Energy Harvesing and Low Power Techniques for IoT

CmpE490: Internet of Things Course

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- IoT node architecture
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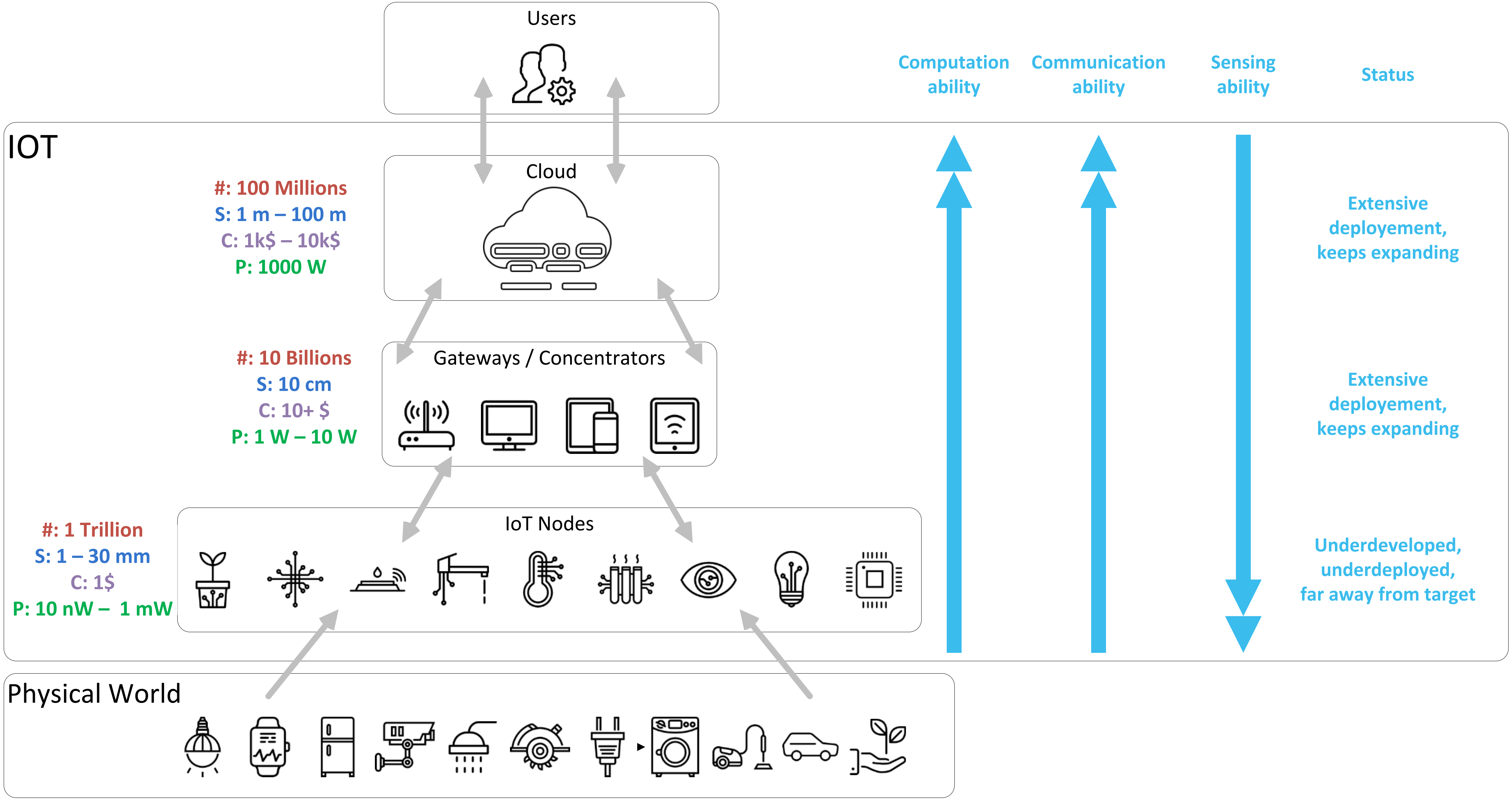
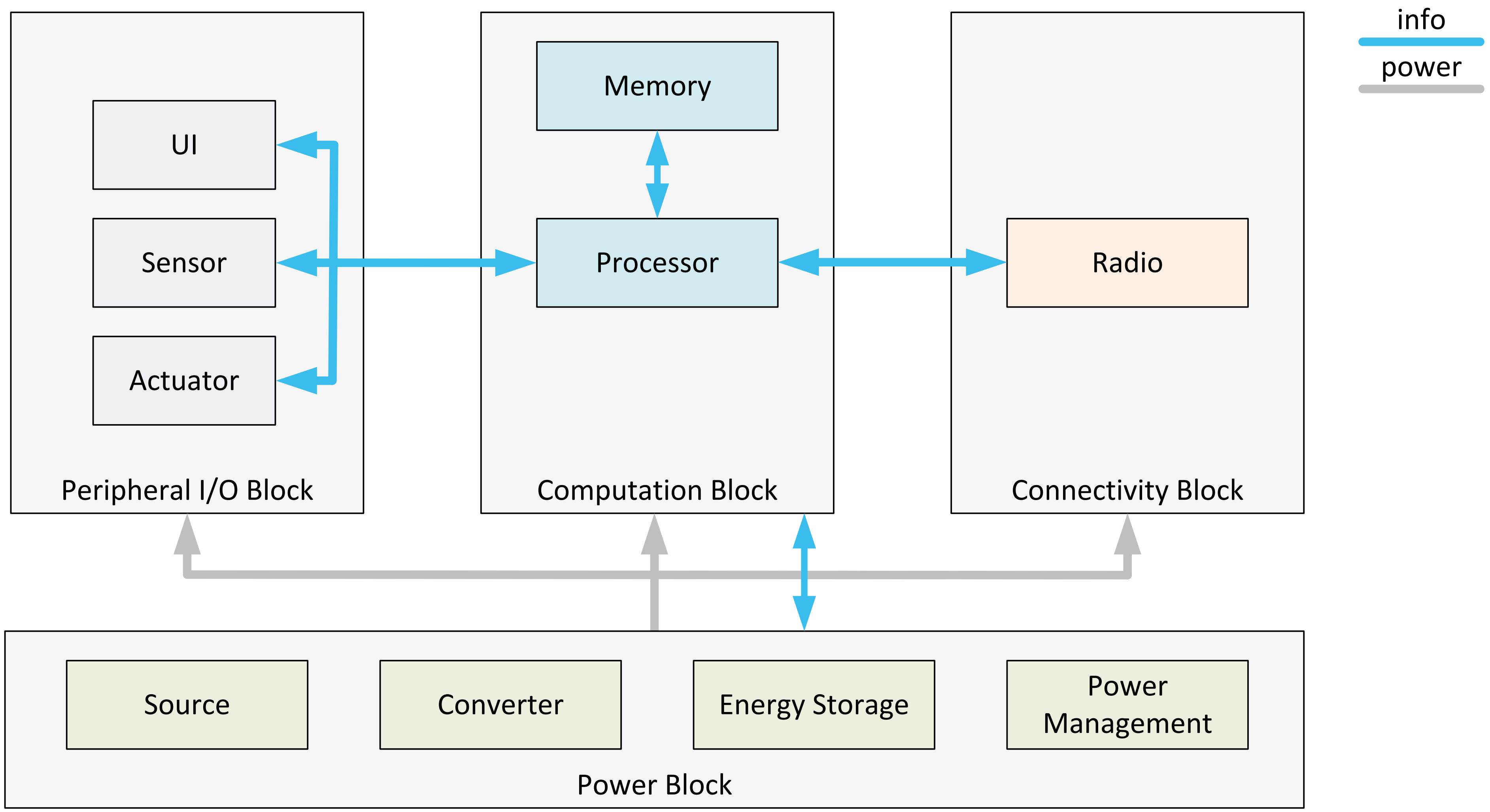
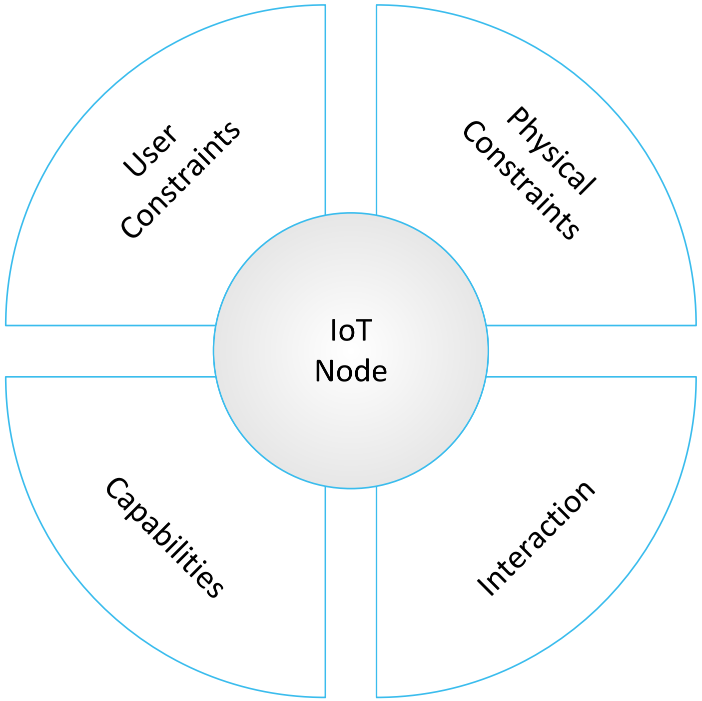
IoT Architecture



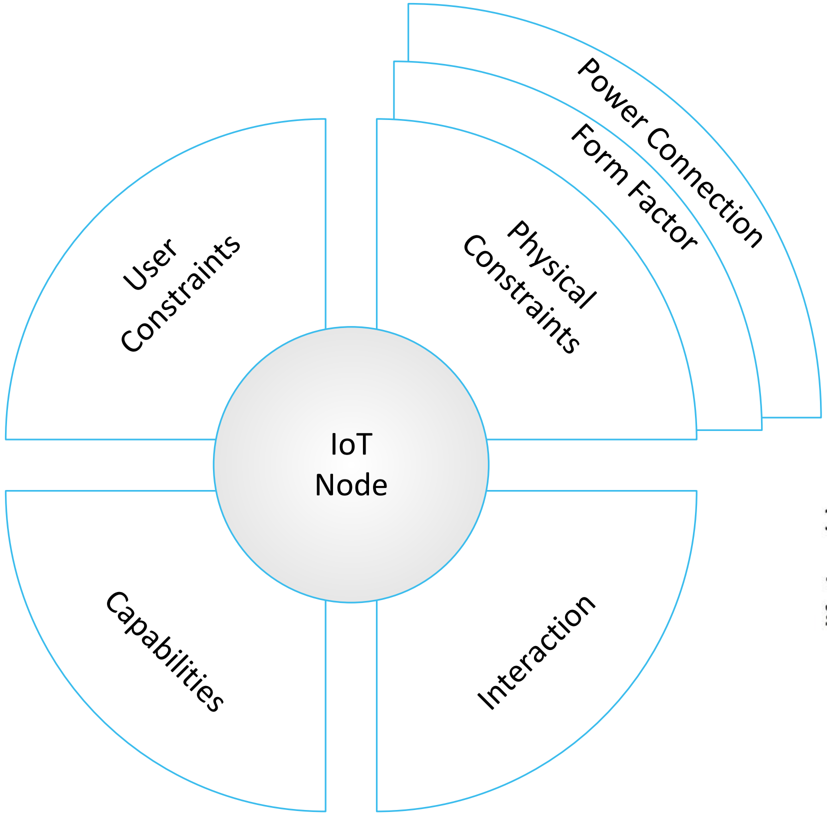
IoT Node Architecture



Design Space Challenges of IoT Node



Design Space Challenges of IoT Node



Miniature, 10 – 1000 mm^3

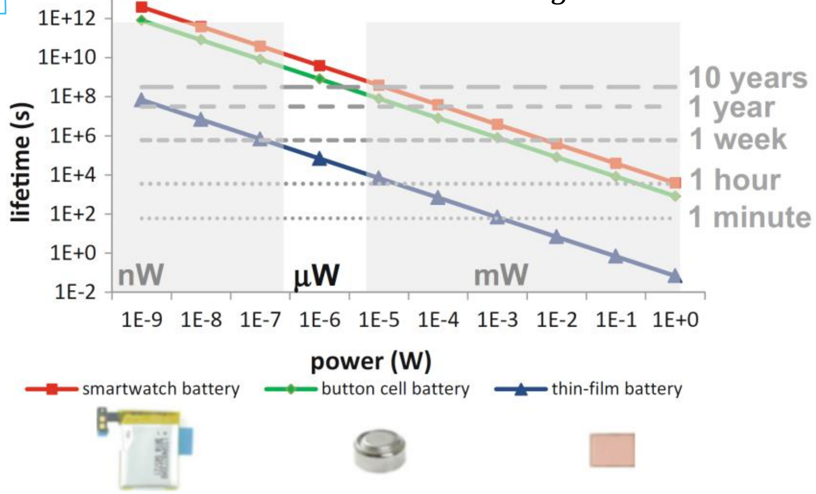
Untethered

Battery powered (limited Power)

Energy harvesting (self-powered)

Small power budget (nW - µW)

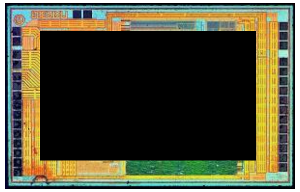
$$t_{lifetime} = \frac{E_{battery}}{P_{average}}$$



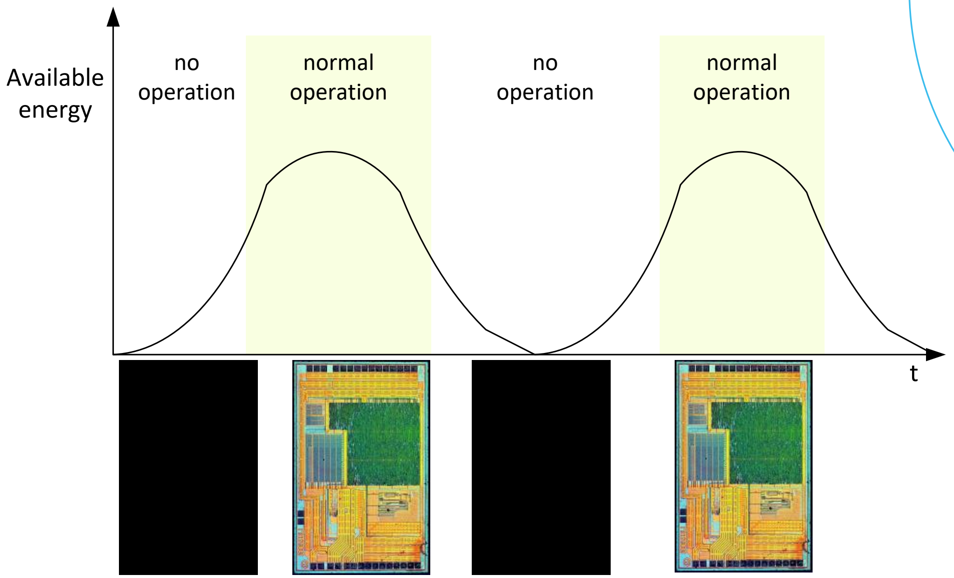
type	cost	capacity	volume	energy density
GH43-03992A	30$	300 mAh	2,400 mm^3	0.12 mAh/mm^3
LR44	<1$	150 mAh (non-rechargeable)	500 mm^3	0.28 mAh/mm^3
Cymbet CBC005	0.2$	5 µAh	0.7 mm^3	6.5 $µAh/mm^3$

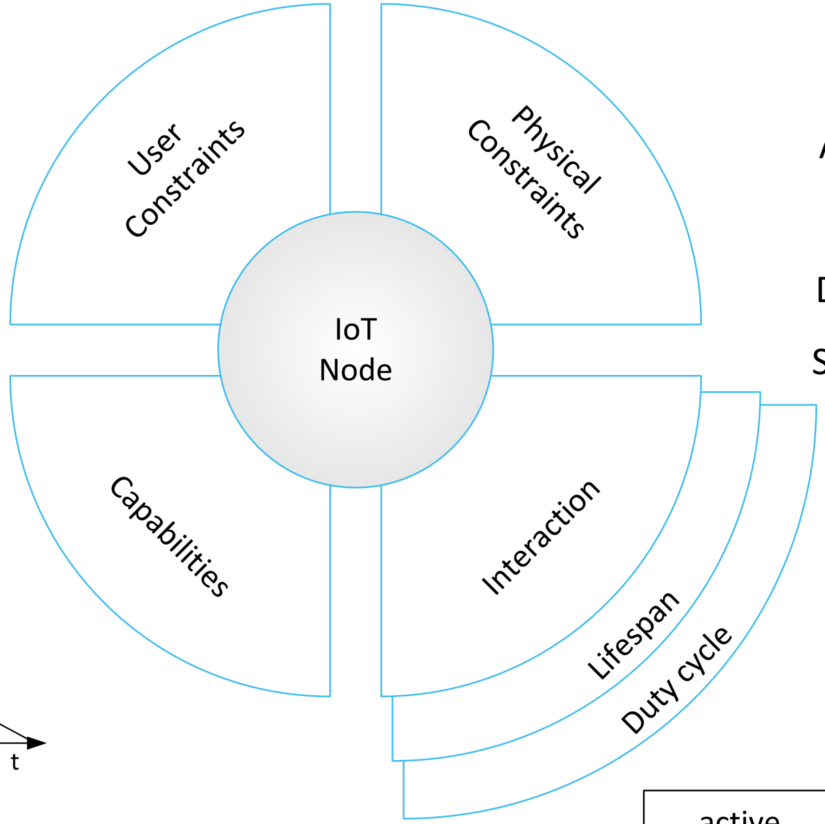
Design Space Challenges of IoT Node

High performance SoC



IoT Node





Meeting power budgets of few µWs

Power saving through duty cycling

Always-on + duty-cycled blocks

Always on block: wake-up management and data retention

Duty cycled block: sense, compute, communicate

Sleep cycles with upper bound on wake up period

$$P_{average} = P_{alwys\_on} + \frac{E_{duty-cycle}}{T_{wake-up}}$$

Design Space Challenges of IoT Node

IoT nodes need to have sensing, computation, and wireless communication capabilities

Repetitive tasks

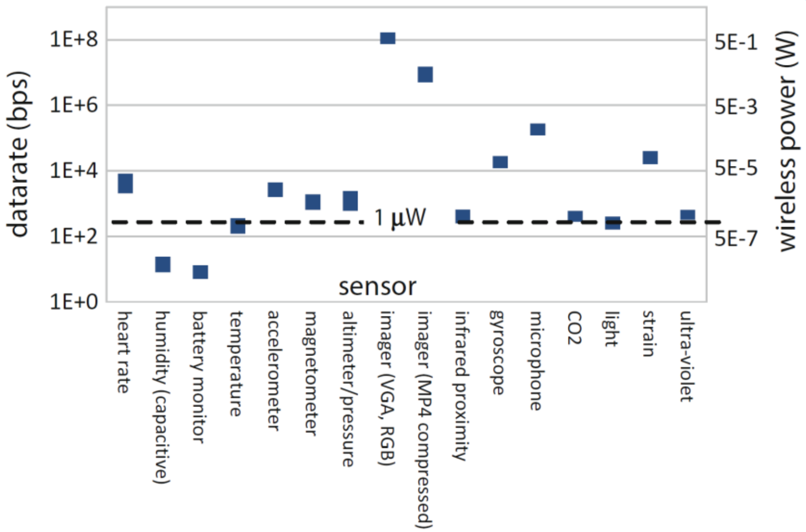
Data logging; decreased performance, increased

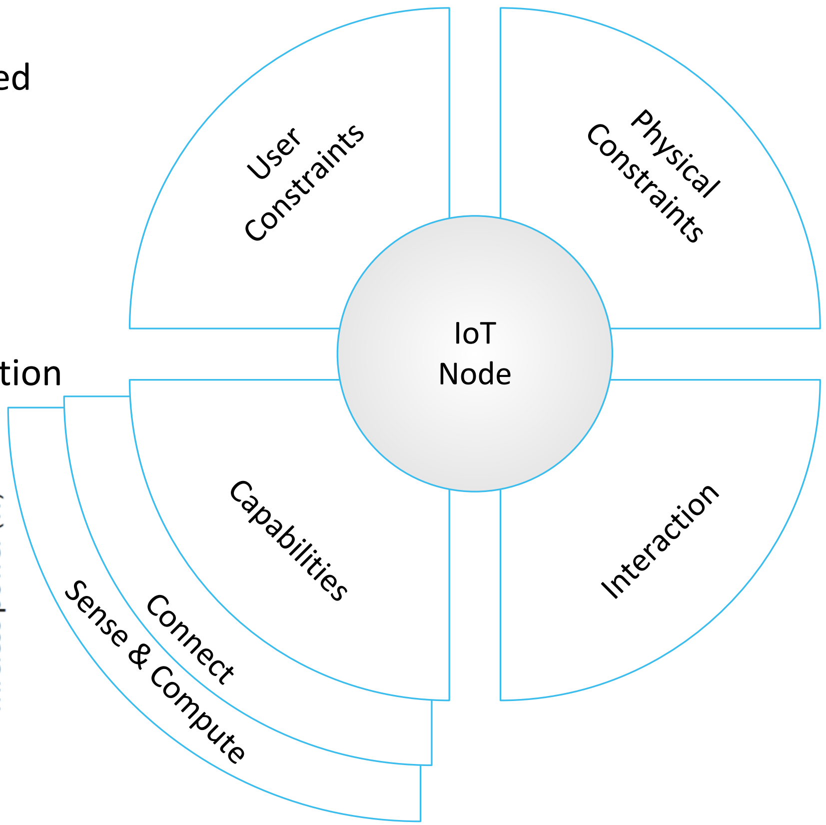
memory requirement

Improved power domain design

Limiting transmission to critical events

Trade off between computation and communication





Design Space Challenges of IoT Node

Low IoT node cost expectation, 1$/node

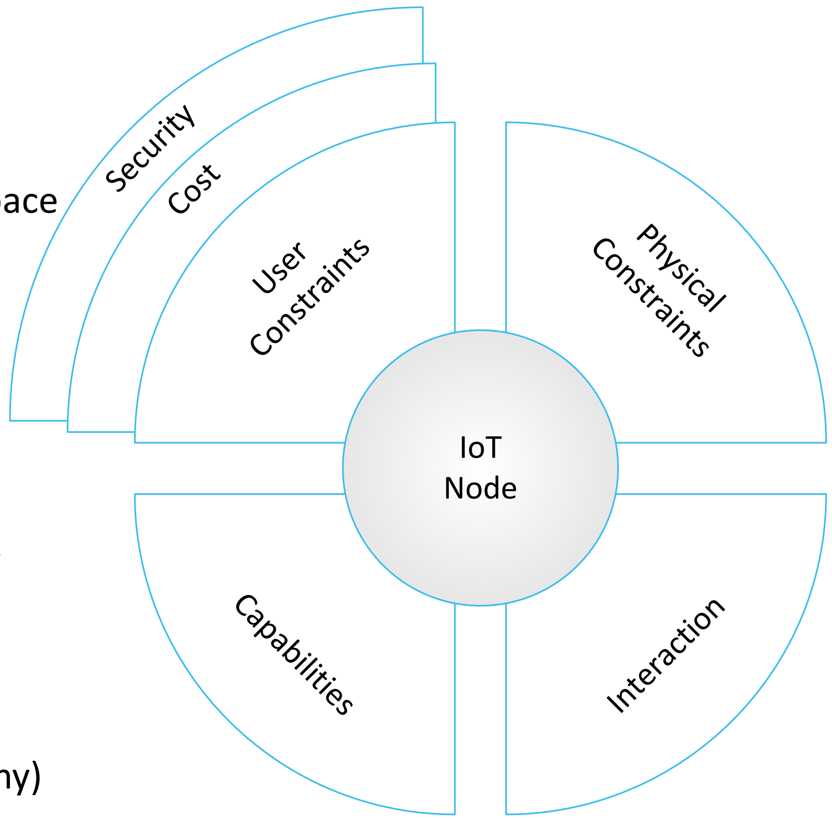
Large sales volumes in highly fragmented IoT space

Ecosystem that favors design reuse

Platform-based design approaches

Security is important as the IoT offers a very large number of backdoors to attackers

Traditional solutions (e.g., firewall, cryptography) are not applicable, due to limited power budget and cost



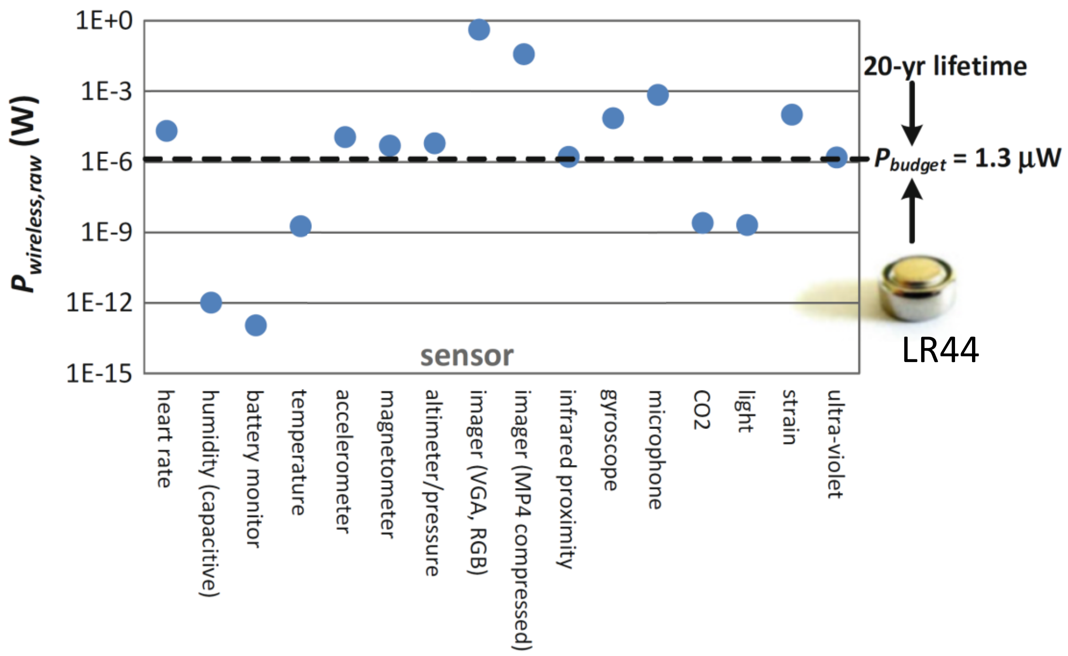
Design Space Trade-off: Computation vs. Communication

Best-in-class commercial radios consume an energy in the order of tens of nJ/bit, further advances in ultra-low power radios will only moderately reduce the energy per bit.

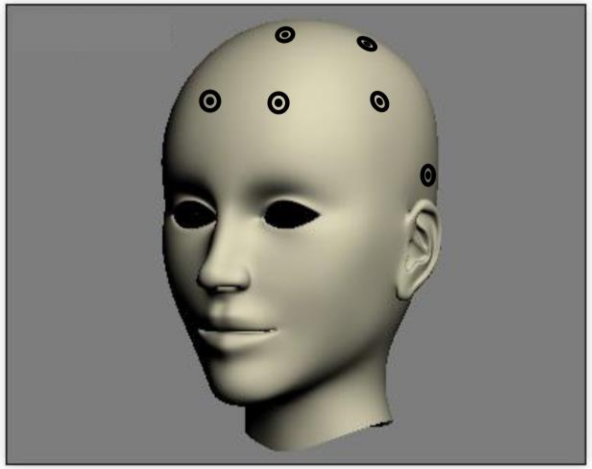
Smart ("cognitive", "attentive") nodes are needed to significantly reduce the wireless power consumption by performing on board computation.

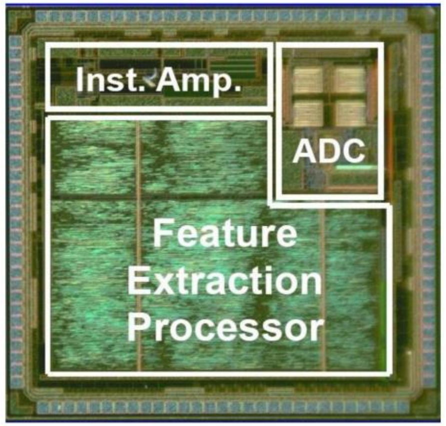
Simple nodes communicate raw data and computation is done in cloud

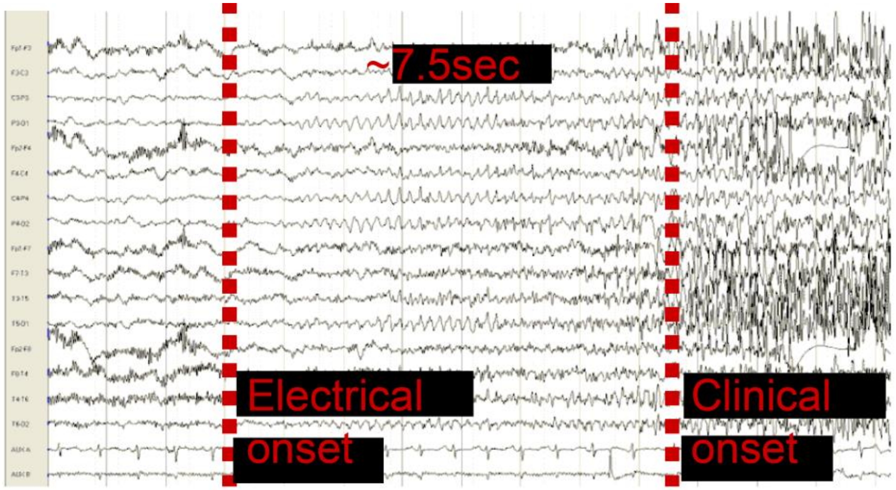
$$P_{wireless,raw} = E_{bit} \cdot N_{bit,measure} \cdot f_{measurement}$$



Computation vs. Communication: Epileptic Seizure Onset Detection



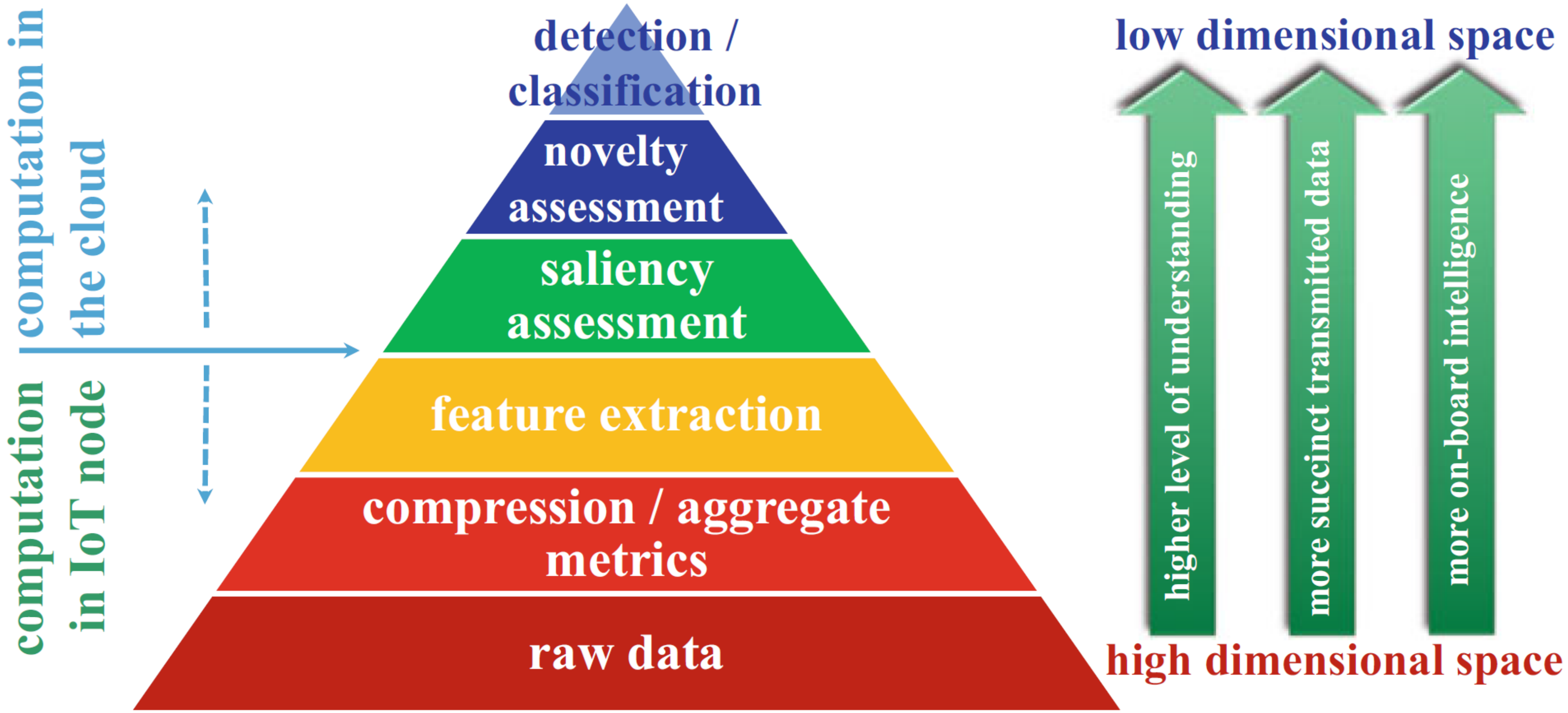




	No local processing	Local feature extraction
Capture	**75 µW**	**75 µW**
Digital Processing	**--**	**2 µW**
Radio (cc2550) - Active: bit-rate*40nJ/bit - Start-up 2.4 µW - Idile mode: 0.46 µW	**1733 µW** - 43.2kb/s * 40nJ/bit - 4.8µW - 0.46 µW	**43 µW** - 2kb/2s * 40nJ/bit - 2.4µW - 0.46 µW
Total	**1808 µW**	**120 µW**

[Verma, Naveen, et al. "A micro-power EEG acquisition SoC with integrated seizure detection processor for continuous patient monitoring." VLSI Circuits, 2009 Symposium on. IEEE, 2009.]

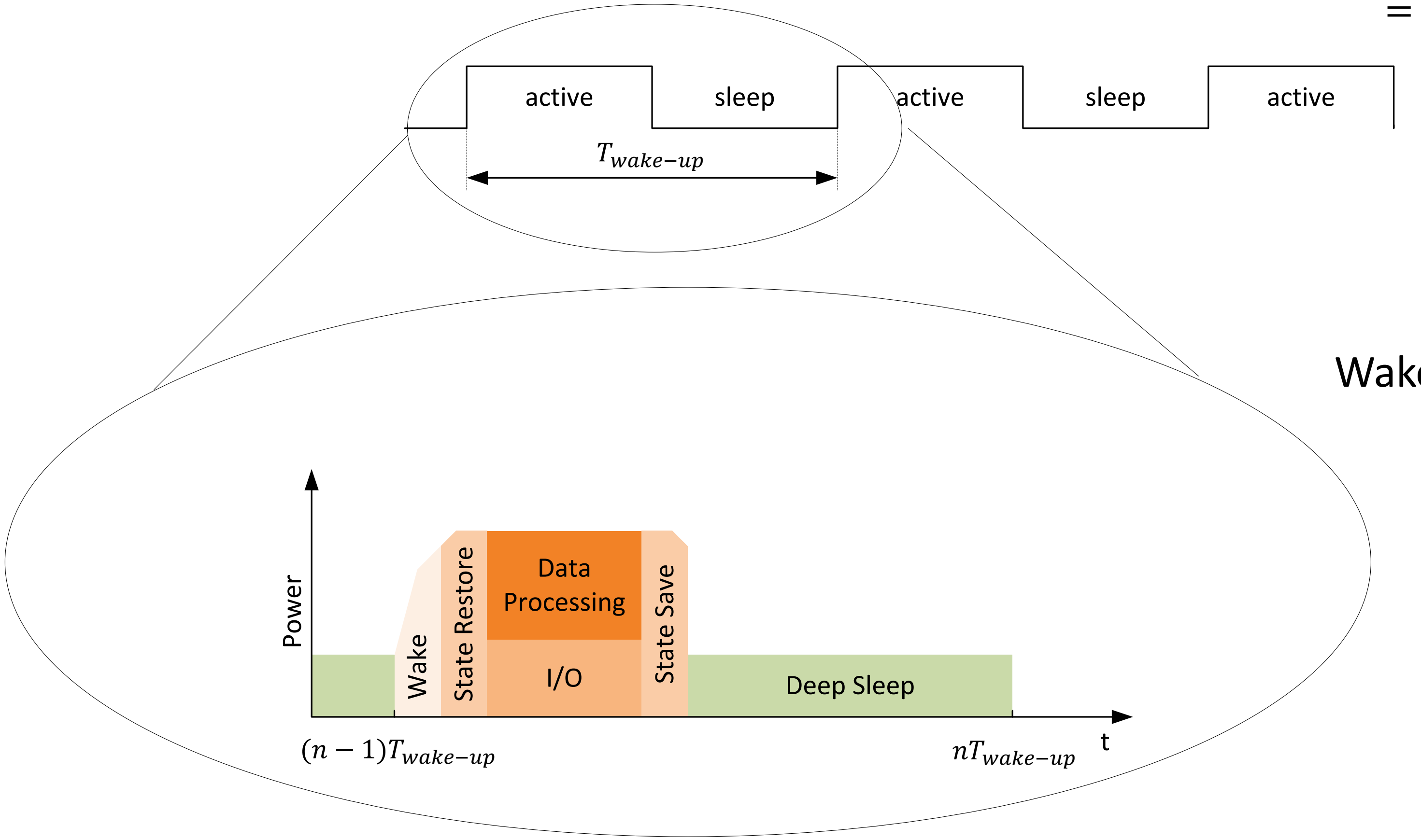
Computation vs. Communication: Semantic Understanding



Design Space Trade-off: Duty Cycling

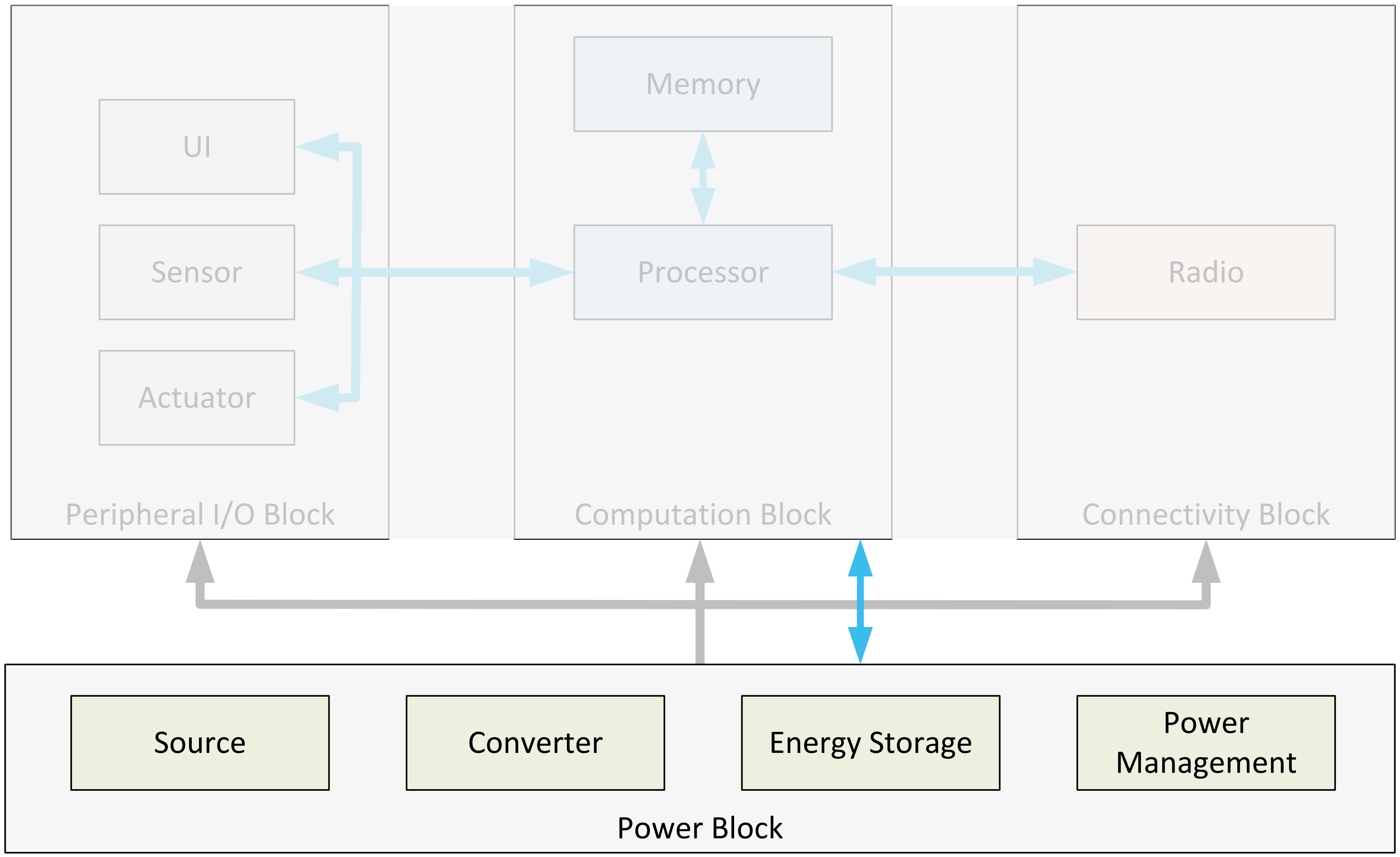
Repetitive tasks + Limited power => Duty cycled operation

$$P_{average} = P_{alwys\_on} + \frac{E_{duty-cycle}}{T_{wake-up}}$$
$$= P_{leakage} + P_{deep\_sleep} + \frac{E_{wake} + E_{I/O} + E_{state} + E_{processing}}{T_{wake-up}}$$

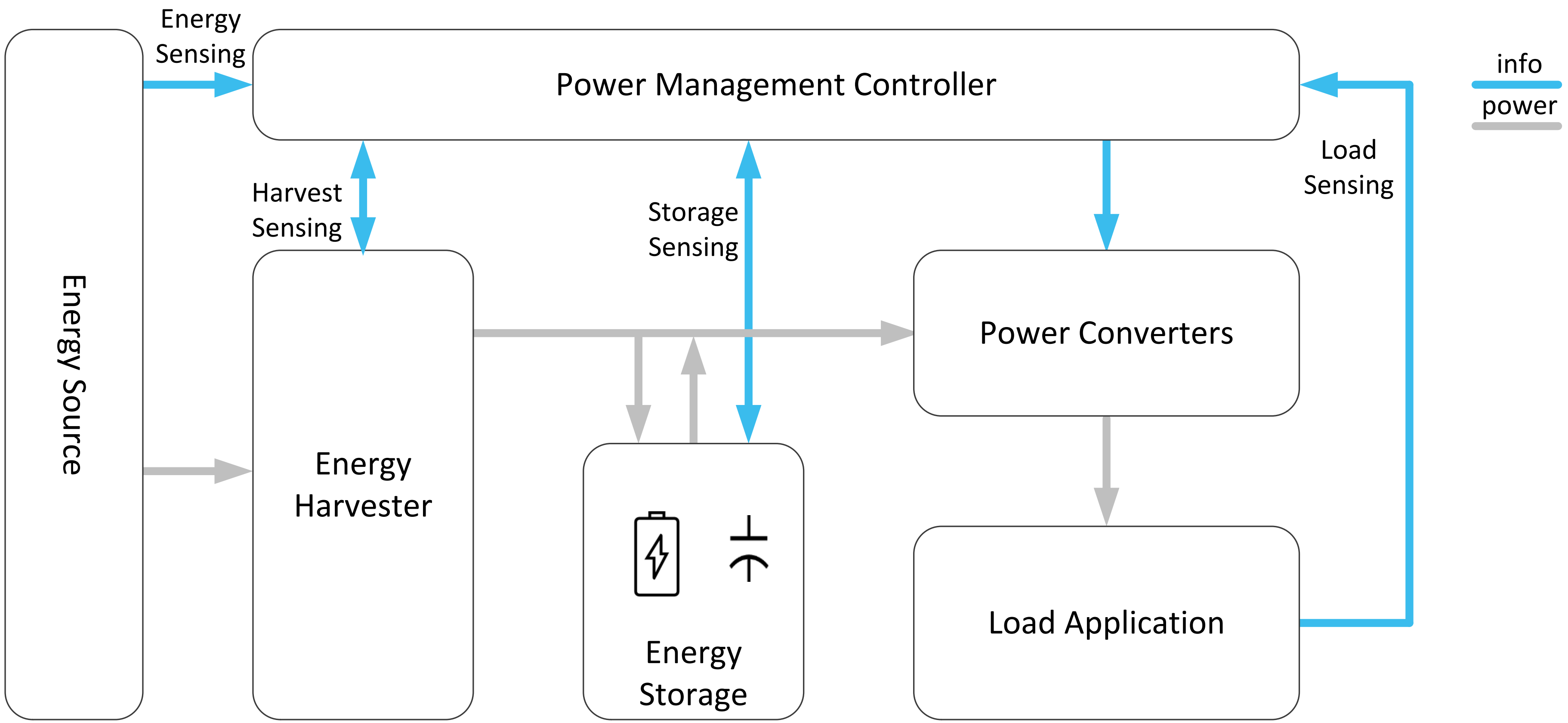


Wake-up sources
- Event Driven
  - Digital trigger (hardware interrupt, logical trigger)
  - Analog trigger (comparator)
- Time Driven
  - Real time clock generator
  - Watchdog timer

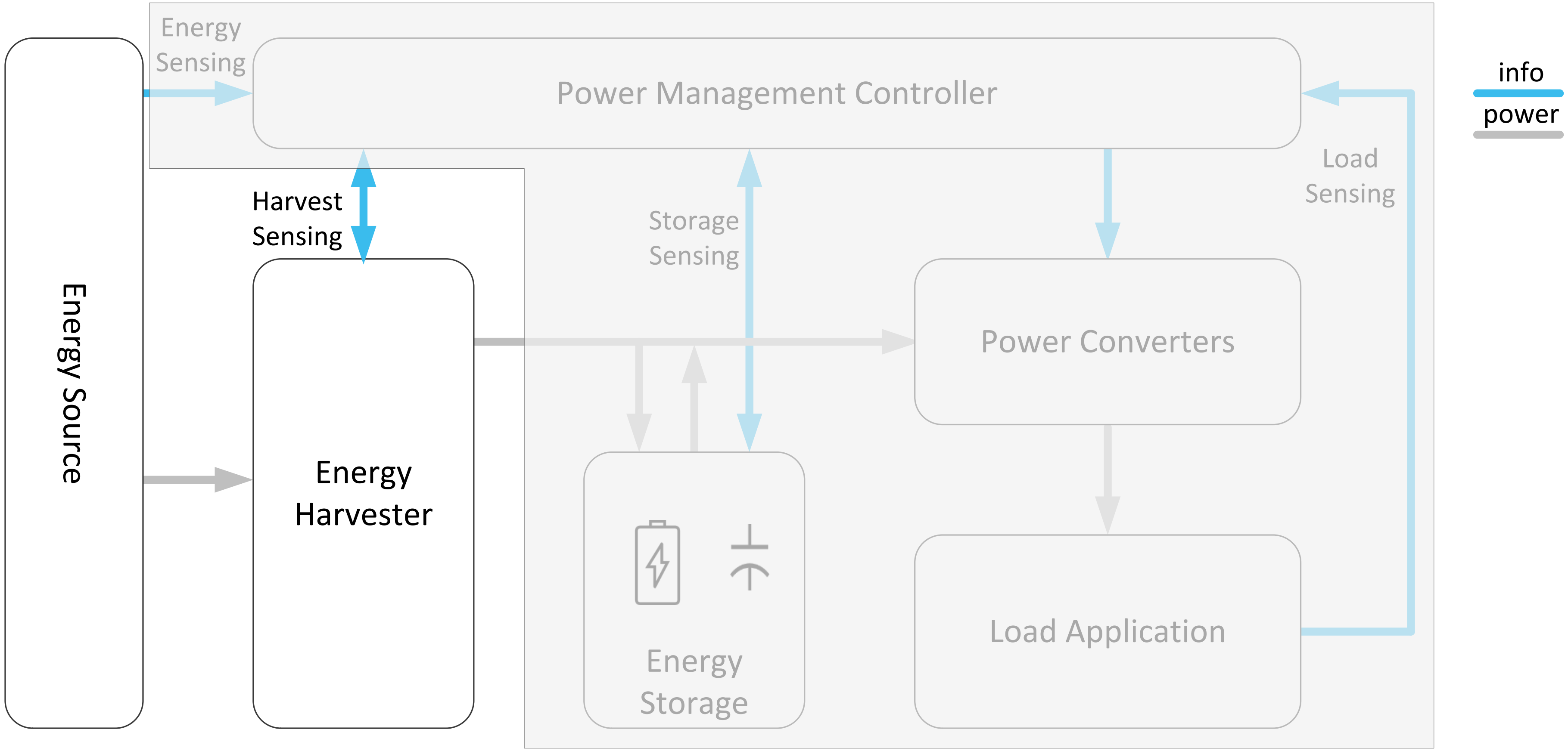
Powering the IoT Node



Power Block


Energy Sensing
Power Management Controller
info
power
Load Sensing
Harvest Sensing
Storage Sensing
Energy Source
Energy Harvester
Power Converters
Energy Storage
Load Application

Energy Harvesting



Energy harvesting (a.k.a. power harvesting or energy scavenging) is the process by which ambient energy is captured, stored and used by small wireless autonomous devices (wearable, sensor networks).

Energy Harvesting – Solar

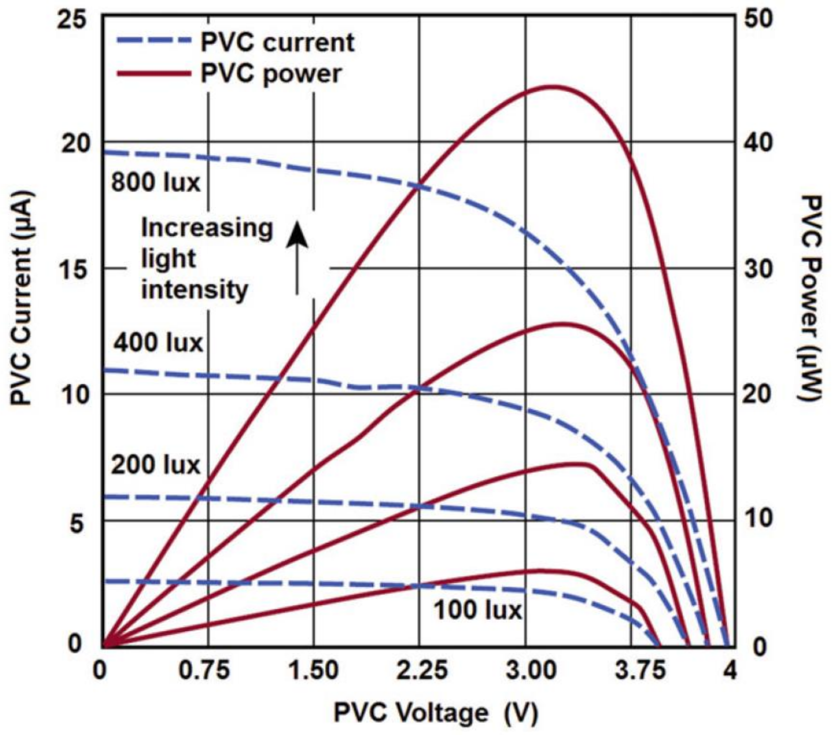
Characteristics

- Most researched energy harvesting technique
- Possible to harvest ambient light
- Low efficiency solar panel

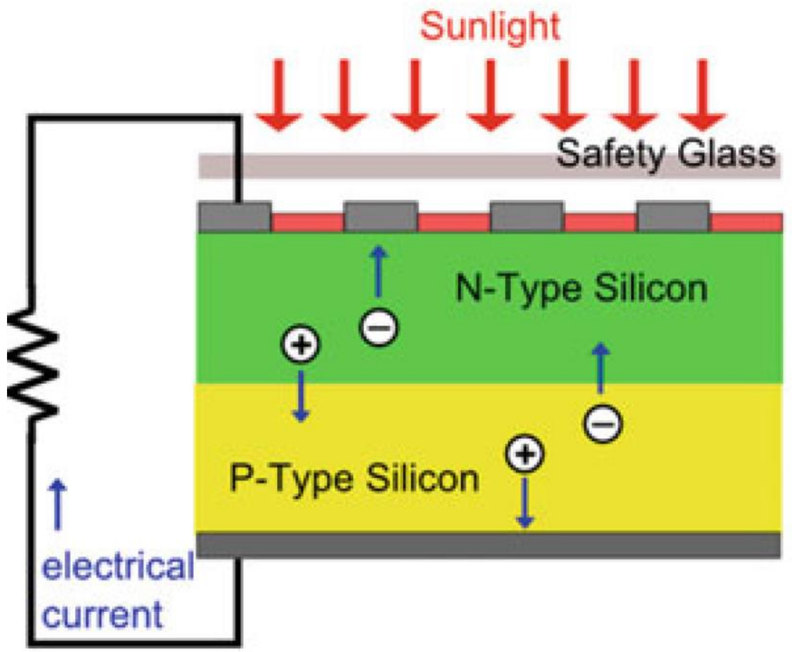
  Single junction p-n theoretical limit ~35%

  46% efficiency achieved by multijunction p-n
- Suitable for remotely operated devices – agriculture, smart city, structural health monitoring
- Wide power range – mW to hundreds of W

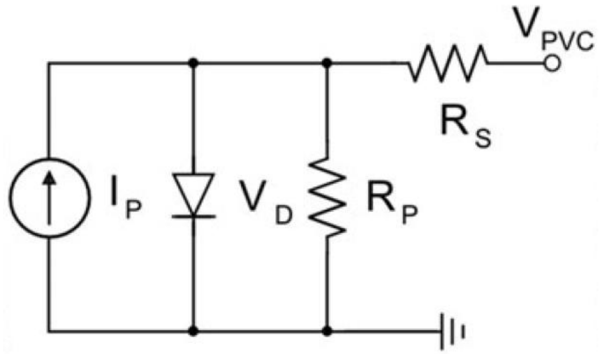
V-I Characteristics



Physics



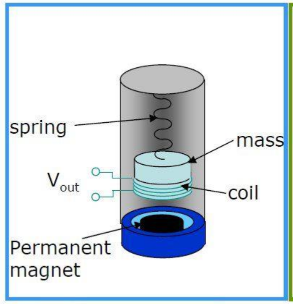
Circuit model

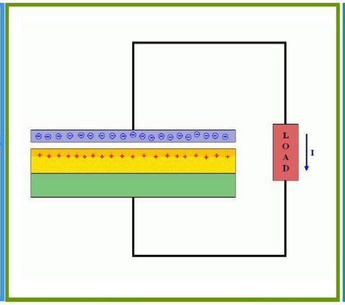


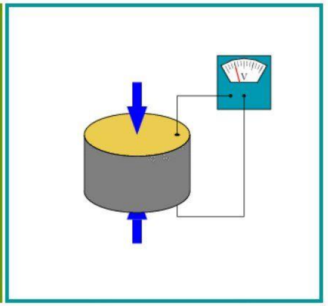
Energy Harvesting – Vibration

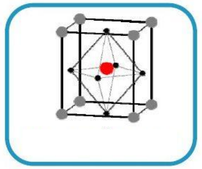
Types of vibration harvesters

- Electromagnetic – electrical conductor movement through magnetic field
- Electrostatic – relative motion of variable capacitor plates
- Piezoelectric – piezo materials produce voltage when mechanically stressed









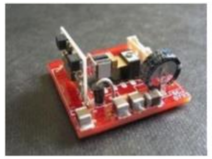
Comparison

Type	Advantage	Disadvantage
Electromagnetic	• No need for smart material • No external voltage source	• Bulky size • Difficult integration, incompatible MEMS • Max voltage 0.1V
Electrostatic	• No need for smart material • Compatible with MEMS • Voltages 2~10V	• External voltage (charge) source • Mechanical constraints needed • capacitive
Piezoelectric	• No external voltage source • Voltages 2~10V • Compact • Compatible with MEMS	• Depolarization • Brittle material • Charge leakage • High output impedance

Perpetuum PMG17 (England)

Up to 45mW @ 1g rms (15Hz)

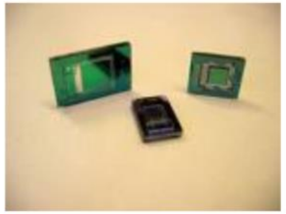
nPower® PEG



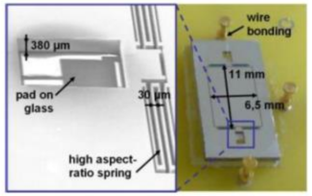
Micro-electromagnetic generator S. Beeby 2007, (UK)

Mide' Volture (USA)
5mW @ 1grms (50Hz)

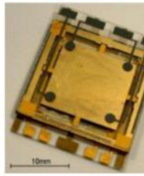
Holst-IMEC (Germany)
Micro PZ generator
500Hz 60uW @ 1g



ESIEE Paris – A. Mahmood Parracha



Imperial College, Mitcheson 2005 (UK)
Electrostatic generator 20Hz
2.5uW @ 1g



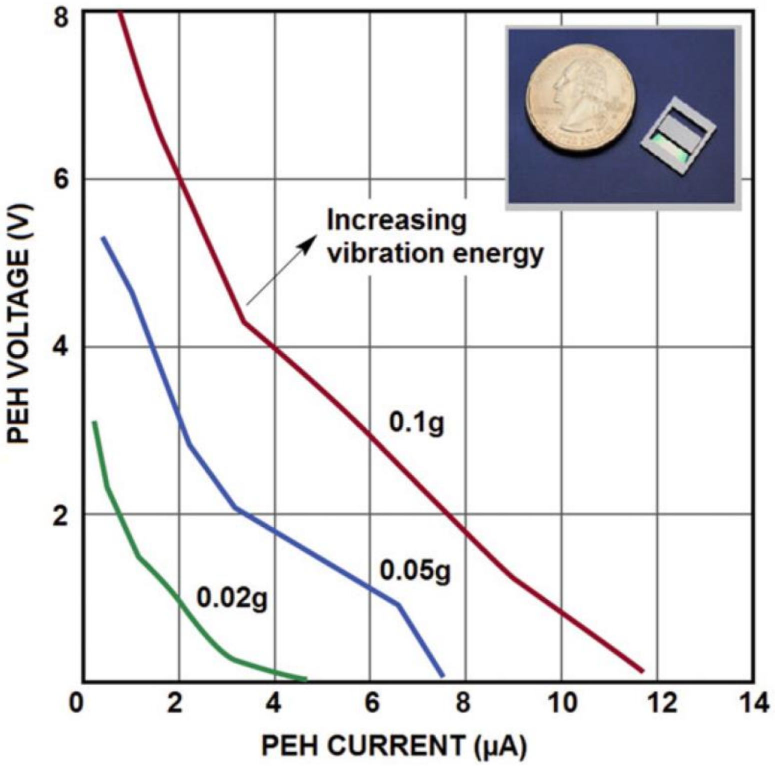
Microlab at UC Berkeley (Mitcheson)

Energy Harvesting – Vibration / Piezoelectric

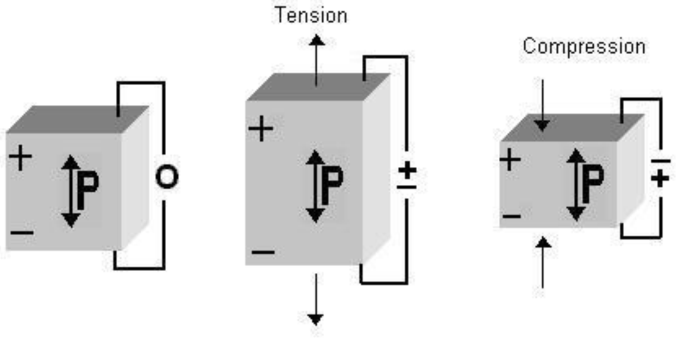
Characteristics

- Piezoelectric crystals can be embedded together with MEMS
- Possible to harvest motion energy
- Resonance drivers
- Suitable for industry applications, condition of equipment monitoring, wearables

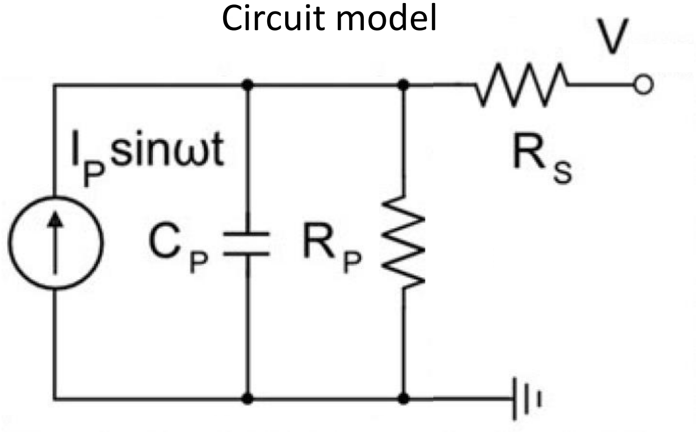
V-I Characteristics



Physics



Circuit model

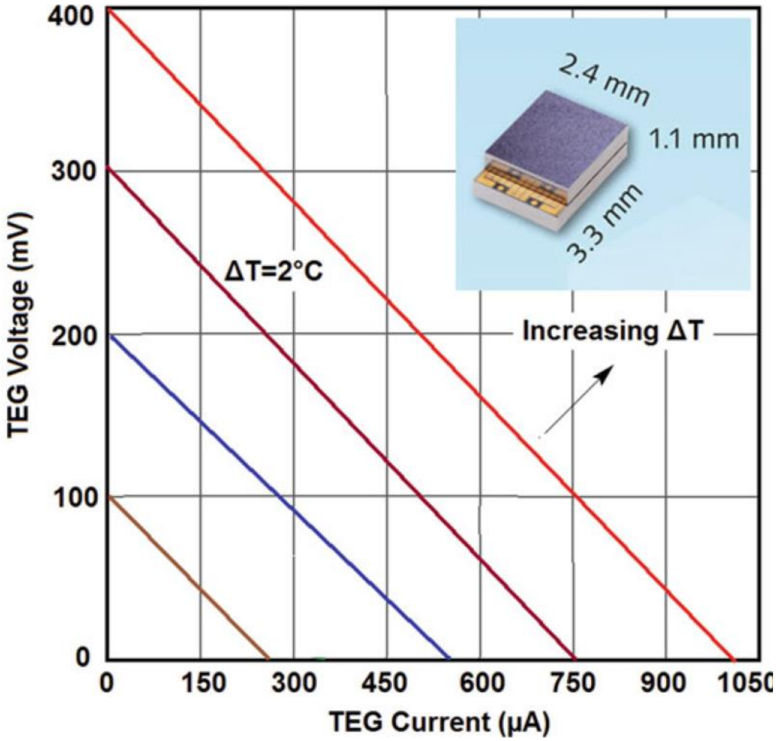


Energy Harvesting – Thermal

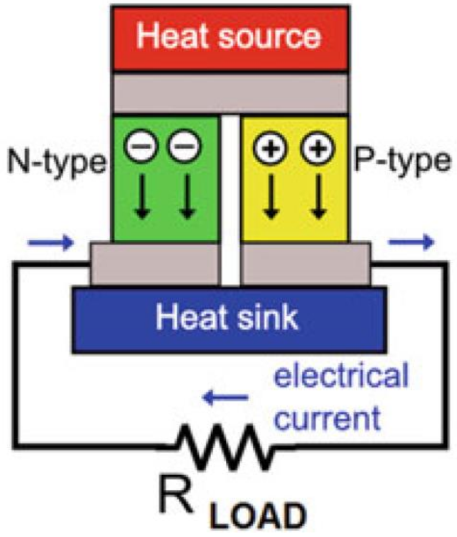
Characteristics

- Thermal gradients (Thermoelectric)
- No moving parts –> no maintenance
- Scalable to the nanoscale
- Most losses result in heat
- The power generated by a TEG is proportional to the square of (ΔT)
- Variation in the temperature of the heat source can also lead to unstable voltage output.
- Waste heat from many systems could be harvested home, industry, background, human body

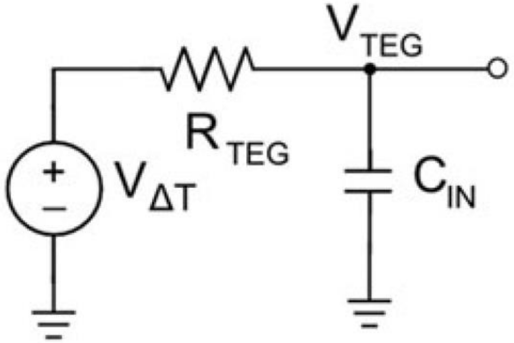
V-I Characteristics



Physics



Circuit model

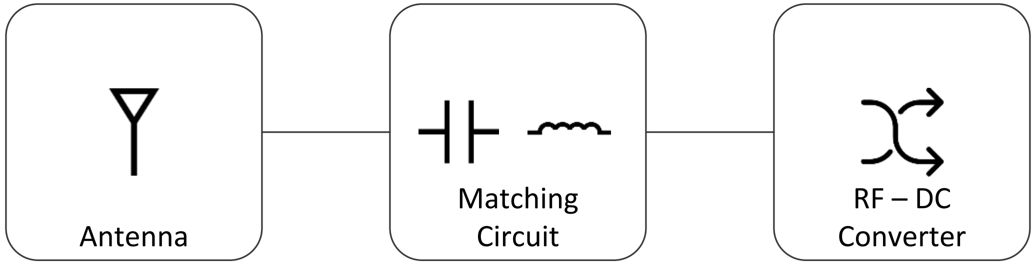


Energy Harvesting – RF

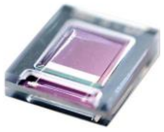
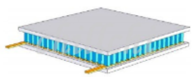
Characteristics

- Freely available ambient RF energy – TV, GSM, WiFi
- Always available
- Suitable for low power budget devices
- 3W transmitter -> mW within 1m and µW at around 10m.
- Industrial Monitoring, Smart Grid, Defense, Smart buildings, Remote monitoring
- Efficiency inversely proportional to distance
- Being informed about the amount of power that the system is required to handle helps the designer in choosing the right technology and method.

Harvester Architecture



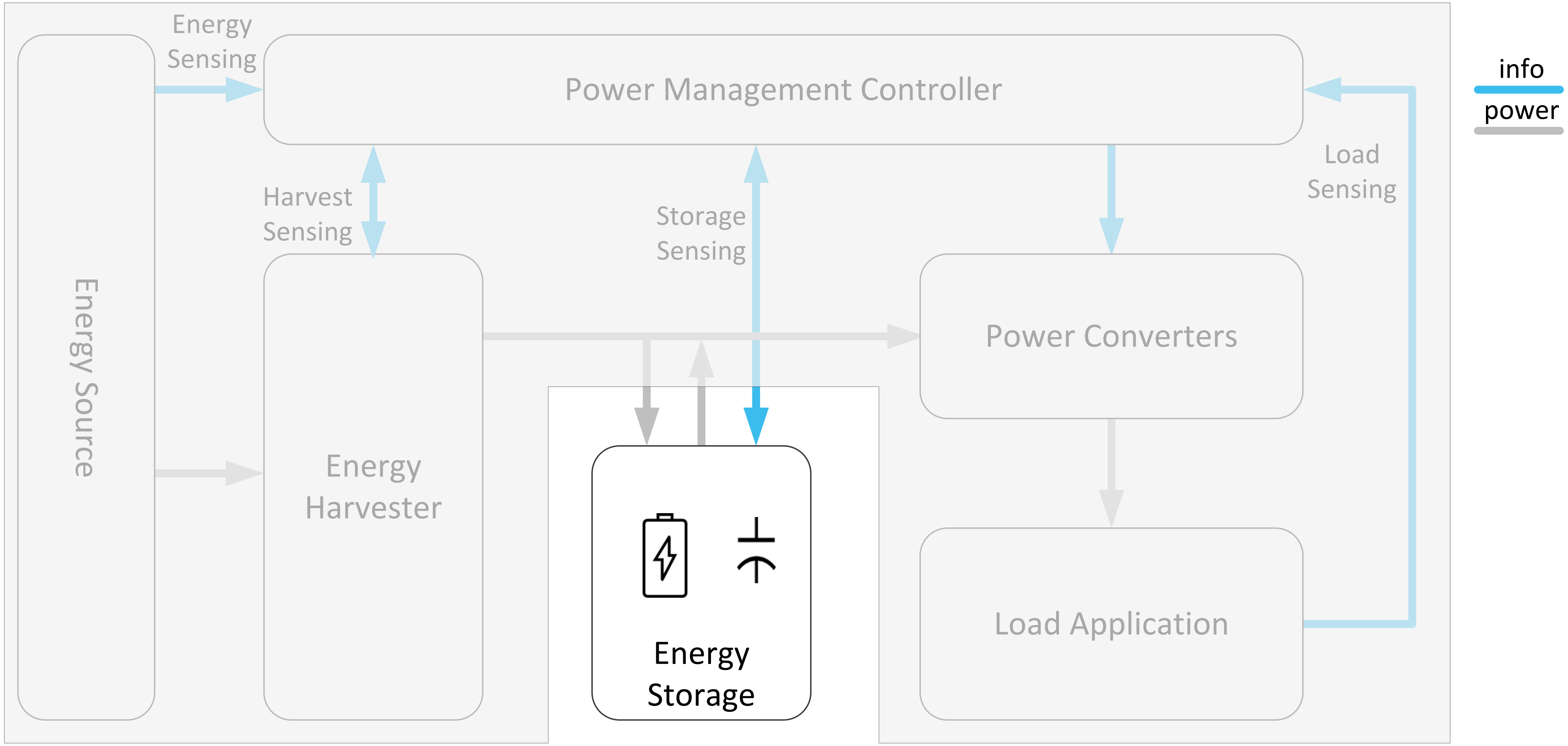
Energy Sources – Wrap-up

Energy Source	Challenge	Typical Impedance	Typical Voltage	Typical Power Output	Cost of Harvester
Light 	Conform to small surface area; Wide input voltage range	Varies with light input; Ωs to 10s of kΩs	DC: 0.5V to 5V [Depends on # of cells in array]	10µW – 15mW (Outdoors: 0.15 mW – 15 mW)	0.5 $ - 10 $
Vibration 	Variability of vibration frequency	Constant impedance 10s of kΩs to 100kΩs	AC: 10s of volts	1µW – 20mW	2.5 $ - 50 $
Thermal 	Small thermal gradients; Efficient heat sinking	Constant Impedance 1Ω to 100s of Ωs	DC: 10s of mV to 10V	0.5mW – 10mW (20°C gradient)	1 $ - 30 $
RF 	Coupling & Rectification	Constant impedance Low kΩs	AC: Varies with distance and power 0.5V to 5V	Wide range	0.5 $ to 25 $

Energy Sources – Commercial Examples

Energy Source	Voc (max)	Isc (max)	V_{MPP}	P_{MPP}	Dimensions (L x W x H mm^3)	Power Density ($\mu\mathrm{W}/\mathrm{mm}^3$)
Light (EnOcean) 	4 V	7 µA (@200 lux)	3 V (@200 lux)	14 µW (@200 lux)	35 x 13 x 1	0.03
Vibration (Microgen) 	8 V	14 µA (@0.1 g)	4 V (@0.1 g)	56 µW (@0.1 g)	15 x 15 x 6	0.04
Thermal (Micropelt) 	0.3 V	750 µA (@ ΔT = 2°C)	0.15 V (@ ΔT = 2°C)	56 µW (@ ΔT = 2°C)	4 x 3 x 1	4.67
RF (PowerCast) 	0.275 V	240 mA (@ 0dBm)	0.175 V (@ 0dBm)	35 µW (@ 0dBm)	14 x 14 x 2.3	0.08

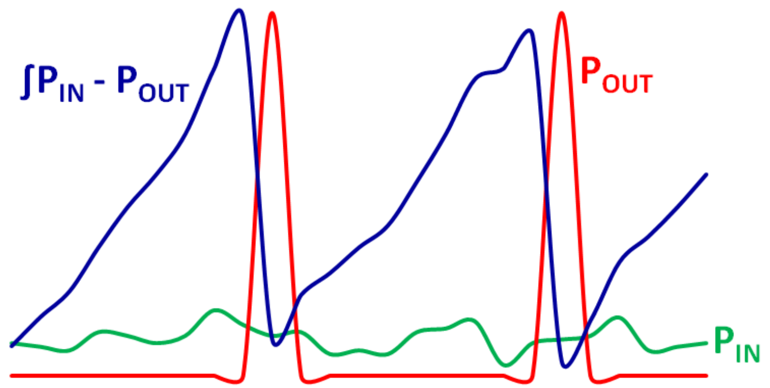
Energy Storage



Energy Storage

- Energy harvesting requires energy storage element or a buffer.
- In IoT storage elements or buffers are implemented in the form of a capacitor, standard rechargeable lithium battery, non- rechargeable primary batteries or new technology like thin-film batteries.
- Some applications require power for only a very short period of time, as short as the discharge time of a capacitor.
- Other applications require relatively large amounts of power for an extended duration, use of a traditional AA or a rechargeable lithium battery is necessary.

Energy Buffering



	Li-Ion Battery	Thin Film Battery	Super Cap
Recharge cycles	Hundreds	Thousands	Millions
Self-discharge	Moderate	Negligible	High
Charge Time	Hours	Minutes	Sec-minutes
Physical Size	Large	Small	Medium
Capacity	0.3-2500 mAh	12-1000 µAh	10-100 µAh
Environmental Impact	High	Minimal	Minimal

Conclusion & Future Directions

IoT is expected to grow through the convergence

with other social trends and technology undertakes;

Accelerated urbanization and increased human population

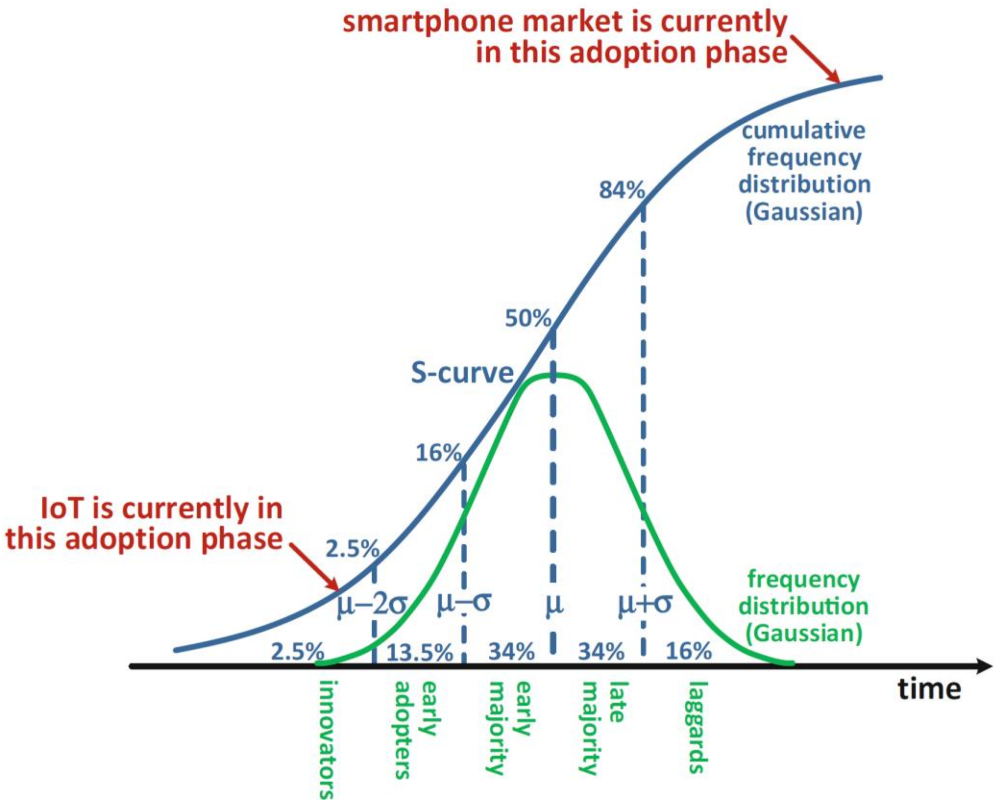
Geo socialization

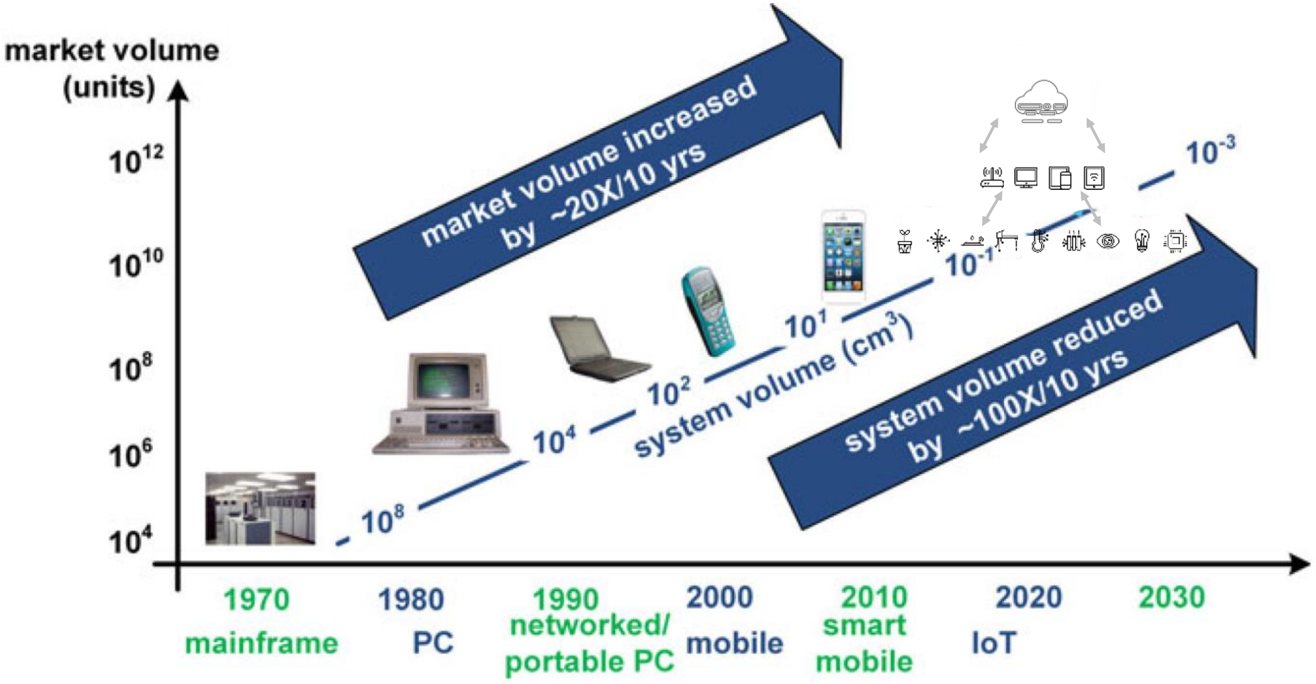
Pervasive assistive or proactive robot technology

Constant and data-driven product upgrade

Three-dimensional remote physical interaction

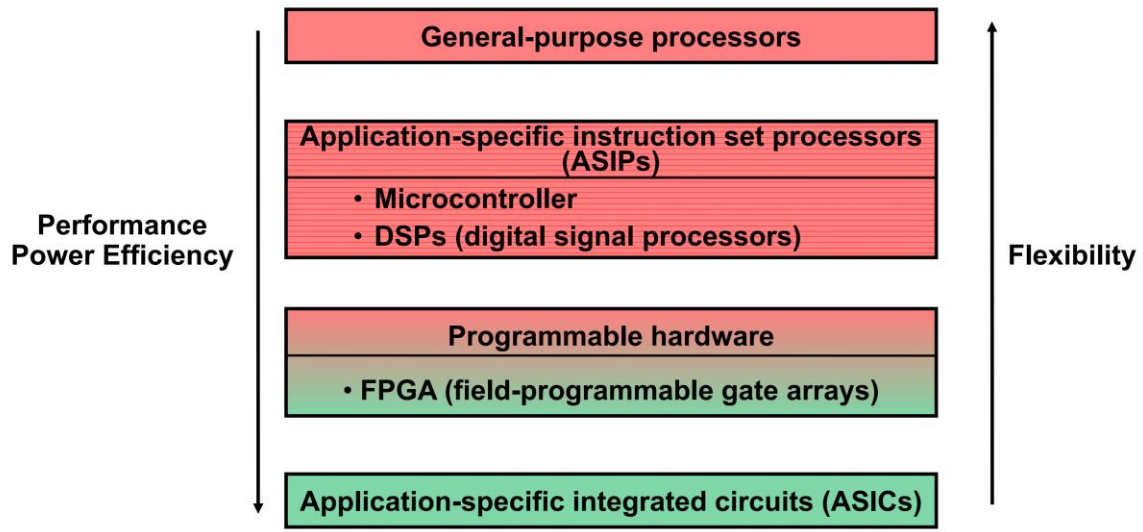
participatory sensing



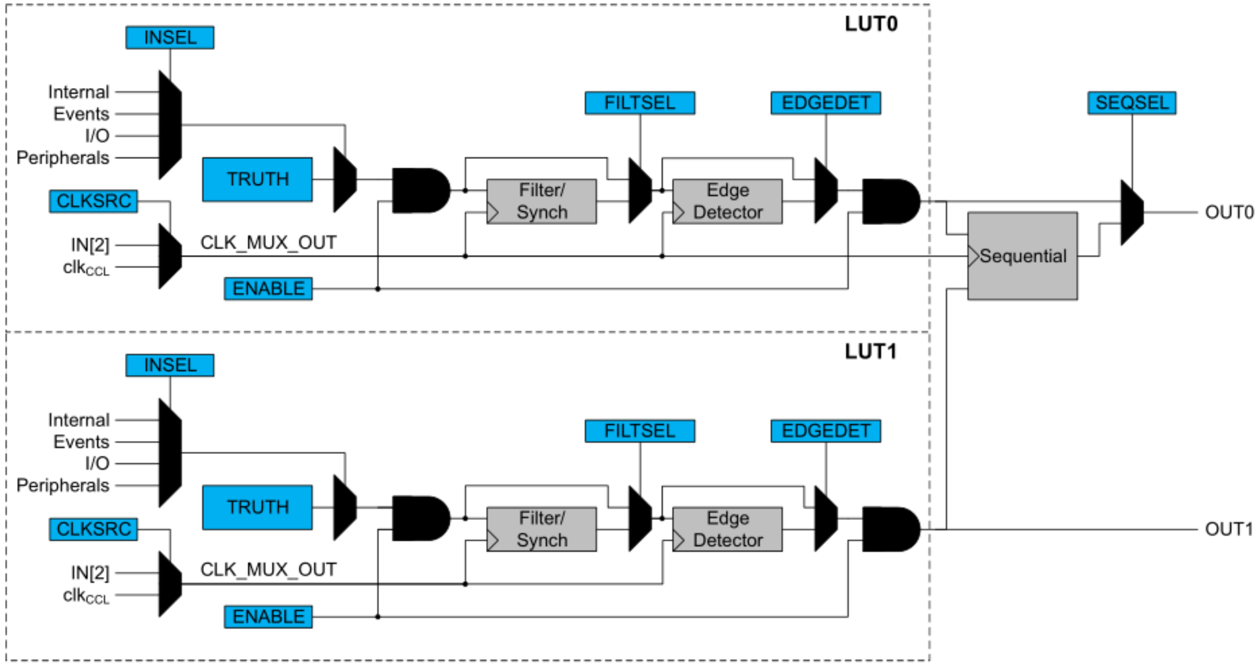


Conclusion & Future Directions

Short term trend for embedded system in IoT



Current state – Configurable custom logic from Atmel



Thank you.
Q&A

Resources

- Priya, Shashank, and Daniel J. Inman, eds. Energy harvesting technologies. Vol. 21. New York: Springer, 2009.
- Beeby, Stephen, and Neil White. Energy harvesting for autonomous systems. Artech House, 2010.
- Panda, Preeti Ranjan, et al. Power-efficient system design. Springer Science & Business Media, 2010.
- Lee, Hyung Gyu, and Naehyuck Chang. "Powering the IoT: Storage-less and converter-less energy harvesting." Design Automation Conference (ASP-DAC), 2015 20th Asia and South Pacific. IEEE, 2015.
- http://www.ewp.rpi.edu/hartford/~ernesto/F2012/ET/MaterialsforStudents/Ott/Shen2009-Thesis-PiezoelectricEnergyHarvestingLowFreq.pdf
- https://cora.ucc.ie/bitstream/handle/10468/1410/thesis.pdf?sequence=2&isAllowed=y
- http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1043&context=ceendiss
- http://www.eit.lth.se/sprapport.php?uid=823
- http://www.eembc.org/ulpbench/elektroniknet_article_2015_07_21/
- http://www.atmel.com/images/Redefining_the_Power_Benchmark.pdf
- http://www.silabs.com/whitepapers/manage-the-iot-on-an-energy-budget
- http://www.mouser.com.tr/applications/energy_harvesting/
- http://www.linear.com/doclist/?ci=1799&dt=70
- http://www.iop.org/resources/energy/
- http://assets.madebydelta.com/docs/share/Produktudvikling/Power_converter-for-energy-harvesting.pdf
- http://www.psma.com/sites/default/files/uploads/tech-forums-energy-harvesting/presentations/2012-apec-113-low-power-converter-technology-energy-harvesting_0.pdf