Optimal IoT Sensor Design

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CS698T, Lecture 12

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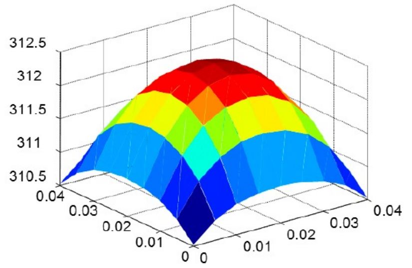
Wearable Sensors

Wearable sensor design requirements

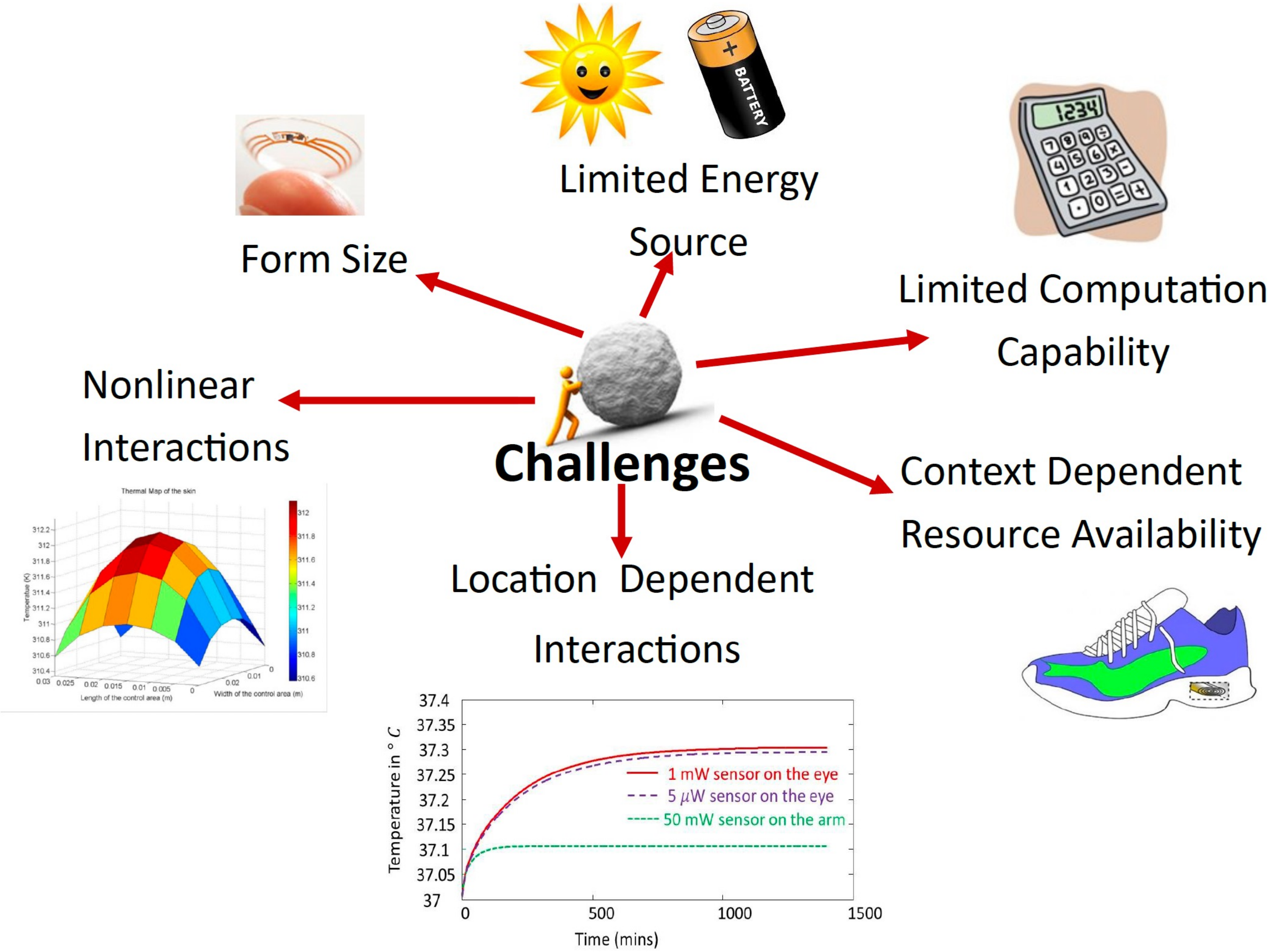
Enable long term operation



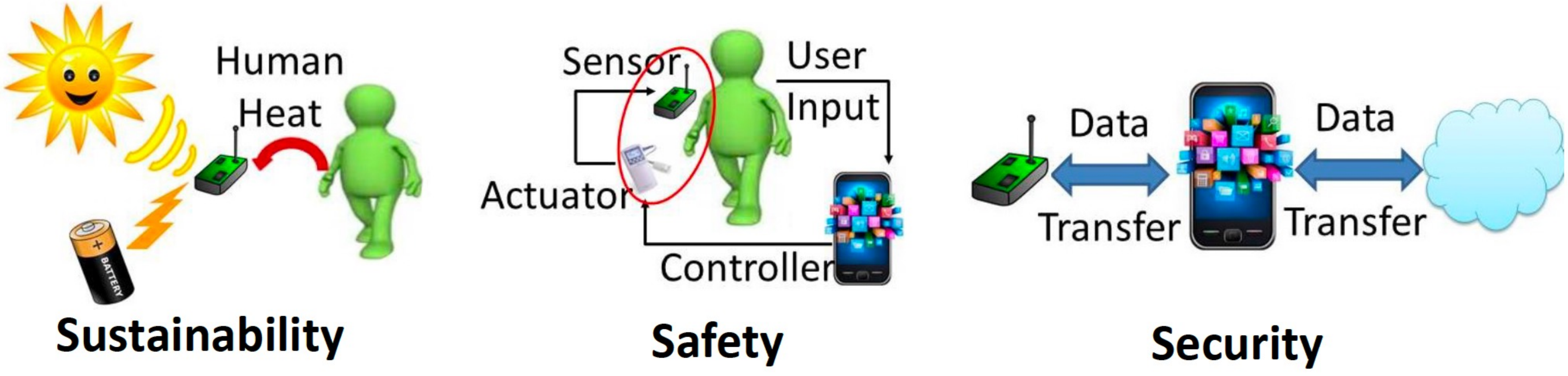
Avoid physical injury due to sensor operation

Data Security

Wearable Sensors Challenges



Optimal Wearable Sensor Design

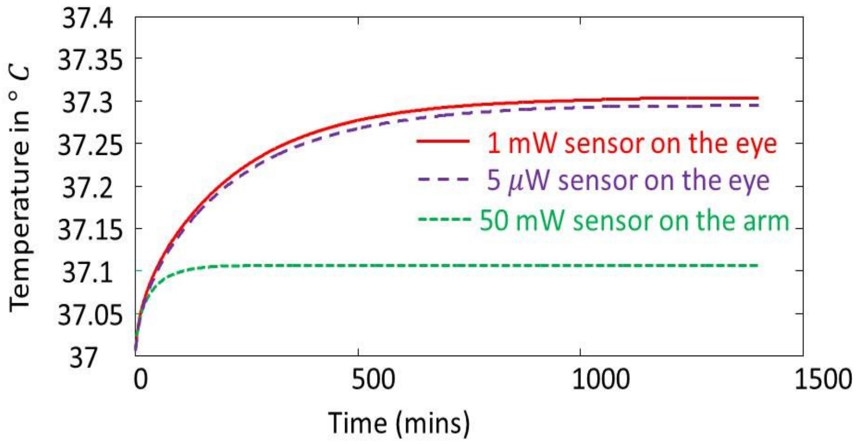


Problem Statement:

Given a set of design requirements expressed in the form of a set of favorable states, find a sensor design that always keeps the system in one of the favorable states.

Thermal Safety

- Thermal effects of a sensor on the human varies with the location and placement of the sensor



- Thermal interaction of the sensor with the skin tissue is represented using Penne's Bioheat equation:

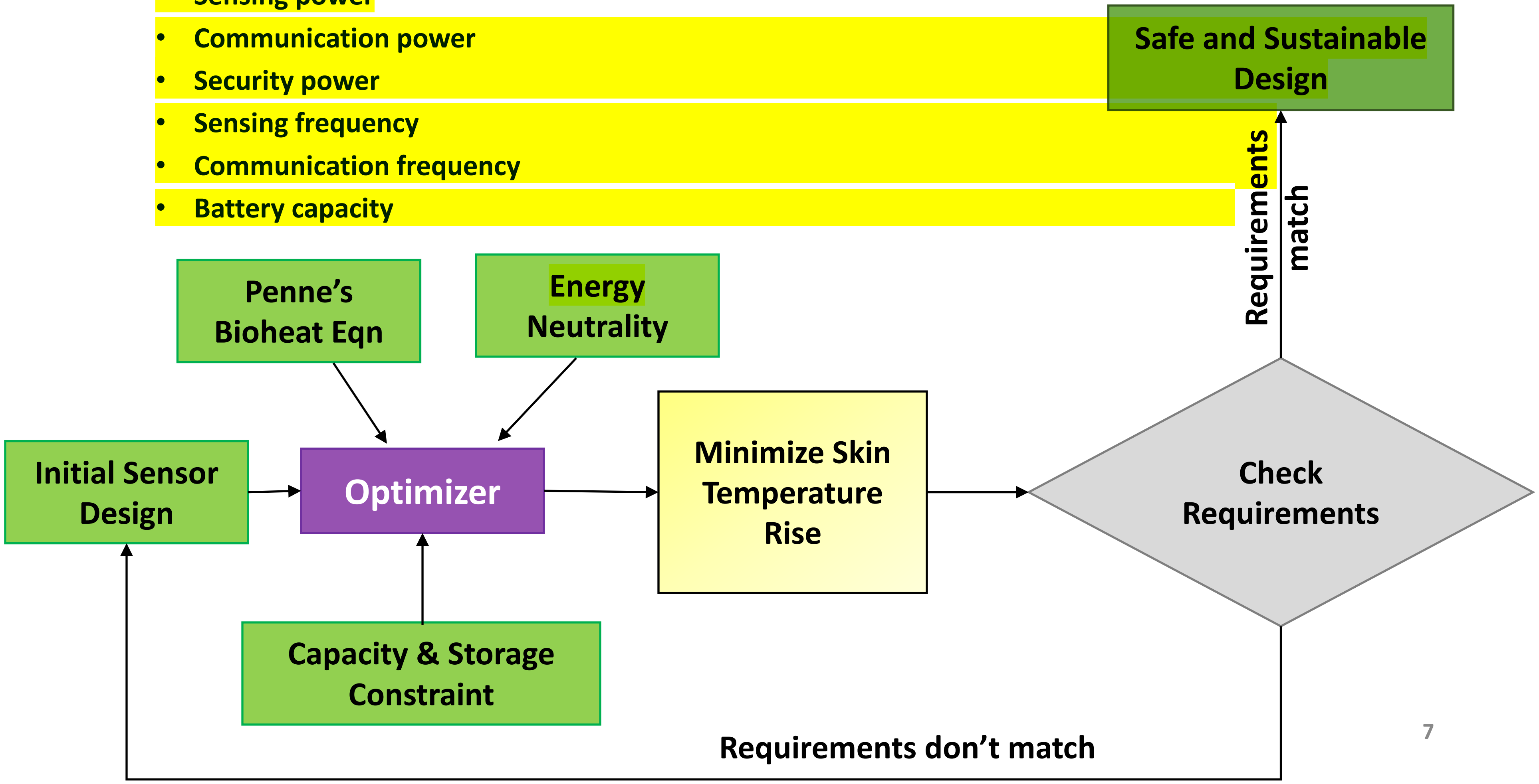
$$\rho C_p \frac{dT}{dt} = K\nabla^2 T - b(T - T_b) + \rho \mathrm{SAR} + P_{avg}$$

ρ: Mass density
C_p: Specific heat
K: Thermal conductance
T: Temperature of the body part

b: Blood perfusion constant
T_b: Blood temperature
SAR: Specific absorption rate of the tissue
P_{avg}: Average power required by the sensor

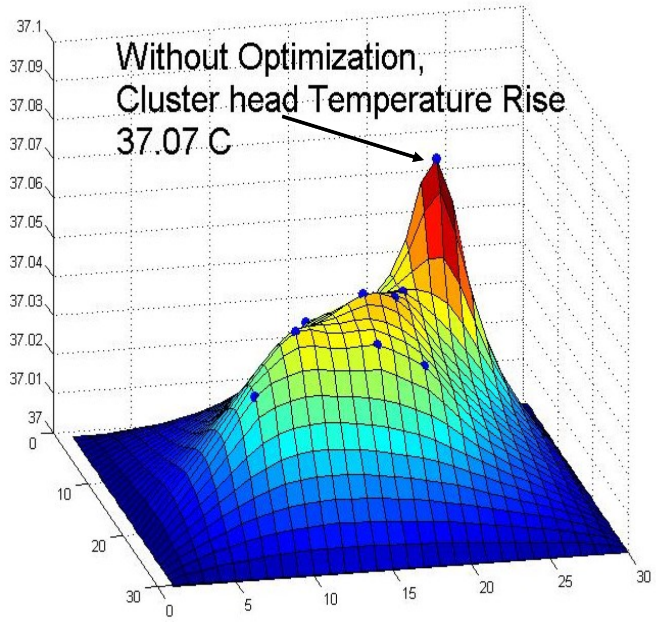
Optimization Problem Formation – Thermal Safety [1]

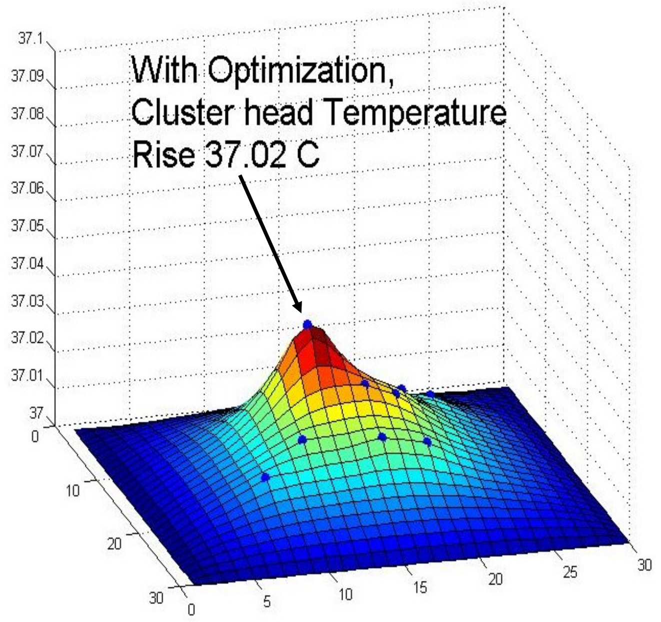
- To minimize increase in the skin temperature, optimize sensor design parameters
  - Sensing power
  - Communication power
  - Security power
  - Sensing frequency
  - Communication frequency
  - Battery capacity



Thermal Safety Example Results [1]

- **Aim:** Skin temperature increase should not be more than 0.02 C
- **Initial values:** Minimum values of available wearable sensors
- **Validation:** Shimmer 2R platform with ECG sensor wore for 12 hours





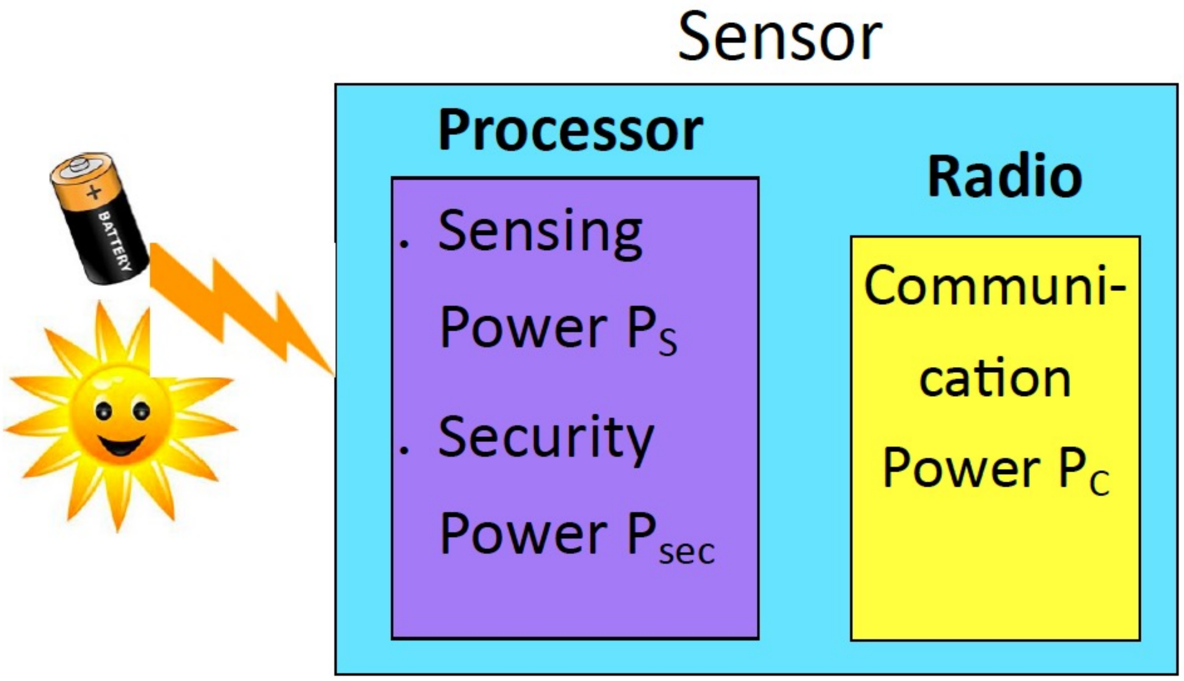
Energy Harvesting Methods [2]

- Solar Energy - Photovoltaic technology generates direct current from semiconductors when illuminated by photons
- Piezoelectricity – Generates current proportional to the applied pressure
  - Requires dynamic pressure, does not work with the static pressure
  - Energy of a vibrating body transfers to a piezoelectric body when the oscillating frequency of a vibrating body and the resonating frequency of a piezoelectric body are synchronized
- Radio energy – Harvesting energy from radio waves using a transmitter, enables wireless charging of the sensors
  - the amount of energy received at the receiver end is not equal to the exact value sent by transmitter
- Thermal Energy – generates electricity when there is a difference in the temperature
- Wind Energy – harvests energy from the wind using turbines
  - Wind energy cannot be considered as a primary source for electricity generation due to its intermittent behavior which causes instability to the power system
- Human body - energy from heat and motion [5]
  - Sensors need to be worn all the time
  - Human moving is unpredictable and slow
  - Body heat changes w.r.t. time of the day and activities
- Bio Energy – harvests energy from the plants produced electric signals
  - Soil energy for powering wireless sensors – provides an average power of 60 to 100 µW that is sufficient to power the BLE sensor

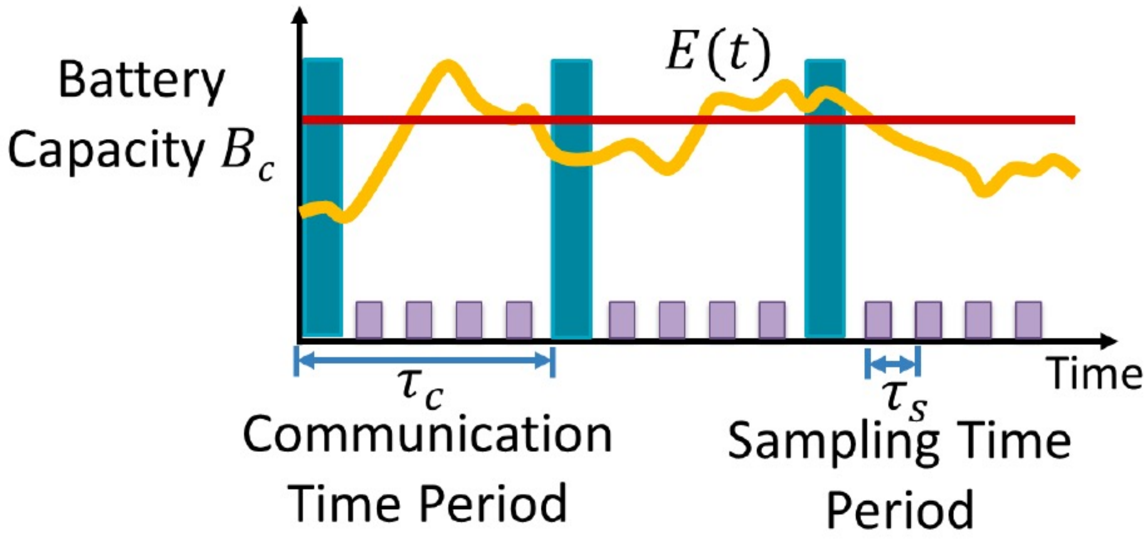
Analysis of Energy Harvesting Techniques [4]

Energy source	Technology	Power density	Advantages	Disadvantages	Application domains
Solar	PV cell	10 - 100 mW / cm^2 (outdoor) < 100 μW / cm^2 (indoor)	High-output voltage Low fabrication costs Predictable	Unavailable at night Non-controllable	Environment monitoring, healthcare, agriculture
RF	Antenna	0.01 - 0.1 μW / cm^2 1- 10 mW / cm^2	Available anywhere, anytime Predictable Controllable	Distance dependent Low-power density	Environment monitoring
Mechanical vibrations and pressure	Piezoelectric	4 - 250 μW / cm^3	High-power density No external voltage source Simplicity design and fabrication Controllable	Highly variable output Unpredictable	Infrastructure monitoring, automotive
	Electromagnetic	300 - 800 μW / cm^3	High-output currents Robustness Low-cost design Controllable	Relatively large size Unpredictable	
	Electrostatic	50 – 100 μW / cm^3	High-output voltage Relatively larger output power density Possibility to build low-cost devices Controllable	Requires bias voltage Unpredictable	
Human heat	Piezoelectric Pyroelectric	< 35 μW / cm^2	Sustainable and reliable Available Controllable	Low-power density Unpredictable	Healthcare
Biomechanical	Electromagnetic Piezoelectric Triboelectric Electrostatic	< 4 μW / cm^3 < 300 μW / cm^3	Available Controllable	Low-power density Unpredictable	Healthcare
Bio [102]	Metal electrodes	Extremely low wattage	Available Controllable	Extremely low wattage Suitable for nanoscale electrical devices	Environmental sensing in agricultural applications

Energy Neutrality



Energy obtained from scavanging source is E(t)

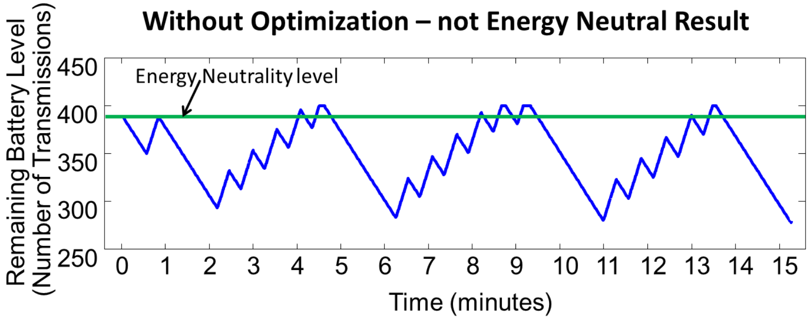


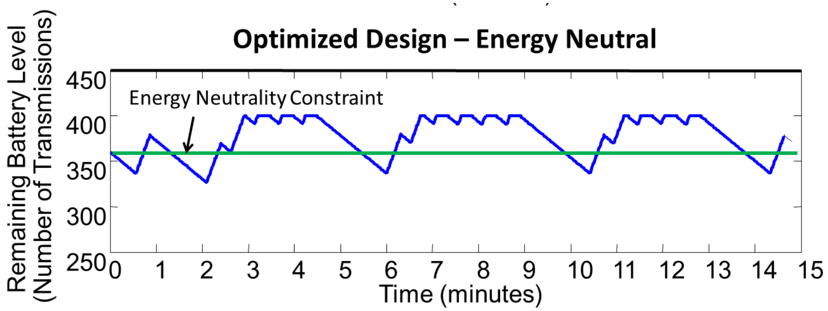
Optimization Problem Formulation – Energy Neutrality [1]

- **Find data sending frequencies when the scavenging source is available and unavailable that optimize the use of scavenged energy such that**
  - **Solar Energy: obtained when the scavenging source is available**
  - **Energy Neutrality: for every computation, current battery level = initial battery level**
  - **Storage Constraint: battery level ≥ 0**
  - **Battery Capacity Constraint: Stored Energy ≤ Battery Capacity**

Results

- MSP430 Solar Energy Harvesting Development toolkit
  - **Harvests energy from solar or ambient light**





Optimal Sensor Design for Mobile (Moving) Sensors [3]

- Deploy edge computing nodes near the IoT devices and offload the sensor computation on these high compute devices to save energy and reduce computation delay
- Mobility in IoT devices
  - Forces the system to find the nearest edge computing device for offload
  - Multiple edge computing devices
  - Difficult to predict the available resources, channel conditions etc
- Solution Approach
  - Consider user mobility and available energy harvested energy
  - Use of Lyapunov Optimization to optimize the harvestable energy, the task partition factor, the transmit power and the CPU-cycle frequencies

Technical Challenges in Developing Self-Sustainable IoT Devices [4]

- Harvested energy modeling
  - The availability of the harvested energy varies mostly with time in a non-deterministic manner.
- Harvested energy storage
  - Requirements: low cycling degradation, low current leakage, high energy density, and continued operation in harsh conditions
- Energy harvesting from multiple sources
- Size and cost efficiency
- Environmental impact with renewable energy sources

Reading Material

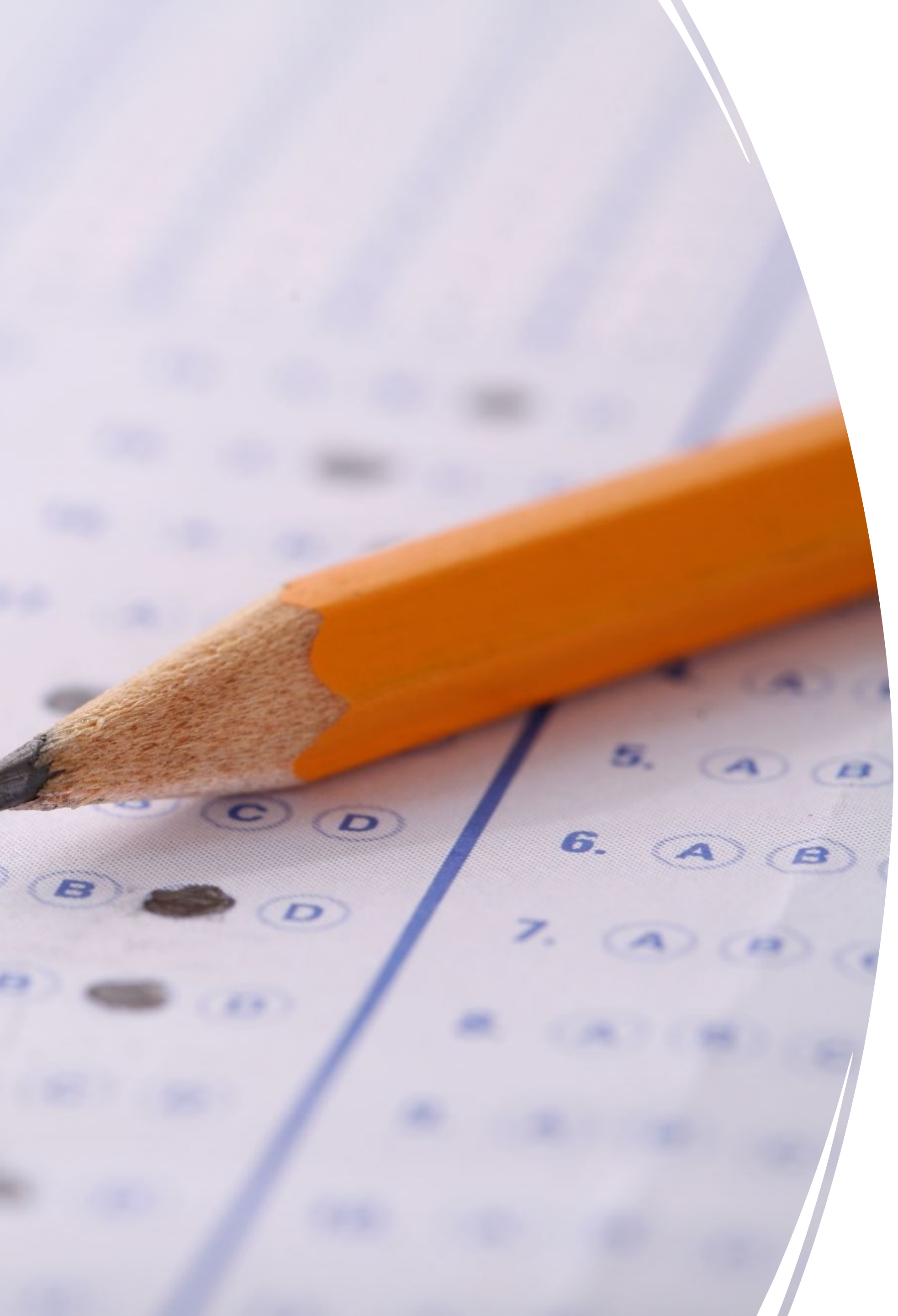
1. Priyanka Bagade, Ayan Banerjee, and Sandeep KS Gupta. "Optimal design for symbiotic wearable wireless sensors." In *2014 11th International Conference on Wearable and Implantable Body Sensor Networks*, pp. 132-137. IEEE, 2014

2. Akbari, Saba. "Energy harvesting for wireless sensor networks review." In *2014 Federated Conference on Computer Science and Information Systems*, pp. 987-992. IEEE, 2014.

3. Mobility-Aware Offloading and Resource Allocation in an MEC-enabled IoT Network with Energy Harvesting, 2021

4. Energy Harvesting Techniques for Internet of Things (IoT), 2021

5. A Hybrid Energy Harvesting Design for On-Body Internet-of-Things (IoT) Networks



Midterm Exam Evaluation

- Average: 28.6 / 40, Median: 30 / 40, Max:40 , Min: 10
- Descriptive questions
  - Rumor routing disadvantage
    - 2 separate disadvantages are expected
    - Needed a reason why each points is a valid disadvantage
  - Bridge monitoring system architecture
    - Needed separate answer (with respective numbering) to each of the 5 questions/points. A single paragraph containing answers in random order got partial credits.
    - Needed at least one reason for your design choices (it was mentioned as part of the question)

Questions?