New Vistas in Urban Infrastructures

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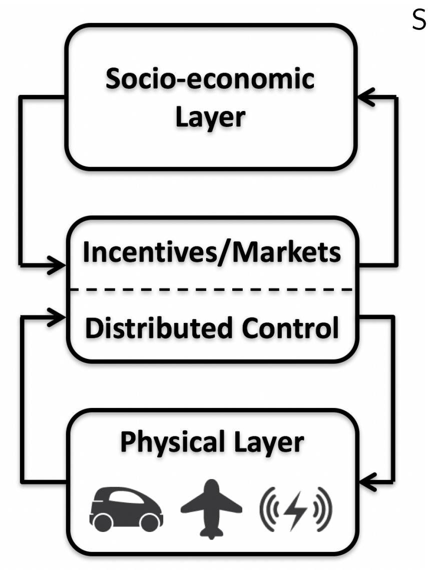
Urban Infrastructure—Co-Designing Incentives & Control



Societal-scale infrastructure systems are networked cyber-physical systems tightly integrated with a socio-economic layer

- that serve communities & support economic interaction
- that learn and adapt from large, heterogeneous sets of data
- in which decisions result from co-design of distributed control and incentives—information exchanges are constrained by the cyber layer which mediates between physical system, human decision-makers, governing bodies, and 3rd party solution providers

1. Urban Mobility


Humans

Data

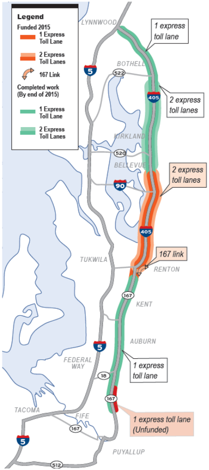
- Transportation cyber-physical infrastructure
- Multi-Modal—Vehicles/ride sharing/mass transit/cyclists/pedestrians
- Sensing/Actuating Infrastructure—Loops, sensors, metering, traffic control
- Mechanisms—Carpools, variable tolls, transit rebates, targeted information, online routing apps, multi-sided mobility markets

Problems: serious traffic jams, ineffective/uncoordinated control, individualized solutions targeted for users, legacy systems, slow policy change process

Example 1—Traffic Congestion Management

Consider an integrated corridor management scenario. . .

- we have models of the non-linear flow dynamics and controllers (e.g., metering lights, coordinated traffic signal control, special-use lanes, variable speed limits)
- resilience: distance to failure
- consider a set of congestion pricing policies



Hard Problem: forecast travel demand & co-design a distributed controller and adaptive pricing strategy to keep the system from failing

2. Air Transportation

Humans

Data

- Air traffic infrastructure
- Commercial and privately operated airplanes, unmanned air vehicles
- Sensing/Actuating Infrastructure—Air traffic control, regulatory agencies
- Mechanisms—Takeoff/landing slots, jetway markets

Problems: fragile network susceptible to cascading & crippling delays, challenges to safety and privacy with the rise of UAVs, legacy system, slow policy change process

Example 2—Dependencies in Multi-Modal Transportation

Consider the impacts of road congestion on flight delays. . .

- we have models of the non-linear road and air traffic dynamics
- welfare: minimal aggregate passengers delays
- consider incentives in terms of new itinerary offers/bids

Hard Problem: forecast travel demand & design dynamic incentives to minimize delays

3. Electric Grid

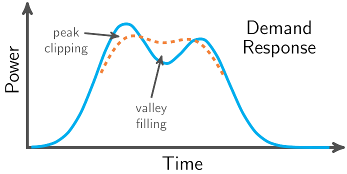
- Distribution and transmission infrastructure
- Control and sensing infrastructure—(micro-)PMUs, smart meters, inverters
- Mechanisms—Demand response, energy markets, regulations

Problems: fragility and uncertainty (e.g., w/ integration of renewables), legacy systems, slow policy change process

Example 3—Electricity Demand Response

Consider the design of a dynamic demand response system to mitigate the fluctuation of generation from renewables…

- we have models of the non-linear power flow
- performance: match supply and demand
- consider a set of demand response schemes; indirect load control through pricing



Hard Problem: forecast aggregate demand & design strategies for re-configuring networks to match supply and demand.

Challenges

- Complex physical dynamics coupled with uncertainty (e.g., adversarial input, random disturbances, partial data, humans in the loop. . .)
- Real-time interaction of people with physical dynamics based on the (limited, inaccurate) information they have and their perceptions
- Behavior of people is not well characterized (either individually or on aggregate); in addition learning must happen in closed loop
- Co-design, the simultaneous design of physical control and incentive mechanisms, is a new field, the space of unintended consequences has not been characterized—fairness and equity vs performance
- Policy and regulations—timescale for change is drastically different than the rate at which users make decisions, data is collected, and new technologies are being adopted

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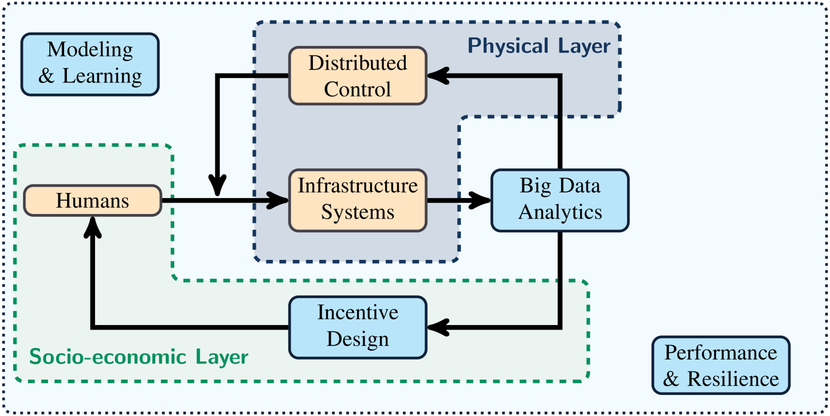
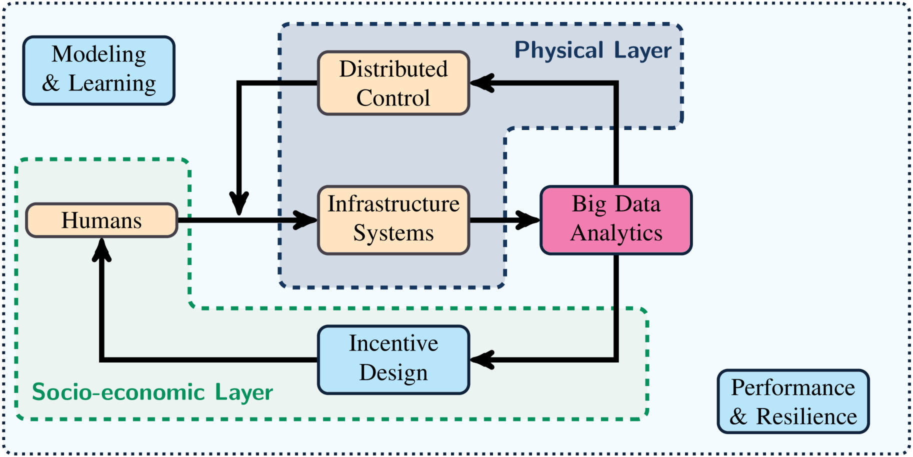
New Vistas in Urban Infrastructure



Vision

- understand the fundamental limits of performance, resilience, and social welfare in next-generation infrastructure
- develop capabilities to assess and control the associated tradeoffs between performance, resilience, and social welfare

Big Data Analytics


Modeling & Learning

Physical Layer

Distributed Control

Humans

Infrastructure Systems

Big Data Analytics

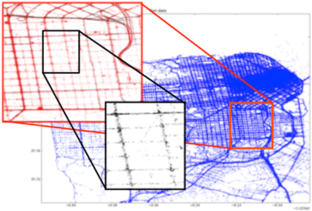
Incentive Design

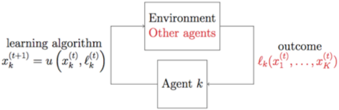
Socio-economic Layer

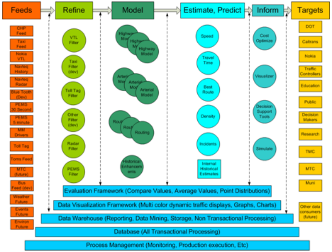
Performance & Resilience

Big Data Analytics—Challenges

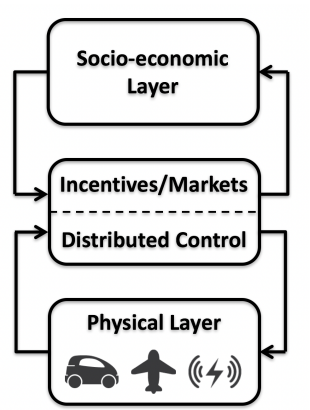
- Infrastructure data taxonomy
  - spatio-temporal data available at unprecedented scales
  - coexistence of aggregated data and individual agent traces
  - missing data and data gaps
- Nature of the problems
  - Decision making in streaming data
  - Activity/state inference in closed-loop (learning in closed loop with incentives)
  - Privacy/disaggregation tradeoffs
- Computational/Complexity Issues
  - nonlinearity, nonconvexity
  - large scale nullspaces, biconvex formulations
  - computational architecture to reflect mathematical nature of the problem







Big Data Analytics—Key Features



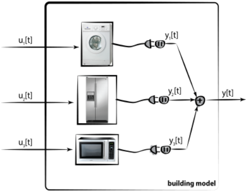
- large numbers of distributed sensors are generating real time data,
- real-time data needs to be analyzed using provably correct algorithms
- it also needs to provide actionable information in real-time.

Calls for a framework that (i) avoids actions based on stale data, (ii) has the ability to intervene in a streaming data process for actuation, (iii) allows human participation and has the ability to use aggregated data for individual actor actuation, & (iv) performs anomaly predictions as well as predicts future needs

Data Disaggregation, Privacy and the Data Market

Can we develop scalable privacy-preserving disaggregation algorithms that generalize across applications, & factor in spatio-temporal dependencies?

- smart meters allow high fidelity consumption data to be collected



Key Questions & Goals:

- ingest whole building energy signal & side information——e.g., billing data, weather, devices and their brands, etc.)
- produce device level consumption—availability of this information leads directly to privacy concerns, not only about device consumption but also other factors considered private

Goal: leverage aggregated data streams in privacy-preserving algorithms for producing actionable information in real-time.

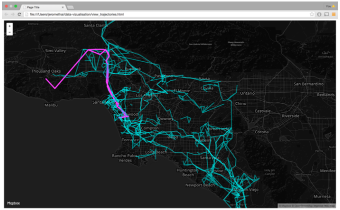
Data Disaggregation, Privacy and the Data Market

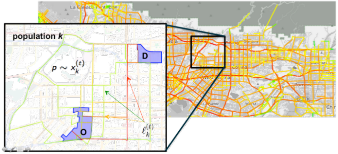
Can we develop scalable privacy-preserving disaggregation algorithms that generalize across applications, & factor in spatio-temporal dependencies?

- broad use of smart devices allow bundles of traces to be collected

Key Questions & Goals:

- ingest & fuse Call Data Records (CDRs) and data from loops, GPS, bluetooth, etc.
- infer Nash (user equilibrium) & dynamic traffic assignment inference from CDR-inferred origin-destinations via convex optimization
- privacy: flow inference without trajectory inference?





Goal: leverage aggregated data streams in privacy-preserving algorithms for producing actionable information in real-time.

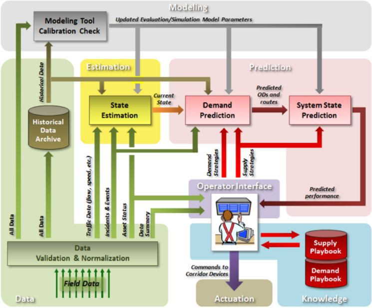
Scalable, Consistent Decisions via Hierarchical Control

Can we develop data-driven models with dynamics based models for actuation of large control systems at scale?

- multi-modal demand data is increasingly becoming available

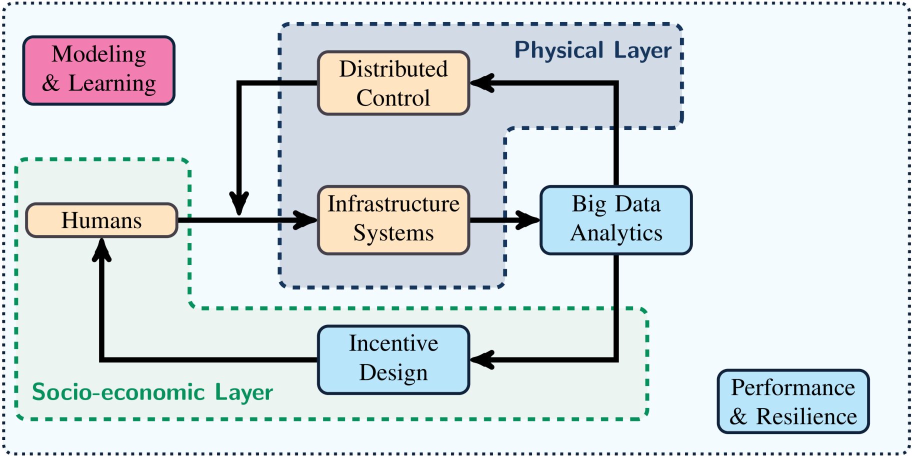
Key Questions:

- design coordinated signal-timing policy compatible with existing infrastructure?
- decision-support policies (e.g., queue prioritization) consistent with today's procedures and coordination architecture, and yet increase efficiency of operations



Goal: Co-design of control laws that operate (i) at multiple spatio-temporal scales; (ii) on a system where demand is a function of incentives; (iii) in a hierarchical control environment with a system model learned in closed-loop

Modeling & Learning

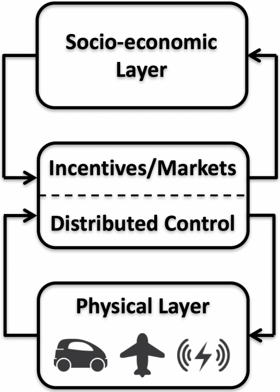


Modeling & Learning—Challenges

- Humans in the loop
  - shape both demand and supply
  - they are often not perfectly rational
- In-situ measurements
  - difficult to isolate individual treatment effects
- Shared autonomy
  - human decision-makers are coupled with autonomous systems in many control environments
  - policy and control decisions occur on very different time-scales

Modeling & Learning—Key Features

- Human beings and their communities are core stakeholders
- Human beings are consumers, participants, controllers. . .
- We need to understand:
    - how to model human decision makers' choices and actions
    - how to design automation that shares control authority with human
    - the resulting behavior, with associated risks, of the system as a whole



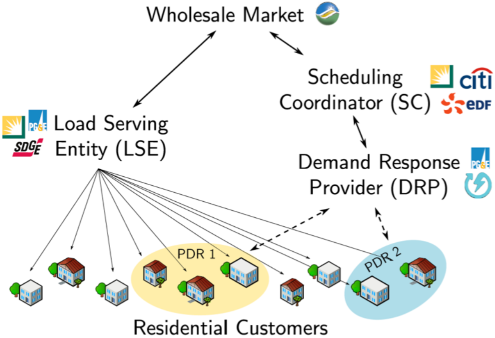
Calls for new framework for (i) modeling human decision-makers in the midst of automation & (ii) provably correct design and risk models/insurance in shared autonomy

Causal Inference of Human Behavior

Can we develop novel techniques to understand individual effects of a treatment?

Key Questions & Goals:

- Impossible to observe the effect conditional on both treatment and non-treatment
- Randomized controlled trial infeasible or impractical

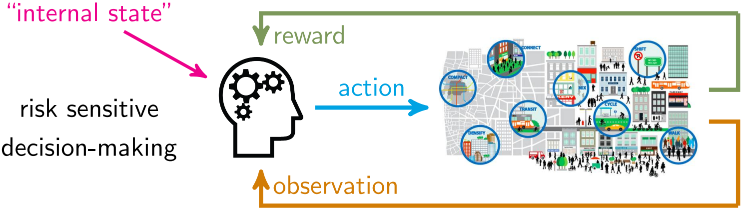


Goal: use the variation inherent in large high-frequency data sets to perform causal inference.

Causal Inference of Human Behavior

Can we learn plausible models of human behavior and preferences, with theoretical foundations, by drawing on "smart" infrastructure data?

- Humans tend to treat losses and gains differently & make decisions based on reference points and distortions of event probabilities.



"internal state"

reward

risk sensitive decision-making

action

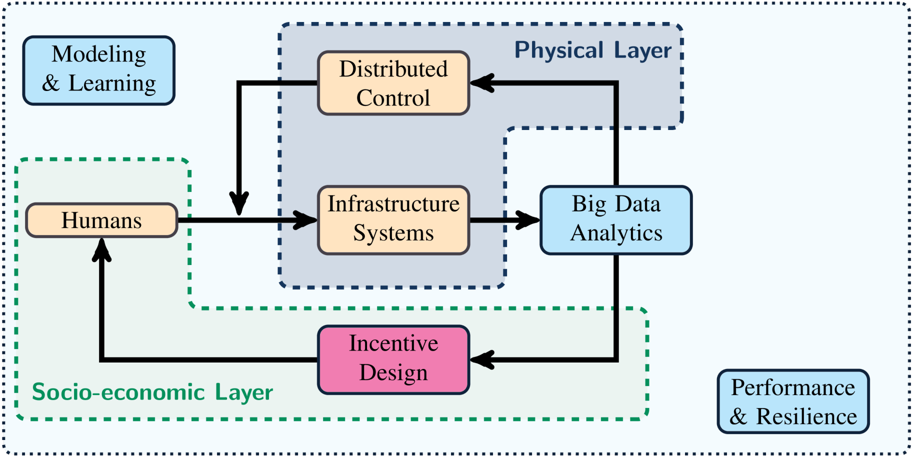
observation

Key Questions & Goals:

- rational, utility maximization models tend not to capture these effects

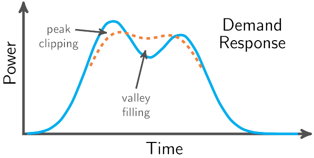
Goal: leverage fine grained user choice data to develop (real-time) algorithms for learning and designing incentives in closed loop

Incentive Design

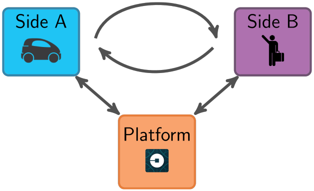


Socio-Economic Layer & Incentive Design—Challenges

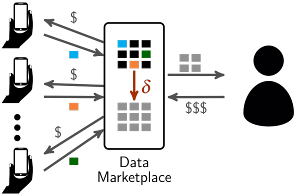
- New Smart Services
  - enables shaping user behavior via incentives for efficient resource utilization.
  - e.g., demand response



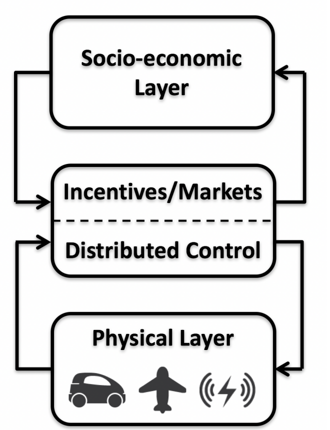
- New Sharing Platforms/Economies
  - cyber platforms for sharing resources and governing transactions among decentralized participants.
  - e.g., ride-sharing



- Emerging Data Market
  - enables detailed traces of user behavior and consumption patterns potentially at the expense of privacy
  - necessitates design of incentives for fair compensation of users for data access.
  - e.g., privacy-aware data-sharing



Socio-Economic Layer & Incentive Design—Key Features



- multi-sided markets that necessitate capturing incentives of multiple sides.
- Support high temporal resolution for data collection and real-time incentives
- Both user and supply characteristics change because of co-design of physical layer & incentives
  - users' utilities change nonlinearly as a function of incentives.
  - supply changes as a function of physical layer control

Calls for new game theoretic and economic models that (i) capture stochastic, highly dynamic nature of interactions & (ii) couples with big data analytics to enable learning user characteristics and responses in closed loop (as a function of real-time incentives)

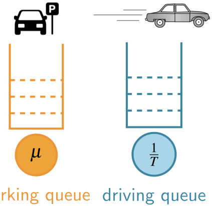
Congestion Mitigation via Shaping Parking Demand

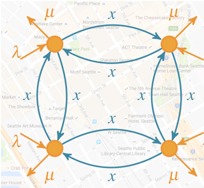
Can we leverage varied data streams which provide a partial view in designing incentives to shape demand and mitigate congestion?

- studies show drivers lack knowledge of price and rely on past experience in deciding where to park.

Key Questions & Goals:

- Develop algorithms for learning data-informed models of parking & congestion.
- Develop a new game-theoretic modeling paradigm (queue-flow networks).
- User interests and incentives are tightly coupled
- Use pricing AND information to shape demand?





Goal: framework for designing incentives under uncertainty, learning & designing in closed loop, and untangling user interests & incentives

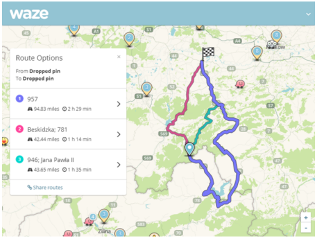
Congestion Mitigation via Information

Can we use information (made available by the cyber infrastructure) to shape demand and mitigate congestion?

- A number of users rely on GPS-based apps such as Waze that provide real-time traffic information and promises to improve traffic congestion experienced by users.

Key Questions & Goals:

- Does providing more information about possible routes to a group of travelers lead to reduced travel time for this group?
- How does heterogeneous information about traffic incidents affect travelers' equilibrium route choices, costs and social welfare?



Goal: design (and efficient computation) of optimal "information structures" that can lead to socially efficient outcomes.

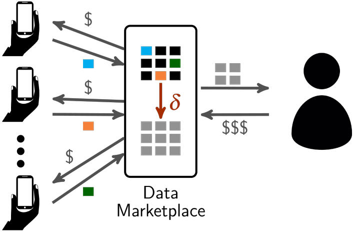
Data Sharing—Contract Design with Strategic Sources

Can we design privacy-aware data sharing mechanisms that leverage the value of information to balance the interests of differently invested parties?

- Companies see the value of data for improving their services. Yet, data exchanges may leak user information or expose intellectual property.

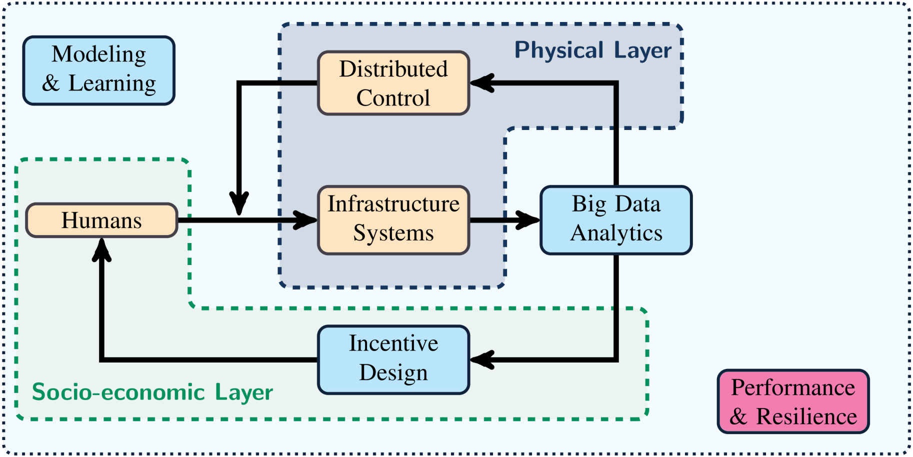
Key Questions :

- What are the appropriate vulnerability metrics and objectives (e.g., balancing fairness/privacy with optimization)?
- Can we design dynamic data sharing mechanisms that balance these objectives?
- Are there cyber/physical constraints that either facilitate or prevent data exchange?



Goal: framework for designing feasible incentive architectures for data exchange compliant w/ constraints imposed by the cyber/physical layer.

Performance & Resilience



Modeling & Learning

Physical Layer

Distributed Control

Infrastructure Systems

Humans

Big Data Analytics

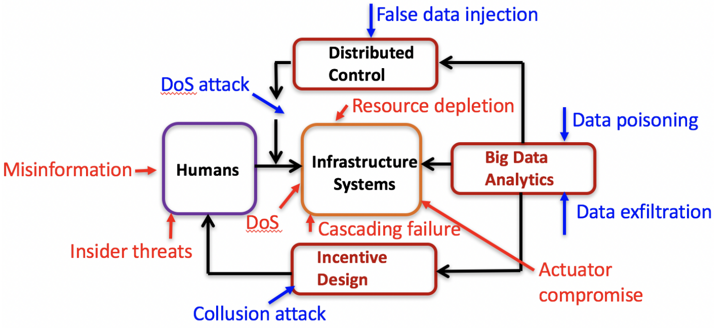
Incentive Design

Socio-economic Layer

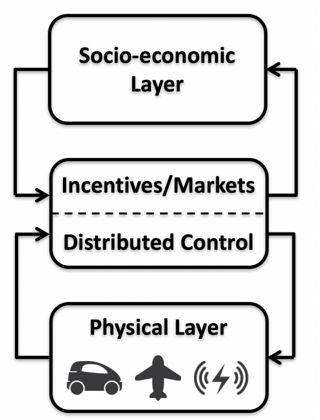
Performance & Resilience

Performance & Resilience—Challenges

- Fragility
    - random faults or malicious attack
    - misconfiguration, random faults, or malicious attacks all may lead to cascading failures
- Economics
    - incentivizing investments in security
    - meterizing risk and designing insurance
- Cyber-Physical Coupling
    - detection and isolation is difficult in large scale systems
    - multiple, simultaneous attacks originating in the cyber or physical layer


False data injection
Distributed Control
DoS attack
Resource depletion
Data poisoning
Misinformation
Humans
Infrastructure Systems
Big Data Analytics
Data exfiltration
DoS
Cascading failure
Insider threats
Incentive Design
Actuator compromise
Collusion attack

Performance & Resilience—Key Features (Desired)



- gurantee performance while providing resilience against multiple, simultaneous attacks
- incentivizing secure & resilient user behavior
- operating through failure via reconfigurability
- learning resilience during operations
- provide quantifiable & verifiable guarantees on safety & performance in hostile environments
- resilience with heterogeneous, resource-constrained IoT devices

Calls for the development of a resilient design methodology for market supported urban infrastructure which requires a rigorous analytical framework to allow the co-design of infrastructures for resilient control, humans in the loop, and incentive design.

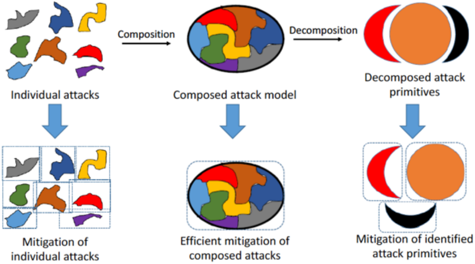
Modeling, Composing, and Mitigating Attacks

Can we model the impact of simultaneous and multi-stage attacks and develop efficient mitigation strategies?

- cyber-physical threats are persistent, adaptive, & coordinated

Key Questions :

- Can we compose multiple simultaneous & sequential attacks via energy-based methods?
- Can we decompose observed attacks & identify novel attack primitives?
- Can we design mitigation strategies with provable resilience, performance and safety, within the co-design framework?

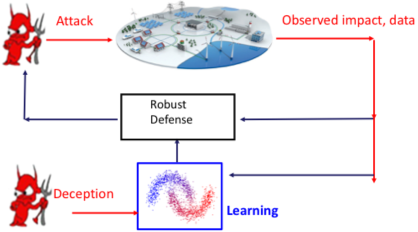


Goal: framework for modeling, composing, decomposing, and mitigating attacks on interdependent infrastructure systems

Learning Resilience Through Operations

In safety-critical systems, can we learn the behavior of users & adversaries?

- next-gen infrastructures are fragile and often unpredictable due to random failures, humans in the loop, and adversarial attacks.

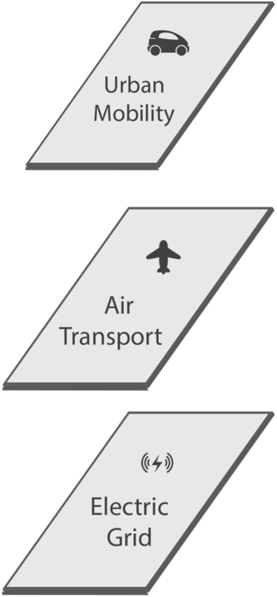


Key Questions :

- How do we learn accurate models of the system in the presence of proactively deceptive & stealthy adversaries?
- How do we ensure the system avoids unsafe states during learning?
- Can we learn at scale in systems with many components?
- How can we quantify the uncertainty of the system state and adversary?

Goal: framework for developing safe learning algorithms, robust to variations in user behavior, disturbances, & adversarial obfuscation.

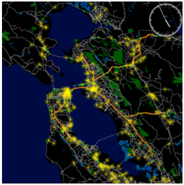
Societal-Scale Infrastructures

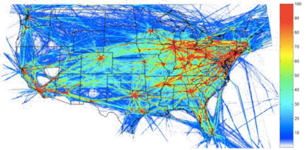


- A resilient traffic system responsive to demand
- Reduce energy footprint of individual consumer

- A decentralized architecture with strategic allocation of capacity-constrained resources
- UAV Traffic Management

- Resilient grid operation with increased visibility
- Incorporation of local, clean and carbon-neutral resources





Core Challenges & the Vision Looking Forward

Challenges

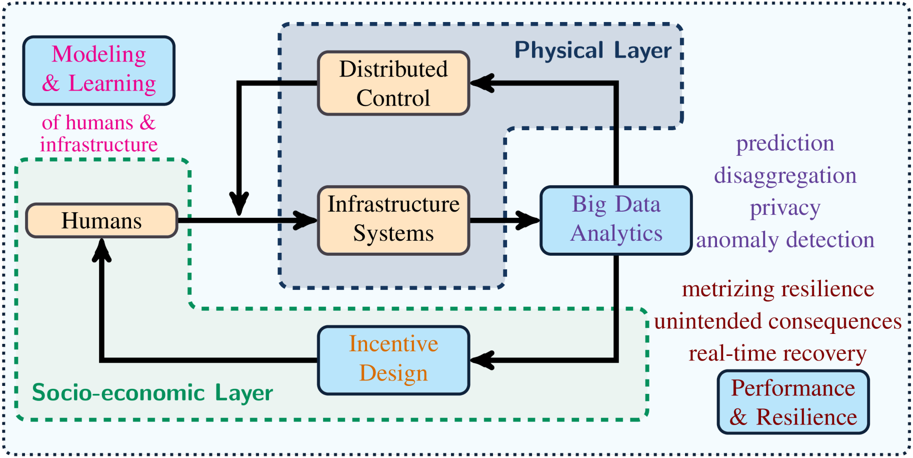
- Complex physical layer coupled with socio-economic layer
- Multi-timescale—Real-time, incomplete information interaction of people with dynamics & slow policy/regulation (much slower than, e.g., rate of technology adoption)
- Emerging field of co-design & understanding unintended consequences—fairness and equity vs performance

Vision & Goals

- understand the fundamental limits of and interplay between performance, resilience, and social welfare in next-generation infrastructure
- develop capabilities to assess and control the associated tradeoffs between performance, resilience, and social welfare

Next-Generation Urban Ecosystem

Key areas with potential for methodological innovations applicable to multiple domains



new services & platforms
information architectures
optimization v. fairness

Thanks

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