6.08: Interconnected embedded systems

Lecture 2
Power #1 and Batteries

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February 20, 2018

Design Exercises

• During office hours, staff will help in depth on design exercises only if others don’t need help on regular exercises

• This hasn’t been a problem yet, but we just want you to keep that in mind

• If you didn’t do the design exercise from last week, consider doing one this week.

February 20, 2018

Administrative

• Only one lab this week! (Lab 03B on Thursday @regular time...there is no Lab 03A)

• Exercise 03 out at 3pm today:
  • Five required exercises
  • Two design exercises

• Office Hours changed:
  • Sunday 4-8pm
  • Tuesday 7-9pm
  • Wednesday 7-10pm
  • Friday 12-4:30pm

February 20, 2018

OLED Protection

• Lots of OLEDs getting broken

• Please treat your kit carefully!

• Do not overtighten the bottom screws...just leave them loose-ish.

• The top ones you can tighten if you want

Feel free to tighten these screws:

Leave the bottom ones loose
Power

- We need to start thinking about power
- So far we’ve been using our device like this (below):
- Where does the power to run our device come from in this configuration?

USB: Universal Serial Bus

- Allows communication between kit and computer using data lines
- Power is provided from the computer over cable as well

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<td>Red</td>
<td>+5 V</td>
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<td>2</td>
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<td>8</td>
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USB Type A & B Pinout

Outer two wires provide +5V and GND

Newer USB

USB 3.0

- 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

\[ P = V \cdot I \]

\[ P = \frac{\text{Joule}}{\text{Coulomb}} \cdot \frac{\text{Coulomb}}{\text{sec}} = \frac{\text{Joule}}{\text{sec}} = \text{Watt} \]
How much does our kit currently consume?

$P_{kit} = V_{cc} \cdot I_{kit}$

$P_{kit} = 5V \times I_{kit}$

Can use an in-series USB current measuring device:

Can also Turn WiFi Off:

```
WiFi.begin("6s08","iesc6s08"); //attempt to connect to wifi
WiFi.mode(WIFl_OFF); //turn off WiFi
```

Running WiFiGetter.ino

- Systems as you have it right now (ESP, OLED, IMU)

- Cycles back and forth between these two:

- Why?

Put the ESP32 into DEEP Sleep

```
esp_sleep_enable_timer_wakeup(10 * uS_TO_S_FACTOR); //set a wakeup timer
esp_deep_sleep_start(); //enter deep sleep (5uA)
```

- Put ESP into deep sleep:
- Should be using 5 uA

- Why not?
Current Readings Summary

- ESP32:
  - Up to ~160 mA with WiFi
  - Up to 70 mA without WiFi
  - ~5 uA in Deep Sleep
  - On the dev board ~25 mA current into other parts (LED, serial communication chip)

- IMU:
  - Accelerometer: 2mA
  - Gyroscope: 6mA

- OLED on its own: Up to ~30 mA

- How much power does this correspond to?
- Let’s run some numbers...

Power Consumption

...Remembering that USB provides a 5V supply

- When running WiFi, OLED, etc...:

Waste

- It turns out all the actual parts on the board run at 3.3V (think about your wiring from lab) and there is a part that drops voltage (called regulator)

- So when running on USB, what is the efficiency of this system? How much power actually goes to devices we want?
Efficiency

• We’ll define our system efficiency as the following:
  \[
  \text{Efficiency} = \frac{\text{Useful Amount}}{\text{Total Amount}} \cdot 100\%
  \]

• In the scope of our Power calculation:

Where does that 0.75W go?

• Most is ultimately lost to heat (put your hand over the ESP when you’re doing GET or POST requests)

• In between some converts to light, radio waves, information

• This power/energy is very real:

Big Picture

• So we now know our lab kit when USB-powered uses ~0.75W and is about 66% efficient

• But so what? We always have power...we just plug it into our laptop, which is itself generally plugged in and we’re good.

• But what if we don’t have infinite power and we need to actually be mobile?

Power/Energy Budget

• If we want to be mobile or remote, we cannot rely on the power grid. MUST either bring energy with us or harvest

• We want our kit/IoT device to last a long time

• How long?
  • Depends on application
    • Apple Watch: ~ 1 day
    • Unattended building sensor: > 1 yr
    • Implanted pacemaker: 5-10 yrs

• Three ways to increase lifetime in such a setting
  • Increase energy source
  • Decrease demand
  • Harvest energy from environment
Batteries

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

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

- Wide differences in:
  - Nominal voltage
  - Current capability
  - Energy capacity
  - Energy density (J/kg or J/m³ or Wh/m³)
  - Discharge characteristics
  - Renewable or one-time

Characterizing Batteries

- We generally characterize batteries by:
  - The voltage they produce
  - Their capacity

- There are lots of caveats and additional characteristics, though:
  - Charge/discharge rate
  - Temperature Ratings
  - Instantaneous Current Ratings

Example:

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

Battery Chemistries

- Primary (non-rechargeable)
  - Alkaline
  - Lithium

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

Battery Voltage

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

- Li-Ion and Li-Poly: 3.7 V

- Can increase battery voltage by placing cells in series
Battery Capacity

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

- Depends on chemistry and size
  - Li AA: 2500-3400 mAh
  - CR2032
    - ~200 mAh
  - LiPoly
    - Variety of sizes
    - iPhone 6: 1810 mAh
    - Apple watch: 205 mAh

*approximately

Capacity/Energy

- Integral of Power Consumed over time

\[
E(t) = \int_0^t P(t) dt
\]

- If Voltage and Current are constant over time:

\[
E = V \cdot I \cdot \Delta t
\]

Our Battery Symbol

- 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

Battery self-discharge

- Self-discharge rates
- How much capacity is lost due to internal resistance
- Alkaline ~ 5yrs
- Lithium-Ion ~ 2-3%/mo
- NiMH ~ 30%/mo
- Lithium: ~1 %/yr

- You don’t want self-discharge to limit your sensor node lifetime!
Voltage of 350 mAh 3.7V battery

Discharge Curve:
(Voltage of battery over time)

This is far from constant

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

Battery Voltage and System Voltage

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

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

- Must regulate

Stable Voltage

- Our Batteries provide us energy, but at a highly-variable voltage
  
  
  
  Voltage Regulators to the Rescue!
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
    • Often 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)
• Can only regulate down in voltage

Switching Supply (non-linear device)

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

Linear Regulators in 6.08 Device

• Constant Current Device (KCL maintained)
• Can only regulate down in voltage
• So far has converted 5.0V to 3.3V for our components

• What is the efficiency?
Switching Supply (non-linear device)

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

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

How efficient are we?

- $3.2V \leq v \leq 4.2V$
- Always @5.0V
- 3.3V Reg
- 3.7V 1200 mAh LiPoly
- 6.08 Battery

• How are we going to manage our battery this year?
Power Board

• The Power Board is an I2C-controlled battery management board

• Takes care of:
  • Charging and discharging battery
  • Voltage regulation
  • Switching between USB and Battery as needed

• Can also:
  • Report battery voltage
  • Provide variable output voltages
  • Estimate battery life remaining

Power Board

• We use a new battery management chip from Analog Devices
• ADP5350

Battery Charging State Machine

• Charging a Lithium-Polymer Battery safely is not a simple task
• ADP5350 takes care of that for us!

Configuration
• Our Power Board will allow automatic charging and usage of the battery as needed.
• When plugged in, it will charge and power components over the micro-USB
• When remote, it will switch to battery-power automatically
• This is what we do in Lab 03B!

In Charging Mode
![Diagram of the charging mode with labels and components]

In Battery-Powered Mode
![Diagram of the battery-powered mode with labels and components]

How efficient are we this year?

6.08 Power System from 2018
Safety

• Never use our LiPoly batteries other than with Power management board!
• Battery plugs into boards JST connector
• Only charge battery through power board

Lithium Polymer Battery

Lithium Polymer Batteries Can Be Dangerous

• Made of Lithium...(the exciting chemical from chemistry class)

• Can be Dangerous!

• Do not stab, crush, abuse the batteries! Keep them in their cardboard box inside the 6.08 kit bag for safety!

Lithium Polymer Batteries: Safety Rules for 6.08

SAFETY NOTICE: In general, never leave a battery unattended while charging. Only charge the battery when it is in your 6.08 fireproof pouch. When not using, disconnect the battery and store in fireproof bag.

SAFETY NOTICE: Never directly connect your battery to anything but the Power Board JST socket. No wires, etc…

SAFETY NOTICE: If your battery is bulging, hot, or damaged, don’t use it! Put it in your fireproof bag and contact staff

SAFETY NOTICE: DO NOT CRUSH OR DROP YOUR 6.08 KIT WITH THE BATTERY. DO NOT SIT ON YOUR 6.08 KIT. DO NOT SHOVE IT AT THE BOTTOM OF YOUR BOOKBAG UNDERNEATH BOOKS

MAINTENANCE NOTICE: Battery connectors are fragile. Insert and remove carefully. If yours breaks, tape the bare wires to prevent shorts and bring it to lab for assistance in fixing or replacing it.

Adapted from 2.007
Lipo Safe Bag

• We have these because of the batteries!

• Designed to contain a fire if it were to happen

• Guy trying to damage bag with much larger battery:
  • https://www.youtube.com/watch?v=2oNQdSUji68

Data Logger

• ESP32 running all the time, and POSTing its battery voltage every 10 seconds to some database

  ![Graph showing battery life](image)

  - 350 mAh battery
  - ~150 mA continuous consumption
  - 350mAh/150mA = 2.3 h
  - So this is about what we’d expect

Using Less Power

• Even in a lot of the code we’ve written so far, we’re wasting a lot of time.

• Any time our code is in a waiting-pattern, it is potentially wasting power

• We can save energy by

  ```
  while(millis() - timer < loop_speed);
  timer = millis();
  ```

  ```
  WIFI.begin("6d88","l69c0d68"); //attempt to connect to wifi
  ```

  ```
  WIFI.mode(WIFI_OFF); //turn off wifi
  ```

  ```
  esp_sleep_enable_timer_wakeup(18 * 1000 * 1000 * 1); //set a wakeup timer
  esp_deep_sleep_start(); //enter deep sleep (5s)
  ```
Sleep

- ESP32 can conserve power in several ways*:
  - Turn off WiFi: This can remove 50 to 60mA of current-draw on the system, cutting the consumption by 1/3 to 2/3.
  - Deep Sleep (consume 5 µA!) but almost all functionality is gone, but you can set it to wake with a timer or upon a digital signal (button push)
  - If you really want to stretch a battery’s useful life you want to deeply consider if certain functionality needs to be on all the time

*There are quite a few levels of sleep, but many are not broken out at this point

Duty Cycling

- The key to a long life is sleep!
- Turn on in bursts and turn off otherwise.
- The ratio of the “ON” to overall is called the duty cycle

\[
\text{duty cycle} = \frac{t_{ON}}{T} = \frac{t_{ON}}{t_{ON} + t_{OFF}} \times 100\%
\]

- Example:
  - We have an ESP32 powered with a 200 mAh coin-cell battery.
  - We want it to run for one month
  - If necessary measurement and connection to WiFi requires \( t_{ON} = 10 \text{ sec} \), what is minimum \( T \) to stretch for life span for month

- ESP32:
  - Low Power Mode: 5 µA
  - Run (with WiFi) mode 150 mA

- What must the average current draw be to last one month?
Duty Cycling

• Adjust Duty Cycle to achieve Average Current:

\[ \text{duty cycle} = \frac{t_{ON}}{T} = \frac{t_{ON}}{t_{ON} + t_{OFF}} \times 100\% \]

Harvesting Energy from Environment

Duty cycling

• Great for infrequent events
  • Monitoring temperature, humidity in room
  • Wildfire monitoring in field
  • Corrosion in pipelines
  • Etc.

• When done at higher frequencies, it can also be used to control higher-power devices more efficiently (to be explored this week in lab)

• With right hardware you can even duty cycle very fast and still be responsive to human use!

Energy harvesting

• Could also scavenge energy from environment
  • Solar
  • Heat
  • Mechanical

• Use to power system directly or recharge battery
  • Use as energy comes in
  • Store energy from times of plenty and use later

• Potentially “limitless” lifetime
• Very active area of research
Energy harvesting

• Solar photovoltaic
  • Photons turn into current in a semiconductor (usually Si)
  • Generate voltage ~0.7 V
    • Can be increased by stacking cells in series
  • Current increases with on area
  • Output depends on incident light intensity!

2.2 inches dia
5 V @ 40 mA

https://www.adafruit.com/products/700
http://electronicdesign.com/content/content/73937/73937-fig2.gif

Low-Profile Wearable Body-Powered Thermoelectric Generator

• Low profile, lightweight, conformal.
• Utilization of small temperature difference
• Utilization of natural convection for cooling

Credit: Krishna Settaluri MIT ‘2010

Energy harvesting

• Thermo-electric generator
  • Thermoelectric material converts temperature difference into voltage

40 K temp difference
1.8 V @ 368 mA

Trends: Energy Scavenging

MEMS Generator

Jose Mur Miranda/ Jeff Lang
Vibration-to-Electric Conversion
~ 10mW

Power Harvesting Shoes

Joe Paradiso (Media Lab)
After 3-6 steps, it provides 3 mA for 0.5 sec
~10mW
Ambient RF

Prudential Center
FM Stations:
WZLX 100.7, WBMW 104.1, WMXJ 106.7, and WOKS-FM 107.9, WBOS 92.9, WBQT 96.9, and WROJ-FM 105.7.
Power output:
22,000 watts
Recovered:
~ 0.2 milliwatt

Grape Power

Go up on 6th floor of 34...behind lockers is really long antenna

Grape Juice Voltage

Copper penny
Zinc screw
Newman's Own
Grape Juice

Infinite Power! If we ignore the time/energy it takes to produce grapefruit juice!

Gastric Fluid Powered

Research conducted at MIT: Phil Nadeau
Using 4mm x 4mm electrodes (Zn/Cu), 10uW of average power from in brief (< 30 min) in vivo measurements

Fig. 3. Photo of GMB prototype.
In Lab This Week

• Hook up Power Board

• Mess with it a bit

• Implement PWM control of High-Illumination LED

• Sign up for piazza