Reducing Energy Consumption & Maximizing Battery Life

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Agenda

- Electrical quantities
- Design
- Measurement
- Optimization
- Conclusion

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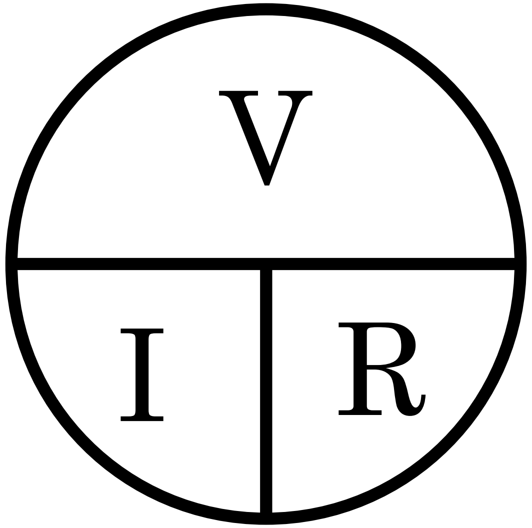
Electrical Quantities

Quantity		Unit		Description
Voltage	V	volt	V	How much electrons want to flow
Current	I	ampere	A	How many electrons are flowing
Charge	C	coulomb	C	How many electrons are gathered
Resistance	R	ohm	Ω	How much the circuit inhibits electron flow
Power	P	watt	W	The rate at which work is performed
Energy	E	joule	J	The amount of work performed

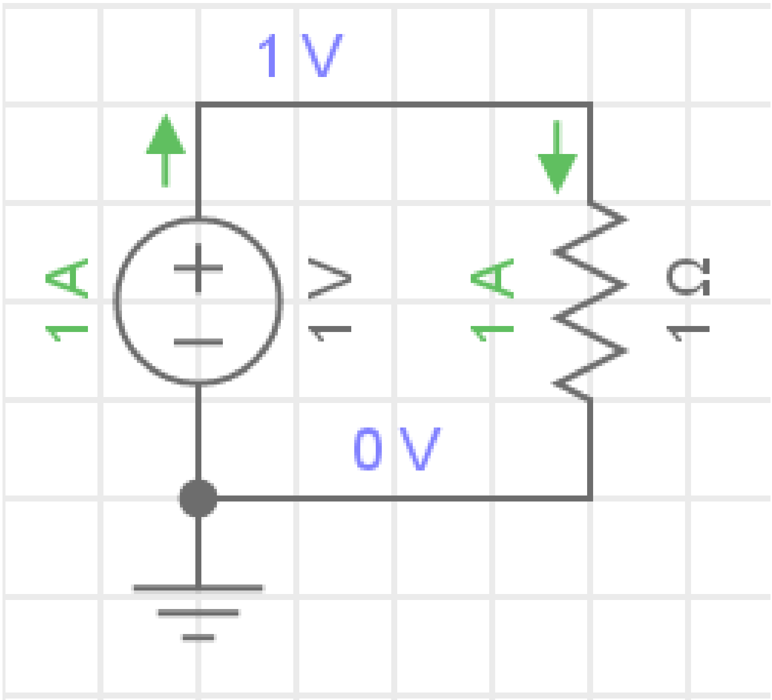
Ohm's Law



$$V = I * R$$

$$I = V / R$$

$$R = V / I$$



Voltage = Current * Resistance

Power

$$P = V * I = V^2 / R = I^2 * R$$

Power = Voltage * Current

Energy

$$\mathrm{E} = \int P\,dt$$

$$\mathrm{E} = \int_{t=0}^{T} P\,dt \approx \sum_{n=0}^{N} P_n\,\Delta t$$

$$\text{Energy} = \text{Power consumed over time}$$
$$= \text{work performed}$$

Charge

$$\mathrm{C} = \int I \, dt$$

$$\mathrm{C} = \int_{t=0}^{T} I \, dt \approx \sum_{n=0}^{N} I_n \, \Delta t$$

Charge = Current consumed over time

Like energy but without accounting for voltage

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Initial Design

- Electrical components consume power
- Power design impacts many decisions
  - Component selection
  - Schematic design
  - Software architecture
- Must design for power consumption early
  - Low power consumption does not just happen
  - Adding in low-power and long battery life late in a project causes delays

Initial Design for Low-Power

Select energy-efficient components		**Arrange** components to consume less energy			**Configure** to consume less energy	
Consider active AND sleep modes	Balance features against available components	Consider reset, pull-up and pull-down resistors	Consider power domains, power gating, back-powering	Consider sleep-mode signal state	Disable unused devices & peripherals	Enter lowest possible power state & GPIO state

Many products have multiple power modes and spend a lot of time “sleeping”

Should we design for energy or charge?

Switching Regulators: Optimize for Energy

- Switching regulators convert between voltage and current
  - Step voltage up or down
  - Deliver required current (within limits)
- Advantages
  - Can accommodate a wide range of supply voltages efficiently
- Disadvantages
  - Higher quiescent current (compared to linear regulators) may increase sleep mode energy consumption
  - Has additional efficiency losses that also vary based upon load current, input voltage and output voltage
  - Increased noise and EMI/EMC concerns

Linear Regulators: Optimize for Charge

- Linear regulators, including LDO regulators, regulate voltage
  - Conceptually equivalent to a variable resistor that changes resistance to give fixed output voltage
  - Charge is (mostly) conserved between input and output
- Advantages
  - Simpler to design with lower noise
  - Low quiescent current for great sleep-mode performance
- Disadvantages
  - Requires a minimum drop-out voltage which limits efficiency
  - Dissipates extra energy due to “voltage-drop” as heat proportional to current

Energy / Charge Budget

- Estimate how much power / current each mode consumes
  - Determine modes
  - Estimate for each component
- Estimate how much time is spent in each mode
- Estimate energy / charge per mode
- Estimate total energy / charge over a duration
- For battery-powered devices, balance against total battery energy or charge to estimate battery life

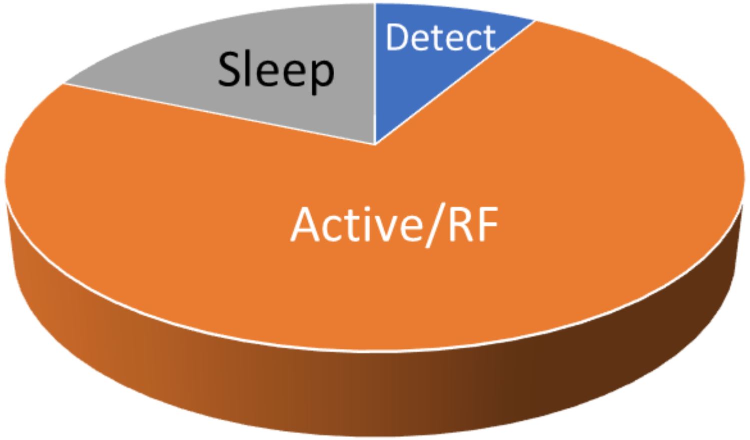
Charge Budget Example : Components

Component Budget	Mode			Units
	Detect	Active/RF	Sleep	
Microcontroller	20000	25000	10	µA
Radio	10	20000	10	µA
Accelerometer	500	500	20	µA
Gyroscope	5000	5000	1.5	µA
ISR Pull-up	18	18	0	µA
LDO	1.5	1.5	1.5	µA
LED	10000	10000	0	µA
Total	35529.5	60519.5	43	µA

Charge Budget Example : Time

Time Budget	Mode			Units
	Detect	Active/RF	Sleep	
Duration per event	0.2	5		s
Events per hour	10	2		events / hour
Duty cycle	0.0556	0.2778	99.6667	%
Current (avg)	19.7	168.1	42.9	µA = µC/s

This product spends most energy in active mode – should consider a switched-mode regulator!



Pie charts are great for visualizing the charge / energy budget

Charge Budget Example : Battery Life

Battery Budget	Value	Units
Current (avg)	230.7	µA
Capacity (avg)	1000	mAh
Target life	180	days
Estimate life	180.6	days
Margin	0.6	days

Energy / Charge Budget: Batteries

- Remember to de-rate the stated battery capacity for
  - Load
  - Lifecycle / age
  - Temperature
  - Memory effects (especially NiCd and NiMH)
- Account for your battery chemistry and discharge curve
  - Different battery chemistries behave differently

Initial Design Checklist (Guideline)

- [ ] Created energy budget
- [ ] Confirmed that design meets energy budget
- [ ] Verified power consumed by all active components
- [ ] Verified power consumed by all pull-up and pull-down resistors
- [ ] Inspected all signals for contention & back-powering while in low power modes
- [ ] Verified that device can wake from all low power modes
- [ ] Verified that microcontroller functions as needed in low-power modes
- [ ] Inspected example code for low-power support with desired framework / RTOS

Use off-the-shelf development boards to prototype low-power mode operation as early as possible in the design cycle

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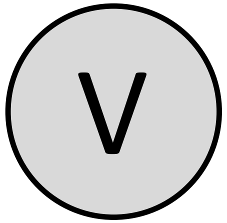
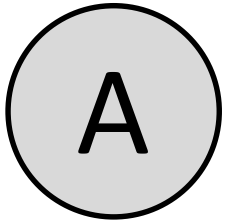
Measurement

- **Voltage** (Voltmeter)
  - Op-amps
- **Current** (Ammeter)
  - Magnetic field - Galvanometer
  - Voltage across resistor – Shunt Ammeter
  - Active circuits - transimpedance amplifier, …
- **Power** & **Energy**
  - Sample voltage & current, multiply together digitally
  - Numerically integrate to compute energy





Akin's laws of spacecraft design: [link]

1. Engineering is done with numbers. Analysis without numbers is only an opinion.

Measurement Concerns

- **Dynamic range** (difference between the minimum value and the maximum value), particularly for current
- **Bandwidth** and sampling **frequency**
- **Voltage drop** – also called burden voltage, insertion loss
- **Ease of use** and ease of capturing your signals of interest
- **Accuracy** – Closeness to the actual value
- **Precision** – Closeness to other measurements at the same value

Measurement Options: Multimeter

- Good for static analysis only
- Procedure
  - Place target device into a mode
  - Make measurement without browning out device
  - Repeat
- Tedious and time consuming = expensive!

Fluke 87V
Source: Fluke

Many multimeters have a burden voltage > 0.6 V when measuring current!

Measurement Options: Oscilloscope

4 Series MSO
Source: Tektronix

- Good for measuring dynamic changes over time
- Procedure
  - Select shunt resistor value & wattage
  - Insert shunt resistor between supply + and device power input +
  - CAREFULLY connect shunt to oscilloscope input – oscilloscopes are normally earth ground referenced for safety, so need
    - Use two probes with mathematical subtract feature (+++offset error)
    - Differential probe
    - Current probe, often a differential probe with built-in shunt resistor(s)
    - Electrically isolate: either float the scope or float both source & target
  - Capture & convert between volts & amps using Ohm’s Law
- BUT limited dynamic range: most scopes are between 8 and 12 bits

Measurement Options: Specialized Equipment

- Specialized devices
  - Joulescope
- 7-digit bench multimeter with waveform analysis
  - Keysight 34470A
  - Tektronix DMM7510
- SMUs (Source Measurement Units)
  - Keithley 2281S
  - Keysight B2901A
  - R&S NGL 200 power supply series
- High-end, dedicated equipment
  - Keysight N6705C
  - Keysight CX3300 family

Source: Jetperch LLC

Source: Keysight

Source: Keysight

Source: Keysight

Capacitance & Bandwidth

Your target device's capacitance reduces measurement bandwidth!

1 µF load capacitance

Source Resistance	Effective Bandwidth
0.01	16 MHz
0.1	1.6 MHz
1	160 kHz
10	16 kHz
100	1.6 kHz
1000	160 Hz

$$BW = \frac{1}{2\pi RC}$$

10 µF load capacitance

Source Resistance	Effective Bandwidth
0.01	1.6 MHz
0.1	160 kHz
1	16 kHz
10	1.6 kHz
100	160 Hz
1000	16 Hz

Cable resistance & inductance increases the effective source resistance

General Recommendations

- Keep cables short to minimize noise pickup and reduce impedance
- Understand voltage drop / burden voltage, bandwidth, and your measurement requirements
- Avoid ground loops in test setup
  - Ensure test setup has a single earth ground path or is fully isolated
  - Think about grounding when adding debugging probes and UART/USB adapters - can introduce ground loops and noise!
- Measure early an often – the cost of fixing an error increases with time between introduction and discovery

Don’t short out the power supply while probing your target board … again …

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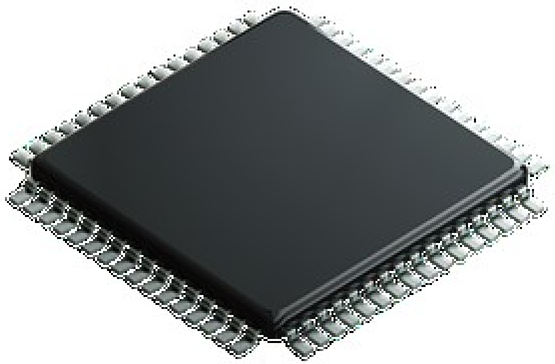
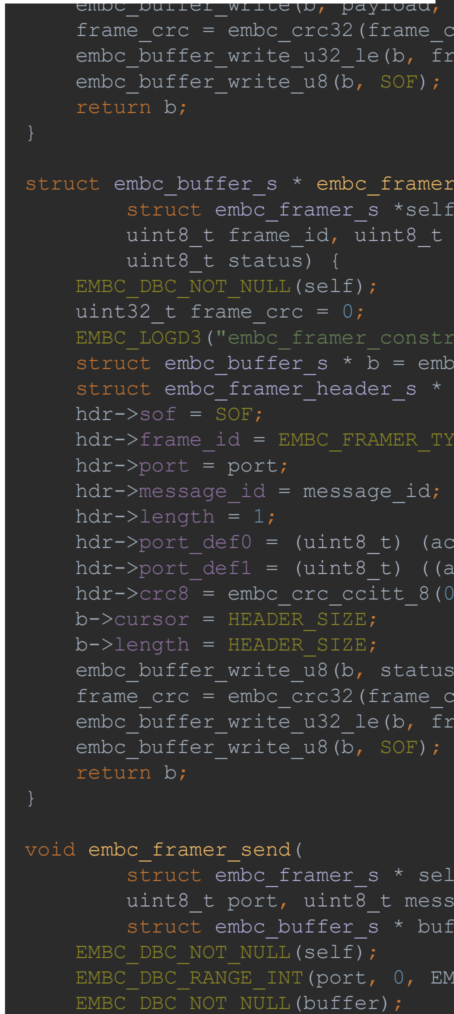
Optimization: Microcontroller



- Peripherals
  - Only enable those needed
  - Use peripheral clock dividers if feasible
- Run mode: idle/sleep/deep-sleep
  - Halt processor when not needed (wait-for-interrupt)
  - Enter lowest possible power state
  - Remember to disable idle peripherals during sleep modes
  - Consider microprocessor wake time in energy consumption calculations
- Clock
  - Select system clock frequency for lowest power
  - Beware of flash wait states
  - Consider switching to lowest power oscillator when in deepest sleep
- For microprocessor / Linux systems, consider off-loading features & peripherals that operate in low power modes to a microcontroller

Optimization: Software

- Profile! Most code doesn't matter for energy consumption
- Reduce active time as much as possible
  - Smaller, tighter, faster code consumes less power
  - Don't spin-wait for long, use a timer or other ISR when wait time exceeds mode switch time (active → sleep → active)
- Consider running performance-critical code segments from core-coupled RAM when flash has wait states
- Minimize core interrupts when possible
  - Use DMA for data flow during sleep modes
  - Take advantage of dedicated hardware - known under different brand names, such as Atmel® SleepWalking



Optimization: Signals & GPIO

- Consider each pull-up / pull-down resistor
  - These resistors consume power, and a single pull-up/pull-down can exceed the entire sleep budget
  - Ensure that the lowest power signal mode matches the pull direction
  - Give special consideration to reset signals and boot mode selection pins, especially when reused for other purposes in the design
- Set GPIO configuration in sleep mode
  - Lowest power mode (often output to 0)
  - Ensure no conflicts
- Be especially careful with regulator enable signals

Optimization: Components

Source: Flickr, bomazi

- Consider both active and sleep currents when selecting components.
- Prefer low quiescent current (low sleep/inactive currents)
- OR use a P-channel MOSFET to disable other components, BUT
  - Ensure that the design does not backpower through signals – most ICs contain a diode between each pin and VCC
  - Ensure that you place a pull-up between the gate and drain
  - Consider leakage currents
- Use care with multiple power domains with individual regulator enables

Optimization: User Interface

- Discrete buttons consume zero current (best for low power design)
- Capacitive touch can be reasonably low-power, but test
- Ensure that the design does not have to scan a button matrix in lowest power mode
- Consider e-ink displays if a display must remain “on”
- Many products naturally want to illuminate LEDs in sleep mode, but this can easily obliterate the power budget

Optimization: Other

- Solder flux residuals can reduce power-ground impedance
  - Keep +V trace spacing as large as possible for µA level sleep currents
  - Considering washing several prototypes to see if that affects sleep current
- Optimize what matters

$$E_{new} = (1 - p) + p\,f$$

Expected improvement:
p = fraction of energy consumed by contributor
f = fraction of original energy now consumed by contributor
E_{new} = total relative energy consumed after change

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Conclusion

- Reducing energy consumption requires effort and attention throughout the entire design process
  - Multi-faceted concern that affects many decisions
  - Deferring low power design increases risk and likelihood of delays
- Components, test equipment and resources exist to help you be successful with reducing energy consumption in your designs
- New instruments allow you to cost-effectively quantify the impact of your design changes for rapid feedback

Thank you!

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