Micro Power Systems Overview

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Thanks to Shad Roundy, Luc Frechette, Jan Rabaey and Paul Wright

If you fall asleep….

- Ambient computing desperately needs new power sources
- A number of promising small scale power sources/energy storage devices are under active development
- Variety of needs/applications indicates that there will not be a "AA Battery" solution to the problem
- "Over the wall" design from application to power source not possible

Topics

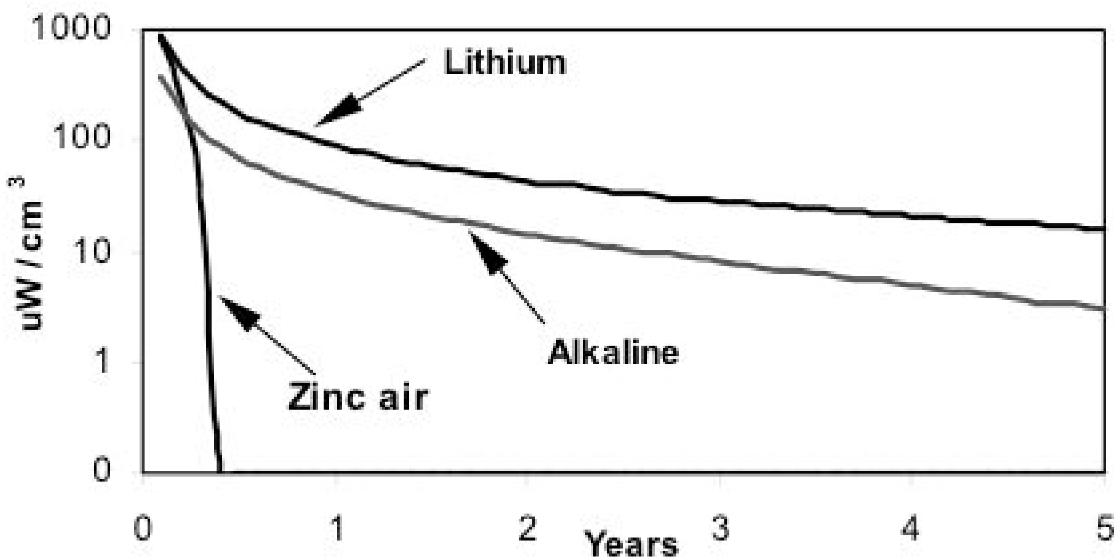
- Driving forces for micro power systems
- Energy scavenging/collecting systems
- Energy distribution mechanisms
- Energy reservoir/ power generation systems
- Design considerations from theory and practice

Why Micro Power Now?

- Simple example
  - At an average power consumption of 100 mW, you need slightly more than 1 cm3 of lithium battery volume for 1 year of operation, assuming you can use 100% of the charge in the battery (which you can't).
- Energy density of rechargeable batteries is less than half that of primary batteries.
- So, someone needs to either replace batteries in every node every ~ 9 months, or recharge every battery every 3 to 4 months.
- In most cases, this is not acceptable.

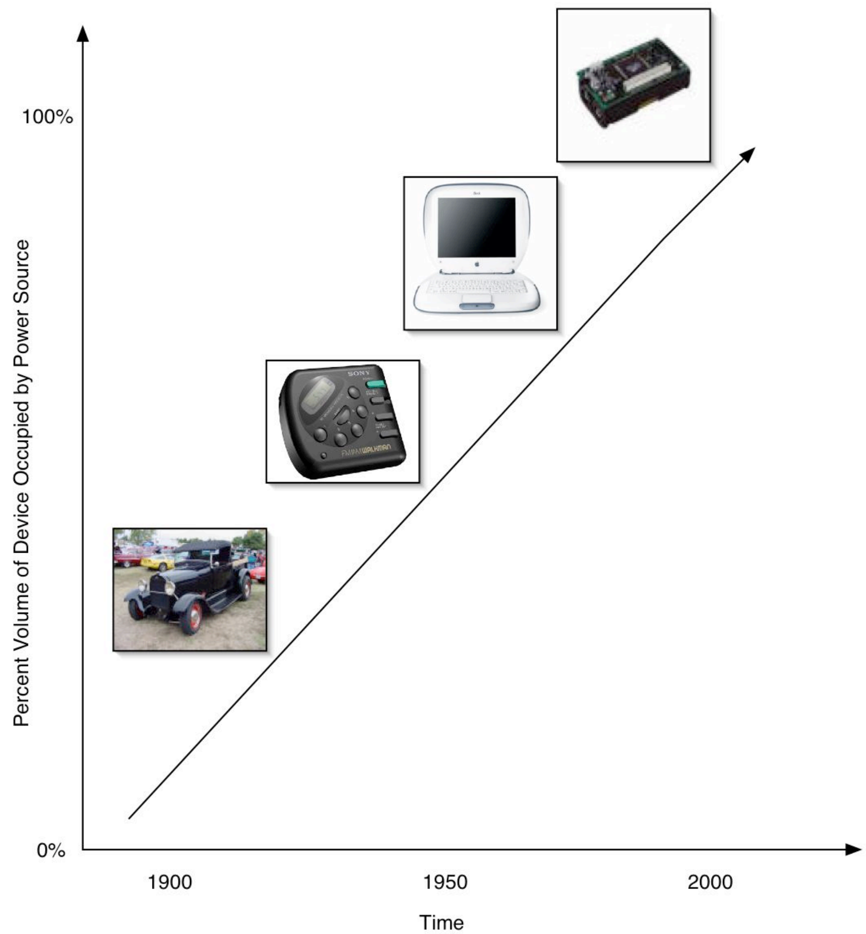
Comparison of Sources

Chemistry	Zinc-air	Lithium	Alkaline
Energy (J/cm^3)	3780	2880	1200



Power Lags Behind

Percent Volume of Device Occupied by Power Source vs. Time



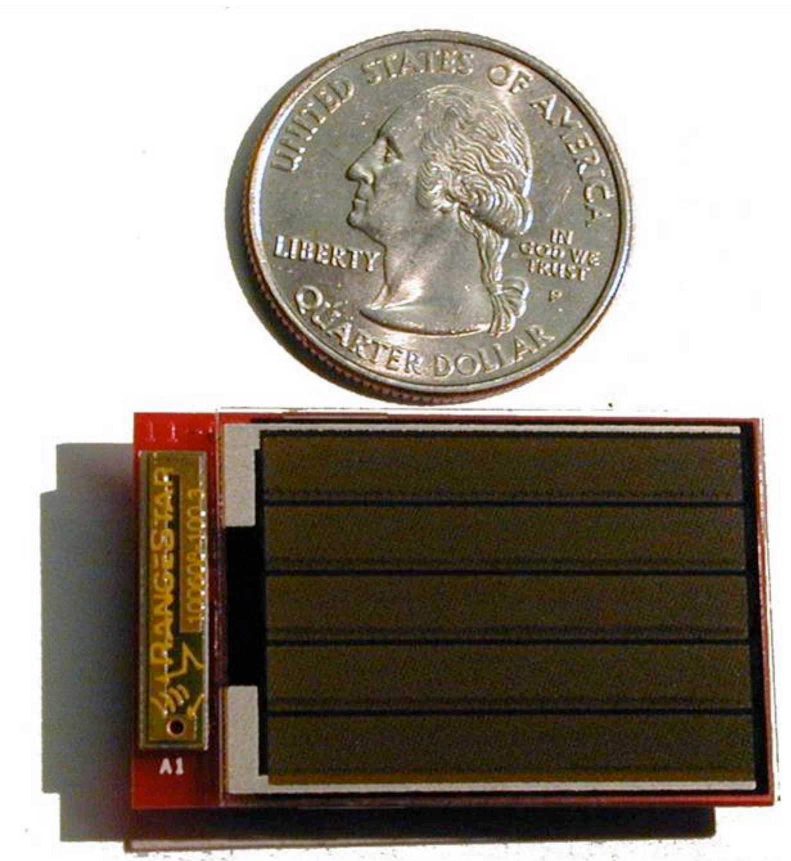
Two Paradigms In Sensor Nets

- Modular
  - Off the shelf tech fabricated together on one small PCB
  - Allows for sensor/design flexibility
- Monolithic
  - Eliminate layers between radio and sensor
  - Goal to design hardware quickly around only desired functionality - lower energy needs
- Different design paradigms create different power needs

Energy Scavenging Areas

- Solar/Ambient Light
- Temperature Gradients
- Human Power
- Air Flow
- Pressure Gradients
- Vibrations

Solar and Ambient Light

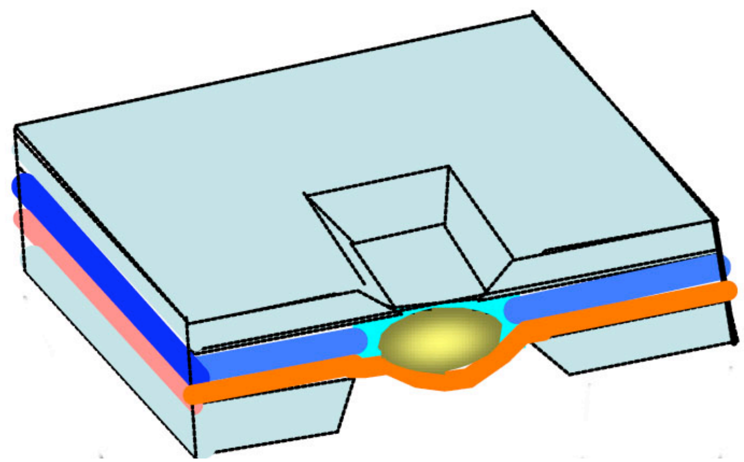


BWRC - BMI - Solar Powered PicoRadio Node

- Sources
  - Noon on a sunny day - 100 mW/cm^2
  - Office Lights: 7.2 mW/cm^2
- Collectors
  - SC Silicon
    - 15% - 30% efficient
    - .6 V open potential - needs series stacks
  - Poly-Silicon
    - 10% - 15% efficient
  - Photoelectric Dyes
    - 5% to 10% efficient

Temperature Gradients

- Exploit gradients due to waste heat / ambient temp
  - Maximum power = Carnot efficiency
  - 10˚C differential - (308K - 298K) /308 = 3.2%
  - Through silicon this can be up to 110 mW/cm^2
- Methods
  - Thermoelectric (Seebeck effect) ~ 40$\mu W/cm^2$ @ 10˚C
  - Piezo thermo engine (WSU) ~ 100's $\mu W/mm^2$ (theoretical)



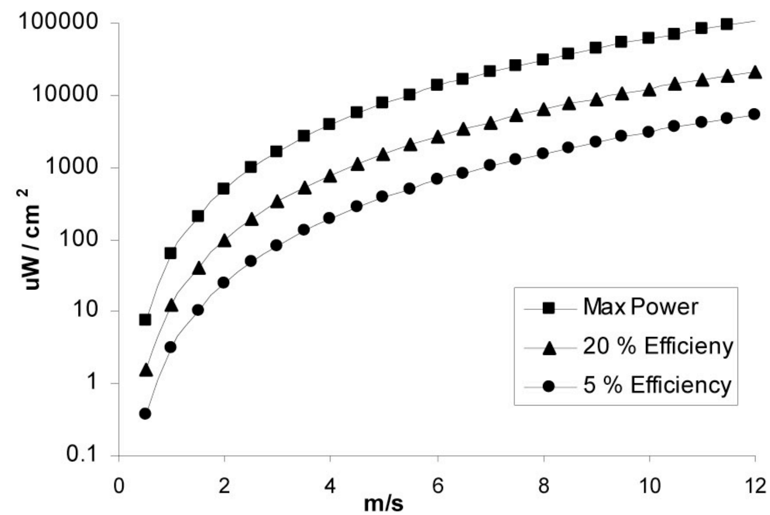
Bahr et al. WSU -Piezo thermo engine

Human Power

- Burning 10.5 MJ a day
  - Average power dissipation of 121 W
- Areas of Exploitation
  - Foot
    - Using energy absorbed by shoe when stepping
    - 330 $\mu W/cm^2$ obtained through MIT study
  - Skin
    - Temperature gradients, up to 15°C
  - Blood
    - Panasonic, Japan demonstrated electrochemically converting glucose

Air Flow

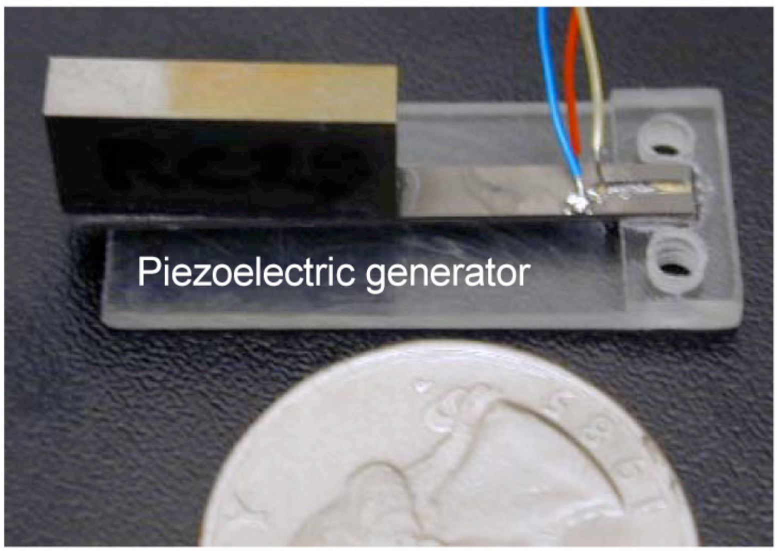
- Power output/ efficiencies vary with velocity and motors
- Applications exist where average air flow may be on the order of 5 m/s
  - At 100% efficiency ~1 mW/cm
- MEMS turbines may be viable



Pressure Gradients

- Using ambient pressure variations
  - On a given day, for a change of .2 inches Hg, density on the order of nW/cm^3
- Manipulating temperature
  - Using 1 cm^3 of helium, assuming 10˚C and ideal gas behavior, $\sim\mu W/cm^3$
- No active research on pressure gradient manipulation

Vibrations



Roundy, UC Berkeley - Piezo Bender

- Sources
  - HVAC
  - Engines/Motors
- Three Rules for Design
  - P ~ M
  - P ~ a^2
  - P ~ 1/*f*
- Existing Designs
  - Roundy ~ 800 μW/cm^3 at 5 m/s^2 (similar to clothes dryer)
- Future Plans
  - MEMS piezo
  - MEMS capacitance

Energy Distribution

- RF Radiation
  - $1/r^2$ fall off (through walls actually $1/r^4$)
  - For a radio station: For an 50,000 W FM station at 20 km, in open air, ~7 μW
- Wires (self defeating)
- Acoustic Power
  - Attenuation is very high in air (better in water)
  - Sound level of 100 dB (1 ft from a lawn mower) corresponds to 0.96 mW/cm^2
- Light
  - Guided Light through walls?

Energy Reservoirs/Power Generation

- Capacitors
- Batteries
- Fuel Cells
- Heat Engines
- Radioactive Sources (!)

Capacitors

- Useful for on chip power conversion
- Possible secondary storage for frequent but non-periodic energy sources
- Energy density too low to be a general secondary storage component

Ultra-Capacitors

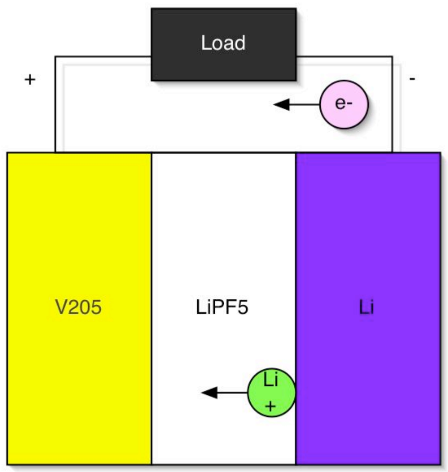
Available Performance	Lead Acid Battery	Ultra-capacitor	Conventional Capacitor
Charge Time	1 to 5 hrs	0.3 to 30 s	10^{-3} to 10^{-6} s
Discharge Time	0.3 to 3 hrs	0.3 to 30 s	10^{-3} to 10^{-6} s
Energy (Wh/kg)	10 to 100	1 to 10	<0.1
Cycle Life	1000	>500,000	>500,000
Specific Power (W/kg)	<1000	<10,000	<100,000
Charge/discharge efficiency	0.7 to 0.85	0.85 to 0.98	>0.95

ELNA Co. http://www.elna.co.jp/en/ct/c_dynac1.htm

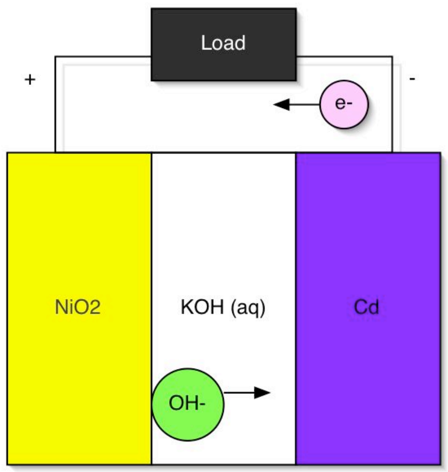
- Differ from capacitors in surface area - take advantage of highly porous electrodes
- Good potential for secondary storage
- Issues:
  - Size
  - Leakage
  - Distribution of Pores

Battery Basics

- Closed system with respect to reactants (except zinc-air)
- Area of electrodes determines power
- Volume of electrodes determines capacity
- Chemistry of battery affects potential, limiting current density and cycle life



Discharge Examples

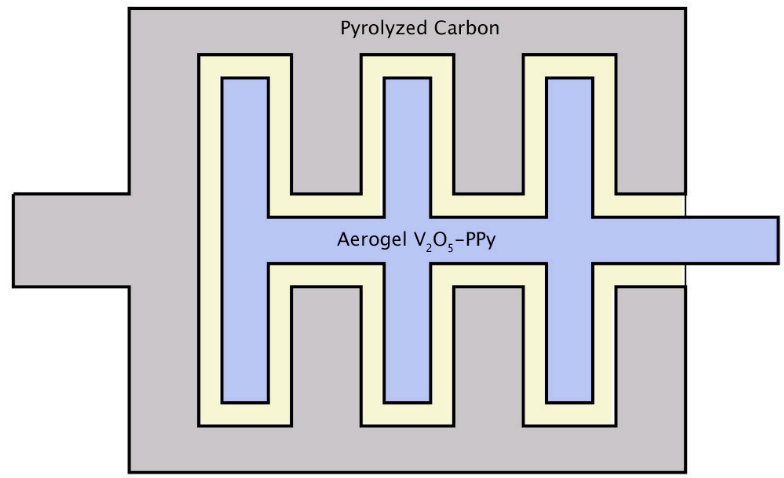


Micro Batteries

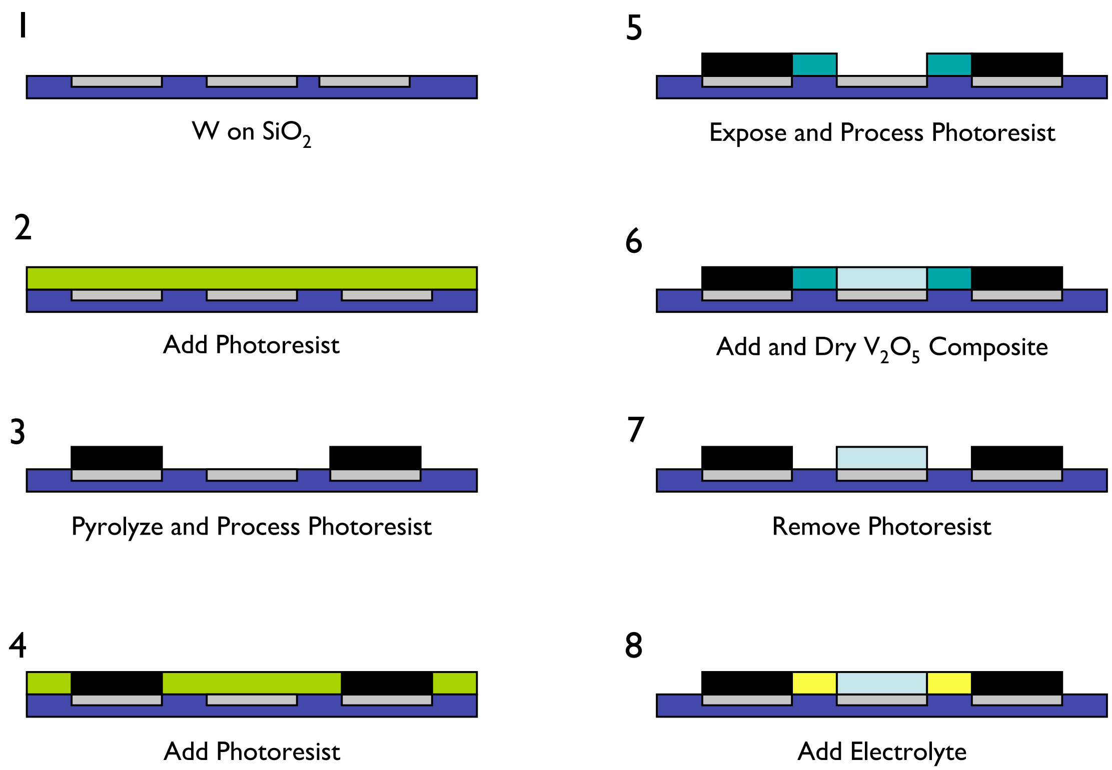
- Ni/NaOH/Zn (Harb, BYU)
  - Shows excellent cyclability
  - Sealing Problems
  - Low potentials
- Thin Film Lithium (Bates, ORNL)
  - 1-D microscale, 2-D macro
  - Uses lithium metal
  - Shows promise for high power densities
- 3-D Lithium-Ion (Dunn, UCLA)
  - Very High Power Densities
  - In initial stages

Micro Batteries

- Microfabrication Friendly Li-Poly-Ion
  - Photoresist based anode (graphite)
  - Sol-Gel process cathode (V_2O_5)
  - Spin-on Electrolyte (PEO)

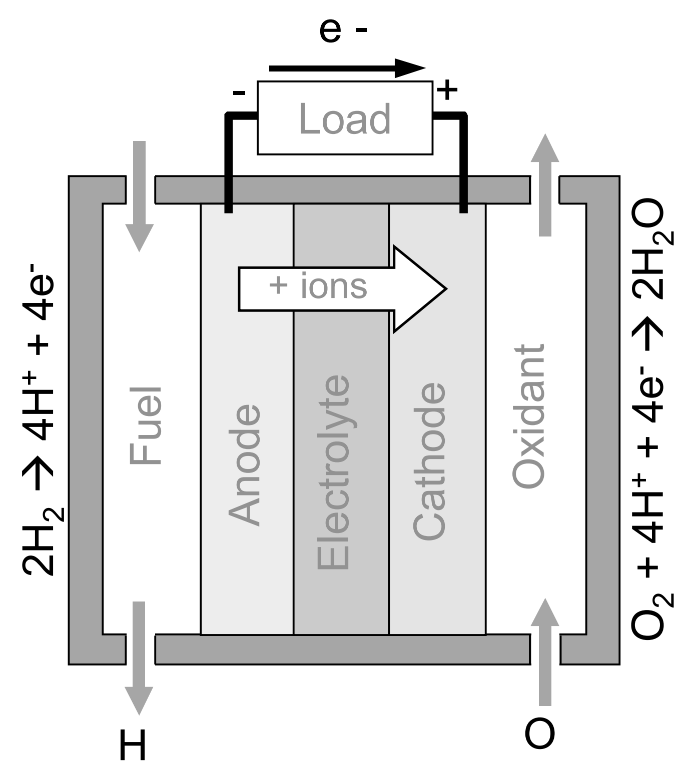


Micro Batteries

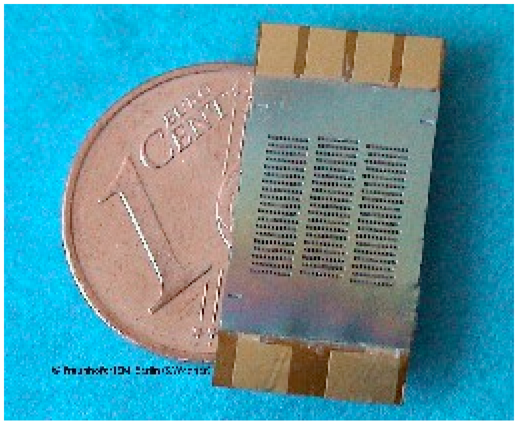


Fuel Cell Basics

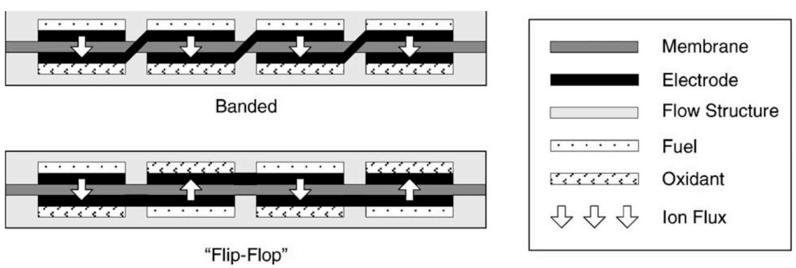
- Like a battery, current is directly dependant on available electrode area
- Unlike a battery the reactant is stored elsewhere
- Methanol energy density is 17.6 kJ/cm3.
  - 6 X lithium
  - 15 X rechargeable lithium.



MEMS Fuel Cell



Fraunhofer

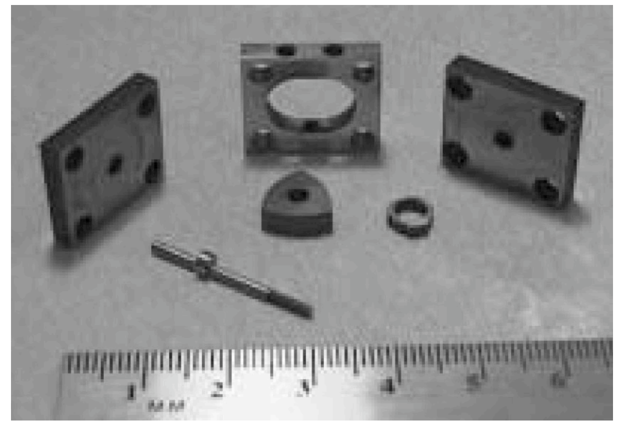


S.J. Lee et. al., Stanford University

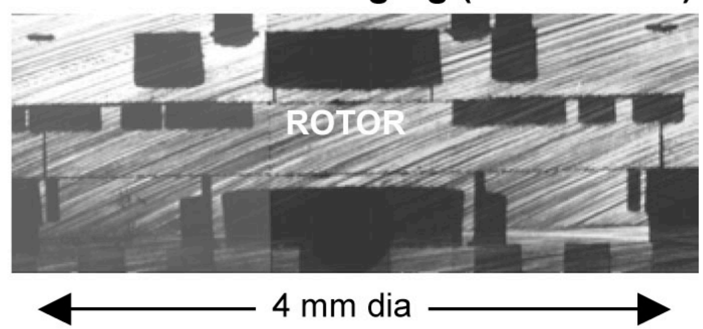
- Current Generation
  - Toshiba 1 cm^3 hydrogen reactor (15% efficient)
  - Produces 1 watt
  - Transients may be too slow for low duty cycles
- Next Generation
  - Planar Arrays
    - Fraunhofer - 100 mW/cm^2
    - Stanford - > 40 mW/cm^2 (research in progress)

Micro Heat Engines

- MEMS scale parts for meso scale engine
  - 1 cm^3 volume
  - 13.9 W
  - Poor transient properties
- Micro size heat engine
  - ICE's, thermoelectrics, thermoionics, thermo photo voltaics via controlled combustion
  - Meant for microscale applications with high power needs



Microturbine bearing rig (section A-A)



Bencharmarking Radioactivity

- High theoretical energy density
- Power density inversely proportional to half life
- Demonstrated power on the order of nanowatts (reactor-less)
- Obvious Environmental concerns

Material	Half-life (years)	Activity volume density (Ci/cm^3)	Energy density (J/cm^3)
^{238}U	4.5×10^9	6.34×10^{-6}	2.23×10^{10}
^{63}Ni	100.2	506	1.6×10^8
^{32}Si	172.1	151	3.3×10^8
^{90}Sr	28.8	350	3.7×10^8
^{32}P	0.04	5.2×10^5	2.7×10^9

Pause

- Primary batteries are not practical given the application area of most wireless sensor systems
- A variety of energy reservoir options as well as energy scavenging options exist
- Power source chosen depends on the nature of the task and the area of deployment - comes back to modular vs. monolithic

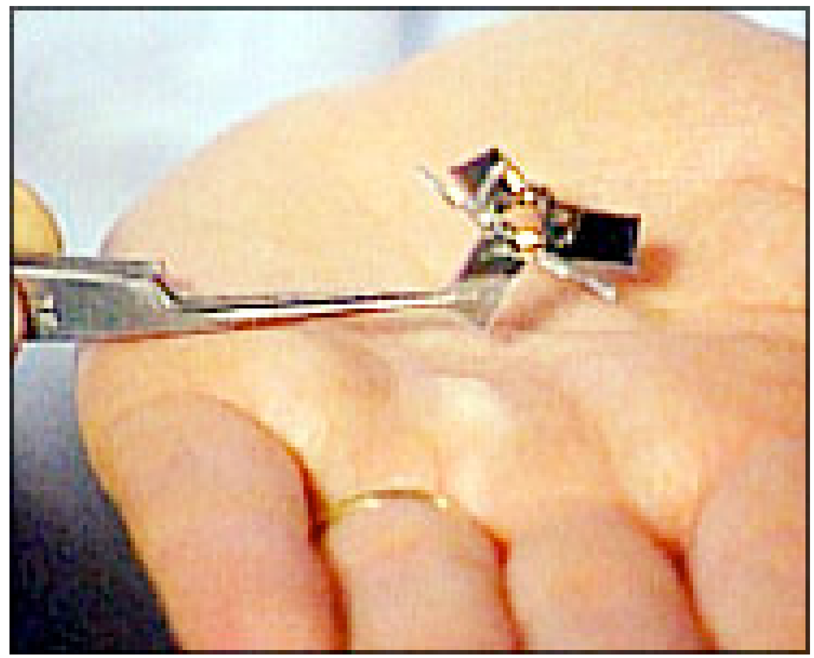
Pause

Power Source	P/cm^3 (μW/cm^3)	E/cm^3 (J/cm^3)	P/cm^3/yr (μW/cm^3/Yr)	Secondary Storage Needed	Voltage Regulation	Comm. Available
Primary Battery	-	2880	90	No	No	Yes
Secondary Battery	-	1080	34	-	No	Yes
Micro-Fuel Cell	-	3500	110	Maybe	Maybe	No
Ultra-capacitor	-	50-100	1.6-3.2	No	Yes	Yes
Heat engine	-	3346	106	Yes	Yes	No
Radioactive(^{63}Ni)	0.52	1640	0.52	Yes	Yes	No
Solar (outside)	15000 *	-	-	Usually	Maybe	Yes
Solar (inside)	10 *	-	-	Usually	Maybe	Yes
Temperature	40 * †	-	-	Usually	Maybe	Soon
Human Power	330	-	-	Yes	Yes	No
Air flow	*380 ††*	-	-	Yes	Yes	No
Pressure Variation	*17 †††*	-	-	Yes	Yes	No
Vibrations	200	-	-	Yes	Yes	No

* Denotes sources whose fundamental metric is power per **square** centimeter rather than power per **cubic** centimeter.
† Demonstrated from a 5 ºC temperature differential.
†† Assumes air velocity of 5 m/s and 5 % conversion efficiency.
††† Based on a 1 cm^3 closed volume of helium undergoing a 10 ºC temperature change once per day.

Example One: Setup

- Task
  - A/V gathering, some fixed nodes, some self moving nodes
  - Variable assignments, needs may change during time of interest
- Deployment Scale
  - 10 to 100 nodes



Fearing, R UC Berkeley - Fly Project

Example One: Proposed Solution

- Sensor Methodology - Modular
  - Hardware modules can be swapped (camera, microphone, motion sensor)
  - Shorter design time allows for quickly adapted solutions
- Power Source - Micro Fuel Cell or Micro Heat Engine
  - A/V applications require much energy
  - Requires high bandwidth transmitter (Bluetooth or greater)
  - With adequate storage tanks nodes can spend days to weeks in field

Example Two: Setup

Hill, J UC Berkeley - Spec Mote

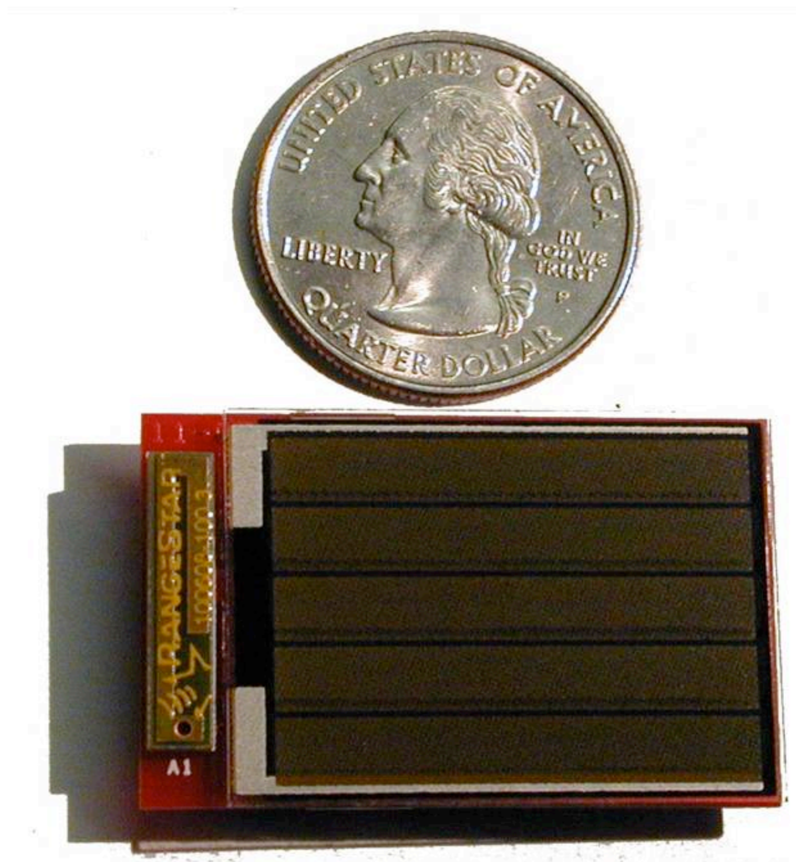
- Task
  - Low frequency measurements of simple quantities (light levels, temperatures, etc)
  - Long duration (weeks to years)
  - Larger area with fixed and piggybacked mobile nodes
- Scale
  - Thousands of nodes

Example Two: Proposed Solution

- Design: Monolithic
  - Cheaper per part
  - Extra design time worth extra durability in field and lower cost
  - Can be optimized for low power/ low duty cycle
- Power Source: Energy Scavenger with ultra capacitor or µBattery
  - Scavenging mechanism can be chosen based on environments
  - Storage system to be chosen by infrequency/amount of energy scavenging available

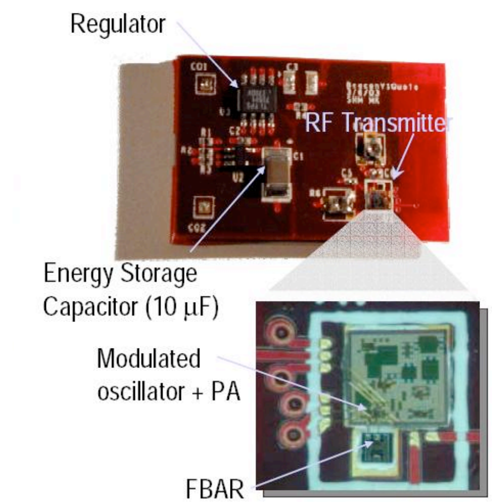
Example Three: PicoBeacon

- Solar Powered Beacon
  - No Sensor
  - No Scheduler
- A simple study to see what was possible with off-the-shelf power products



Example Three: PicoBeacon

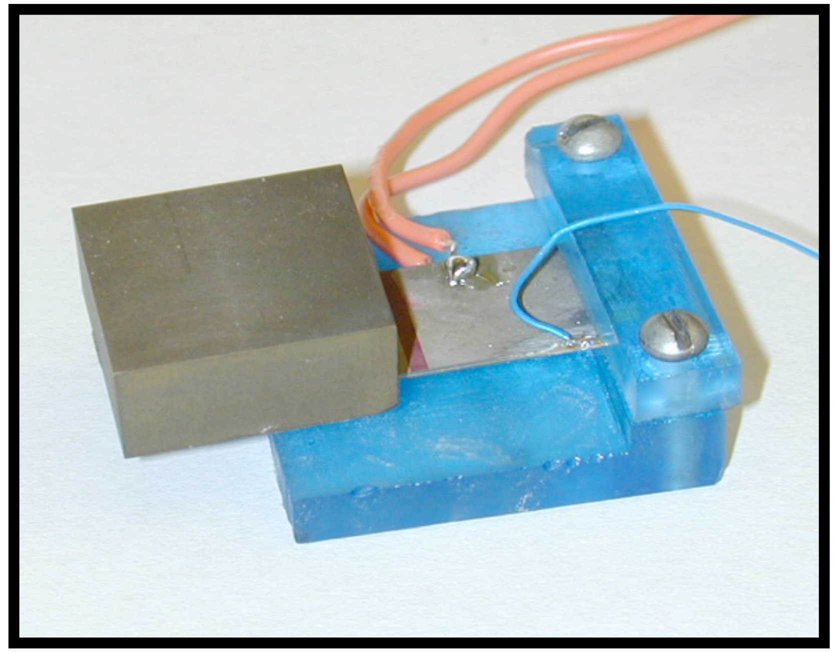
- What was learned
  - For solar sources
    - Light intensity directly affects duty cycle
    - Power conditioning at this level must be very minimal
  - For vibration sources
    - Self tuning will greatly help
    - Secondary storage critical



Light Level	Duty Cycle
Dim Indoor	0.36%
Flourescent	0.53%
Overcast Out	5.6%
Bright Indoor	11%
High Light	100%
Vibration Level	
2.2 m/s^2	1.6%
5.7 m/s^2	2.6%

Example Four: Tiny Temp Node

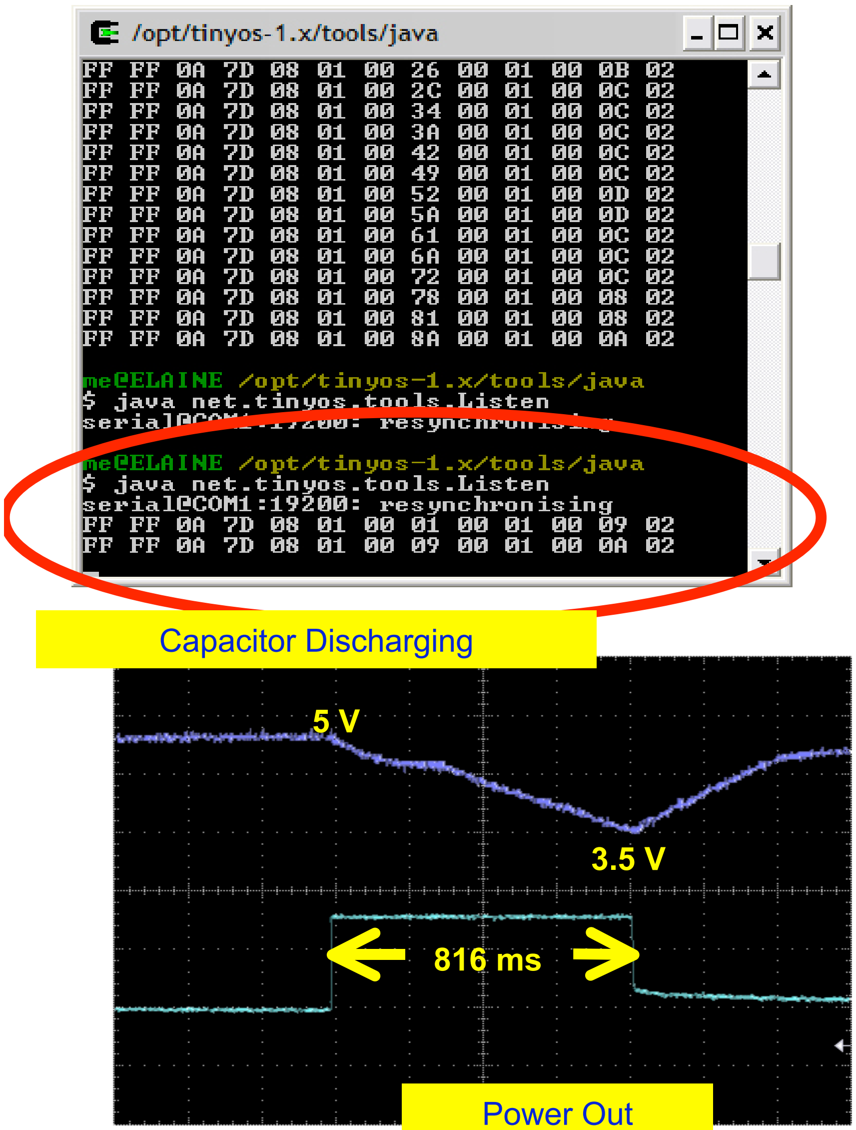
- Goal
  - Create a purely scavenging based temperature sensor and beacon
  - No hopping
  - One way



Example 4: Tiny Temp Node

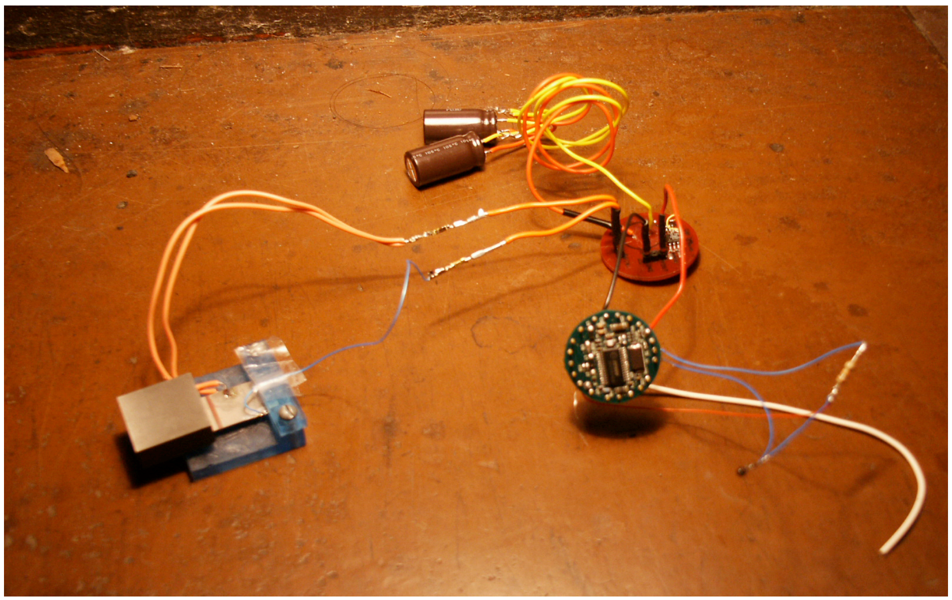
Vibration Source	Frequency of Peak (Hz)	Peak Acceleration (m/s^2)
Kitchen Blender Casing	121	6.4
Clothes Dryer	121	3.5
Door Frame (just after door closes)	125	3
Small Microwave Oven	121	2.25
HVAC Vents in Office Building	60	0.2-1.5
Wooden Deck with People Walking	385	1.3
Bread Maker	121	1.03
External Windows (size 2ftx3ft) next to a Busy Street	100	0.7
Notebook Computer while CD is Being Read	75	0.6
Washing Machine	109	0.5
Second Story of Wood Frame Office Building	28/100	0.2
Refrigerator	240	0.1

Example 4: Tiny Temp Node



- Results
  - 3 People
  - Running for 40 minutes
  - 2 packets sent!
  - Efficiency < .01%

Example Four: Tiny Temp Node



- What was learned
  - Even tiny operating systems have a boot up time
  - Better power conditioning required
  - A larger secondary storage source is required to take measurements independently of available energy
  - Begin to think about different ways to handle sleep and awake

Other Concerns

- What effect does the power source have on either sensing quality or environment?
  - Metal
  - Waste product
  - Waste heat
- How varied is the power requirement?
  - Fully Active = Tens of mW's
  - Sleep = ~10 μW
  - 3 orders of magnitude difference
  - At a few μW, power conditioning circuitry often wastes more in process than sleep mode requires

Conclusion

- In terms of density and size, power sources for microelectronics are at a critical point
- Theoretical and practical limitations to both sources and electronics show that there is no one ideal choice for every application
- Just as nodes need to be designed with power sources in mind, power sources need to be flexible enough to consider application (no more AA batteries)
- Hybrid systems of one or more energy scavenging/power producing technologies combined with an adequate reservoir seem the most promising
  - Able to use stored/scavenged energy most efficiently
  - Able to meet varied load demands