6.S08: Interconnected embedded systems

Lecture 07
Power, Batteries, and Sleep

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Administrative Notes

• L06B and L07B this week (power)

• EX07 out soon, due 4/02/2017 (Sunday after Spring Break)

• Final Project Teams due by this Friday

• GPS is working again in 38-500
Motivation

Many IoT sensor nodes are battery-powered

Want them to last a long time
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

\[ P = V \cdot I \]

\[ P = \frac{\text{Joule}}{\text{Coulomb}} \cdot \frac{\text{Coulomb}}{\text{sec}} = \frac{\text{Joule}}{\text{sec}} = \text{Watt} \]


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:

\[ E = V \cdot I \cdot \Delta t \]
Where/How much energy?

- Transistors in electronics consume energy
- Turning on/off a transistor is effectively charging a capacitor!
- 50% of energy is lost during charging
Power & Energy Consumption

\[ E_T = N \cdot E_S + P_L \cdot T \]

- **Total Energy Consumed**
- **Dynamic dissipation**
  - Number of "Switch Actions" to Complete Task
  - Energy Per Switch
- **Static dissipation**
  - Power Lost to Leakage
  - Time to Complete Task
Power or energy budget

• We want our 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
  • Increase energy source
  • Decrease demand
  • Harvest energy from environment
Batteries

• Voltage sources with finite energy storage

• Wide differences in
  • Nominal voltage
  • Current capability
  • Energy capacity
  • Energy density (J/kg or J/m^3 or Wh/m^3)
  • Discharge characteristics
  • Renewable or one-time
Battery chemistries

• Primary (non-rechargeable)
  • Alkaline
  • Lithium

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

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

• Depends on chemistry
• NiMH: 1.2 V
• Alkaline: 1.5 V
• 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 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!
Battery capacity

• 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

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>2,870mAh</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>

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!

Li-Poly
350 mAH

3.7V
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 discharge curves

- Different chemistries have different discharge curves
- Voltage will change over time...it is not constant
  - Can use battery voltage to estimate remaining capacity
  - System must be able to accommodate varying voltage
### Battery Data Sheet

#### 3. Specification

<table>
<thead>
<tr>
<th>Item</th>
<th>Specifications</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Capacity</td>
<td>1200mAh</td>
<td>0.2C&lt;sub&gt;5&lt;/sub&gt;A discharge, 25℃</td>
</tr>
<tr>
<td>Nominal Voltage</td>
<td>3.75V</td>
<td>Average Voltage at 0.2C&lt;sub&gt;5&lt;/sub&gt;A discharge</td>
</tr>
<tr>
<td>Standard Charge Current</td>
<td>0.2 C&lt;sub&gt;5&lt;/sub&gt;A</td>
<td>Working temperature: 0~40℃</td>
</tr>
<tr>
<td>Max Charge Current</td>
<td>1C&lt;sub&gt;5&lt;/sub&gt;A</td>
<td>Working temperature: 0~40℃</td>
</tr>
<tr>
<td>Charge cut-off Voltage</td>
<td>4.2V</td>
<td>CC/CV</td>
</tr>
<tr>
<td>Standard Discharge Current</td>
<td>0.5C&lt;sub&gt;5&lt;/sub&gt;A</td>
<td>Working temperature: 25℃</td>
</tr>
<tr>
<td>Discharge cut-off Voltage</td>
<td>2.75V</td>
<td></td>
</tr>
<tr>
<td>Cell Voltage</td>
<td>3.7-3.9V</td>
<td>When leave factory</td>
</tr>
<tr>
<td>Impedance</td>
<td>≤50mΩ</td>
<td>AC 1KHz after 50% charge, 25℃</td>
</tr>
<tr>
<td>Weight</td>
<td>Approx.22g</td>
<td></td>
</tr>
<tr>
<td>Storage temperature</td>
<td></td>
<td>Best 20±5℃ for long-time storage</td>
</tr>
<tr>
<td>≤1month</td>
<td>-10~45℃</td>
<td></td>
</tr>
<tr>
<td>≤3month</td>
<td>0~30℃</td>
<td></td>
</tr>
<tr>
<td>≤6month</td>
<td>20±5℃</td>
<td></td>
</tr>
<tr>
<td>Storage humidity</td>
<td>65±20% RH</td>
<td></td>
</tr>
</tbody>
</table>
Battery

• 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.
• Battery management board (Powerboost1000C) will help with this some, but your usage is also important
Lithium Polymer Battery Safety
Safety

• Never use our LiPoly batteries other than with Powerboost board!
• Battery plugs into boards JST connector
• Only charge battery through power boost board (ideally when you’ve removed it from breadboard)
LiPoly Video (Shorting Battery)

• Directly connecting a wire to a Raw Li-Poly Battery is very dangerous. Do not do this:
Lithium Polymer Batteries: Safety Rules for 6.S08

SAFETY NOTICE: Never leave a battery unattended while charging. Only charge the battery when it is in your 6.S08 fire-retardant pouch. When not using, disconnect the battery, return to the cardboard box it came in (for structural protection) and store in fire-retardant bag.

SAFETY NOTICE: Never directly connect your battery to anything but the PowerBoost 1000C JST socket. No wires, etc…

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

SAFETY NOTICE: DO NOT CRUSH OR DROP YOUR 6.S08 KIT WITH THE BATTERY. DO NOT SIT ON YOUR 6.S08 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
More, (some repeated) general warnings and advice

- Do NOT immerse the battery in water or other liquids. Keep or store the battery in a cool and dry place/environment.
- Do NOT use or store the battery near any source of heat.
- Use a charger that is clearly specified to be compatible for charging the battery and has appropriate charging protection (voltage, current, temperature).
- Do NOT install the battery in reverse polarity.
- Do NOT connect the battery to an electrical outlet or other incompatible power source.
- Do NOT discard the battery in fire.
- Do NOT short circuit the battery. Do NOT connect the positive and negative terminals to each other with metallic object(s) or other conductive material(s).
- Do NOT transport or store the battery together with metal objects, such as hairpins, necklaces, or any other conductive object or material.
- Do NOT strike, crush, puncture, disassemble, or throw the battery.
- Do NOT directly solder the battery or battery terminals.
- Do NOT pierce the battery.
- Lithium batteries should be used only with proper voltage, current, and temperature protection circuitry and protection.
- Do NOT use or leave the battery in a high temperature environment (for example, under direct sunlight or in a vehicle in hot weather). Failure to take this precaution can lead to overheating of battery and/or fire or explosion. Also, performance of battery will degrade and lifetime will be reduced.
- Do NOT use battery in a location where there is high static-electricity or magnetic fields, otherwise safety devices may be damaged which cannot be visible.
- If the battery leaks and the electrolyte get into the eyes, do NOT rub eyes. Instead, rinse and wash eyes with clean water, and immediately seek medical attention.
- If the battery gives off an odor, generates heat, becomes discolored or deformed, or in any way appears abnormal during use, recharging, or storage, immediately remove it from the device or battery charger and stop using it.
- In case the battery terminals are dirty, clean the terminals with a dry cloth before use. Otherwise, poor performance may occur due to the poor connection with the instrument or device.
- Be aware that discarded batteries may cause fire or explosion. Therefore, apply a non-conductive tape to the battery terminals to insulate them before discarding.

*from Adafruit*
Only interact with the battery through the PowerBoost Board!!!

- Prevents over-charging
- Prevents shorting
- Prevents over-discharging

Physical Damage is other risk:

- Never stab/bend/juggle your battery
- Do not bend the yellow top of the battery
- Respect and keep battery safe in the fire-retardant bag and disconnected when not in use
- Do not crush your setup
Stabbing Battery

• Demonstrating risk of physical damage (DO NOT DO THIS):
Using Batteries with Electronics
Battery voltage and system voltage

- Batteries come in 1.2, 1.5, 3.0, 3.7 V, etc.
- Our components are powered at 3.3 V or 5 V
- How to connect?
  - Either place batteries in series (end-to-end)
  - Voltages add
  - Can also place batteries in parallel (side-by-side)
  - Capacities add
- Most components have a range of allowable supply voltage
  - IMU: 1.9 V .. 3.6 V
  - Freescale K20 microcontroller: 1.71 V .. 3.6 V
  - ESP8266: 3.0 V .. 3.6 V
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
  
  • 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

\[ \text{Efficiency} = \frac{\text{amount going to what we want}}{\text{total amount used}} \]

If \( i = 50mA \) and supply voltage is at \( v = 5.0V \) what is the efficiency of this system? (i.e. how much power is consumed by the circuit and not the regulator?)
Linear Regulators in 6.S08 Device

- Constant Current Device (KCL maintained)
- Can only regulate down in voltage
Switching Supply (non-linear device)

- Constant 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 increase (boost) or decrease (buck) voltage
- Linear regulators can’t!

3.7V 1200 mAH LiPoly (with protection circuit)

3.2V ≤ v ≤ 4.2V

Reg

Always @5.0V

Circuit
PowerBoost 1000C

- Battery Management charges/discharges/protects battery electrically
- Switching supply converts battery’s varying voltage to ~5.0V output
How efficient is our entire 6.S08 system?

$3.2V \leq v \leq 4.2V$

3.7V
1200 mAH
LiPoly

$\nu_0 = 0$

$\nu$:
$0.0\leq v \leq 4.2V$

$\nu$:
$0.0\leq v \leq 4.2V$

Power Boost
Reg (90%)

$\nu_0 = 0$

$i_{in}$

pin

$p_{in}$

$p_{out}$

Always @5.0V

3.3V Reg

Always @3.3V

6.S08
Circuit

$i_{out}$

$\approx 0.9$

$0.66$

so about 60%
Using Less Power
Sleep

• Even if it’s not “doing anything”, aka \texttt{delay(100)}, the microcontroller consumes energy
  • Just from being ON (Static dissipation)
  • And every clock cycle (Dynamic dissipation)

• We can save energy by
  • Lowering system voltage \( P \sim V^2 f \)
  • Lowering operating frequency*
  • Disabling clock to regions of chip
  • Sleeping core
  • Using “backup”

*Double Edged-Sword Though...too slow and static power consumption can start to dominate
Sleep

• ARM Cortex specifies 3 power modes
• Freescale (now NXP) K20 microcontroller breaks them down into 13 different power modes
Sleep

- 13 different power modes
  - Normal
    - Run: normal mode
    - Wait: CPU core in sleep
    - Stop: CPU core in deep sleep
  - Very Low Power (VLP)
    - Run, Wait, Stop
    - Runs core at lower frequency (4 MHz)
  - Low-leakage stop (LLS)
    - LLS, VLLS3, VLLS2, VLLS1
    - Disable or shut down peripherals
    - Less and less SRAM on
  - BAT (battery backup)
    - Uses 32 kHz real-time clock (RTC) to keep time

<table>
<thead>
<tr>
<th>Mode</th>
<th>Typical current (@3.0 V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run</td>
<td>34 mA</td>
</tr>
<tr>
<td>Run (peripheral clocks stopped)</td>
<td>30 mA</td>
</tr>
<tr>
<td>Wait</td>
<td>12.5 mA</td>
</tr>
<tr>
<td>Stop</td>
<td>0.35 mA</td>
</tr>
<tr>
<td>VLPR</td>
<td>1.46 mA</td>
</tr>
<tr>
<td>VLPW</td>
<td>0.61 mA</td>
</tr>
<tr>
<td>VLPS</td>
<td>5.9 µA</td>
</tr>
<tr>
<td>LLS</td>
<td>2.6 µA</td>
</tr>
<tr>
<td>VLLS3</td>
<td>1.9 µA</td>
</tr>
<tr>
<td>VLLS2</td>
<td>1.59 µA</td>
</tr>
<tr>
<td>VLLS1</td>
<td>1.47 µA</td>
</tr>
<tr>
<td>BAT</td>
<td>0.19 µA</td>
</tr>
</tbody>
</table>
Sleep

- Choose the lowest sleep that retains functionality
- For example, can still do UART, I2C, ADC in some sleep modes
Sleep

- Also consider time-to-wake-up
- Deeper sleep usually means longer wake-up
  - Especially if you shut down oscillators or save SRAM to Flash
    - Takes time to start up oscillators and re-load SRAM

---

Table 5. Power mode transition operating behaviors

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Min.</th>
<th>Max.</th>
<th>Unit</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{\text{POR}} )</td>
<td>After a POR event, amount of time from the point ( V_{\text{DD}} ) reaches 1.71 V to execution of the first instruction across the operating temperature range of the chip.</td>
<td>—</td>
<td>300</td>
<td>( \mu \text{s} )</td>
<td>1</td>
</tr>
<tr>
<td>( \text{VLLS1} \rightarrow \text{RUN} )</td>
<td></td>
<td>—</td>
<td>112</td>
<td>( \mu \text{s} )</td>
<td></td>
</tr>
<tr>
<td>( \text{VLLS2} \rightarrow \text{RUN} )</td>
<td></td>
<td>—</td>
<td>74</td>
<td>( \mu \text{s} )</td>
<td></td>
</tr>
<tr>
<td>( \text{VLLS3} \rightarrow \text{RUN} )</td>
<td></td>
<td>—</td>
<td>73</td>
<td>( \mu \text{s} )</td>
<td></td>
</tr>
<tr>
<td>( \text{LLS} \rightarrow \text{RUN} )</td>
<td></td>
<td>—</td>
<td>5.9</td>
<td>( \mu \text{s} )</td>
<td></td>
</tr>
<tr>
<td>( \text{VLPS} \rightarrow \text{RUN} )</td>
<td></td>
<td>—</td>
<td>5.8</td>
<td>( \mu \text{s} )</td>
<td></td>
</tr>
<tr>
<td>( \text{STOP} \rightarrow \text{RUN} )</td>
<td></td>
<td>—</td>
<td>4.2</td>
<td>( \mu \text{s} )</td>
<td></td>
</tr>
</tbody>
</table>
Duty cycling

• The key to a long life is sleep!

• Example
  • Freescale K20
    • BAT mode 0.19 μA
    • Run mode 34 mA
  • Want to run 1 month on coin cell (200 mAh)
  • If $t_{ON} = 1$ sec, what is minimum $T$?

$$duty\ cycle = \frac{t_{ON}}{T} = \frac{t_{ON}}{t_{ON} + t_{SLEEP}}$$
Duty cycling

• The key to a long life is sleep!

• Example
  • Freescale K20
    • BAT mode \( \sim 0.19 \, \mu A \)
    • Run mode 34 mA
  • Want to run 1 month on coin cell (200 mAh)
  • If \( t_{ON} = 1 \, \text{sec} \), what is minimum \( T \)?
  • 720 h/mo \( \Rightarrow 0.28 \, \text{mA} \) max average draw
Duty cycling

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

- All of our code thus far is in repeated loops
  - Measure orientation every 50 ms
  - Read GPS every 10 sec
  - Send data every 10 sec
  - Etc.

- This limits responsiveness
  - Can be up to 50 ms from sensing input

- And limits sleep
  - Cannot sleep longer than 50 ms!
  - Even if orientation hasn’t changed, or GPS is the same, etc.
Asynchronous events

- Alternatively could use *interrupts*
  - Runs a piece of code asynchronously
  - Such as in response to a button press, accelerometer threshold, data in UART, etc.
- We will not use interrupts explicitly in 6.S08
  - Though they are in several of our libraries
- But if you continue in IoT, microcontrollers, etc... you will want to learn them!
Energy-efficient microcontrollers

- Increasing importance of energy efficiency has given rise to microcontrollers with ever-lower power usage
  - Freescale K20
    - Run: 472 µA/MHz
    - BAT: 190 nA
  - Silicon Labs EFM32 Gecko
    - Run: 180 µA/MHz
    - Shutoff: 20 nA, 160 µsec wakeup
  - ATMEL SAML 21
    - Run: 95 µA/MHz (down to 35 µA/MHZ)
    - Deep sleep: 200 nA
Communications

- WiFi module also sleeps
- In normal operation, sleeps and wakes periodically when connected to AP
  - Wakes to maintain connection to AP
  - Wake interval called DTIM
    - ~100’s ms

Challenges with ESP are:

- deep sleep requires reconnection with AP
- Max currents are high (170 mA or more)

http://jeelabs.org/book/1526f/
Low-power wireless

- Bluetooth Low Energy (BLE), Zigbee, etc. are specifically designed for low power usage
  - Lower peak current
  - Fast wakeup and authenticate
  - Brief headers
- Look into for final projects maybe

<table>
<thead>
<tr>
<th>CLASSIC BLUETOOTH VS. BLUETOOTH SMART</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Feature</strong></td>
</tr>
<tr>
<td>Maximum TX power</td>
</tr>
<tr>
<td>Typical range</td>
</tr>
<tr>
<td>RF channels</td>
</tr>
<tr>
<td>Maximum usable data throughput (typical)</td>
</tr>
<tr>
<td>Typical wake-up time</td>
</tr>
<tr>
<td>Typical authenticated data TX time</td>
</tr>
<tr>
<td>Typical peak current draw</td>
</tr>
<tr>
<td>Maximum number of simultaneously connected devices</td>
</tr>
<tr>
<td>Security</td>
</tr>
</tbody>
</table>
Harvesting Energy from Environment
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
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
Energy harvesting

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

40 K temp difference
1.8 V @ 368 mA

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

• In a connected system, can choose what to do locally versus server-side

• Tradeoff
  • communications power vs. CPU power
  • Limited local storage vs. infinite server storage