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

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 $P_{IN} < P_{OUT}$

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

• 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- Vendors do not publish quantity pricing

![Battery Pack Prices](image)

**GLOBAL LITHIUM-ION BATTERY PACK PRICES**
In U.S. dollars per kilowatt-hour, 2011-2021

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Price per kWh-hour</td>
<td>$946</td>
<td>$760</td>
<td>$680</td>
<td>$600</td>
<td>$520</td>
<td>$440</td>
<td>$360</td>
<td>$320</td>
<td>$280</td>
<td>$240</td>
<td>$132</td>
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</table>

**Battery Pack Specifications**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Lead Acid</th>
<th>NiCd</th>
<th>NiMH</th>
<th>Li-Ion</th>
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<tbody>
<tr>
<td></td>
<td>Cobalt</td>
<td>Manganese</td>
<td>Phosphate</td>
<td></td>
</tr>
<tr>
<td>Specific energy (Wh/kg)</td>
<td>30-50</td>
<td>45-80</td>
<td>60-120</td>
<td>150-250</td>
</tr>
<tr>
<td>Internal resistance</td>
<td>Very Low</td>
<td>Very low</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>Cycle life (80% DOD)</td>
<td>200-300</td>
<td>1,000</td>
<td>300-500</td>
<td>500-1,000</td>
</tr>
<tr>
<td>Charge time</td>
<td>8-16h</td>
<td>1-2h</td>
<td>2-4h</td>
<td>1-2h</td>
</tr>
<tr>
<td>Overcharge tolerance</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Self-discharge/mont (room temp)</td>
<td>5%</td>
<td>20%</td>
<td>30%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Protection circuit consumes</td>
<td>3%</td>
<td>month</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell voltage</td>
<td>2V</td>
<td>1.2V</td>
<td>1.2V</td>
<td>3.6V</td>
</tr>
<tr>
<td>Charge cutoff voltage (V/cell)</td>
<td>2.4V Float 2.25</td>
<td>Full charge by voltage signature</td>
<td>4.29 typical</td>
<td>Some go to higher V</td>
</tr>
<tr>
<td>Discharge cutoff voltage (V/cell, 1C)</td>
<td>1.75V</td>
<td>1.00V</td>
<td>2.50-3.00V</td>
<td>2.50V</td>
</tr>
<tr>
<td>Peak load current</td>
<td><a href="mailto:5C@0.2C">5C@0.2C</a></td>
<td>20C@1C</td>
<td><a href="mailto:5C@0.5C">5C@0.5C</a></td>
<td>2C@&lt;10C</td>
</tr>
<tr>
<td>Charge temperature</td>
<td>-20 to 50°C (-4 to 122°F)</td>
<td>0 to 45°C (32 to 113°F)</td>
<td>0 to 45°C (32 to 113°F)</td>
<td></td>
</tr>
<tr>
<td>Discharge temperature</td>
<td>-20 to 50°C (-4 to 122°F)</td>
<td>-20 to 59°C (-4 to 149°F)</td>
<td>-20 to 60°C (-4 to 140°F)</td>
<td></td>
</tr>
<tr>
<td>Maintenance requirement</td>
<td>3-6 months (toping chg)</td>
<td>Full discharge every 90 days when in use</td>
<td>Maintenance-free</td>
<td></td>
</tr>
<tr>
<td>Safety requirements</td>
<td>Thermally stable</td>
<td>Thermally stable, fuse protection</td>
<td>Protection circuit mandatory</td>
<td></td>
</tr>
<tr>
<td>In use since</td>
<td>Late 1800s</td>
<td>1950</td>
<td>1990</td>
<td>1991</td>
</tr>
<tr>
<td>Toxicity</td>
<td>Very High</td>
<td>Very High</td>
<td>Very High</td>
<td>Low</td>
</tr>
<tr>
<td>Coulombic efficiency</td>
<td>~90%</td>
<td>~70% slow charge, ~90% fast charge</td>
<td>99%</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>

*SOURCE: BloombergNEF*

**Images:**
- BloombergNEF
- PAUL HORN / Inside Climate News
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

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Nominal voltage</th>
<th>Rated capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>9V</td>
<td>9 volts</td>
<td>570mAh</td>
</tr>
<tr>
<td>AAA</td>
<td>1.5 volts</td>
<td>1,150mAh</td>
</tr>
<tr>
<td>AA</td>
<td>1.5 volts</td>
<td>2,670mAh</td>
</tr>
<tr>
<td>C</td>
<td>1.5 volts</td>
<td>7,800mAh</td>
</tr>
<tr>
<td>D</td>
<td>1.5 volts</td>
<td>17,000mAh</td>
</tr>
</tbody>
</table>

*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
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 \( \Rightarrow 37.5 \) Wh

This is our maximum \( E_{STORE} \)
What’s the minimal system?

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

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

• Full power – 345 mA (at 3.3V)

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

Looks like this should be doable...

*Any issues with this approach?*
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 cm³
- 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

---

### ESP32-C3 Wi-Fi + Bluetooth® Low Energy SoC

#### Work mode

<table>
<thead>
<tr>
<th>Mode</th>
<th>Description</th>
<th>All Peripherals Clocks Disabled (mA)</th>
<th>All Peripherals Clocks Enabled (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active (RF working)</td>
<td>TX</td>
<td>802.11b, 1 Mbps, @20.5 dBm</td>
<td>345</td>
</tr>
<tr>
<td></td>
<td>802.11g, 54 Mbps, @18 dBm</td>
<td>285</td>
<td></td>
</tr>
<tr>
<td></td>
<td>802.11n, HT20, MCS7, @17.5 dBm</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td></td>
<td>802.11n, HT40, MCS7, @17 dBm</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>RX</td>
<td>802.11b/g/n, HT20</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td></td>
<td>802.11n, HT40</td>
<td>84</td>
<td></td>
</tr>
</tbody>
</table>

#### CPU Frequency (MHz)

<table>
<thead>
<tr>
<th>Mode</th>
<th>CPU Frequency (MHz)</th>
<th>Description</th>
<th>All Peripherals Clocks Disabled (mA)</th>
<th>Typ</th>
<th>All Peripherals Clocks Enabled (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern-sleep</td>
<td>160</td>
<td>CPU is idle</td>
<td>16</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CPU is running</td>
<td>23</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Modern-sleep</td>
<td>80</td>
<td>CPU is idle</td>
<td>13</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CPU is running</td>
<td>17</td>
<td>22</td>
<td></td>
</tr>
</tbody>
</table>

#### Power modes

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

---

### Modules having power in specific power modes:

- [ ] Active
- [ ] Active and Modern-sleep
- [ ] Active, Modern-sleep, and Light-sleep
- [ ] optional in Light-sleep
- [ ] All modes
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!

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

Not our ESP32
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
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?

<table>
<thead>
<tr>
<th>Power budget</th>
<th>Read sensors</th>
<th>MCU subsystem</th>
<th>ESP32C3</th>
<th>26.00</th>
<th>LED</th>
<th>5.00</th>
<th>33.00</th>
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<tbody>
<tr>
<td>Sensor subsystem</td>
<td>SGP41</td>
<td>3.00</td>
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<td></td>
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<td>9.56</td>
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<td>Power subsystem</td>
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<td></td>
<td></td>
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<td></td>
<td>8.84</td>
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<tr>
<td>cycle time (ms)</td>
<td>51.40</td>
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<td></td>
<td></td>
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</tr>
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<td>3.6</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.4%</td>
</tr>
</tbody>
</table>
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?
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!
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

![Diagram showing battery voltage and regulated voltage with a regulator block]

\[ V \text{ can vary (INPUT)} \quad \text{always constant } V \text{ (OUTPUT)} \]
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
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
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

\[
350 \text{ mA} \times 0.5 \text{ } \Omega = 175 \text{ mV} \ [\text{pretty small}]
\]
\[
130 \mu\text{A} \times 0.5 \text{ } \Omega = 65 \mu\text{V} \ [\text{ugh...}]
\]
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

• 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 $\Delta T$

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 @ $T_c=300°C$

Watts Output
at selected Cold Face temperatures

Copyright © 2012. All rights reserved. Custom Thermoelectrics, 1461 Industrial Park Road, STE 2, Redwood City, CA 94063
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