ARTIST Workshop at DATE'06
W4: "Design Issues in Distributed, Communication-Centric Systems"

Information Society Technologies

Current Trends and Work Directions in Sensor Networks

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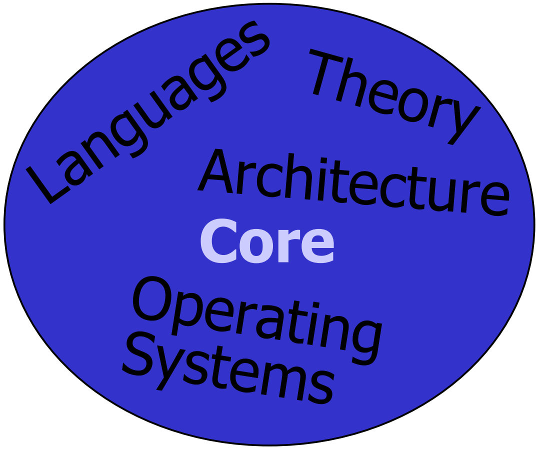
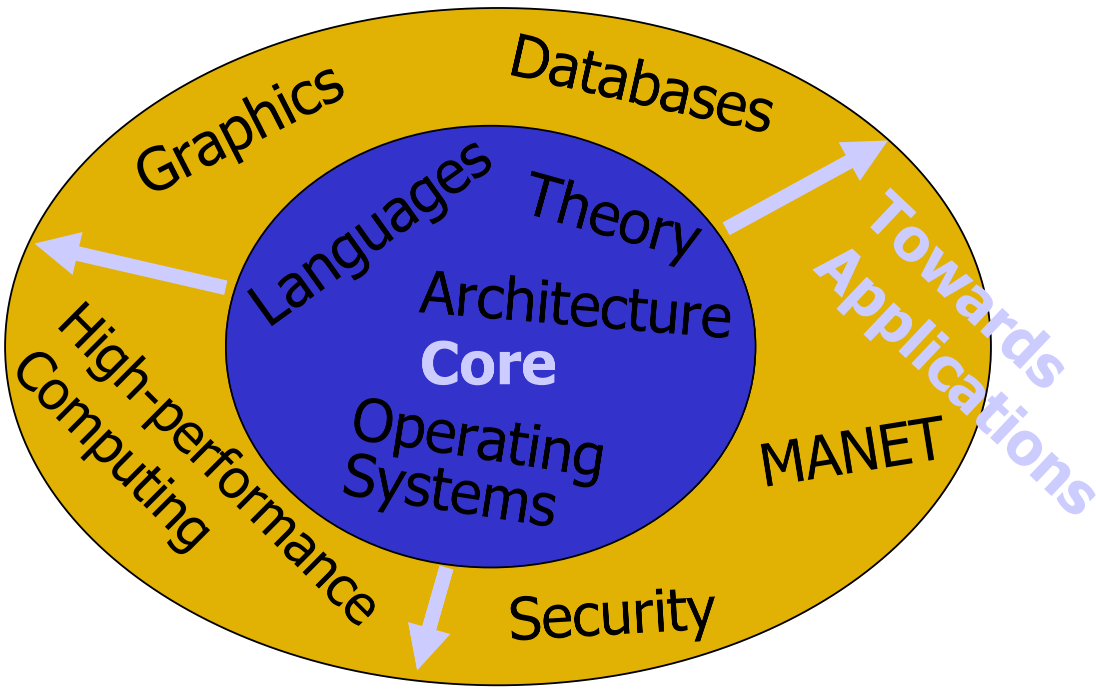
Where is Computer Science Research Going?

The beginning:



Where is Computer Science Research Going?



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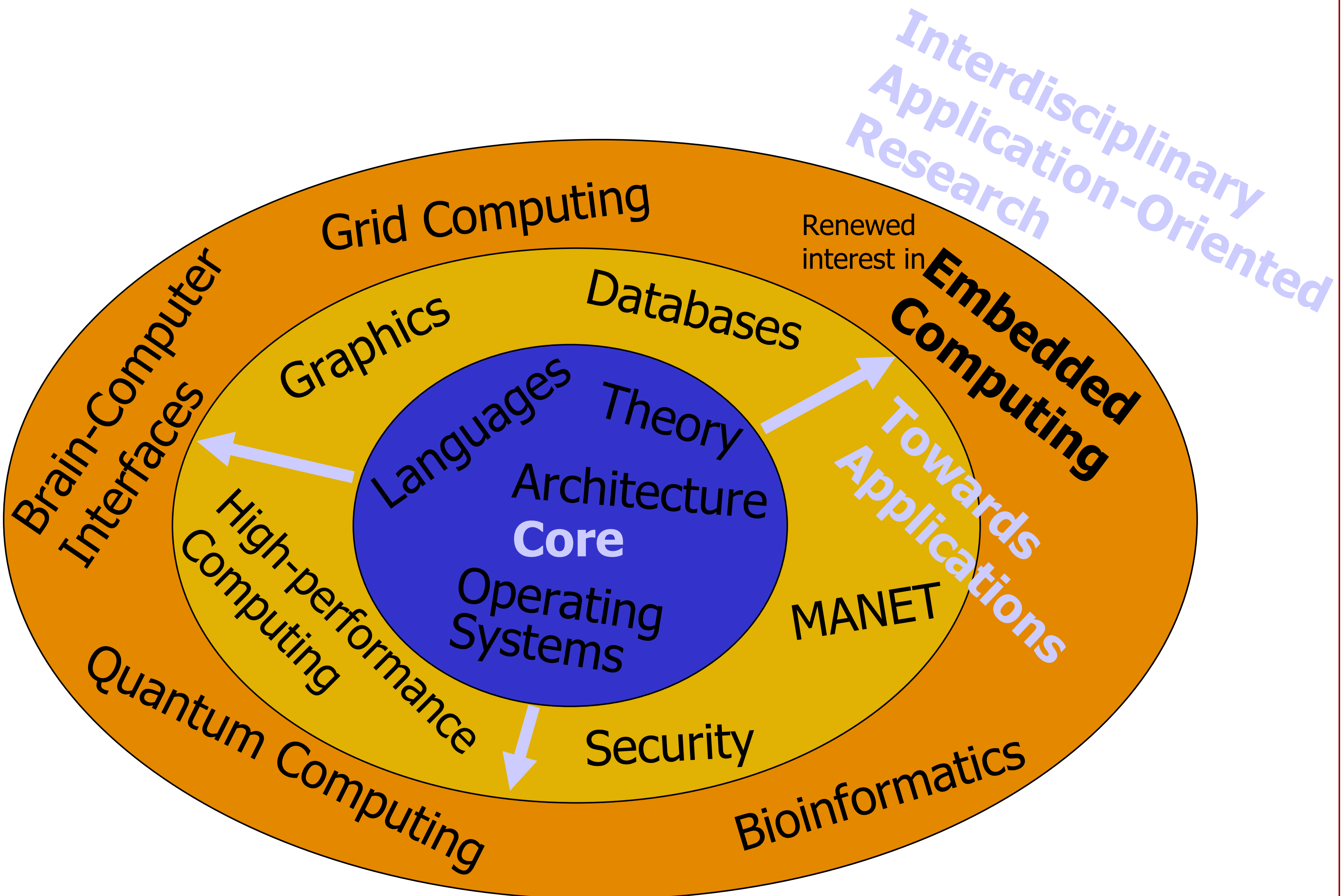
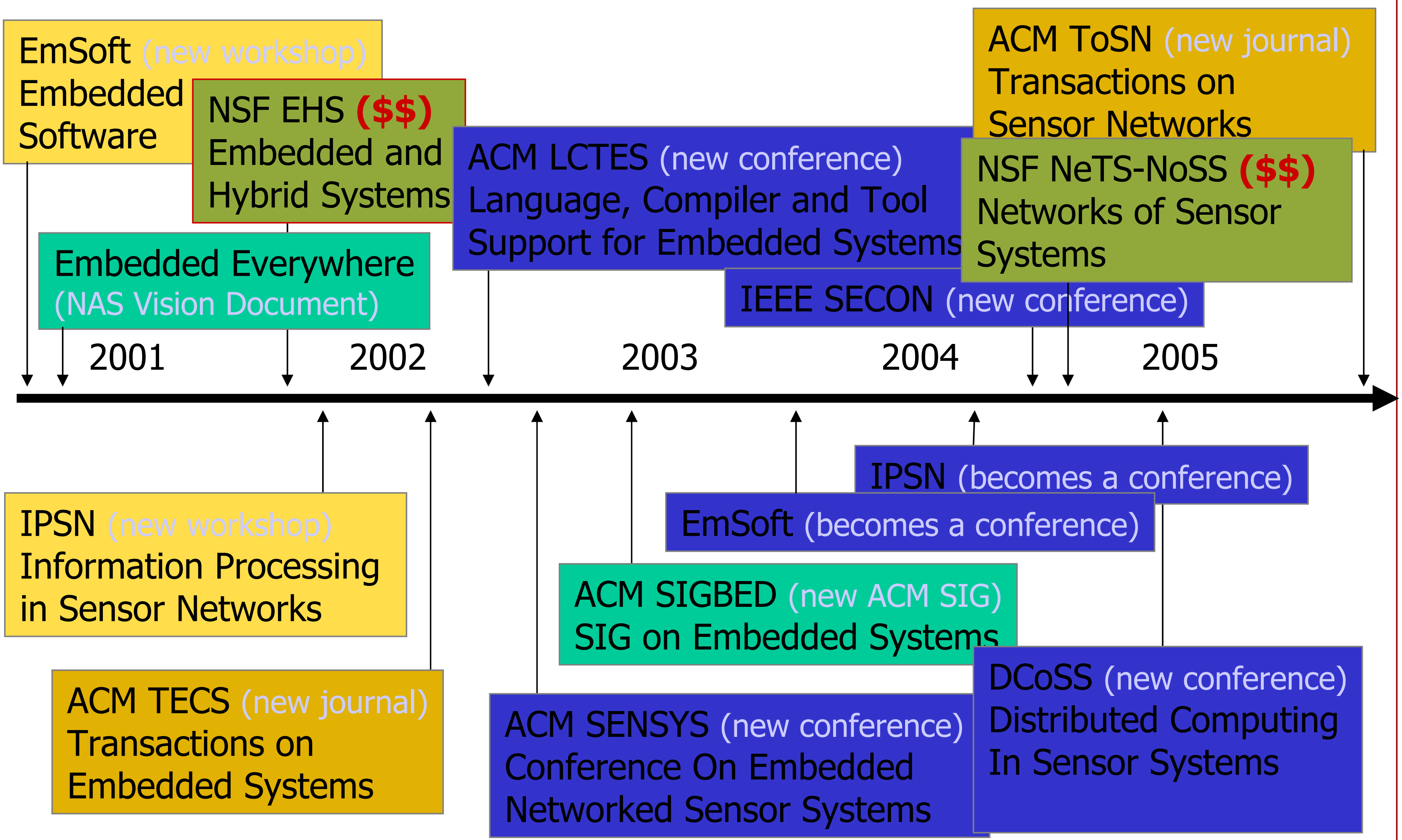


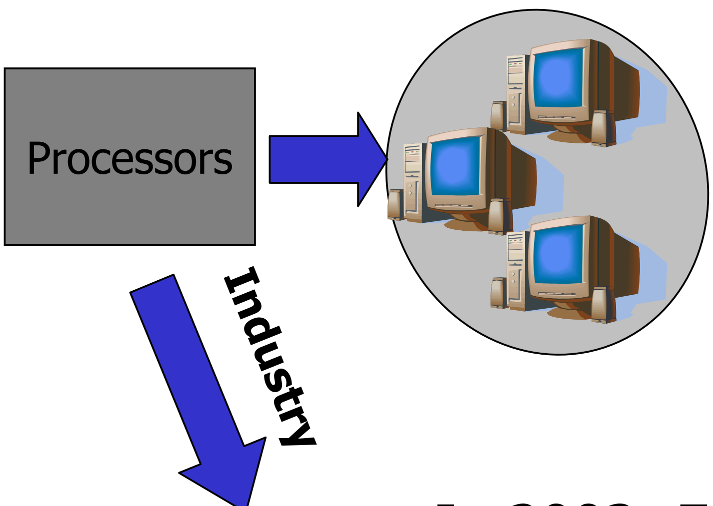
Expanding Interest in Embedded Computing and Sensor Networks



Trends in Embedded Systems

The Next Frontier

Where is embedded computing going?



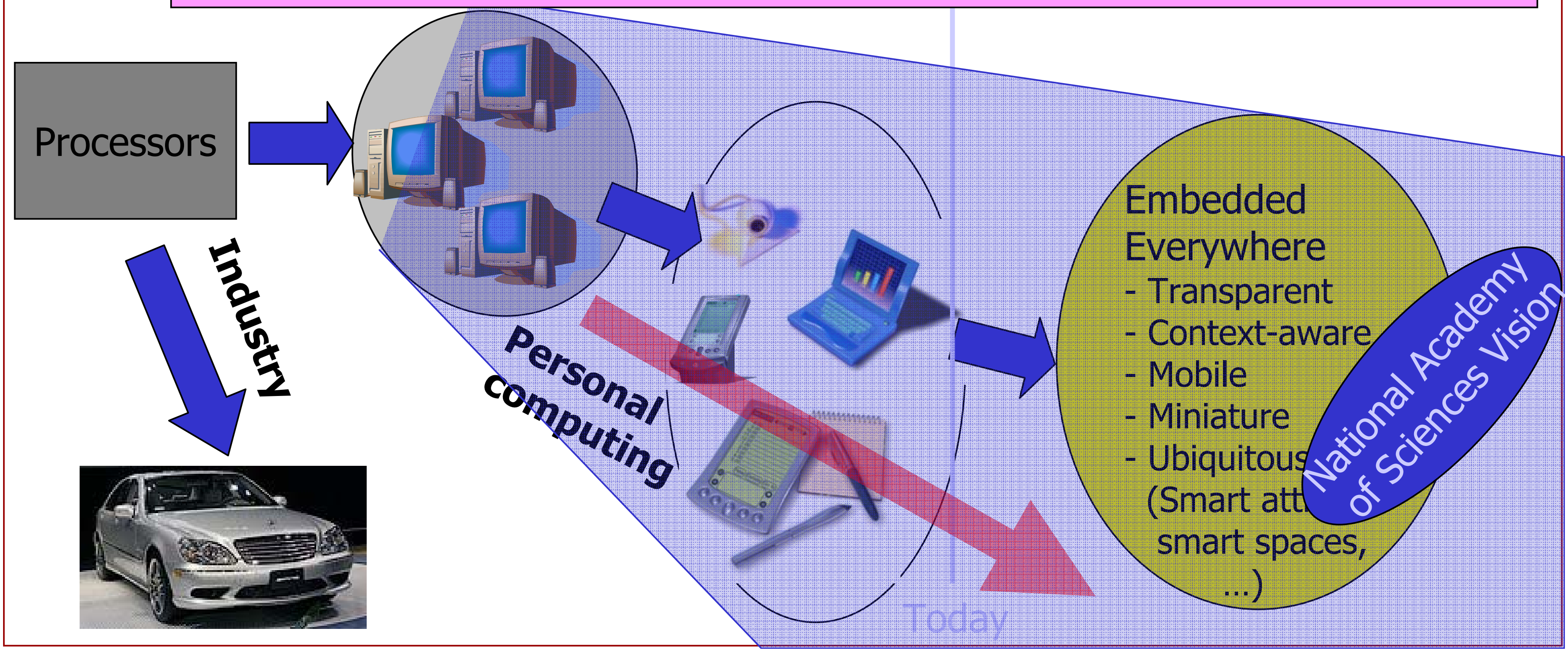
In 2003: Embedded processors are 98% of all processors manufactured

It's only the beginning…

Trends in Embedded Systems

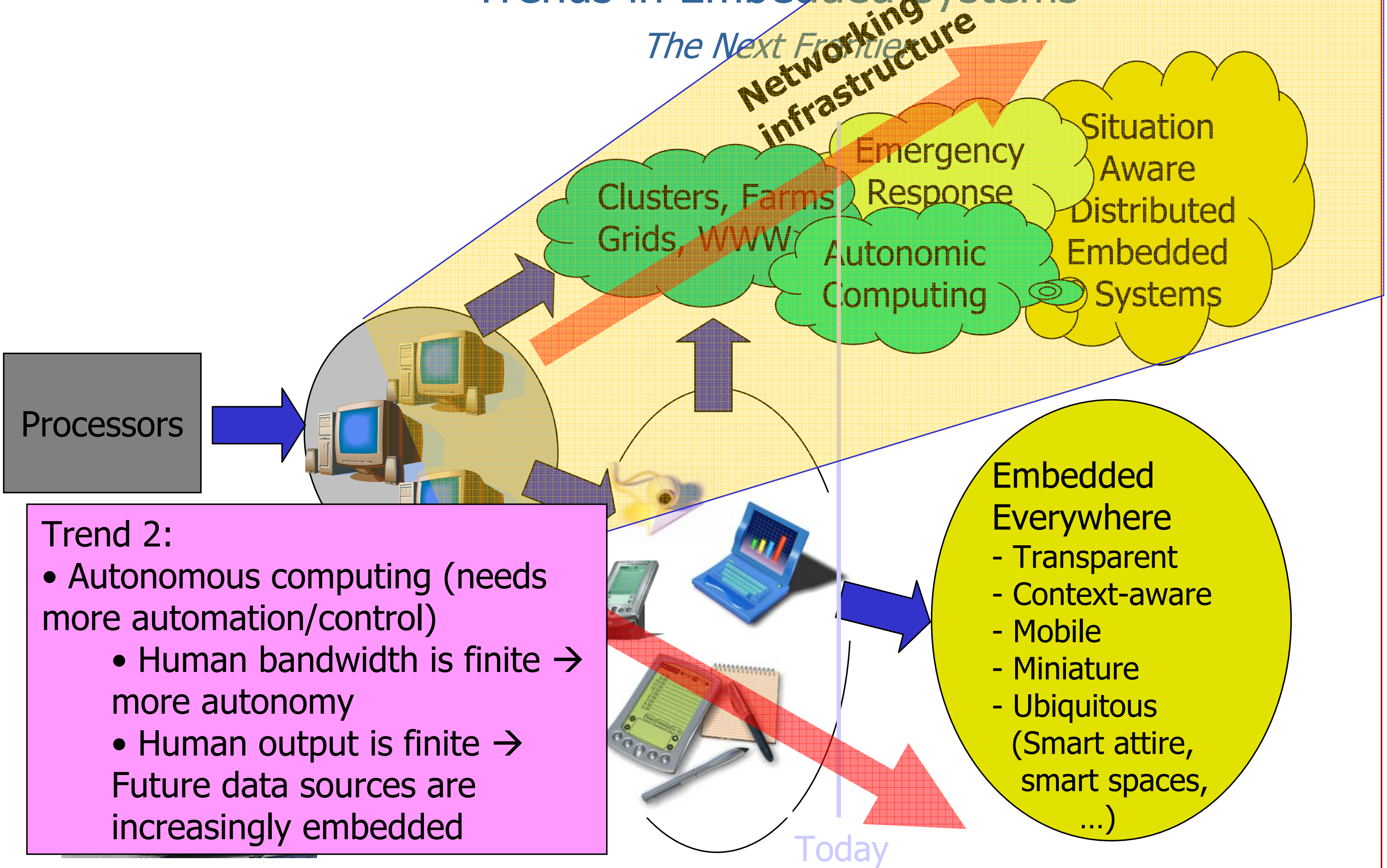
The Next Frontier

Trend 1:
- Invisible computing (needs more sensing)
  - Ubiquitous – instrument what we use most (attire, personal effects, …)
  - Context-aware (new sensors, new effectors)



Trends in Embedded Systems

The Next Frontier

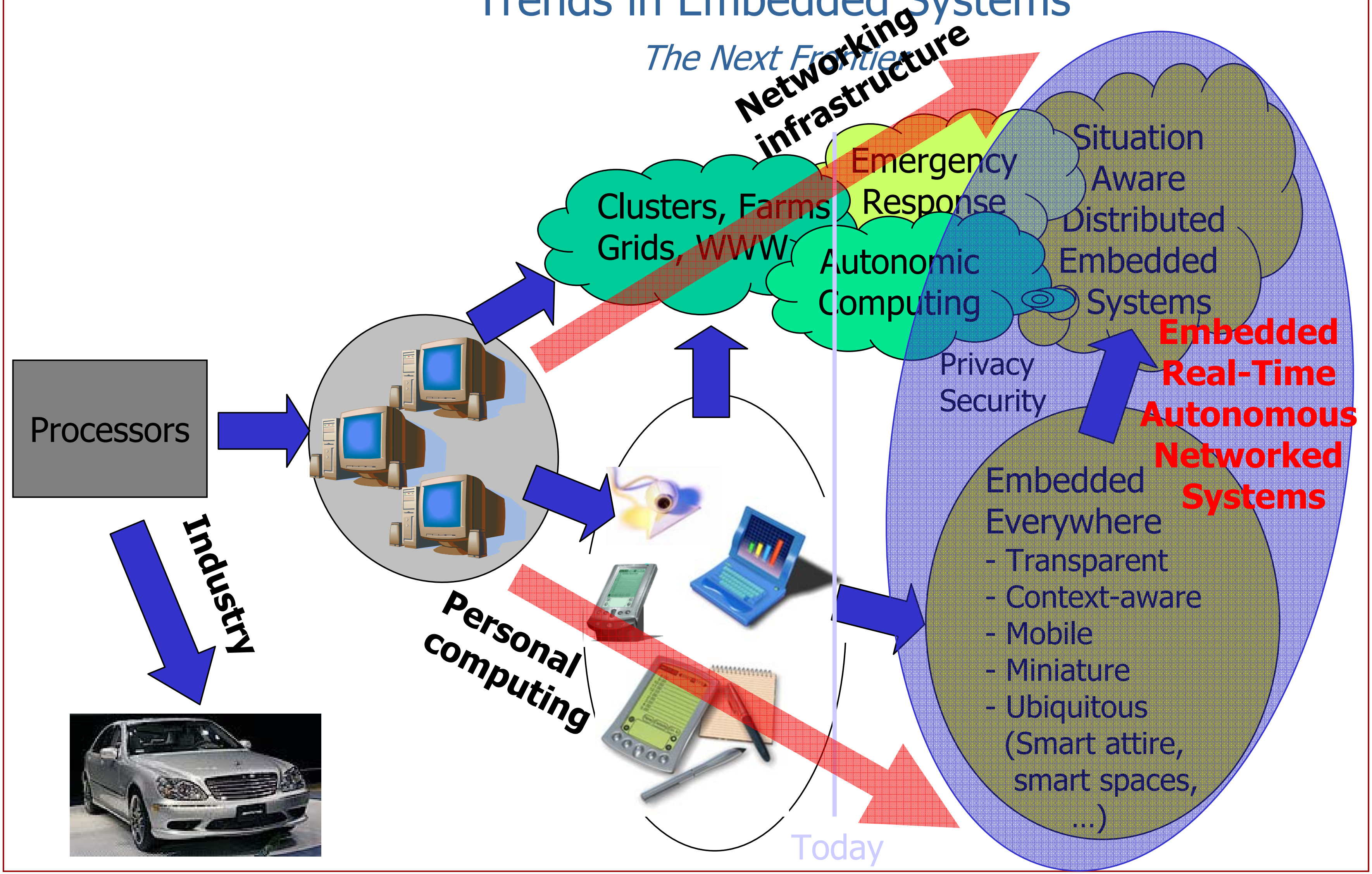


Trend 2:

- Autonomous computing (needs more automation/control)
  - Human bandwidth is finite → more autonomy
  - Human output is finite → Future data sources are increasingly embedded

Trends in Embedded Systems

The Next Frontier



Sensor Networks: Emerging Embedded Application Domain

Habitat Monitoring

Precision Agriculture

Network Applications

Disaster Response

Features

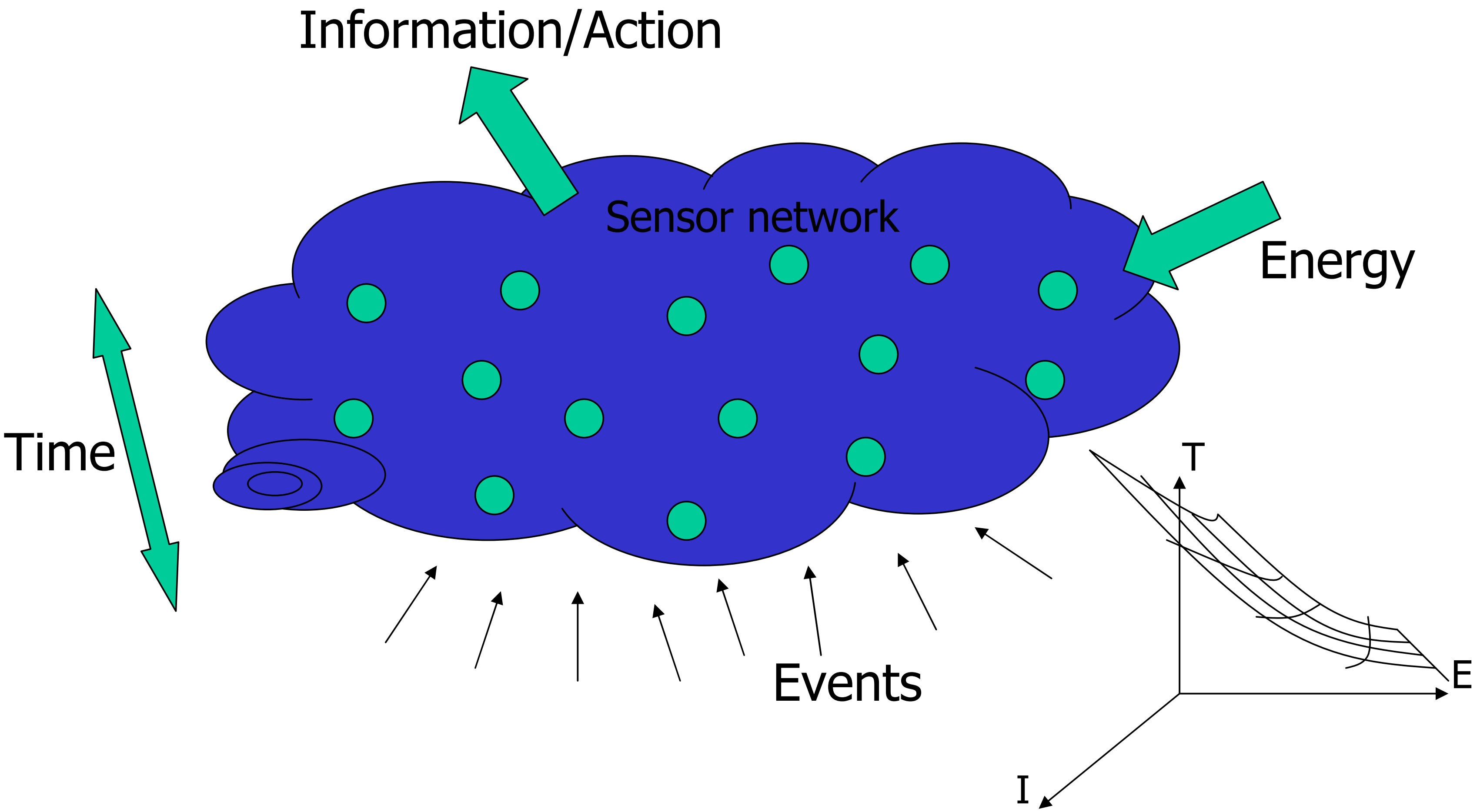
- Ad hoc deployment
- Massive distribution
- Interaction with a physical environment
- Unattended operation

Target Tracking

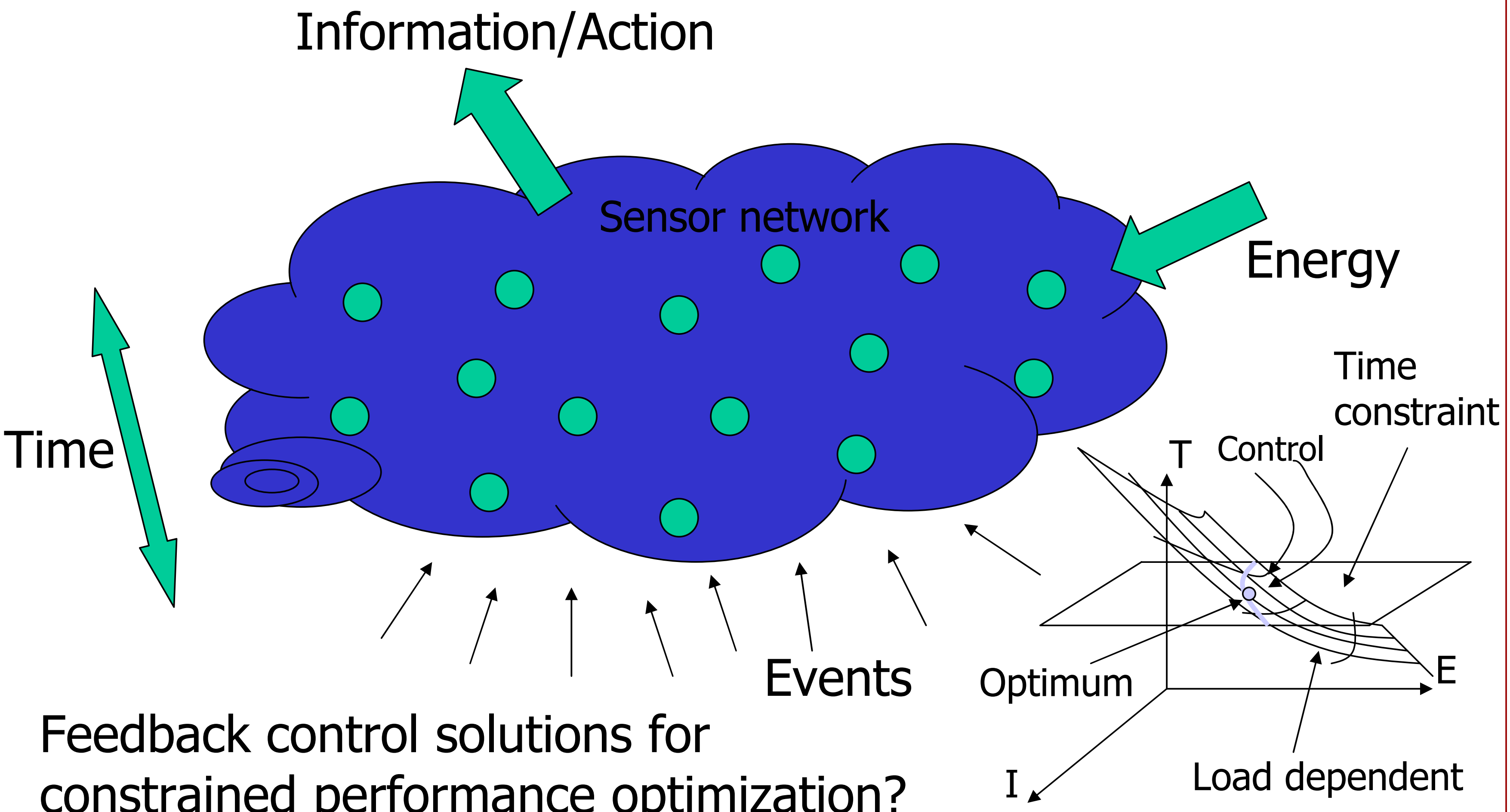
Infrastructure Protection

Border Control

Fundamental Performance Tradeoffs in Sensor Networks

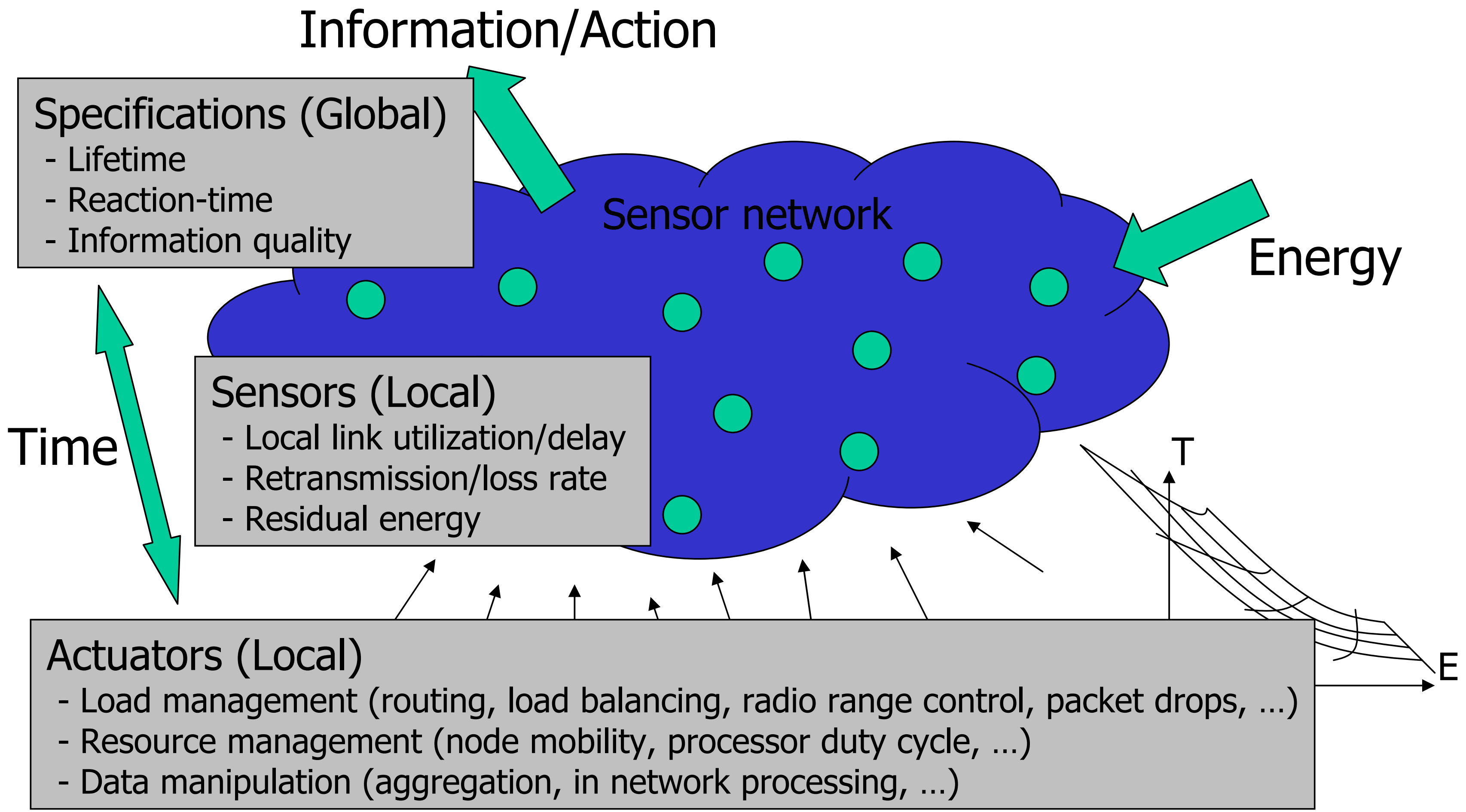


Constrained Optimization and Feedback Control in Sensor Networks



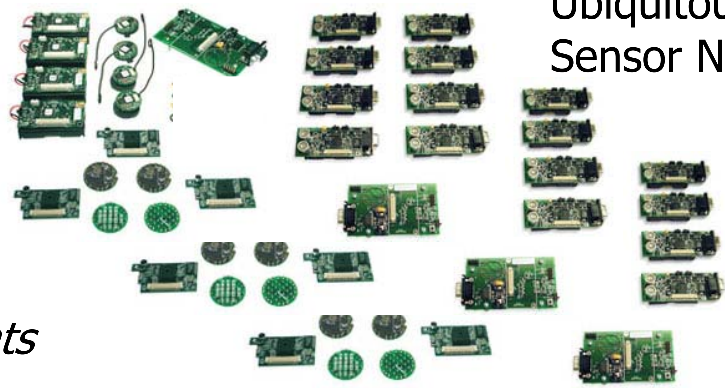
Feedback control solutions for constrained performance optimization?

Performance specifications, Sensors and Actuators in Sensor Networks



Sensor Network Analysis Challenges

Trend: *Moving from single device to networks of thousands of small components*



Ubiquitous Sensor Networks

Challenges:

Analysis of **aggregate** properties (e.g., real-time Capacity, lifetime)

Controllable emergent **global** behavior

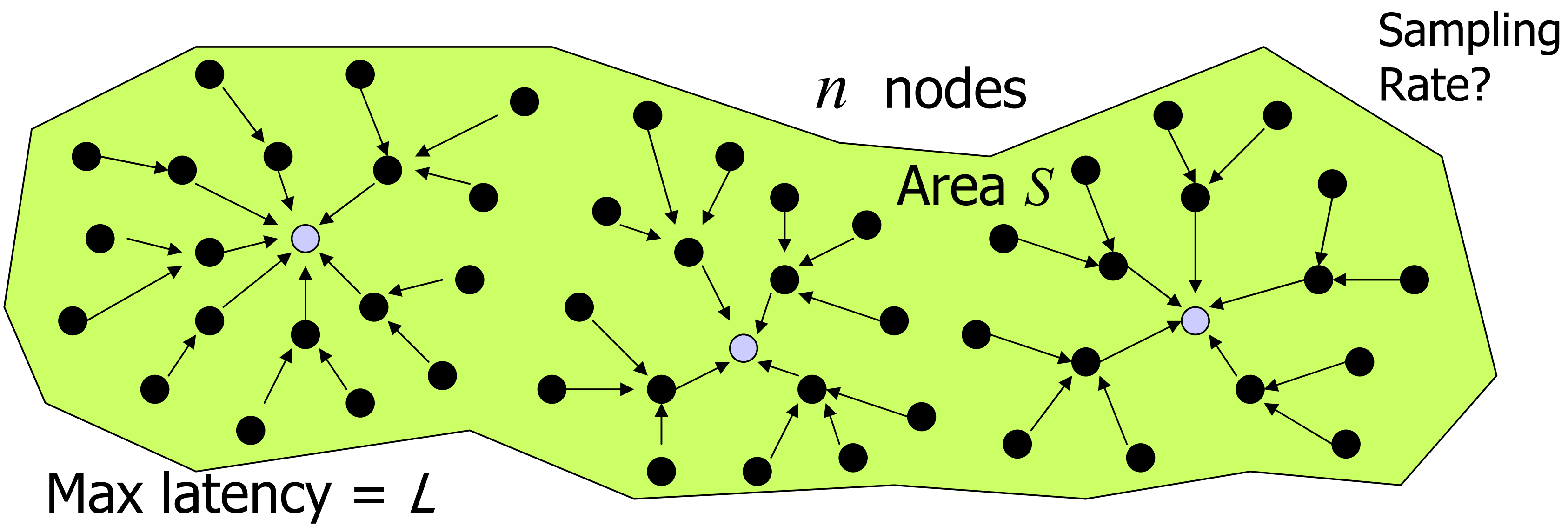
Analysis of **spatio-temporal** behavior

Real-Time Analysis of Sensor Networks

- What is the relation between radio range, network density, total number of nodes, number of sinks, packet length, packet scheduling policy, MAC-layer protocol, and end-to-end **packet ability to meet deadlines?**
- Which load conditions satisfy given delay bounds on communication (i.e., are suitable load set points)?

Capacity Planning for Real-Time Wireless Sensor Networks

- Recent work established wireless network capacity bounds
- What if traffic has deadlines and only bits that make it by the latency constraint are counted towards throughput?
- Problem: express *real-time* network capacity that quantifies the throughput of timely bits only as a function of network parameters and time constraints



Network Real-time Capacity

- Network bandwidth is the bottleneck (communication scheduling problems)
  - Task processing time → packet transmission time
  - Scheduler queue → network queue
- Intuitively, network schedulability *decreases* with:
  - Increased packet size (task processing time), C
  - Increased distance between source and destination, L
  - Decreased end-to-end latency constraint, D
- Schedulability decreases with CL/D
- Is there a bound $Capacity_{RT}$, such that all packets, i, reach their destinations by their deadlines if:

$$\sum_i \frac{C_i L_i}{D_i} \leq Capacity_{RT}$$

Real-Time Capacity

- ***The total capacity theorem:*** In a ***load-balanced*** network of n nodes, each with a radio of transmission speed W and m neighbors on average, if communication is localized within at most N hops:

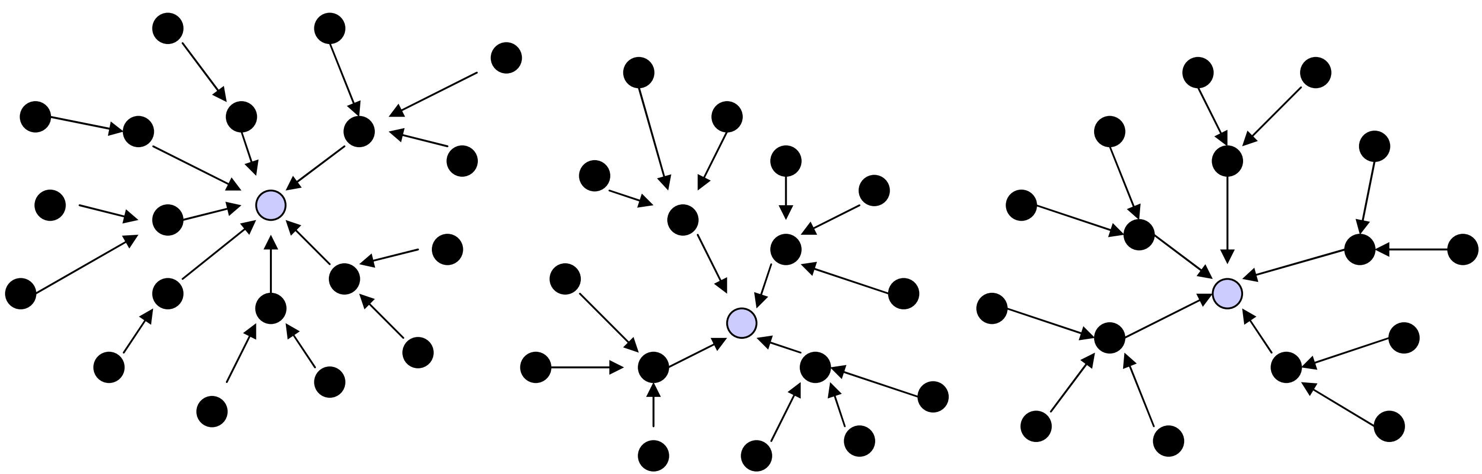
$$Capacity_{Opt} = \frac{nW}{m}\left(1 + \frac{1}{N} - \sqrt{1 + \left(\frac{1}{N}\right)^2}\right)$$

- For large N:

$$Capacity_{Opt} \approx \frac{nW}{mN}$$

Real-time Capacity of Multi-hop Data-Collection in Sensor Networks

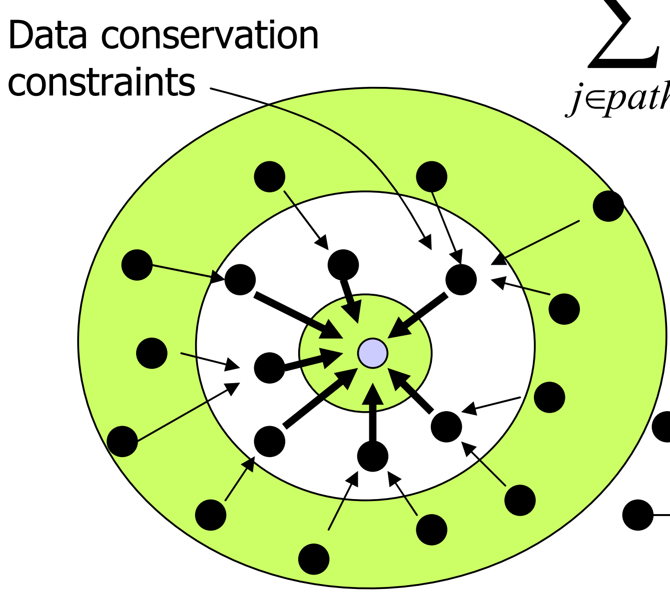
- In a ***data collection*** sensor network with K collection points, maximum path length N, and radio transmission speed W, what is a sufficient bound on real-time capacity?

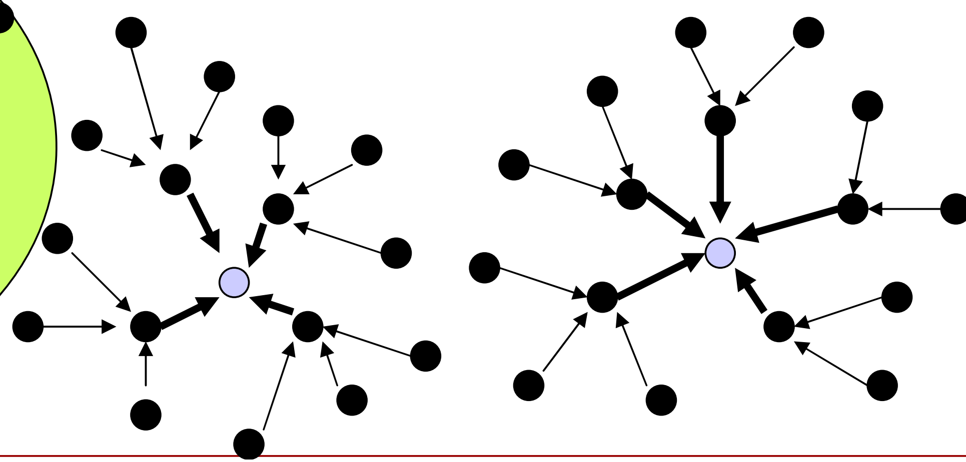


Real-time Capacity of Multi-hop Data-Collection in Sensor Networks

- In a ***data collection*** sensor network with K collection points, maximum path length N, and radio transmission speed W, what is a sufficient bound on real-time capacity?

$$\sum_{j \in path} \frac{U_j(1 - U_j/2)}{1 - U_j} \leq 1, \quad U_j \propto 1/j$$

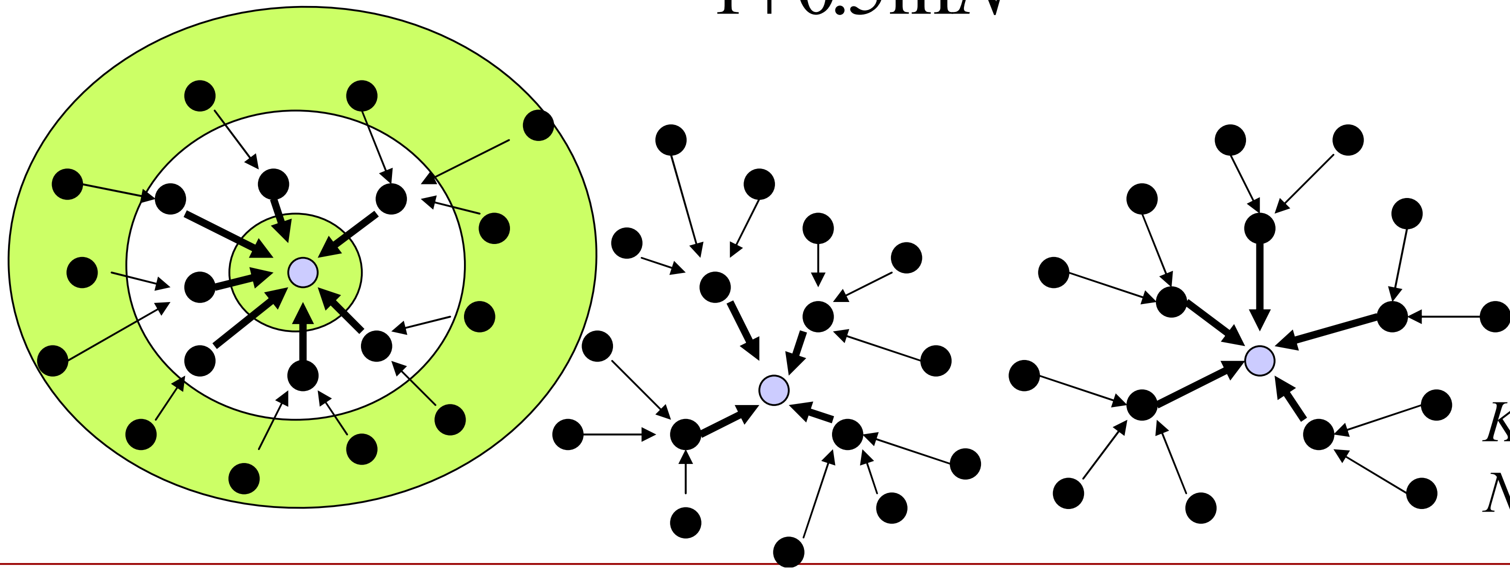




Real-time Capacity of Multi-hop Data-Collection in Sensor Networks

- In a ***data collection*** sensor network with K collection points, maximum path length N, and radio transmission speed W, a sufficient bound on real-time capacity is:

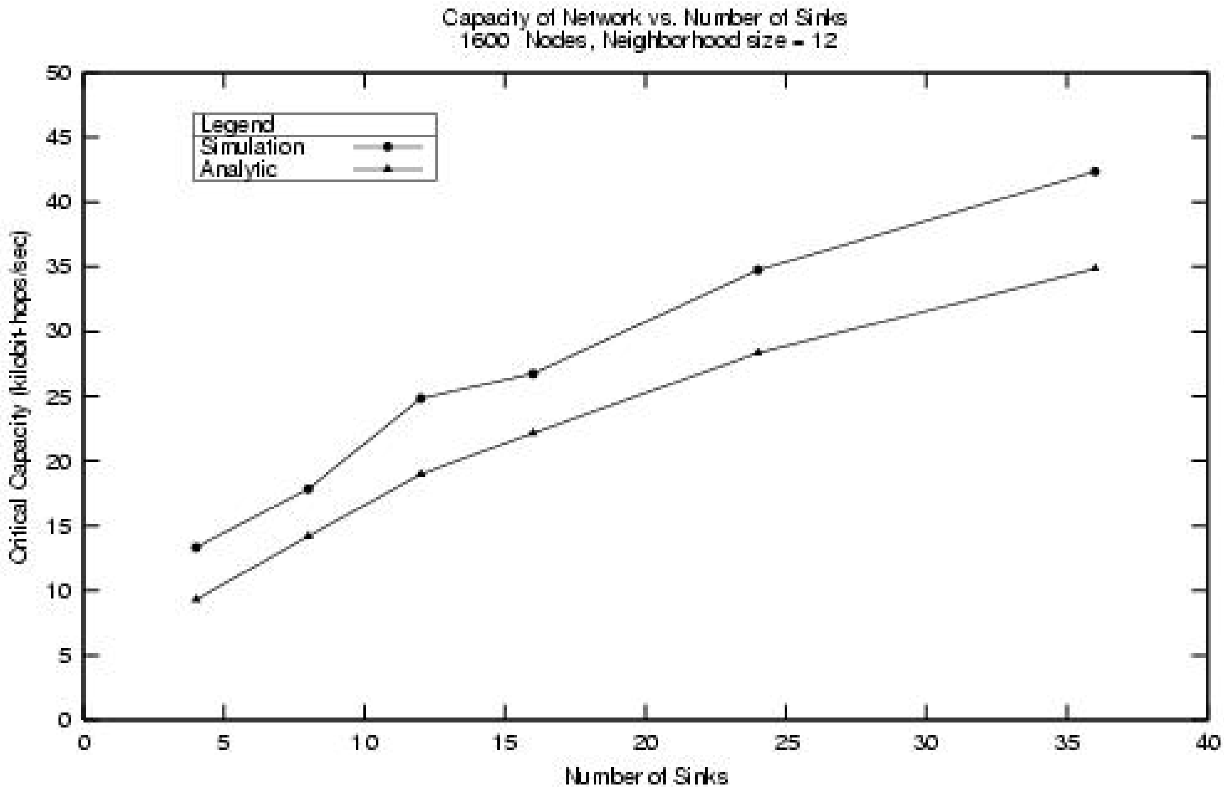
$$Capacity_{DC} \approx \frac{KNW}{1+0.5\ln N}$$



$K=3$
$N=2$

Evaluation: How Pessimistic is Real-time Capacity?

- Simulation versus analytic prediction of the onset of deadline misses in a 1600 node network

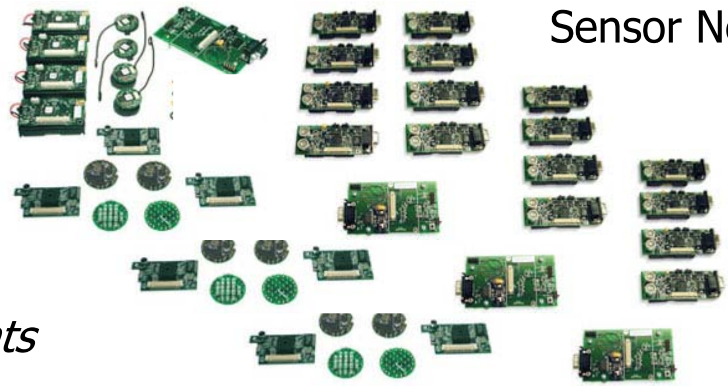


Open Questions in Sensor Network Schedulability/Capacity Analysis

- Non-uniform sensor node density
- Arbitrary load distribution (e.g., parts of the network generate more information than others)
- Irregular radio and sensing ranges
- MAC-layer scheduling and routing policies
- Lack of reliability (packet drops/retransmissions)
- Encoding at the link and physical layers
- Ambient effects (temperature, humidity, …)
- Effect of mobility

Sensor Network Analysis and Control Challenges

__Trend:__ Moving from single device to networks of thousands of small components



Ubiquitous Sensor Networks

Challenges:

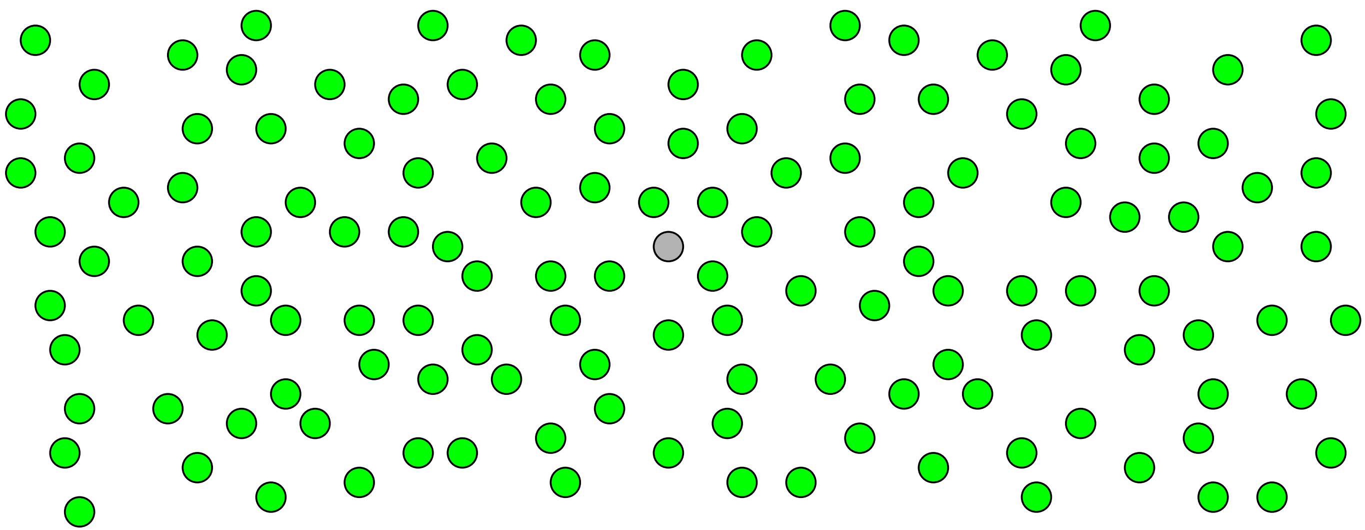
- Analysis of **aggregate** properties (e.g., real-time capacity)
- Controllable emergent **global** behavior
- Analysis of **spatio-temporal** behavior

Convergence of Global Behavior in Sensor Networks

- Sensor network protocols are localized; nodes act independently, locally, in response to local stimuli.
- How to argue about the global effects of such localized protocols when performed by all nodes?
- How to induce and analyze convergence to desired global properties?
- How to incorporate time and capacity constraints?
- Inspirations from control theory (convergence, stability), Markov decision theory (Markov chains, stochastic models), biology (behavior of social insects, swarm intelligence, bio-differentiation), physics (phase transitions, crystallization), …

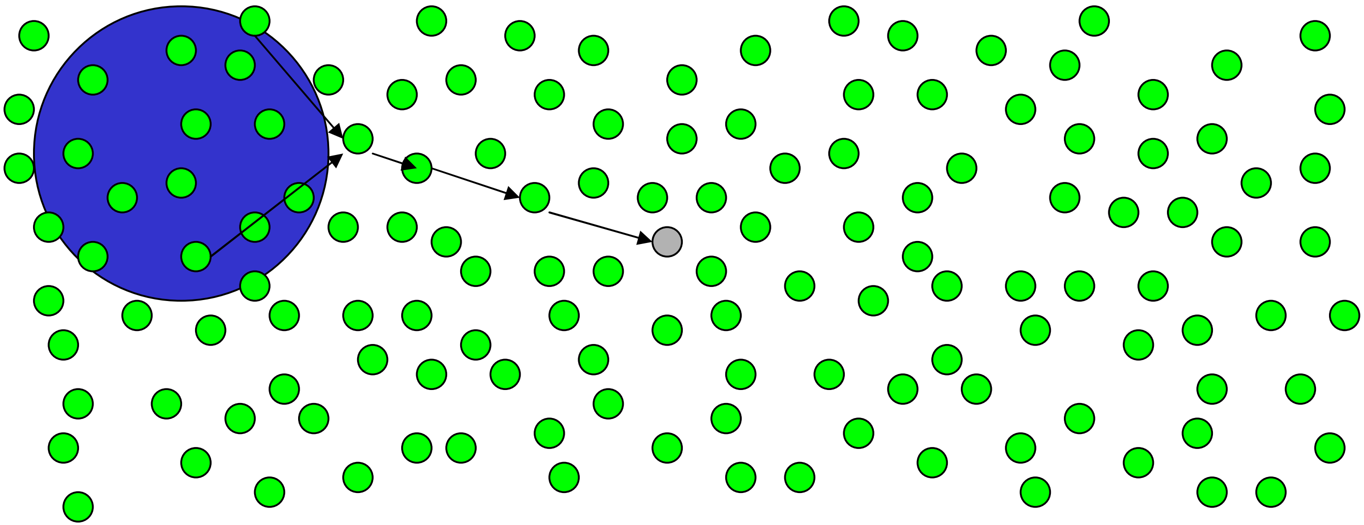
Example:
Lifetime Maximization

- Consider data collection by centralized nodes



Lifetime Maximization

- Data is transmitted towards a base-station leading to increased energy consumption along the path



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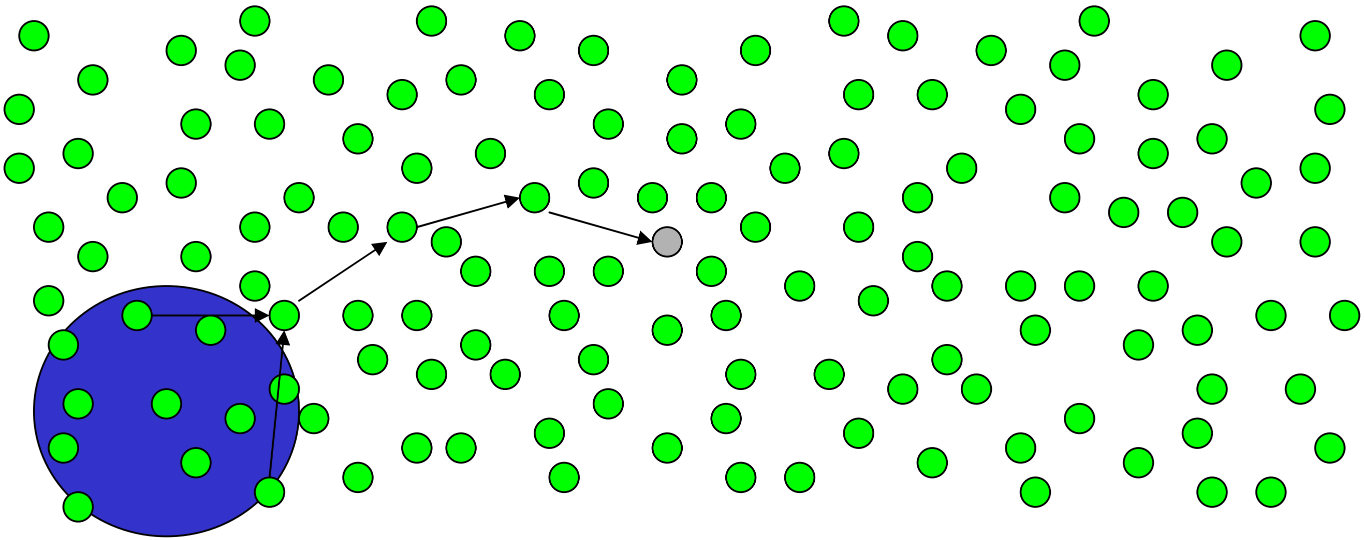
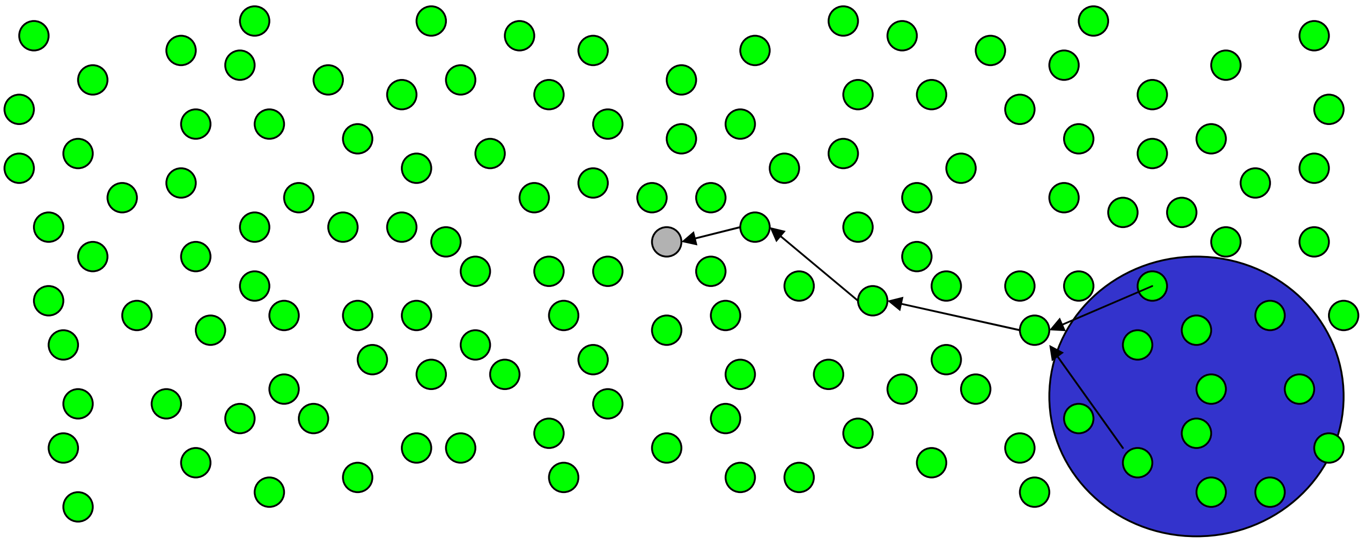


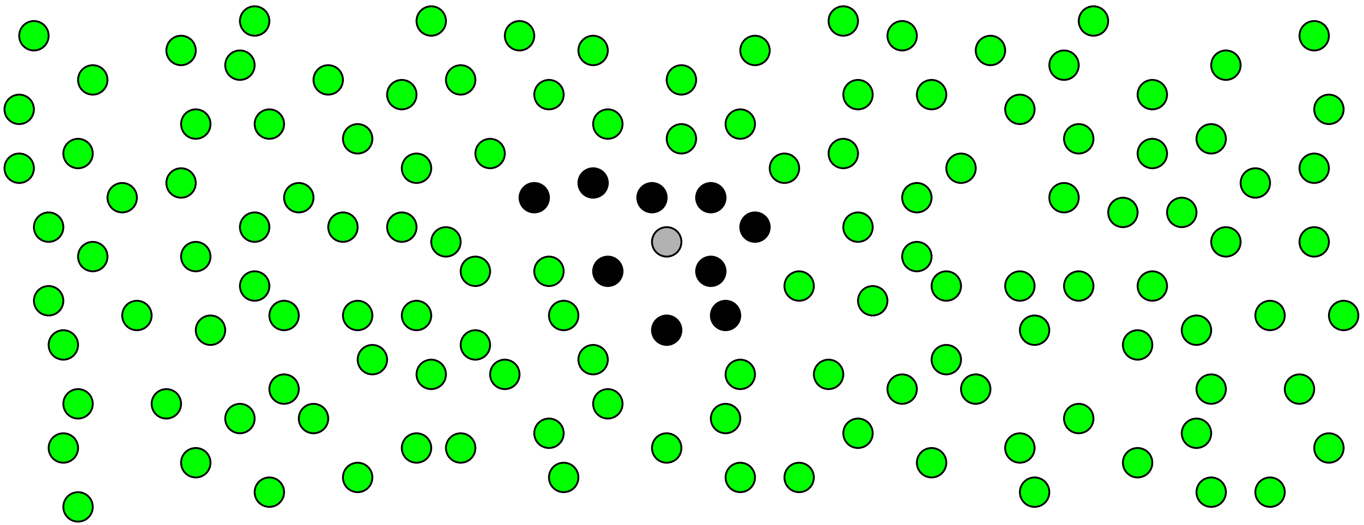
Lifetime Maximization

❖ Data is transmitted towards a base-station leading to increased energy consumption along the path



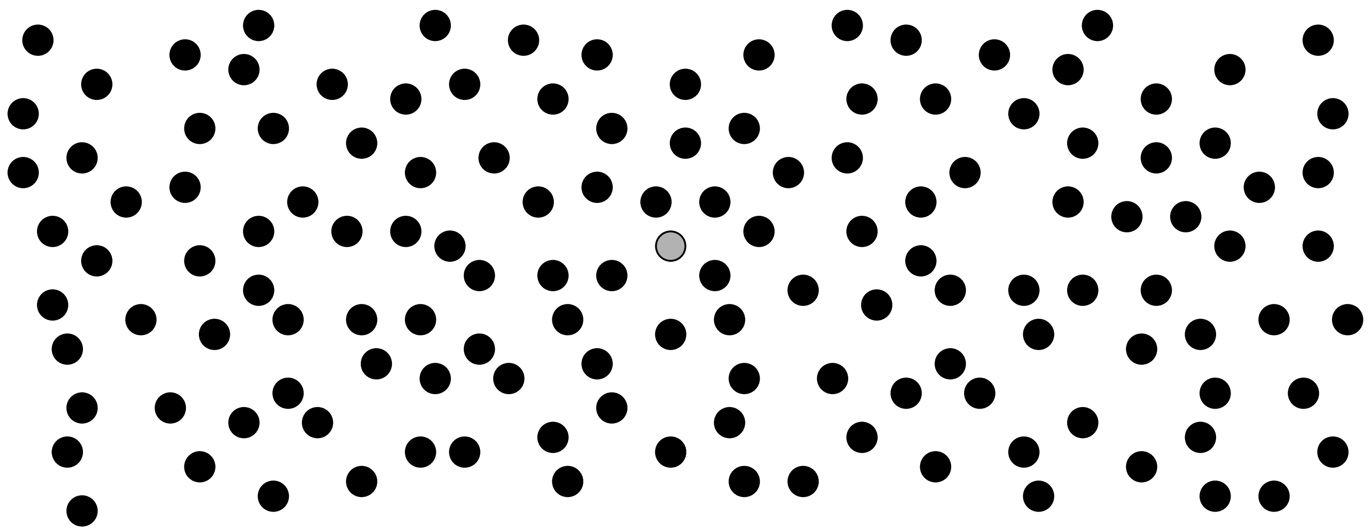
Lifetime Maximization

- Nodes towards the center get depleted from energy



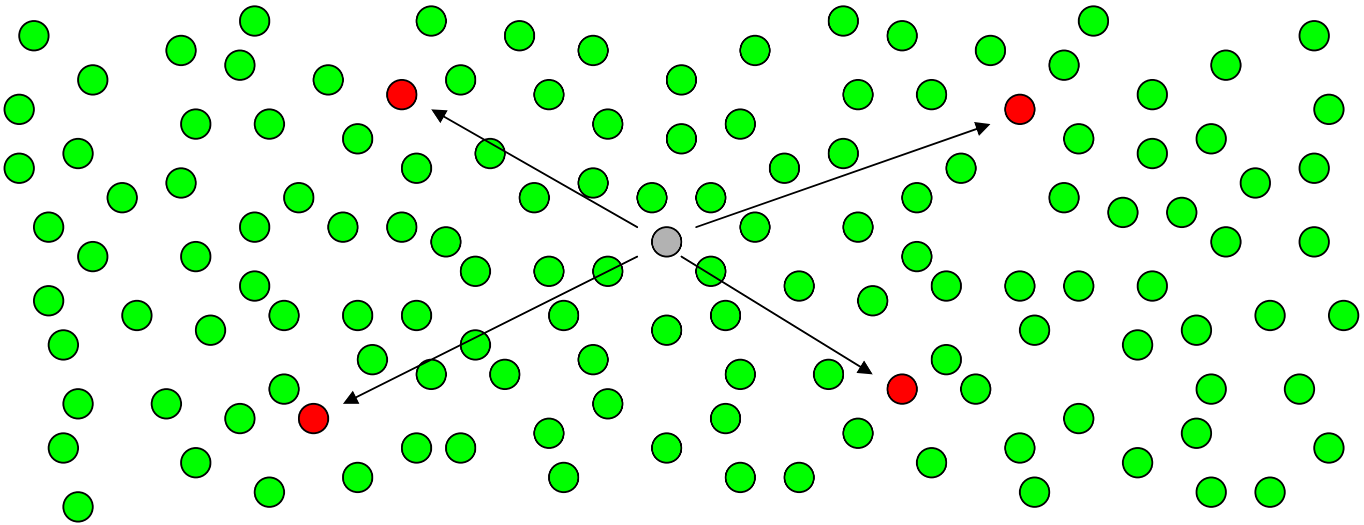
Lifetime Maximization

- The network becomes partitioned and unusable



Lifetime Maximization

- Implications:
  - Push computation into the network
- Open Questions:
  - How to distribute computation and communication to maximize lifetime?
  - How to adapt distribution to current input data patterns?



Sensor Network Analysis and Control Challenges

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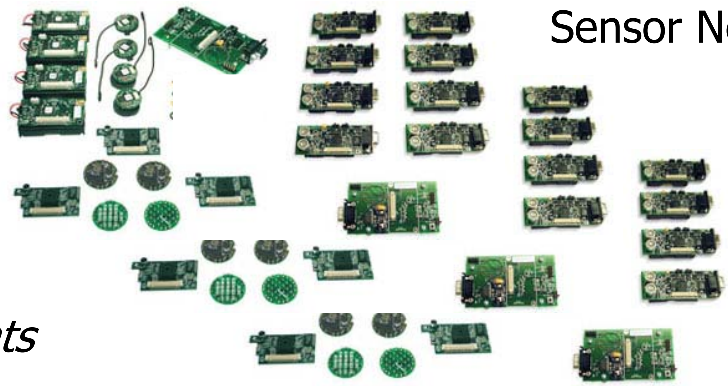


Ubiquitous Sensor Networks

Challenges:

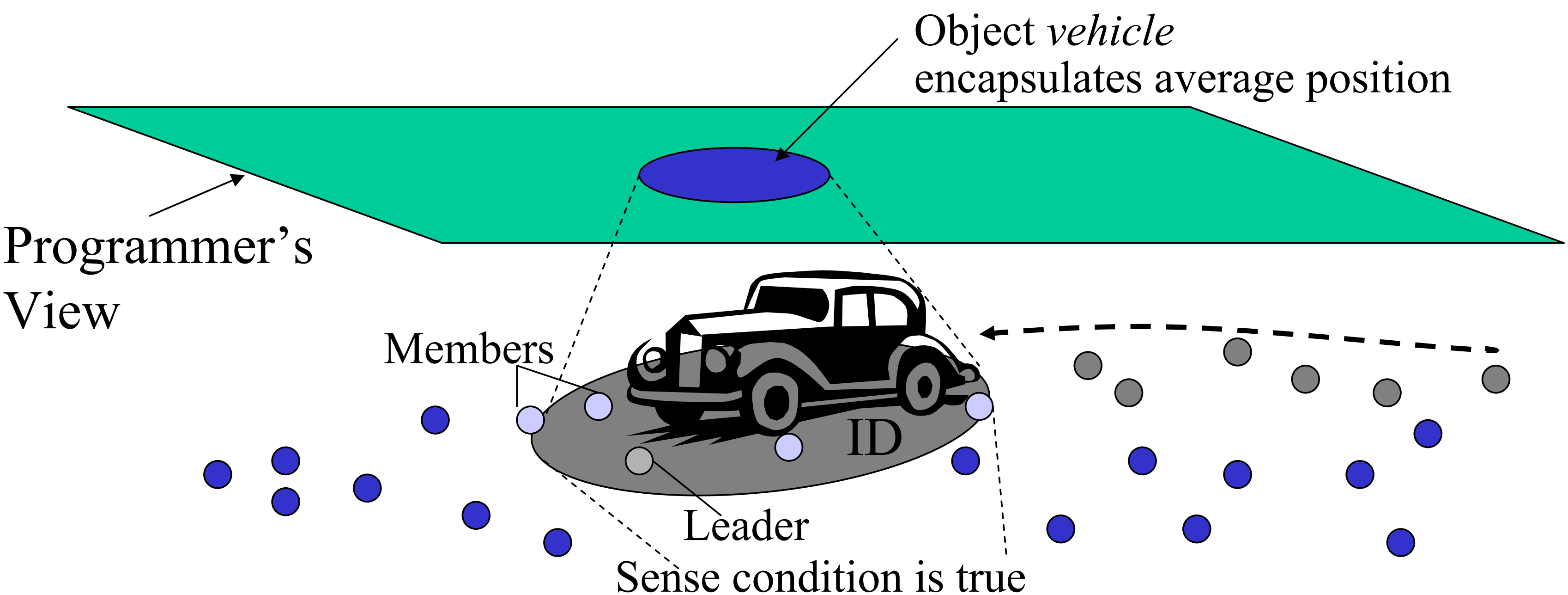
Analysis of **spatio-temporal** behavior

Analysis of **aggregate** properties (e.g., real-time capacity)

Controllable emergent **global** behavior

A Spatio-Temporal Problem: Real-Time Tracking

```
begin object vehicle
  sense: magnetic() + motion();
  collect: avg (position);
end
```



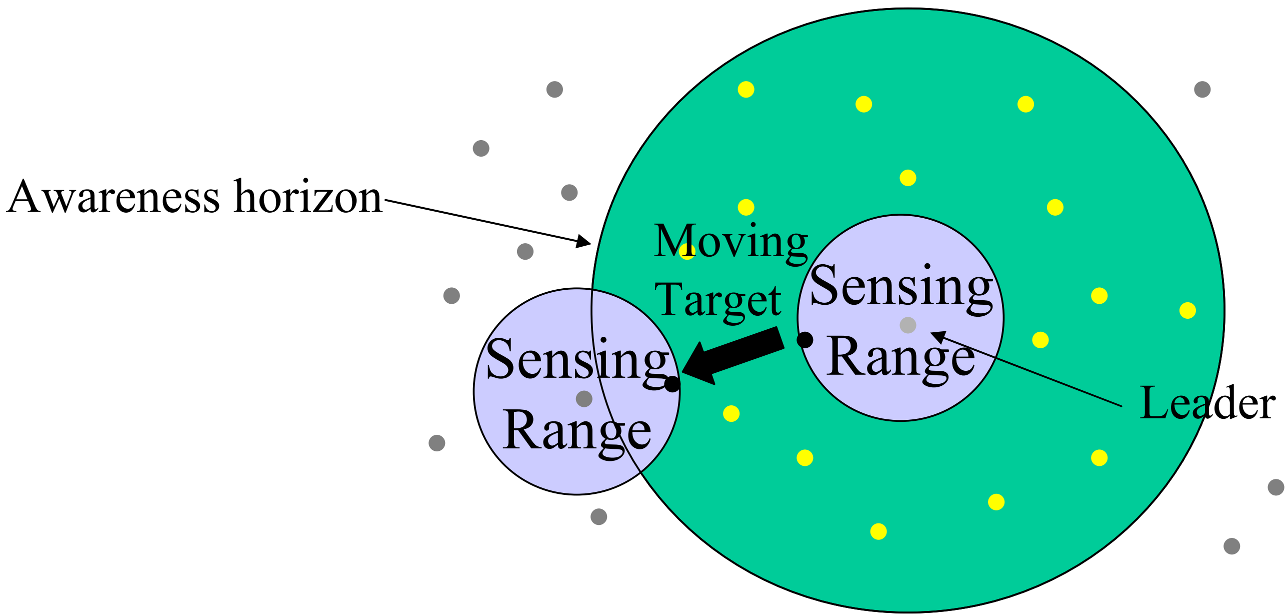
Challenge: Unique Representation

- Unique representation
  - Object instantiation (discovery of external entities – assignment of object IDs)
  - Uniqueness: all sensors that sense the same vehicle agree with high probability on its object ID
  - Object migration and handoff (to track mobile physical entities in the environment)
  - The spatio-temporal problem: unique representation depends on temporal and spatial properties (e.g., external velocity, size, and protocol overhead)

    How to analyze limits of spatio-temporal correctness?

Unique Representation

- Target is made known within some “awareness horizon”
- Nodes within the horizon agree that they see the same target
- Target should not move fast enough to be sensed by a node outside that horizon
- Members of the horizon dynamically change depending on target location



Open Questions

- What is the underlying foundation for analysis of spatio-temporal behavior in sensor networks?

What is the maximum trackable speed of a target? How does it depend on network resource parameters, target parameters, and load?

How to control the maximum trackable speed by trading off other parameters (such as tracking accuracy)?

What is the right model for analyzing such a system?

Conclusions

- Embedded computing is of growing importance in computer science as a discipline
- Real-time analysis must catch up with sensor network realities
  - Fundamentally new problems with space and time constraints
  - Aggregate results as opposed to microscopic models
- Convergence and aggregate behavior analysis techniques must be developed
  - Real-time control of aggregate network properties