The Internet of Things and Multiagent Systems

Tutorial

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Introduction to the Internet of Things

Representative Applications of IoT

Architectures for the IoT

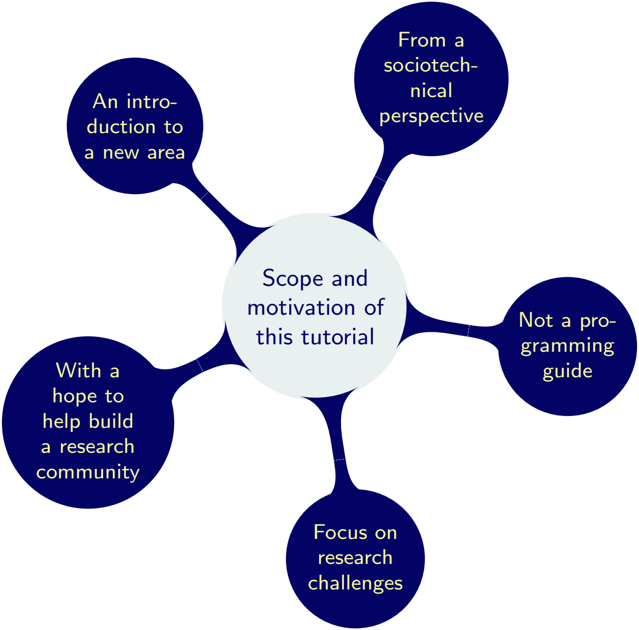
Discovery and Selection

Achieving Coherence and Cooperation

Decentralization and Interaction for IoT

Governing Interactions in the IoT

Synthesis



Scope and motivation of this tutorial

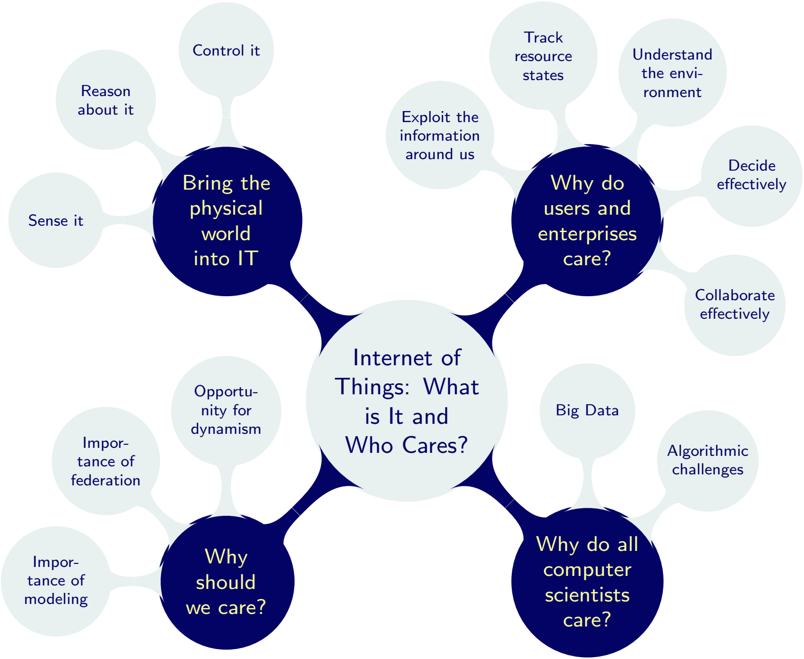
An introduction to a new area

From a sociotechnical perspective

Not a programming guide

Focus on research challenges

With a hope to help build a research community



Internet of Things: What is It and Who Cares?

Bring the physical world into IT
- Sense it
- Reason about it
- Control it

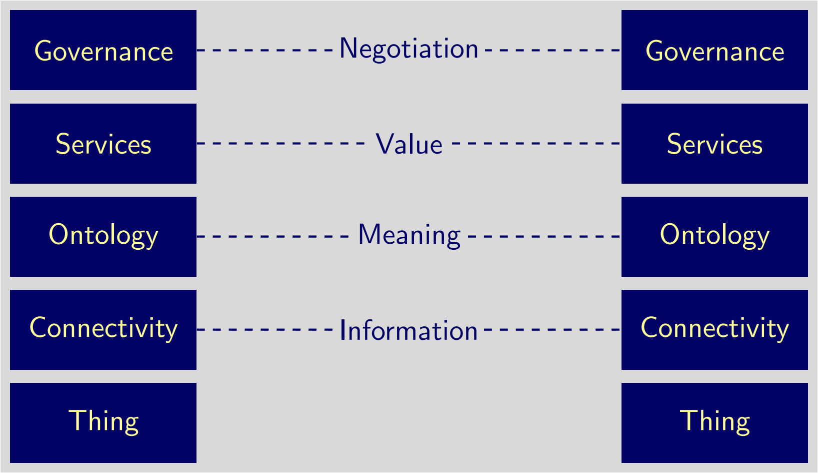
Why do users and enterprises care?
- Exploit the information around us
- Track resource states
- Understand the environment
- Decide effectively
- Collaborate effectively

Why should we care?
- Importance of modeling
- Importance of federation
- Opportunity for dynamism

Why do all computer scientists care?
- Big Data
- Algorithmic challenges

IoT Federation Levels

Each level offers abstractions for what transpires at or flows across that level



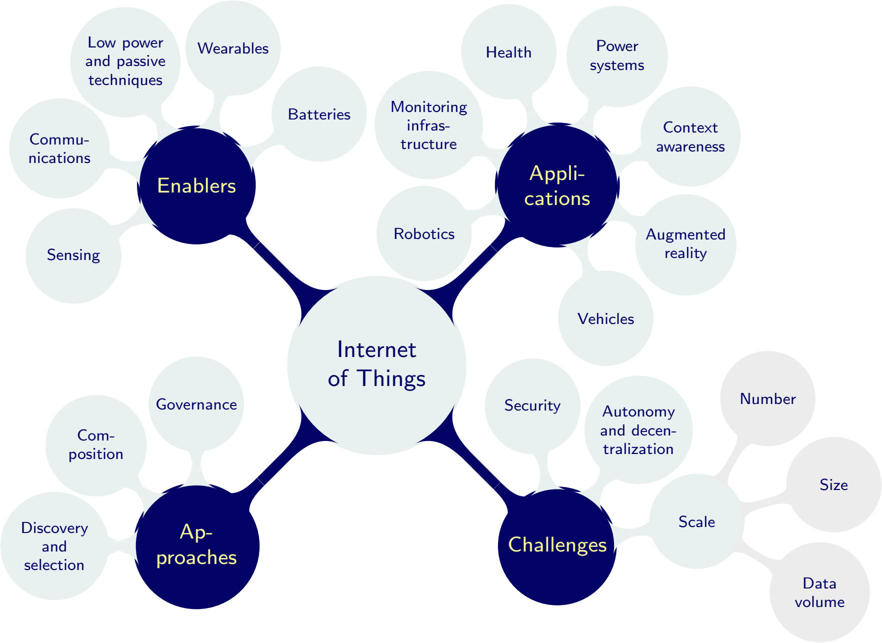
Governance - - - - - - - - - Negotiation - - - - - - - - - Governance

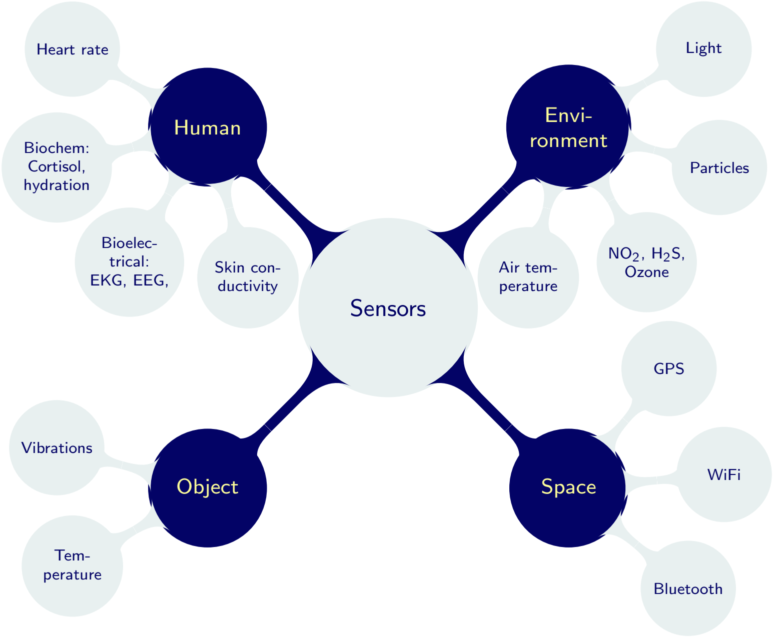
Services - - - - - - - - - - - Value - - - - - - - - - - - Services

Ontology - - - - - - - - - - Meaning - - - - - - - - - - Ontology

Connectivity - - - - - - - - - Information - - - - - - - - - Connectivity

Thing   Thing


Internet of Things
Enablers
Low power and passive techniques
Wearables
Batteries
Communications
Sensing
Applications
Health
Power systems
Monitoring infrastructure
Context awareness
Robotics
Augmented reality
Vehicles
Approaches
Governance
Composition
Discovery and selection
Challenges
Security
Autonomy and decentralization
Scale
Number
Size
Data volume



Sensors
Human
Heart rate
Biochem: Cortisol, hydration
Bioelectrical: EKG, EEG,
Skin conductivity
Environment
Light
Particles
NO_2, H_2S, Ozone
Air temperature
Object
Vibrations
Temperature
Space
GPS
WiFi
Bluetooth

Core: Connectivity

Combination of low and high-bandwidth

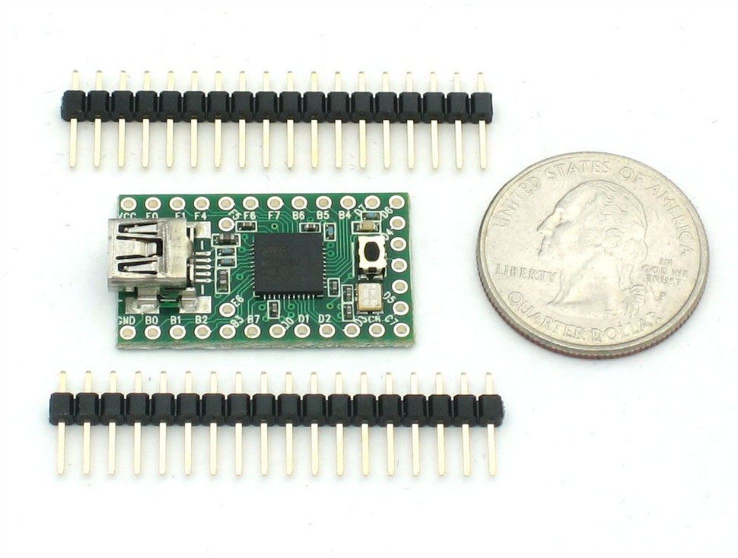
- Low-bandwidth connectivity
  - Between RFID tags and readers
  - Between sensors and base stations
- High-bandwidth
  - Wireless, with aggregator nodes such as smartphones and Arduino devices
  - Broadband, from aggregator nodes to store data in the cloud

Core: Passive and Low Power Technologies

Many dimensions

- Passive (batteryless)
  - No power
  - Require a proximal (within ∼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: $10^{-3}\ W$)
  - 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

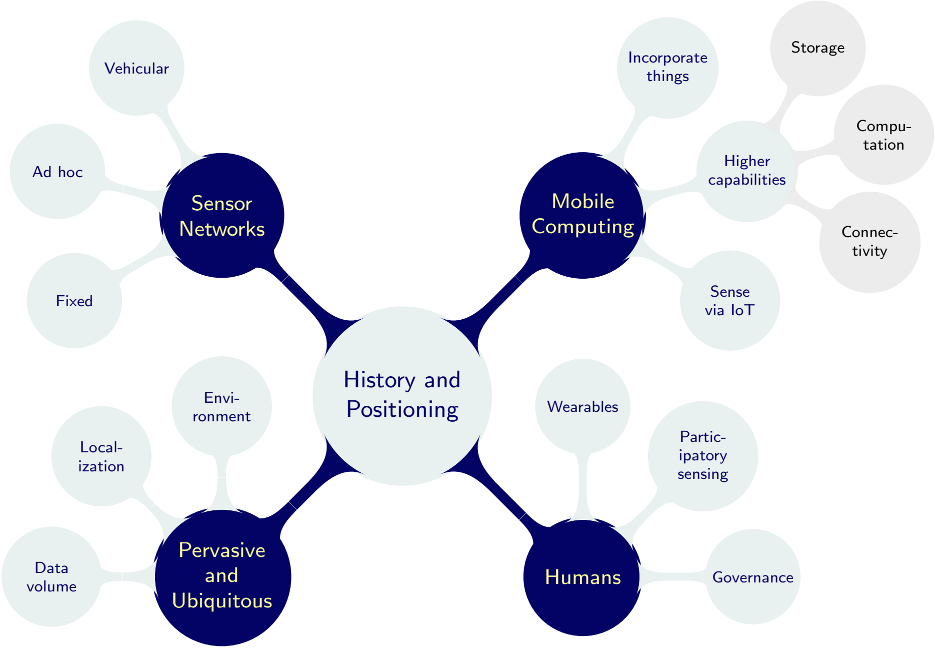
	Prototype	**Commercial 1**	**Commercial 2**
	NCSU ASSIST	EnOcean STM 31xC	Semtech SX1282
Voltage	0.5 V	2.1 V	1.0 V to 1.6 V
Processor	16b MSP430	Custom	8b CoolRISC
Power consumption	$<1\,\mu$W @200 kHz	5.1 mA @3–5 V	1.2 μW 32 kHz; 600 *mu*W typical
Power harvesting	RF, solar thermoelectric	Yes	No

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 μW @200 kbps	30 mW @125 kbps	∼40 mW
Reception power	200 μW WBAN Rx 120 nW @12.5 kbps Wake Up	40 mW	∼12 mW

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


History and Positioning
Sensor Networks
Vehicular
Ad hoc
Fixed
Mobile Computing
Incorporate things
Higher capabilities
Storage
Computation
Connectivity
Sense via IoT
Pervasive and Ubiquitous
Environment
Localization
Data volume
Humans
Wearables
Participatory sensing
Governance

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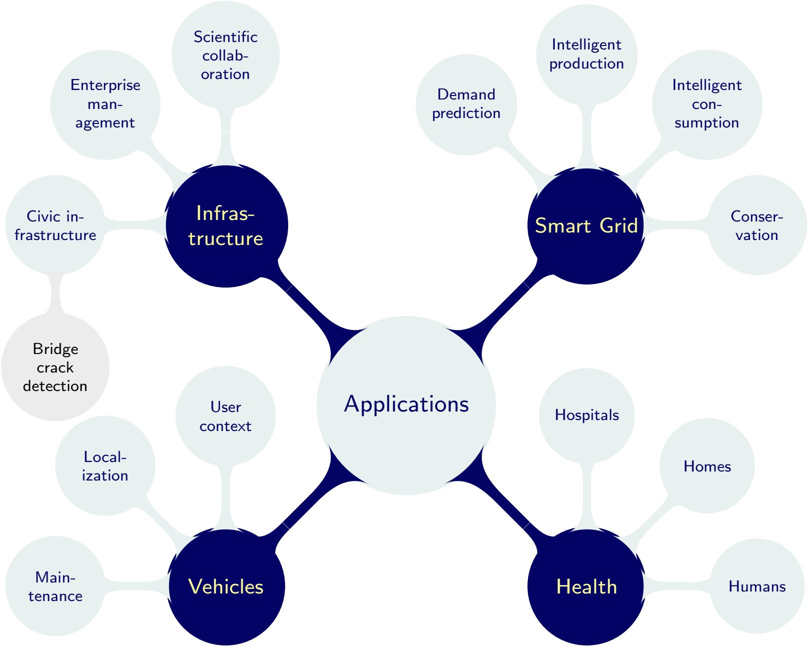
Synthesis


Applications
Infrastructure
Scientific collaboration
Enterprise management
Civic infrastructure
Bridge crack detection
Smart Grid
Demand prediction
Intelligent production
Intelligent consumption
Conservation
Vehicles
User context
Localization
Maintenance
Health
Hospitals
Homes
Humans

Vehicle Sensors

© Munindar P. Singh

Vehicle Actuators

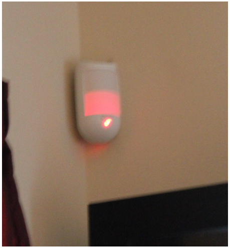
Over the air modification of Tesla chassis elevation

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

Internet of Homes and Hotels?

© Munindar P. Singh

© Nest.com



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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

© Craig Hayslip, Oregon State University

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

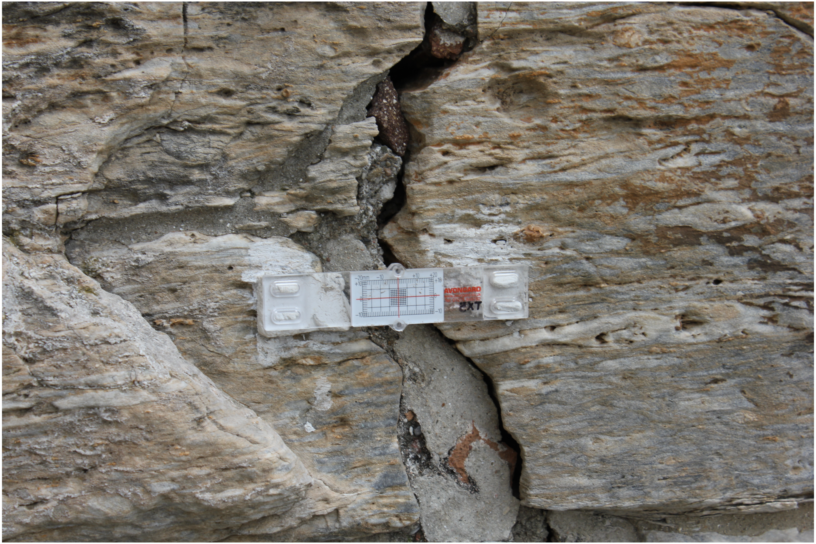
Internet of Dogs

Tagged stray dog in Istanbul

© Munindar P. Singh

Internet of Monuments?

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



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Introduction to the Internet of Things

Representative Applications of IoT

Architectures for the IoT

- Enabler: Communication
- Enabler: Cloud
- Enabler: Data Technologies
- Challenges in Realizing the IoT

Discovery and Selection

Achieving Coherence and Cooperation

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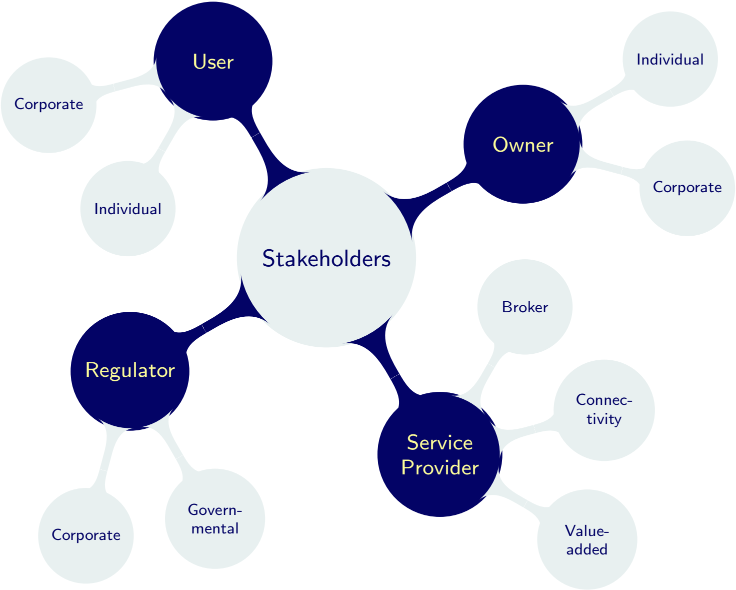
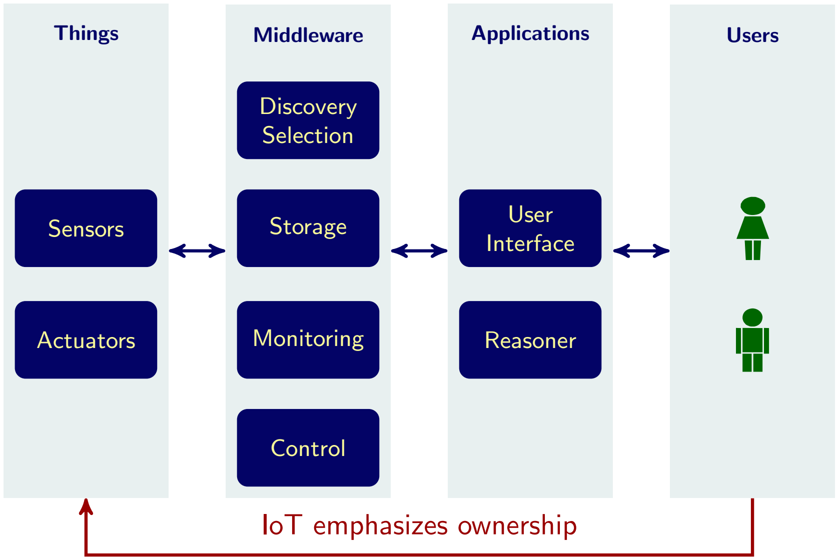
Synthesis

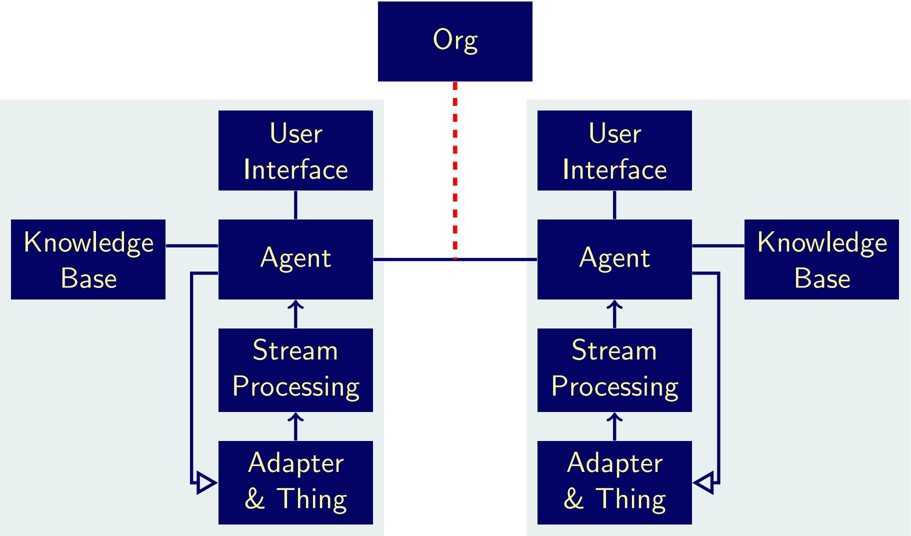

Stakeholders
User
Corporate
Individual
Owner
Individual
Corporate
Regulator
Corporate
Govern-mental
Service Provider
Broker
Connec-tivity
Value-added

Main Architectural Elements

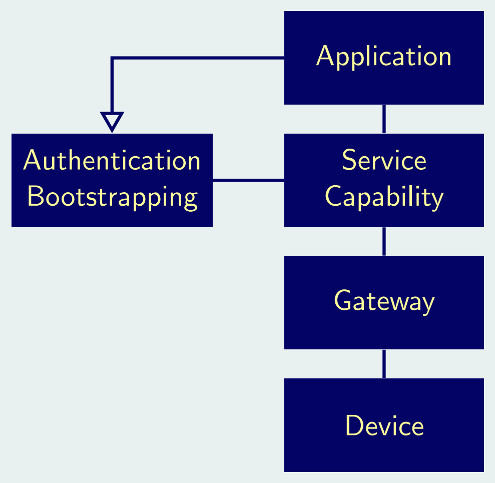


Decentralization Calls for a Multiagent Architecture

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)

HTTP	Application layer	MQTT CoAP
TCP	Transport layer	UDP
IPv4 IPv6	Network layer	6LoWPAN Zigbee
Ethernet WiFi	Data link layer	IEEE 802.15.4
Information Resource		Thing

Protocol: MQTT

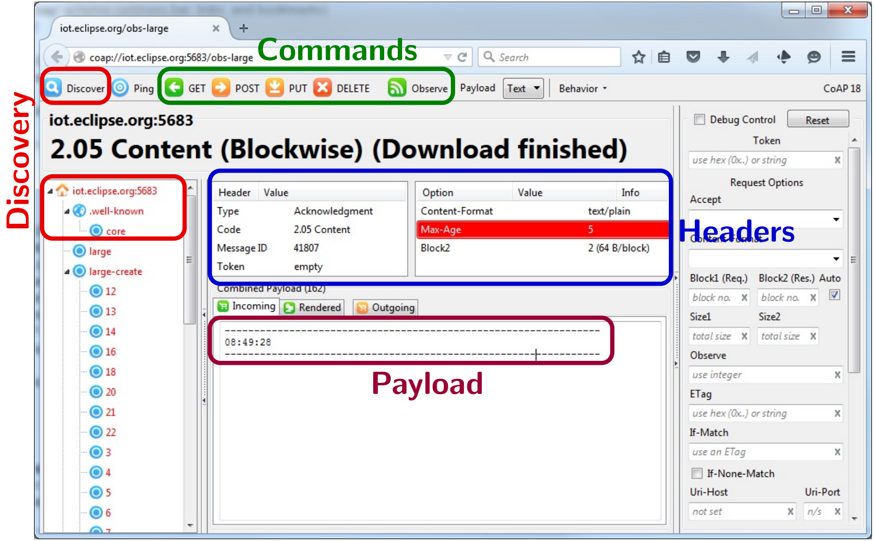
Née Message Queue Telemetry Transport

- 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



iot.eclipse.org:5683

2.05 Content (Blockwise) (Download finished)

Header	Value
Type	Acknowledgment
Code	2.05 Content
Message ID	41807
Token	empty

Option	Value	Info
Content-Format	text/plain	
Max-Age	5	
Block2	2 (64 B/block)	

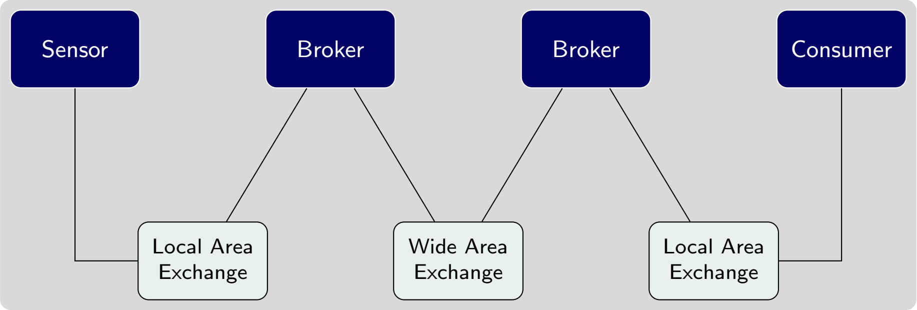
```
---------------------------------------------------------------------
08:49:28
---------------------------------------------------------------------
```

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, . . .

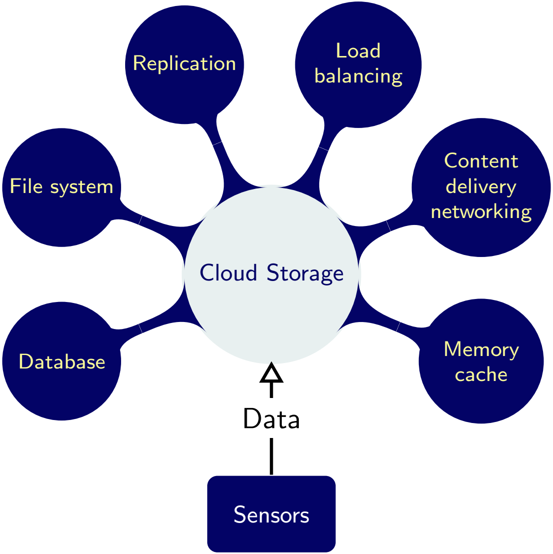
XMPP: Extensible Messaging and Presence Protocol

- 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

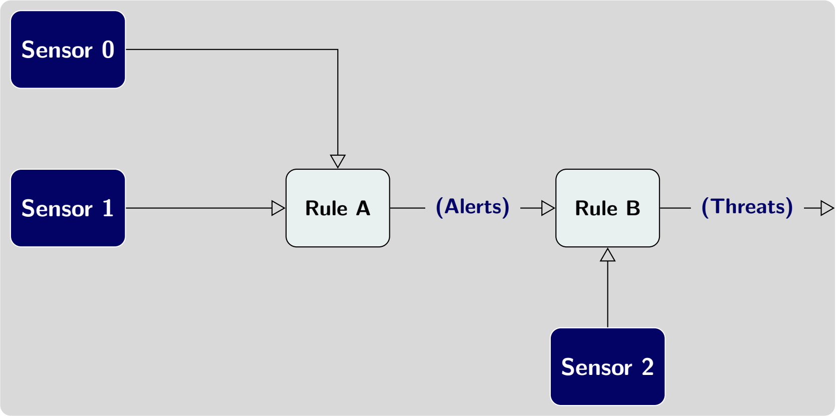
Cisco's term for decentralized or "ground-level" variant of cloud computing

- 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



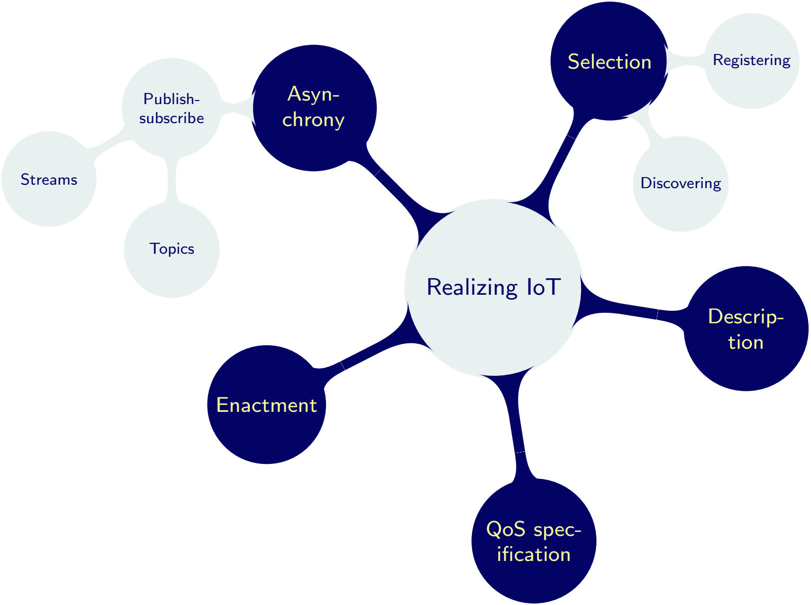
Linked Data Highlights

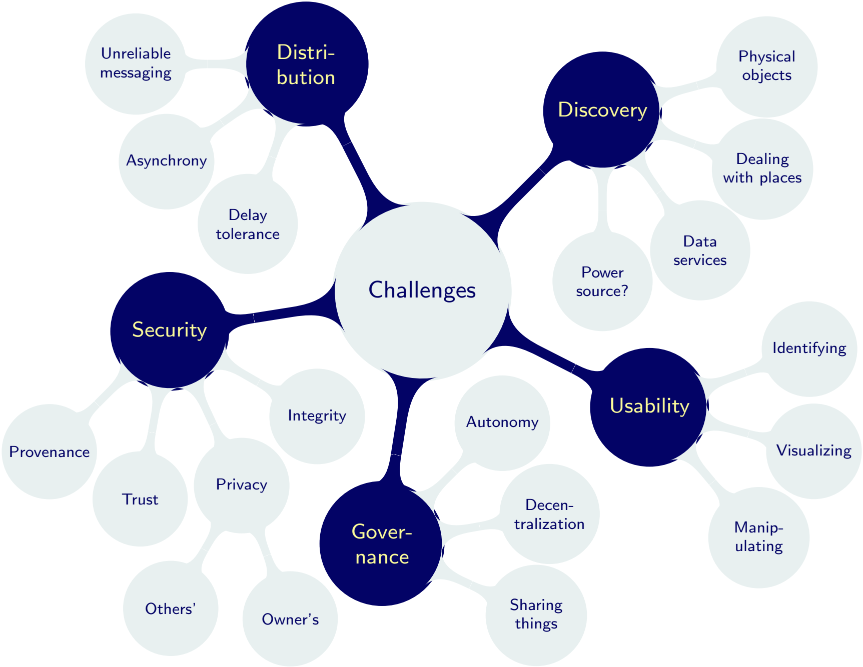
- Web-based identity and network
  - URIs identify resources
  - Deferencing a URI produces a resource description
  - Resources link to other resources
- Web-based semantics
  - Encoded in a Semantic Web language, such as the Resource Description Framework, RDF
- Exploit underlying architecture, e.g., 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
Asynchrony
Publish-subscribe
Streams
Topics
Selection
Registering
Discovering
Description
Enactment
QoS specification


Challenges
Distribution
Unreliable messaging
Asynchrony
Delay tolerance
Discovery
Physical objects
Dealing with places
Data services
Power source?
Security
Integrity
Provenance
Trust
Privacy
Others'
Owner's
Governance
Autonomy
Decentralization
Sharing things
Usability
Identifying
Visualizing
Manipulating

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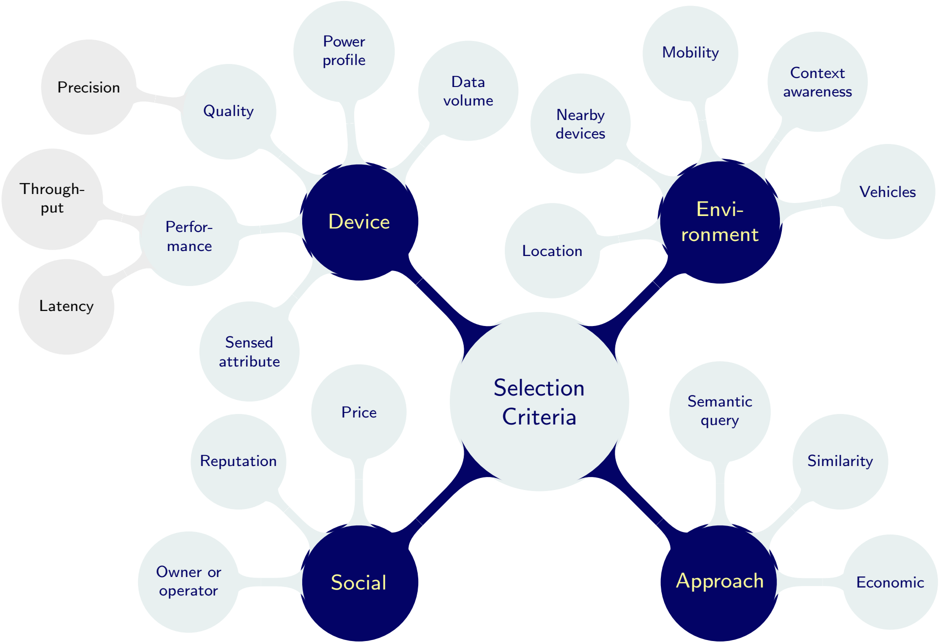
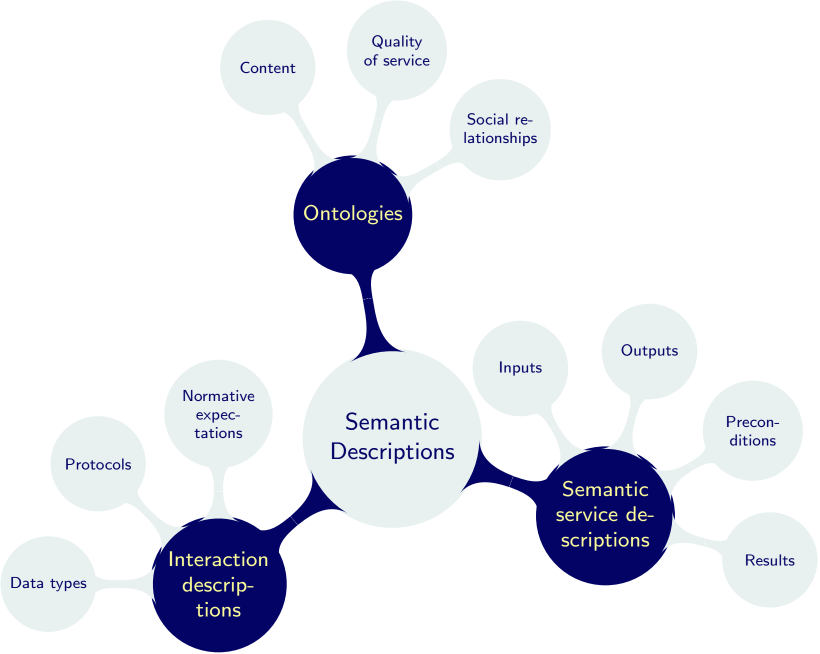
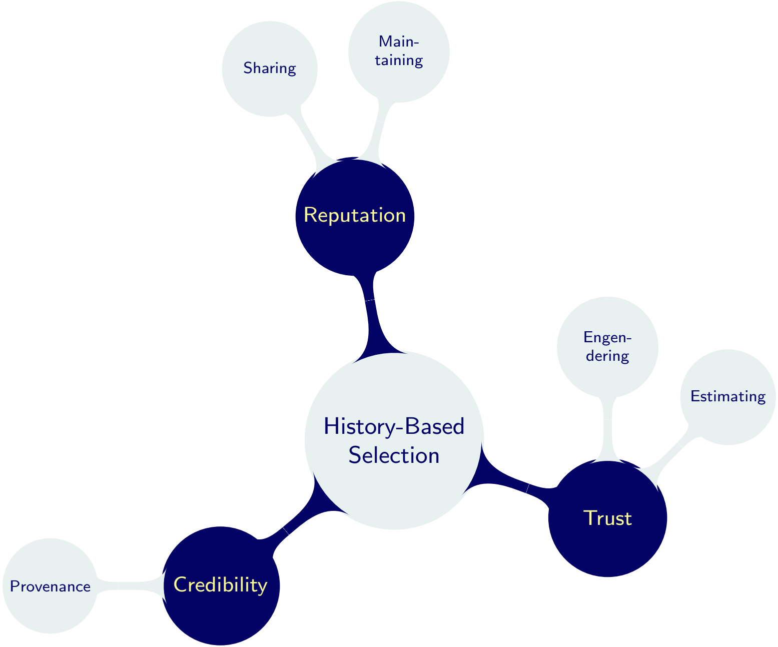

Selection Criteria
Device
Quality
Precision
Power profile
Data volume
Performance
Throughput
Latency
Sensed attribute
Environment
Nearby devices
Mobility
Context awareness
Vehicles
Location
Social
Price
Reputation
Owner or operator
Approach
Semantic query
Similarity
Economic


Content
Quality of service
Social relationships
Ontologies
Inputs
Outputs
Normative expectations
Semantic Descriptions
Preconditions
Protocols
Semantic service descriptions
Results
Interaction descriptions
Data types



History-Based Selection

Reputation

Sharing

Maintaining

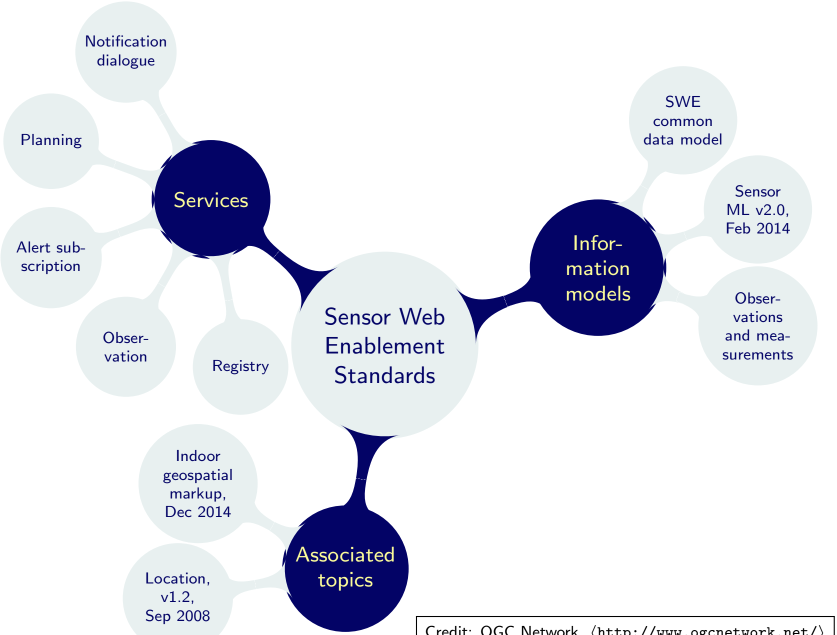
Trust

Engendering

Estimating

Credibility

Provenance



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

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Sharing, Fusing, and Revising Information

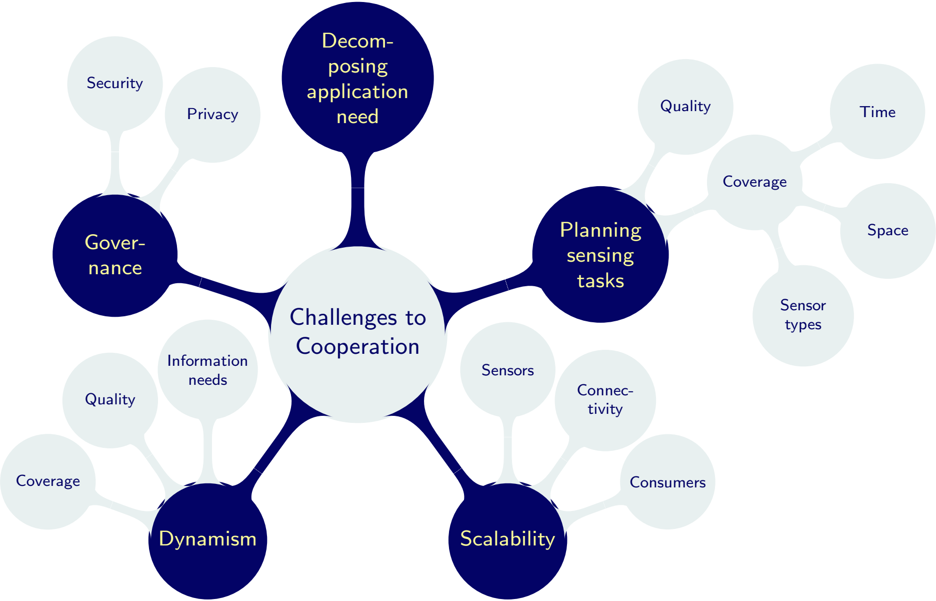
Inspired by social computing

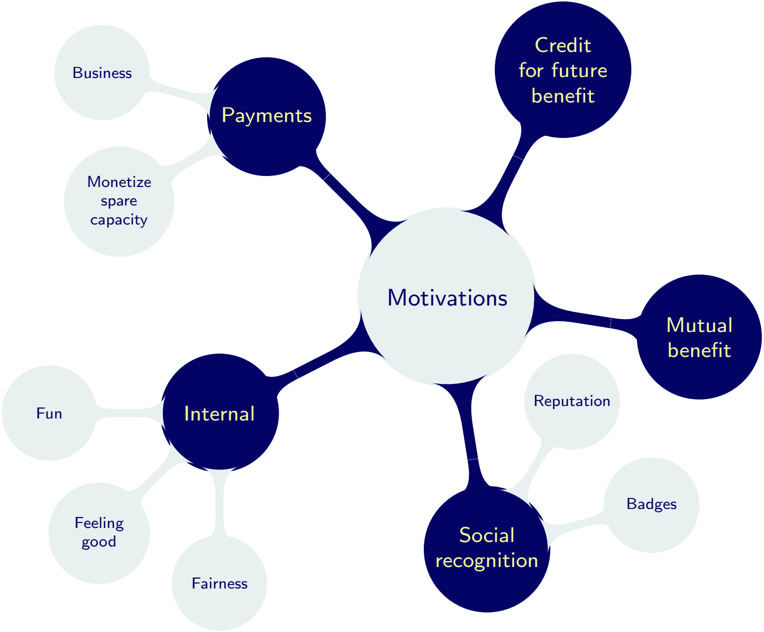
- Folk wisdom about aggregating knowledge
- Galton's Vox Populi
  - Median of many estimates represents the voice of the people
  - Underlying intuition of crowdsourcing
- Condorcet Jury Theorem
  - If each information source is better than 50% accurate (binary case)
  - Then their majority is even more 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

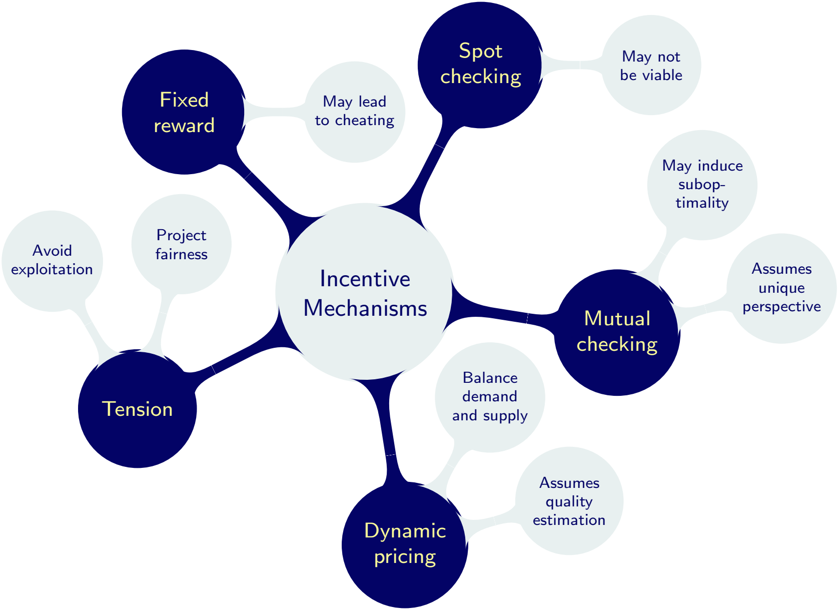
Assumptions in Participatory Sensing

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

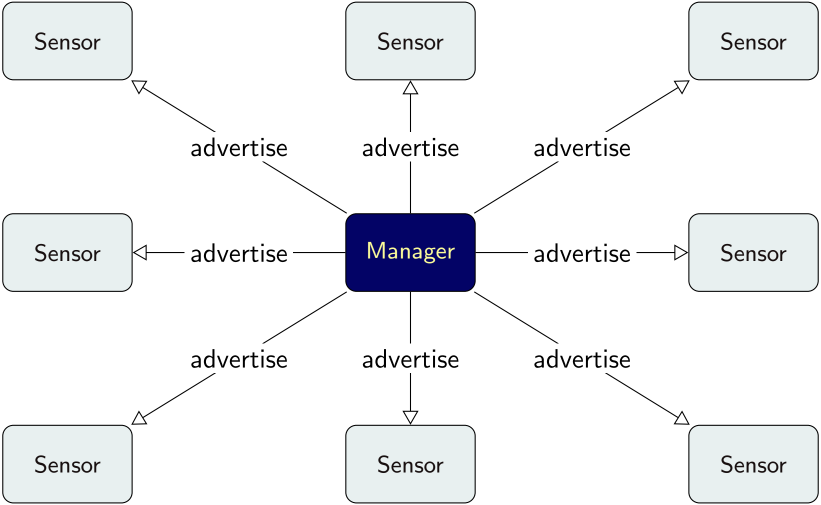

Challenges to Cooperation
Decomposing application need
Governance
Security
Privacy
Planning sensing tasks
Quality
Coverage
Time
Space
Sensor types
Dynamism
Information needs
Quality
Coverage
Scalability
Sensors
Connectivity
Consumers


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


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

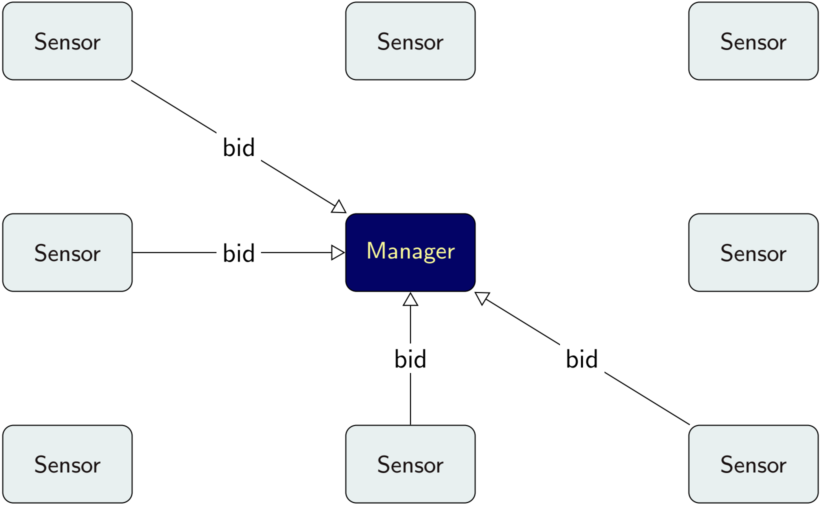
Contract Net Protocol: 1

Announce



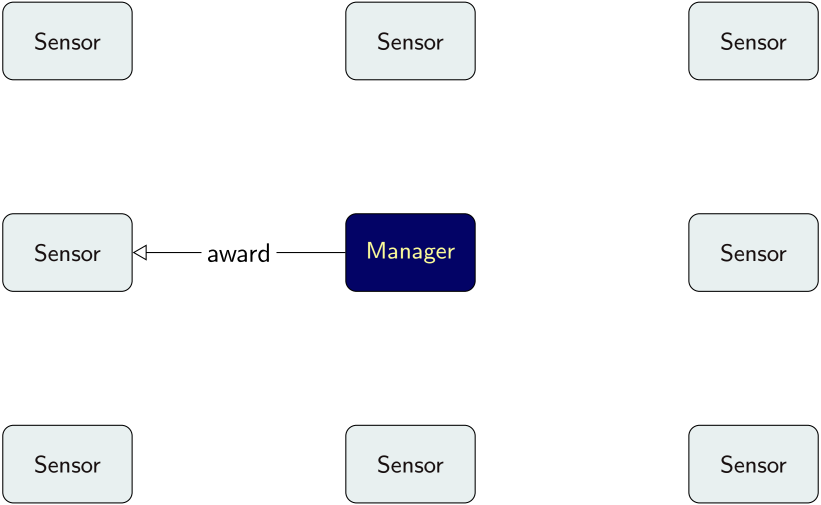
Contract Net Protocol: 2

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

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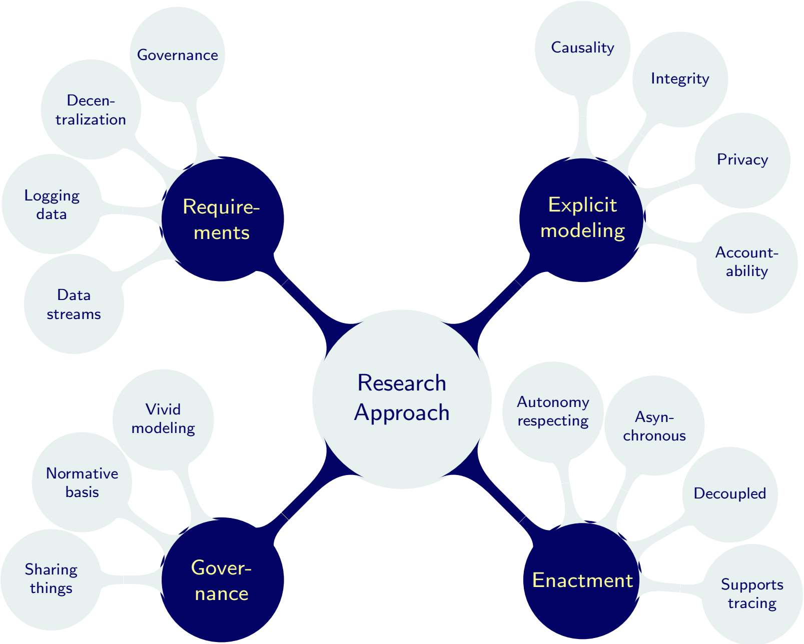
Decentralization and Interaction for IoT

Governing Interactions in the IoT

Synthesis


Research Approach
Requirements
Governance
Decentralization
Logging data
Data streams
Explicit modeling
Causality
Integrity
Privacy
Accountability
Governance
Vivid modeling
Normative basis
Sharing things
Enactment
Autonomy respecting
Asynchronous
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]
}
```

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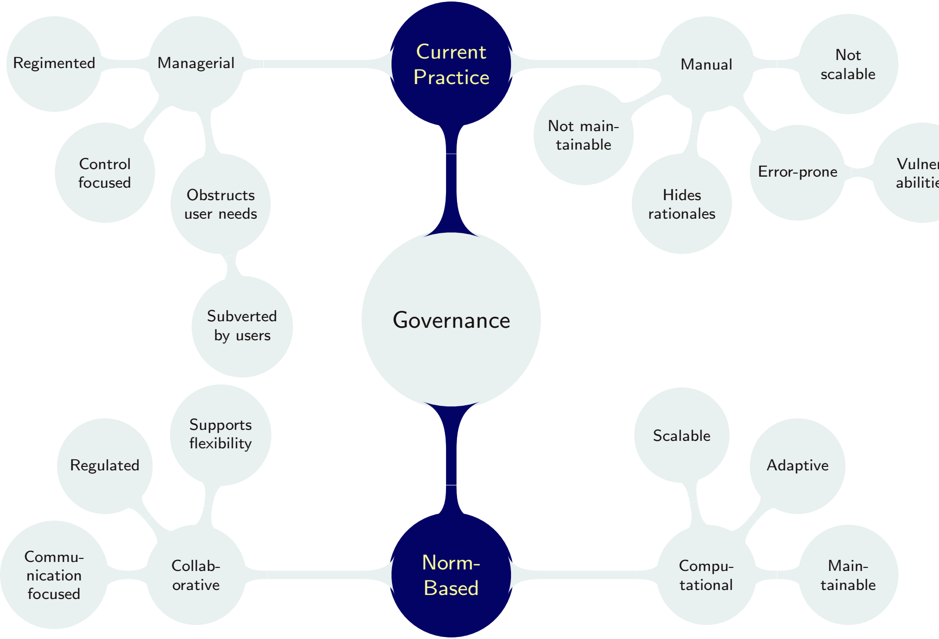
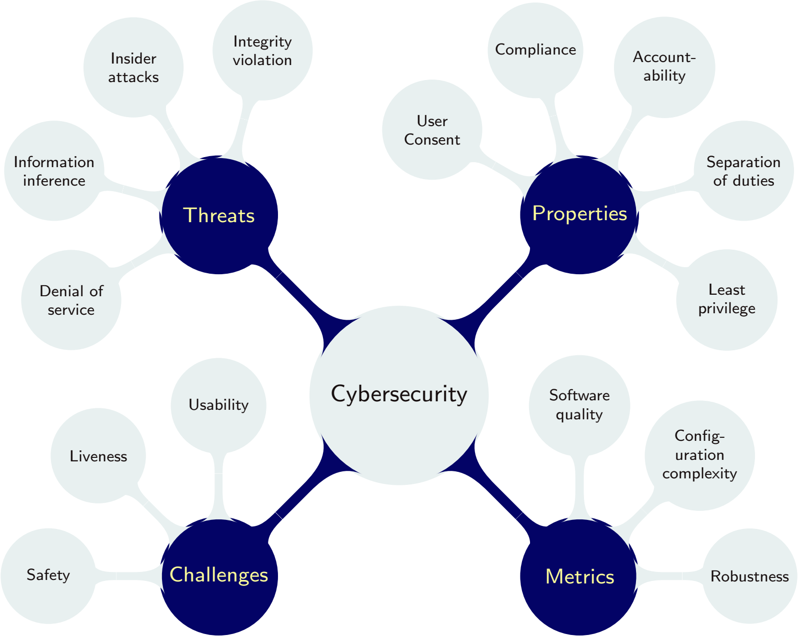

Governance
Current Practice
Managerial
Regimented
Control focused
Obstructs user needs
Subverted by users
Manual
Not scalable
Not maintainable
Hides rationales
Error-prone
Vulner abilitie
Norm-Based
Collaborative
Regulated
Supports flexibility
Communication focused
Computational
Scalable
Adaptive
Maintainable


Cybersecurity
Threats
Insider attacks
Integrity violation
Information inference
Denial of service
Properties
User Consent
Compliance
Account-ability
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 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

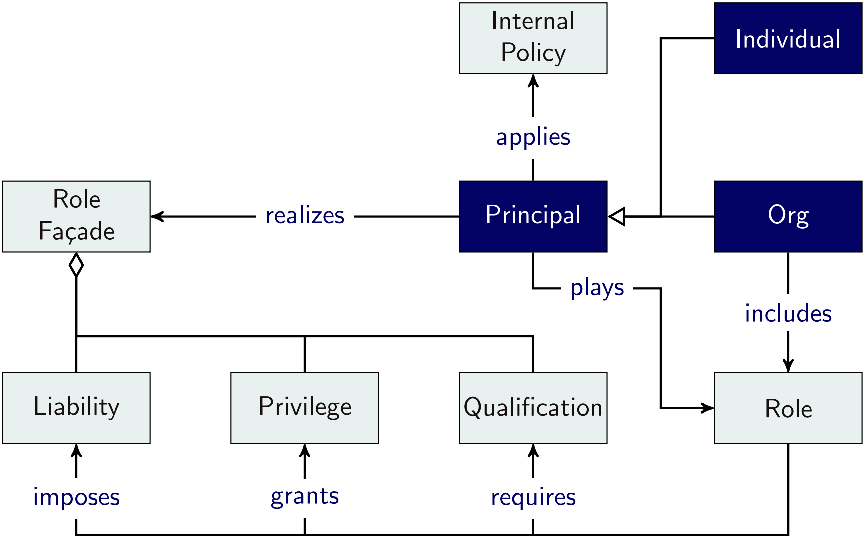
Principles of Governance: What Policies Give Us

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



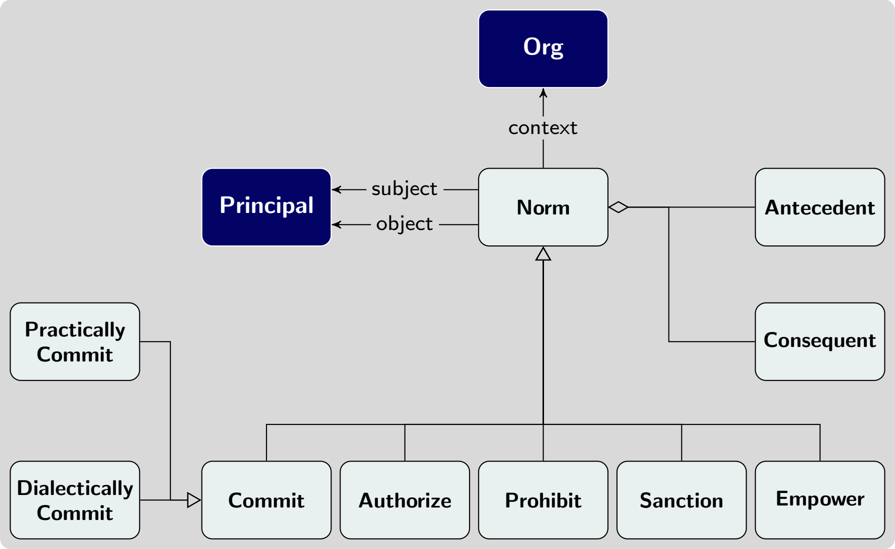
Achieving Governance: Principals and Orgs

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

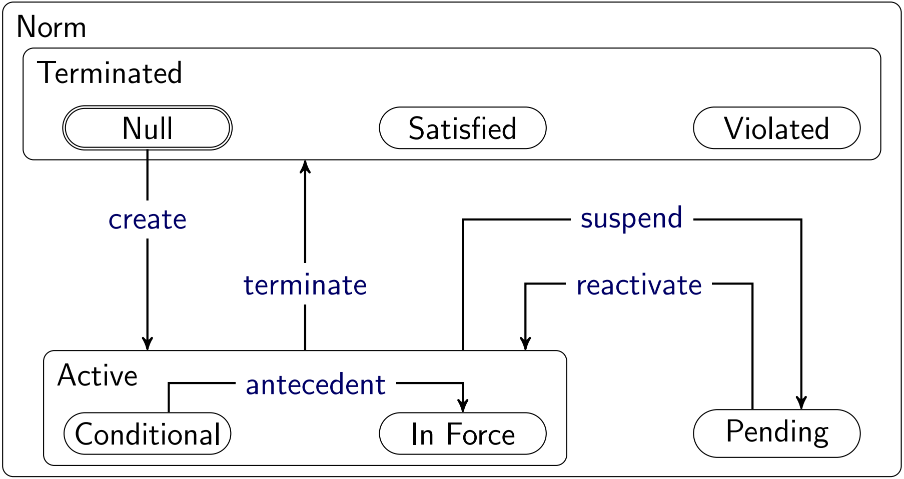


Norms as Façades

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

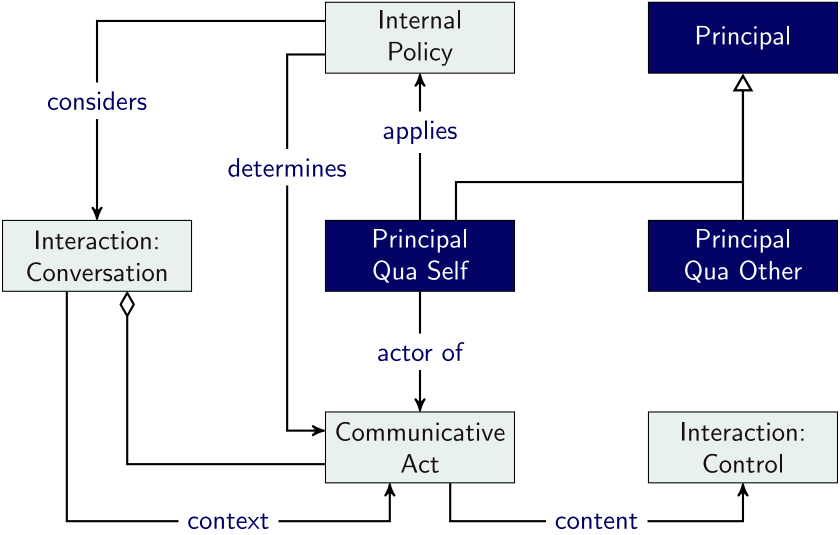
Unifying Norms and Policies for Governance

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



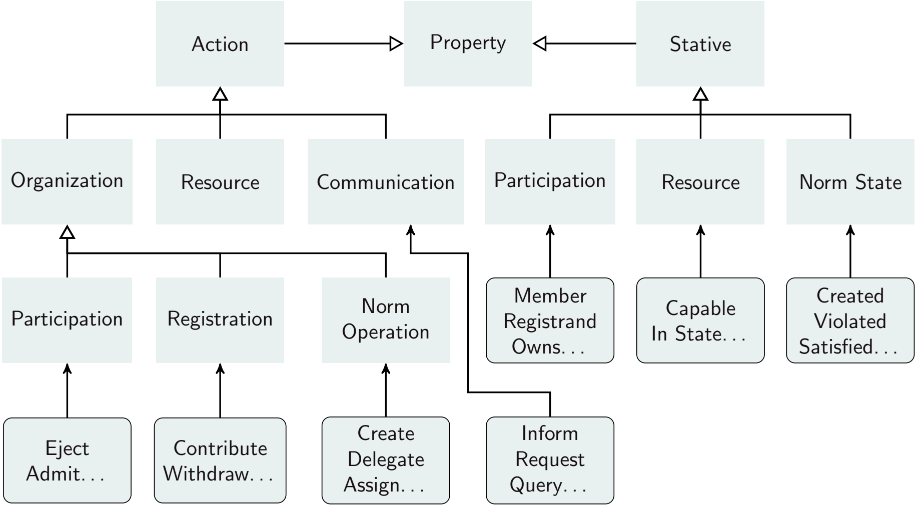
Governance and Policies: Information Model

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 relational algebra (Jun Yang's notation); maps to SQL

Query for which Cardio Care commitments are detached

```
((\select_{(stamp >= stamp38)} (
 (TakeCharge) \join
 (\rename_{ceID, nuID, phID, patID, ceMagnitude, stamp38}
  (\select_{ceMagnitude = tcThreshold} (CardiacEvent)))))
     \union
  (\select_{(stamp >= stamp37)}
    ((\select_{ceMagnitude = tcThreshold}
      (CardiacEvent)) \join
      (\rename_{tcID, nuID, phID, patID, tcThreshold, stamp37}
       (TakeCharge)))));
```

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 [RE 2014, 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 [KER 2016]
  - TBD: Formalization of normative robustness and resilience
  - TBD: Reasoning about sanctions for design of Orgs

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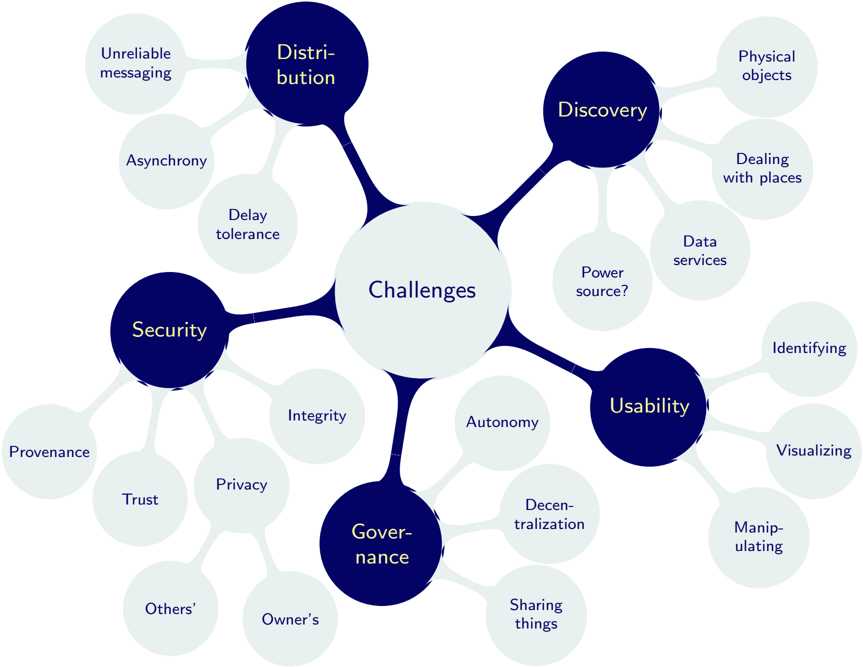
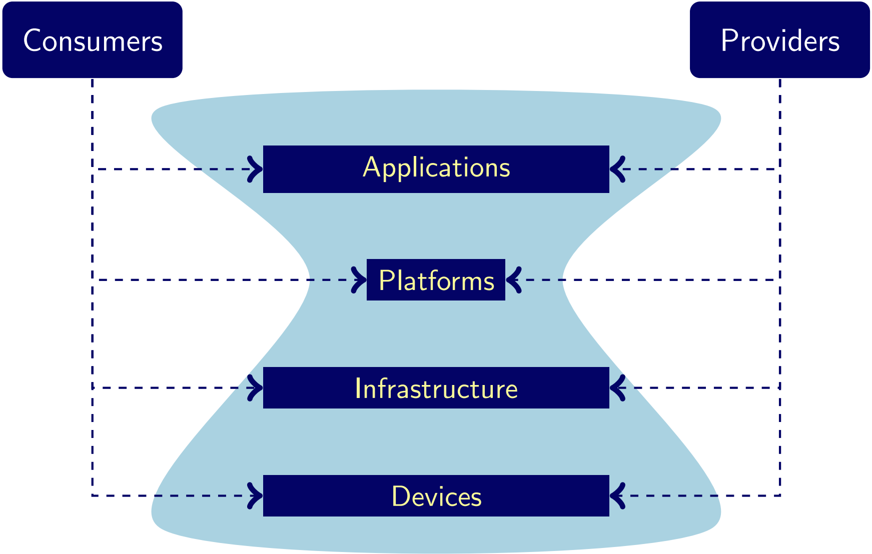

Challenges
Distribution
Unreliable messaging
Asynchrony
Delay tolerance
Discovery
Physical objects
Dealing with places
Data services
Power source?
Security
Provenance
Trust
Privacy
Others'
Owner's
Integrity
Governance
Autonomy
Decentralization
Sharing things
Usability
Identifying
Visualizing
Manipulating

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
- Read and publish in
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  - IEEE Internet Computing

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