Self-Sustaining, Self-Powered, Power Conscious ICs for Micro-Scale Systems

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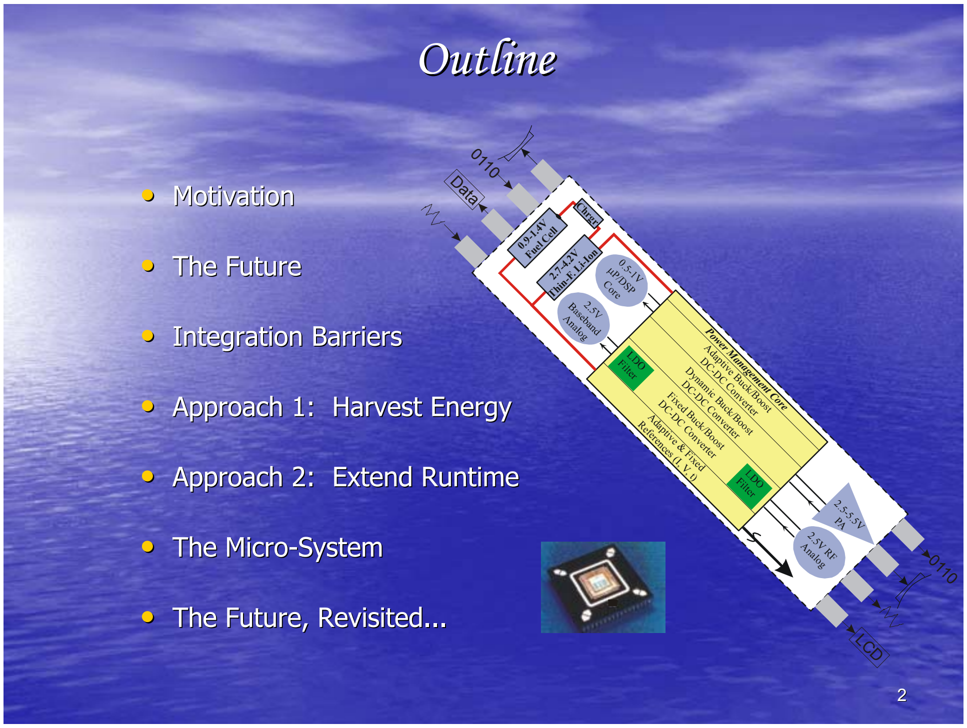

Outline

- Motivation
- The Future
- Integration Barriers
- Approach 1: Harvest Energy
- Approach 2: Extend Runtime
- The Micro-System
- The Future, Revisited...

Motivation

- **Demand:** Military reconnaissance, remote space/field meters/monitors, implantable biomedical devices, and portable/mobile consumer electronics.
  - → *Portable (small and compact)*
  - → *Lightweight*
  - → *Long-Lasting (long life)*
  - → *Self-Powered*
  - → *Self-Sustaining*

Power Management
- *> Bias circuits*
- *> References*
- *> Regulators*
- *> Watch-dog functions*
- *> Protection Circuits*
- *> ...*

Front-End Interface
- *> Sensors*
- *> Filters*
- *> Amplifiers*
- *> A/D Converters*
- *> ...*

Back-End Interface
- *> D/A Converters*
- *> Filters*
- *> Amplifiers*
- *> Power Drivers*
- *> ...*

- **Desirable Solution: *Total Integration***

And for portability and low cost,

Total Chip Integration

- → *System-on-Chip (SoC) – integrate into silicon*
- → *System-in-Package (SiP) – integrate into the chip package*
- → *System-on-Package (SoP) – annex to the chip package*

The Future

International Technology Roadmap for Semiconductors[1]

Year		2000	2001	2002	2003	2004	2005	2008	2011	2014
Technology [nm]		180	130			90		60	40	30
Platform		BiCMOS & CMOS					Analog CMOS			
Digital										
Supply Voltage	Maximum (best performance) [V]	1.8	1.5		1.2		1.1	0.9	0.6	
	V_{pp} (Tran + DC Accuracy - ± 3 % V_{nom})* [mV]	108	90		72		66	54	36	
	Minimum (lowest power) [V]	1.5	1.2		0.9		0.8	0.6	0.5	0.3
	V_{pp} (Tran + DC Accuracy - ± 3 % V_{nom})* [mV]	90	72		54		48	36	30	18
Maximum Power	w/ Heatsink [W]	108	130	140	150	160	170	171	177	186
	Battery (hand-held) [W]	1.7	2.0	2.1	2.3	2.4	2.6			
Maximum Current	w/ Heatsink (P ÷ $V_{best\text{-}perf.}$)* [A]	60	87	93	125	133	154	190	295	310
	Battery (hand-held - P ÷ $V_{lowest\text{-}power}$)* [A]	1.1	1.7	1.75	2.6	2.7	3.25			
Die size (µ-PU & ASIC) [mm^2]		310		325	340	356	372	427	489	561
Maximum # of wiring levels		7		8			9		10	
Minimum mask-count		23	24					26	28	29
Frequency (across chip) [GHz]		1.386	1.600	1.724	1.857	2.000	2.155	2.655	3.190	3.825
Analog Requirements										
Supply Voltage [V]		1.8 - 3.3			1.8 - 2.5			1.5 - 1.8		1.5
RF Frequency [GHz]		0.9 - 10							0.9 - 100	
Analog Frequency [GHz]		0.1 - 5							0.1 - 10	
Filter Density [fF/µm^2]		2.8	3.2	3.5	3.7	3.8	4	5	7	10
RF Bypass Filter Density [fF/µm^2]		6	7	7.5	8	9	10	15	20	30

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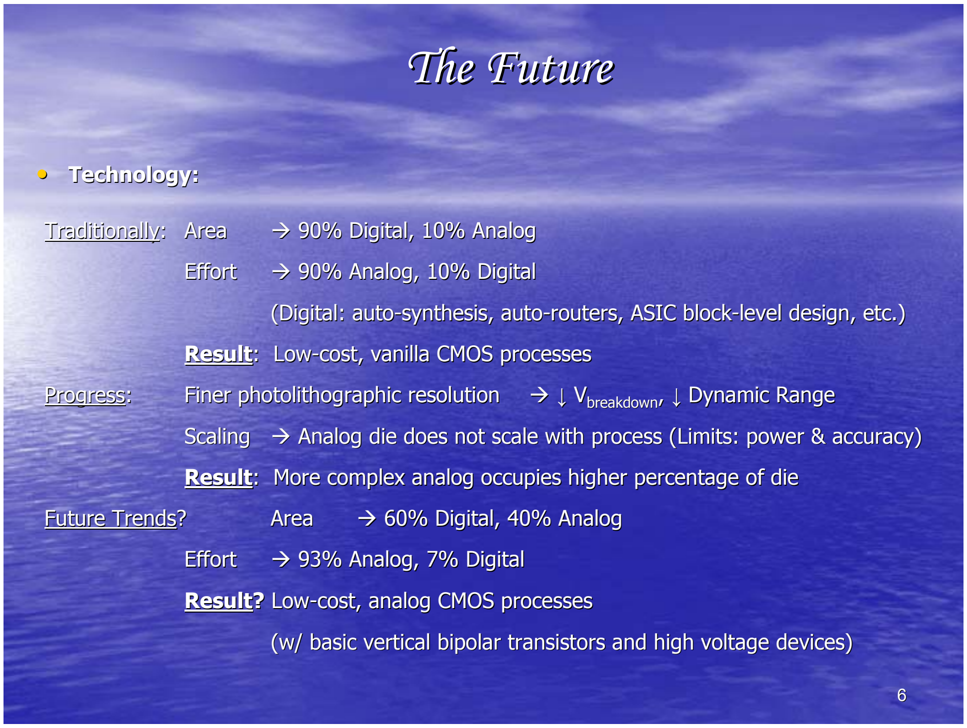
1 - International Technology Roadmap for Semiconductors - Web: http://public.itrs.net.

* Derived

The Future

- **Highlights:**

Low Voltage	Portable, ↑ η, 0.3-1.5V_{core_supply} → Battery Operation → Integrated Batteries
High Accuracy	10-40mV of Abs. V_{supply} Accuracy (DC + ac + Tran)
High Efficiency	Battery: 0-5W, 0-5A & Stationary: 0-190W, 0-300A
High Noise Content	1MHz to 100GHz (switching load)
Low Filter Density	10fF/μm^2 ∴ 1nF in 316 x 316 μm^2 (155mm^2 → 28% of projected die size) L_{max} ~ 50-100nH



The Future

- **Technology:**

Traditionally: Area → 90% Digital, 10% Analog
Effort → 90% Analog, 10% Digital
(Digital: auto-synthesis, auto-routers, ASIC block-level design, etc.)
Result: Low-cost, vanilla CMOS processes

Progress: Finer photolithographic resolution → ↓ $V_{breakdown}$, ↓ Dynamic Range
Scaling → Analog die does not scale with process (Limits: power & accuracy)
Result: More complex analog occupies higher percentage of die

Future Trends? Area → 60% Digital, 40% Analog
Effort → 93% Analog, 7% Digital
Result? Low-cost, analog CMOS processes
(w/ basic vertical bipolar transistors and high voltage devices)

Integration Barriers

→ **Energy Sources**: Thermoelectric, RF-Derived, Solar, & Vibration-Based Generators (MEMS) → **Low Energy**

→ **Energy Storage Devices**:

Capacitors – MEMS, CMOS Poly-Poly-Active, & CMOS Capacitor Multipliers

Inductors – MEMS, Planar Al- and Cu-Based, & CMOS Inductor Multipliers

Batteries – Thin-Film Polymer Lithium-Ion

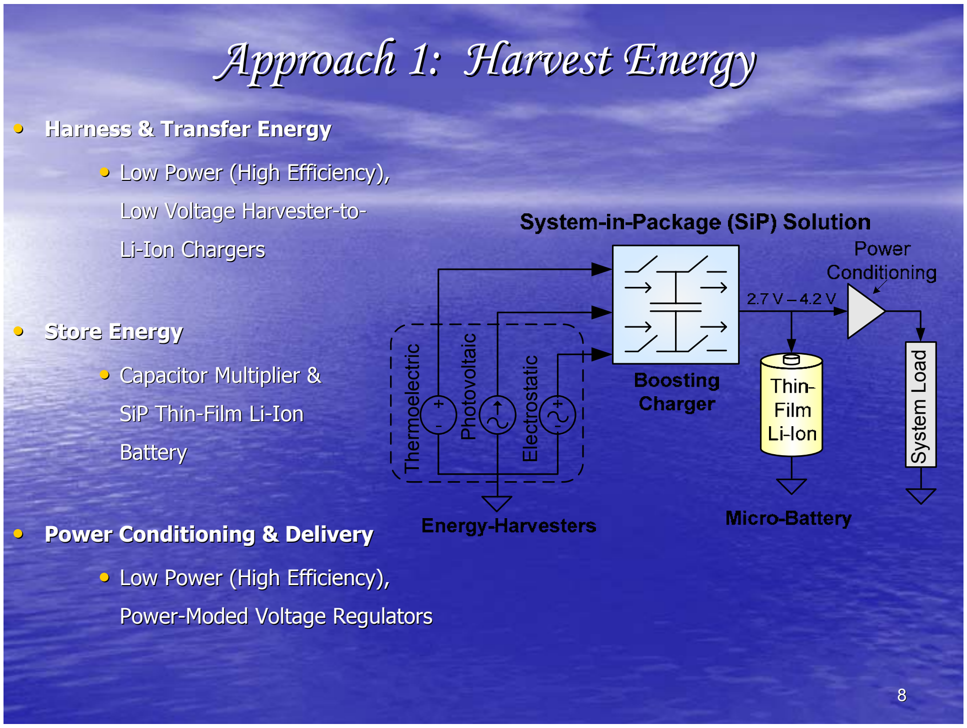
Chip-Scale Fuel Cells → **Low Integration Density**

→ **CMOS Power Management Circuits**:

Mode managers, regulators, chargers, references, monitors, bias currents & voltages, etc. → **Voltage Headroom & Power Losses**

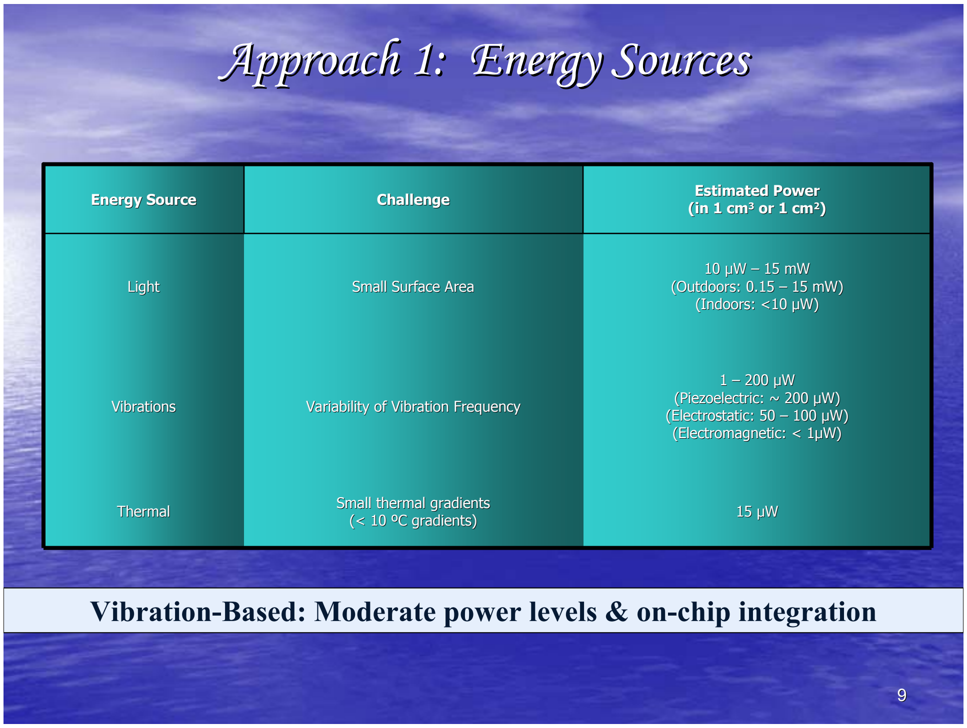
→ **Application Circuits**:

Transceivers, Monitors, Sensors, CPUs, etc. → **Wide Power Range**



Approach 1: Harvest Energy

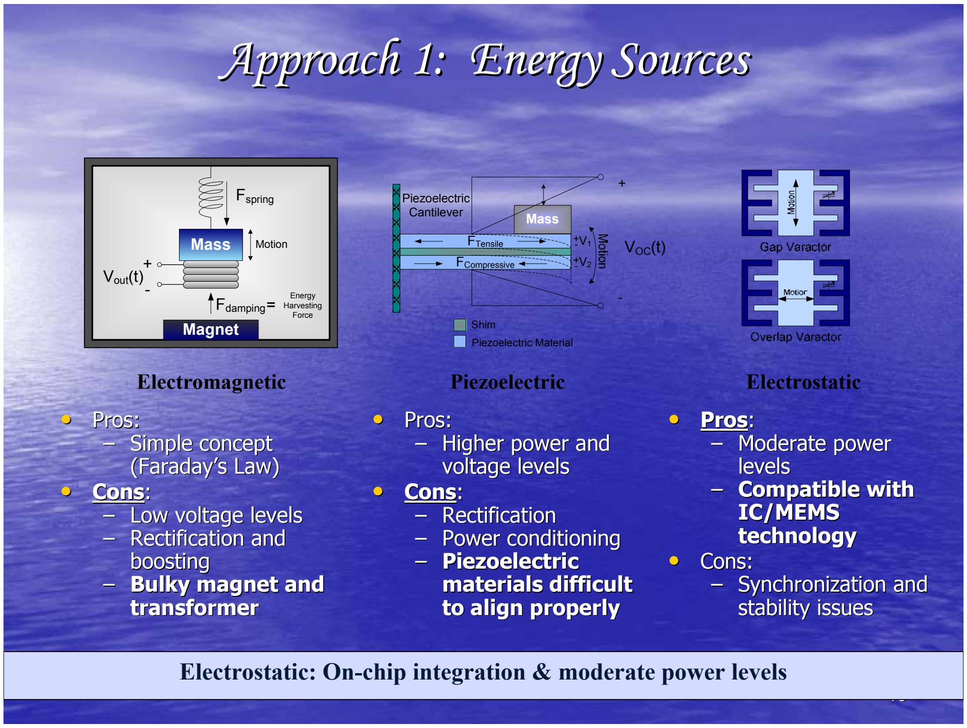
- **Harness & Transfer Energy**
  - Low Power (High Efficiency), Low Voltage Harvester-to-Li-Ion Chargers
- **Store Energy**
  - Capacitor Multiplier & SiP Thin-Film Li-Ion Battery
- **Power Conditioning & Delivery**
  - Low Power (High Efficiency), Power-Moded Voltage Regulators



Approach 1: Energy Sources

Energy Source	Challenge	Estimated Power (in $1\ cm^3$ or $1\ cm^2$)
Light	Small Surface Area	10 μW – 15 mW (Outdoors: 0.15 – 15 mW) (Indoors: <10 μW)
Vibrations	Variability of Vibration Frequency	1 – 200 μW (Piezoelectric: ~ 200 μW) (Electrostatic: 50 – 100 μW) (Electromagnetic: < 1μW)
Thermal	Small thermal gradients (< 10 ºC gradients)	15 μW

Vibration-Based: Moderate power levels & on-chip integration



Approach 1: Energy Sources

Electromagnetic

- Pros:
  - Simple concept (Faraday's Law)
- **Cons**:
  - Low voltage levels
  - Rectification and boosting
  - **Bulky magnet and transformer**

Piezoelectric

- Pros:
  - Higher power and voltage levels
- **Cons**:
  - Rectification
  - Power conditioning
  - **Piezoelectric materials difficult to align properly**

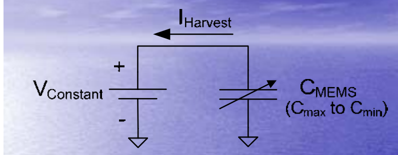
Electrostatic

- **Pros**:
  - Moderate power levels
  - **Compatible with IC/MEMS technology**
- Cons:
  - Synchronization and stability issues

Electrostatic: On-chip integration & moderate power levels

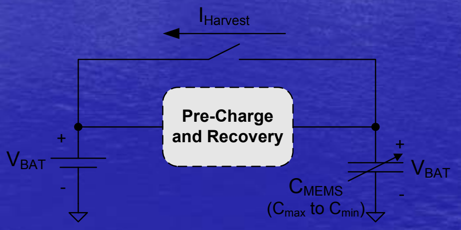
Approach 1: Harvesting Circuit

- **Electrostatic V-Constrained Basics**



- $\overset{\uparrow}{Q} = \overset{\uparrow}{C}\,V$
- $I = dQ/dt = C\,(\partial V/\partial t) + V\,(\partial C/\partial t) \approx V\,(\partial C/\partial t)$
- $E_{Harvest} = 0.5\,(C_{Max} - C_{Min})\,V^2$
  - If ΔC = 100pF & V = 4V, $E_{Harvest}$ = 800pJ

- **How?**
  - 1. Pre-Charge C_{MEMS}
  - 2. Harvest
  - 3. Recover Residual



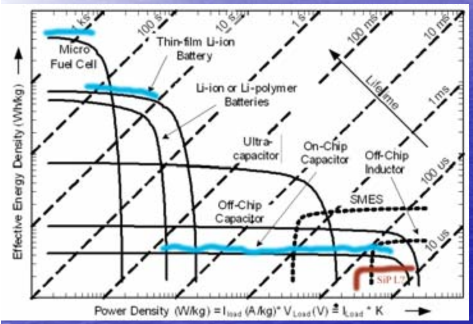
- **Challenges:**

Synchronization | Pre-Charge Control
Power Losses (Net Gain) | Clock Feed-Through | Charge Leakage

Approach 2: Extend Runtime

- **Goal** = **Extend Operation Life** (i.e., battery life or runtime)

Ragone Plot



* **Fuel Cells**: Slow, highest energy at light Loads

* **Li-Ion**: Faster, highest energy during burst-peak loads

* **Capacitor**: Fastest, highest energy during high peak transient (high di/dt) loads

* **Inductor**: Cumbersome & slow but able to transfer energy in the form of current

Approach → **Mode-hop** from device to device to **extract energy from highest energy devices** (i.e., stay on flat traces)

Approach 2: Fuel Cells

- Fuel Cell (FC): Electrochemical energy conversion device

  Fuel (e.g., hydrogen) + Oxidant (e.g., oxygen) → Water + Electricity (e.g., current)
- Categories:

Alkaline FC (AFC)	Phosphoric Acid FC (PAFC)
Molten Carbonate FC (MCFC)	Solid-Oxide FC (SOFC)
Proton-Exchange Membrane FC (PEMFC)	Direct Methanol FC (DMFC)...

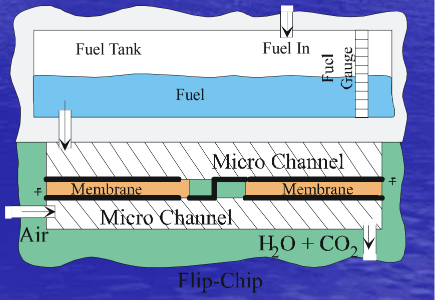
- DMFC is a variant of PEMFC:

  Extracts hydrogen from liquid methanol directly, without the need of a bulky fuel reformer (necessary in other FC to transform hydrocarbon fuels into hydrogen).

  → Therefore,

  best suited for miniaturization

  (40% η at 50-130ºC)



Approach 2: Fuel Cells

- DMFC:

  * Issues:

  a. Methanol crossover: Fuel leakage/loss across membrane

  * High temperature, diluted methanol, and exotic electrolytes help.

  b. Relatively low current ratings (i.e., low power)

  * More concentrated methanol and ultra-capacitor technologies help.

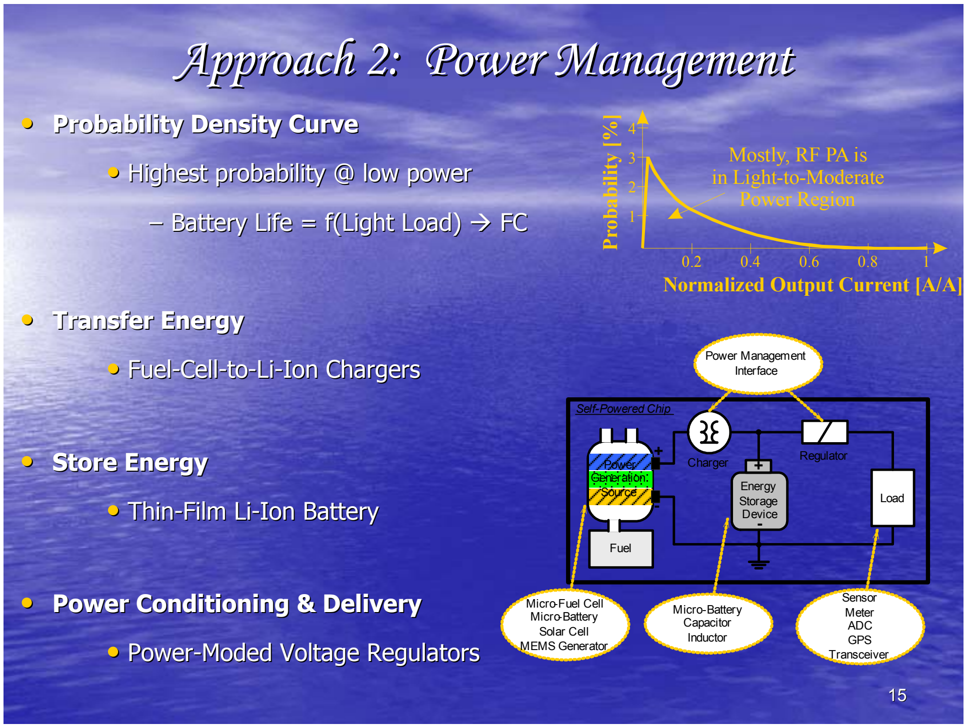
  c. High over-potentials: Slow electrolyte kinetics (slow response times - low BWs)

  * Active catalysts help

  * Constant fuel-flow control helps

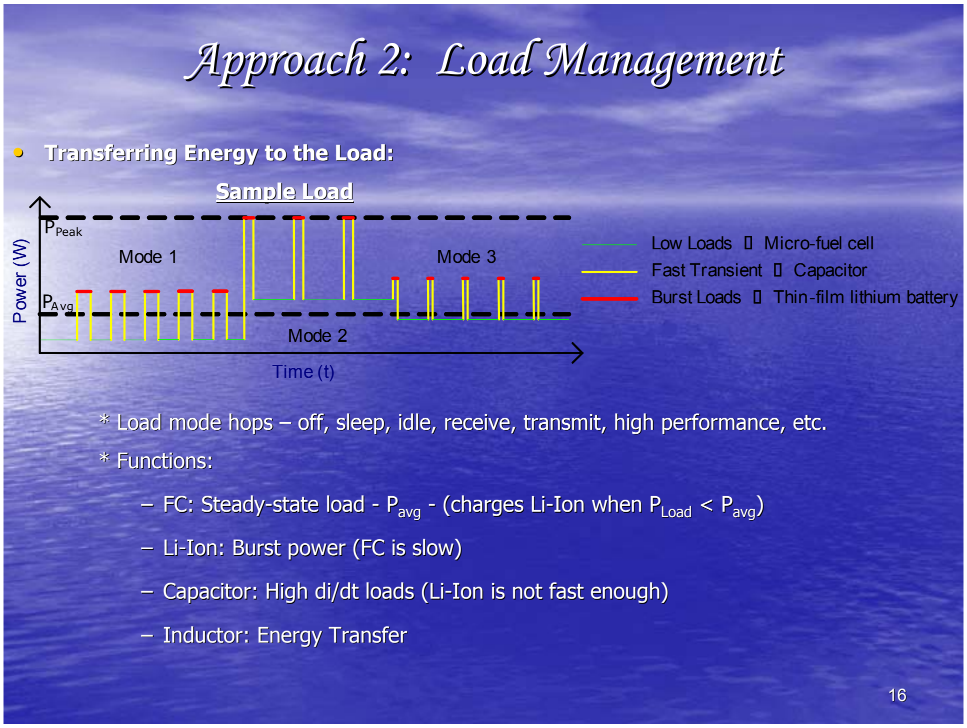
  d. Limited tank size & reduction in fuel concentration

  * Energy & Power decrease over time



Approach 2: Power Management

- **Probability Density Curve**
  - Highest probability @ low power
    - Battery Life = f(Light Load) → FC
- **Transfer Energy**
  - Fuel-Cell-to-Li-Ion Chargers
- **Store Energy**
  - Thin-Film Li-Ion Battery
- **Power Conditioning & Delivery**
  - Power-Moded Voltage Regulators



Approach 2: Load Management

- **Transferring Energy to the Load:**

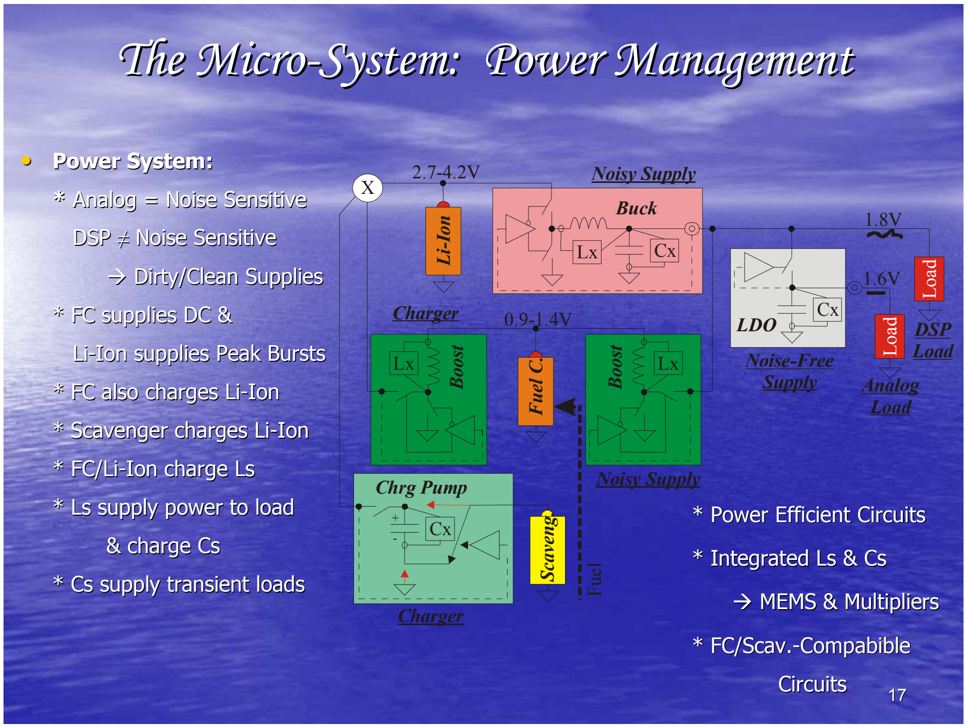
<u>Sample Load</u>

Low Loads ▯ Micro-fuel cell
Fast Transient ▯ Capacitor
Burst Loads ▯ Thin-film lithium battery

* Load mode hops – off, sleep, idle, receive, transmit, high performance, etc.

* Functions:

- FC: Steady-state load - P_{avg} - (charges Li-Ion when $P_{Load} < P_{avg}$)
- Li-Ion: Burst power (FC is slow)
- Capacitor: High di/dt loads (Li-Ion is not fast enough)
- Inductor: Energy Transfer



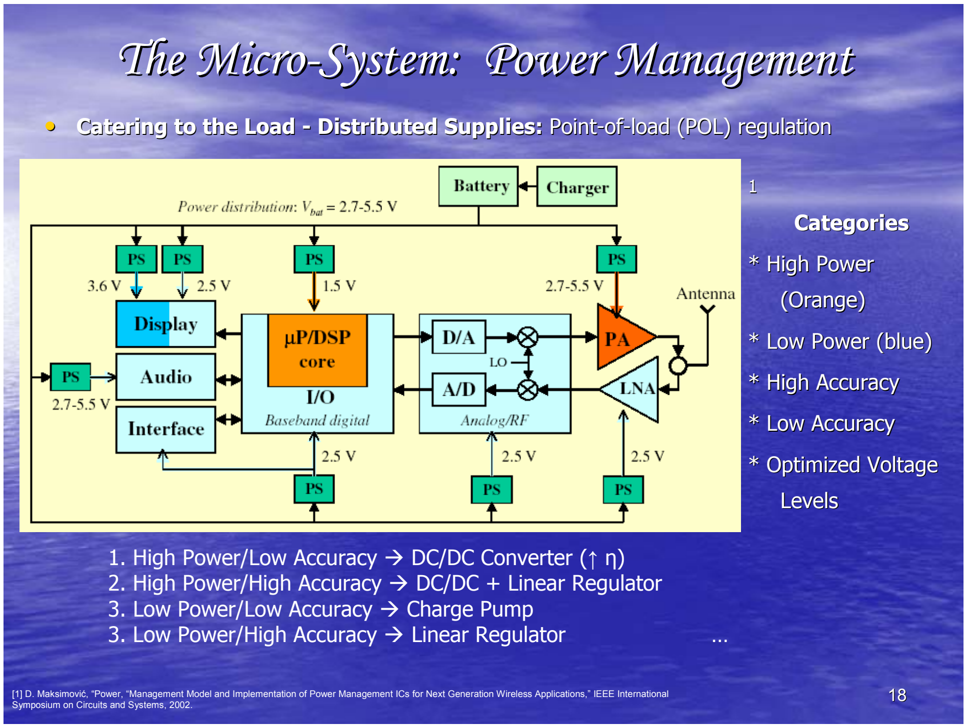
The Micro-System: Power Management

- **Power System:**
  - * Analog = Noise Sensitive
    DSP ≠ Noise Sensitive
    → Dirty/Clean Supplies
  - * FC supplies DC &
    Li-Ion supplies Peak Bursts
  - * FC also charges Li-Ion
  - * Scavenger charges Li-Ion
  - * FC/Li-Ion charge Ls
  - * Ls supply power to load
    & charge Cs
  - * Cs supply transient loads

* Power Efficient Circuits

* Integrated Ls & Cs
→ MEMS & Multipliers

* FC/Scav.-Compabible
Circuits



The Micro-System: Power Management

- **Catering to the Load - Distributed Supplies:** Point-of-load (POL) regulation

[1]

Categories

* High Power
(Orange)

* Low Power (blue)

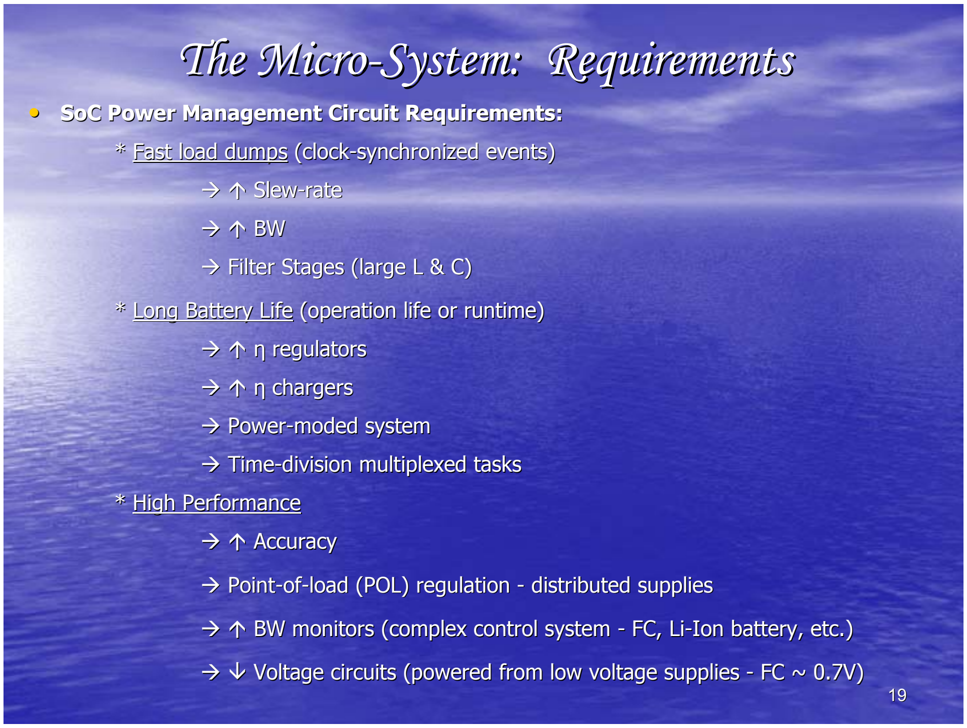
* High Accuracy

* Low Accuracy

* Optimized Voltage
Levels

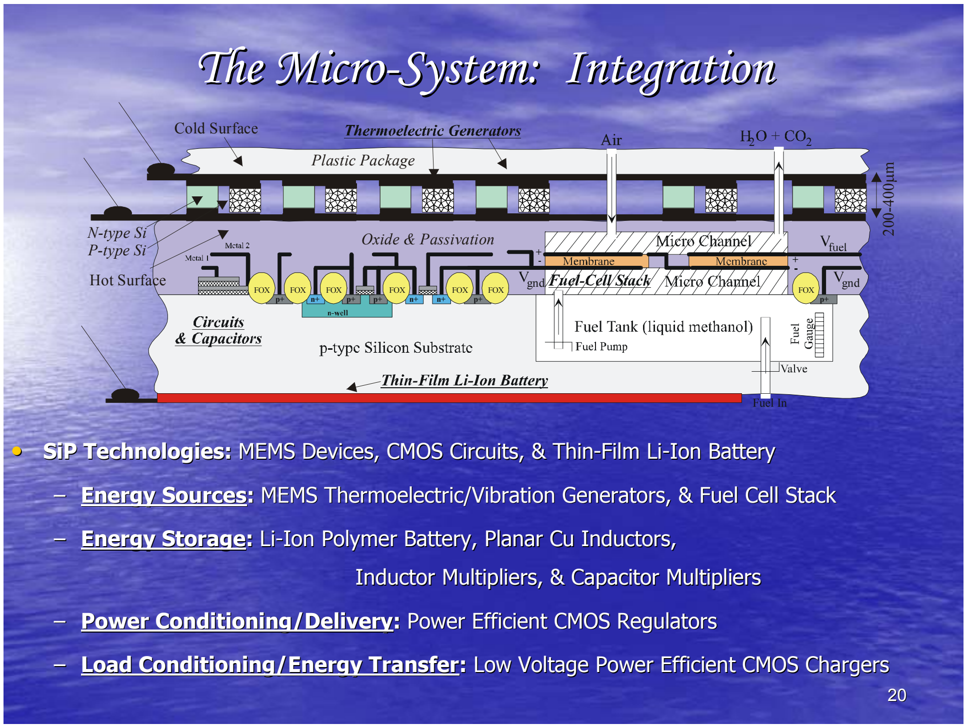
1. High Power/Low Accuracy → DC/DC Converter (↑ η)
2. High Power/High Accuracy → DC/DC + Linear Regulator
3. Low Power/Low Accuracy → Charge Pump
3. Low Power/High Accuracy → Linear Regulator …

[1] D. Maksimović, "Power, "Management Model and Implementation of Power Management ICs for Next Generation Wireless Applications," IEEE International Symposium on Circuits and Systems, 2002.



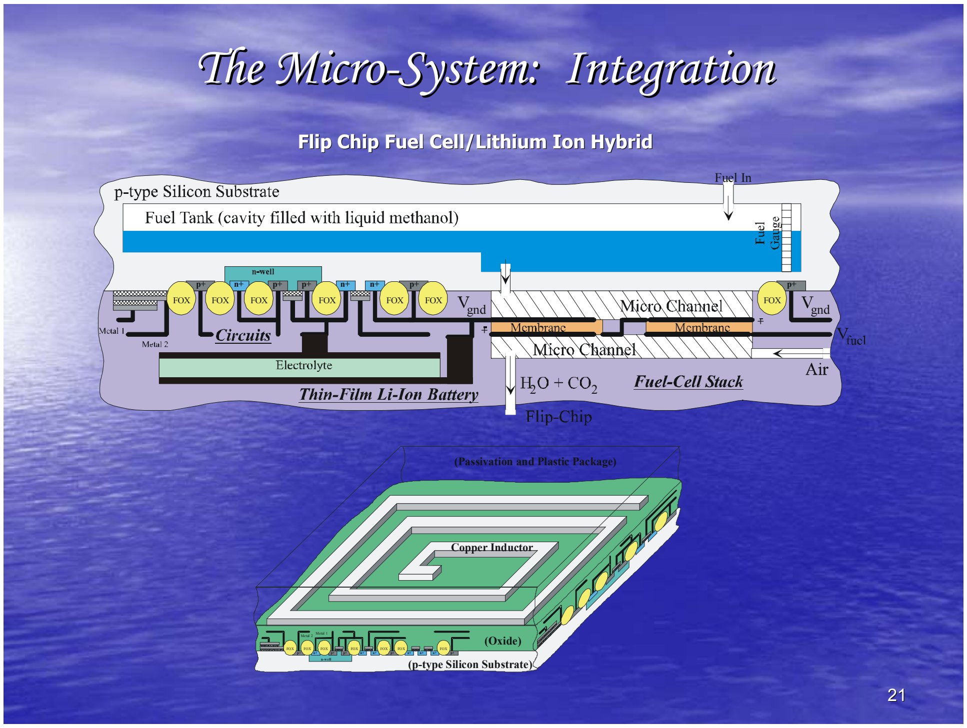
The Micro-System: Requirements

- **SoC Power Management Circuit Requirements:**
  - * Fast load dumps (clock-synchronized events)
    - → ↑ Slew-rate
    - → ↑ BW
    - → Filter Stages (large L & C)
  - * Long Battery Life (operation life or runtime)
    - → ↑ η regulators
    - → ↑ η chargers
    - → Power-moded system
    - → Time-division multiplexed tasks
  - * High Performance
    - → ↑ Accuracy
    - → Point-of-load (POL) regulation - distributed supplies
    - → ↑ BW monitors (complex control system - FC, Li-Ion battery, etc.)
    - → ↓ Voltage circuits (powered from low voltage supplies - FC ~ 0.7V)



The Micro-System: Integration

- **SiP Technologies:** MEMS Devices, CMOS Circuits, & Thin-Film Li-Ion Battery
  - **Energy Sources:** MEMS Thermoelectric/Vibration Generators, & Fuel Cell Stack
  - **Energy Storage:** Li-Ion Polymer Battery, Planar Cu Inductors, Inductor Multipliers, & Capacitor Multipliers
  - **Power Conditioning/Delivery:** Power Efficient CMOS Regulators
  - **Load Conditioning/Energy Transfer:** Low Voltage Power Efficient CMOS Chargers



The Micro-System: Integration

Flip Chip Fuel Cell/Lithium Ion Hybrid

The Micro-System: Challenges

- **Package Integration:**

  * Fuel Cells * Energy Scavengers * Planer Cu Inductors

  * Thin-Film Li-Ion * Power MEMS Inductors * Bulk Capacitors

  * Re-Fueling (unnecessary for disposable applications) * Testability

- **Power Management:**

  * Multiple-Chargers-to-Single-Battery System * Multiple-Source-to-Single-Output Supply

  * Accurate/Fast System Health Monitors * Emergency Battery Handoff

- **CMOS/BiCMOS Supply Circuits:**

  * Fuel-Cell Compatible Boost Regulator * Fast Capacitor Multipliers

  * Efficient, Low-Voltage Power Switches * Efficient Inductor Multipliers

  * Scavenger-Compatible Intermittent Trickle Boost Charger

  * Fuel-Cell Compatible Boost Charger

  * Safe Mode-Hop Manager and PM Brain

  * …

The Future, Revisited…

- **The Road**: ***Design Bridges → SiP/SoP/SoC***
  Product/Market/Process/Device/Circuit/
  System/IC/Package/PCB/Application
- **The Means**: *Technology Leaps → Robust, Low V, Low I_{in}, High I_{out}, High Perf.*
  *Mixed-Signal ICs → **Integration** of Power Passives, Batteries*
  (fuel cells, Li-ion)…
- **The Goal**: ***Portable, Self-Powered, Self-Sustaining**, Battery-Operated,*
  System-on-Package (SoP) Solutions

- End -