ENGINEERING FOR impact

mit 6.900

Lecture 12

March 21, 2023

TODAY

- Power management

Thu: final concept presentations

Fri: no lab…

Our system(s): MILO, Valerie, etc.

- We can recast our systems from a *functional* point of view to an *energy* view
- We have three fundamental elements
  - Energy inputs: sources of new energy (solar panels, etc.)
  - Storage: places to store energy (batteries, etc.)
  - Energy sinks: consumers of energy (MCU, sensors, etc.)

Our goal is simple: make sure this system can run *forever**

**or as long as specified*

Power management

If $P_{IN} = 0$, how long will system run?

$$\frac{E_{STORE}}{P_{OUT}}$$

This is the classic case of a battery-operated system (w/o recharging)

Power management

Assume P_{OUT}, P_{IN} are *time-average* power *out* and *in*, averaged over reasonable interval

What are the conditions on P_{OUT}, P_{IN}, and E_{STORE} if we want system to run forever?

$$P_{OUT} \leq P_{IN}$$

Does E_{STORE} matter?

Yes, serves to meet non-time-averaged need: *aka* instantaneous need, or during any interval where $P_{IN} < P_{OUT}$

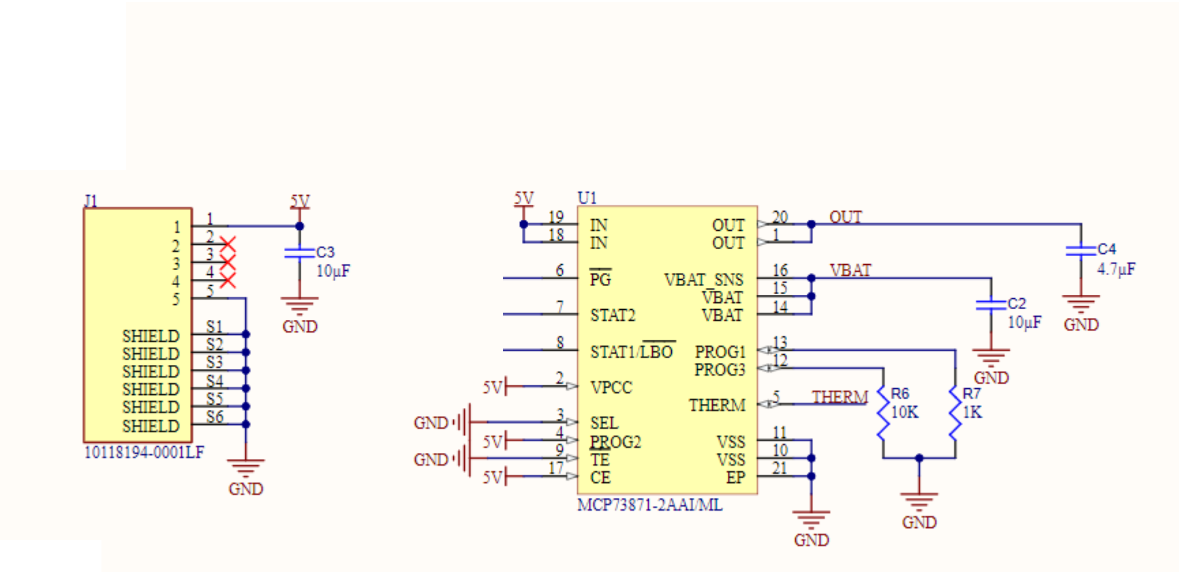
Power budget

How do we know if $P_{OUT} > \ P_{IN}$, or how long our system will last? ➔ **power budget**

- Every team will want to create one
- An account of all energy **sources** and **sinks**
- This will help you estimate system lifetime **and** know where to put your effort to increase that lifetime (if needed)

Power management

MILO power board



- For MILO, *source* is the USB power to charge the battery
- Let's first figure out how long that battery will last, $P_{IN} = 0$

Batteries

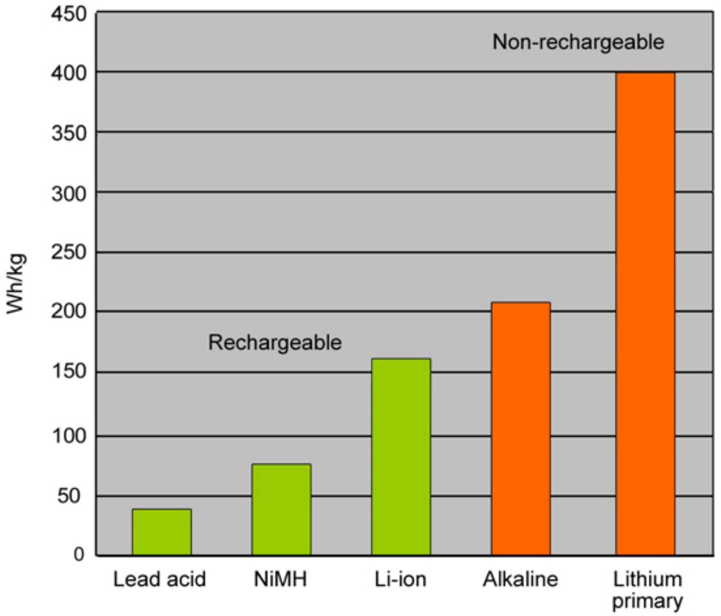
- Primary solution and means of enabling mobile electronics
- Store energy chemically and then release it electrically

- Can be modeled as voltage sources with finite "life span" (finite total stored energy E_{STORE})

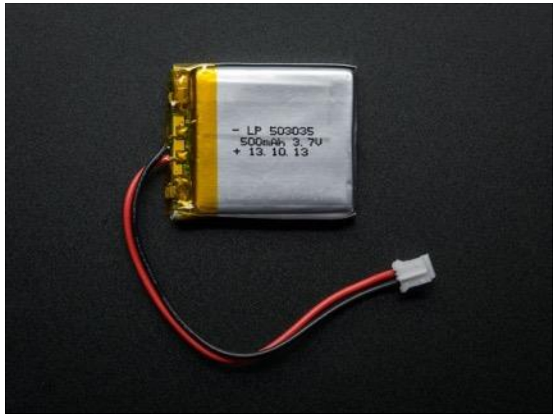
- Specifications include:
  - Nominal voltage
  - Instantaneous current capability
  - Energy capacity
  - Energy density (J/kg or J/m^3 or Wh/m^3)
  - Discharge characteristics
  - Renewable or one-time
  - Cost

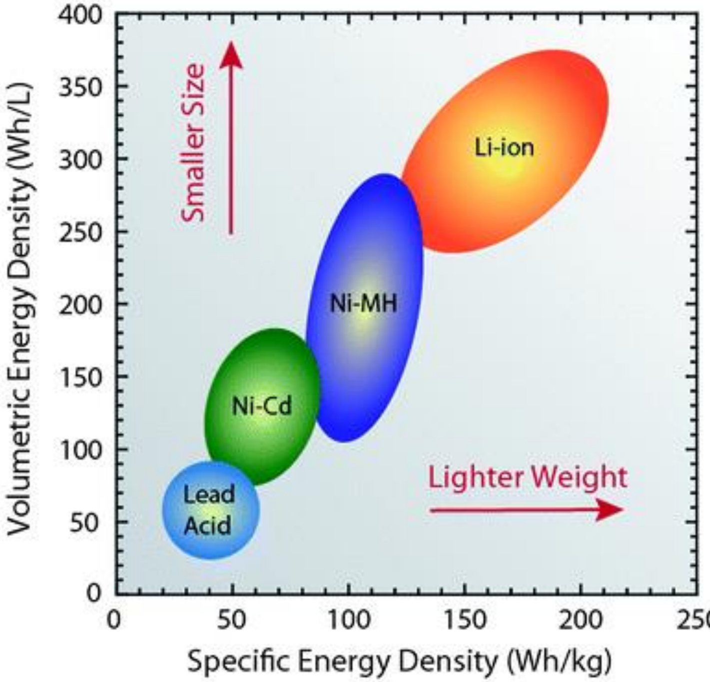
Battery chemistries

- Primary (non-rechargeable)
  - Alkaline
  - Lithium



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

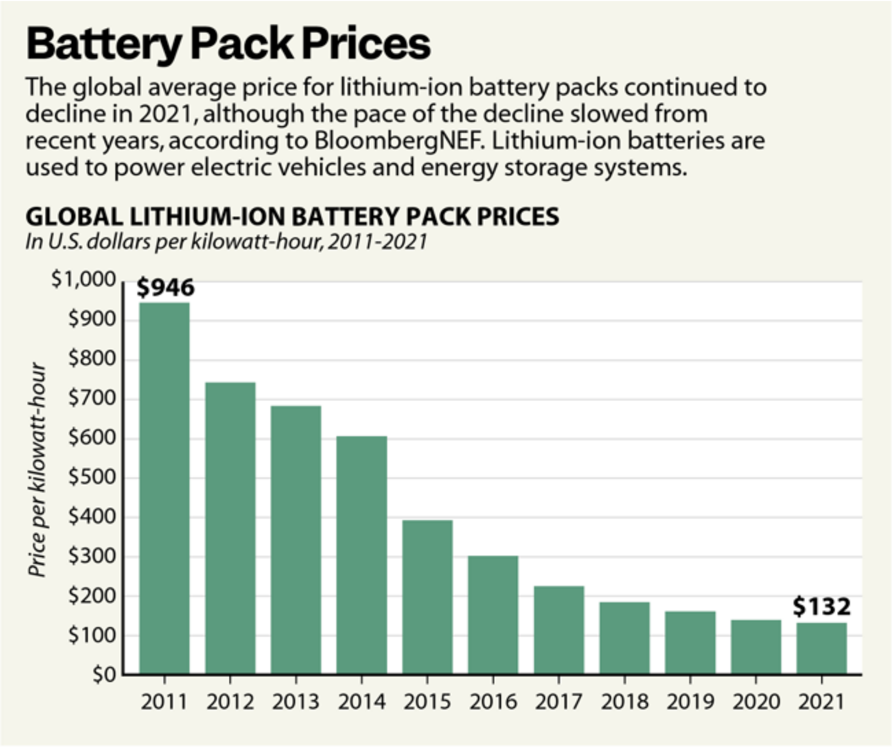




http://batteryuniversity.com/learn/article/primary_batteries

Battery cost

- This is difficult to find
- Most metrics are for large (EV) packs
- Vendors do not publish quantity pricing



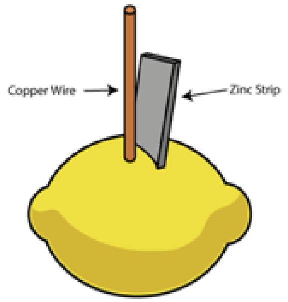
SOURCE: BloombergNEF PAUL HORN / Inside Climate News

Specifications	Lead Acid	NiCd	NiMH	Li-ion[1] Cobalt	Li-ion[1] Manganese	Li-ion[1] Phosphate
Specific energy (Wh/kg)	30–50	45–80	60–120	150–250	100–150	90–120
Internal resistance	Very Low	Very low	Low	Moderate	Low	Very low
Cycle life[2] (80% DoD)	200–300	1,000[3]	300–500[3]	500–1,000	500–1,000	1,000–2,000
Charge time[4]	8–16h	1–2h	2–4h	2–4h	1–2h	1–2h
Overcharge tolerance	High	Moderate	Low	Low. No trickle charge		
Self-discharge/ month (room temp)	5%	20%[5]	30%[5]	<5% Protection circuit consumes 3%/month		
Cell voltage (nominal)	2V	1.2V[6]	1.2V[6]	3.6V[7]	3.7V[7]	3.2–3.3V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20 typical Some go to higher V		3.60
Discharge cutoff voltage (V/cell, 1C)	1.75V	1.00V		2.50–3.00V		2.50V
Peak load current Best result	5C[8] 0.2C	20C 1C	5C 0.5C	2C <1C	>30C <10C	>30C <10C
Charge temperature	–20 to 50°C (–4 to 122°F)	0 to 45°C (32 to 113°F)		0 to 45°C[9] (32 to 113°F)		
Discharge temperature	–20 to 50°C (–4 to 122°F)	–20 to 65°C (–4 to 149°F)		–20 to 60°C (–4 to 140°F)		
Maintenance requirement	3–6 months[10] (toping chg.)	Full discharge every 90 days when in full use		Maintenance-free		
Safety requirements	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory[11]		
In use since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		
Coulombic efficiency[12]	~90%	~70% slow charge ~90% fast charge		99%		
Cost	Low	Moderate		High[13]		

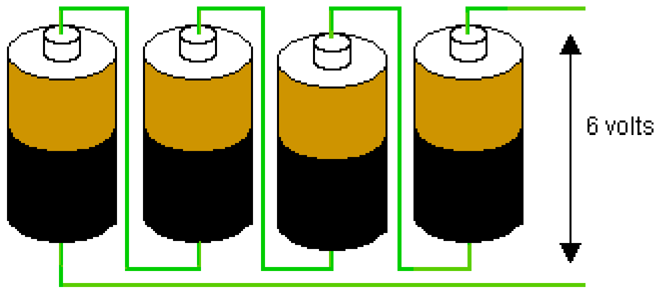
Battery voltage (nominal)

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



- Increase battery voltage by placing cells in series
- Increase current capability by placing cells in parallel



Battery capacity

- This is E_{STORE}
- Usually specced 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 (volume or weight)
  - Li AA: 2500-3400 mAh
- CR2032 (coin cell)
  - ~200 mAh

- Lithium-Ion
  - Variety of sizes
  - iPhone 13: 3227 mAh
  - Pebble watch (original): 130 mAh

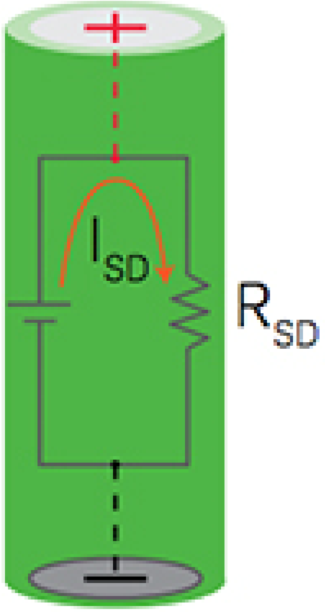
Alkaline batteries

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*

Battery self-discharge

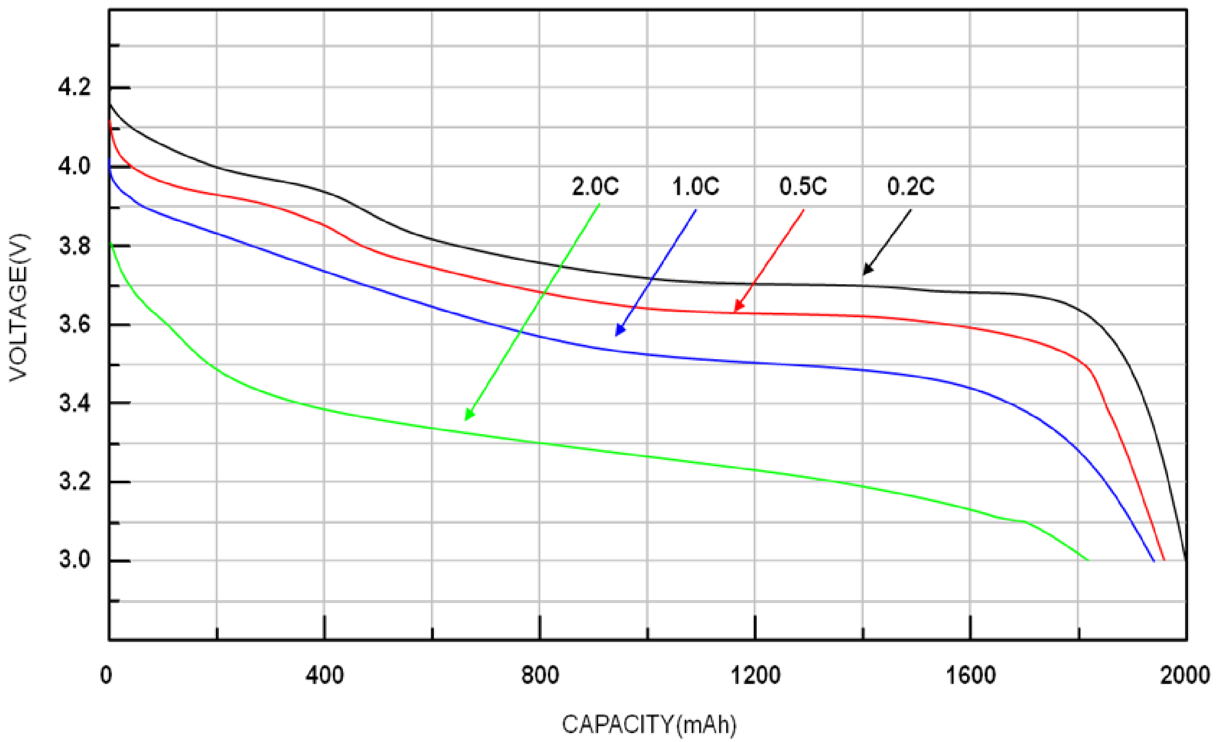
- There is a parasitic resistance between the battery positive and negative terminals
- This is the ultimate limit on battery lifetime
- Examples
  - Alkaline ~ 5yrs
  - Lithium-Ion ~ 2-3%/mo
  - NiMH ~ 30%/mo
  - Lithium: ~1 %/yr



Battery discharge curves

- Battery is **not** an ideal voltage source
- The voltage depends on the instantaneous current draw (Thevenin resistance)…and the remaining capacity
- Discharge (and charging) rates in units of “C”
  - 1C = discharge 1× capacity in 1 hr
  - 2C = discharge 2× capacity in 1 hr
  - Etc.
- To get the most out of a battery, you want to use it moderately
- The more current you pull from it, the less you’ll get overall

2000 mAh cell



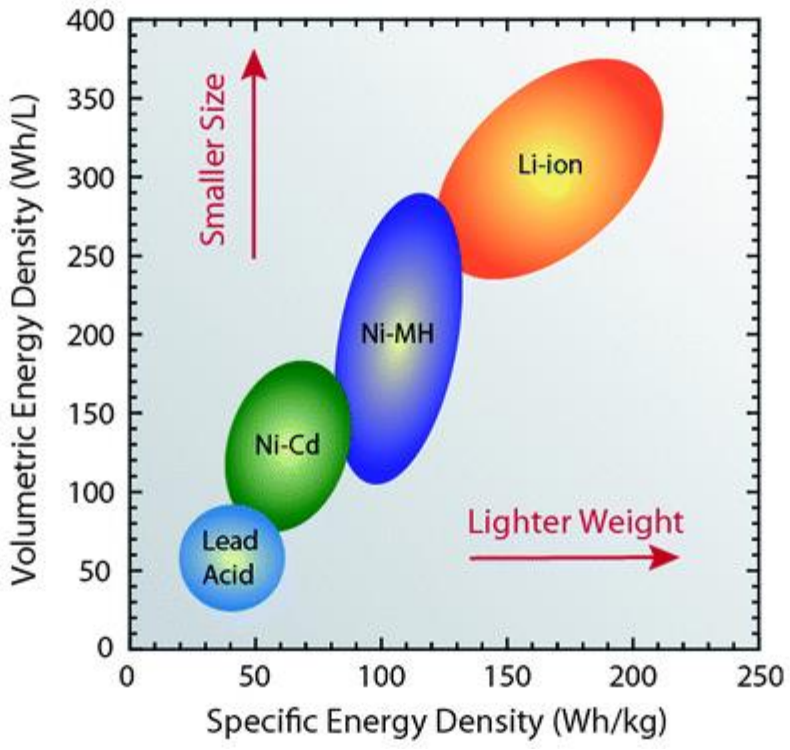
Batteries

- For MILO we want to run >12 h between charges ➔ $P_{IN} = 0$

Is this even possible?

- Let’s do analysis
  - Assume we use a Li-ion battery
  - Assume our battery volume is limited by our system size
    - 5 cm x 5 cm x 5 cm = 125 cm^3
    - 300 Wh/L for Li-ion ➔ 37.5 Wh

This is our maximum E_{STORE}



Wh = Watt-hour = Energy
1 L = 1000 cm3

What’s the minimal system?

- Let’s find our minimum P_{OUT}
- ESP32C3 in deep sleep
  - Not too useful, but it gives an upper limit
- Deep sleep – 5 µA (at 3.3V)
  - 16.5 µW

$$\frac{37.5\ Wh}{16.5\ \mu W} = 2.3\ million\ hours \approx 250\ years$$

- Full power – 345 mA (at 3.3V)

$$\frac{37.5\ Wh}{345\ mA\ \ 3.3V} = 33\ hours$$

Looks like this should be doable…

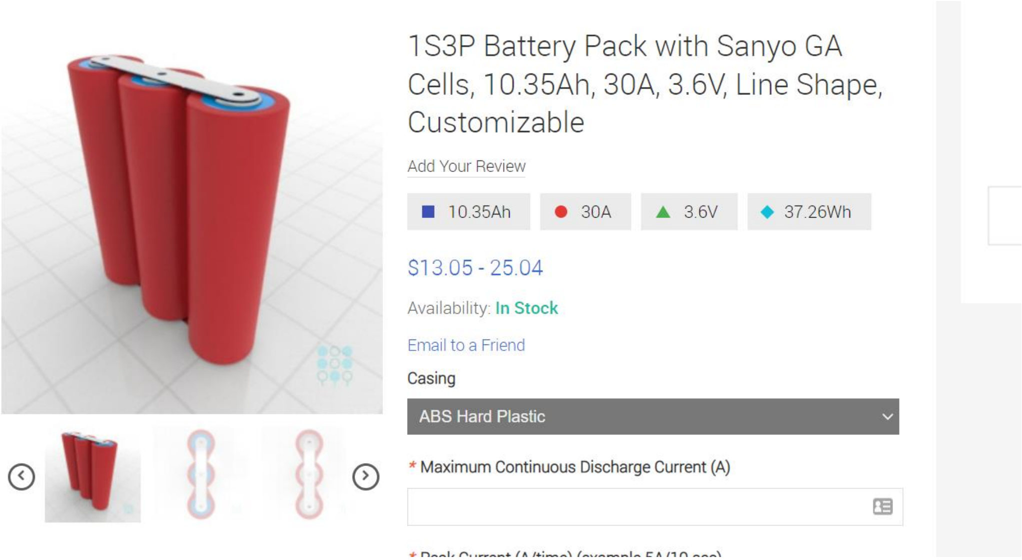
Any issues with this approach?

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

Let’s be more specific

- This requires large and expensive Li-ion battery
- Specs: 3.6V, 10350mAh = 37.3 Wh
- Dimension(mm): 65 x 55 x 18 = ~65.4 cm^3
- Cost: ~$0.35/Wh [assuming $13.05]

- There’s an opportunity to reduce BOM by getting smaller battery
  - We ultimately chose 2200 mAh battery for MILO



The main strategy

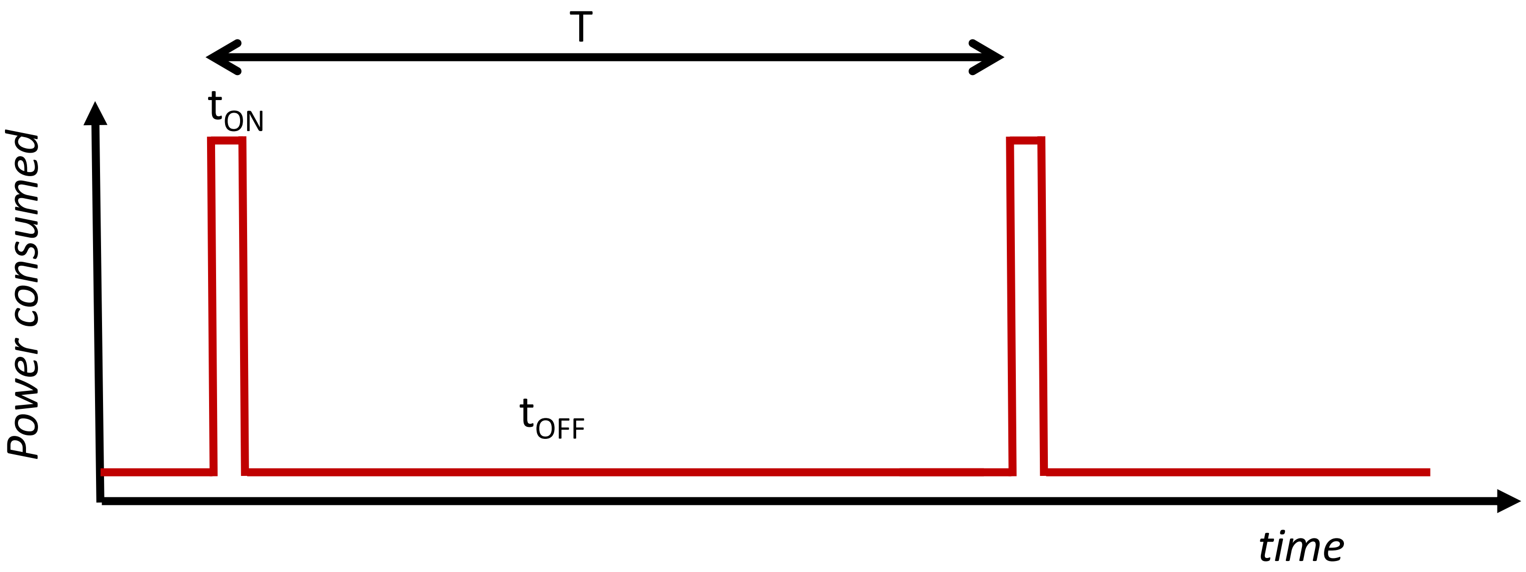
- For an embedded system, the main strategy is to **sleep** as long as possible
- Most events are intermittent and can be measured either as needed (via interrupts) or cyclicly (once per second, minute, etc.)
- ESP32C3 (and other modern systems) run fast (160 MHz)
  - That is **160 Million** clock cycles/second – That's **a lot** of time to do stuff

Do what you need, then sleep

Duty Cycling

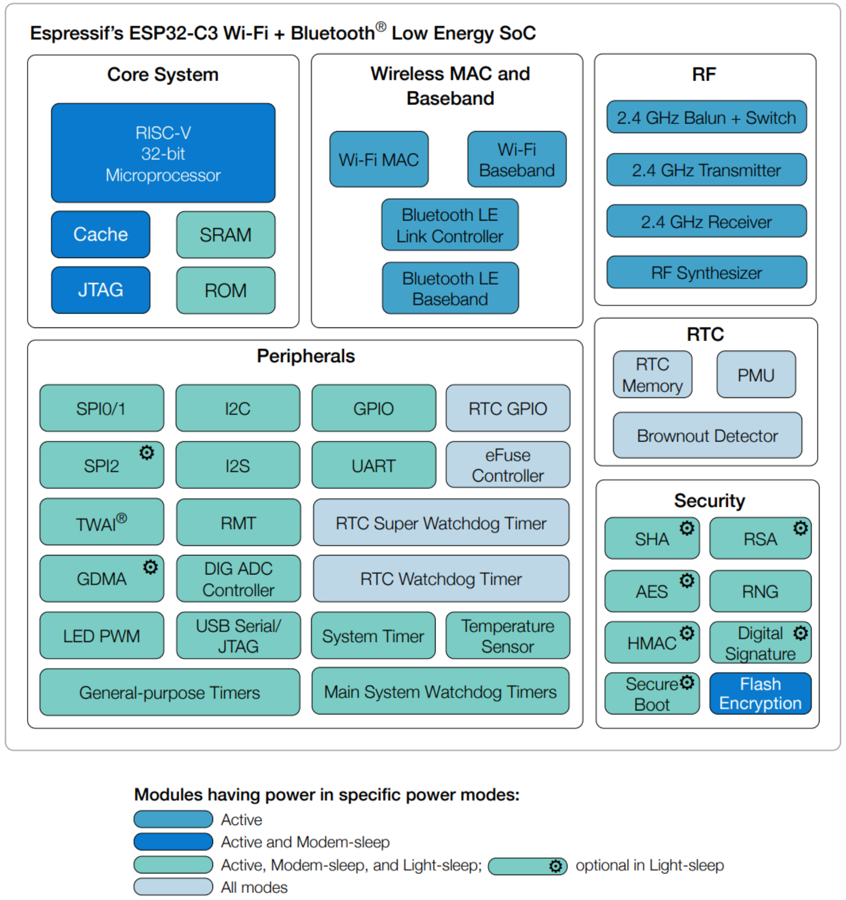
- Turn on in bursts, do what is needed, and turn off otherwise
- The ratio of the "ON" to overall is called the duty cycle
- This can be extended to >2 sections

$$duty\ cycle = \frac{t_{ON}}{T} = \frac{t_{ON}}{t_{ON} + t_{OFF}} \cdot 100\%$$



Sleep

- tldr: Turn off unnecessary parts of your system when you don't need them!
- Starts with MCU…but extend to all energy consumers
- ESP32C3 has 4 power modes



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)[1]
Modem-sleep[2,3]	160	CPU is idle	16	21
		CPU is running	23	28
	80	CPU is idle	13	18
		CPU is running	17	22

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

ESP32C3 Sleep

- ESP32C3 has basically 4 power modes
- From ESP32C3 data sheet…
  - **Active mode**: CPU and chip radio are powered on. The chip can receive, transmit, or listen.
  - **Modem-sleep mode:** The CPU is operational and the clock speed can be reduced. Wi-Fi base band, Bluetooth LE base band, and radio are disabled, but Wi-Fi and Bluetooth LE connection can remain active.
  - **Light-sleep mode:** The CPU is paused. Any wake-up events (MAC, host, RTC timer, or external interrupts) will wake up the chip. Wi-Fi and Bluetooth LE connection can remain active.
  - **Deep-sleep mode:** CPU and most peripherals are powered down. Only the RTC memory is powered on. Wi-Fi connection data are stored in the RTC memory. The RTC timer or the RTC GPIOs can wake up the chip from the Deep-sleep mode.
- Also from ESP32C3 data sheet…

WiFi/BT and sleep modes

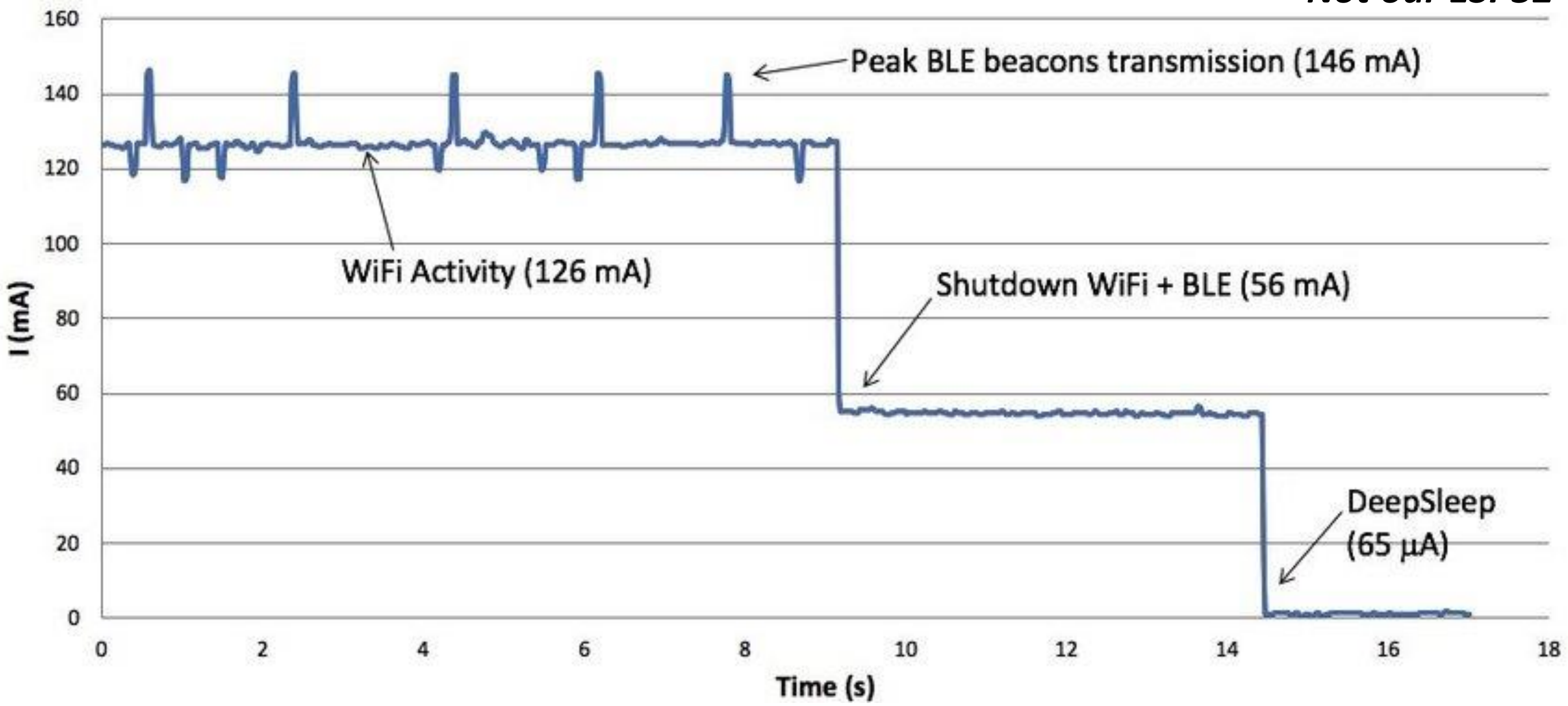
In deep sleep and light sleep modes, wireless peripherals are powered down. Before entering deep sleep or light sleep modes, applications must disable WiFi and BT using appropriate calls (`esp_bluedroid_disable()`, `esp_bt_controller_disable()`, `esp_wifi_stop()`). WiFi and BT connections will not be maintained in deep sleep or light sleep, even if these functions are not called.

ESP32C3 Sleep

- There are commands in ESP32C3 datasheet to enter sleep
- How to exit?
  - Either a timer
  - Or an interrupt
- Waking up is not instantaneous
  - It takes >>1 clock cycle
  - ESP32C3 docs do not list wake-up times
  - Internet says
    - ~200-300 ms from deep sleep
    - ~500 μs from light sleep
    - These are not super impressive specs…

ESP32 power consumption is very complicated!

Not our ESP32

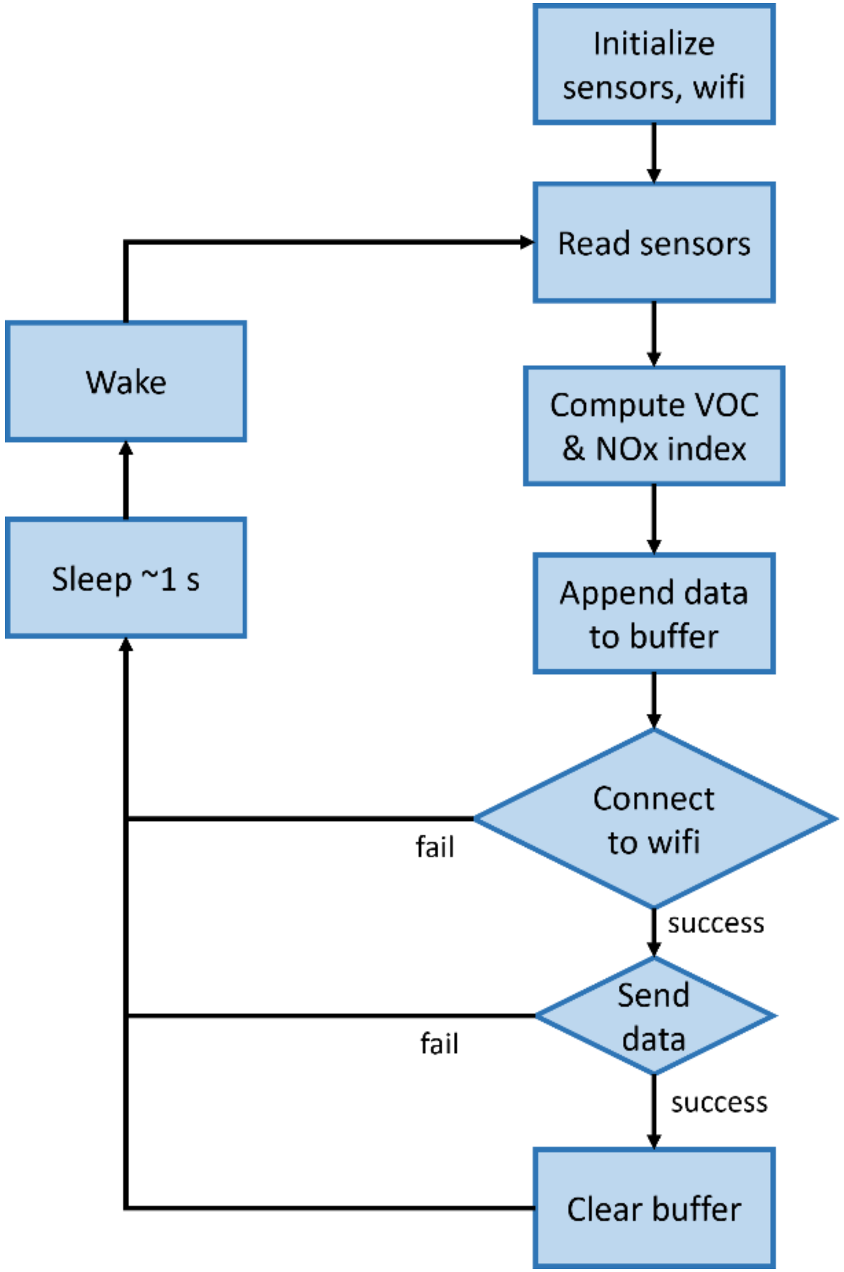


https://www.researchgate.net/figure/Energy-consumption-of-Sparkfun-ESP32-Things_fig4_332407808

MILO loop

Basically:

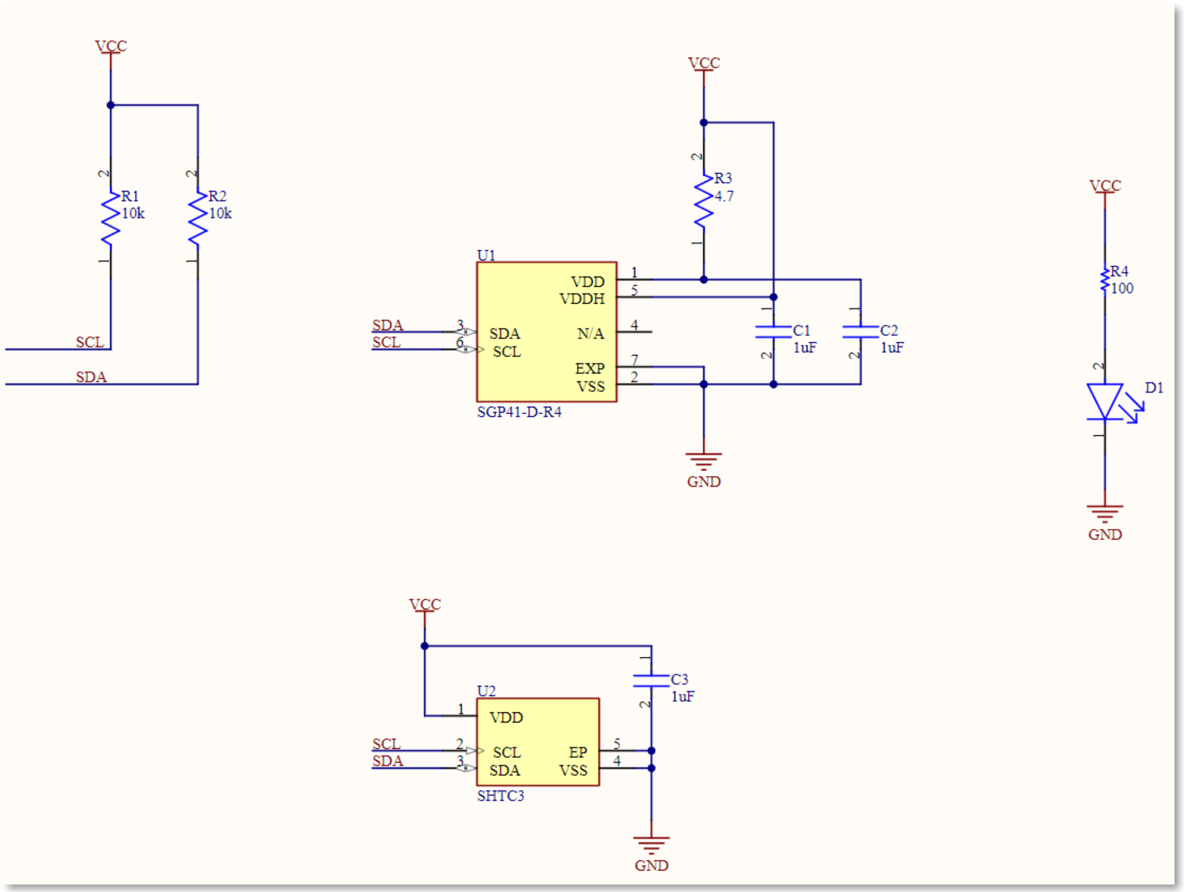
- Read sensors
  - No WiFi needed
- Do some math
  - No WiFi needed
  - No sensors needed
- Transmit data (let’s do this once/minute)
  - WiFi needed
  - No sensors needed
- Sleep
  - Let’s use light sleep



A more detailed power budget

- Often expressed in terms of mA vs. mW
  - This assumes a given system voltage, so be careful!
  - If using multiple system voltages, create extra columns, or express everything in terms of mW
- Look through each subsystem and identify energy sinks
- *Example:* sensor board
  - SHTC3, SGP41
  - LED
  - I2C lines:
    - SCL runs about 50% duty cycle
    - Assume same for SDA

Sensor board



A more detailed power budget

- Assumptions
  - 2200 mAh battery that we purchased (~$3/ea in bulk)
  - 10 sec cycle time
  - Takes 70 ms to read sensors, 100 ms to do math, 2s to transmit, and the rest is sleep
  - Use light sleep mode

Where are we spending most of our energy?

A	B	C	D	E	F
Power budget					
	Read sensors				
MCU subsystem					
ESP32C3	28.00				
LED	5.00				
	33.00				
Sensor subsystem					
SGP41	3.00				
SHTC3	0.90				
LED	5.00				
I2C	0.66				
	9.56				
Power subsystem					
MCP73871	0.03				
AP7361C	0.06				
LEDs	5.00				
Therm	0.05				
PROG1	3.70				
	8.84				
cycle time (ms)	51.40				total current (mA)
10000	70				duration (ms)
	3.6				charge (mA-sec)
	0.4%				% energy
					mA
					mA-h
					h

Reducing power

- WiFi is taking up 82% of our power budget
- What if we only transmit data once every 10 cycles?
  - Assume transmit time ~ const
- Now, most energy spent during sleep

How can we further reduce energy usage?

Power budget					
	Read sensors	Math	Xmit data	Sleep	
MCU subsystem					
ESP32C3	28.00	28.00	345.00	0.13	
LED	5.00	5.00	5.00	5.00	
	33.00	33.00	350.00	5.13	
Sensor subsystem					
SGP41	3.00	0.03	0.03	0.03	
SHTC3	0.90	0.07	0.07	0.07	
LED	5.00	5.00	5.00	5.00	
I2C	0.66	0.33	0.33	0.00	
	9.56	5.43	5.43	5.10	
Power subsystem					
MCP73871	0.03	0.03	0.03	0.03	
AP7361C	0.06	0.06	0.06	0.06	
LEDs	5.00	5.00	5.00	5.00	
Therm	0.05	0.05	0.05	0.05	
PROG1	3.70	3.70	3.70	3.70	
	8.84	8.84	8.84	8.84	
cycle time (ms)	51.40	47.27	364.27	19.07	total current (mA)
10000	70	100	200	9630	duration (ms)
	3.6	4.7	72.9	183.7	charge (mA-sec)
	1.4%	1.8%	27.5%	69.4%	% energy
			Average current/cycle	26.49	mA
			Battery capacity	2200	mA-h
			Lifetime	83.1	h

Reducing power

- Turn off those LEDs!
  - **Increase lifetime by 60%!**
- Some options
  - Reduce current draw (dimmer)
  - Power LEDs from GPIO instead of 3V3 rail
    - But will potentially lose direct readout of power
  - Or remove them entirely (do we really need one per board?)

5.5 days of runtime! →

Power budget					
	Read sensors	Math	Xmit data	Sleep	
MCU subsystem					
ESP32C3	28.00	28.00	345.00	0.13	
LED	5.00	0.00	0.00	0.00	
	33.00	28.00	345.00	0.13	
Sensor subsystem					
SGP41	3.00	0.03	0.03	0.03	
SHTC3	0.90	0.07	0.07	0.07	
LED	5.00	0.00	0.00	0.00	
I2C	0.66	0.33	0.33	0.00	
	9.56	0.43	0.43	0.10	
Power subsystem					
MCP73871	0.03	0.03	0.03	0.03	
AP7361C	0.06	0.06	0.06	0.06	
LEDs	5.00	5.00	5.00	5.00	
Therm	0.05	0.05	0.05	0.05	
PROG1	3.70	3.70	3.70	3.70	
	8.84	8.84	8.84	8.84	
cycle time (ms)	51.40	37.27	354.27	9.07	total current (mA)
10000	70	100	200	9630	duration (ms)
	3.6	3.7	70.9	87.4	charge (mA-sec)
	2.2%	2.3%	42.8%	52.8%	% energy
			Average current/cycle	16.56	mA
			Battery capacity	2200	mA-h
			Lifetime	132.9	h

Reducing power

- Sleep! ← this is your main tool
- Efficient code
  - The sooner I can sleep, the better
  - Avoid blocking code (~~`delay()`~~)
- MCU choice
  - Many MCUs now focus on energy efficiency
  - Ex: ATMEL SAM L10
    - Run: down to 25 μA/MHZ
    - Deep sleep: <100 nA
- Peripherals
  - Different sensors, etc., offer better/worse active/sleep power consumption
- Screens
  - Avoid to reduce power
- Batch wireless data transmission to amortize overhead of connection + headers

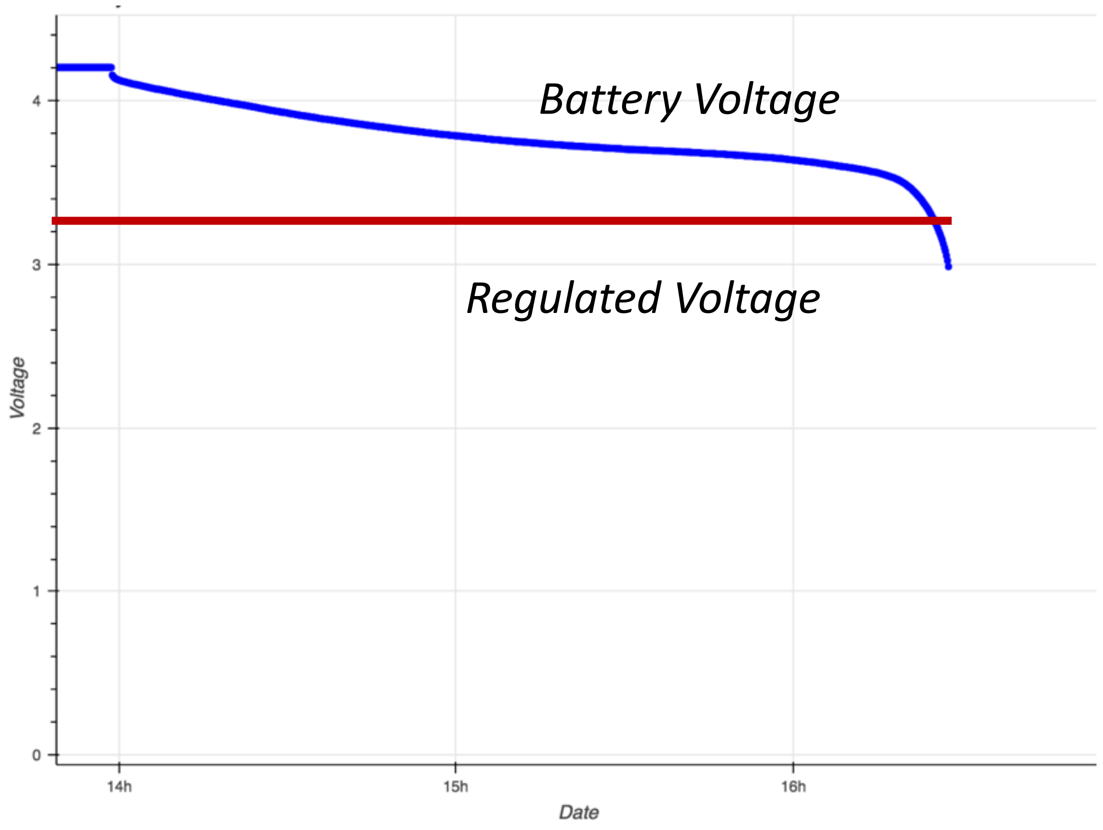
Voltage conversion

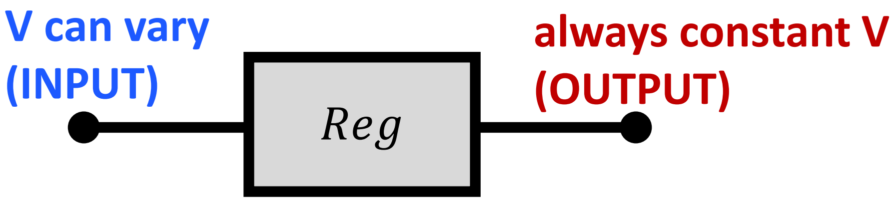
- If the nominal battery voltage is 3.7 V, but our system wants 3.3V?
- What if we also need 1.8 V? or 5 V? or -12 V?

Need a voltage converter/regulator

Stable Voltage

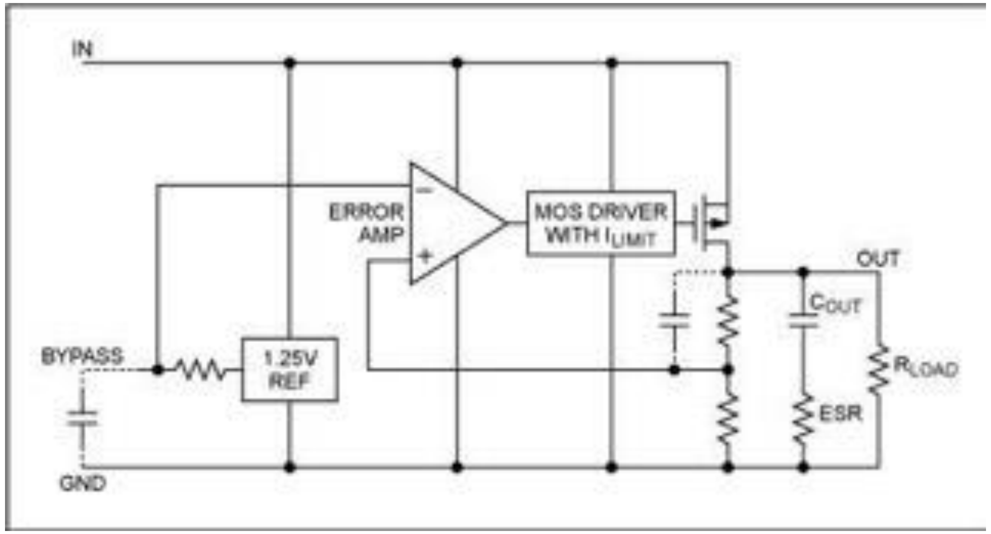
- Regulator can compensate for the variations in battery voltage that always occur





Linear voltage regulator ("LDO")

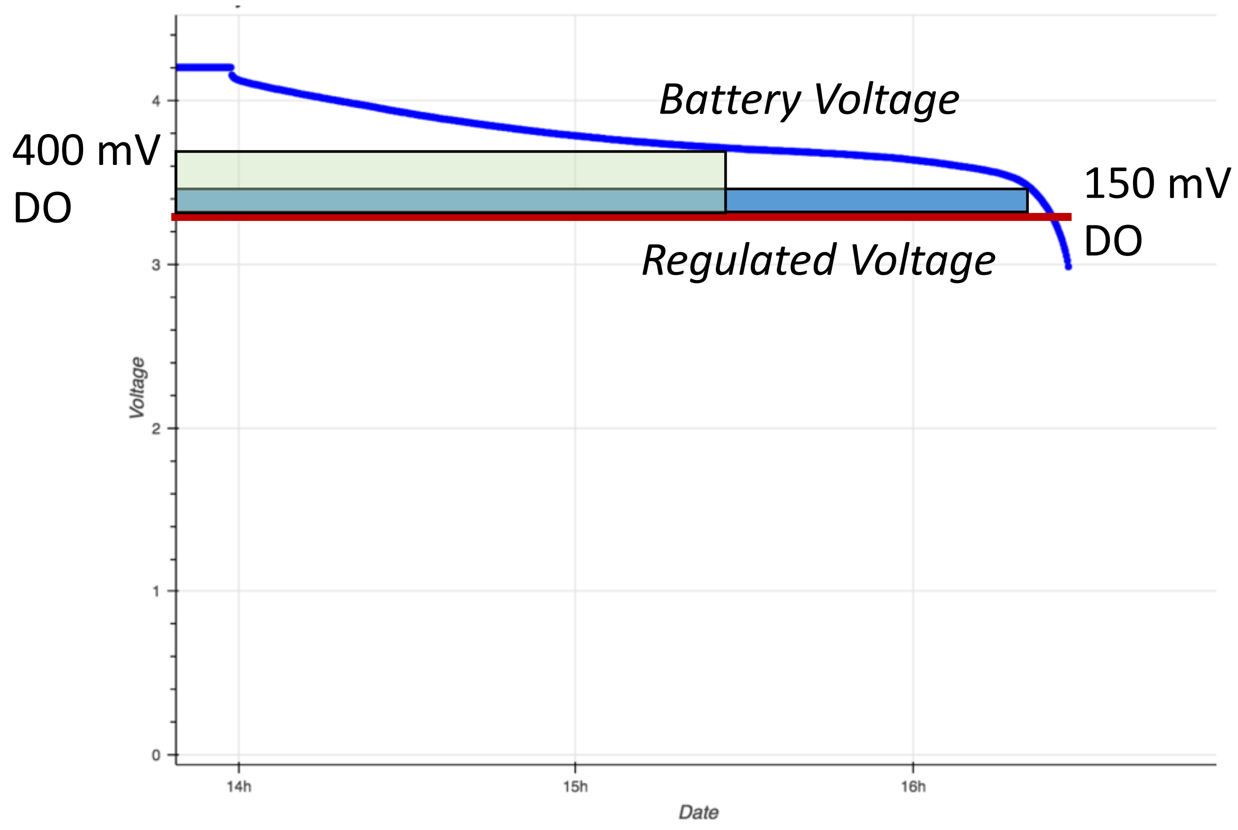
- Use transistors, diodes, and other active devices to convert voltage
- Provides fixed output voltage
  - Measures output voltage and controls internal transistors to keep that voltage constant
  - All-analog design
- Can only regulate voltage **down**
- Current in = current out
- Difference between input and output power is lost as heat
- LDOs are
  - Easy (IC + ~2 caps)
  - Low noise
  - Inexpensive (AP7361C ~$0.258 @ 1k)



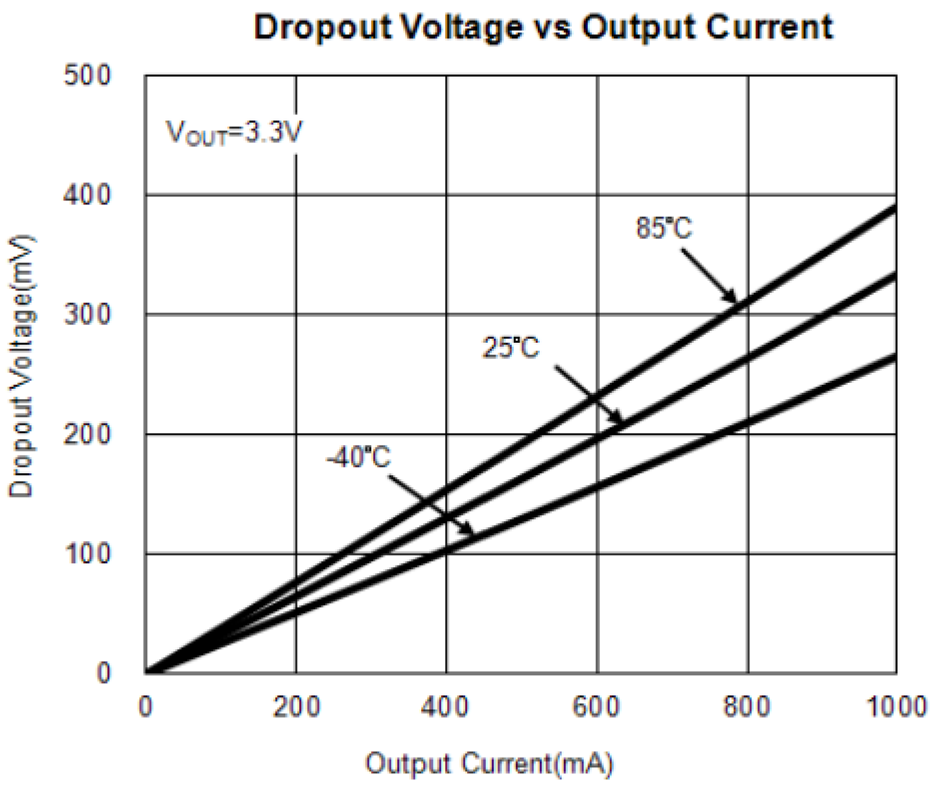
- Key specs
  - Dropout voltage
    - LDO : low dropout
  - Output voltage
  - Current capability
  - Price
  - Package

Stable Voltage

- Dropout voltage limits usable battery capacity

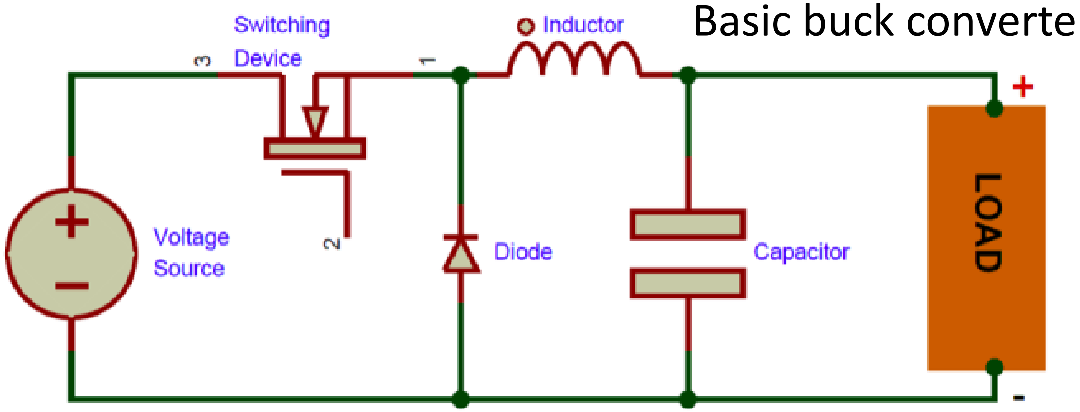


AP7361C



Switching regulators

- Use transistors (as switches), Ls, and Cs to convert voltage
  - Ideally no lossy elements
- Can provide lower (buck), higher (boost) voltage
  - Or even buck-boost
- Much higher efficiency
- Key specs
  - Similar to linear regulator
  - But can have ~0 dropout
  - Great for larger currents (>1 A)
- But
  - More expensive than LDO (TPS628303 $0.55 @ 1k)
  - Requires 2 caps + at least one external inductor (takes up a lot of space)
  - Layout is much more finicky
  - Will create high-frequency spikes that can interfere with some electronics



Basic buck converter

TPS628303

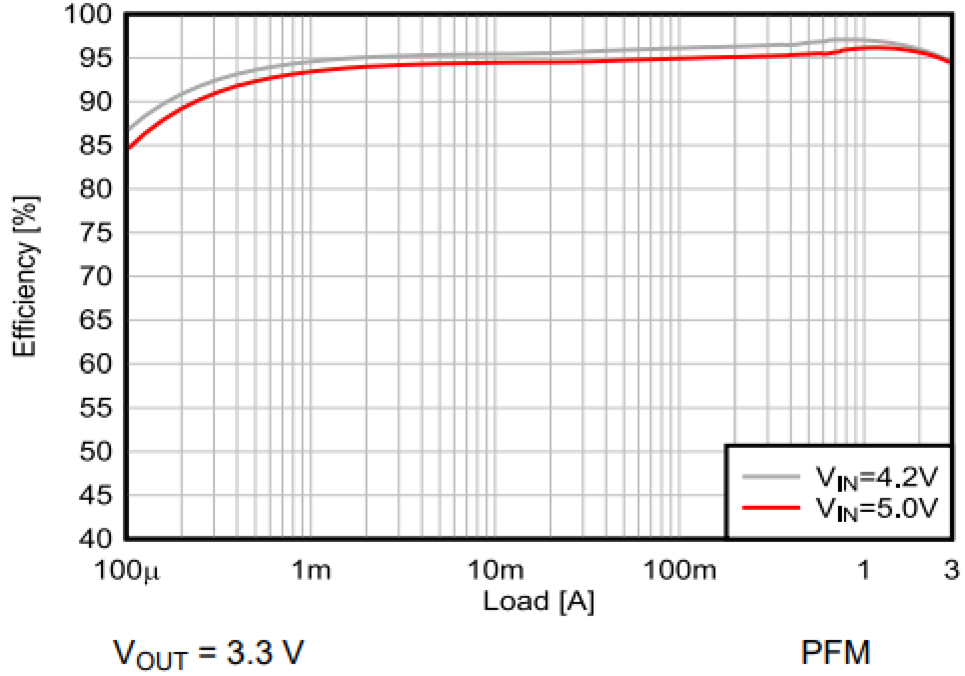
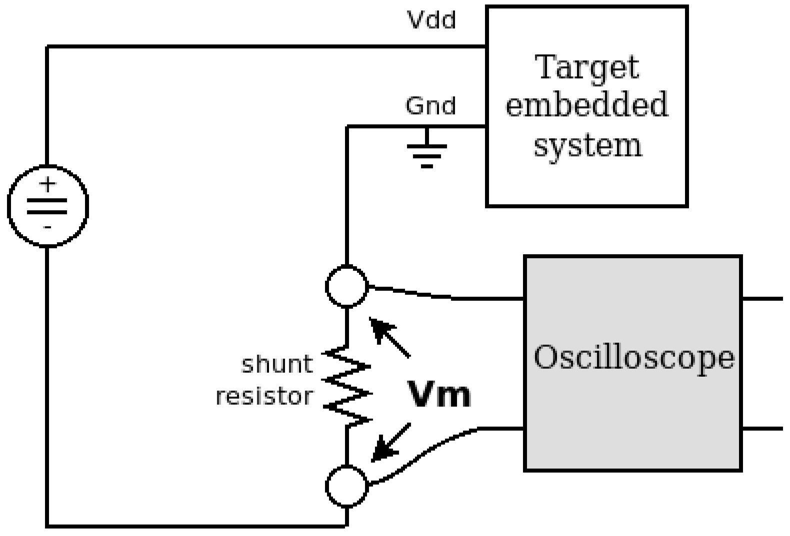


Figure 9-3. Efficiency versus Output Current

Measuring power consumption

- This can get tricky…
- If your system is not changing over time
  - Use power supply with current meter display
    - Usually good to a few mA
  - Use USB power measuring widget
- Shunt resistor + oscilloscope
  - Add in a small resistor into the path of the current you want to measure
  - Connect a oscilloscope to either side (via TP)
    - Only works if you connect to low side
- Resistor choice can be tricky
  - Want small resistor to minimize voltage drop
  - But large enough to see a measurable voltage
  - Hard to do if current is changing by 1000x



Here they use a low-side shunt
Can also do on high side (on Vdd)

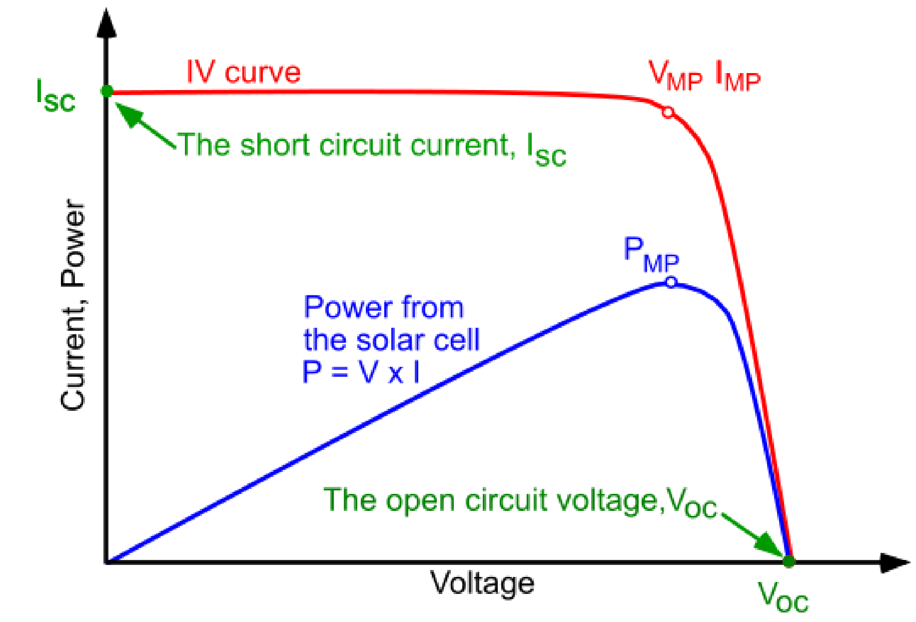
350 mA x 0.5 Ω = 175 mV [pretty small]
130 μA x 0.5 Ω = 65 μV [ugh…]

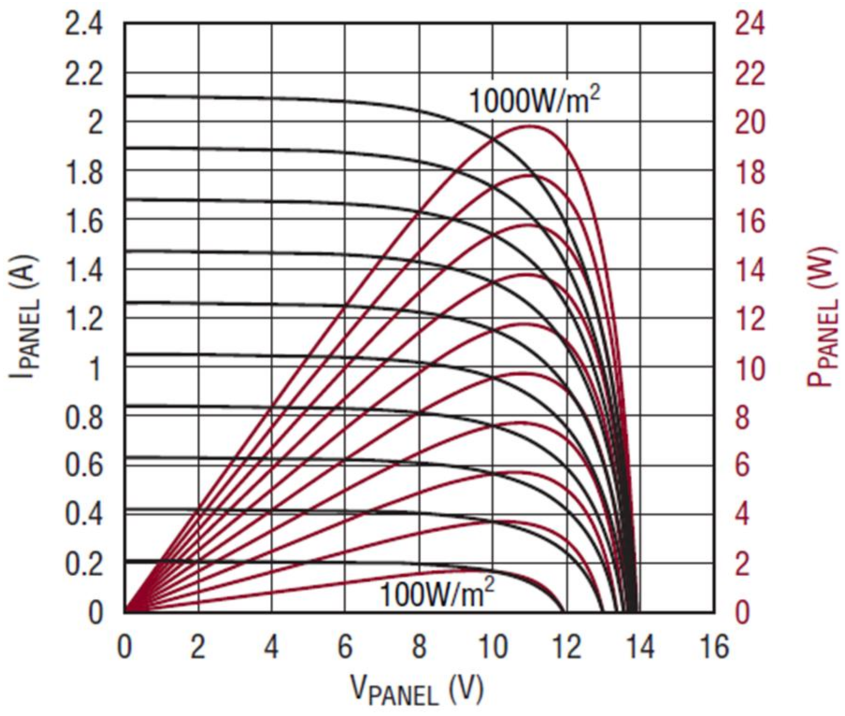
Energy harvesting

- Use $P_{IN} \geq 0$ to supplement a battery
- Power sources
  - Solar
  - Heat
  - Wind
  - Mechanical
  - Etc.
- Remember, unless $P_{IN} \geq P_{OUT}$
  - Your system will eventually run out of juice

Solar photovoltaic (PV)

- This is basically an LED run backwards (not quite)
  - V_{oc} can be increased by stacking cells in series
  - I_{sc} can be increased by stacking cells in parallel
- At V_{OC} or I_{SC}, output power = 0
- Maximum output power occurs near "knee" of I-V characteristic
  - The specific voltage (V_{MP}) varies with incidence sunlight
- If you are trying to maximize power, you can set up a control system to stay at this max power
  - MPPT: maximum power point tracker
  - This requires DC/DC converter + MCU





Solar photovoltaic (PV)

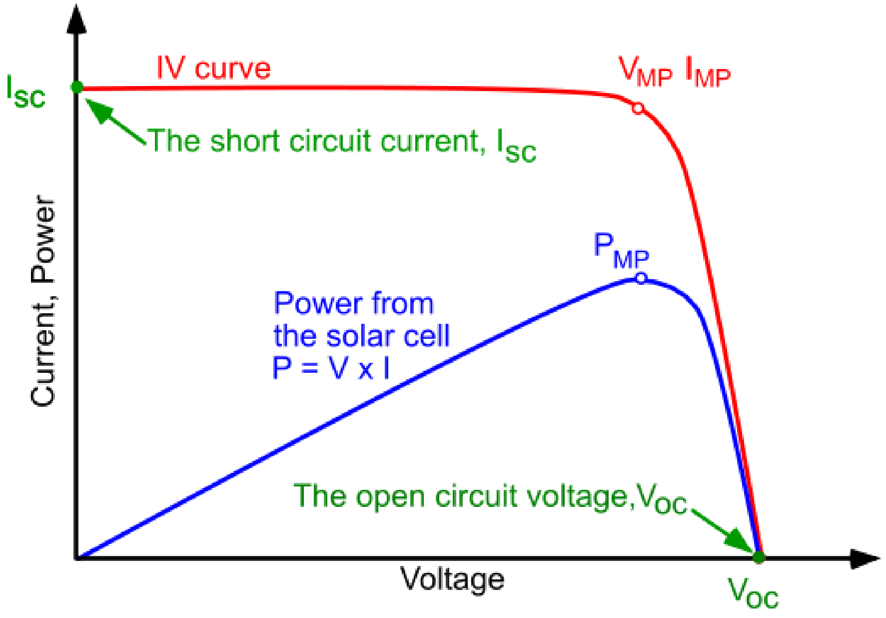
- Less expensive solar chargers leverage fact that voltage at MPPT is ~constant
  - MCP73871 in our power board has a VPCC pin

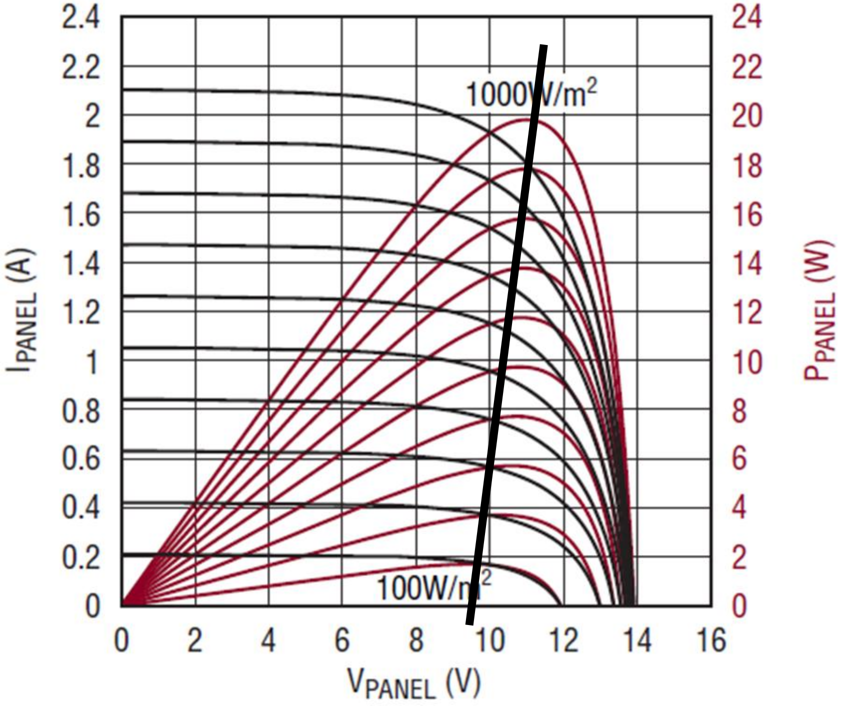
3.3 Voltage Proportional Charge Control (VPCC)

If the voltage on the IN pin drops to a preset value determined by the threshold established at the VPCC input due to a limited amount of input current or input source impedance, the battery charging current is reduced. If possible, further demand from the system is supported by the battery. To enable this feature, simply supply 1.23V or greater to the VPCC pin. This feature can be disabled by connecting the VPCC pin to IN.

For example, a system is designed with a 5.5V rated DC power supply with ±0.5V tolerance. The worst condition of 5V is selected, which is used to calculate the VPCC supply voltage with divider.

  - Create a voltage divider that hits 1.23 V at your low-threshold
  - If panel voltage dips below this, MCP IC will reduce current draw to restore voltage
    - Aka "MPPT"-lite
  - There are online design guides for this (Adafruit, ADI)



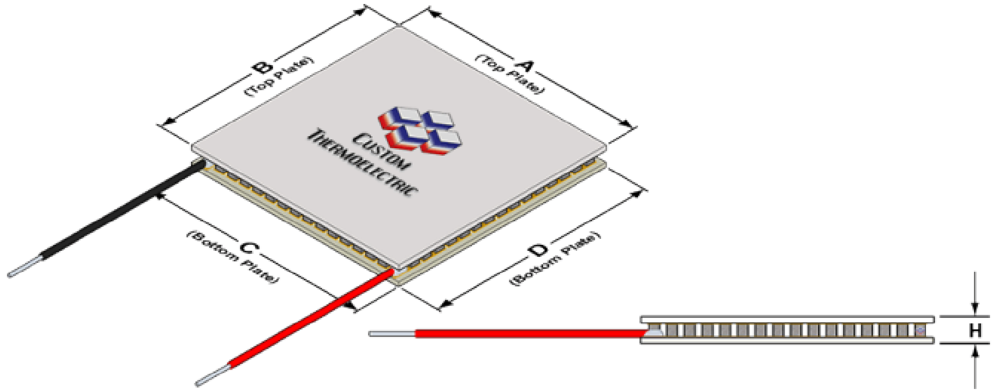


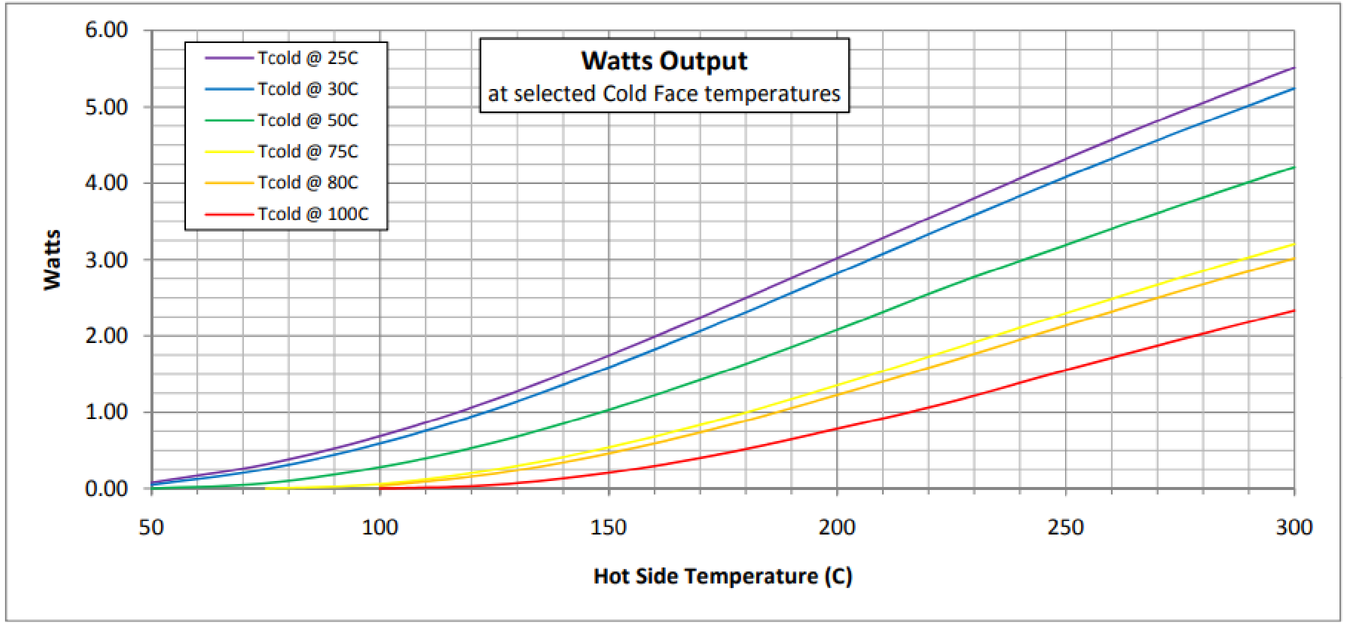
Other harvesters

- Thermoelectric
  - The opposite of a thermocouple
  - Here: $\Delta T \Rightarrow \Delta V$
  - Pros: Thin, low profile, solid state
  - Cons:
    - Expensive ($27.40 @ 100)
    - Needs large ΔT

1261G-7L31-04CL ThermoElectric Generator 30 x 30mm

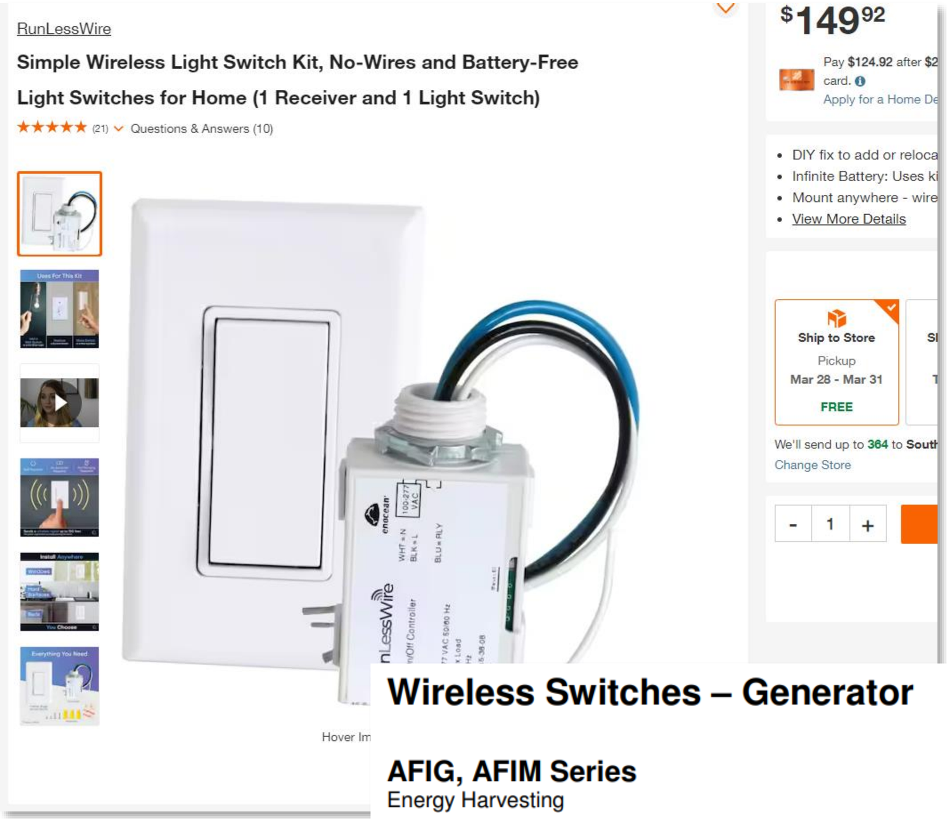
Weight (w/o leads)
11.2 grams
AC Resistance
3.5 ohms @ 27°C
Thermal Conductivity
1.72 watts/m K @ T_h=300°C

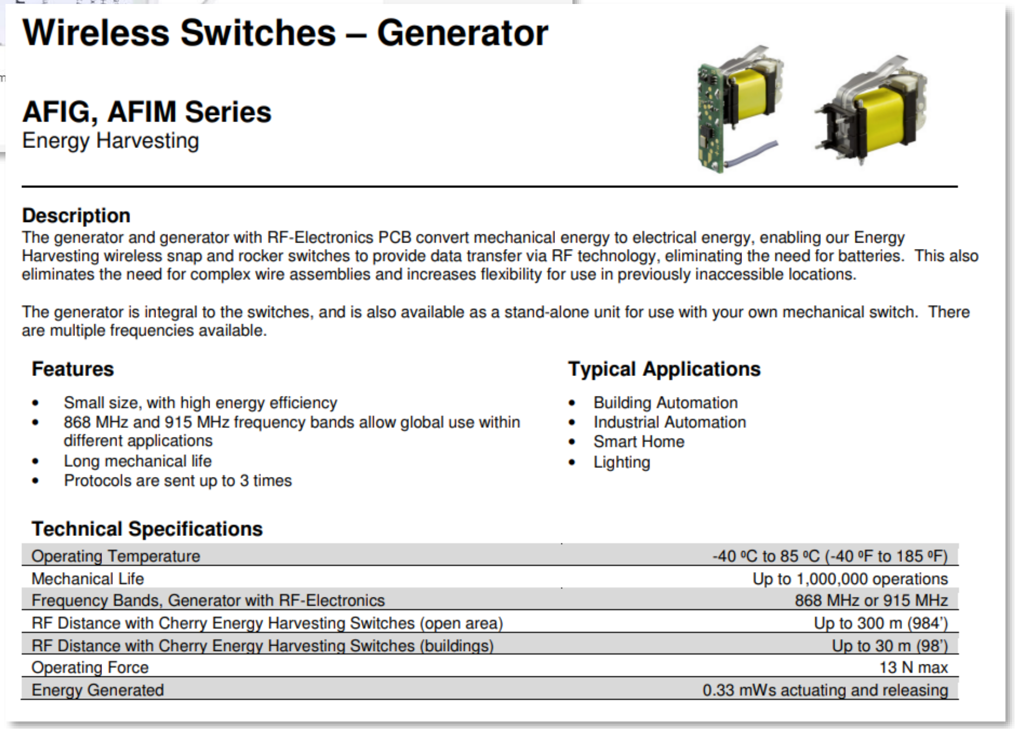




Other harvesters

- Mechanical
  - Harvest from energy of pressing switch
- Not a lot of energy
- Not cheap
  - $9.95 @ 50k
- But as electronics power ↓, these become more feasible





Wireless Switches – Generator

AFIG, AFIM Series
Energy Harvesting

Description
The generator and generator with RF-Electronics PCB convert mechanical energy to electrical energy, enabling our Energy Harvesting wireless snap and rocker switches to provide data transfer via RF technology, eliminating the need for batteries. This also eliminates the need for complex wire assemblies and increases flexibility for use in previously inaccessible locations.

The generator is integral to the switches, and is also available as a stand-alone unit for use with your own mechanical switch. There are multiple frequencies available.

Features
- Small size, with high energy efficiency
- 868 MHz and 915 MHz frequency bands allow global use within different applications
- Long mechanical life
- Protocols are sent up to 3 times

Typical Applications
- Building Automation
- Industrial Automation
- Smart Home
- Lighting

Technical Specifications

Operating Temperature	-40 ºC to 85 ºC (-40 ºF to 185 ºF)
Mechanical Life	Up to 1,000,000 operations
Frequency Bands, Generator with RF-Electronics	868 MHz or 915 MHz
RF Distance with Cherry Energy Harvesting Switches (open area)	Up to 300 m (984')
RF Distance with Cherry Energy Harvesting Switches (buildings)	Up to 30 m (98')
Operating Force	13 N max
Energy Generated	0.33 mWs actuating and releasing