Why is Low Power Circuit Design Important?

Thanks to integrated circuit technology, electronic devices have greatly decreased in size and mass over the past few decades. Most of us routinely carry or wear electronics every day. While VLSI (Very Large Scale Integration) technology, particularly CMOS, has enjoyed the rapid exponential growth characterized by Moore's Law, energy storage technology (mainly batteries) has grown much more slowly.

Application Areas for Low-Power Electronics

- Portable computing, communication, and multimedia devices
  - Laptops
  - Palmtops
  - Cell phones
  - Pagers
  - Video Recorders
  - Cameras
  - Watches (Power < 500nW @ 1.5V)
  - Portable instruments and measurement devices
- Remote sensing
  - Long-term environmental monitoring in wilderness areas or the ocean
  - Mobile robots
  - Satellites and space probes
- Implantable biomedical devices
  - Pacemakers
  - Defibrillators
  - Muscle stimulators
  - Neuroprosthetic devices
    - Cochlear implants to restore hearing loss
    - Retinal and cortical stimulators to restore vision loss
    - Neural control of prosthetic limbs

Low power systems are usually smaller and cheaper to manufacture (smaller heat sinks, no cooling fans, smaller power supplies, smaller batteries).

Barriers to Low Power Design

- Existing circuit libraries and standard cells…
  - …often have inadequate circuit architectures for low-voltage or low-current operation
  - …often are designed for fixed bias currents at the mA level.
- Lack of adequate, design-oriented transistor models for low-current operation.
- Designers are afraid of breaking "the psychological microamp barrier" (Eric Vittoz).
- Lack of a power-conscious culture among designers

Energy and Power

Power is simply *the rate of energy transfer.*

Energy is our limited resource, and power is the rate at which we consume (or replenish) that resource.

SI unit for energy = joule (J)

$1\text{ J} = 1\text{ N}\cdot\text{m} = 1\text{ kg}\cdot\text{m}^2/\text{s}^2 = 1\text{ V}\cdot\text{C} = 1\text{ W}\cdot\text{s}$

SI unit for power = watt (W)

$1\text{ W} = 1\text{ J/s} = \text{V}\cdot\text{C/s} = \text{V}\cdot\text{A}$

- ✓ A 1-watt system consumes 1 joule of energy each second.

In circuit design, the watt-hour (Wh) is generally more useful as a unit of energy than the joule (watt-second) since our devices generally run for hours, not seconds.

$1\text{ J} = 1\text{ W}\cdot\text{s} = 1.16 \times 10^{-5}\text{ W}\cdot\text{h}$

$1\text{ W}\cdot\text{h} = 3600\text{ J}$

Energy density of common fuels:

coal	2.9×10^7 J/kg	= 8100 Wh/kg
oil	4.3×10^7 J/kg	= 12,000 Wh/kg
gasoline	4.4×10^7 J/kg	= 12,000 Wh/kg = 1.3×10^8 J/gallon
natural gas	5.5×10^7 J/kg	= 15,000 Wh/kg
U_{235} (fission)	8.0×10^{13} J/kg	= 22,000 MWh/kg

- ➢ If it takes 2 minutes to pump 15 gallons of gasoline into your car, at what rate of power are you recharging your car's energy supply?

Amazingly enough, the energy content of all food sold in the U.S. is listed on the container (in Calories).

1 food Calorie = 1000 calories = 4180 J

Example: A Big Mac, large fries, and Coke = 1360 Calories = 5.7 MJ = 1,600 Wh

- ➢ Most people consume about 2000 Calories per day. What is the average power dissipation of a human being, in watts?

Other forms of energy (remember freshman physics?):

Kinetic energy of a moving object = ½ mass x velocity squared

$$U = \tfrac{1}{2}mv^2$$

Example: What is the kinetic energy in an 80-kg person walking at 1.0 m/s?

$$U = (1/2)(80\text{ kg})(1\text{ m/s})^2 = 40\text{ J} = 11\text{ mWh}$$

Potential energy in a gravitational field = mass x gravitational acceleration x height

$$U = mgh$$

Example: What is the potential energy of a 5-kg rock one meter above the ground on Earth ($g = 9.81\text{ m/s}^2$)?

$$U = (5\text{ kg})(9.81\text{ m/s}^2)(1\text{ m}) = 49\text{ J} = 14\text{ mWh}$$

- ➢ Suppose we have a box-shaped reservoir of width W, length L, and height H. If this reservoir is filled to the top with water, what is the total potential energy of that water with respect to the bottom of the reservoir? Assume the water has a density of ρ, and the gravitational constant is g.

Electrical potential is measured in volts, and is analogous to height in the previous case. Charge is analogous to mass. Electrical potential energy = charge x voltage.

$$U = QV$$

Example: A 5 V battery stores 1 kJ of energy. How many electrons with 5 V potential can this battery dispense before becoming depleted?

$$Q = U / V = 1000\text{ J} / 5\text{ V} = 200\text{ C}$$

Number of electrons = $Q / q = 200\text{ C} / 1.6 \times 10^{-19}\text{ C} = 1.3 \times 10^{21}$ electrons

We can easily derive the expression for **electrical power** by noting that power is energy per unit time (1 W = 1 J/s), and current is charge per unit time (1 A = 1 C/s):

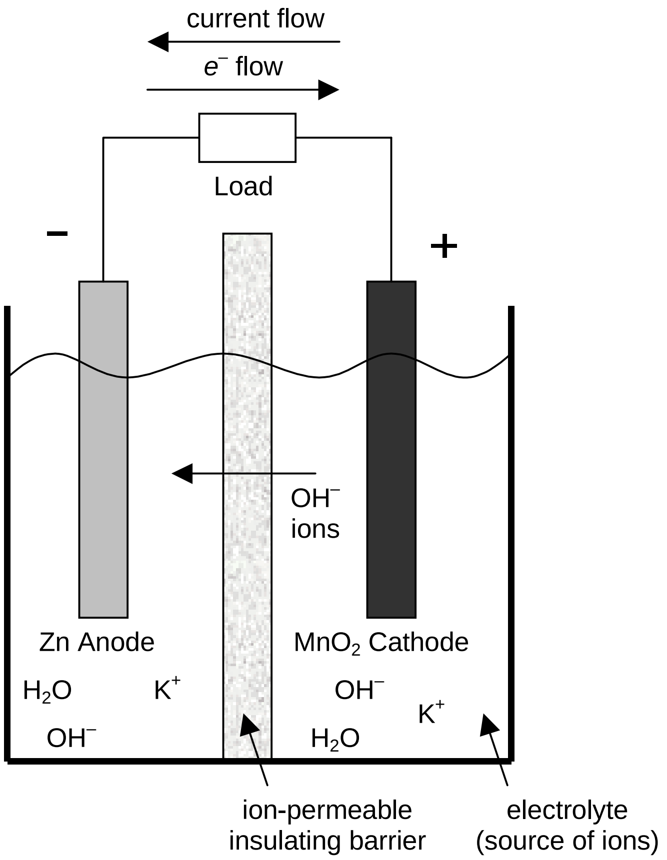
$$P = U / t = QV / t = (Q / t)V = IV$$

Power Sources for Low-Power Devices

Batteries – Most Common Power Source for Portable Electronics

Batteries convert chemical energy into electrical energy by means of a reduction-oxidation (redox) reaction.

Example: Alkaline cell operation



anode reaction (oxidation): $Zn + 2\ OH^- \rightarrow Zn(OH)_2 + 2e^-$

cathode reaction (reduction): $2\ MnO_2 + H_2O + 2e^- \rightarrow Mn_2O_3 + 2\ OH^-$

electrolyte: KOH (K^+, OH^- in solution)

overall reaction: $\mathbf{Zn + 2\ MnO_2 + H_2O \rightarrow Zn(OH)_2 + Mn_2O_3}$

Electron flow (i.e., current) external to the battery balances internal ionic flow.

Two classes of batteries:

- Primary batteries – Non-rechargeable
- Secondary batteries – Rechargeable (Redox reaction can be driven backwards)

PRIMARY (NON-RECHARGEABLE) BATTERIES

Type	**Anode/Cathode/ Electrolyte**	**Open-Circuit Voltage (V)**	**Operating Voltage (V)**	**Energy Density (Wh/kg)**	**Energy Density (Wh/L)**	**Cost**	**Applications/Notes**
Zinc-Carbon (“heavy duty” dry cell)	$Zn/MnO_2+C/$ NH_4CL, $ZnCL_2$	1.5	1.5-1.0	60-100	100-170	lowest	Older technology Sloping discharge curve
Alkaline	$Zn/MnO_2/$ KOH	1.5	1.5-1.1	130-180	320-440	low	Most common primary battery Sloping discharge curve
Mercury	Zn/HgO/ KOH	1.35	1.3	100	450	high	Cannot supply high current
Zinc-Air	Zn/Air/ KOH	1.5	1.3	340	1050	moderate	Highest volumetric energy density
Silver (Silver Oxide)	$Zn/Ag_2O/$ KOH	1.55	1.5	120	370-470	high	Cannot supply high current Flat discharge curve
Lithium (many different types)	Li/various/ various	3.0-4.0	3.0 (typical)	230-380	440-850	high	Very long shelf life (5-20 years), Flat discharge curve, Best at high and low temp.

SECONDARY (RECHARGEABLE) BATTERIES

Type	**Anode/Cathode/ Electrolyte**	**Open-Circuit Voltage (V)**	**Operating Voltage (V)**	**Energy Density (Wh/kg)**	**Energy Density (Wh/L)**	**Cost**	**Applications/Notes**
Nickel-Cadmium (Nicad, Ni-Cd)	Ni/Cd/ KOH	1.2	1.2-1.1	35-45	100-120	moderate	Commonly available 250-1000 recharge cycles Flat discharge curve
Nickel-Metal Hydride (NiMH)	$Ni/ZrNi_2$ or $LaNi_5/KOH$	1.2	1.2-1.1	40-70	130-210	high	Replacing Nicads 500 recharge cycles Flat discharge curve
Lithium Ion	$C/LiCoO_2/$ lithium salts	4.0	3.0	50-150	100-200	high	500-2000 recharge cycles Flat discharge curve
Lead Acid	$PbO_2/Pb/$ H_2SO_4	2.1	2.0	30-40	100	moderate-high	250-1000 recharge cycles Flat discharge curve Very high currents possible

Battery Types Grouped by Application

Primary batteries

- General consumer electronics (portable audio equipment, toys, etc.)
    - Alkaline (Duracell, Energizer, etc.) – Standard AAA, AA, C, D, 9V cells
    - Zinc-Carbon (old technology, but cheap) – Standard AAA, AA, C, D, 9V cells
- Film cameras and flash units
    - Alkaline
    - Lithium
- Wristwatches
    - Silver – "Button" batteries
- Hearing aids
    - Zinc-Air – "Button" or "coin" batteries
- Smoke detectors
    - Mercury
    - Lithium
- CMOS memory backup
    - Lithium
- Medical implants (pacemakers, etc.)
    - Mercury – Used in implants before 1972
    - Zinc-Air – Used in many modern implants
    - Lithium-SVO (silver vanadium oxide) – Used in implantable defibrillators, where they can supply microamps for years and occasional amp-level pulses.

Secondary batteries

- General consumer electronics (portable audio equipment, toys, etc.)
    - Nickel-Cadmium (Nicad) – Available in standard AAA, AA, C, D, 9V cells
    - Nickel-Metal Hydride (NiMH) – Available in standard AAA, AA, C, D, 9V cells
- Cell phones
    - Nickel-Metal Hydride (NiMH)
    - Lithium Ion
- Laptops
    - Nickel-Metal Hydride (NiMH)
    - Lithium Ion
- Palmtops
    - Lithium Ion
- Handheld video recorders
    - Lead acid (older models)
    - Lithium Ion
- Gasoline automobiles
    - Lead acid
- Electric/hybrid automobiles
    - Lead acid (General Motors EV1 electric car)
    - Nickel-Metal Hydride (NiMH) (newer EV1; Honda Insight hybrid gas/electric car)

A Battery is not an ideal voltage source! All batteries have a finite internal resistance (R_{int}). This causes the terminal voltage to drop as more current is drawn. Batteries with large internal resistances show poor performance in supplying high current pulses.

Battery	Typical internal resistance of fresh battery
9V Zinc-Carbon	35 Ω
9V Lithium	16-18 Ω
9V Alkaline	1-2 Ω
AA Alkaline	0.15 Ω (0.30 Ω at 50% discharge)
AA NiMH	0.03 Ω (0.04 Ω at 50% discharge)
D Alkaline	0.1 Ω
D Ni-Cd	0.009 Ω
D Lead-Acid	0.006 Ω
AC13 Zinc-Air	5 Ω
675 Mercury	10 Ω
76 Silver	10 Ω

Internal resistance generally increases as the battery discharges. A typical alkaline "AA" battery starts with R_{int} = 0.15 Ω, but at 90% discharge, R_{int} = 0.75 Ω.

Batteries are often rated with capacities in mAh or Ah. Multiply by battery voltage to get energy.

Example: "This 3 V battery has a capacity of 500 mAh @ 1 mA; 470 mAh @ 10 mA"

Sometimes capacity is expressed in terms of the **C rate.** The number following the letter C is the discharge time in hours.

Example: "This battery has a C/10 capacity of 2 Ah and a C/5 capacity of 1.8 Ah."

- ✓ Note that these scales are typically nonlinear! The capacity typically decreases with increased current draw.

Typical battery energies

Battery	Voltage (V)	Capacity (mAh)	Energy (Wh)	Energy density (Wh/kg)	Energy density (Wh/L)
AAA Alkaline	1.5	1,150	1.7	140	440
AA Alkaline	1.5	2,850	4.3	190	520
C Alkaline	1.5	8,000	12.0	180	440
D Alkaline	1.5	16,000	24.0	170	420
9V Alkaline	9	570	5.1	110	220
AA Carbon-Zinc (primary)	1.5	950	1.4	95	170
AA Alkaline (primary)	1.5	2,850	4.3	190	520
AA Lithium (primary)	1.5	2,900	4.4	290	520
AA Ni-Cd (secondary)	1.2	800	1.0	44	120
AA NiMH (secondary)	1.2	1,200	1.4	53	170

- ✓ Secondary batteries provide only about 20-30% the energy density of primary batteries!

Other Power Sources for Low-Power Systems

Solar Power

How much power is in sunlight? Maximum after traveling through the atmosphere: 1kW/m^2 (noon, summer, cloudless day)

Night, full moon: 1 mW/m^2

Average power per day: In middle latitudes (U.S., Europe, Japan, northern China, southern Australia), 100W/m^2 in winter, 250W/m^2 in summer.

Indoors: only 500-1000mW/m^2

Typical solar cell efficiency: 10% (2-5% for inexpensive cells)

Example: If we use a small (10cm^2) solar cell with 10% efficiency, indoors we can expect to get 500-1000µW, outdoors 1W under optimum conditions.

Inductively-Coupled Power Link

Used in medical implants, radio-frequency identification (RF ID) tags, and smart cards. Alternating current through a large, external coil creates a magnetic field. The portable device has a small pickup coil that changes the magnetic field back into electric current. Basically a transformer with a small secondary coil.

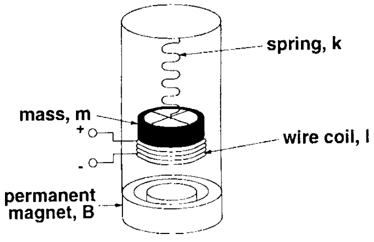
In medical implants, an externally-powered coil is placed on or near the skin. The internal coil in the implant can power electronics directly (e.g., muscle stimulators) or recharge internal batteries (e.g., pacemaker).

Vibration-Based Power Generation

From: R. Amirtharajah and A.P. Chandrakasan (1998). Self-Power Signal Processing Using Vibration-Based Power Generation. *J. Solid-State Circuits* 33:687-695.

Using a 0.5g weight suspended from a spring, Amirtharajah and Chandrakasan estimate 400µW "best case" power generation during human walking.

Some recent wristwatches use a similar technique.



Other possible power sources

- Thermal gradients
- Fluid flow
- Small fuel cells
- Light sent through optical fibers
- Micromachined batteries