# The Internet of Things and Multiagent Systems

## Tutorial

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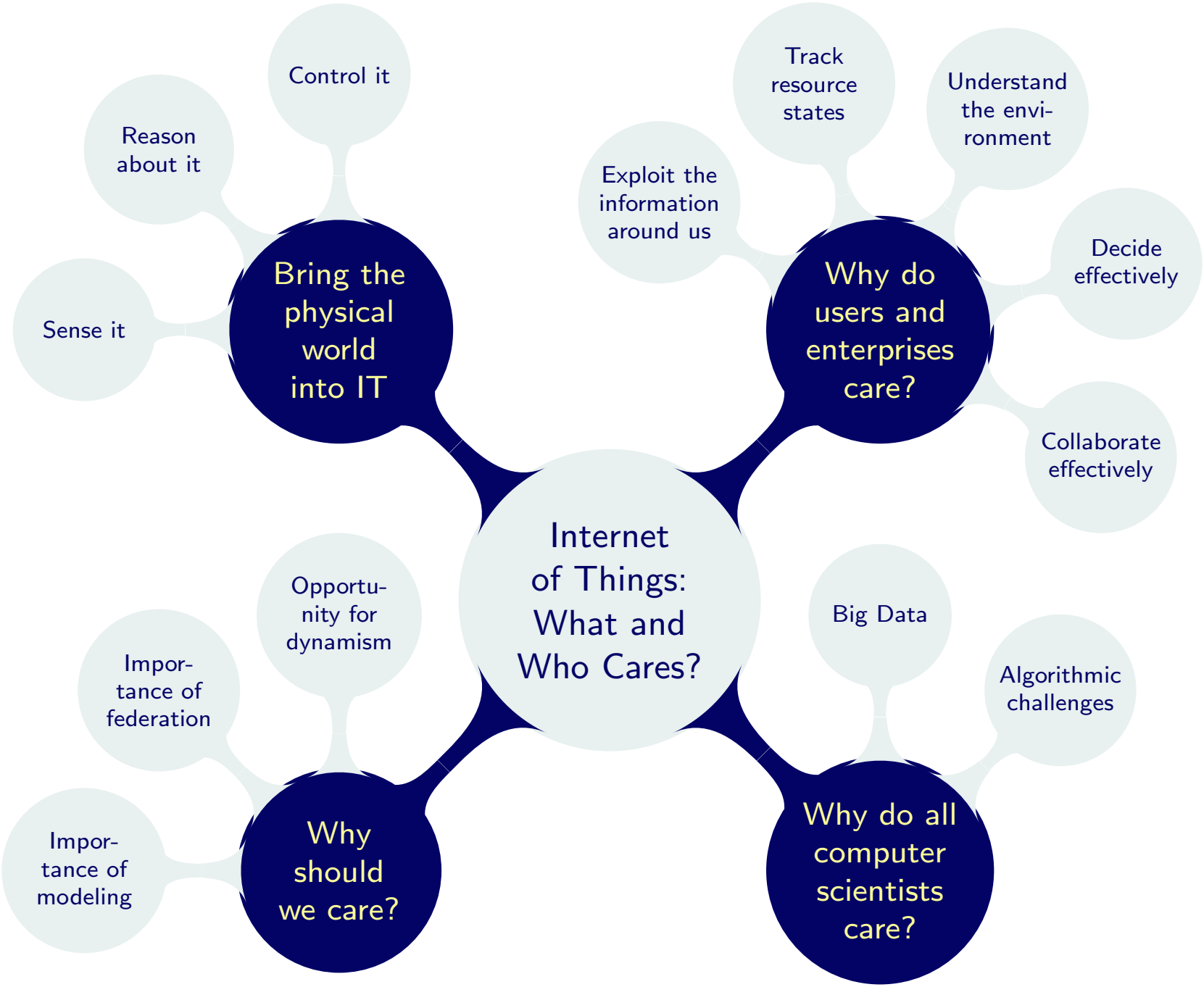
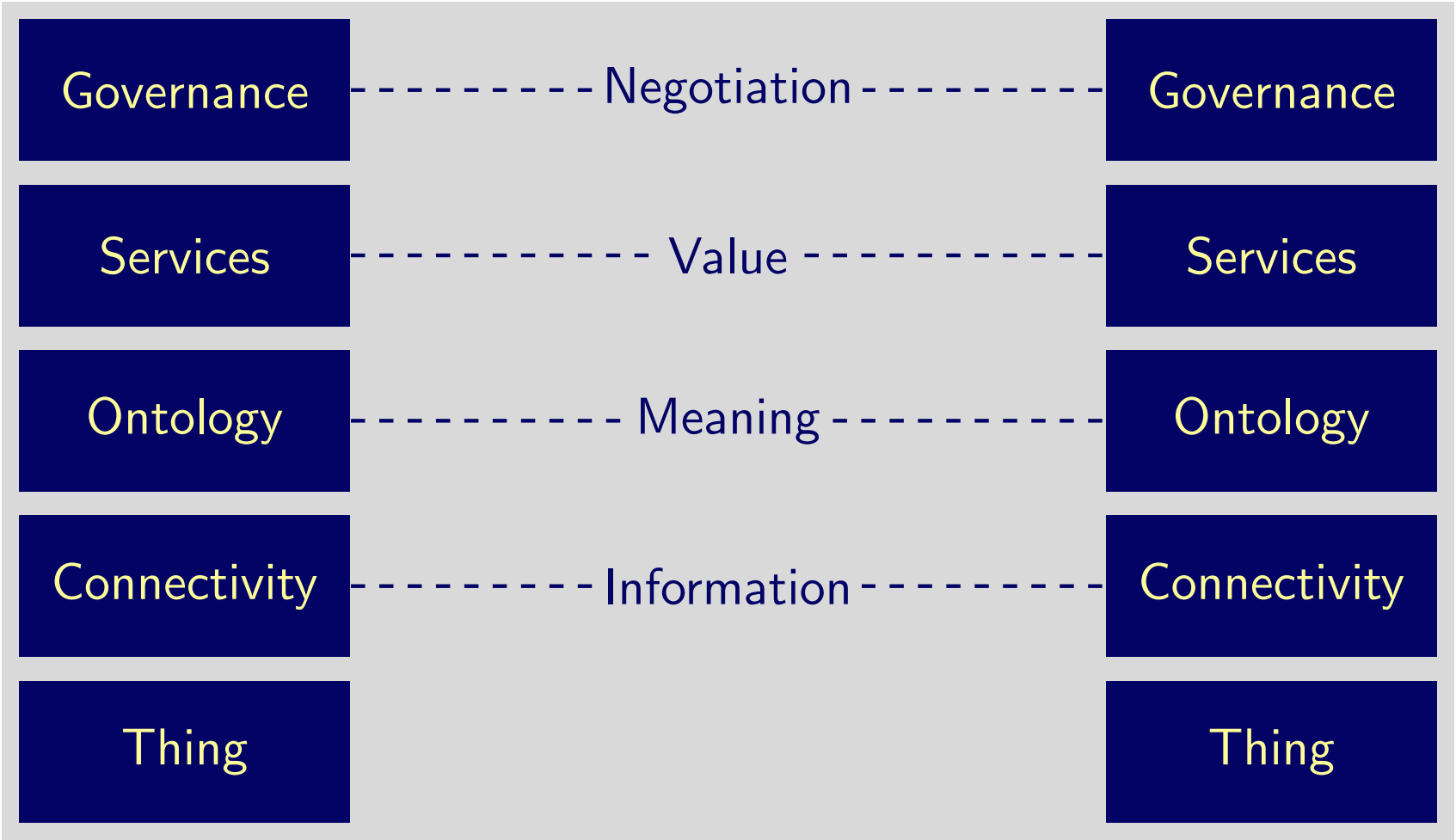
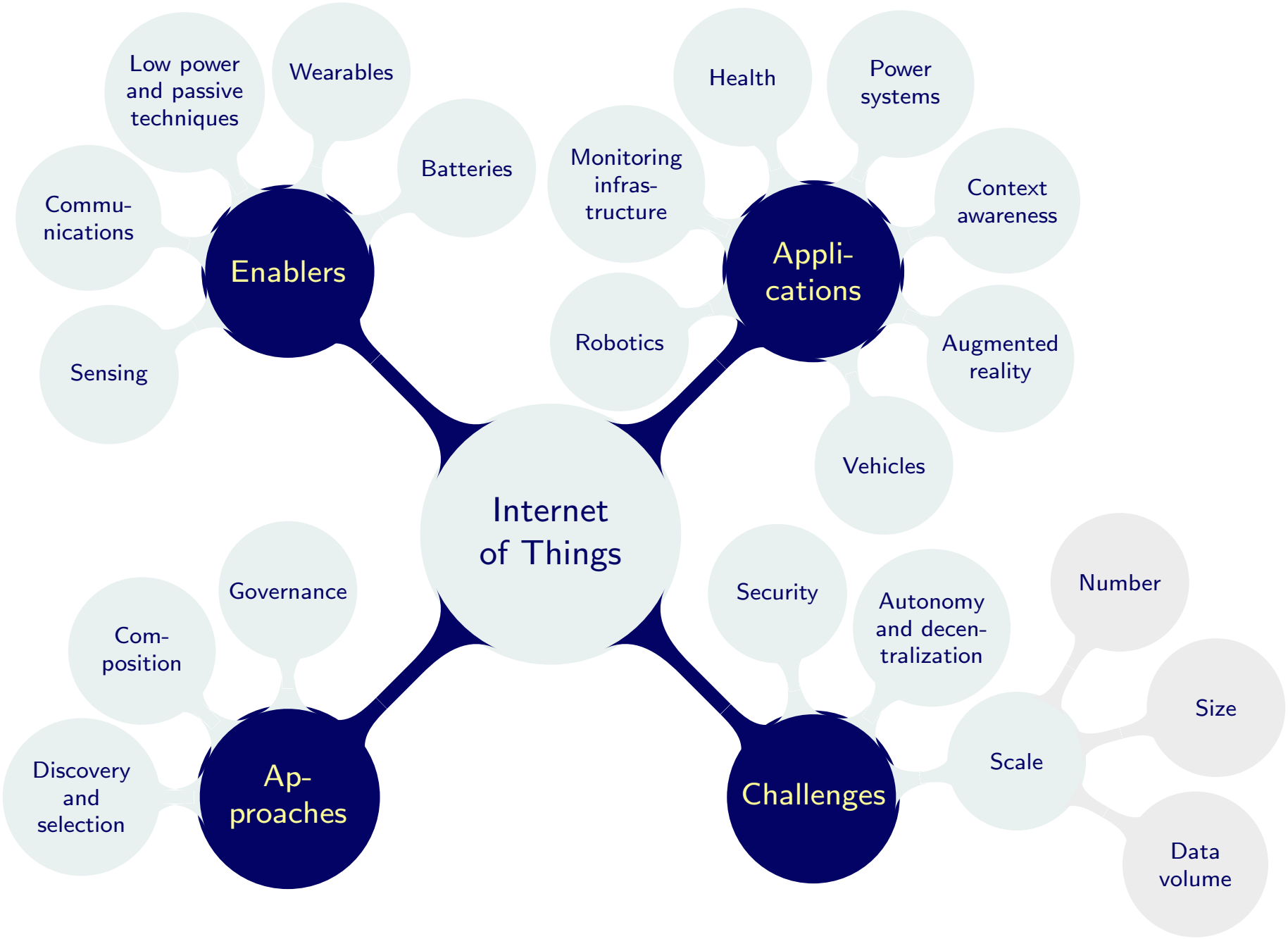
# Introduction to the Internet of Things

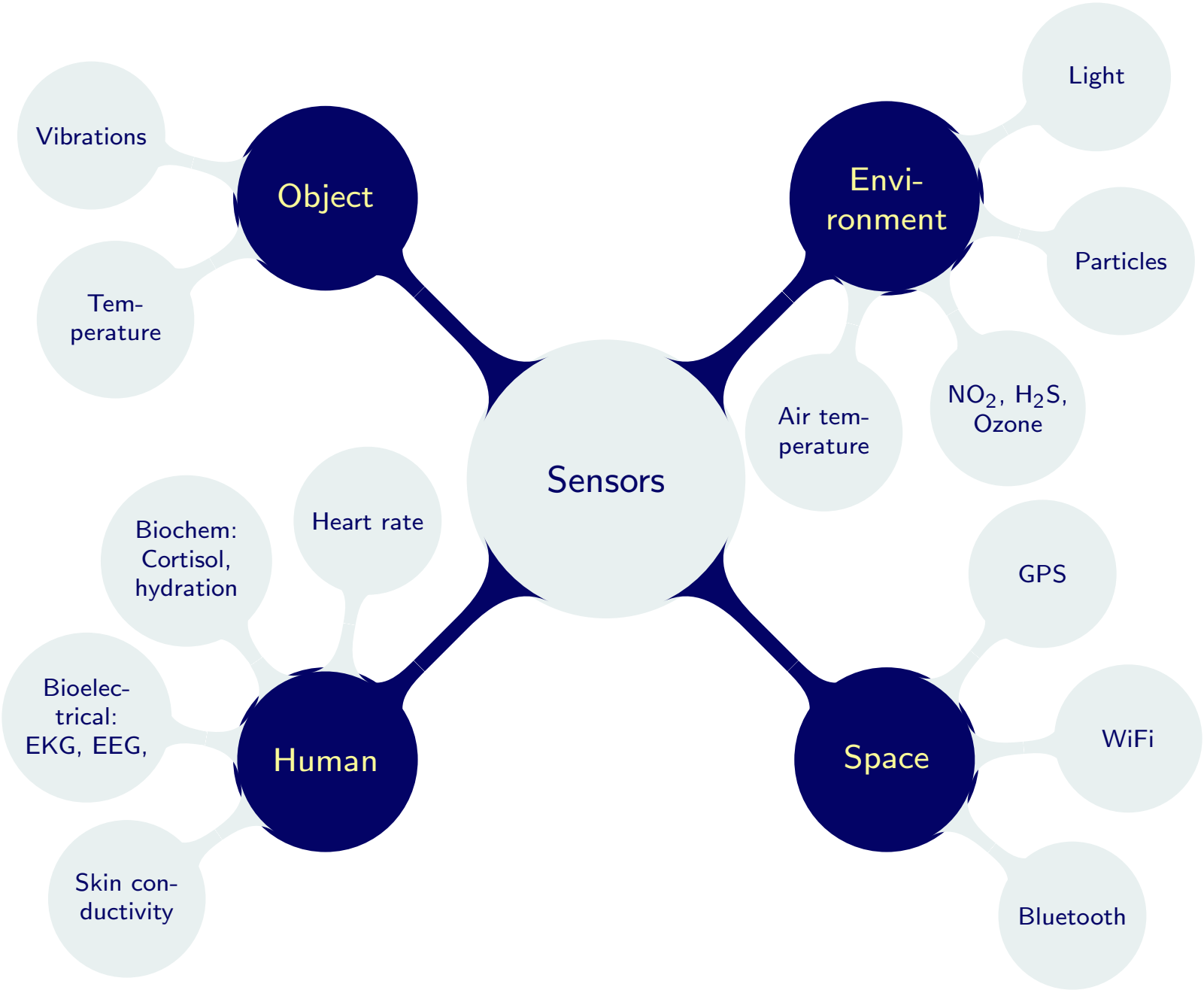

Scope and motivation of this tutorial
An introduction to a new area
From a sociotechnical perspective
Not a programming guide
With a hope to help build a research community
Focus on research challenges


Internet of Things: What and Who Cares?
Bring the physical world into IT
Control it
Reason about it
Sense it
Why do users and enterprises care?
Track resource states
Understand the environment
Exploit the information around us
Decide effectively
Collaborate effectively
Why should we care?
Opportunity for dynamism
Importance of federation
Importance of modeling
Why do all computer scientists care?
Big Data
Algorithmic challenges

# IoT Federation Levels




Internet of Things
Enablers
Low power and passive techniques
Wearables
Batteries
Commu-nications
Sensing
Appli-cations
Health
Power systems
Monitoring infras-tructure
Context awareness
Robotics
Augmented reality
Vehicles
Ap-proaches
Governance
Com-position
Discovery and selection
Challenges
Security
Autonomy and decen-tralization
Scale
Number
Size
Data volume


Sensors
Object
Vibrations
Tem-
perature
Envi-
ronment
Light
Particles
Air tem-
perature
$NO_2$, $H_2S$,
Ozone
Human
Heart rate
Biochem:
Cortisol,
hydration
Bioelec-
trical:
EKG, EEG,
Skin con-
ductivity
Space
GPS
WiFi
Bluetooth

# Core: Connectivity

## Combination of low and high-bandwidth

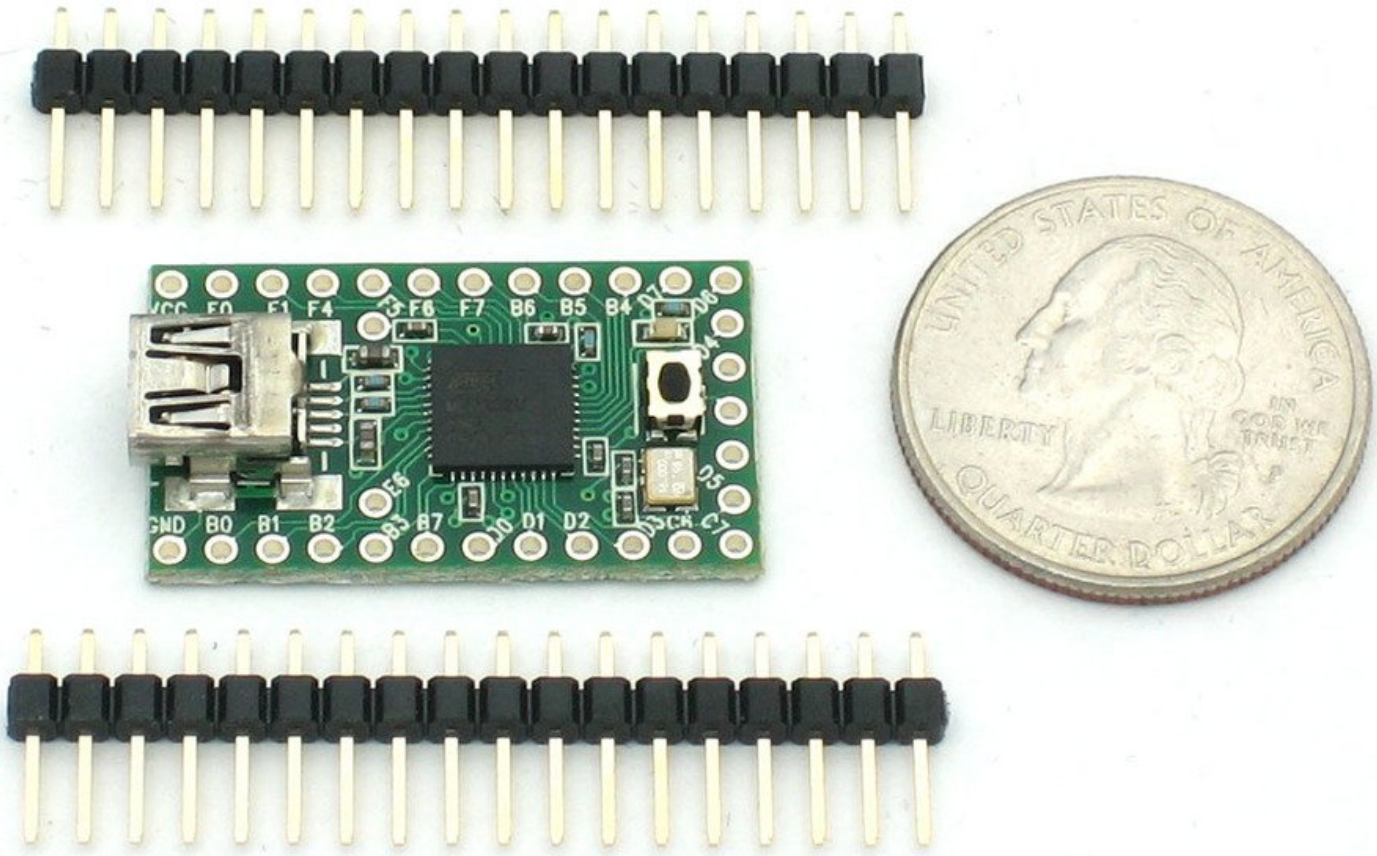
- Low-bandwidth connectivity
  - Between RFID tags and readers
  - Between sensors and base stations
- High-bandwidth
  - Wireless, with aggregator nodes such as smartphones and Arduino devices
  - Broadband, from aggregator nodes to store data in the cloud

# Core: Passive and Low Power Technologies

## Many dimensions

- Passive (batteryless)
  - No power
  - Require a proximal (within $\sim$10 cm) reader
- Active, battery-based
  - Can send information
  - Can last years but need battery replacement
- Active, self-powered
  - Harvest power from the
    - Environment, e.g., solar
    - Human body, temperature differential
    - Human body, movement
  - Enough power to transmit to a local, e.g., on-body, hub
    - Low-power radio: $10^{-7}\,W$ (versus Bluetooth: $10^{-3}\,W$)
    - Human body, temperature differential
    - Human body, movement
  - Can potentially last "forever"

# Microcontrollers for Programmably Controlling Actuators




© Adafruit, New York

# Constrained Node Networks

## Data and communication

| **Class** | **RAM (data)** | **Flash (code)** | **Access** |
|---|---|---|---|
| C0 | $\ll$10 KiB | $\ll$100 KiB | Via others |
| C1 | 10 KiB | 100 KiB | Constrained protocols, e.g., CoAP |
| C2 | 50 KiB | 250 KiB | Capable, but prefer lightweight |

Credit: IETF RFC 7228, May 2014, ⟨`http://tools.ietf.org/html/rfc7228`⟩

# Constrained Node Networks

## Power

| Name | Energy limitation | Example power source |
|---|---|---|
| E0 | Event | Event-based harvesting |
| E1 | Period | Battery: recharge or replace |
| E2 | Lifetime | Nonreplaceable battery |
| E9 | None | Mains power |

Credit: IETF RFC 7228, May 2014, ⟨http://tools.ietf.org/html/rfc7228⟩

# Constrained Node Networks

## Communication strategy

| Name | Energy limitation | Strategy |
|---|---|---|
| P0 | Normally off | Reattach on demand |
| P1 | Low power | Appears connected: high latency possible |
| P9 | Always on | Always connected |

Credit: IETF RFC 7228, May 2014, ⟨http://tools.ietf.org/html/rfc7228⟩

# Power Effectiveness: Processors

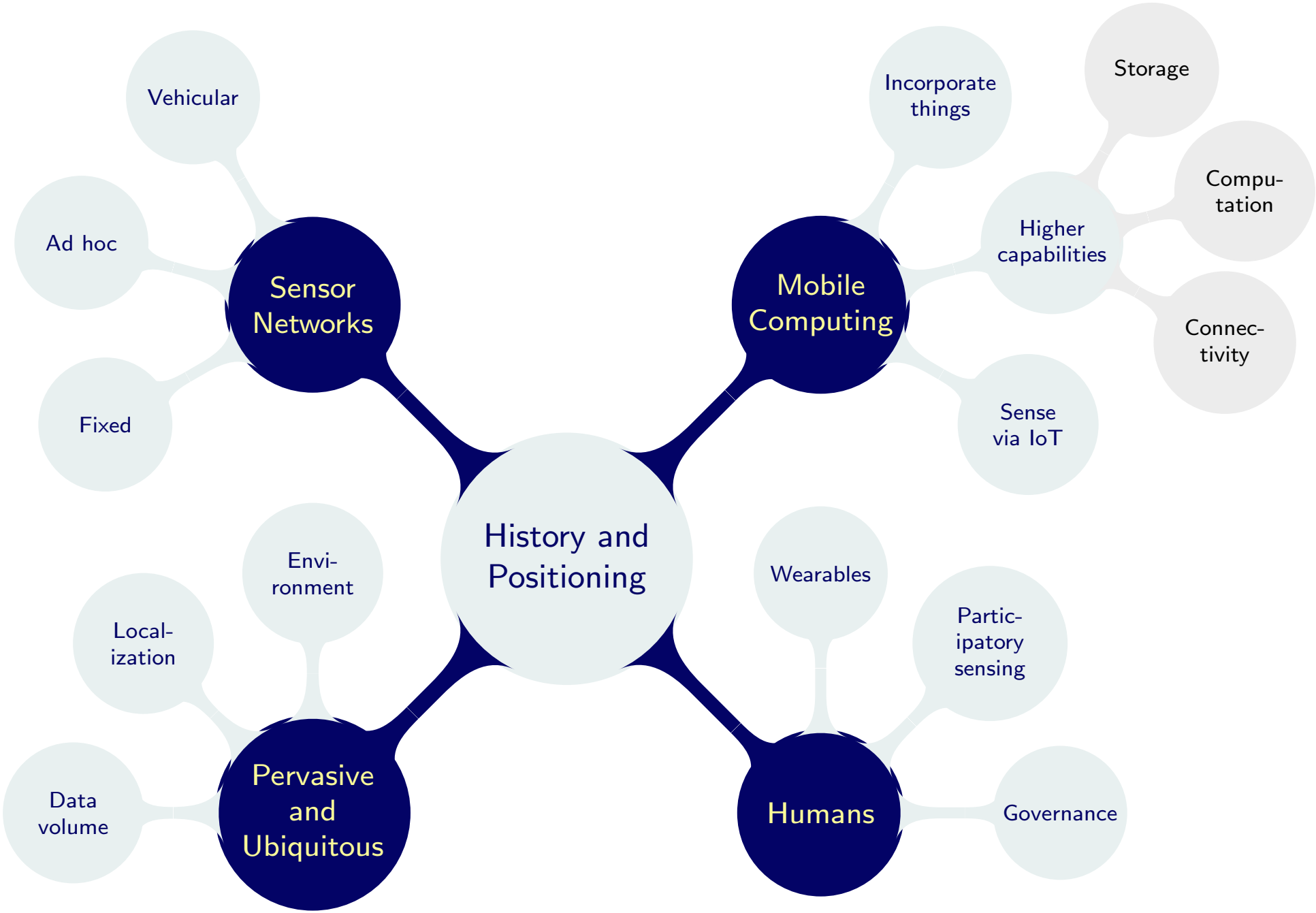
| | **Prototype** | **Commercial 1** | **Commercial 2** |
|---|---|---|---|
| | NCSU ASSIST | EnOcean STM 31xC | Semtech SX1282 |
| Voltage | 0.5 V | 2.1 V | 1.0 V to 1.6 V |
| Processor | 16b MSP430 | Custom | 8b CoolRISC |
| Power consumption | $<$1 $\mu$W @200 kHz | 5.1 mA @3–5 V | 1.2 $\mu$W 32 kHz; 600 *mu*W typical |
| Power harvesting | RF, solar thermoelectric | Yes | No |

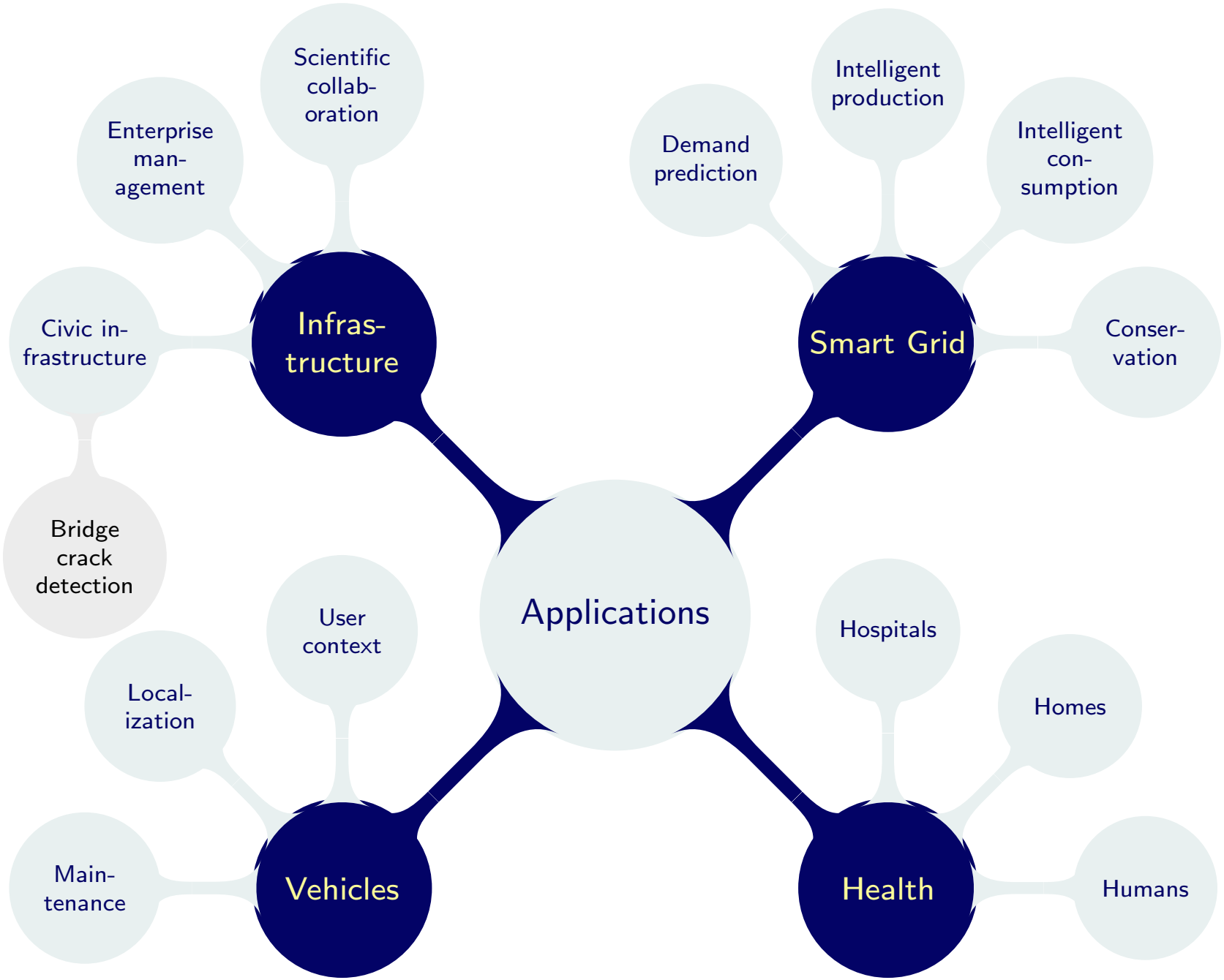
Credit: ASSIST Center, NCSU, ⟨`http://assist.ncsu.edu/`⟩

# Power Effectiveness: Radios

| | **Prototype** | **Commercial 1** | **Commercial 2** |
|---|---|---|---|
| | NCSU ASSIST | EnOcean STM 31xC | Semtech SX1282 |
| Voltage | 0.5 V to 1.0 V | 2.1 V | 1.0 V to 1.6 V |
| Transmission power | 6 $\mu$W @200 kbps | 30 mW @125 kbps | $\sim$40 mW |
| Reception power | 200 $\mu$W WBAN Rx<br>120 nW @12.5 kbps Wake Up | 40 mW | $\sim$12 mW |

Credit: ASSIST Center, NCSU, ⟨`http://assist.ncsu.edu/`⟩


History and Positioning
Sensor Networks
Vehicular
Ad hoc
Fixed
Mobile Computing
Incorporate things
Storage
Compu-tation
Higher capabilities
Connec-tivity
Sense via IoT
Pervasive and Ubiquitous
Envi-ronment
Local-ization
Data volume
Humans
Wearables
Partic-ipatory sensing
Governance


Applications
Infras-tructure
Scientific collab-oration
Enterprise man-agement
Civic in-frastructure
Bridge crack detection
Smart Grid
Intelligent production
Demand prediction
Intelligent con-sumption
Conser-vation
Vehicles
User context
Local-ization
Main-tenance
Health
Hospitals
Homes
Humans

# Vehicle Sensors

# Vehicle Actuators

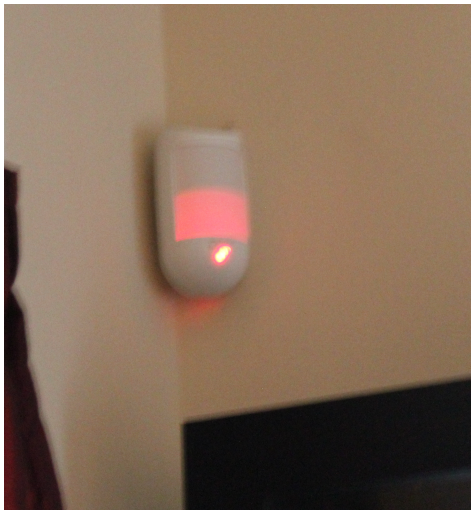
## Over the air modification of Tesla chassis elevation

US Government Work
https://www.flickr.com/photos/departmentofenergy/9522268517

# Internet of Homes and Hotels?


© Munindar P. Singh


© Nest.com



© Munindar P. Singh

# Internet of Trails

## Crabtree Lake Trail near Raleigh, North Carolina

# Internet of Oceans: Global Hybrid Profile Mooring Launch

© Tom Kleindinst, WHOI

# Internet of Oceans: Glider Being Launched

# Smart Grid


© Munindar P. Singh
EU project Scanergy's demo setup at AAMAS 2015
http://scanergy-project.eu

# Internet of Lakes

## Crabtree Lake near Raleigh, North Carolina

© Munindar P. Singh

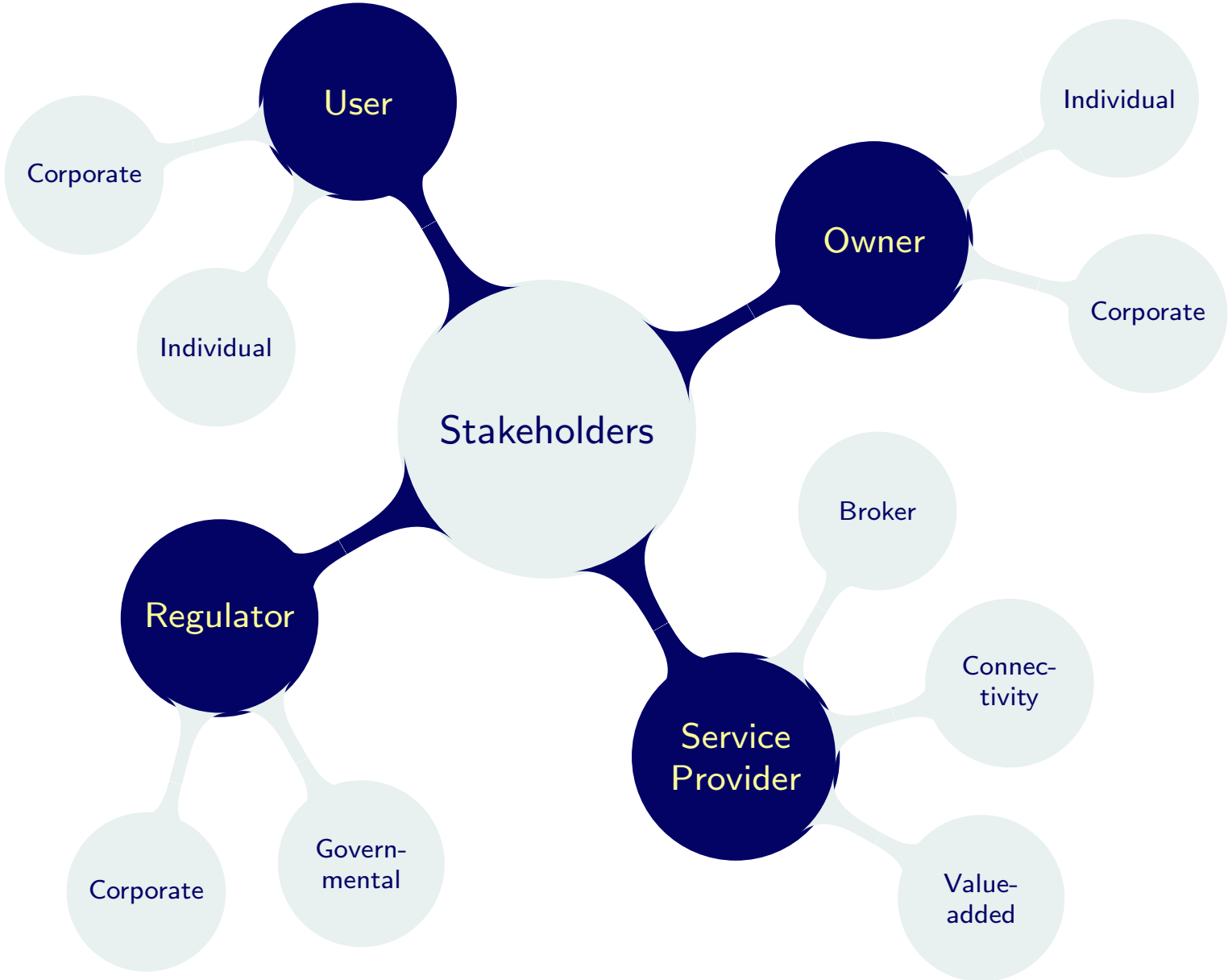
# Internet of Dogs

## Tagged stray dog in Istanbul

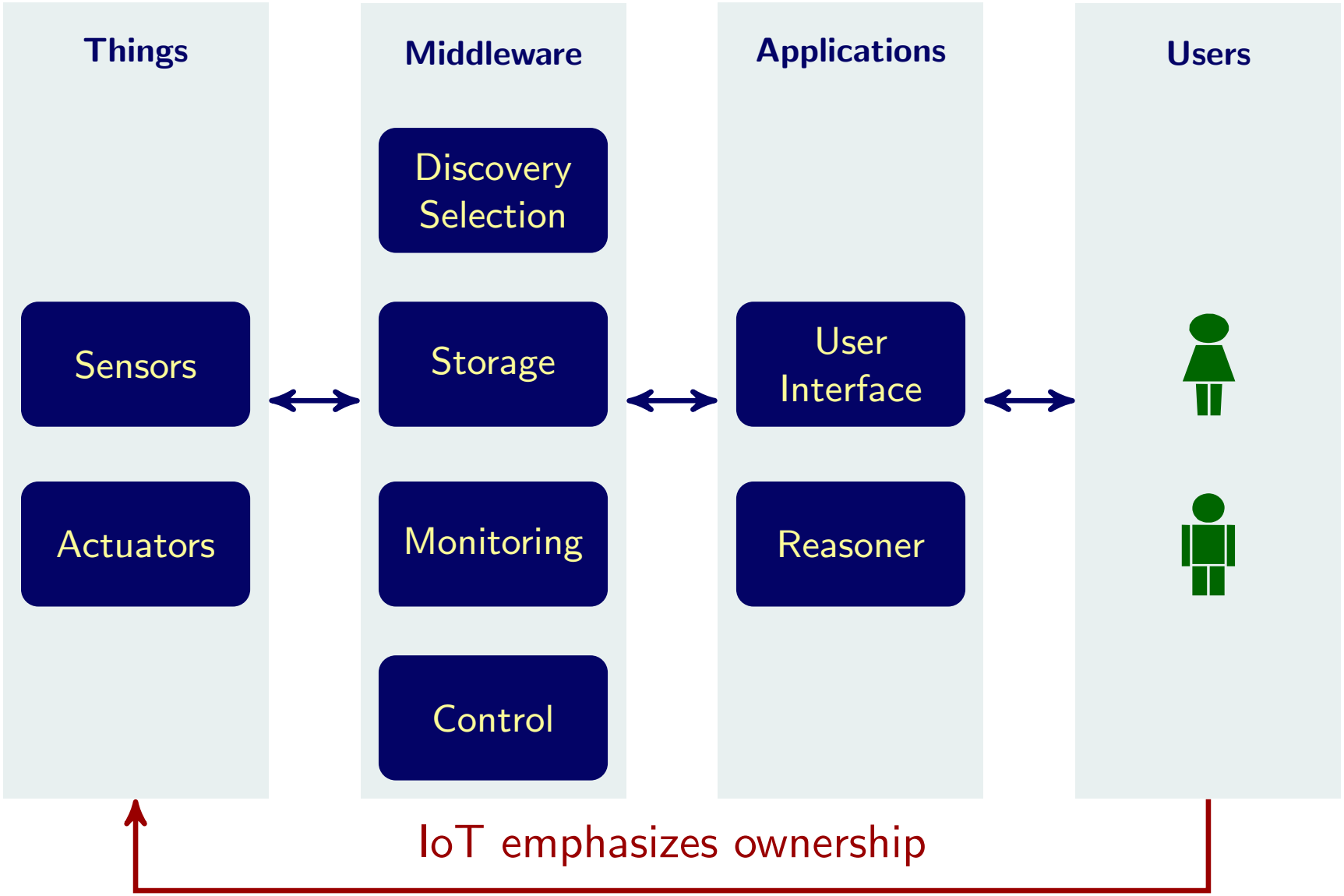
© Munindar P. Singh

# Internet of Monuments?

From the Acropolis; appears to be a visual reader, not an IoT sensor

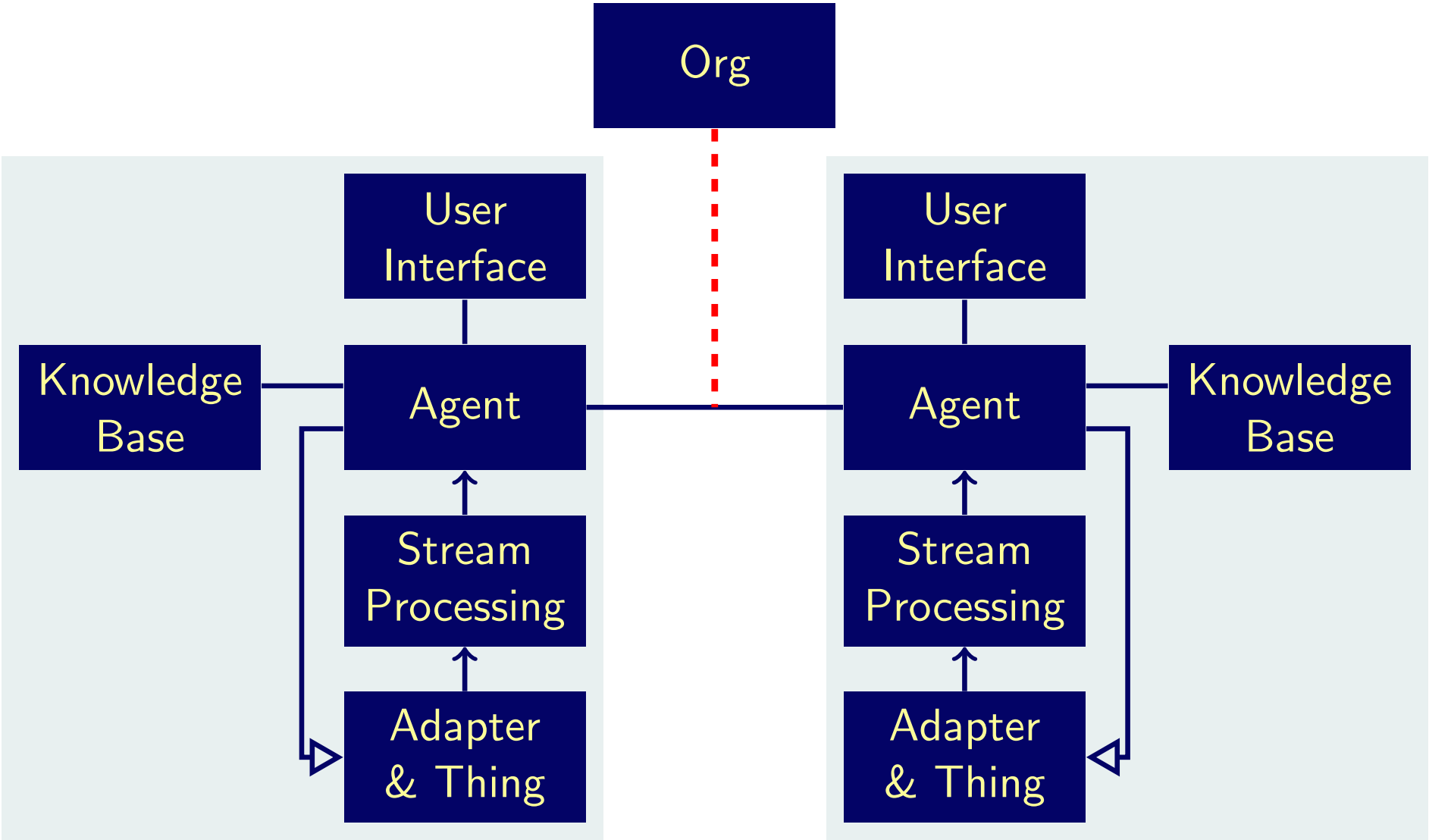

Stakeholders
User
Corporate
Individual
Owner
Individual
Corporate
Regulator
Corporate
Govern-
mental
Service
Provider
Broker
Connec-
tivity
Value-
added

# Main Architectural Elements

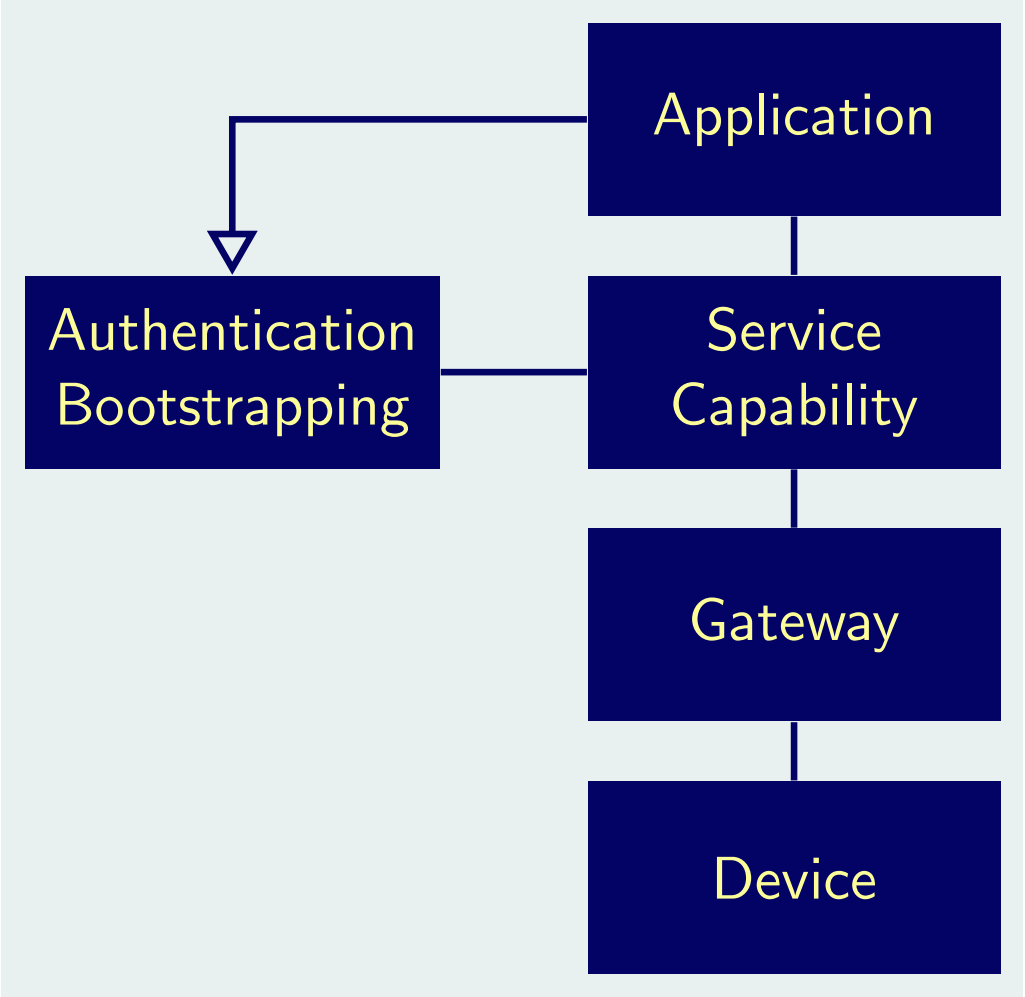


# Decentralization Calls for a Multiagent Architecture

Each agent represents an autonomous party, contains a reasoner; interact within Org



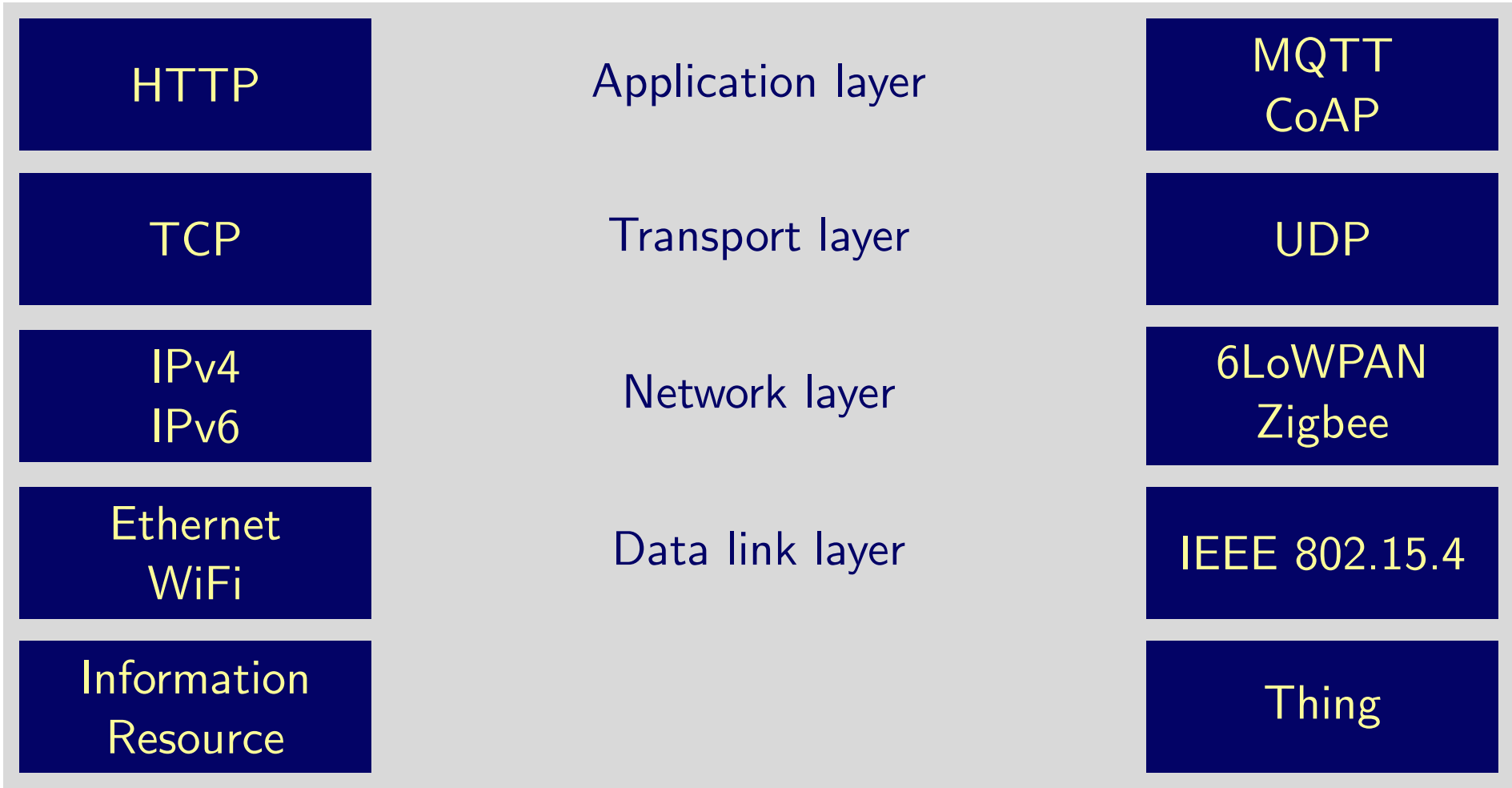
# Emerging Standards Support Decentralization in Principle




Based on ETSI draft TS 102 690, May 2014, ⟨http://docbox.etsi.org/smartM2M/Open/Latest_Drafts/⟩

# Comparing Traditional Web and IoT Protocols

## From ReST to Constrained RESTful Environments (CoRE)



# Protocol: MQTT

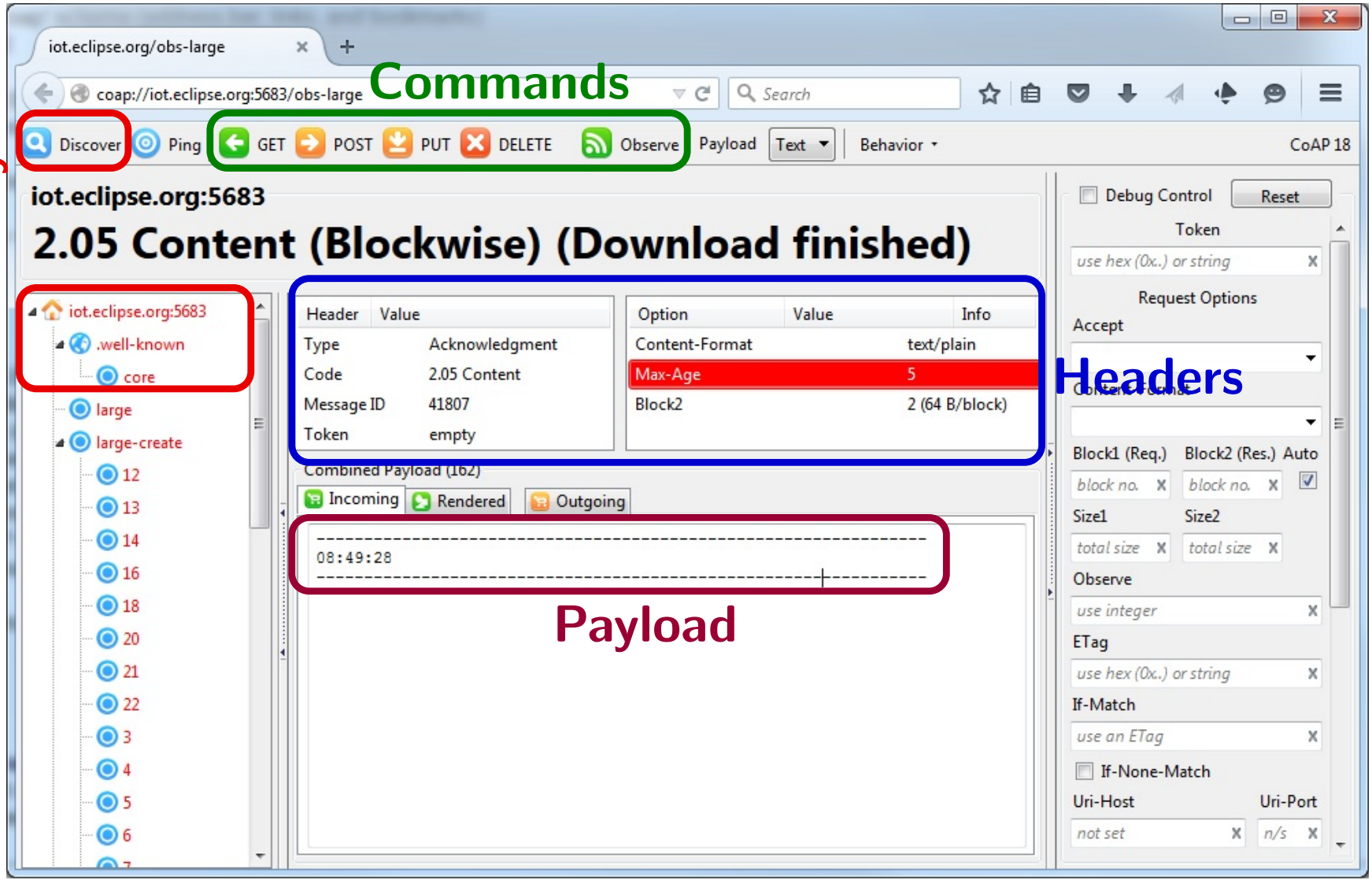
## Née Message Queue Telemetry Transport

- OASIS standard as of November 2014, v3.1.1
- Focused on machine-to-machine communications
- Asynchronous
- Data parsimonious
- Small set of primitives, including
  - Publish
  - Subscribe
  - Create and cancel subscriptions
  - Configure "last will and testament" (LWT) notifications
- Detect disconnections without a DISCONNECT message
  - Send configured LWT notifications
- Three QoS levels (separately specified by sender and receiver)
  0. At most once; message: PUBLISH; no message ID needed
  1. At least once; resend with DUP bit until PUBACK received
  2. Exactly once; server stores, then forwards to receivers

# CoAP: Constrained Application Protocol

- IETF RFC 7252, June 2014
- Asynchronous
- Data parsimonious
- Supports URIs
- Supports resource discovery from server
- HTTP-like verbs: GET, PUT, POST, DELETE
- Small set of request and response types
- Communication patterns
  - Caching
  - Block transfer of large content
- QoS support (message types)
  - Confirmable CON: require acknowledgment
  - Nonconfirmable NON: do not require acknowledgment
  - Duplicates to be ignored by receiver

# CoAP Tooling: Copper Plugin for Firefox

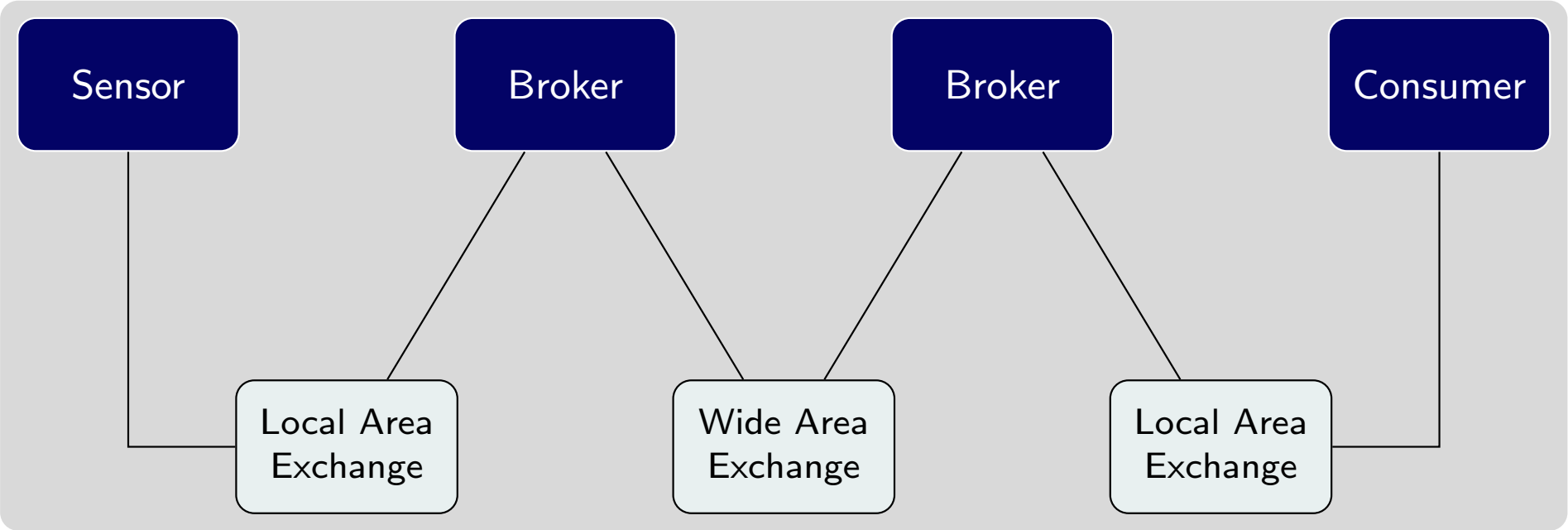



Credit: Matthias Kovatsch, ⟨http://people.inf.ethz.ch/~mkovatsc/copper.php⟩

# AMQP: Advanced Message Queuing Protocol

- OASIS standard as of October 2012, v1.0
- Protocol—distinguish from an API such as JMS
- Decouples communications from destination address
- Long-lived conversations
- Variety of communication patterns
  - Intercept
  - Delegate
  - Multiplex and demultiplex
- Upcoming improvements
  - Traffic flow and QoS
  - Decentralized deployment and governance
  - Multiple underlying protocols

# AMQP Exchange Space Abstraction




Based on work with Ocean Observatories Initiative, UCSD Scripps

# XMPP: Extensible Messaging and Presence Protocol

## Originally meant for collaboration and content sharing

- Adapted and enhanced for IoT via XMPP Extension Protocols
- XEP-0323: Internet of Things – Sensor Data, v0.4, March 2015
- Describes protocols and data formats for variety of needs
  - Request sensor reading and responses thereto
  - Requests with multiple responses
  - Requests to multiple things
  - Discovery: what *features* (including services) a thing supports
    - Different from discovery of a thing
- Specification of quality of data value (termed QoS), e.g.,
  - Missing, estimated, manually read, delayed, invoiced, ...

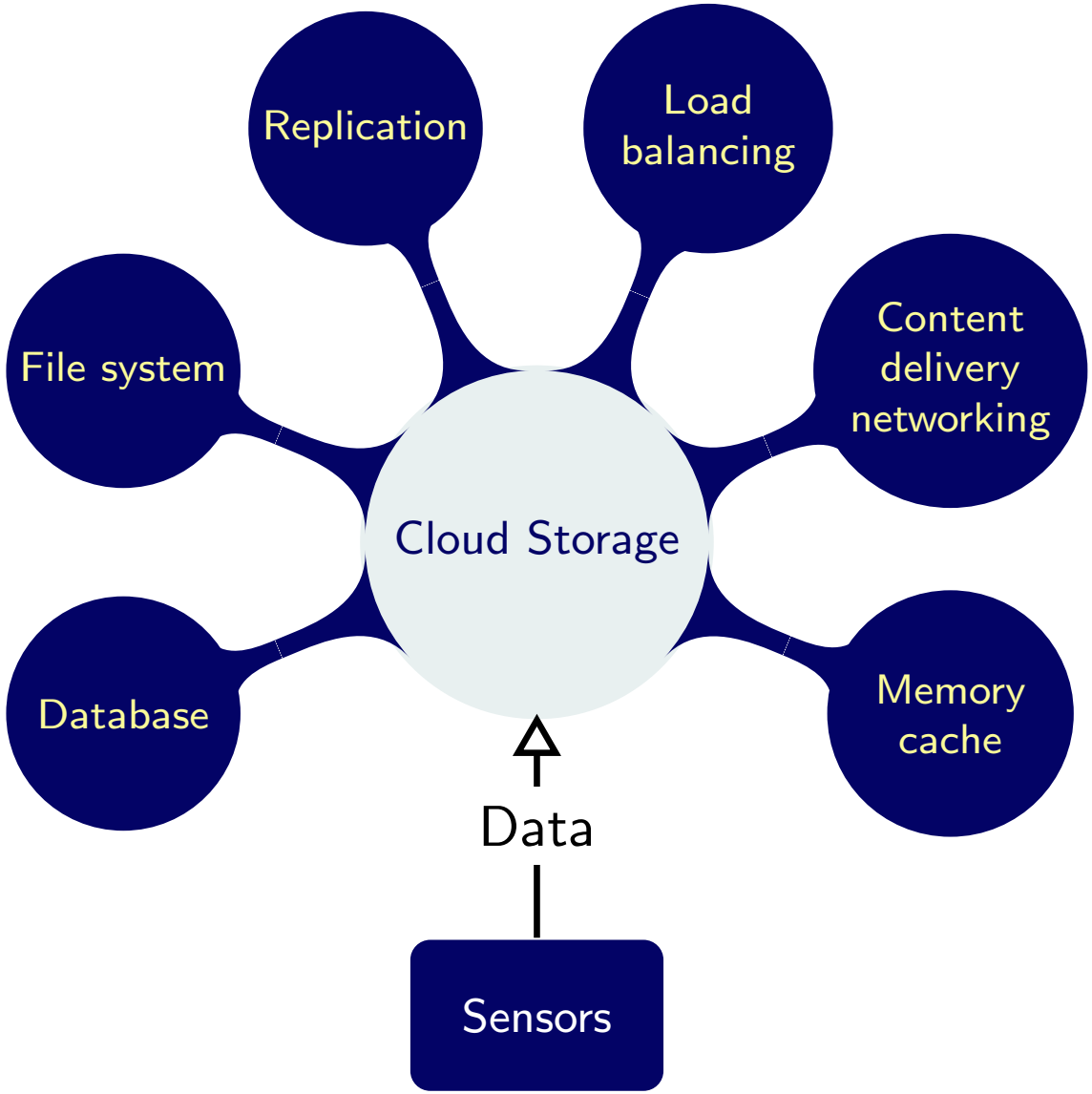
# XMPP: Extensible Messaging and Presence Protocol

- XEP-0347: Internet of Things – Discovery, v0.3, November 2014
- Uses JID or *Jabber ID* or an XMPP address for various resources
  - Registries
  - Provisioning servers
  - Things
- Specifies protocols and data formats for
  - Finding a registry
  - Registering a thing: a thing registers itself
    - Specifies secret data for registration
    - May provide the same data via a sticker (QR-code) on a physical thing
    - Public things remain searchable after being claimed
  - Owner claiming a thing (by supplying the secrets)
    - Only claimed, currently owned, things can be searched
  - Removing a thing from a registry
  - *Disowning* or relinquishing a thing

# Cloud Storage

## Eliminate need to set up complex storage services from scratch

- On demand
- Variety of data services
- NoSQL (and NewSQL) databases
  - Alternative to ACID databases
  - Tradeoff strong consistency for low latency



# Cloud Services

## Querying and transforming data

- Structured Query Language (SQL)
- Rule engines
- Complex event processing (CEP)
- Streaming SQL
  - *Continuous* queries
  - SQL-interface for event processing
- MapReduce programming
- Hosting and executing custom programs

# ETSI's Service Capability Layer

## On top of connectivity: holdall for functional, security, and governance aspects

- Communication
  - Semisynchronous: quick ack followed by full answer
  - Asynchronous
  - Works on top of another protocol, e.g., HTTP and CoAP
- Service capabilities
  - Registration
  - Access control
  - Authentication
  - Data transfer
  - Subscribe and notify
  - Handling groups

# Fog Computing

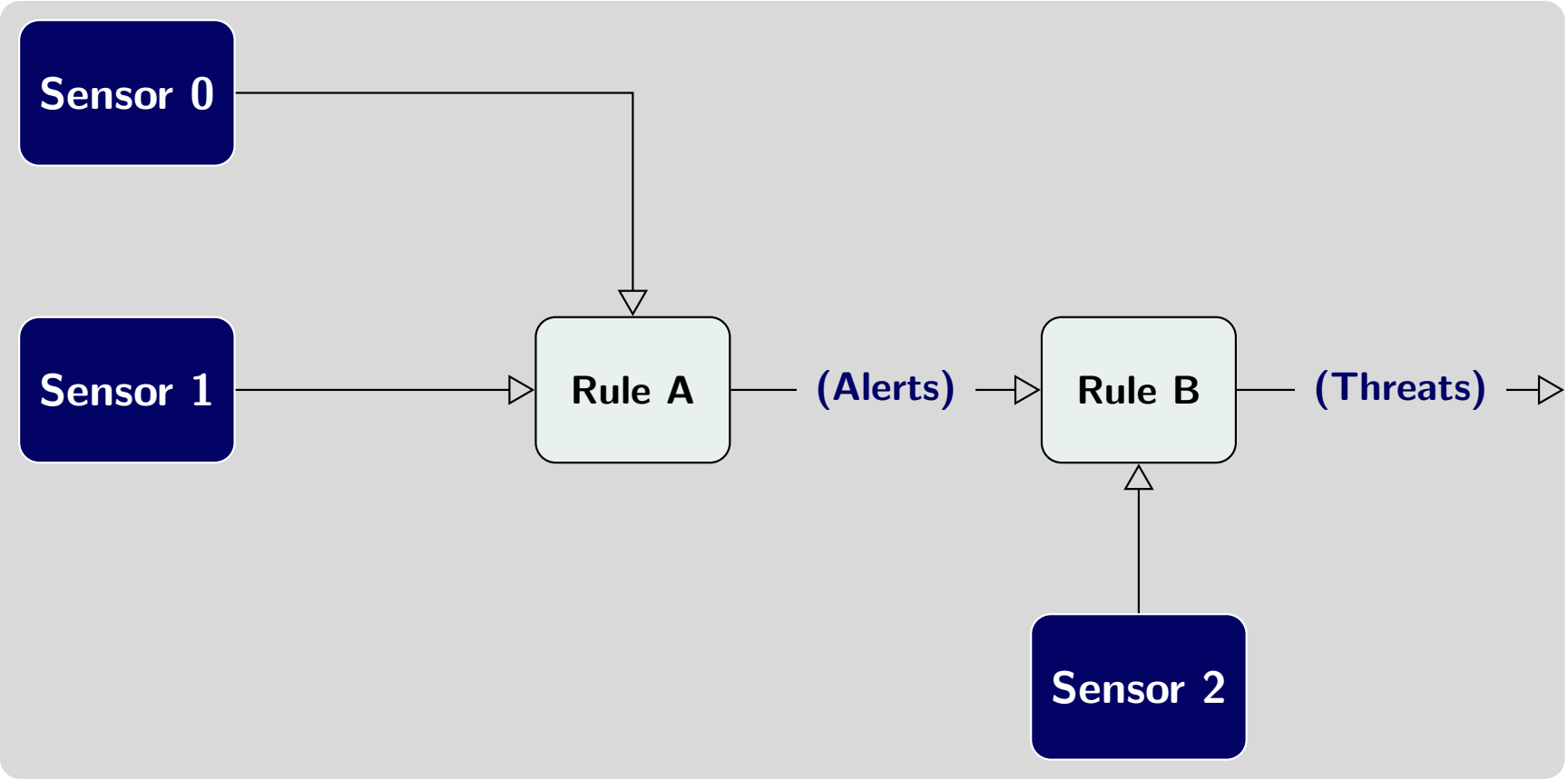
Cisco's term for decentralized or "ground-level" variant of cloud computing

- Intermediary between things and the cloud (data centers)
- Place computing, storage, services near the edge
- Process data closer to where it originates
  - Many devices talk to one another
  - Improve latency and throughput
- Improves treatment of autonomy with gains in
  - Local governance
  - Security

# Event-Driven Architecture

## Consume and produce event streams

- Event attributes: ID, timestamp, and content values



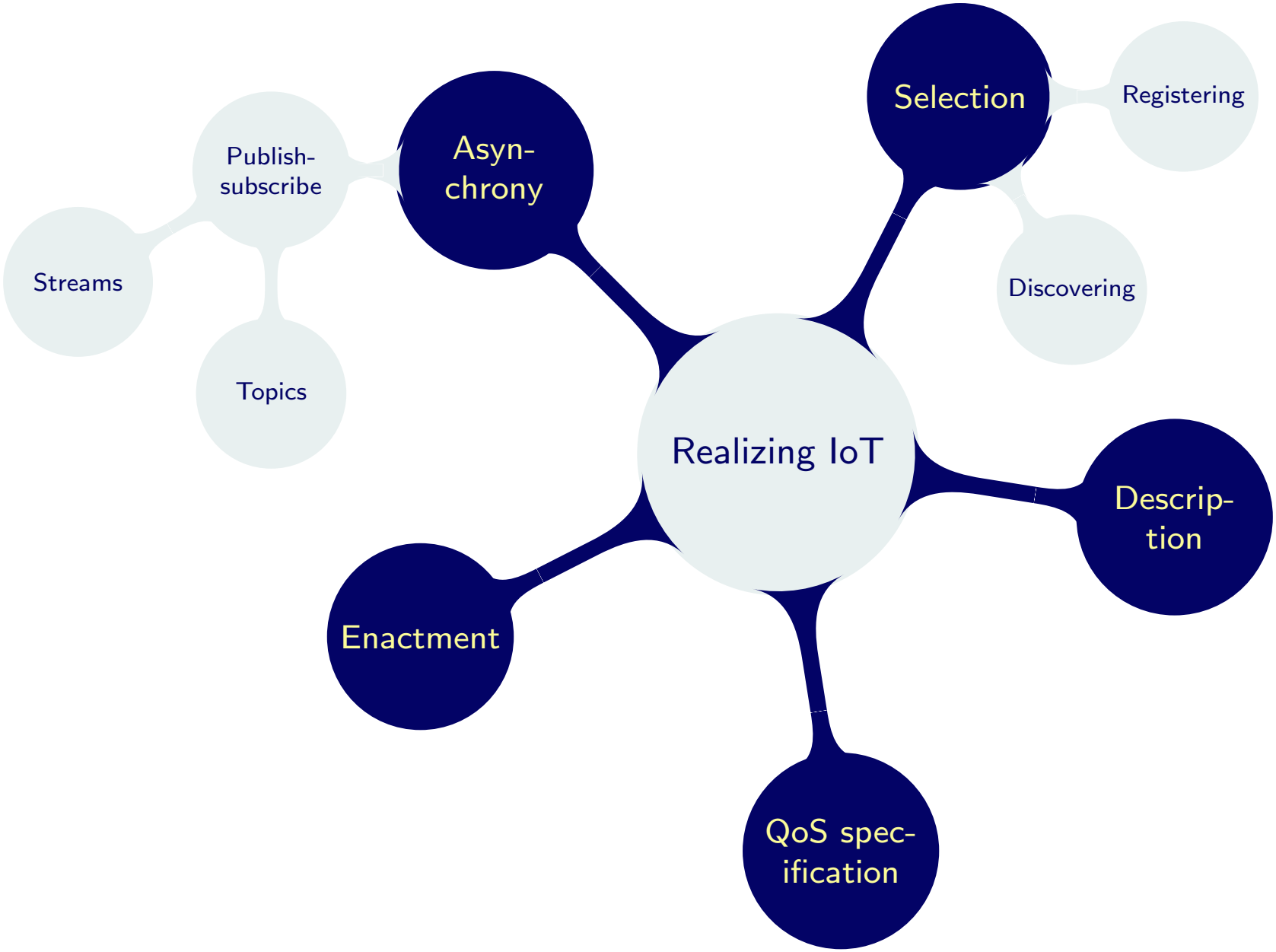
# Linked Data Highlights

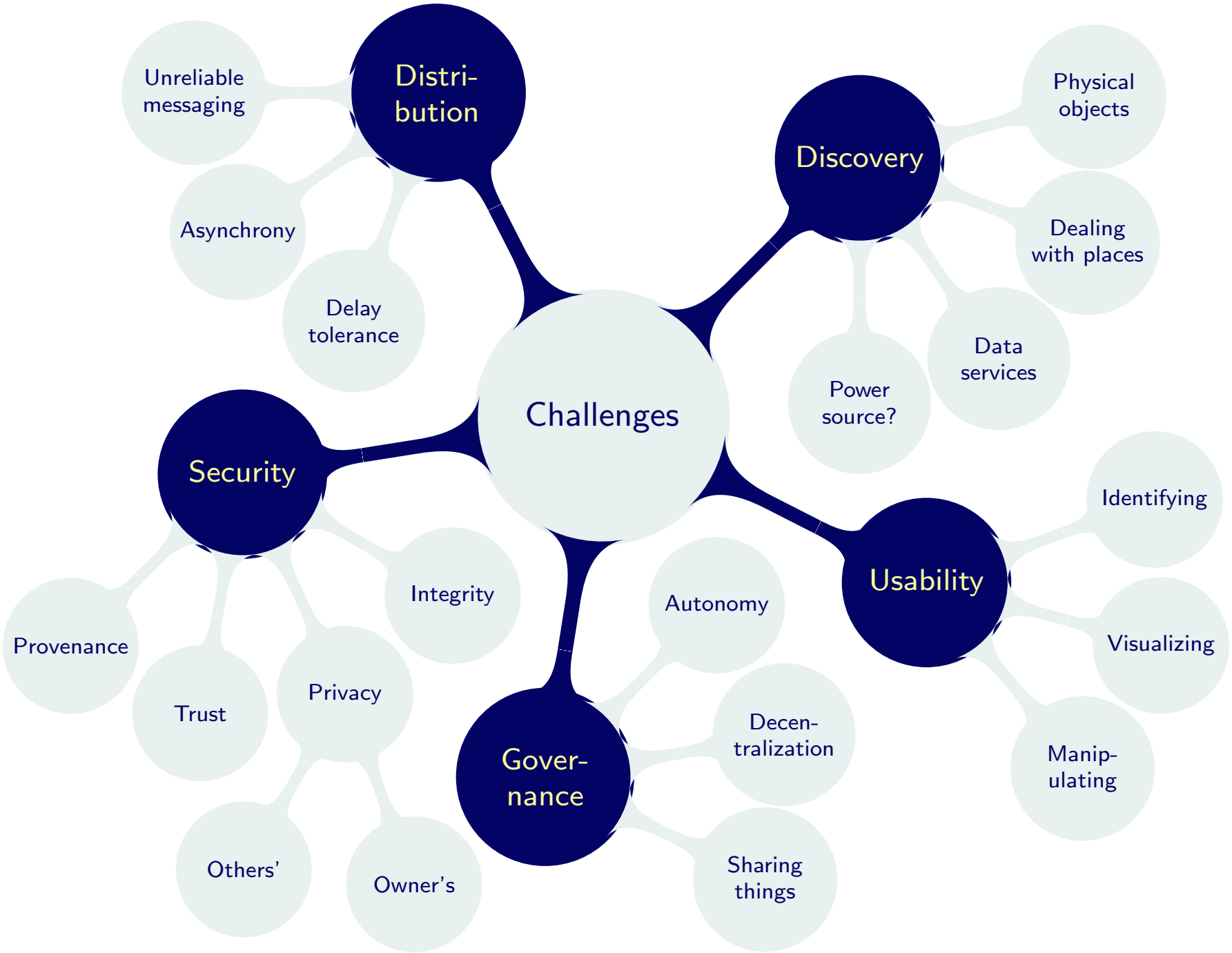
- Web-based identity and network
  - URIs identify resources
  - Deferencing a URI produces a resource description
  - Resources link to other resources
- Web-based semantics
  - Encoded in a Semantic Web language, such as the Resource Description Framework, RDF
- Exploit underlying architecture, e.g., Domain Name System and Web servers, to locate resources

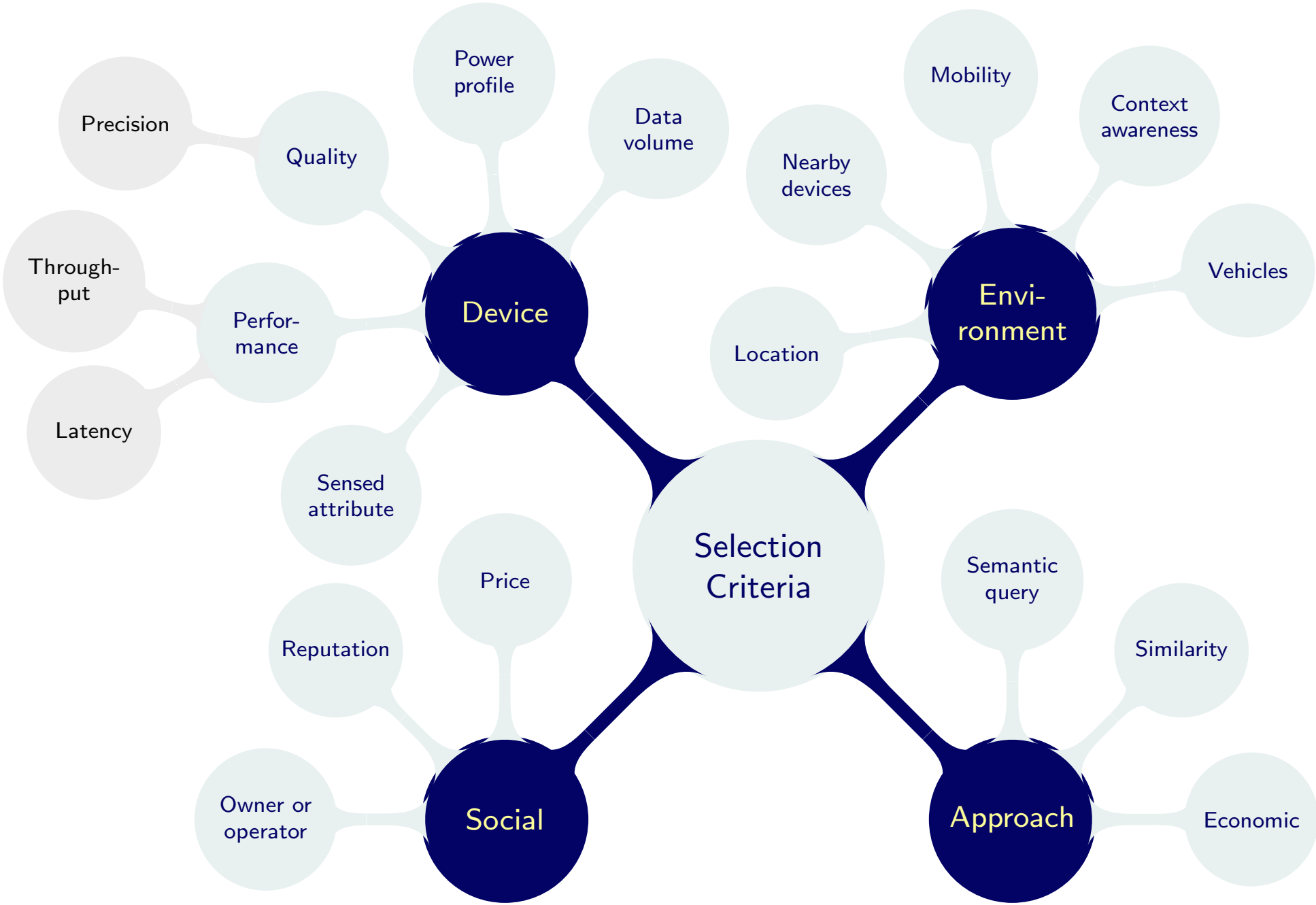
# Linked Data for IoT

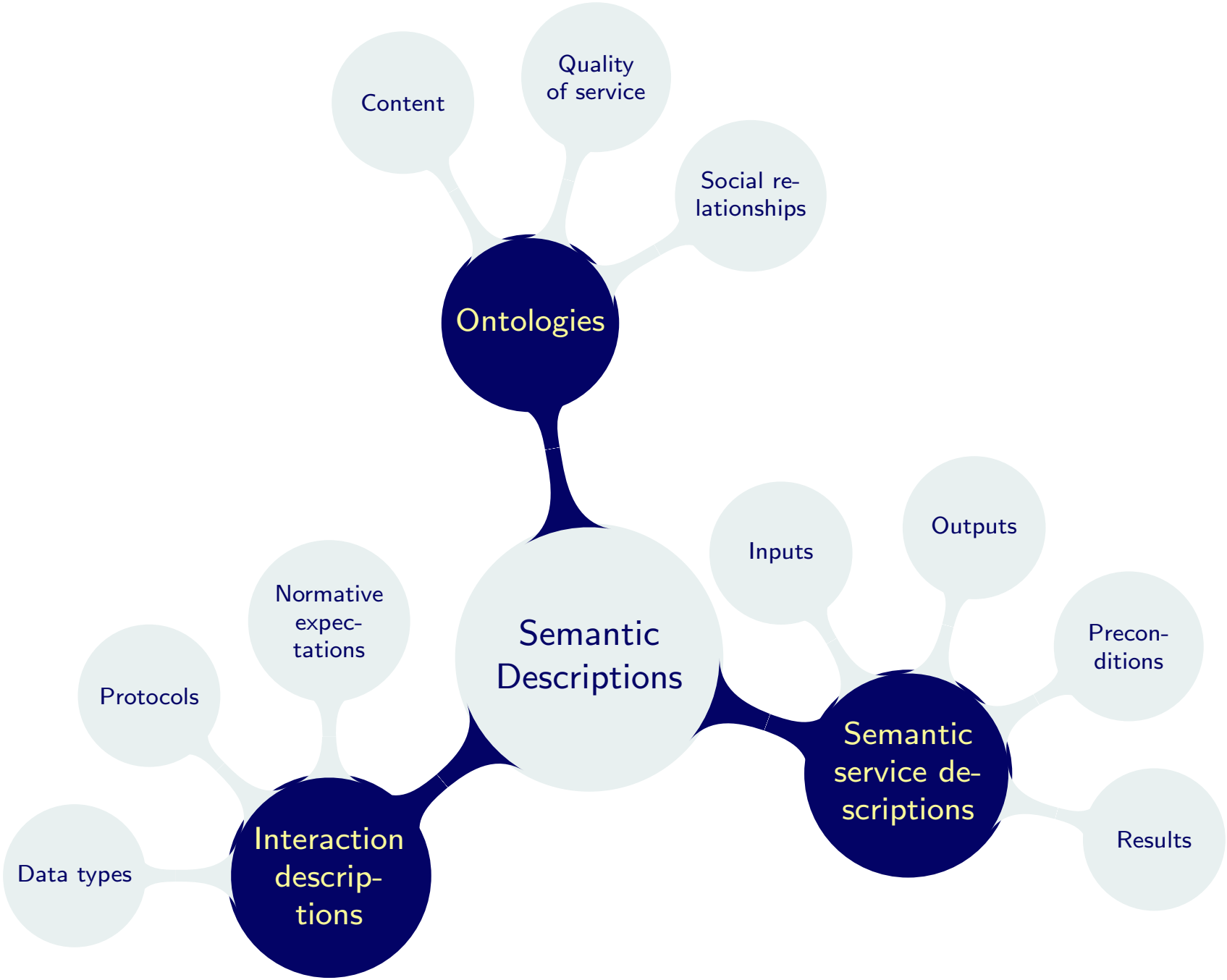
Sensor data is worthless unless linked to something else!

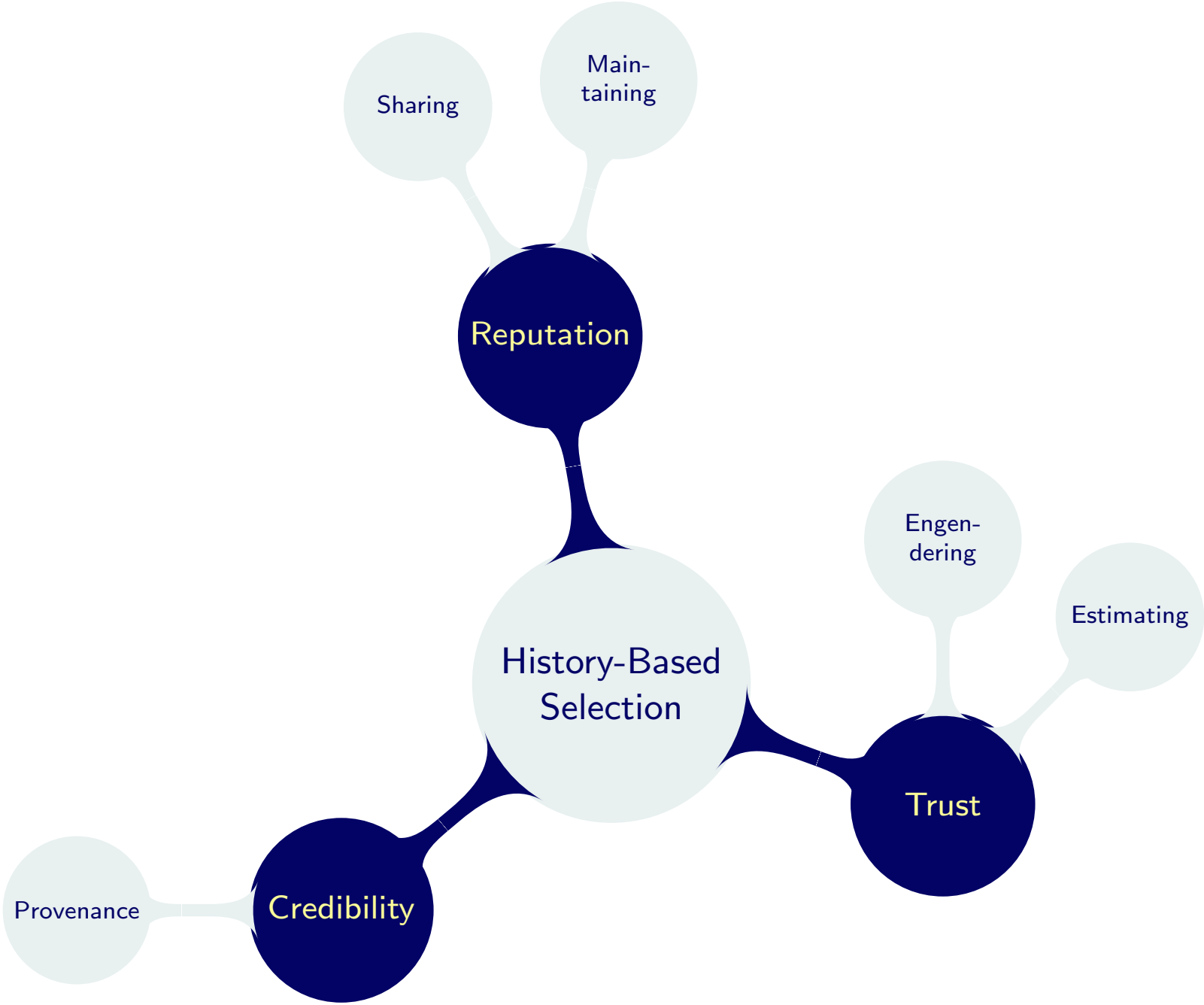
- Describe things
  - Link thing descriptions to one another
  - Enable thing discovery
- Describe the information produced by things
- Describe how to configure things
- Enable things to exchange semantic information
  - Facilitate reasoning
  - Promote interoperability
- Supported by standards that incorporate URIs
  - CoAP, ETSI's Service Capability Layer

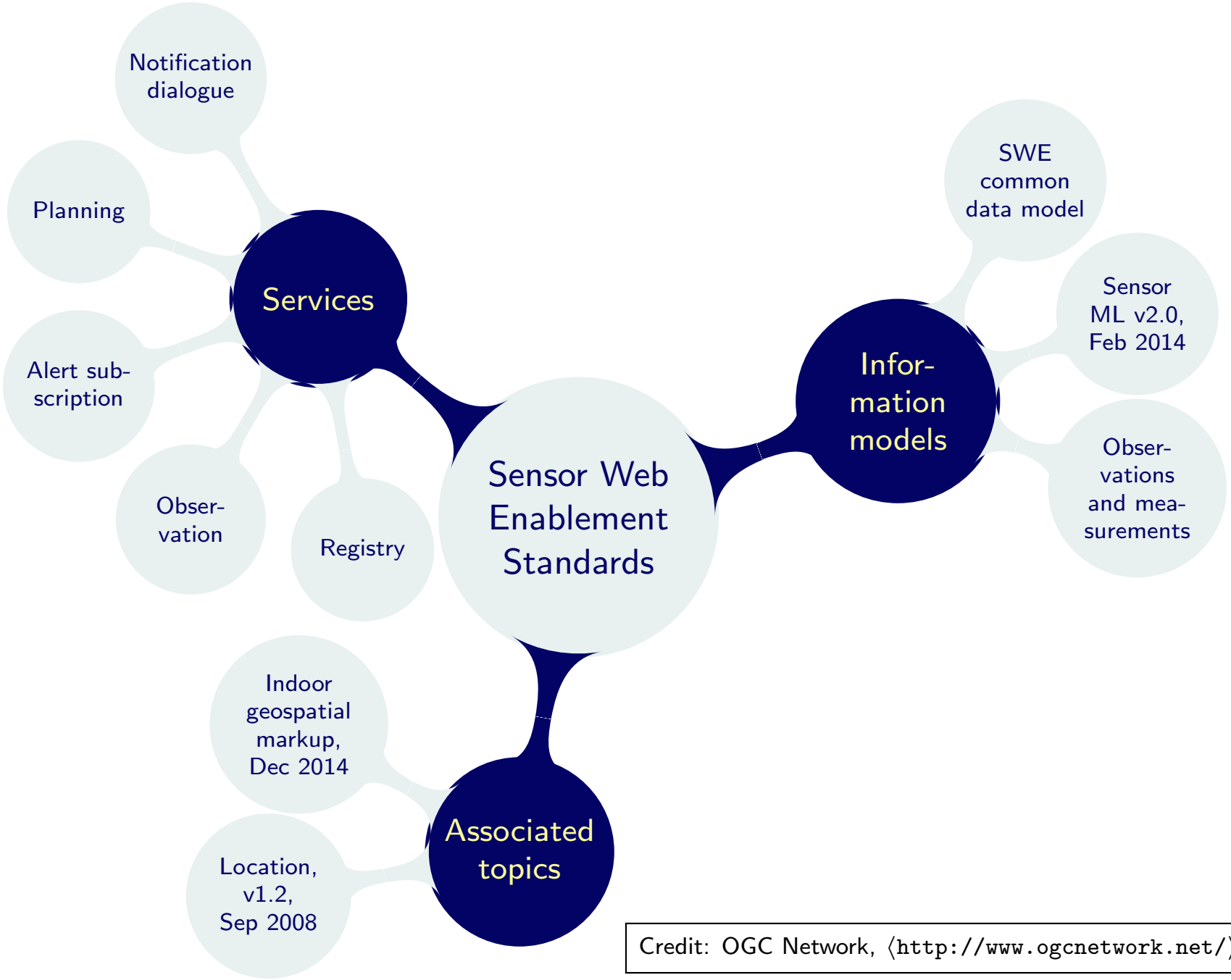

Realizing IoT
Asyn-chrony
Publish-subscribe
Streams
Topics
Selection
Registering
Discovering
Description
Enactment
QoS spec-ification


Challenges
Distri-bution
Unreliable messaging
Asynchrony
Delay tolerance
Discovery
Physical objects
Dealing with places
Data services
Power source?
Security
Integrity
Provenance
Trust
Privacy
Gover-nance
Autonomy
Decen-tralization
Sharing things
Others'
Owner's
Usability
Identifying
Visualizing
Manip-ulating


Selection Criteria
Device
Power profile
Data volume
Quality
Precision
Perfor-mance
Through-put
Latency
Sensed attribute
Environment
Mobility
Context awareness
Nearby devices
Vehicles
Location
Social
Price
Reputation
Owner or operator
Approach
Semantic query
Similarity
Economic


Content
Quality of service
Social relationships
Ontologies
Semantic Descriptions
Inputs
Outputs
Precon-ditions
Results
Semantic service descriptions
Normative expec-tations
Protocols
Data types
Interaction descrip-tions


Sharing
Main-
taining
Reputation
Engen-
dering
Estimating
History-Based
Selection
Trust
Provenance
Credibility




Credit: OGC Network, ⟨http://www.ogcnetwork.net/⟩

# Sharing, Fusing, and Revising Information

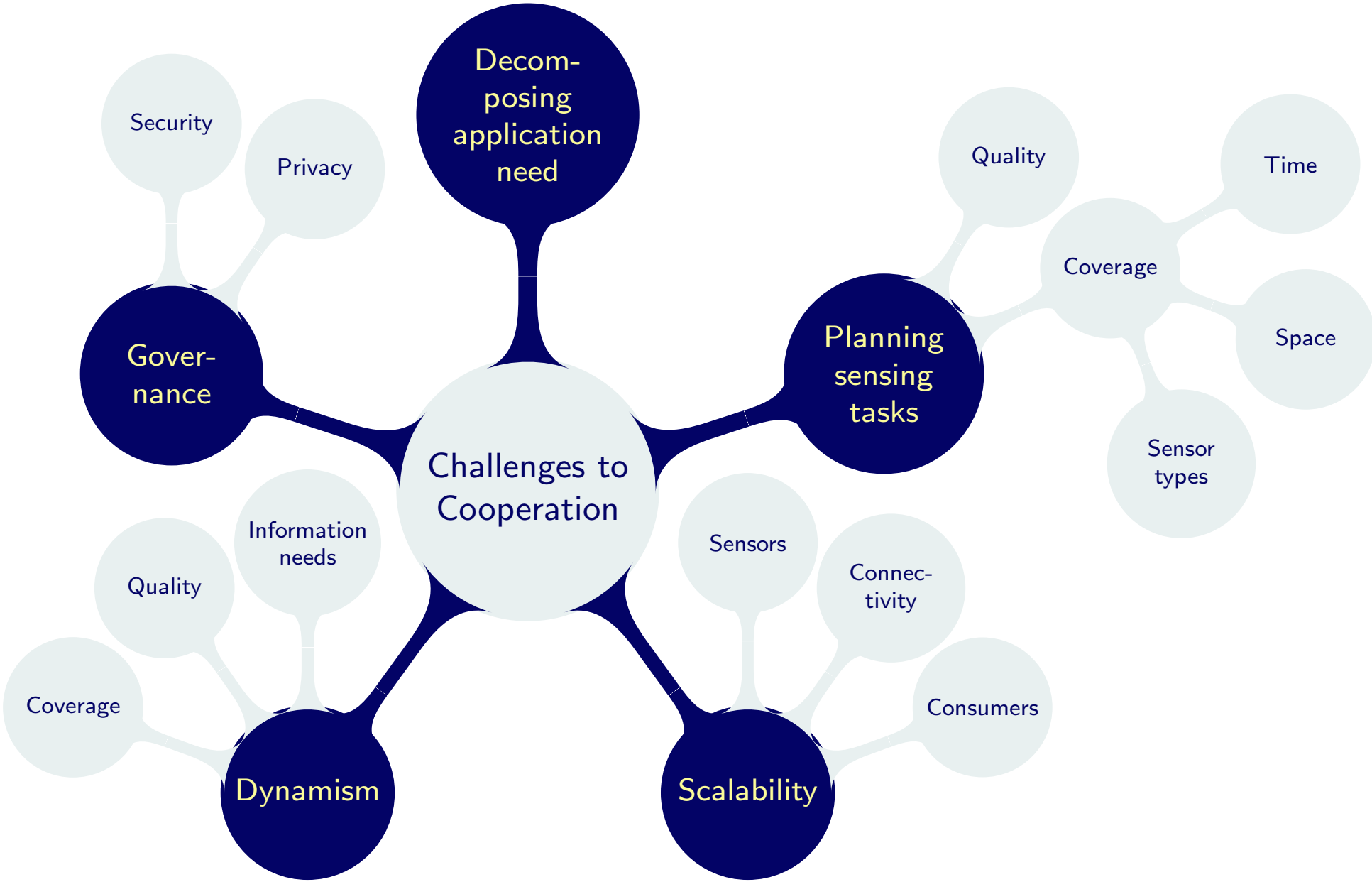
## Inspired by social computing

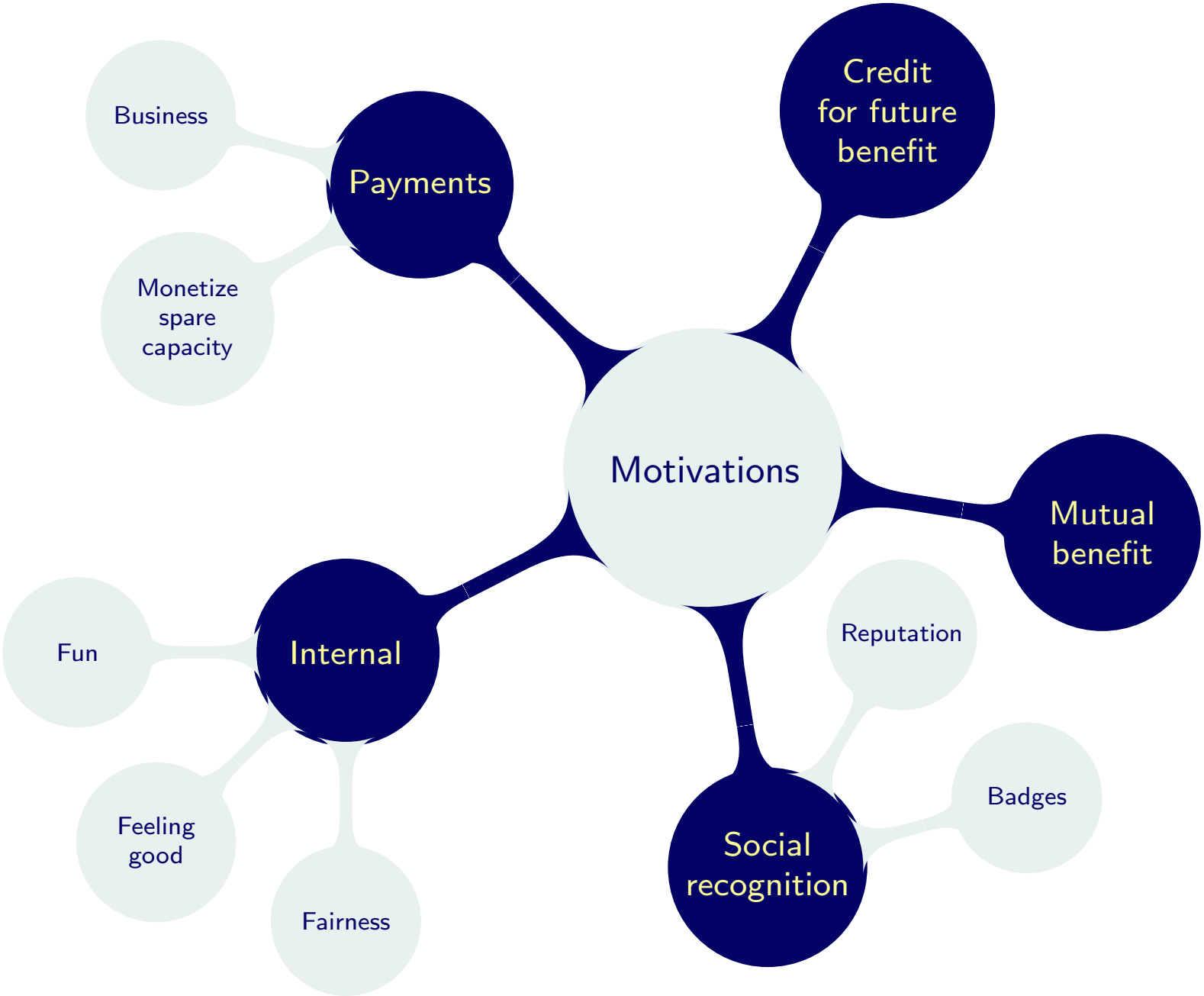
- Folk wisdom about aggregating knowledge
- Galton's Vox Populi
  - Median of many estimates represents the voice of the people
  - Underlying intuition of crowdsourcing
- Condorcet Jury Theorem
  - If each information source is better than 50% accurate (binary case)
  - Then their majority is even more accurate (depending on how many)
- Participatory or community sensing
  - Usually based on phone sensors rather than things as such
  - Includes explicit user actions, e.g., sending a picture

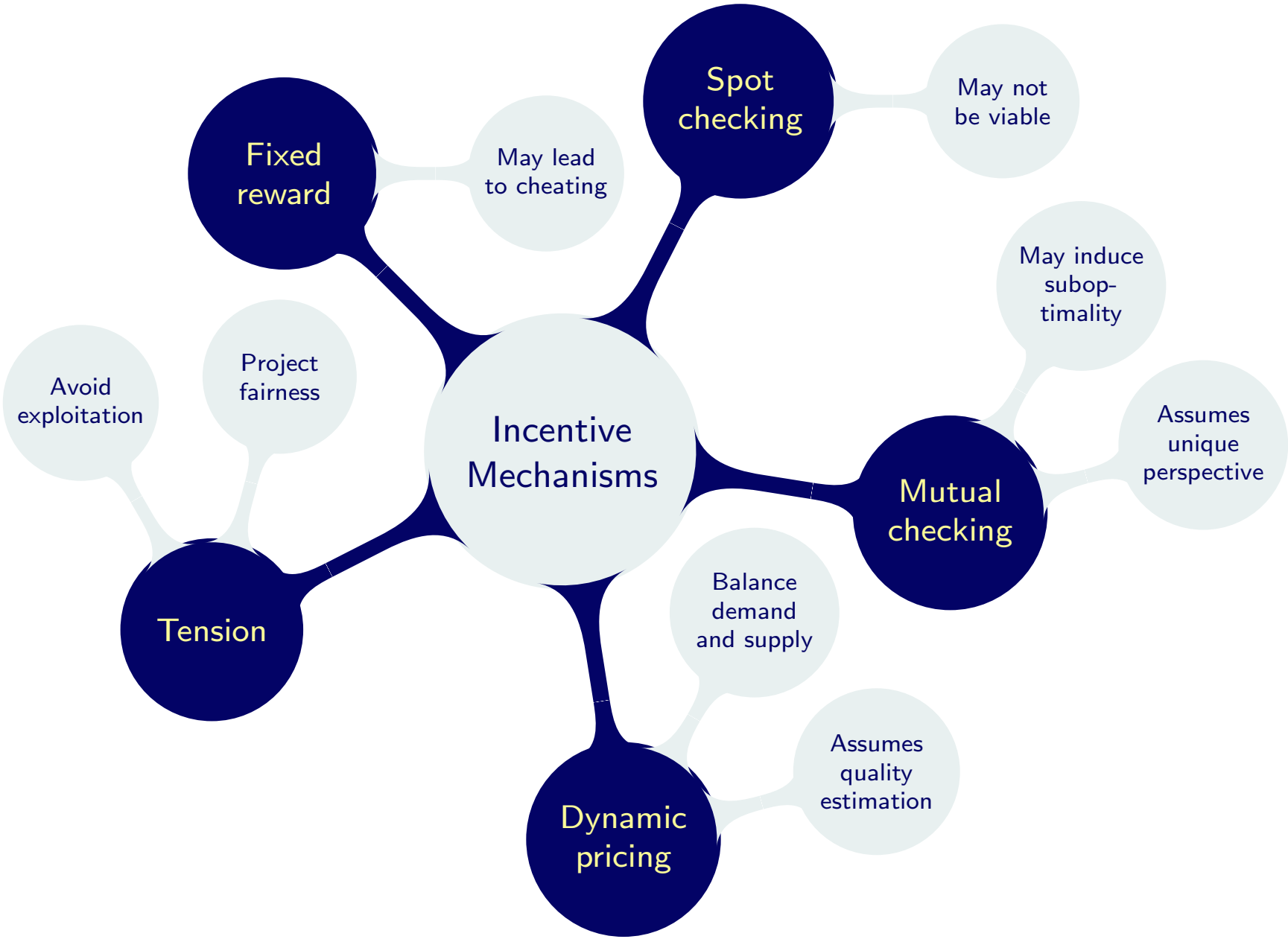
# Assumptions in Participatory Sensing

## Why would anyone participate honestly?

- Sensor owners bear a cost when the sensors provide data
  - Energy
  - Bandwidth
  - Installation and maintenance
- Sensor owners may
  - Refuse to participate
  - Configure their sensors to provide low quality results
  - Instruct their sensors to falsify results
- Majority or central estimates work when
  - The user (consumer) owns and controls all sensors
  - Incentives promote cooperation and verification
  - Other aspects induce *prosocial* behavior

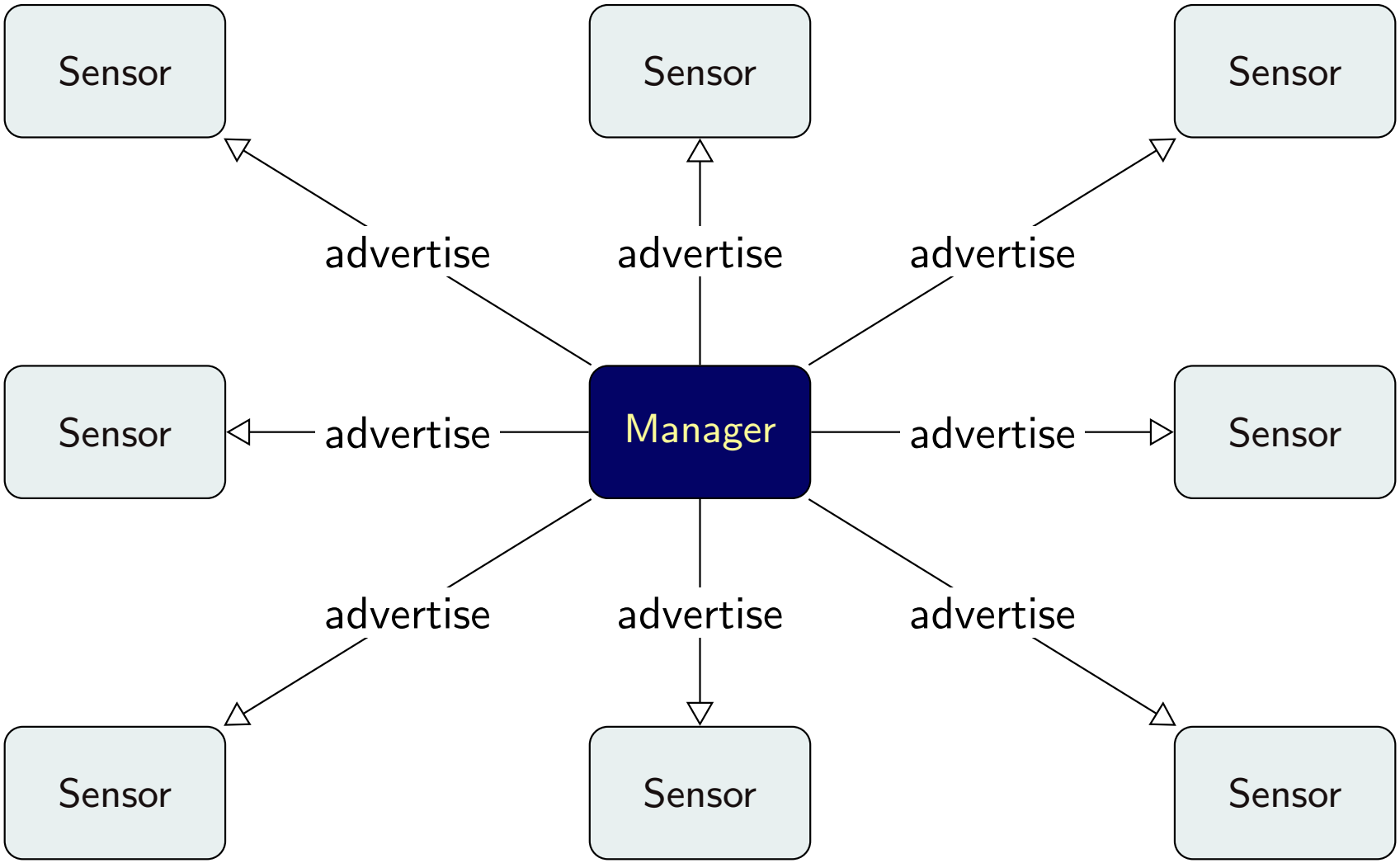

Challenges to Cooperation
Decom-posing application need
Gover-nance
Security
Privacy
Planning sensing tasks
Quality
Coverage
Time
Space
Sensor types
Dynamism
Information needs
Quality
Coverage
Scalability
Sensors
Connec-tivity
Consumers


Business
Payments
Credit for future benefit
Monetize spare capacity
Motivations
Mutual benefit
Fun
Internal
Reputation
Feeling good
Badges
Social recognition
Fairness


Incentive Mechanisms
Fixed reward
May lead to cheating
Spot checking
May not be viable
Mutual checking
May induce subop-timality
Assumes unique perspective
Tension
Avoid exploitation
Project fairness
Dynamic pricing
Balance demand and supply
Assumes quality estimation

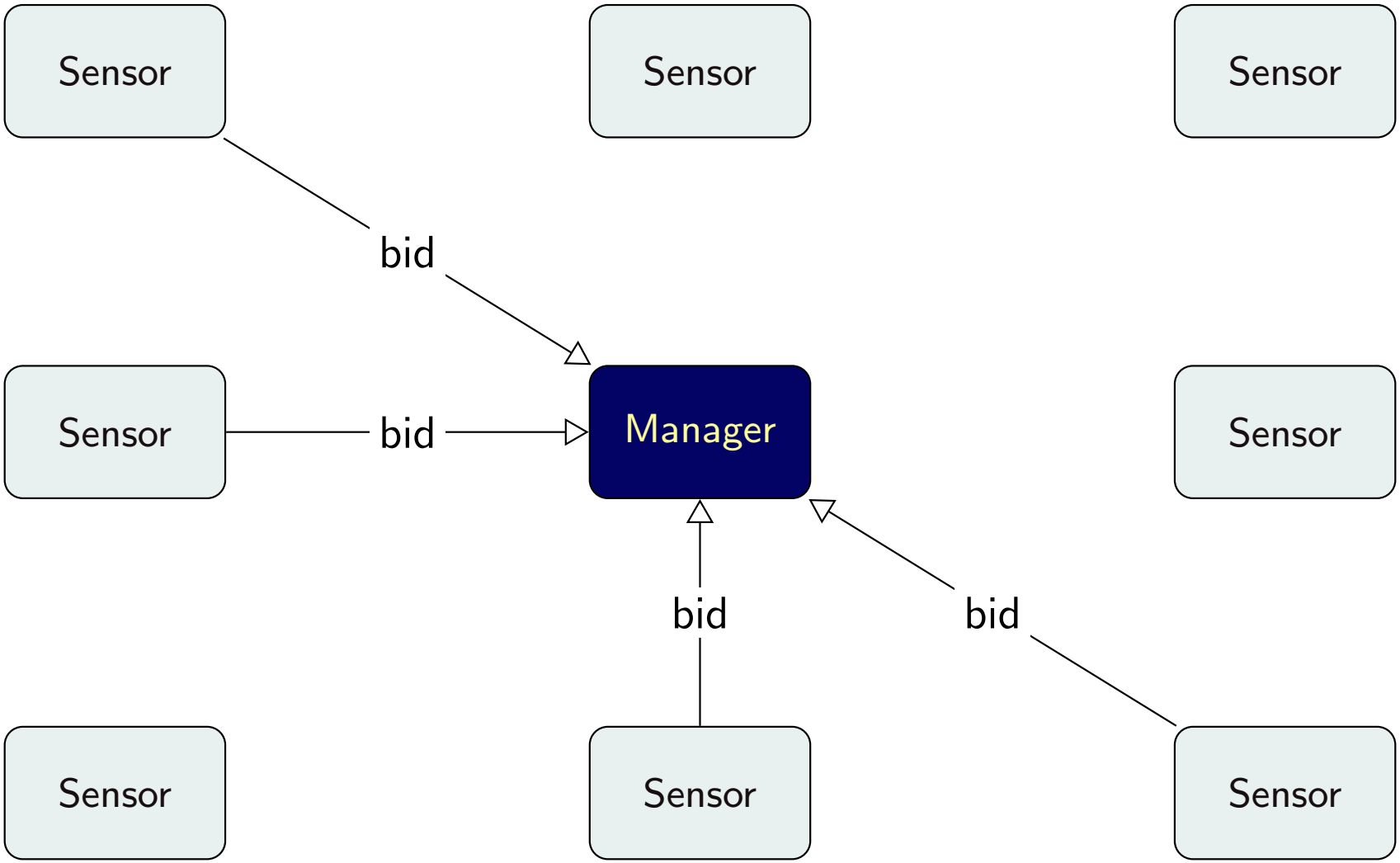
# Contract Net Protocol: 1

## Announce



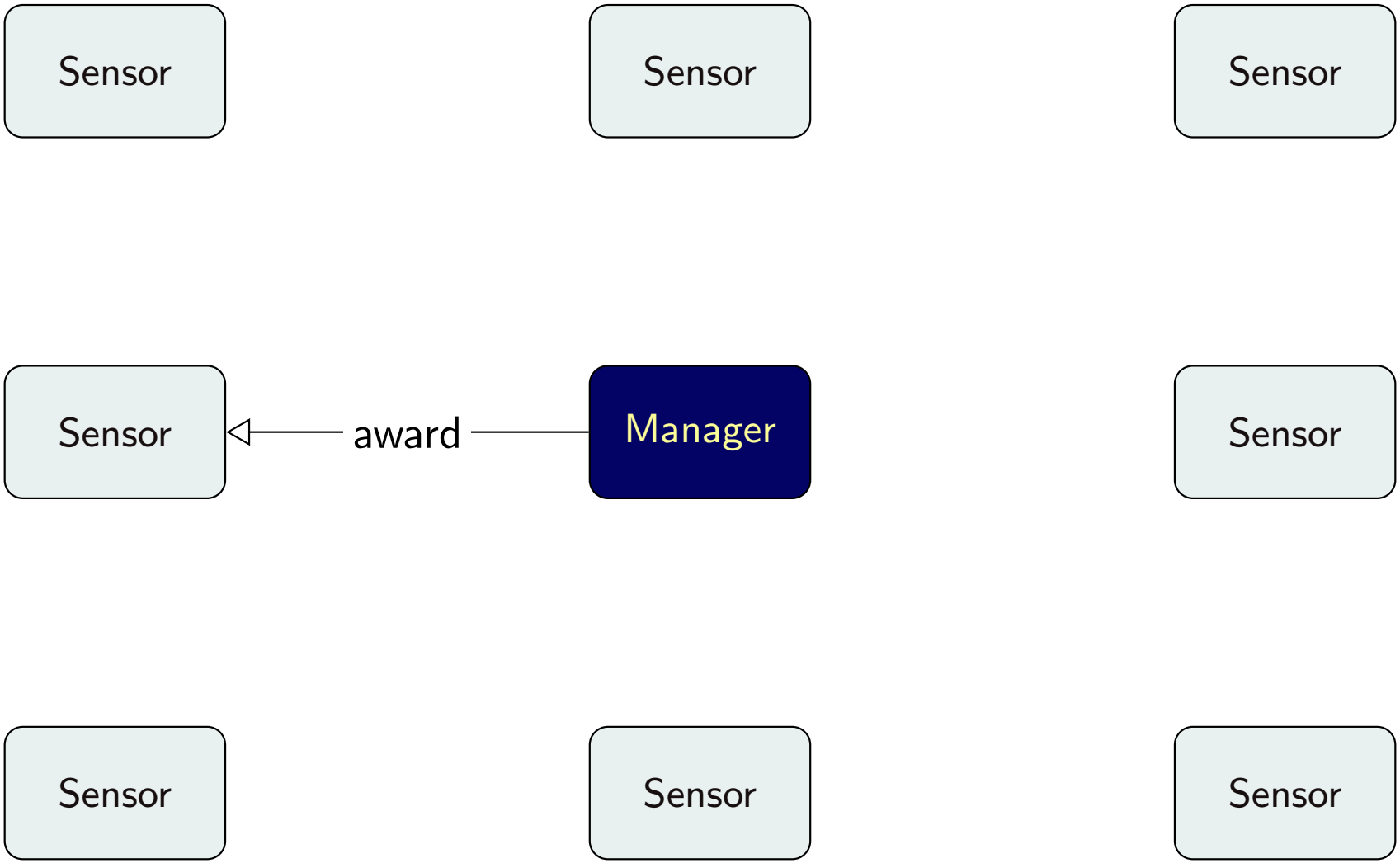
# Contract Net Protocol: 2

## Bid



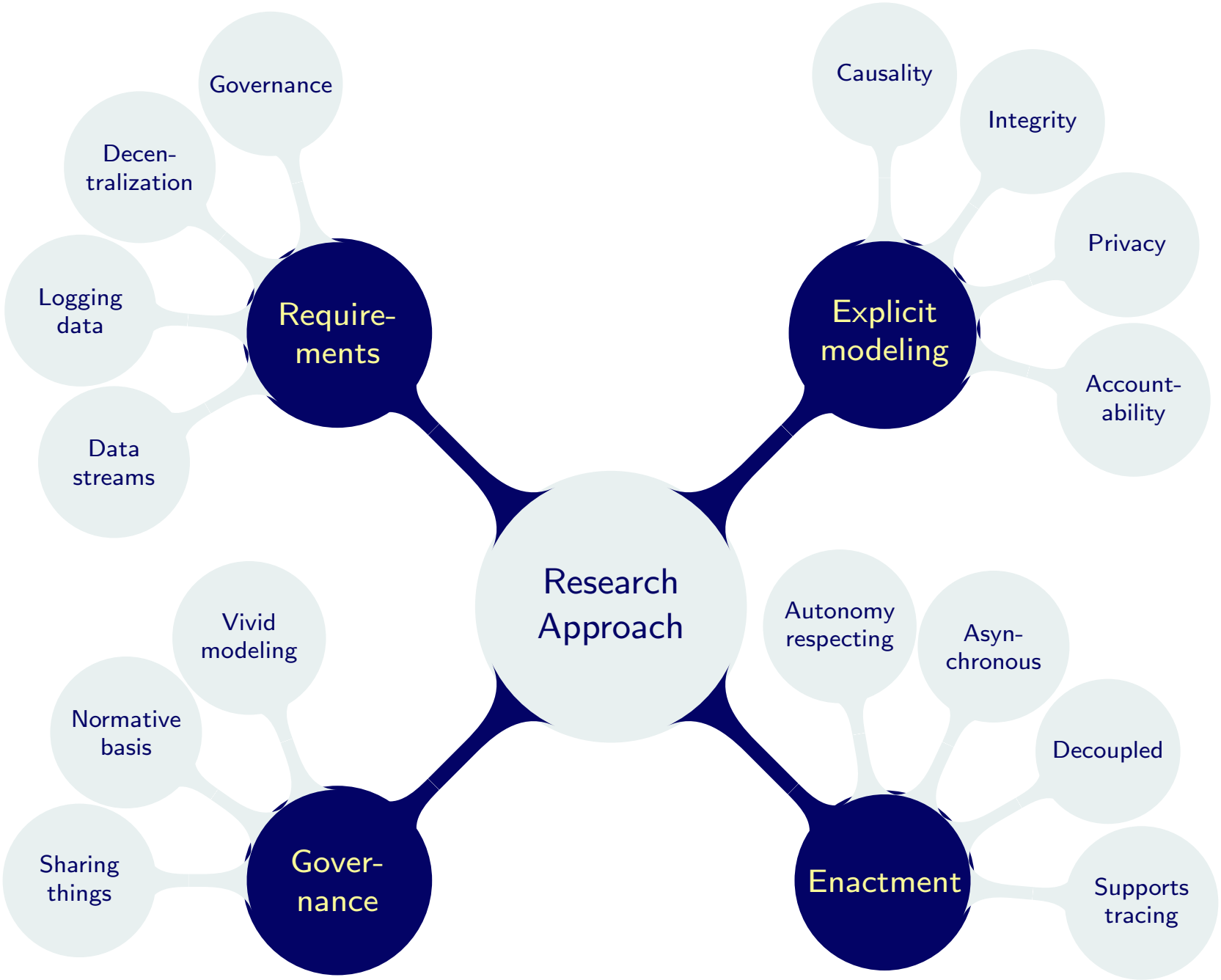
# Contract Net Protocol: 3

## Award



# Contract Net Protocol Evaluated

- Generic protocol
  - Can apply recursively
- Supports important properties
  - Robustness against sensor failure
  - Robustness against connectivity failure
  - Incorporating economic features
- Not well specified
  - Confuses interaction and internal reasoning
  - Limited to two-party interactions


Research Approach
Require-ments
Governance
Decen-tralization
Logging data
Data streams
Explicit modeling
Causality
Integrity
Privacy
Account-ability
Gover-nance
Vivid modeling
Normative basis
Sharing things
Enactment
Autonomy respecting
Asyn-chronous
Decoupled
Supports tracing

# The *Contract Net* Protocol

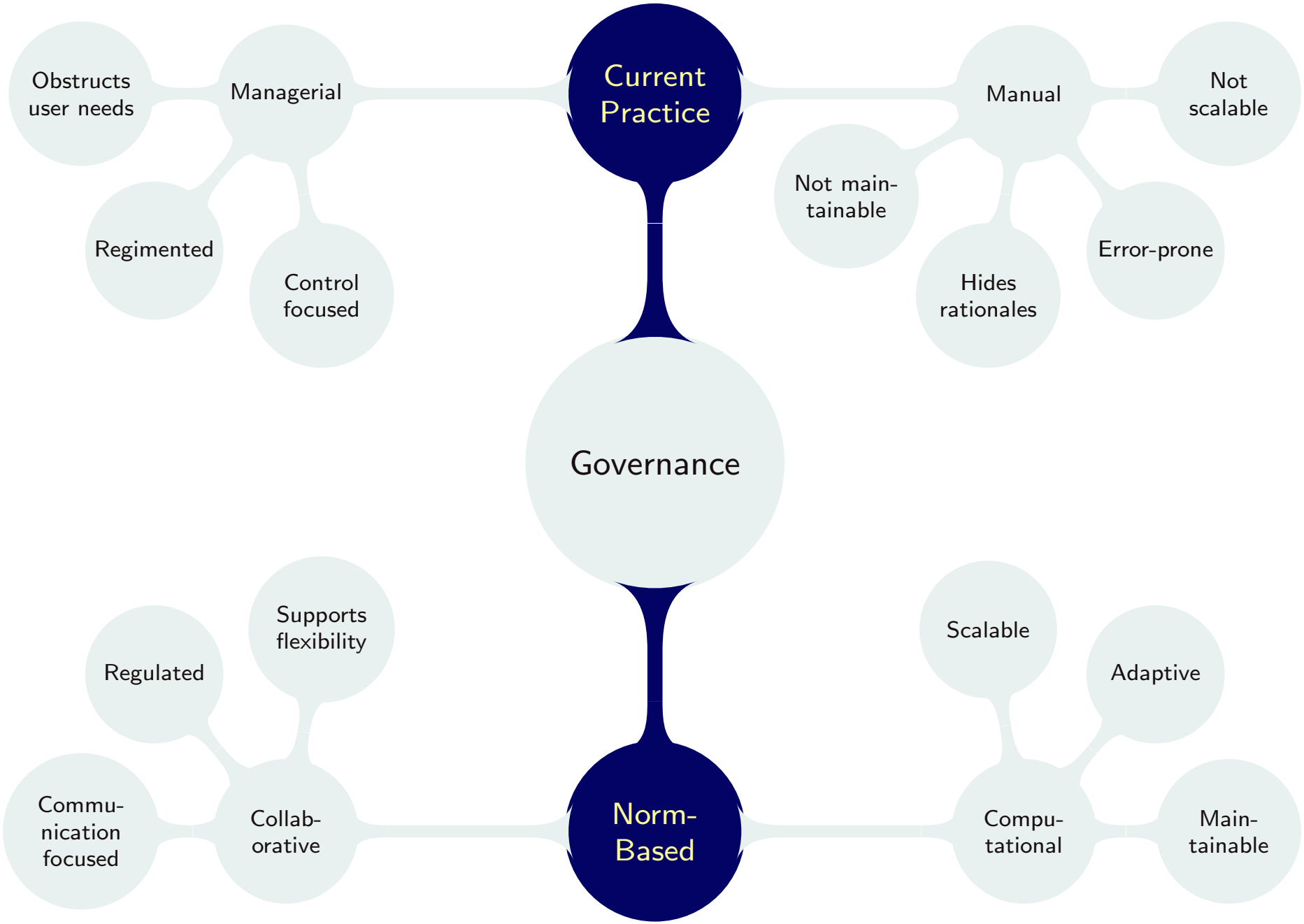
## BSPL (afternoon tutorial tomorrow)

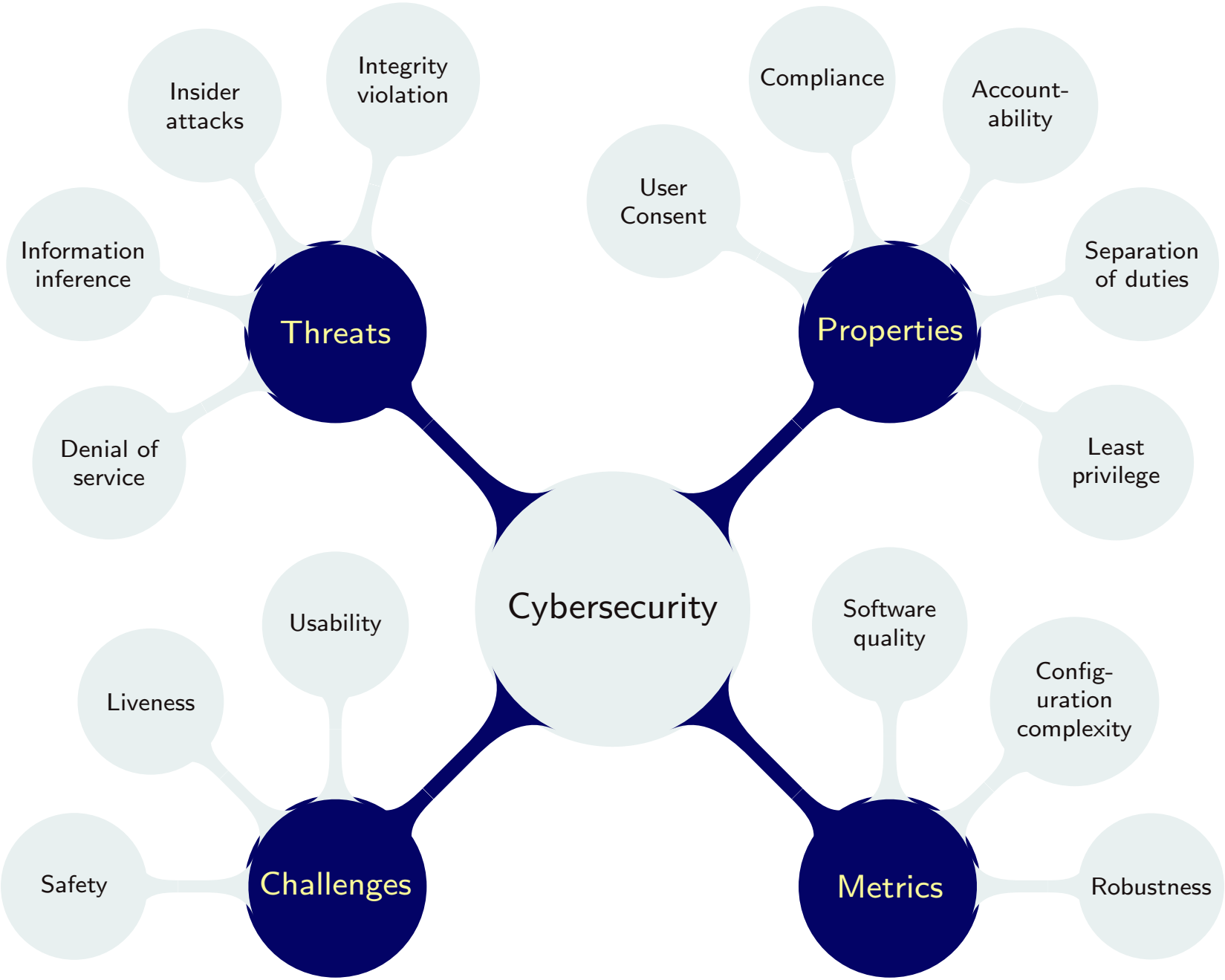
```
Contract Net {
 role Manager uni, Bidder ⊒ Winner uni
 parameter out ID key, out request, out response, out decision

 Manager ↦ Bidder: CfB[out ID, out request]

 Bidder ↦ Manager: bid[in ID, in request, out response]

 Manager ↦ Winner: award[in ID, in request, in response, out
     decision]
}
```


Governance
Current Practice
Obstructs user needs
Managerial
Regimented
Control focused
Manual
Not scalable
Not maintainable
Error-prone
Hides rationales
Norm-Based
Supports flexibility
Regulated
Communication focused
Collaborative
Scalable
Adaptive
Computational
Maintainable


Cybersecurity
Threats
Insider attacks
Integrity violation
Information inference
Denial of service
Properties
Compliance
Account-ability
User Consent
Separation of duties
Least privilege
Challenges
Usability
Liveness
Safety
Metrics
Software quality
Config-uration complexity
Robustness

# Governance for Secure Collaboration

## Broadly, administering sociotechnical systems to serve stakeholder needs

Existing and emerging standards, such as ETSI's, provide partial support for governance

- Resource management
  - Devices
  - Channels
- Group management
  - Membership creation, verification, maintenance...
  - Subscriptions, announcements
  - Permissions
- Credential management
  - Authentication
  - Authorization

Operational specifications but no formal representation or model

Credit: ETSI draft TS 102 690, May 2014, ⟨http://docbox.etsi.org/smartM2M/Open/Latest_Drafts/⟩

# Governance: Critique

- Currently, automated support comes with managerial imposition: by superiors on subordinates
  - Control over managed resources
  - Necessary but not sufficient
  - Unsuited to many settings
    - When user needs aren't met, they subvert managerial diktats
    - Resulting in vulnerabilities
- Currently, governance is manual via out-of-band communications
  - Low productivity
  - Poor scalability to fine-grained, real-time governance decisions
  - Hidden, implicit considerations yield low confidence in correctness and poor maintainability
    - Lead to errors
    - Therefore, vulnerabilities

# Governance Challenges in IoT

## Accommodating autonomy, heterogeneity, and dynamism

- Support *configurational adaptation*
  - Resource sharing: Offer ocean instrument for sharing
  - Affiliation: Add new laboratories
  - Sanction: Allow external sharing of results to fulfill deliverables
- Support *operational adaptation*
  - Resource sharing: Preempt low-priority users in case of oil spill
  - Affiliation: Forbid unilateral publishing of results
  - Sanction: Absolve researcher who reveals results to prevent public endangerment (extenuating circumstances)
- Research challenges
  - Abstractions to capture rules of encounter
  - Methods to design and analyze such abstractions
  - Methods to implement such abstractions

# Foundations of Secure Collaboration over IoT

## Social perspective that complements technical (data, application, infrastructure) perspectives

- *Policy:* An implementation-independent specification of decision making
- *Normative basis:* Key relationships are reflected in norms, to be used a standard of correctness for interactions
- *Social context:* An Org (as a microsociety) recursively provides the context for the norms among and policies of its members
- *Interaction orientation:* How agents apply policies to enter into, monitor, and enact normative relationships

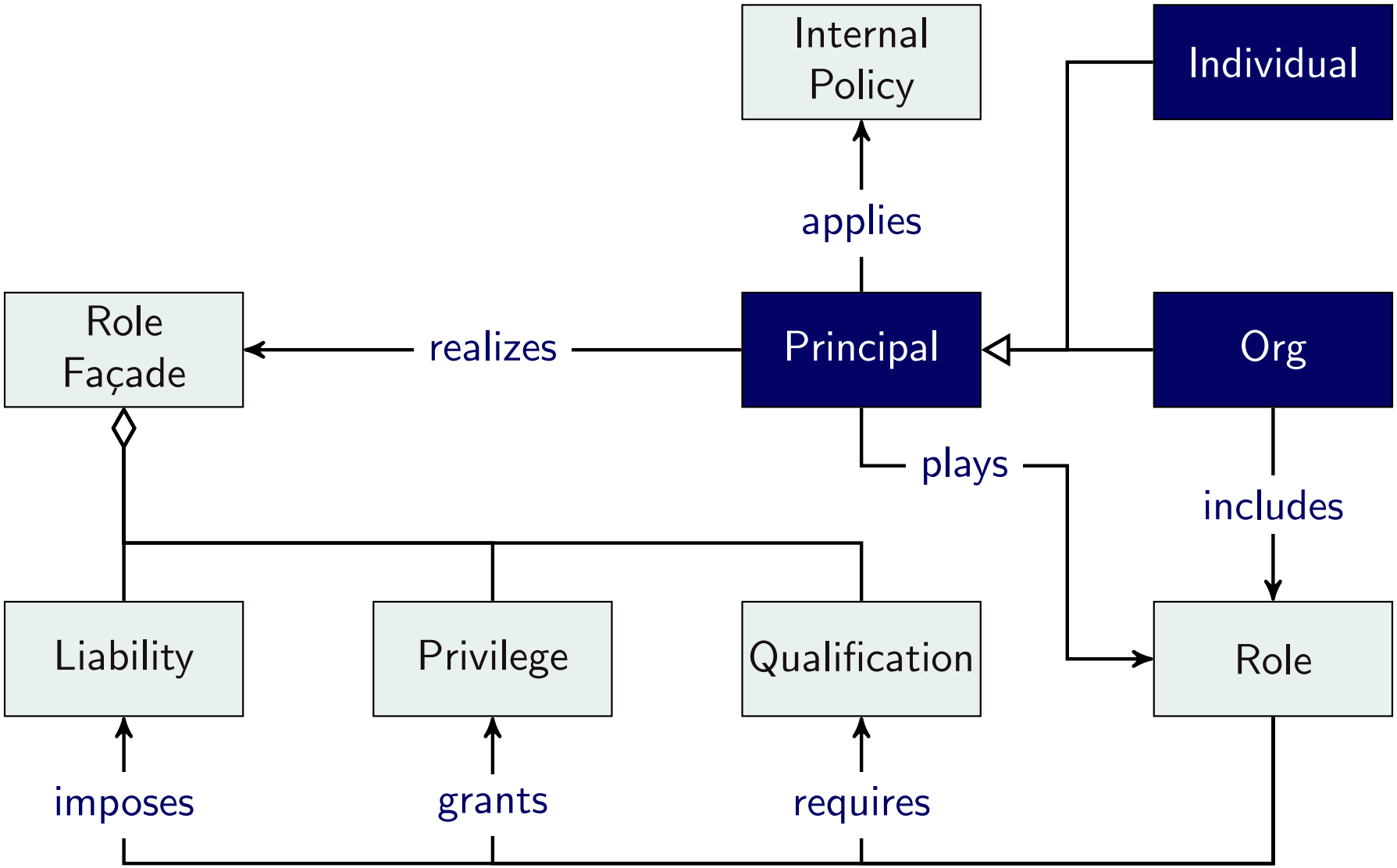
# Principles of Governance: What Policies Give Us

## Administration that is intelligent and intelligible

- Vividness of modeling
  - Grounded in applications; modeled entities are real
- Minimality of operational specifications
  - Leaving restrictions unstated except where essential to correctness
- Reification of representations
  - Explicit: hence, inspectable, sharable, and manipulable

# Overview of Policy-Governed Secure Collaboration

## Conceptual Model



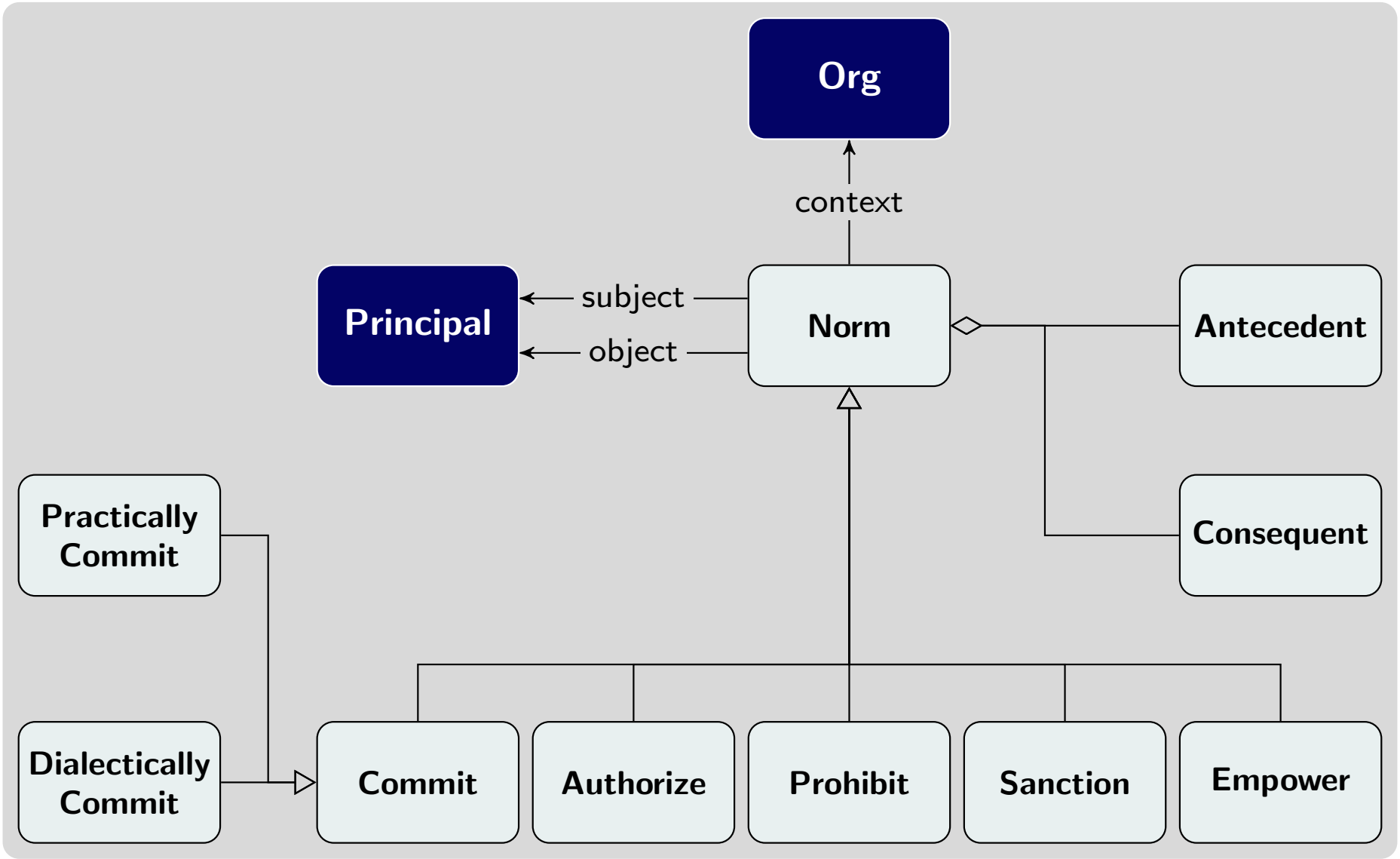
# Achieving Governance: Principals and Orgs

## Put collaboration in organizations center stage

- Principals are the stakeholders: people and organizations
  - Provide a locus for interaction
- Orgs are like *institutions:* have an identity and life time distinct from their members; also principals
  - Examples: NCSU, DoD, OOI, ...
  - Provide a locus for roles
  - Characterized via norms
  - Potentially enforce norms on members playing specific roles
    - An Org's main hold over its members is the threat of expulsion

# Types of Directed Normative Relationships or Norms

## Declarative; composable; manipulable

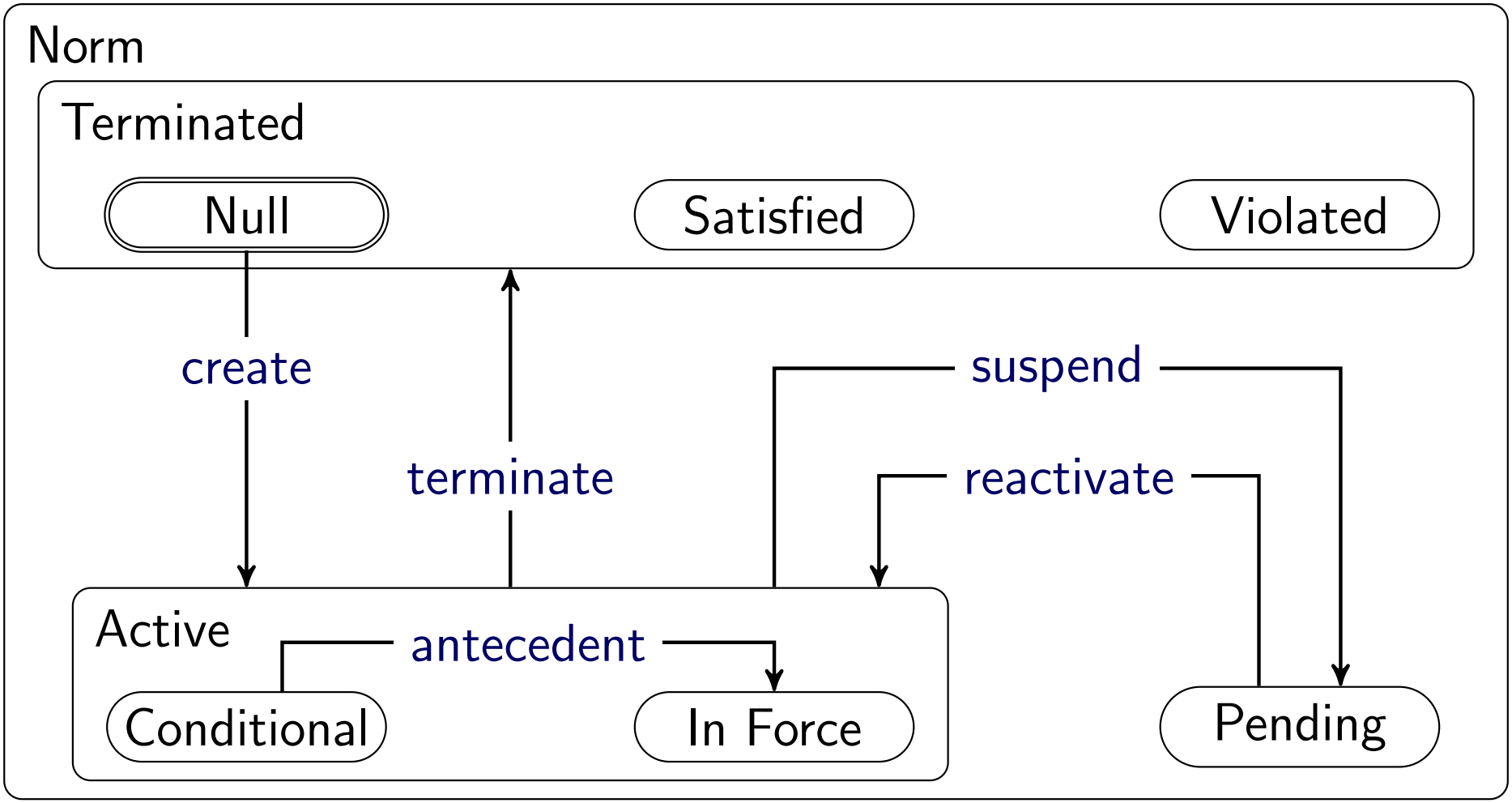


# Norms as Façades

| **Norm** | **Subject's Façade** | **Object's Façade** |
|---|---|---|
| *Commitment* | Liability | Privilege |
| *Authorization* | Privilege | Liability |
| *Power* | Privilege | Liability |
| *Prohibition* | Liability | Privilege |
| *Sanction* | Liability | Privilege |

# Life Cycle for Norms: 1

## Using a variant of the UML state diagram notation



# Life Cycle for Norms: 2

## Substate of a terminated norm

| If terminated in | | Then | | | | |
|---|---|---|---|---|---|---|
| **ant** | **con** | **Com** | **Aut** | **Pro** | **San** | **Pow** |
| false | false | null | null | null | null | null |
| false | true | sat | sat | null | null | null |
| true | false | vio | vio | sat | null | vio |
| true | true | sat | sat | vio | sat | sat |

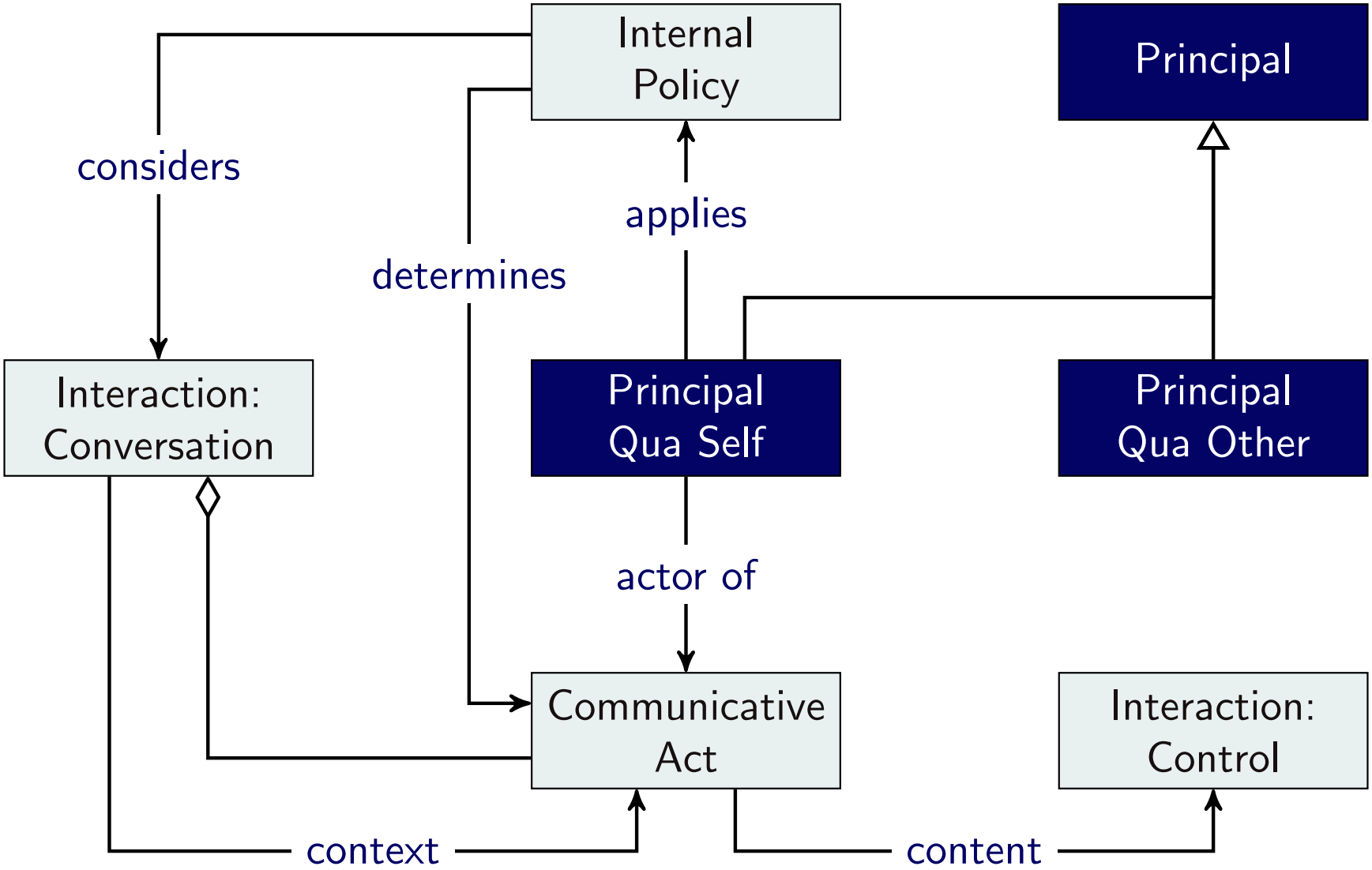
# Unifying Norms and Policies for Governance

## Promoting precision, verifiability, modularity, and reusability for secure collaboration

- Norms characterize interactions in terms of expectations and accountability
  - Provide the standards of correctness for governance
  - Packaged as role façades
  - Adopted by an agent to support its goals and concomitant policies
  - Help identify *policy points*: where policies apply
- An agent adopts policies that, given its role façades and goals,
  - Support discharging its liabilities
  - Potentially exploit its privileges
  - May not individually or collectively comply with norms
  - May thus violate some security expectations

# Governance and Policies: Two Kinds of Interaction

## Conversations with autonomous parties; control over resources



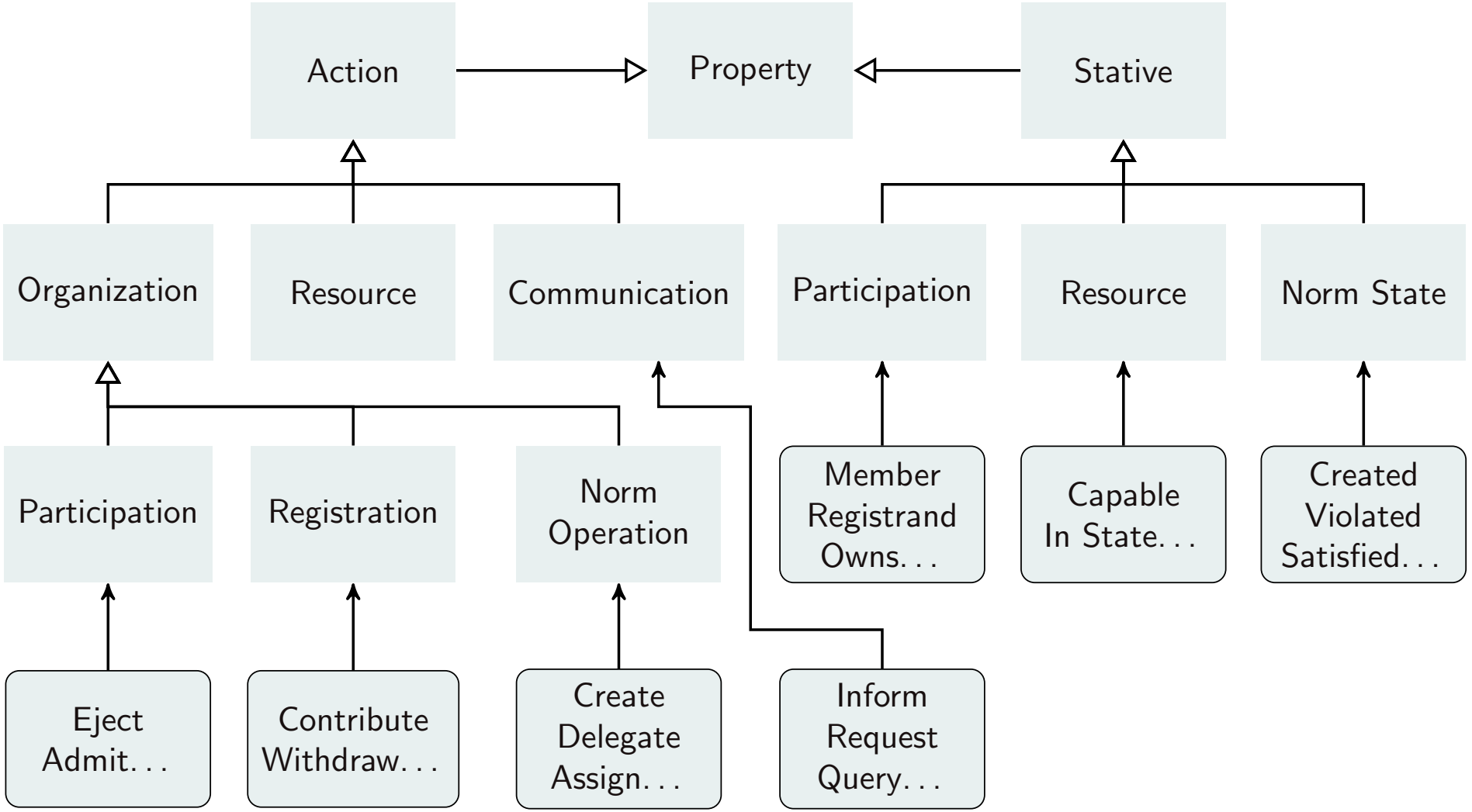
# Governance and Policies: Information Model

Relevant information

- Attributes of the parties involved
  - Qualifications, affiliations
- Attributes of the capabilities involved
  - Interactions to be carried out upon resources
  - Collated as interaction types and resource types
- Attributes of the relationships among the parties involved
  - Participations in different Orgs
  - Arrangements among Orgs (captured as participations)
  - Ongoing interactions

# Vocabulary for Governance and Policies

## Norms and Orgs



# Interactions and Policy Types

## Going beyond access control

- Understand a policy in terms of its cause and its effect
- Cause
  - *Reactive:* triggered by a request from another stakeholder
  - *Proactive:* triggered by local observations
- Effect
  - *Authorization* of action to be taken on behalf of requester
  - *Enablement* of action, which would otherwise not be taken
  - *Expectation* of action, which would now be performed

# An Information Model and Commitment Specification

```
TakeCharge(tcID, nuID, phID, patID, tcThreshold) key tcID
CardiacEvent(ceID, nuID, phID, patID, ceMagnitude) key ceID
CPR(cprID, nuID, phID, patID, cprDuration) key cprID

commitment CardioCare nuID to phID
create TakeCharge
detach CardiacEvent [, TakeCharge + 180]
  where ceMagnitude >= tcThreshold
discharge CPR [, CardiacEvent + 5]
```

A Cardio Care commitment from a nurse to a physician is

- *created* upon Take Charge;
- *detached* if a CardiacEvent for this patient happens above the specified threshold within 180 minutes
  - Else the commitment *expires*
- *discharged* if CPR on this patient happens within five minutes of the Cardiac Event (else *violated*)

# Generate Log Schema

```
CREATE TABLE TakeCharge (
   tcID  VARCHAR(10), nuID  VARCHAR(10), phID  VARCHAR(10),
       patID  VARCHAR(10), tcThreshold  VARCHAR(10),
   stamp  DATETIME,
   PRIMARY KEY(tcID)
);

CREATE TABLE CardiacEvent (
   ceID  VARCHAR(10), nuID  VARCHAR(10), phID  VARCHAR(10),
       patID  VARCHAR(10), ceMagnitude  VARCHAR(10),
   stamp  DATETIME,
   PRIMARY KEY(ceID)
);

CREATE TABLE CPR (
   cprID  VARCHAR(10), nuID  VARCHAR(10), phID  VARCHAR(10),
       patID  VARCHAR(10), cprDuration  VARCHAR(10),
   stamp  DATETIME,
   PRIMARY KEY(cprID)
);
```

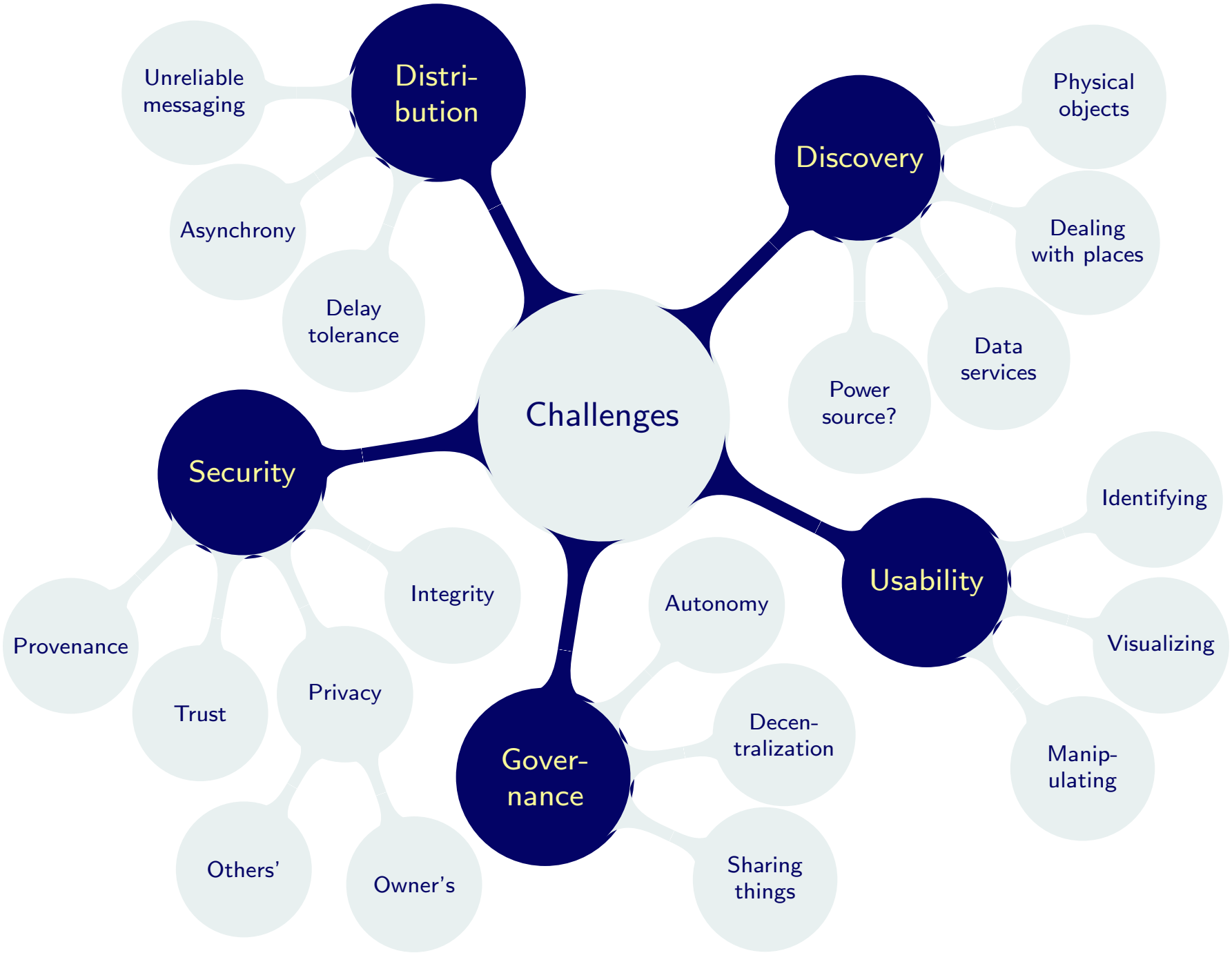
# Generate Canonical Queries for Accountability Checking

## In SQL

Query for which Cardio Care commitments are violated: 200 lines long

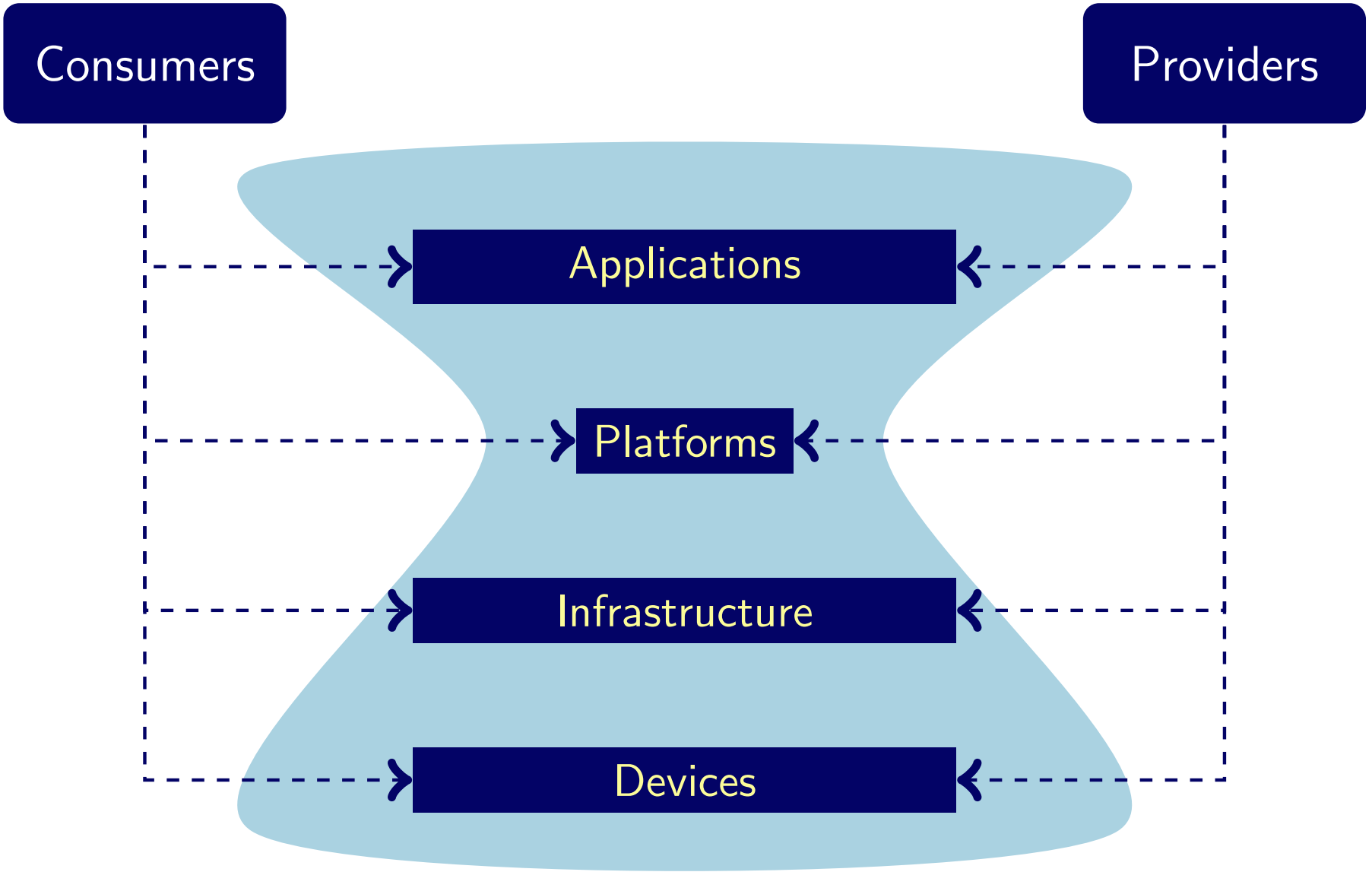
# Challenges and Partial Recent Progress

- Storing and retrieving events to determine the state of a norm
  - Mapping norms to relational databases [AAAI 2015, AAMAS 2016]
- Maintaining alignment of views despite decentralization
  - Communications to guarantee (eventual) alignment [AAMAS 2015]
- Software engineering for sociotechnical systems
  - Abstractions, architecture, and principles [WWW 2016]
- Designing protocols and Org contexts for monitorability
  - Failure of compositionality of monitorability [IJCAI 2015]
  - Automatically close a context to ensure monitorability
- Designing protocols and Org for robustness and resilience
  - Typology of sanctions and sanctioning processes [Draft]
  - TBD: Formalization of normative robustness and resilience
  - TBD: Reasoning about sanctions for design of Orgs
- Design processes conducive to autonomy
  - Abstract formal model of a sociotechnical design process [RE 2014]
  - TBD: Methodologies


Challenges
Distri-bution
Unreliable messaging
Asynchrony
Delay tolerance
Discovery
Physical objects
Dealing with places
Data services
Power source?
Security
Integrity
Provenance
Trust
Privacy
Others'
Owner's
Gover-nance
Autonomy
Decen-tralization
Sharing things
Usability
Identifying
Visualizing
Manip-ulating

# IoT Hourglass: Few Platforms for Many Applications

Benefit from the upper layers; excitement from the lower layer



# Summary and Directions

## Exercise: Collective concept map

- What theme do you remember most from today?
- What additional high-level themes should we consider within
  - Artificial intelligence?
  - Distributed computing?
  - Information systems?
- What IoT research question would be worth pursuing?

# Thanks and Plugs


- Acknowledgments
  - US Department of Defense
  - US National Science Foundation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  - IEEE Internet Computing

http://www.csc.ncsu.edu/faculty/mpsingh/