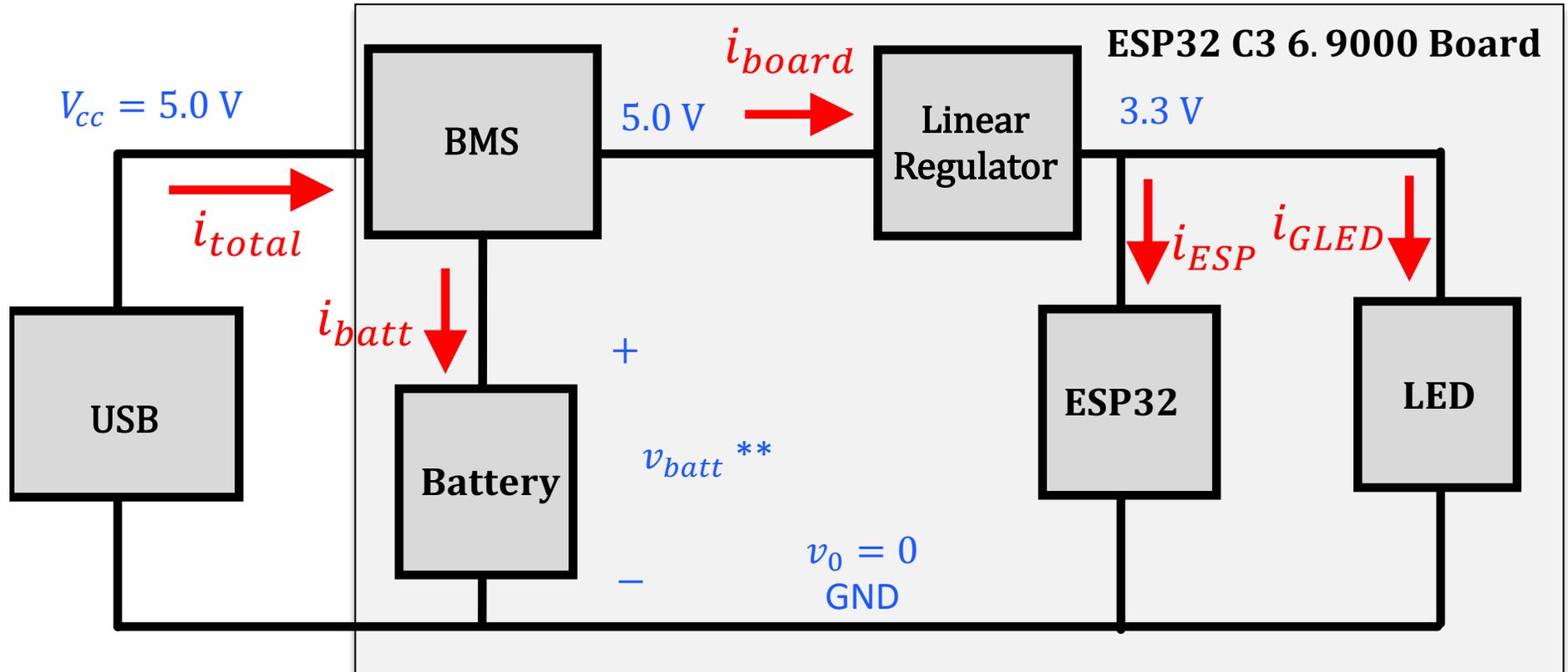
- The board we're using in this class this term...



*System state circa end of week 2*

# Example: ESP32 C3 6.9000 Board

*When plugged into the USB supply...*



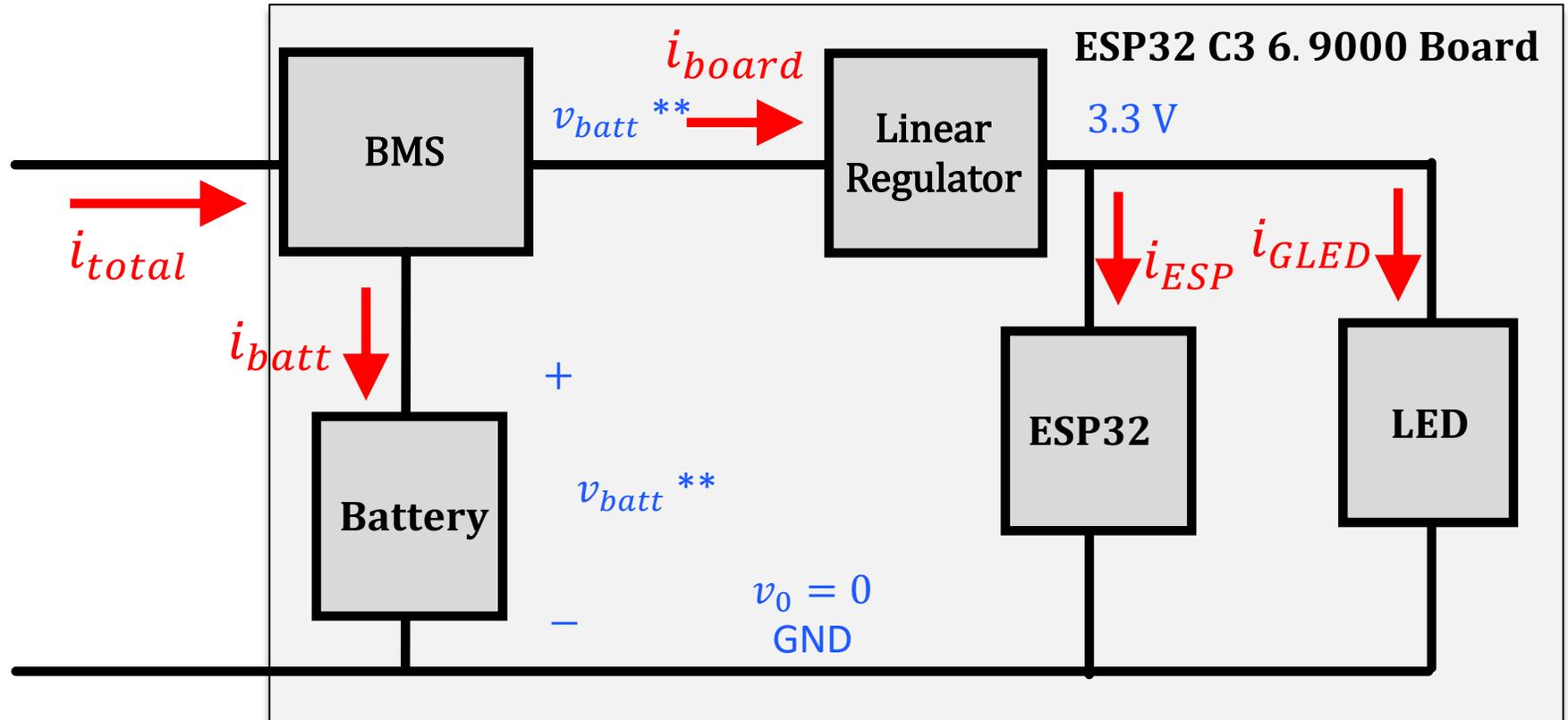
\*\* variable as it charges

Sign of  $p_{batt}$ ?

+

# Example: ESP32 C3 6.9000 Board

*When NOT plugged into the USB supply...*



\*\* variable as it discharges

Sign of  $p_{batt}$ ?

-

# On Project...How much power will be getting used?

- Computation?
- Sensors?
- Communication?
- Actuators/displays/indicators?

# Where to Get Power Consumption Numbers?

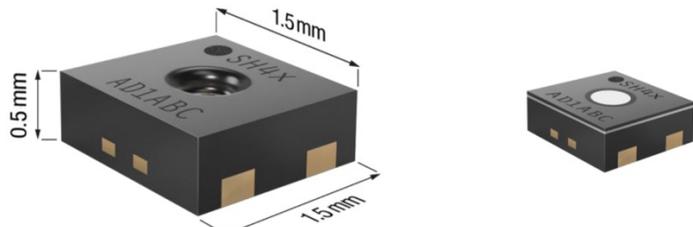
- Always go to the datasheets first to get rough ideas of power needs.
- This is never the actual answer, but it can help you rule out (or in) things
- Rough order of magnitude (based on previous 6.900 projects) Current consumption:
  - **~ nA,  $\mu$ A** likely will not matter
  - **1 – 10 mA** maybe is fine
  - **10 – 100 mA** that's a lot of power! CAUTION!
  - **> 100 mA** that's a crazy amount of power consumption

# Temperature and Humidity Sensors

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

**SENSIRION**

**Datasheet – SHT4x**  
4<sup>th</sup> Gen. Relative Humidity and Temperature Sensor



**Highlights**

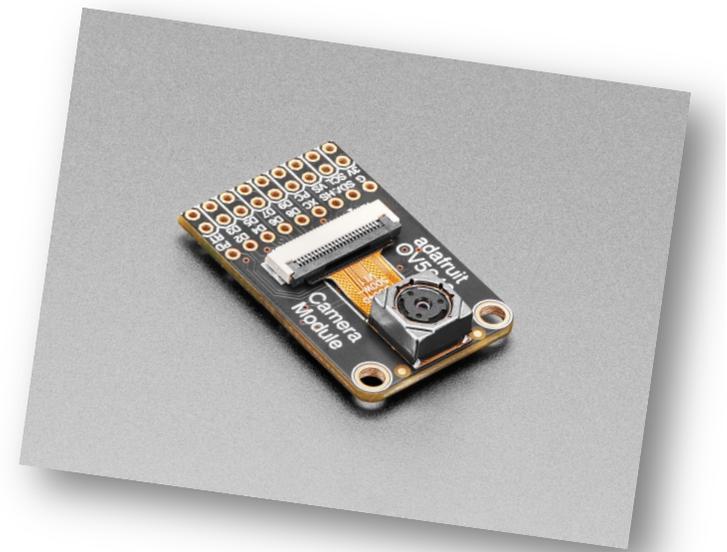
- Accuracies  $\Delta RH = \pm 1.0\%RH$ ,  $\Delta T = \pm 0.1\text{ }^\circ\text{C}$
- VDD = 1.08 V ... 3.6 V
- Avg. current: 0.4  $\mu\text{A}$ , Idle current: 80 nA
- I2C FM+, CRC checksum, multip. I2C addr.
- Patented protection options [1], PTFE membrane and removable protective cover
- Operating range: 0 ... 100 %RH, -40...125  $^\circ\text{C}$
- 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

- These can use a lot of power



# Camera

CV

AI

Train

AI

Model

95% Accuracy

## 8.3 DC characteristics

**table 8-3** DC characteristics (-30°C < T<sub>J</sub> < 70°C) (sheet 1 of 2)

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



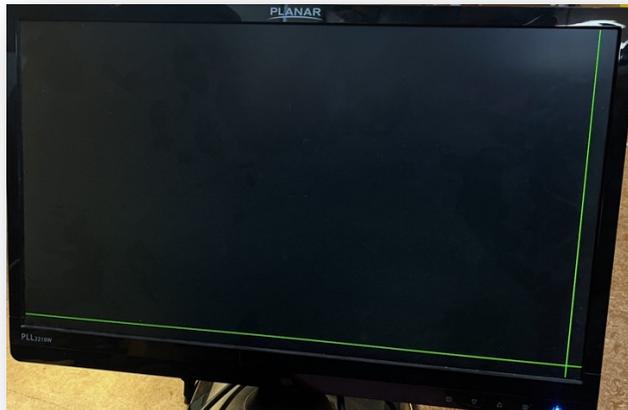
AI

# Power consumption can be data dependent!!!

OV5640 Camera Running and Exposed:



OV5640 Camera Running and Covered:



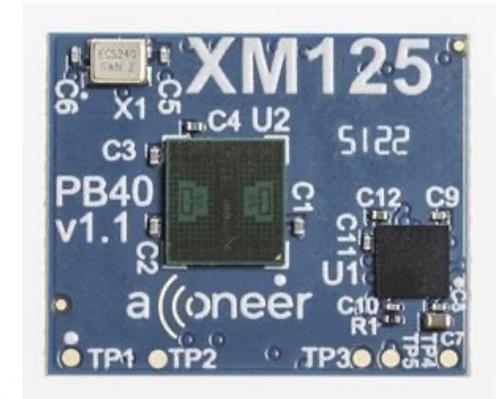
*Achieve a ~30% drop in power consumed by camera and FPGA based off of the \*type\* of data transferred through the system*

# Time-of-Flight Sensors

	 <a href="#">VL6180X carrier</a>	 <a href="#">VL53L4CD carrier</a>	 <a href="#">VL53L0X carrier</a>	 <a href="#">VL53L1X carrier</a>	 <a href="#">VL53L3CX carrier</a>	 <a href="#">VL53L5CX carrier</a>	 <a href="#">VL53L7CX carrier</a>	 <a href="#">VL53L8CX carrier</a>
<b>Maximum range:</b> (1)	60 cm	120 cm	200 cm	400 cm	500 cm	400 cm	350 cm	400 cm
<b>Minimum range:</b>	~10 mm	1 mm	~30 mm	40 mm	10 mm	20 mm		
<b>Field of view:</b>	25°	18°	25°	15° to 27° diagonal, programmable	25°	65° diagonal, up to 8x8 zones	90° diagonal, up to 8x8 zones	65° diagonal, up to 8x8 zones
<b>Other features:</b>	ambient light sensing, low memory footprint <sup>(2)</sup>	low memory footprint <sup>(2)</sup> , ultra-low power mode	low memory footprint <sup>(2)</sup>	low memory footprint <sup>(2)</sup> , 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
<b>Maximum update rate:</b> <sup>(1)</sup>	~150 Hz	100 Hz	50 Hz	100 Hz	125 Hz	60 Hz		
<b>Operating voltage range:</b>	2.6 V to 5.5 V					2.5 V to 5.5 V		3.2 V to 5.5 V
<b>Regulator</b>	2.8 V					3.3 V		1.8 V and 3.3 V
<b>Typical active-ranging supply current:</b>	25 mA	25 mA	20 mA	20 mA	20 mA	100 mA		
<b>Peak supply current:</b>	40 mA					150 mA		
<b>Interface:</b>	I <sup>2</sup> C							I <sup>2</sup> C, SPI
<b>Dimensions:</b>	0.5" × 0.7"							0.5" × 0.9"
<b>1-piece price:</b>	\$13.49	\$12.95	\$14.95	\$18.95	\$16.95	\$19.95	\$19.95	\$24.95

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

# XM125

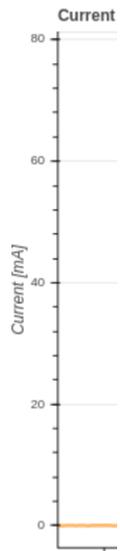


## 4.3 Power consumption summary

Table 4 gives the power consumption and the idle current at  $T_A = 25^\circ\text{C}$ , 1.8 V supply.

**Table 4. Power consumption and idle current.**

Parameter	Min.	Typ.	Max.	Unit
Measurement range: 0.25 m <sup>(1)</sup> , 0.1 Hz update rate		0.06		mW
Measurement range: 0.25 m <sup>(1)</sup> , 1.0 Hz update rate		0.51		mW
Measurement range: 0.25 m <sup>(1)</sup> , 10.0 Hz update rate		4.98		mW
Measurement range: 2.75 m, 0.1 Hz update rate		0.04		mW
Measurement range: 2.75 m, 1.0 Hz update rate		0.33		mW
Measurement range: 2.75 m, 10.0 Hz update rate		3.12		mW
Idle current, hibernate		17.7		$\mu\text{A}$
Idle current, off		6.90		$\mu\text{A}$



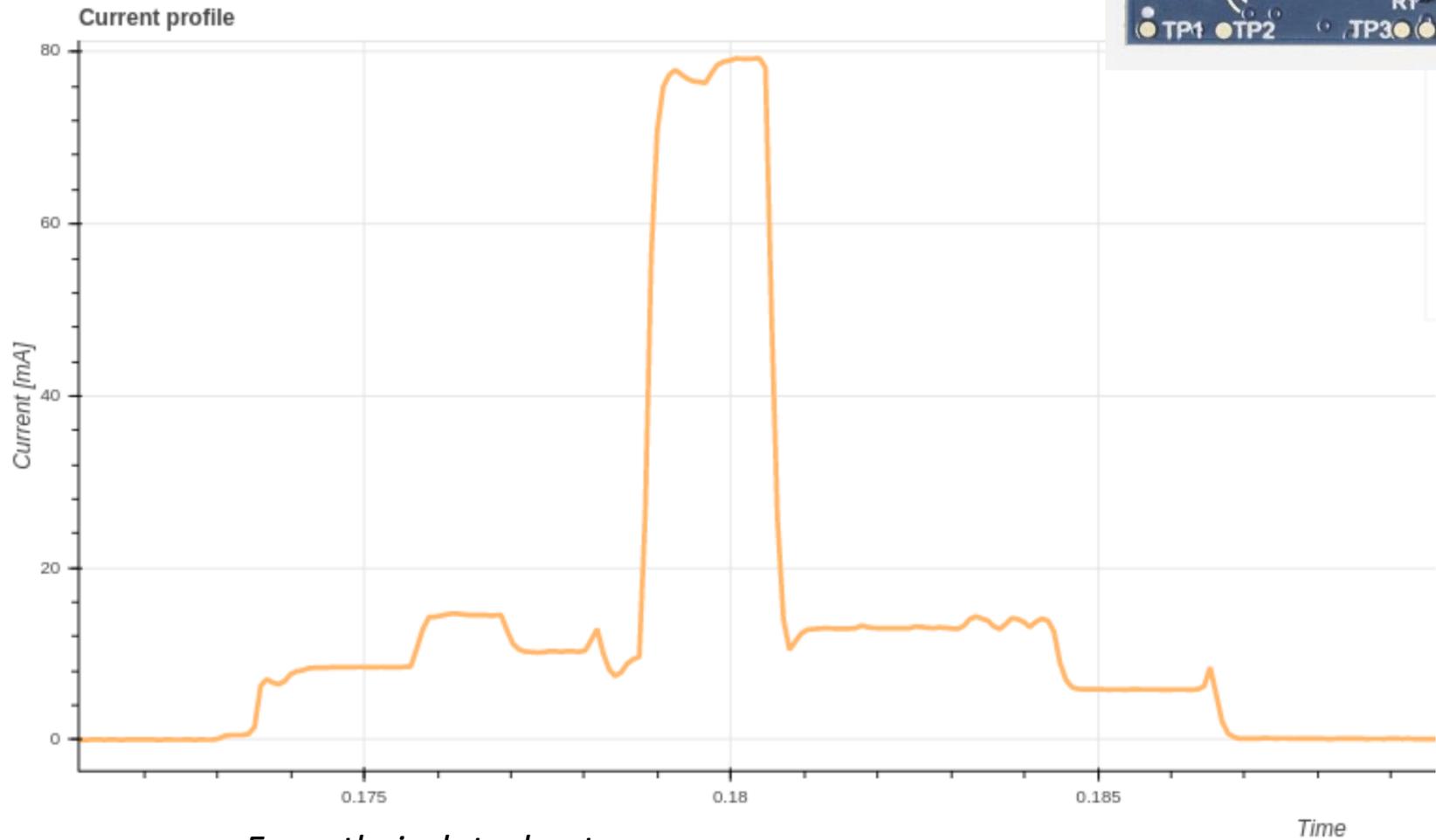
Configuration with Distance detector, profile 5 used.

STM M4 microcontroller is in sleep mode (Stop Mode 1) with full RAM retention and wake-up on RTC enabled.

<sup>(1)</sup>Measurement based on close range (0.05-0.3m).

# XM125

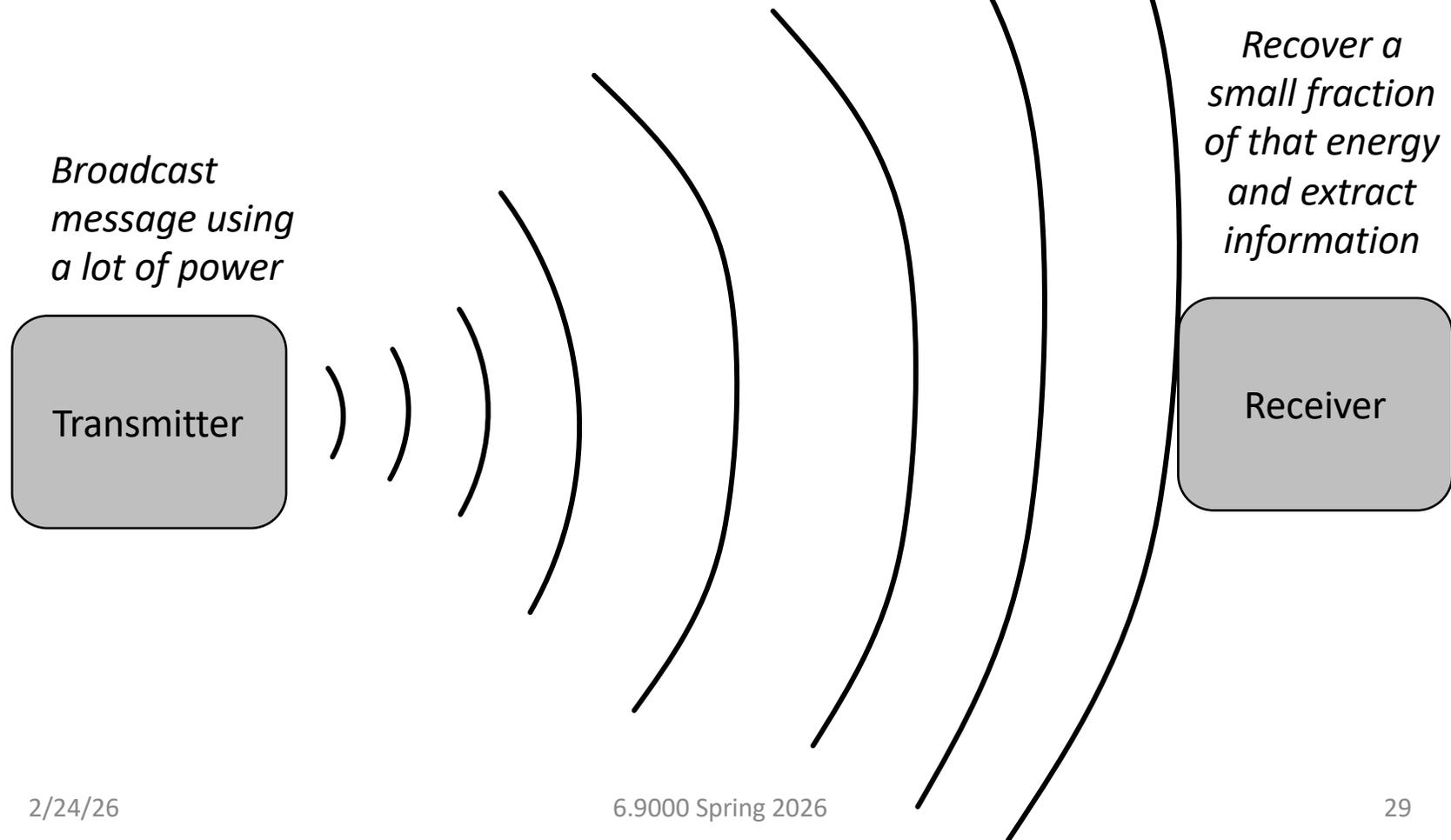
Figure 5.1. Current profile, measurement range 2.75m.



From their datasheet

# 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



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



Earth

3.53 billion miles, 4.5 hours transit time for EM radiation



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



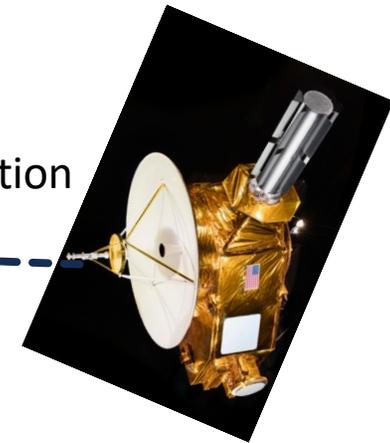
Earth

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



Pluto

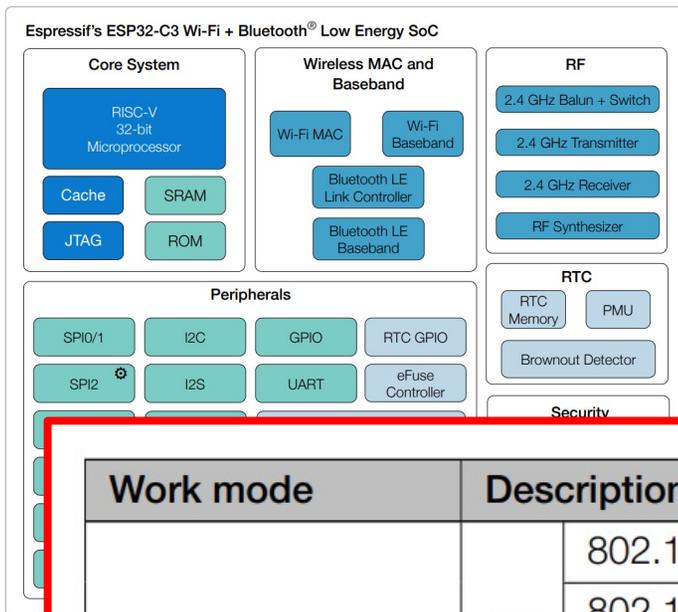
3.53 billion miles, 4.5 hours transit time for EM radiation



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.



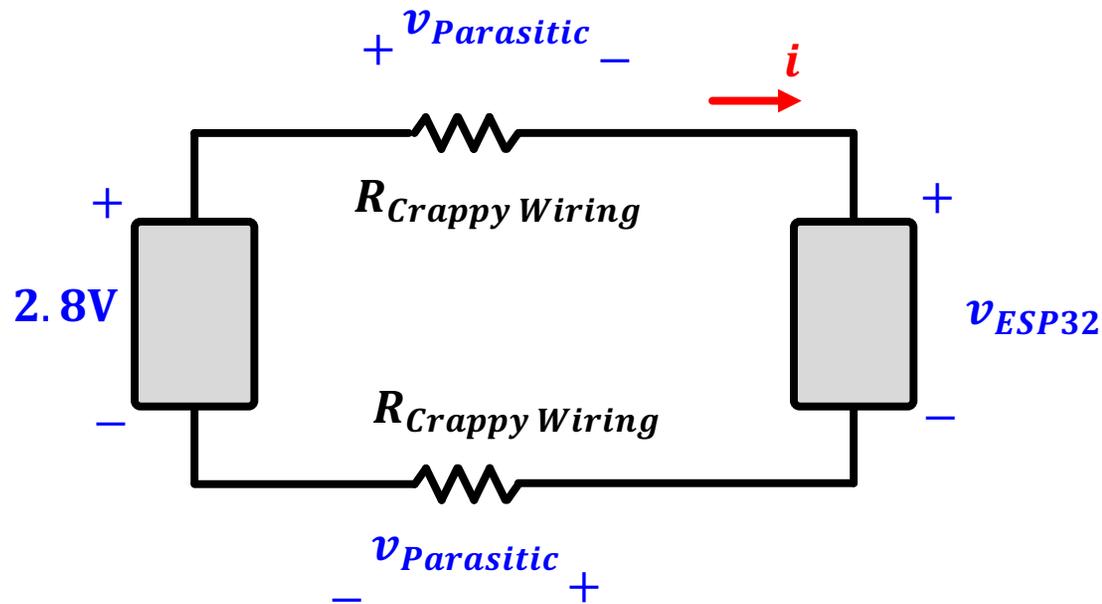
Work mode	Description	Peak (mA)	
Active (RF working)	TX	802.11b, 1 Mbps, @20.5 dBm	345
		802.11g, 54 Mbps, @18 dBm	285
		802.11n, HT20, MCS7, @17.5 dBm	280
		802.11n, HT40, MCS7, @17 dBm	280
	RX	802.11b/g/n, HT20	82
		802.11n, HT40	84

Mode	CPU Frequency (MHz)	Description	Typ	
			All Peripherals Clocks Disabled (mA)	All Peripherals Clocks Enabled (mA) <sup>1</sup>
Modem_sleep <sup>2,3</sup>	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...

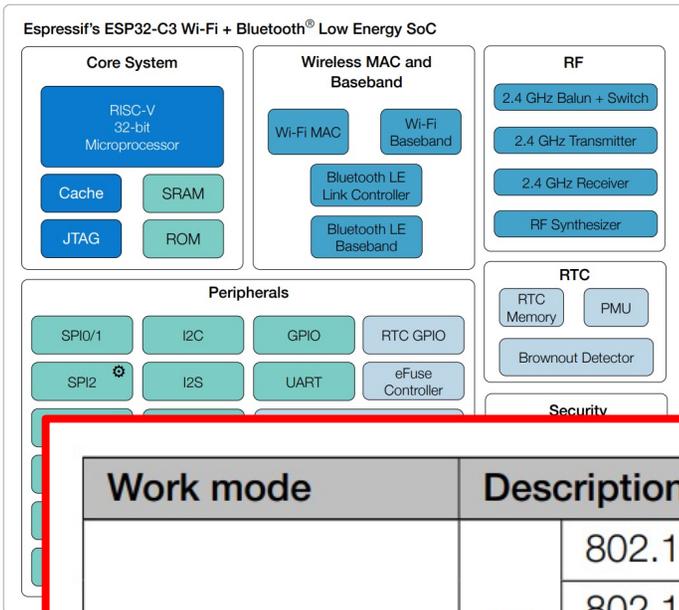
- Why some of you had issues with your ESP on startup or on connecting to WiFi



*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!



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Active (RF working)	TX	802.11b, 1 Mbps, @20.5 dBm	345
		802.11g, 54 Mbps, @18 dBm	285
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	RX	802.11b/g/n, HT20	82
		802.11n, HT40	84

# LoRa?

## LoRa

20 languages

Article Talk

Read Edit View history Tools

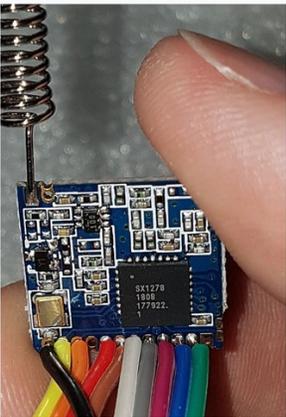
From Wikipedia, the free encyclopedia

*For the deep learning fine-tuning technique, see [Fine-tuning \(deep learning\) § Low-rank\\_adaptation](#).*

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

**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.<sup>[6]</sup> 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.<sup>[7]</sup>



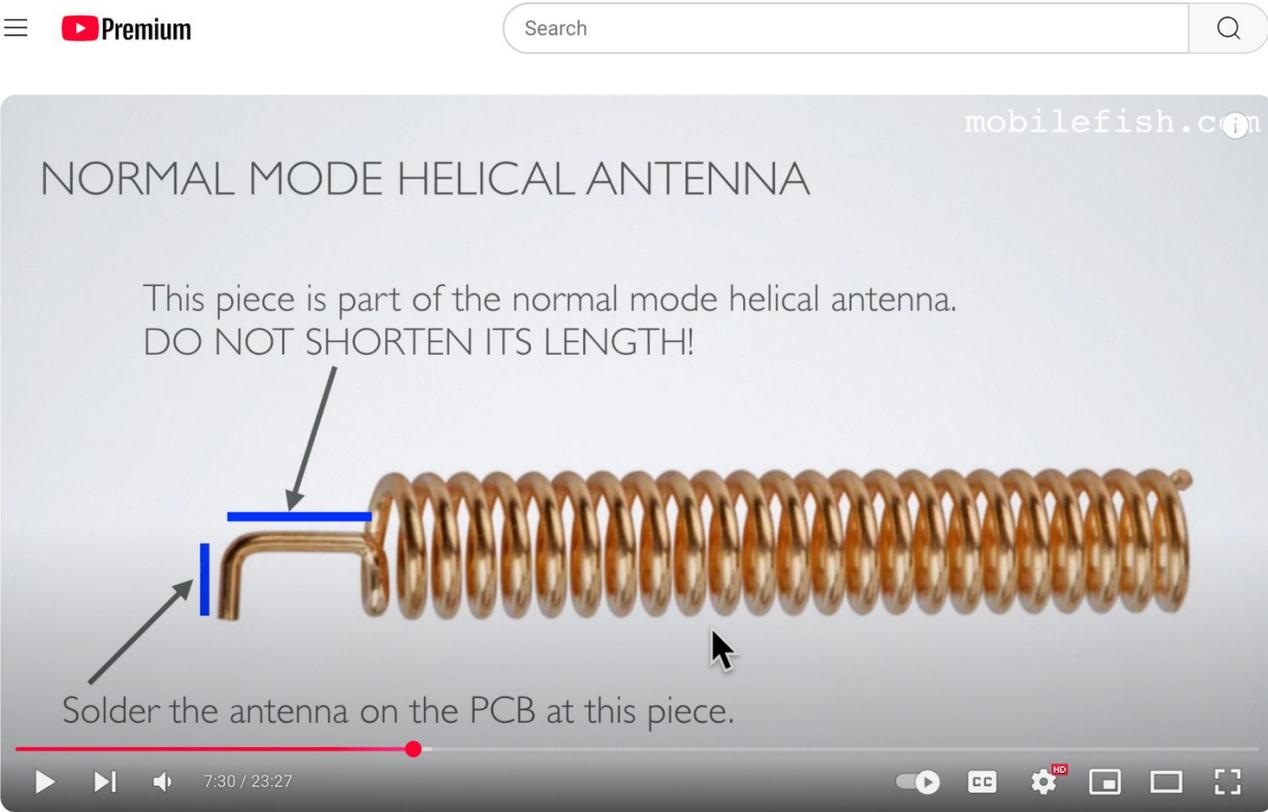
A LoRa module

<b>Developed by</b>	Cycleo, Semtech
<b>Connector type</b>	SPI/I2C
<b>Compatible hardware</b>	SX1261, SX1262, SX1268, SX1270, SX1276, SX1278

- LoRa is “low power” in the relative sense...a lot of modules I was looking at still pull legit amounts of power.

# LoRa

- Need to experiment with antennas and things (



The video player shows a close-up of a copper helical antenna. A blue horizontal line is drawn across the top of the antenna's lead wire. A blue vertical line is drawn at the end of the lead wire. Two arrows point to these lines. Text above the antenna says "This piece is part of the normal mode helical antenna. DO NOT SHORTEN ITS LENGTH!". Text below the antenna says "Solder the antenna on the PCB at this piece." The video player interface includes a search bar, a "Premium" logo, and a progress bar at the bottom.

mobilefish.com

## NORMAL MODE HELICAL ANTENNA

This piece is part of the normal mode helical antenna.  
DO NOT SHORTEN ITS LENGTH!

Solder the antenna on the PCB at this piece.

7:30 / 23:27

204

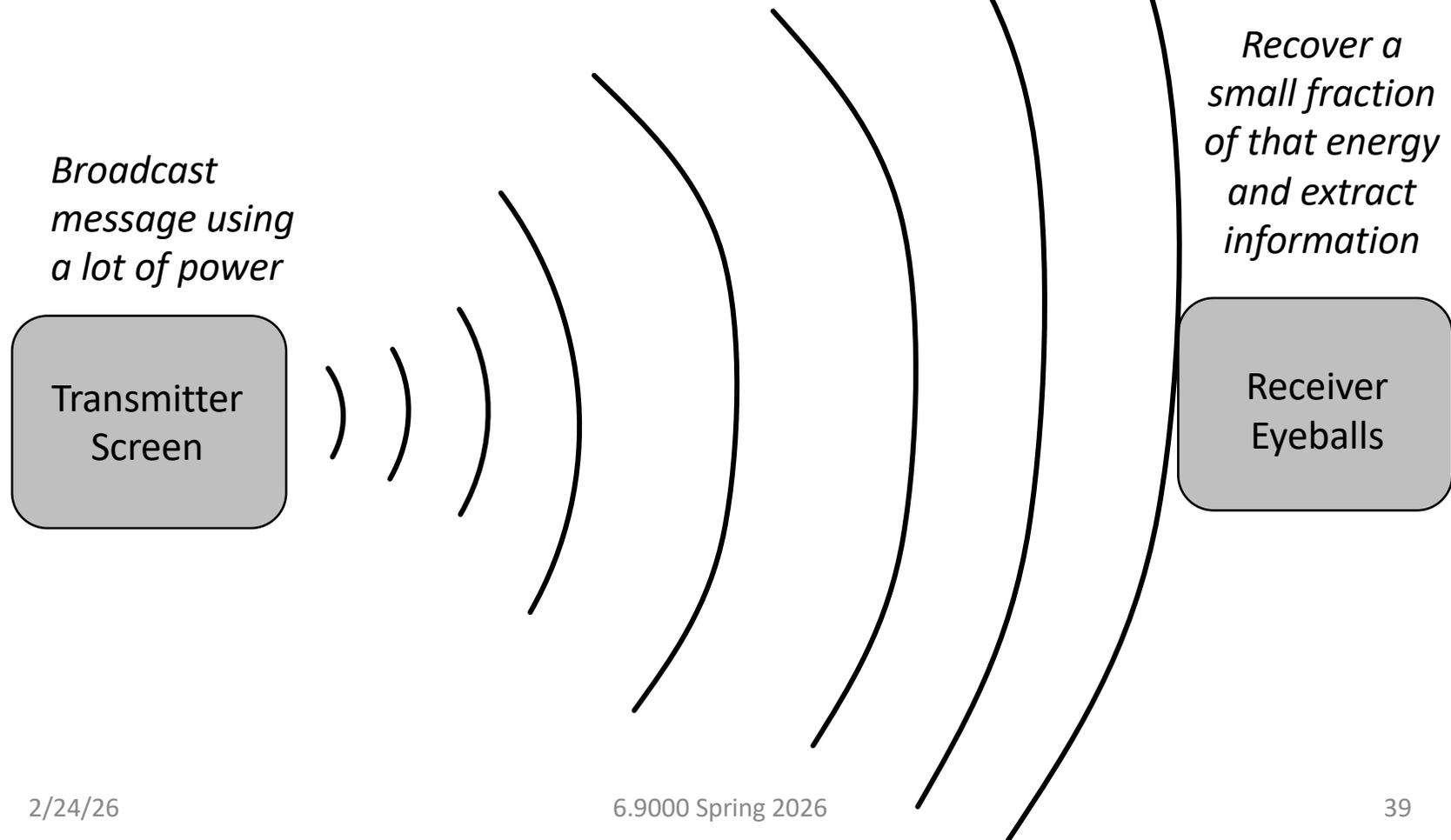
Share Download Clip

# Displays?

- Some of the teams are looking at displays because people apparently matter and may need to “engage” with the “community”
- 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 all the time
- OLED uses decently less power all the time, but more money
- E-Ink uses waayy less power on average, but has large power spikes on refresh and sacrifices in other ways
- Gotta figure that out.

# Computation in General

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

# Conclusion on Power Consumption!

- 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)	All
Modem-sleep <sup>2,3</sup>	160	CPU is running	23	
		CPU is idle	16	
	80	CPU is running	17	
		CPU is idle	13	

<sup>1</sup> In practice, the current consumption might be different depending on which peripheral is used.

<sup>2</sup> In Modem-sleep mode, Wi-Fi is clock gated.

<sup>3</sup> In Modem-sleep mode, the consumption might be higher when accessing flash memory. For example, at 80 Mbit/s, in SPI 2-line mode the consumption is 10 mA.

## 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

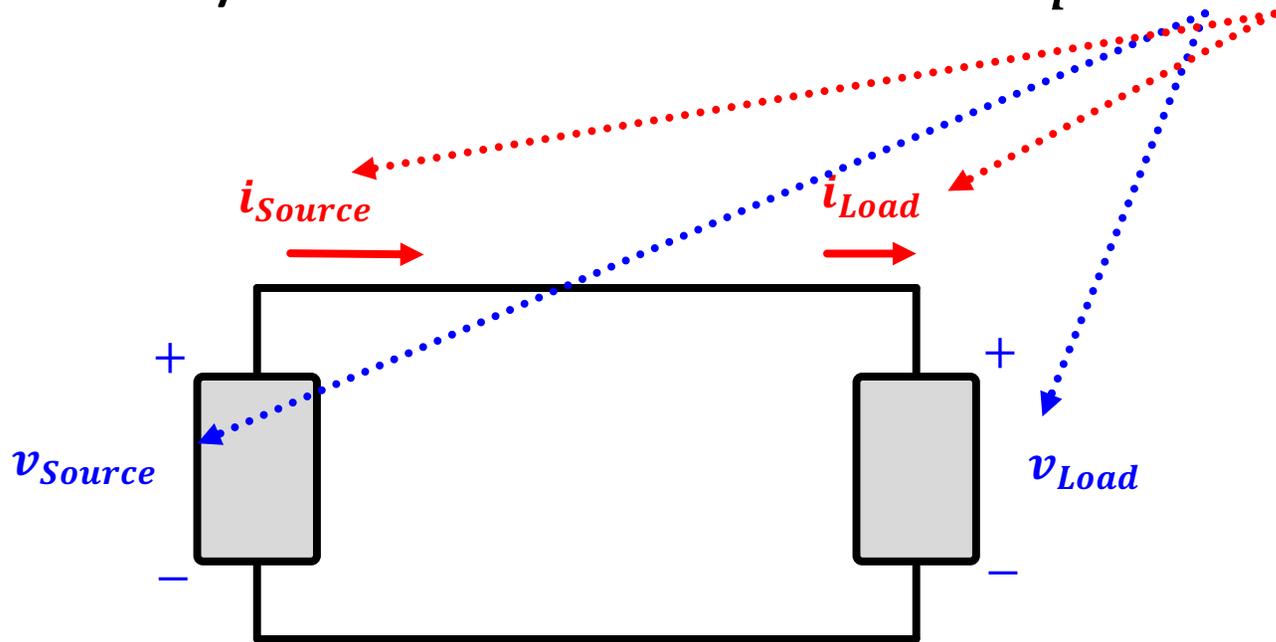
Work Mode <sup>1</sup>	Description	Peak (mA)	
Active (RF working)	TX	802.11b, 1 Mbps, @21 dBm	335
		802.11g, 54 Mbps, @19 dBm	285
		802.11n, HT20, MCS7, @18.5 dBm	276
		802.11n, HT40, MCS7, @18.5 dBm	278
	RX	802.11b/g/n, HT20	84
		802.11n, HT40	87

# BUT...

- 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!

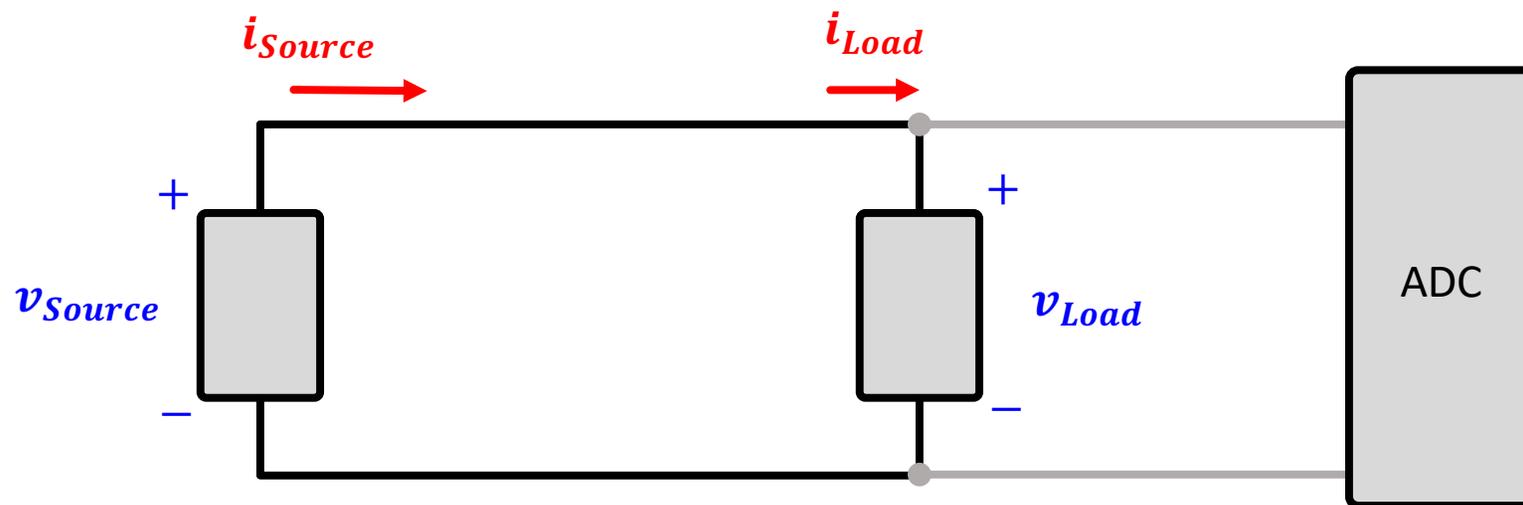
# So...How *Do* You Measure Power?

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



# How Do You Measure Voltage?

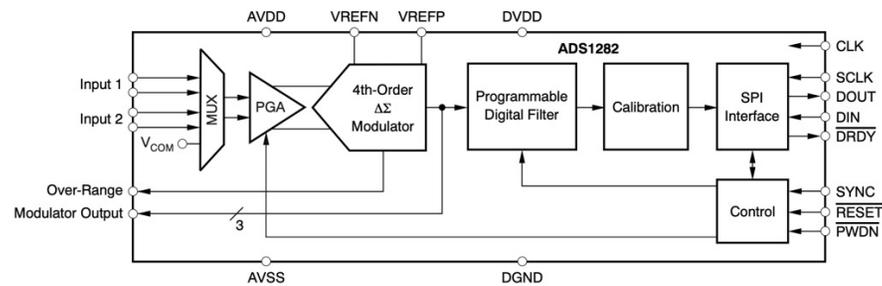
- This one is easy-ish. You can use a voltmeter or an Analog-to-Digital Converter (ADC) and measure in parallel



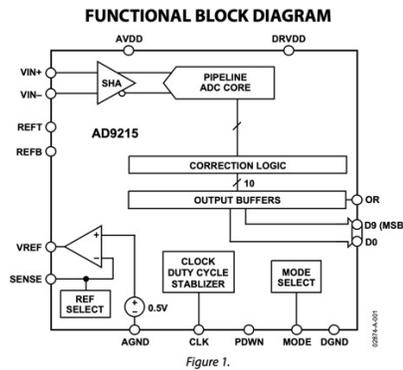
# Tons of great ADCs out there

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

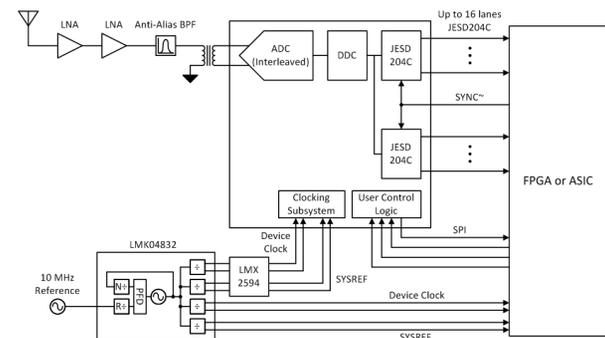
*Texas Instruments' ADS1282 31 bit ADC, capable of 4ksamp/sec (\$20):*



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

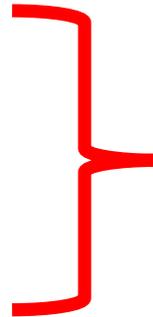


*Texas Instruments' radiation-hardened ADC12DJ5200 12 bit ADC, capable of 10.5Gsamp/sec (\$30,000):*



# ADCs

- High Sample Rate
- High Resolution
- Low Cost



*Pick two*

# 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?

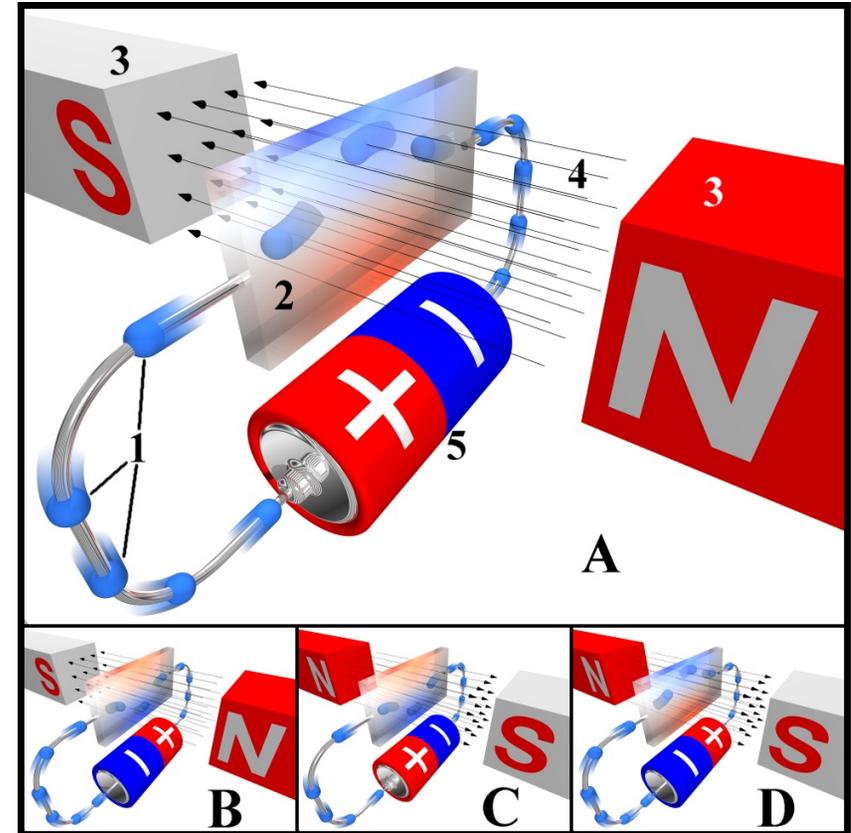
# Coils

- 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](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!

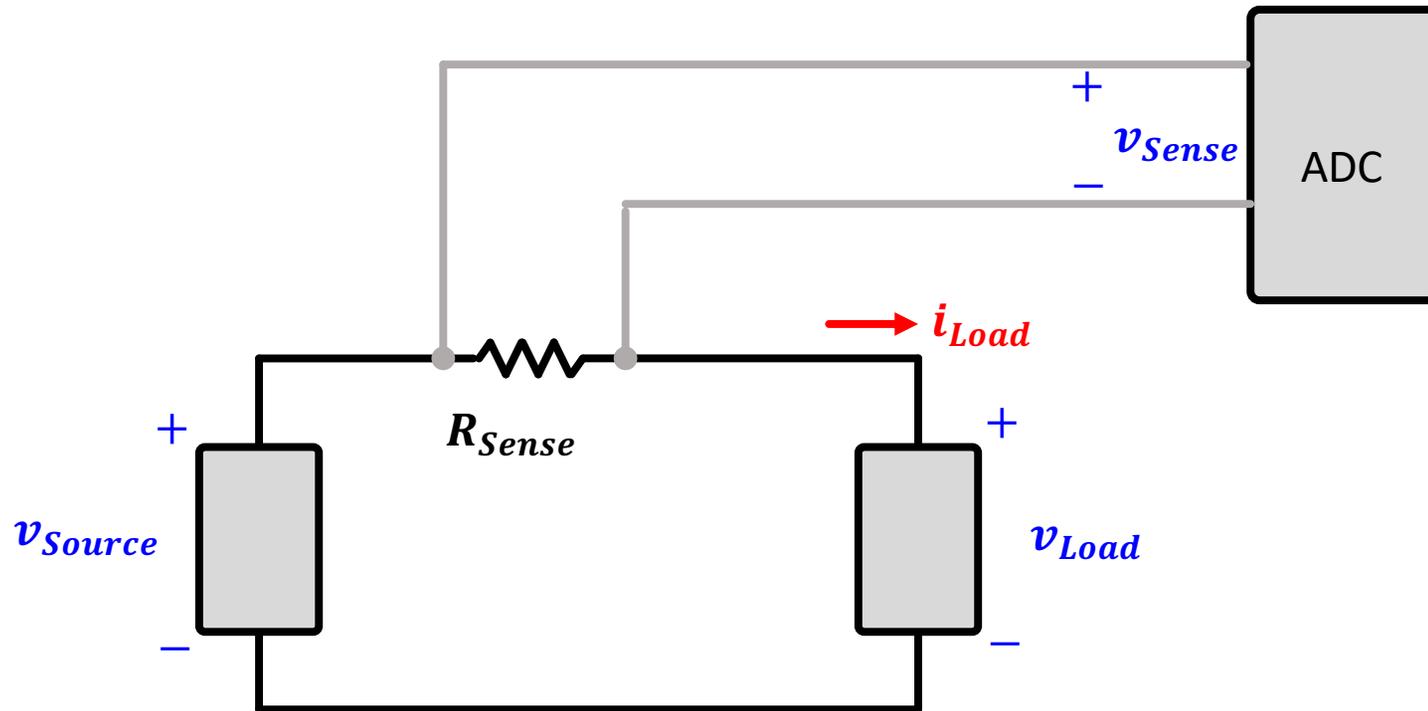
# Use a Current-to-Voltage Converter

- 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 for us? It would need to...
  - Take a current...
  - Reliably convert that current into a voltage...
  - Perhaps ideally in a linear fashion???
  - ???



# How Do You Measure Current?

- Solution:



# Characteristics of this Resistor?

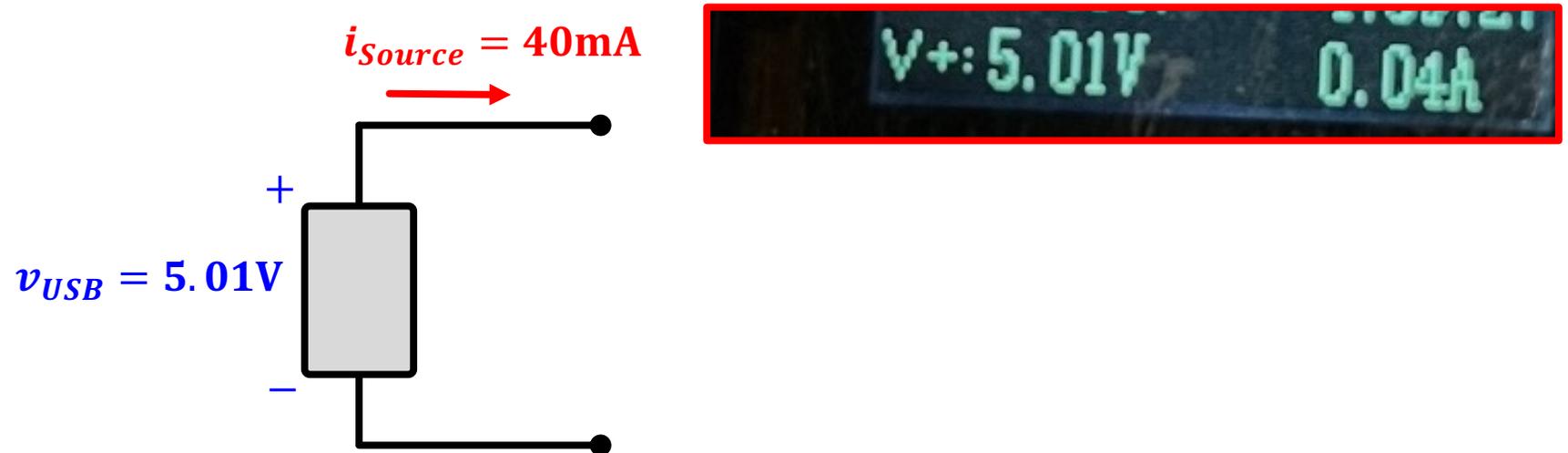
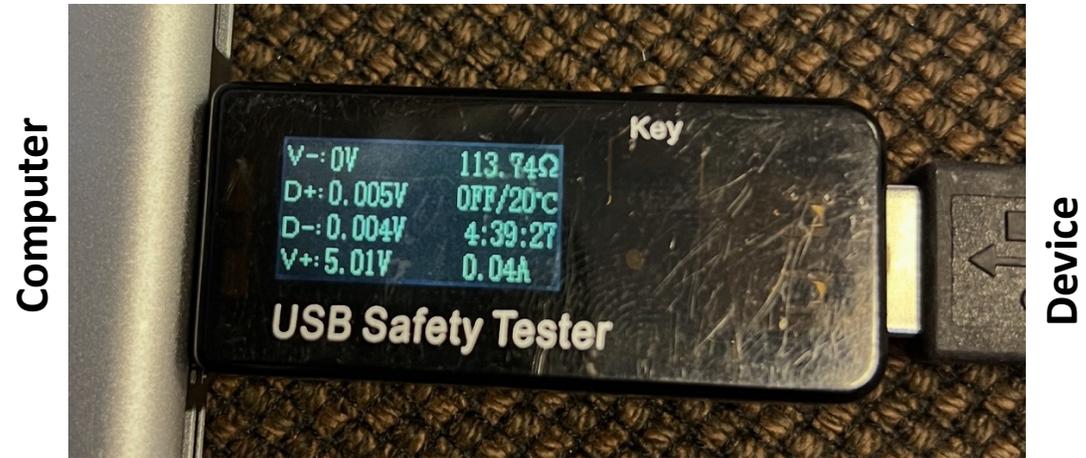
- Value is known to a high precision
- Small? Pros/Cons? What is Small?
- Large? Pros/Cons? What is Large?

# 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!

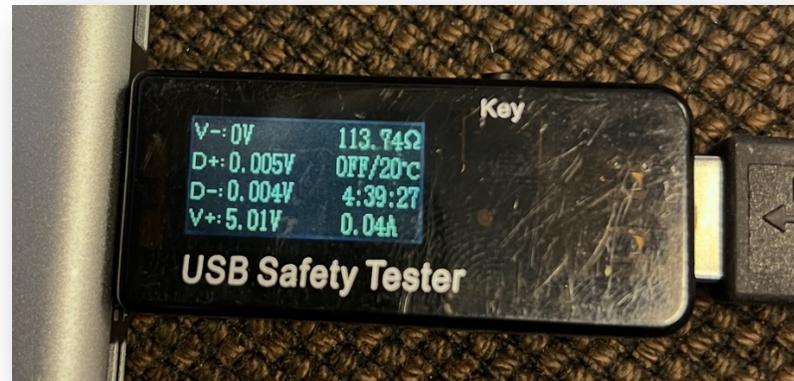
# USB "Safety" Tester

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



# USB “Safety” Tester

- Crack it open...



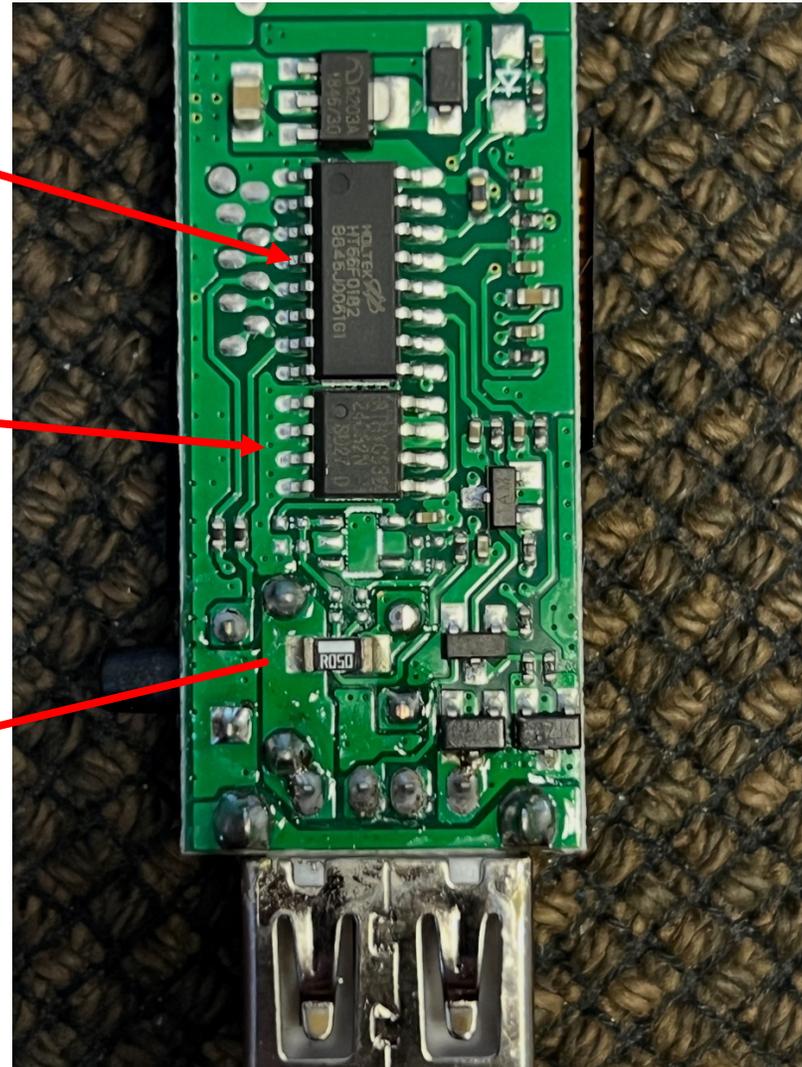
# Operation

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

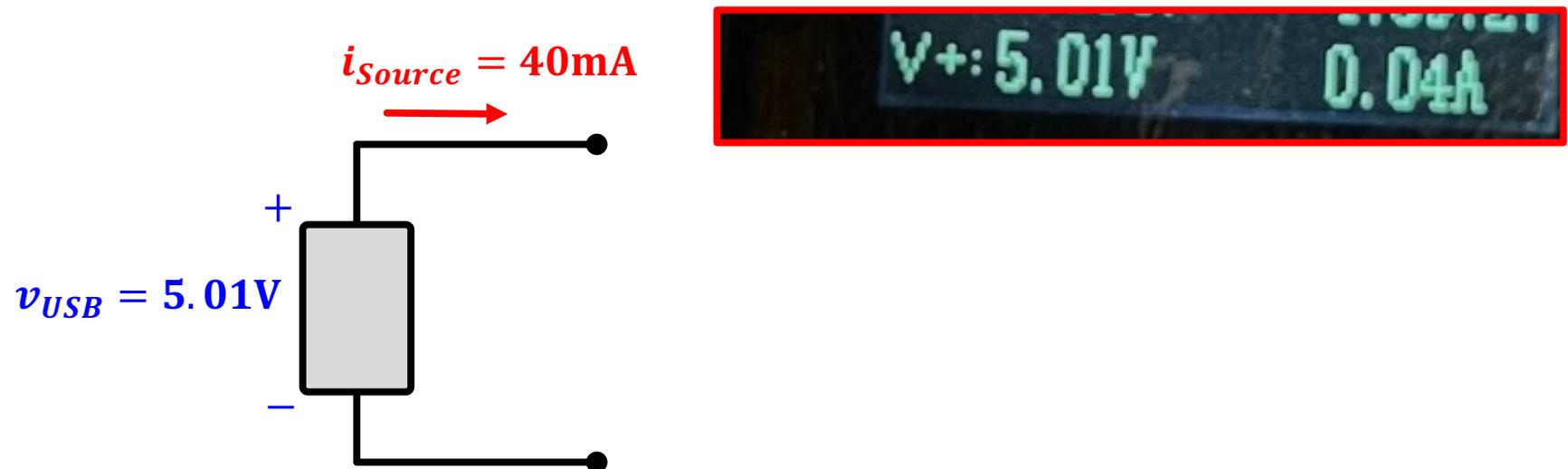


50 mOhm sense resistor...why so physically big?



# Limited Resolution

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



# Resistor Choice....

- The Bigger the resistor in ohms, the better your current resolution (since you get more volts per amp), but....
- ...The more you disturb your system (not good)...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 m $\Omega$
  - Tolerance Equivalent to 0.1%
  - 15-A Continuous From  $-40^{\circ}\text{C}$  to  $+85^{\circ}\text{C}$
  - 10 ppm/ $^{\circ}\text{C}$  Temperature Coefficient ( $0^{\circ}\text{C}$  to  $+125^{\circ}\text{C}$ )



**INA260**

SBOS656C – JULY 2016 – REVISED DECEMBER 2016

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## INA260

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

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# ***PRECISION INTEGRATED SHUNT***

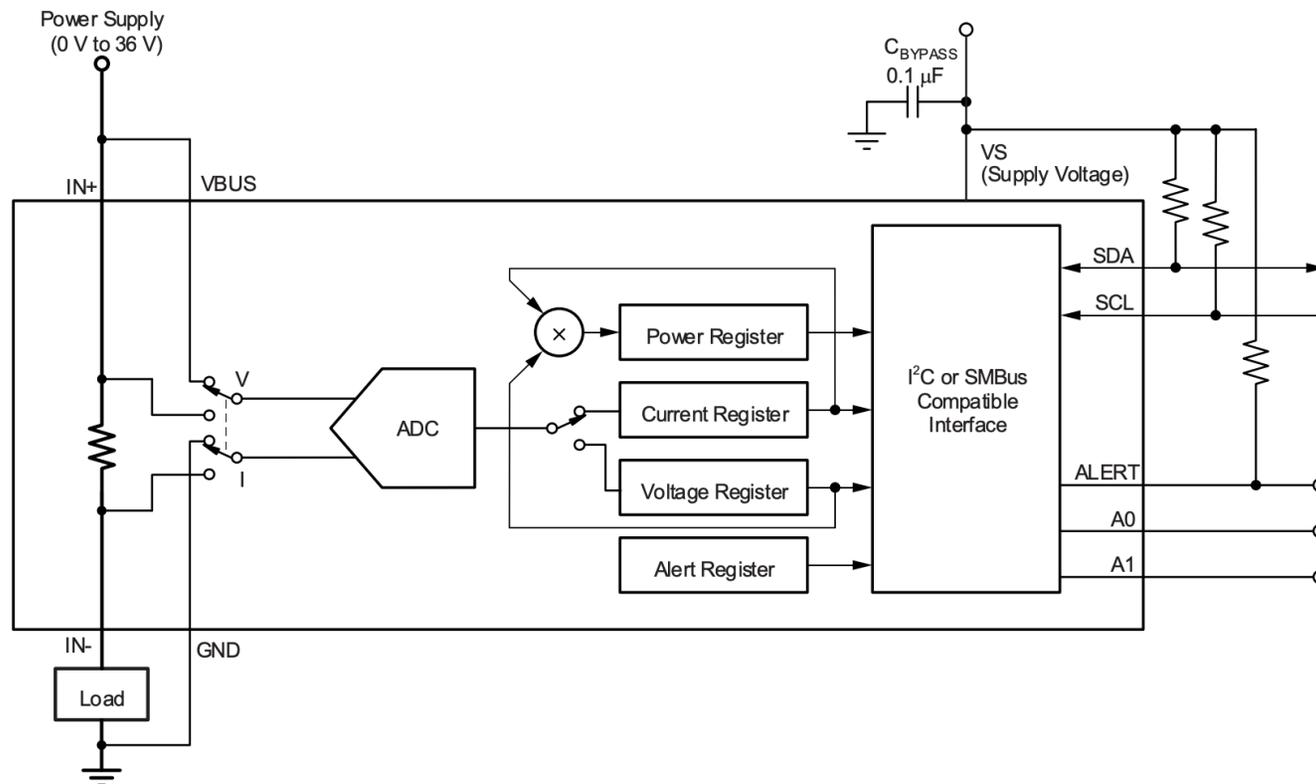
# Texas Instruments' INA260 et al

- Chip (costs few buckos)
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  - 10 ppm/ $^{\circ}\text{C}$  Temperature Coefficient ( $0^{\circ}\text{C}$  to  $+125^{\circ}\text{C}$ )

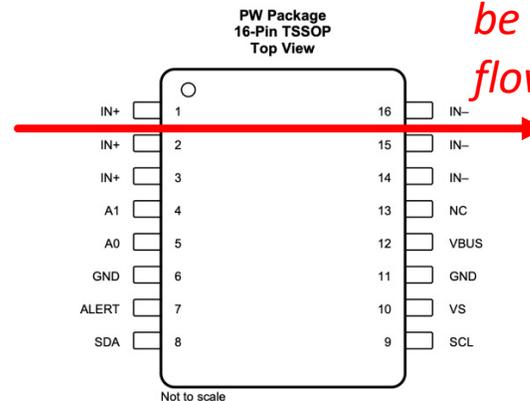
## 9.2 Typical Application



# Pinout

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

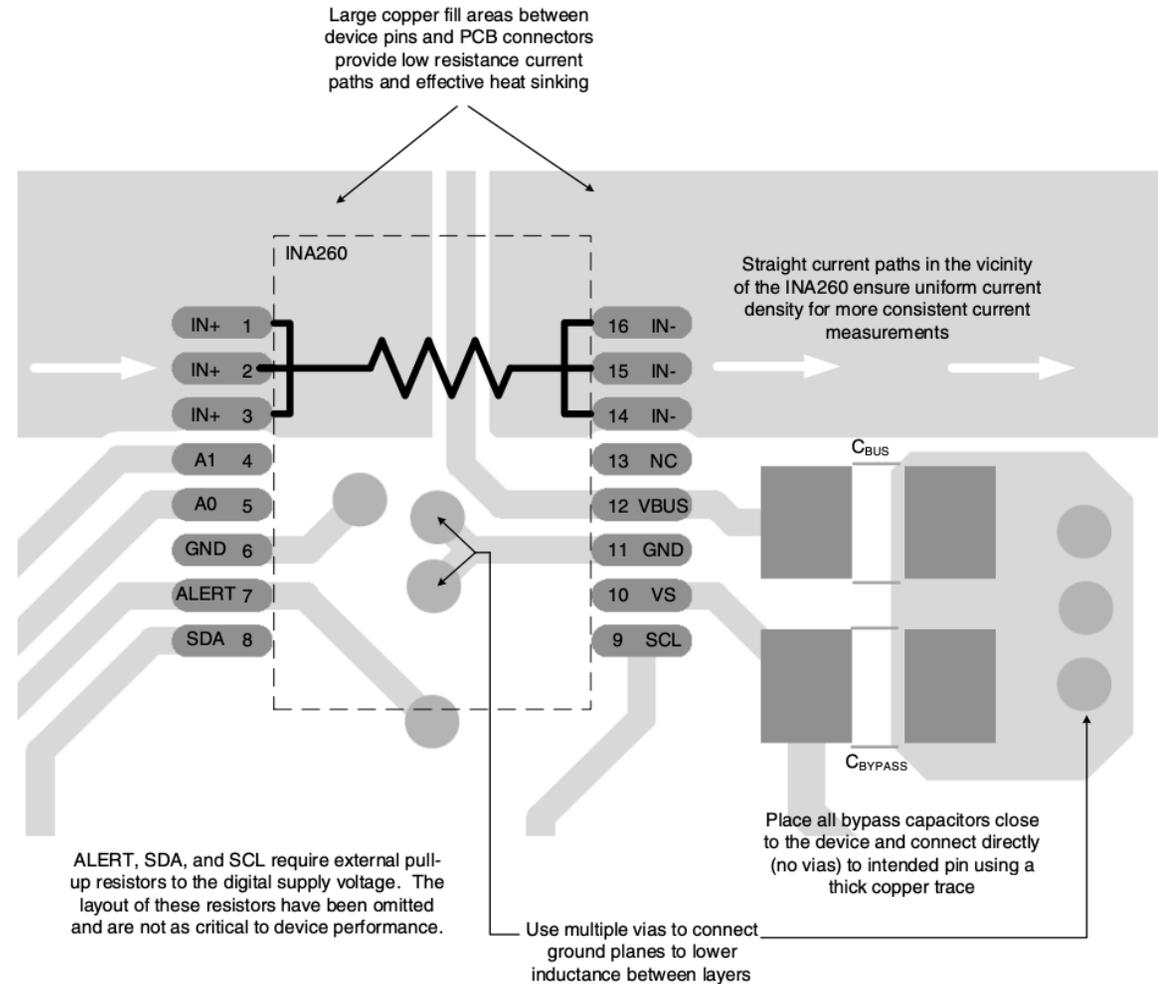
## 6 Pin Configuration and Functions



Pin Functions

PIN		I/O	DESCRIPTION
NAME	NO.		
A0	5	Digital input	Address pin. Connect to GND, SCL, SDA, or VS. <a href="#">Table 2</a> shows pin settings and corresponding addresses.
A1	4	Digital input	Address pin. Connect to GND, SCL, SDA, or VS. <a href="#">Table 2</a> 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

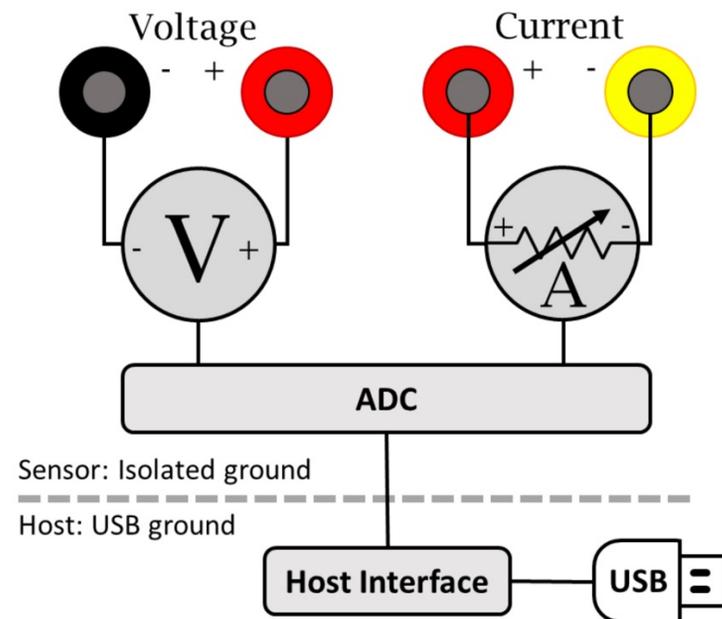


Copyright © 2016, Texas Instruments Incorporated

NOTE: Connect the VBUS pin to the power supply rail

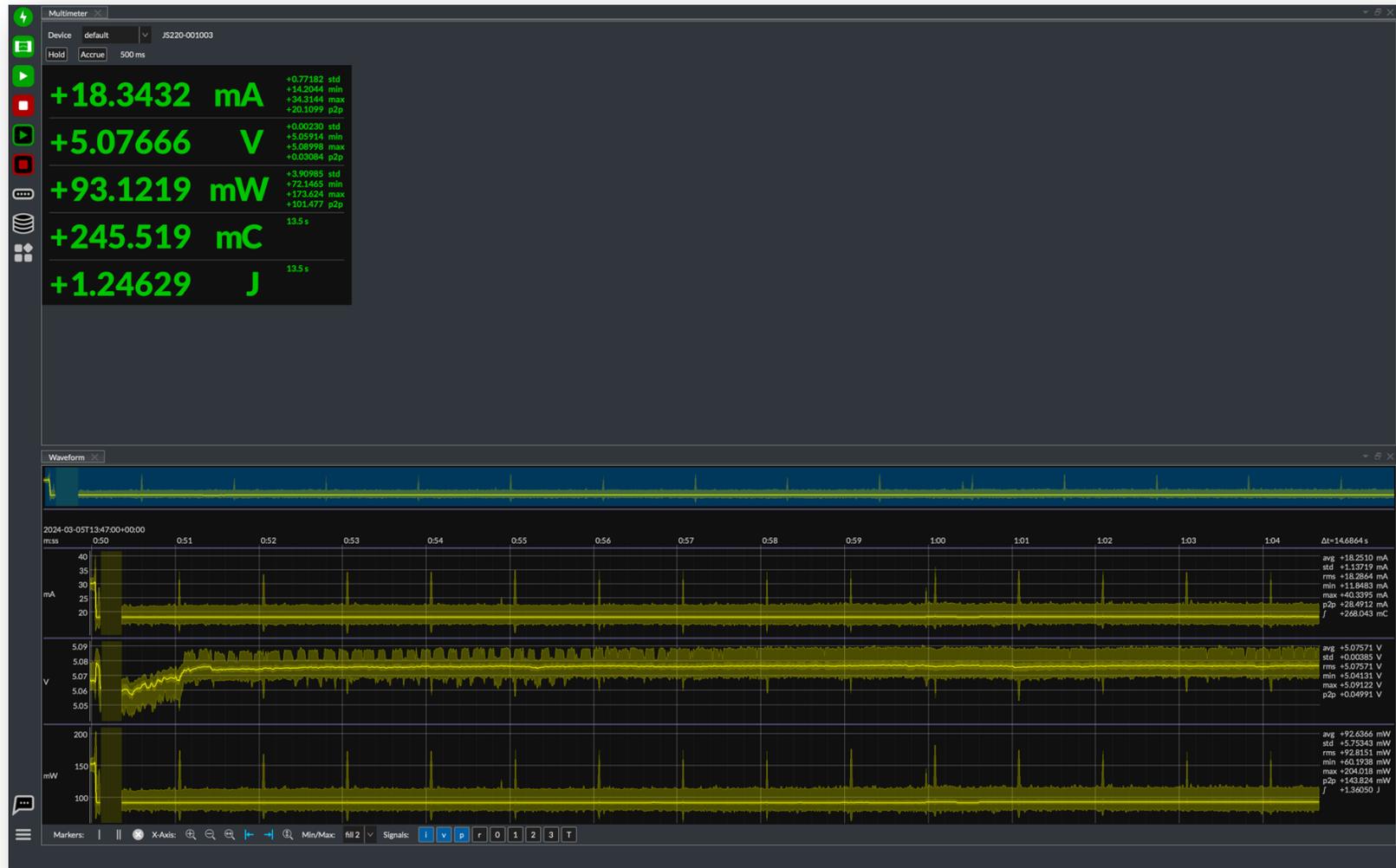
# JouleScope

- Device we'll use in Lab 5 (-ish) soon to measure our devices and which you'll need to use heavily to characterize your system



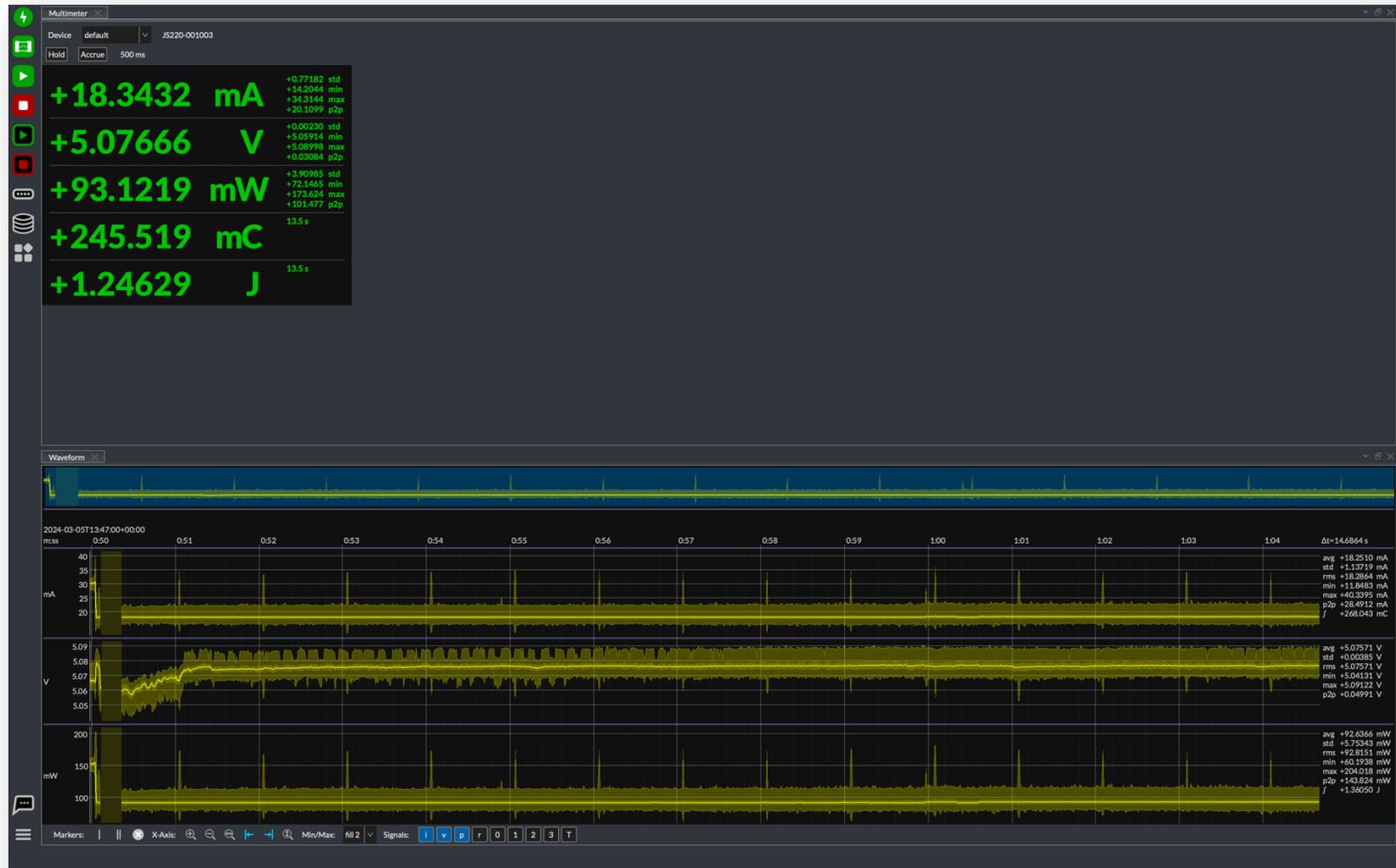
<https://www.joulescope.com/>

# Very Nice Readout



*Application GUI...can readout and do all the stuff.*

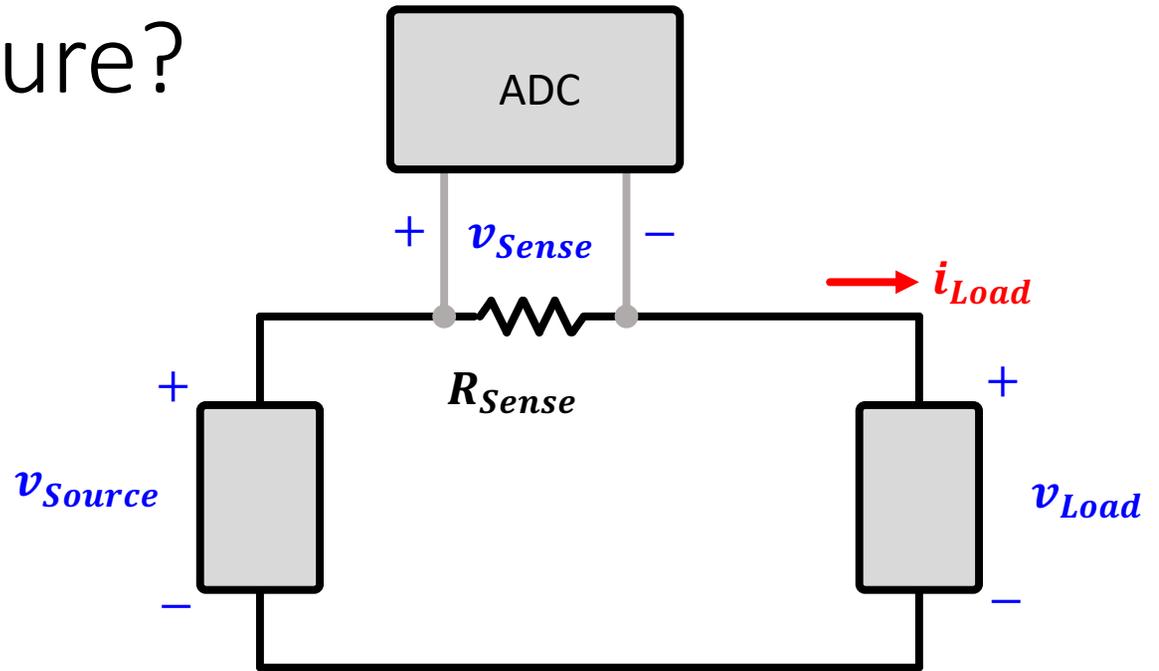
# High Resolution in V, I , and P and in time!



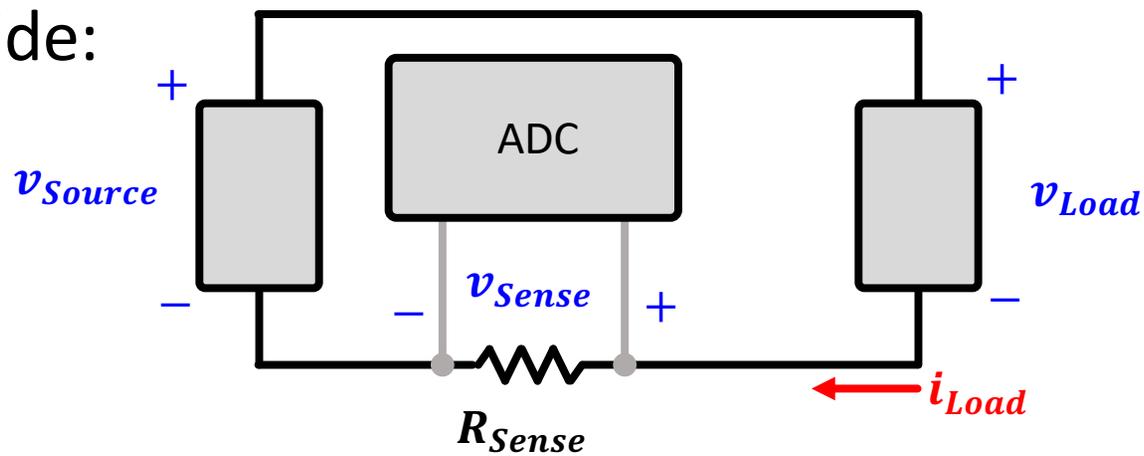
*Application GUI...can readout and do all the stuff.*

# Where to Measure?

- High-Side:

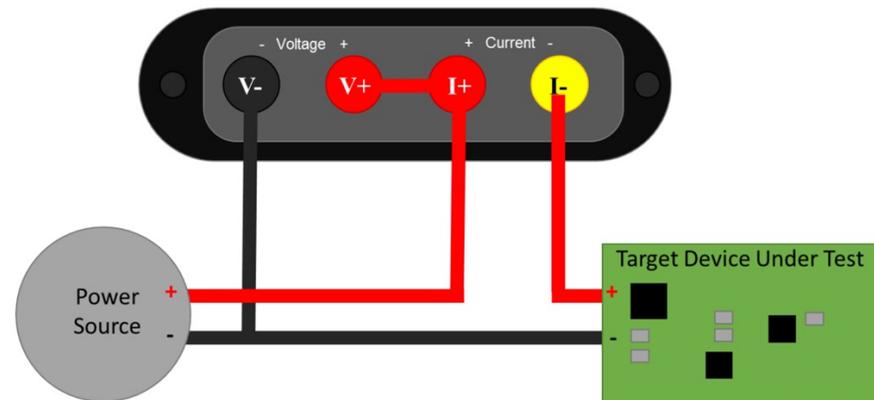


- Low-Side:

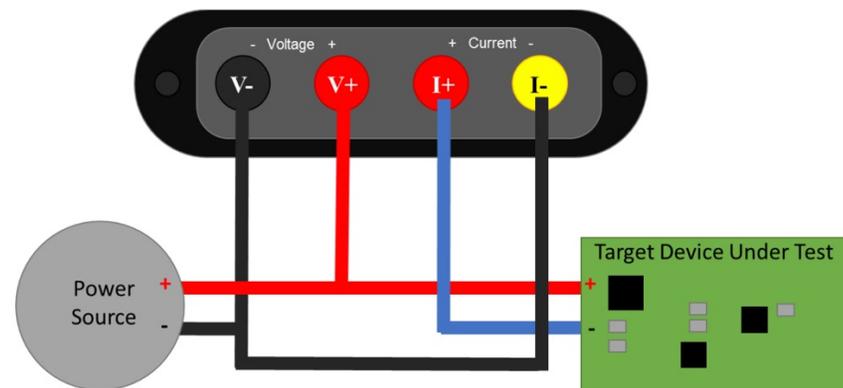


# Joule Scope OK with That

- High-Side



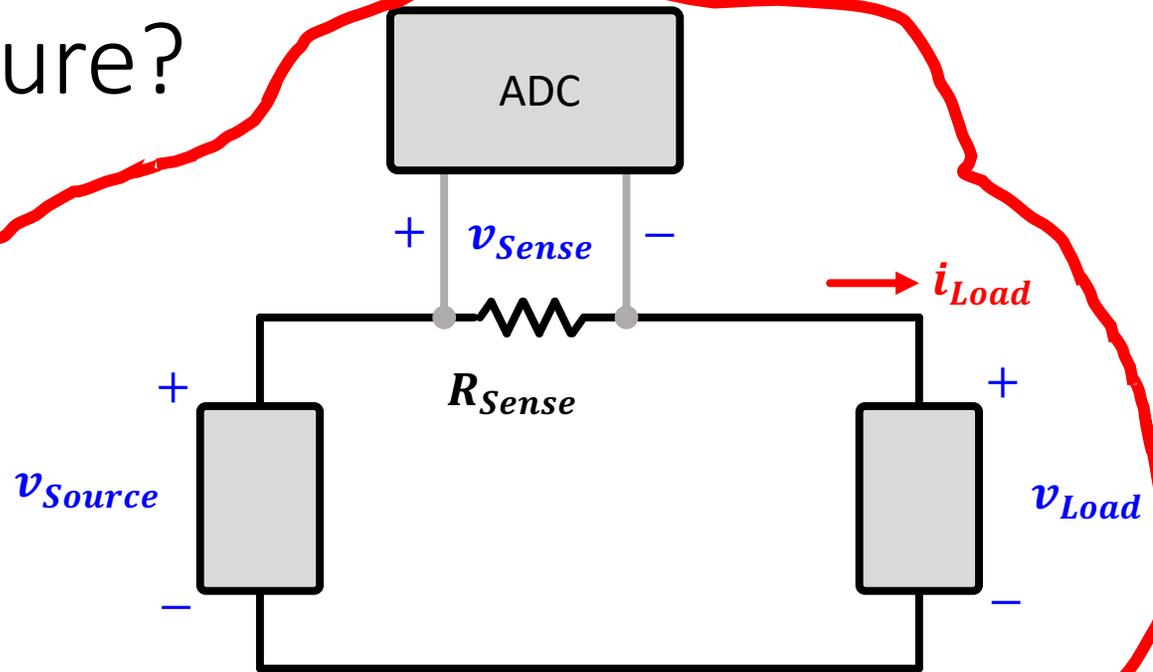
- Low-Side



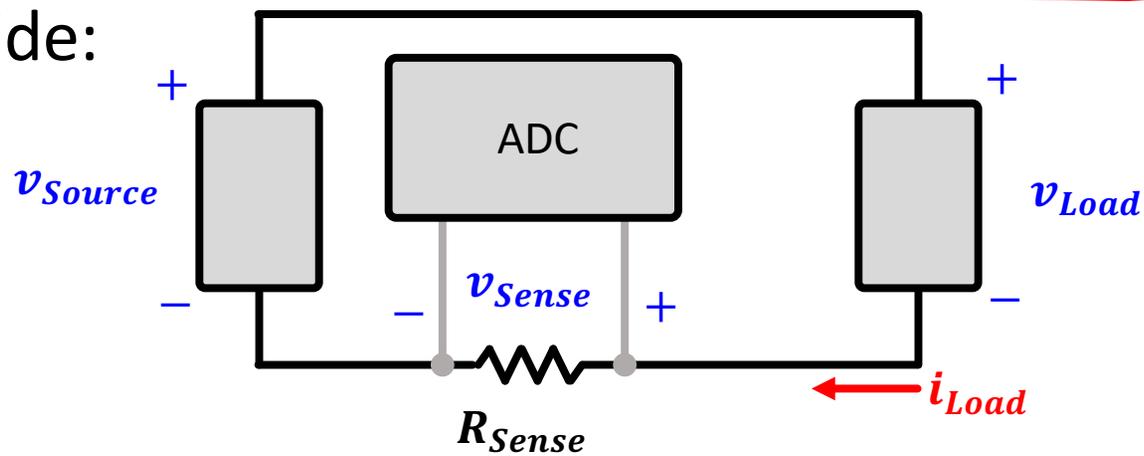
# Where to Measure?

- High-Side:

Generally preferred



- Low-Side:

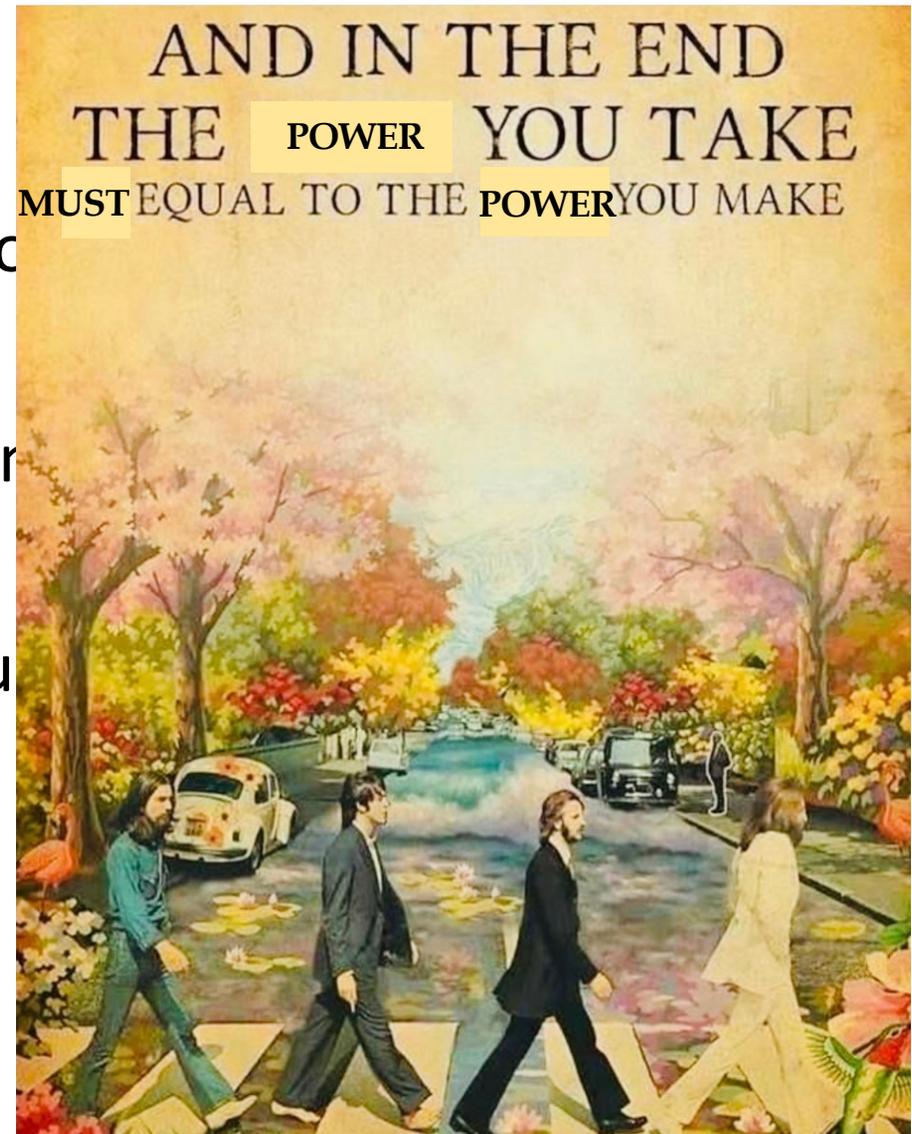


# So in Upcoming Lab you'll use the Joulescope to measure...

- 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!

# Take Take Take, Use Use Use

- What about Giving and/c
- Only talked about consum
- How can we make produ

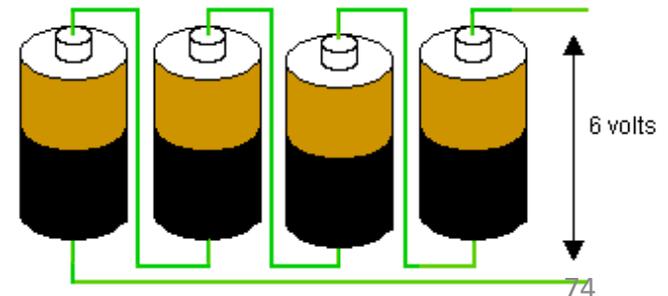
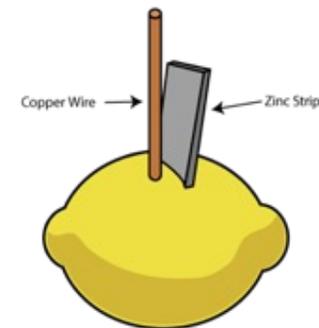


# Batteries

- No matter what you'll all be needing to use batteries.
- Batteries provide a way to store energy chemically and then release it electrically
- Two main classes of battery:
  - Primary Cells (irreversible chemical  $\rightarrow$  electrical energy)
  - Secondary Cells (reversible chemical  $\leftrightarrow$  electrical energy)
- Within those classes are tons of subclasses/variations/etc...

# Battery Voltage

- All batteries are basically two electrodes of differing materials connected by some sort of ionic juice.
- Combinations lead to battery voltages:
  - 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



# Batteries Capabilities

- Batteries only vaguely resemble voltage sources or current sources. They are far from ideal!
- Wide differences in:
  - Nominal voltage
  - Current capability
  - Energy capacity
  - Energy density (Wh/kg)
  - Charge/Discharge rate
  - Renewable or not
- Hugely active area of research

## Days numbered for 'risky' lithium-ion batteries, scientists say, after fast-charging breakthrough in sodium-ion alternative

News By [Rory Bathgate](#) published January 28, 2026

An innovative approach to battery materials could bring sodium-ion energy density and charging speeds far closer to those of lithium-ion, scientists say.

Home > Science

## Edison-Inspired Nickel-Iron Near-Instant Recharges

The downside is a more limited capacity compared to existing lithium-ion options.

By [Jon Martindale](#) February 16, 2026



2/24/26

0.5000 Spring 2026

# 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 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

# Capacity/Energy

- Integral of Power Consumed over time

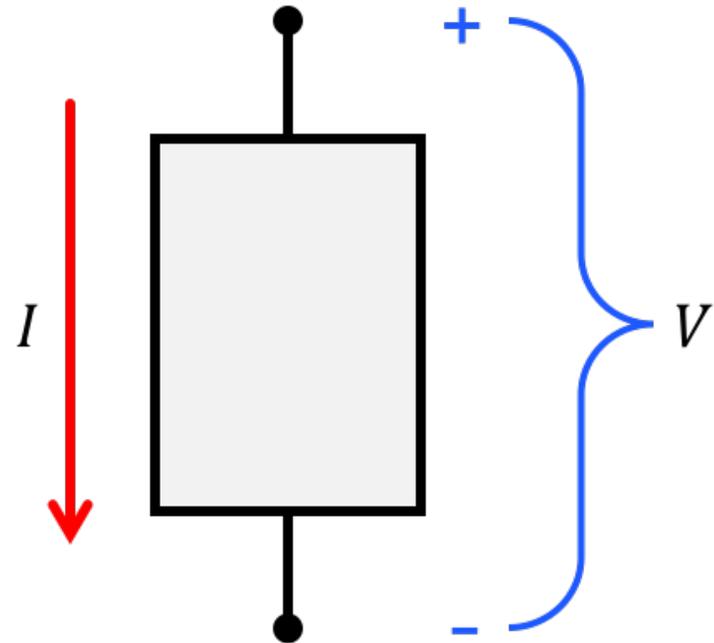
$$E(t) = \int_0^t P(\tau) d\tau$$

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

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

- If Voltage and Current are constant over time:

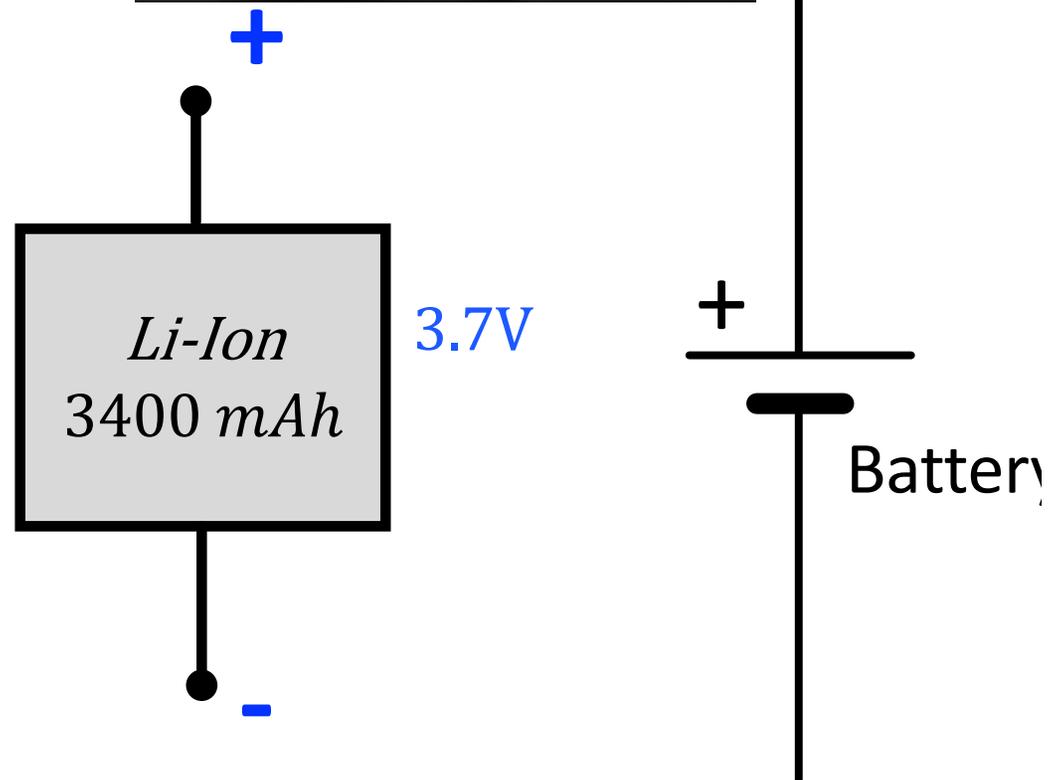
$$E = V \cdot I \cdot \Delta t$$



Our 6.900 Battery  
(3400 mAh @~3.7V)  
contains 44,000 Joules when fully  
charged

# Battery

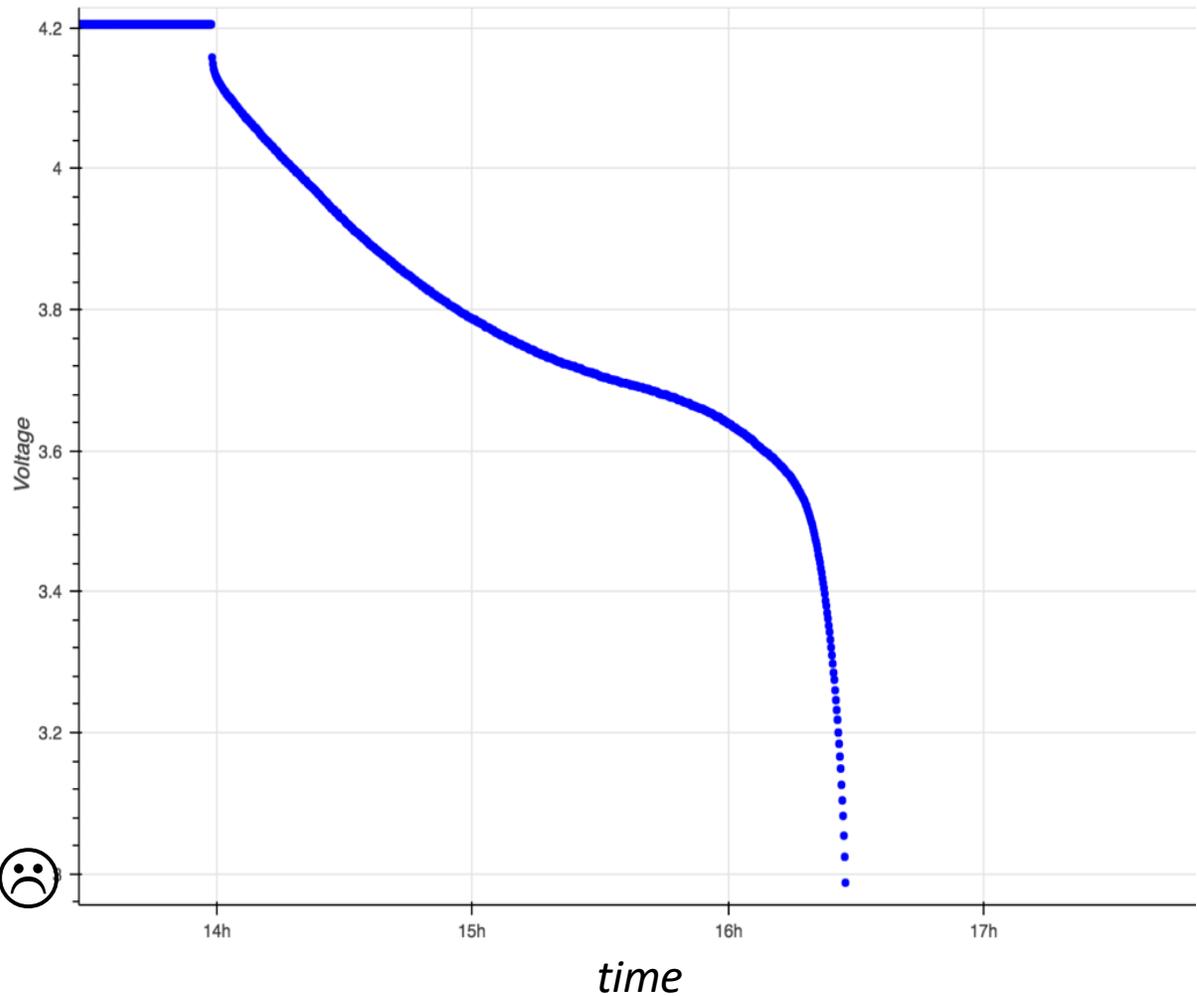
- This seems so nice and easy to think about...3.7 V when it is on, 0V when it is off
- But in real life it isn't so clean and nice...☹️



*Sometimes use one on the right too*

# Voltage of 350 mAh 3.7V battery

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



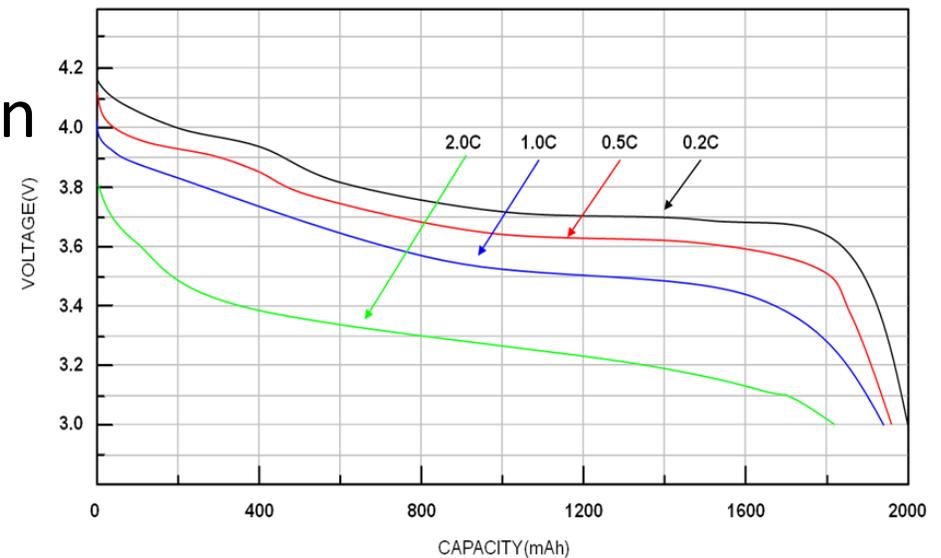
*This is far from a constant  
output voltage*

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

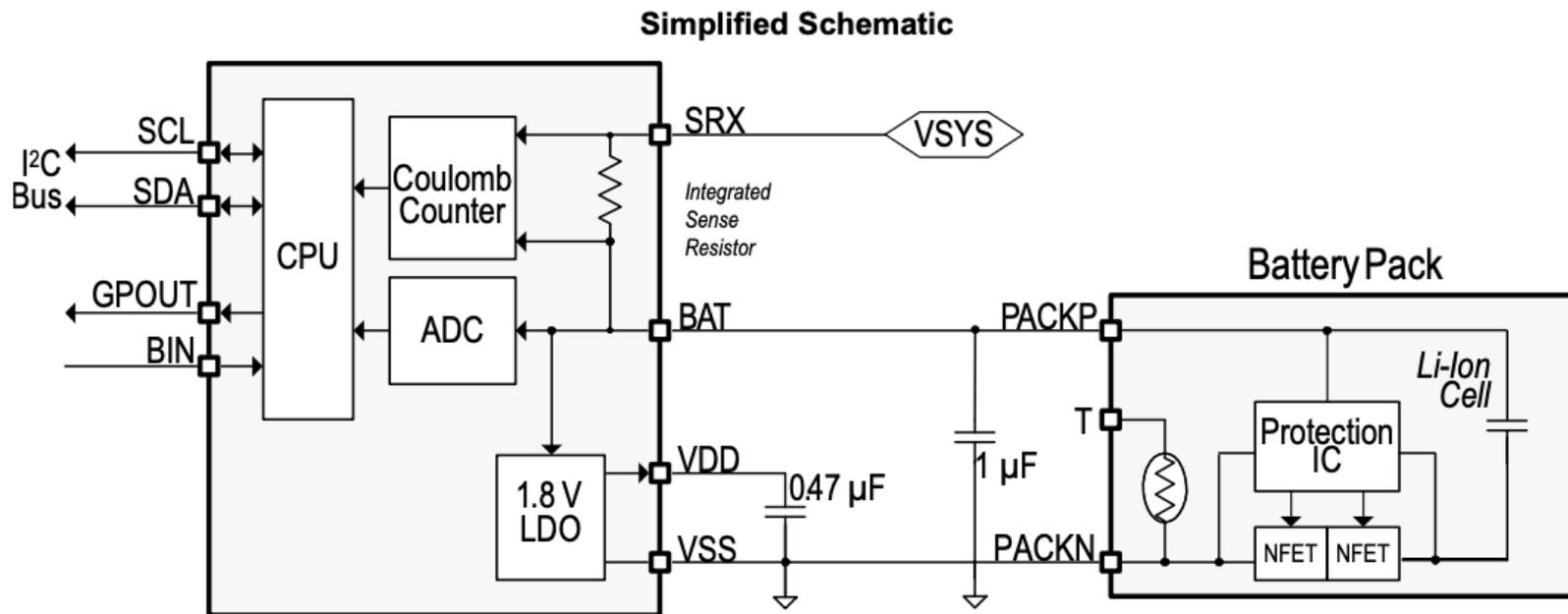


# Fuel Gauge Chips

- The desire to know what your battery % is so great that companies produce “fuel gauge” chips to address this.
- These often use proprietary “algorithms” to “learn” and estimate battery capacity based off of long-term voltage and/or current analysis of the battery.
- A number of manufacturers have rebranded their chips as using “ML” or “AI” though it is usually just a higher order polynomial fitter and some lookup tables, but shhhhh that’s just between you and me.

# One example...

- BQ27421 by TI
- Monitors battery voltage and current and can report back over I2C an actual SOC (%) of battery!



# Has one of the worst datasheets

- Good chip, *awful* datasheet

- 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

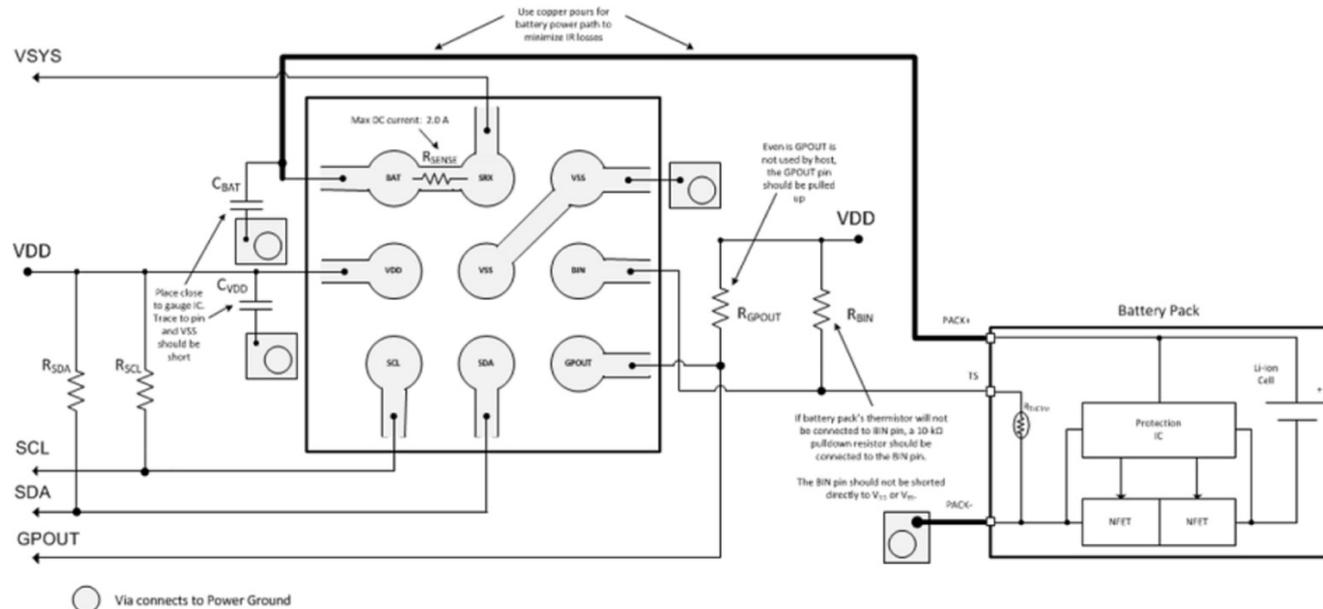
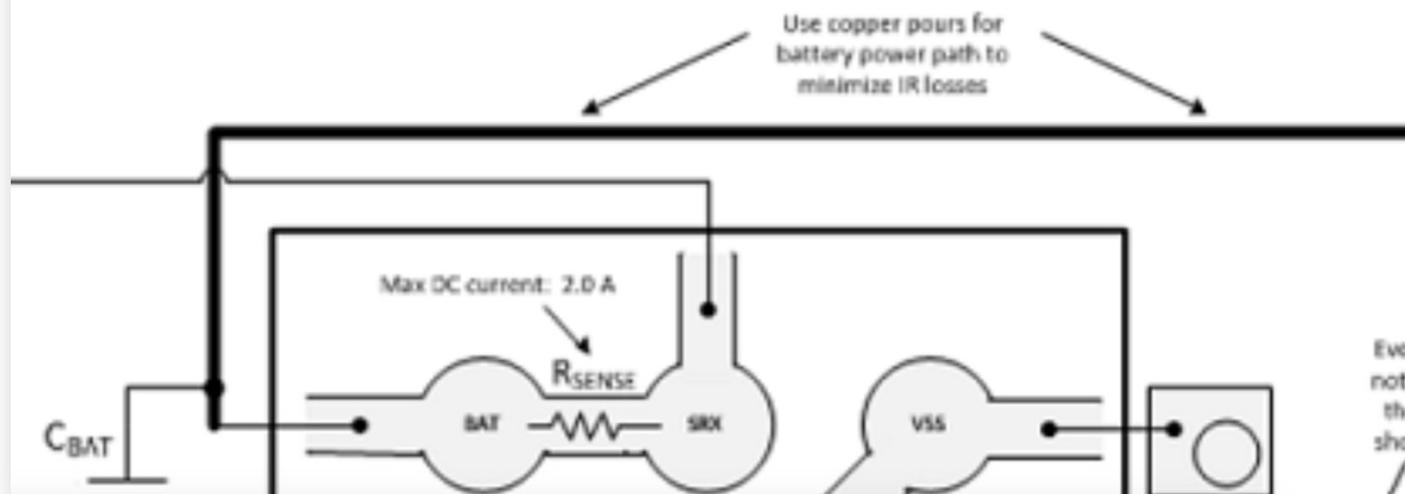


Figure 13. bq27421-G1 Board Layout Example

# Actual resolution of their PDF datasheet

device ground is the center pin (B2). The C1 pin is connected to the board ground plane to the device ground (B2).

## Example



## Mysterious Trace in Battery Fuel Gauge Datasheet

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

- ▲ 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.
- 0
- ▼ For the fuel gauge, I've chosen the TI [BQ27421-g1](#) as I've had good luck with their battery

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't so nice and small, I would probably jump ship and get a different one. – John M Nov 3, 2015 at 19:01

@WillDean I would go off the schematic. – user1844 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**

**3 $\mu$ A 1-Cell/2-Cell Fuel Gauge with ModelGauge**

## General Description

The MAX17048 is a low-current fuel gauge and portable energy monitor powered by a single lithium cell or two cells in series.

## Features and Benefits

# Accurate Fuel Gauging Without Battery Characterization Using ModelGauge m5 EZ Algorithm

Aug 29 2019

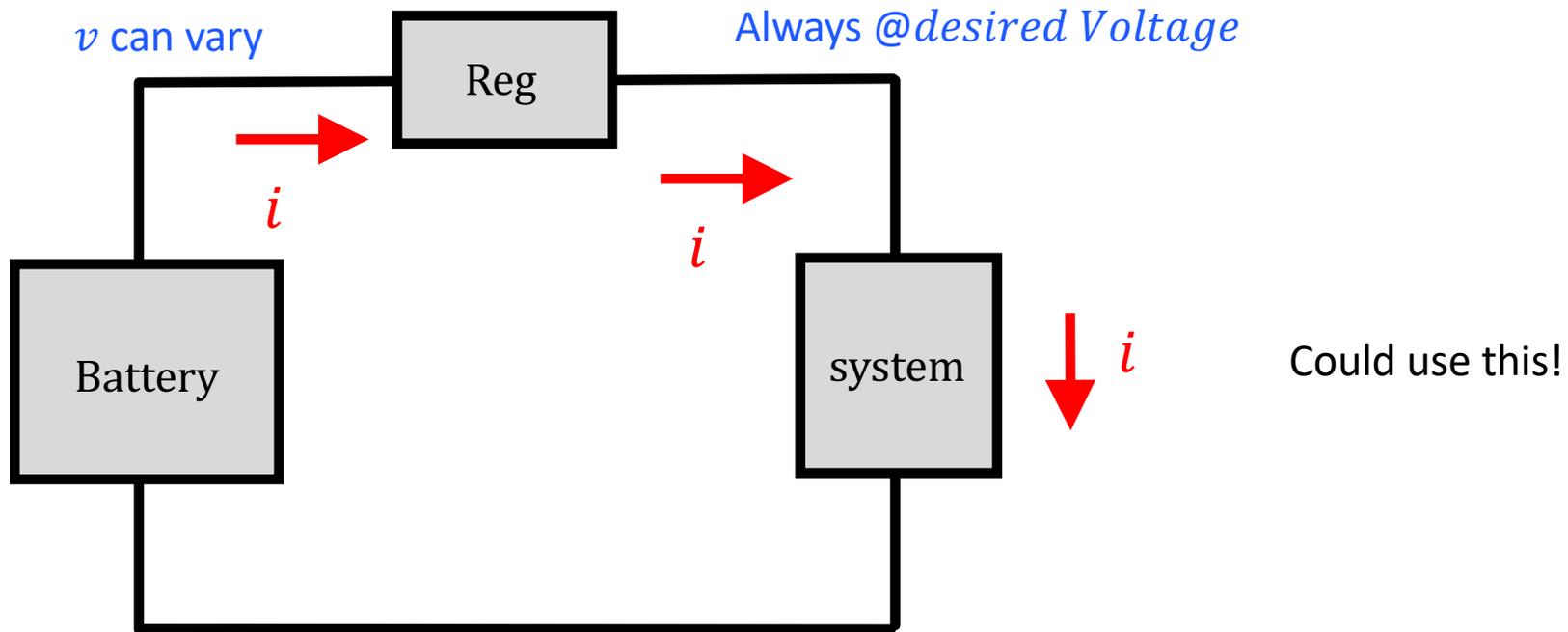
## Abstract

# 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 not variable voltage.
- Never use batteries on their own!

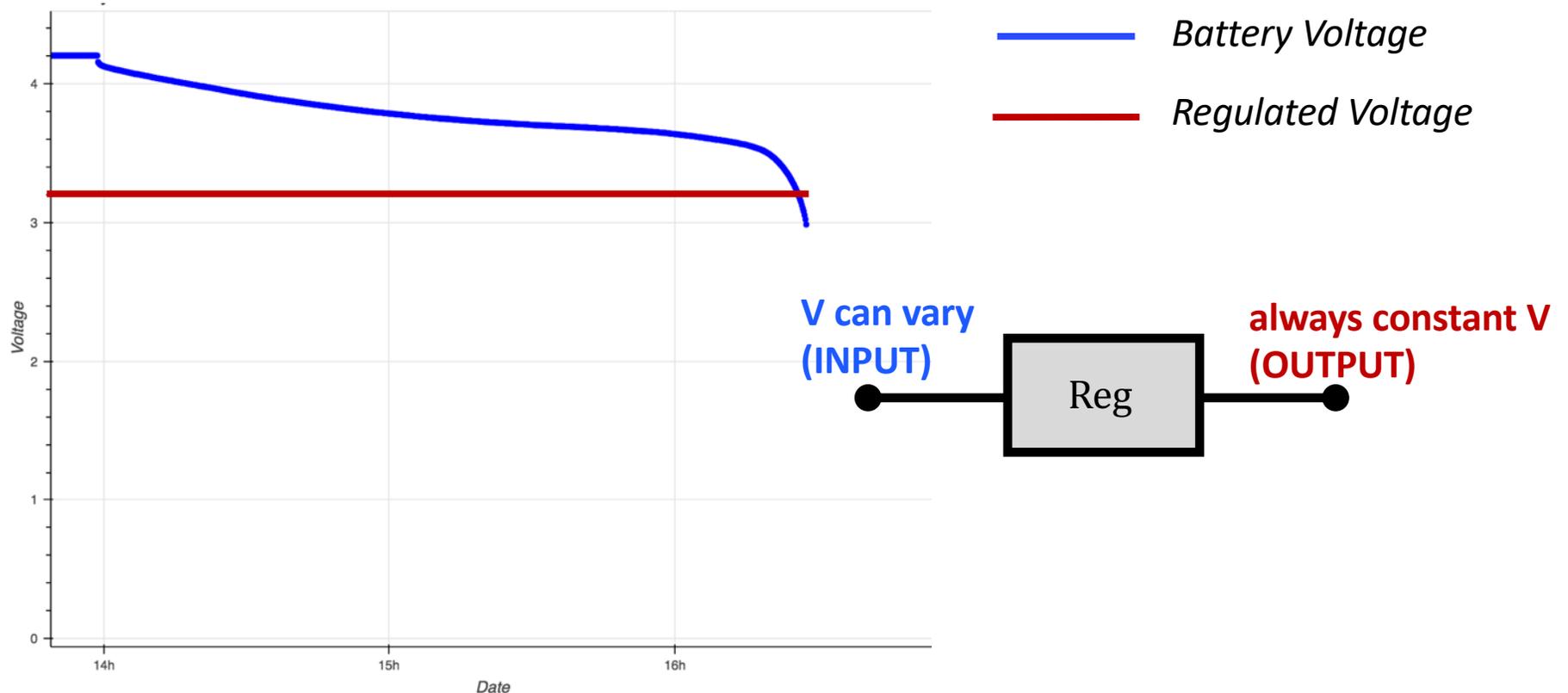
# We already introduced the idea of a regulator!

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



# Stable Voltage

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



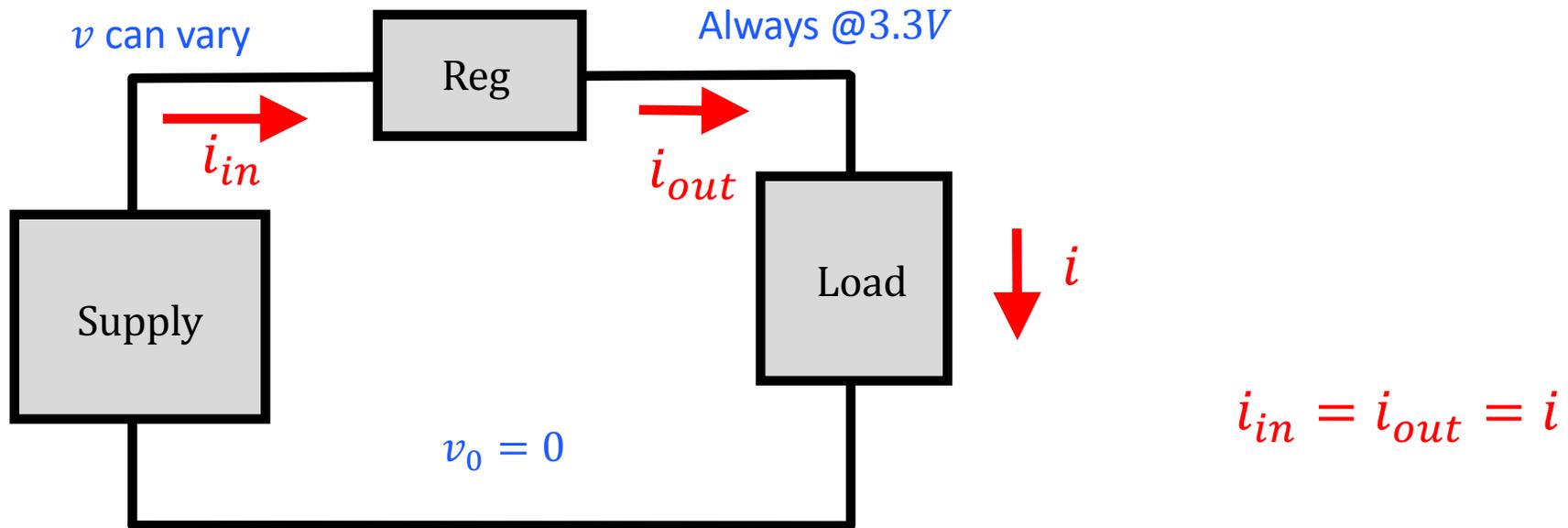
- Voltage Regulators can be used!

# 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



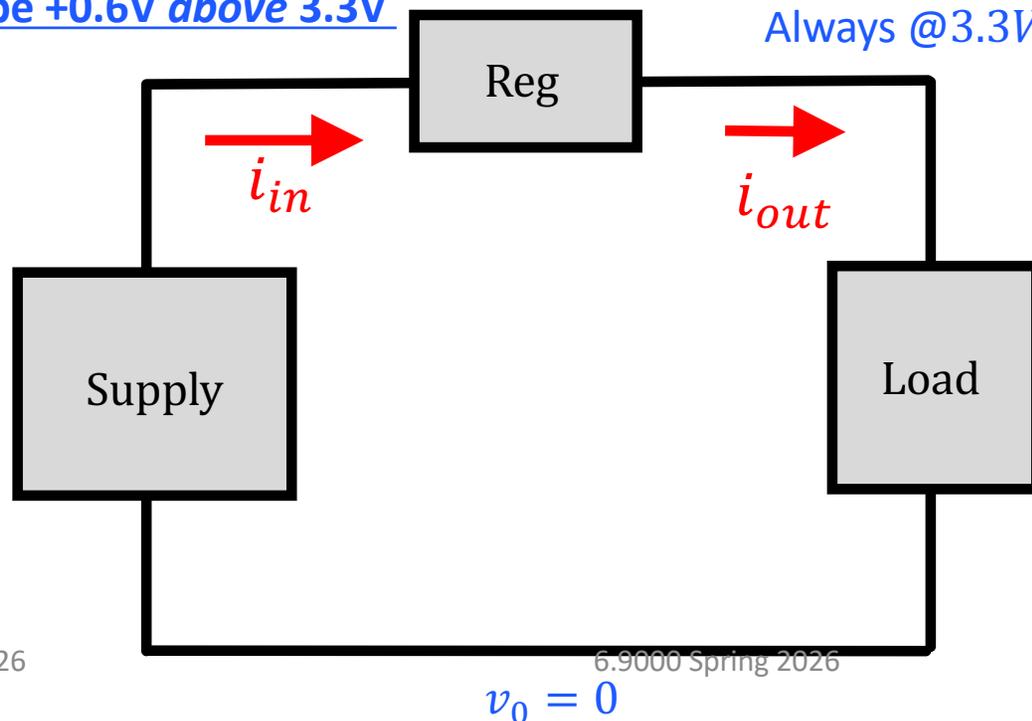
If  $i = 50mA$  and supply voltage is at  $v = 4.1V$  what is the efficiency of this system? (i.e. how much power is consumed by the circuit and not the regulator?)

# 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:

*v* can vary

But must be +0.6V above 3.3V

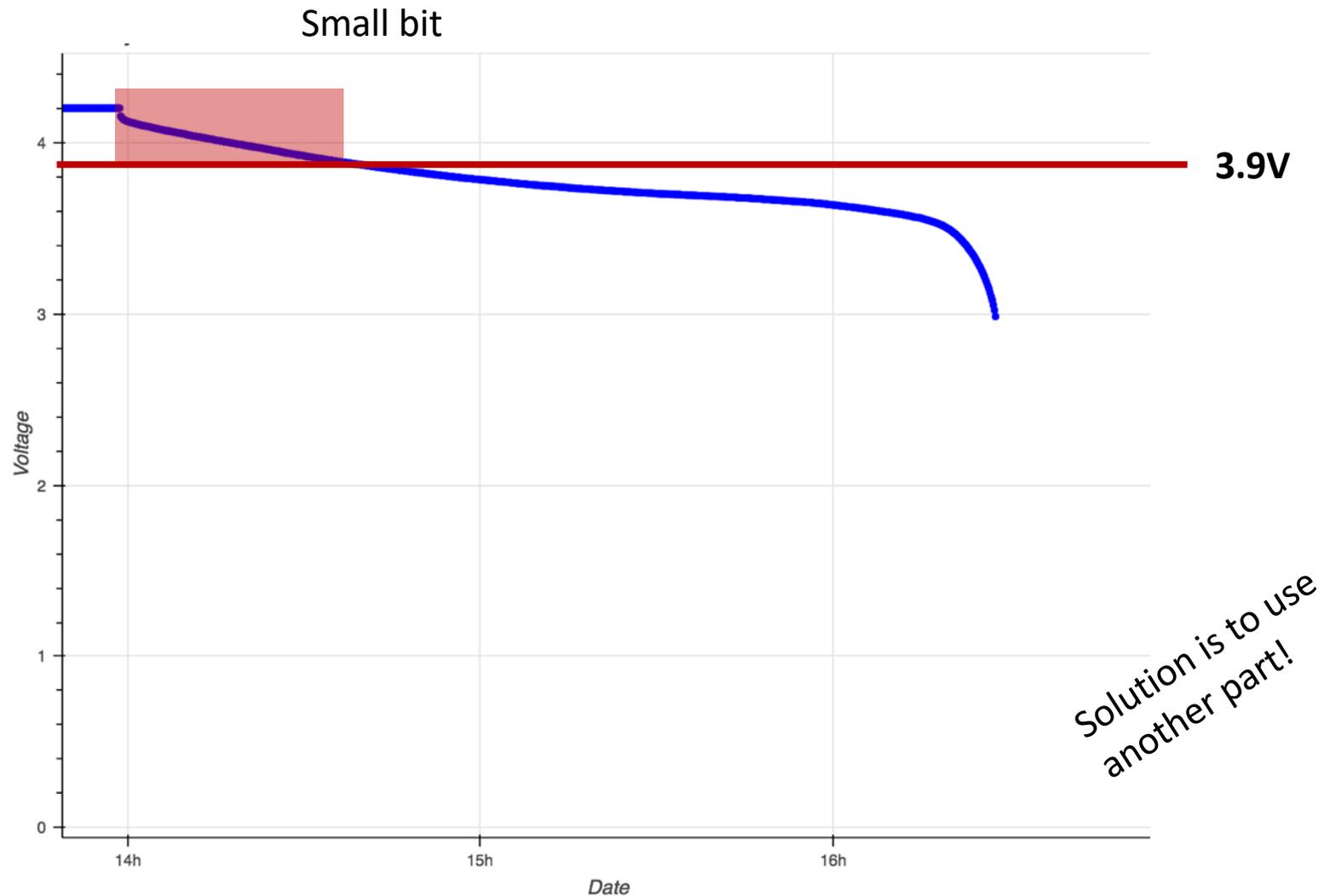


How low can our battery voltage go in this case?

3.9V...not good.

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

# Most of Battery's Life is Unusable!

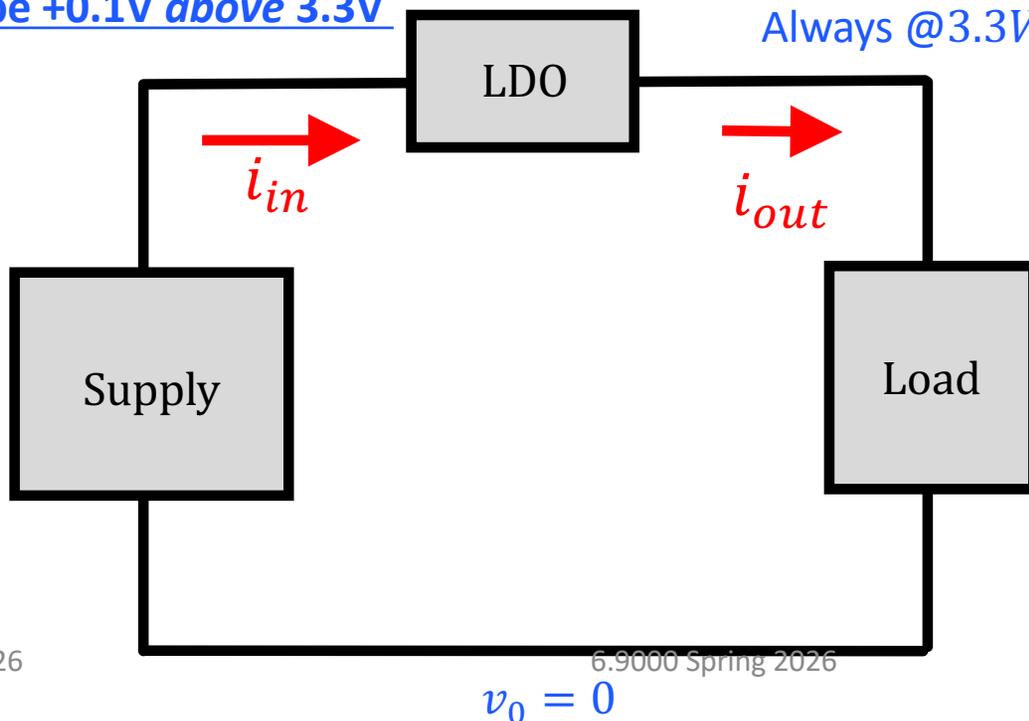


# Problem #1 with Linear Regulators

- 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

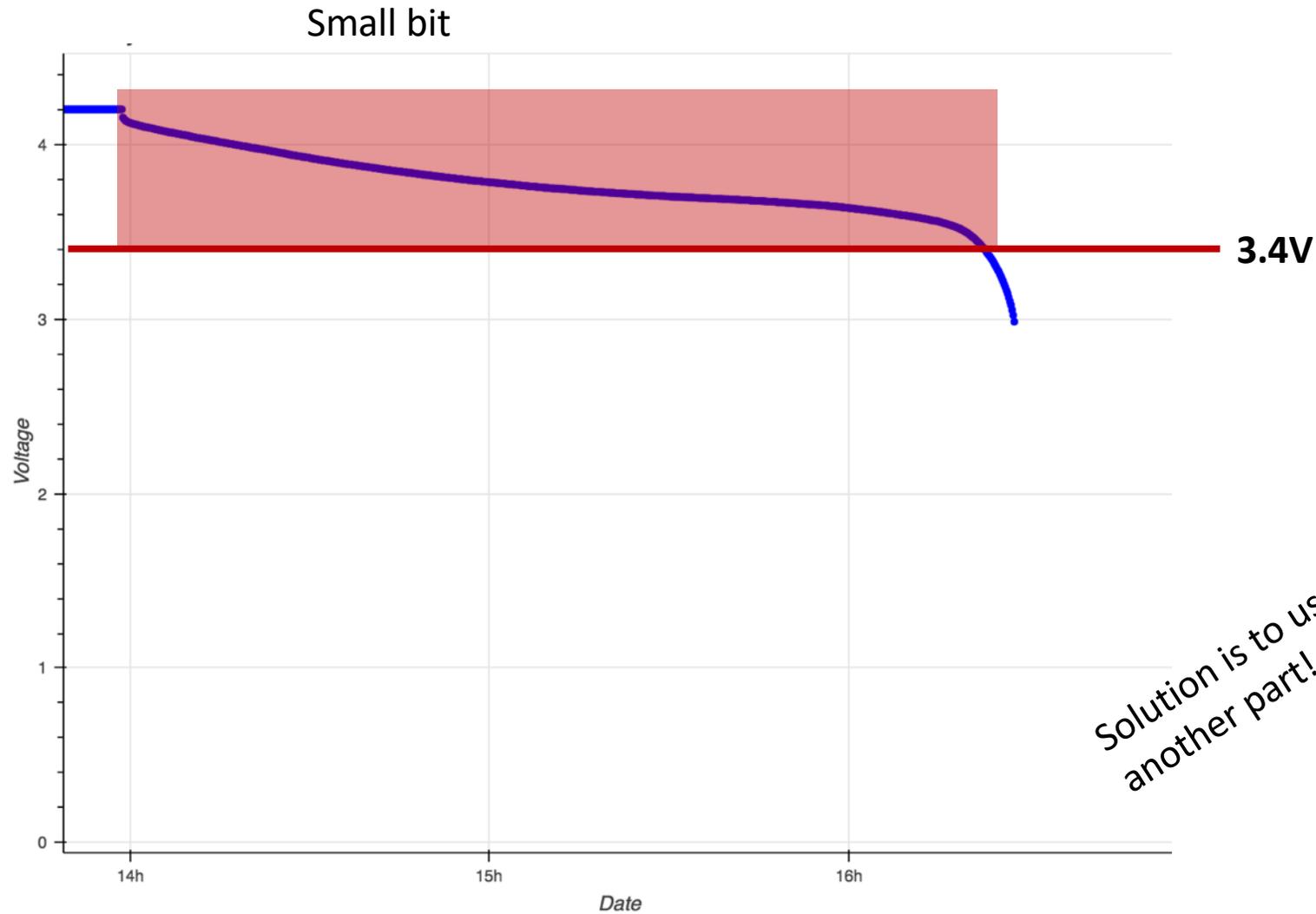


How low can our battery voltage go in this case?

3.9V...not good.

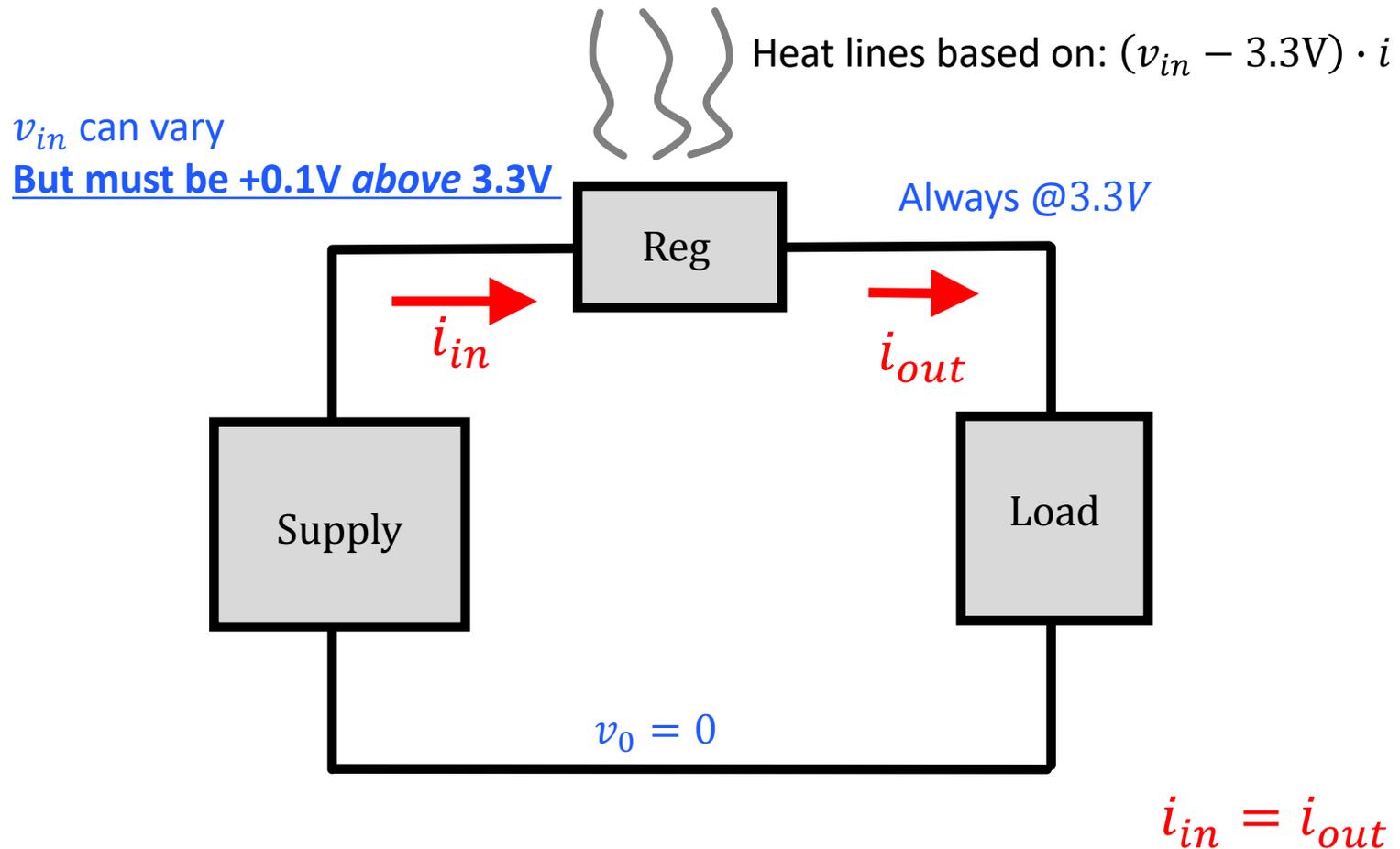
$$i_{in} = i_{out} = i$$

# Using Most of Battery's Life!



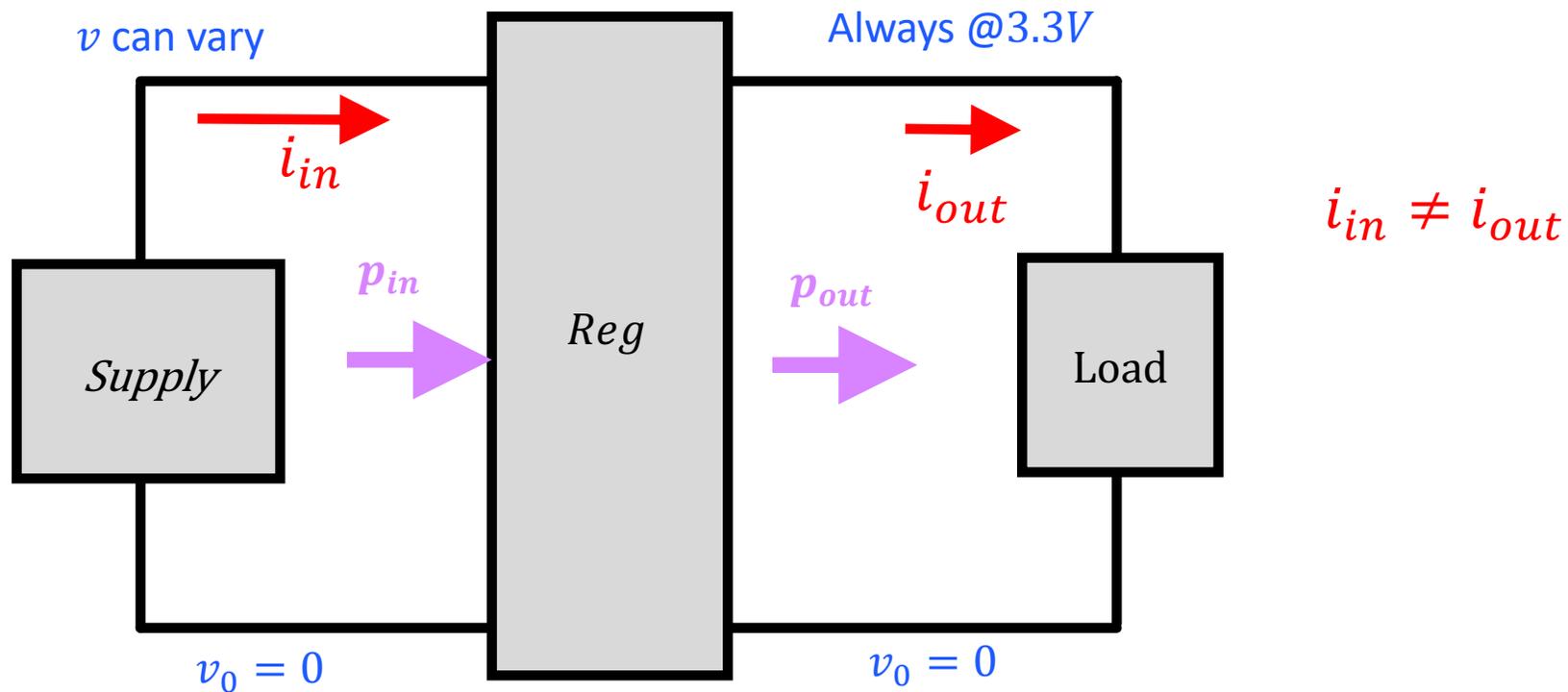
# Problem #2 with Linear Regulators

- Regulate by throwing away excess energy



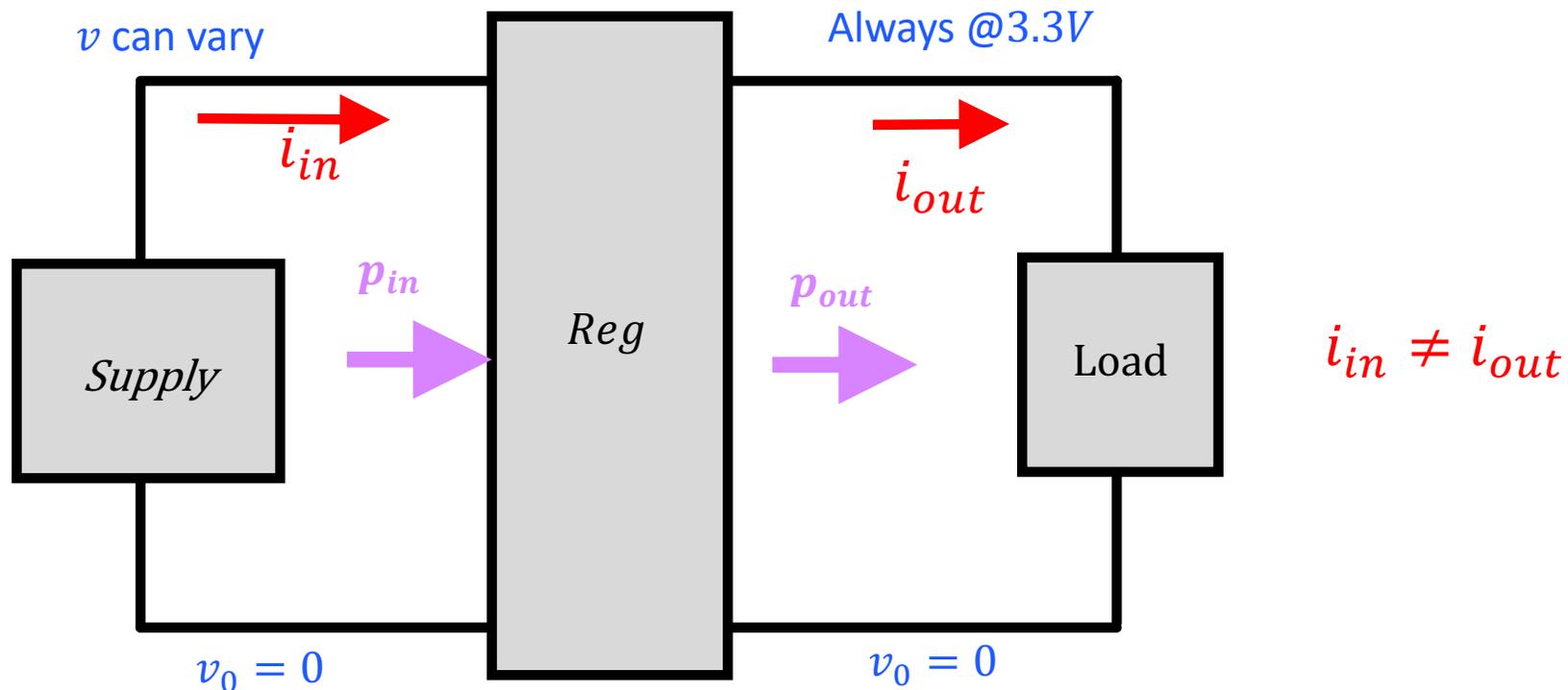
# Switching Supply (non-linear device)

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



# Switching Supply (non-linear device)

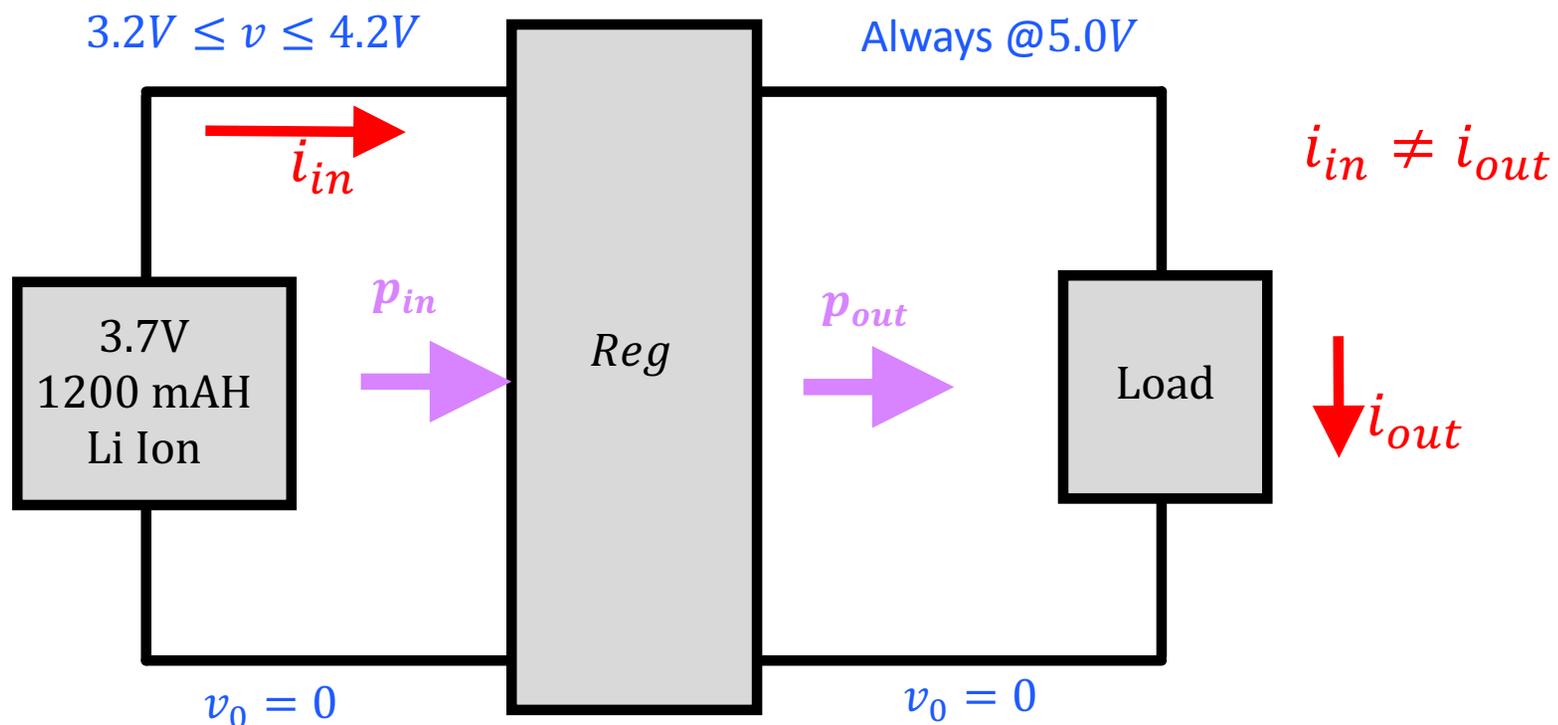
- Scaled Power Device ( $p_{out} = \varepsilon \cdot p_{in}$ )
  - $\varepsilon$  is efficiency and  $0 \leq \varepsilon \leq 1$



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?)

# Switching Supply

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



# The Inefficiency of a Linear Regulator Can be Very Dramatic

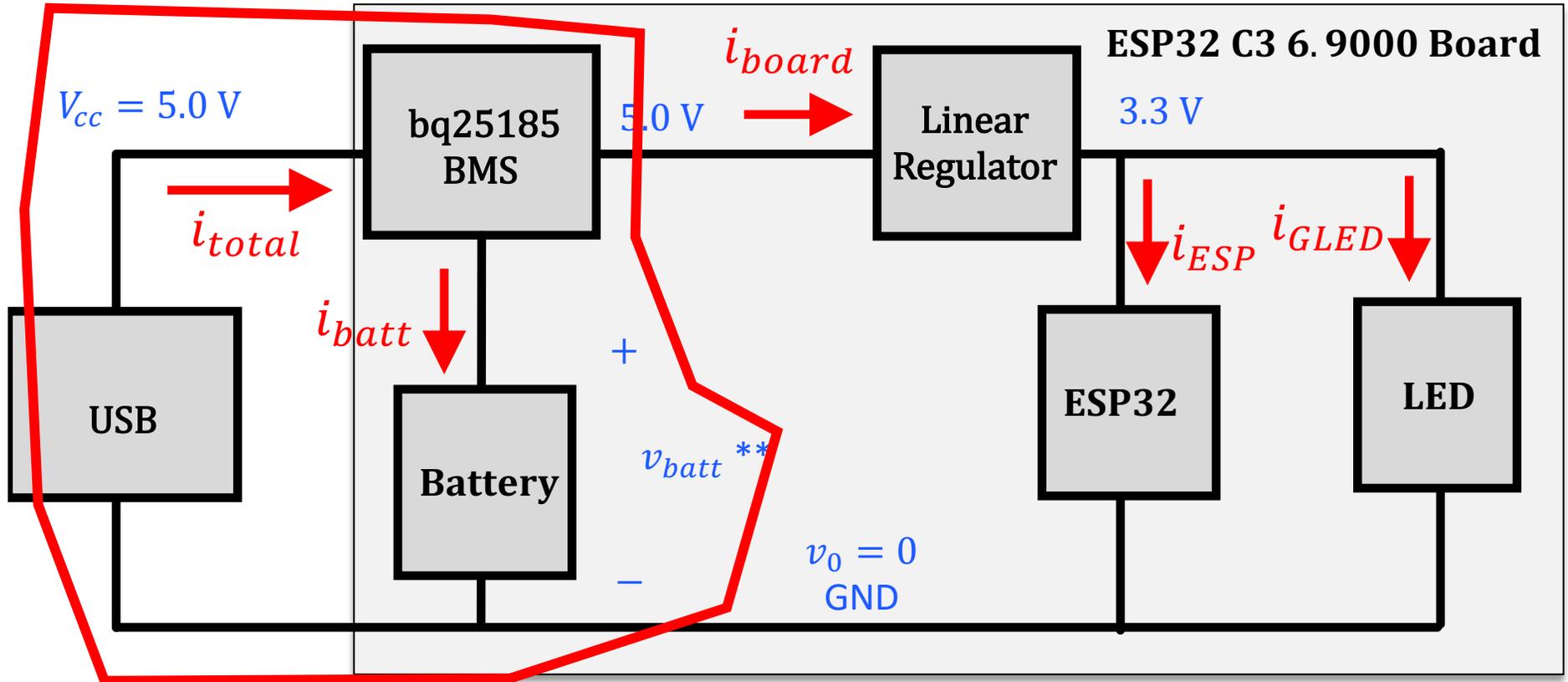
- When plugged in and charging the battery...



*System state circa end of week 2*

# Example: ESP32 C3 6.9000 Board

*When plugged into the USB supply...*



\*\* variable as it charges



**OUCH BQ25185 !**

ouch BQ25185 ! ouch! BQ25185 burnt my finger.. and it really hurt...



---

## BQ25185 1-Cell, 1A Standalone Linear Battery Charger with Power Path, Factory Mode, and Battery Tracking VINDPM

---

### 1 Features

- 1A linear battery charger
  - 3.0V to 18V input voltage operating range
  - 25V tolerant input voltage
  - External resistor programmable operation
    - ILIM/VSET pin sets battery regulation voltage to 3.6V, 3.65V, 4.02V, 4.1V, 4.2V, 4.35V, or 4.4V

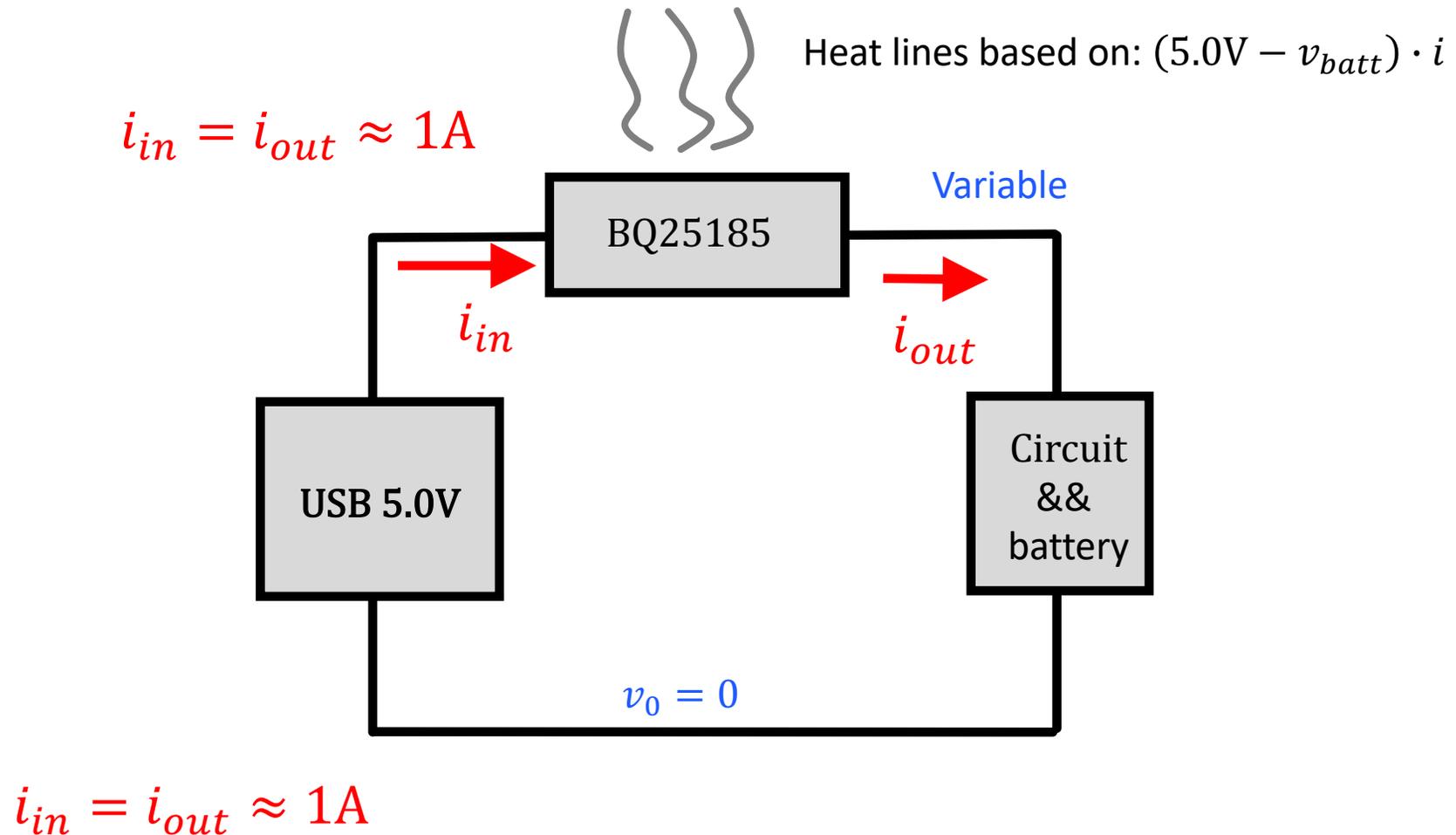
### 2 Applications

- [TWS headset and charging case](#)
- [Smart glasses, AR and VR](#)
- [Smart watches and other wearable devices](#)
- [Retail automation and payment](#)
- [Building automation](#)

### 3 Description

# Linear Battery Charger

- Regulate by throwing away excess energy



# Power Density

- Chip gets very hot...

$$(5.0V - 3.0V) \cdot 1A = 2W$$

dissipation. The device supports up to 1A charging and system loads up to 3.125A.

## Package Information

PART NUMBER	PACKAGE <sup>(1)</sup>	PACKAGE SIZE <sup>(2)</sup>	BODY SIZE (NOM)
BQ25185	DLH (WSON, 10)	2.2mm × 2.0mm	2.2mm × 2.0mm

(1) For all available packages, see the orderable addendum at the end of the data sheet.

(2) The package size (length × width) is a nominal value and includes pins, where applicable.

Page 1 of datasheet

$$= \frac{2W}{2 \times 10^{-3}m \cdot 2.2 \times 10^{-3}m} = 454kW \cdot m^{-2}$$

~50X the thermal flux from the sun received by the planet Mercury

# Influences package design

- And how you should lay it out on PCB!

## 8.4.2 Layout Example

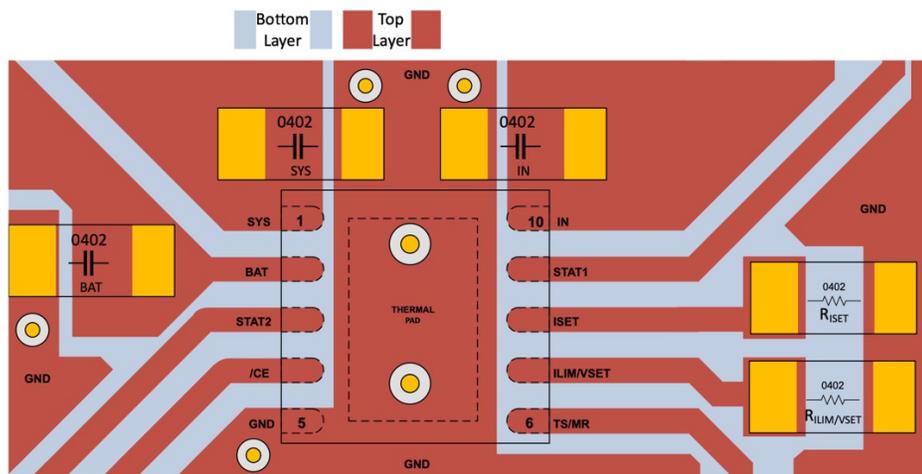


Figure 8-9. Board Layout Example

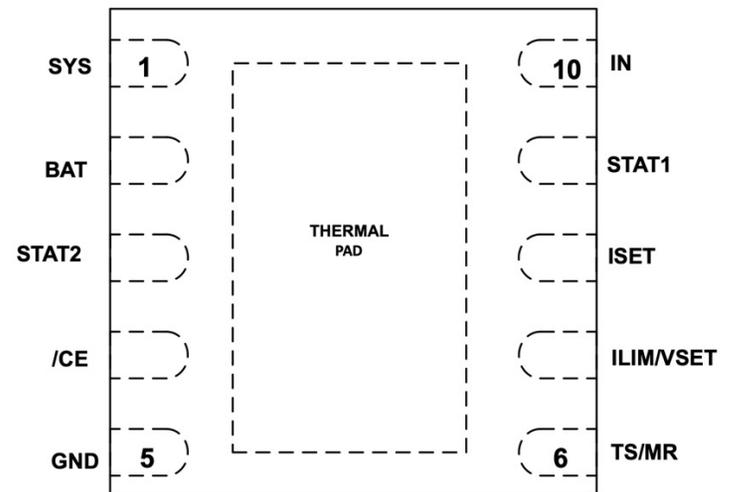


Figure 5-1. DLH Package 10-Pin (top view)

*From the datasheet!*

# Battery Choices

- For projects will need to choose between Primary-Cell or Secondary-Cell Approach
- Primary-Cell: Don't worry about recharging, just replace batteries every so often. Question is...how long can you go?
- Secondary-Cell: Harvest energy from environment along the way and store it temporarily in secondary cell for later usage

# Modern Primary Cell

- Generic primary cells like alkaline batteries lack energy density and other performance characteristics to last during project scope we're assigned.
- There are other chemistries that are more modern which may be appropriate (example):



4Pack EEMB 3.6V D Cell Batteries ER34615 D Size Lithium Batteries 19000mAh Li-SOCL<sub>2</sub> Non-Rechargeable Battery LS-33600 XL-205F for CNC & Printing Machine Tool, Meter, Clock & 2 Year Manufacturer Warranty

[Visit the EEMB Store](#)

4.2 ★★★★★ (275)

50+ bought in past month

\$47<sup>99</sup> (\$12.00 / count)

FREE Returns ▾

Get \$60 off instantly: Pay \$0.00 upon approval for the Amazon Store Card.

Available at a lower price from [other sellers](#) that may not offer free Prime shipping.

Size: **4 Count (Pack of 1)**

# Modern Secondary Cell

- The cell you have in your 6.900 kit is a pretty decent secondary cell in terms of cost, density, etc...
- Will need to recharge

