Co-Design of Complex Systems:
From Autonomy to Future Mobility Systems

… or …

Rethinking ~~AV Development~~ with ~~Foundation Models~~
Society-Critical Systems Co-Design

MIT Mobility Forum

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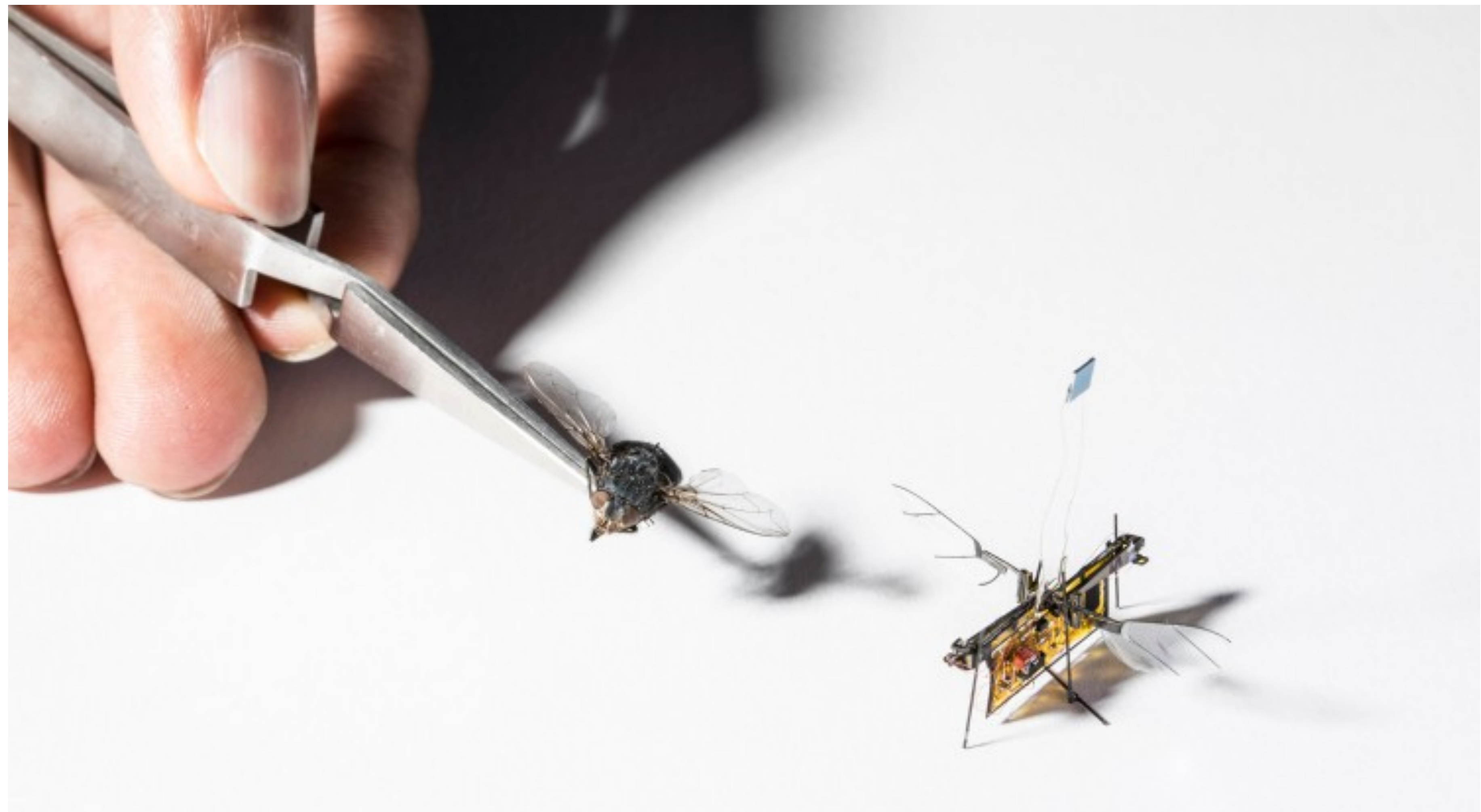
Designing today's engineering systems could have positive societal impact, but is complex

- **Autonomous systems** as a proxy for **complex systems**, which might have **positive societal impact**

Autonomy for safer and efficient mobility (Motional)

Autonomous robots for space exploration (Pavone et al.)



Roboflies to monitor environments (Fuller et al.)

UAVs for search and rescue tasks (Scaramuzza et al.)

Need new tools to model and solve complex systems design optimization problems

- **Societal impact** of new technologies depends on their **joint design** with **existing systems**

Intermodal mobility networks (NASA UAM)

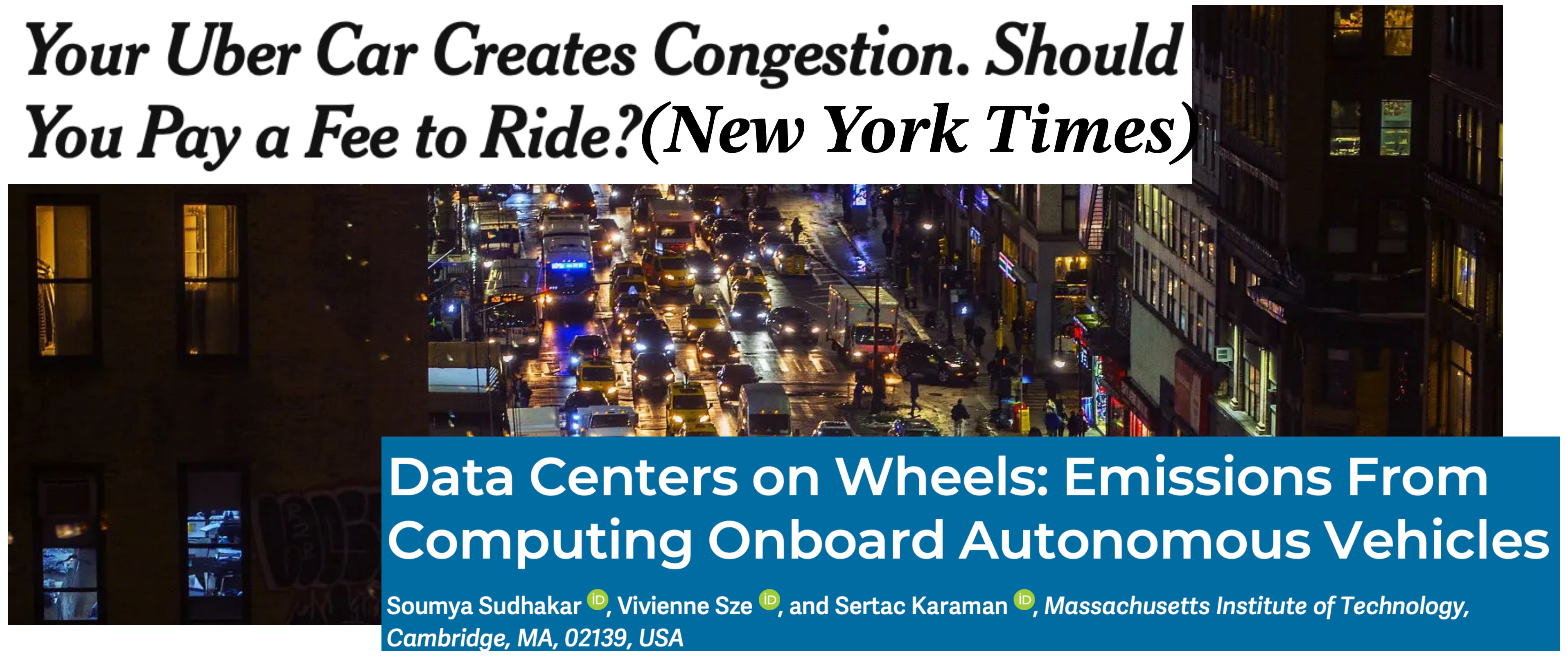
Networks of tankers (Signal Ocean)

*Example - Autonomy: **Heaven** or **hell**?*

***30%** of the cars would be enough*

First**- and **last-mile** mobility could make **public transit** more **convenient** and **attractive

*More **affordable**, **sustainable***



Single components are slowly well understood, but we still lack a (*formal* and *practical*) theory for the **task-driven co-design** of **complex systems**

Agenda

- **Motivation**
  - *New challenges of engineering design*
  - *Motivation from autonomy and mobility*
  - *Desiderata for co-design*
- **Monotone Co-Design**
  - *Modeling design problems*
  - *Examples across domains*
  - *Design queries and optimization*
  - *From autonomy to mobility systems*
- **Strategic interactions**
  - *Game theory to deal with strategic interactions*
  - *Partial order games*
- **Outlook on future research**

Driven by **societal challenges**, I develop **efficient computational tools** to **automate** the **formulation** and **solution** of **large**, **complex system design problems**

Website containing all papers and more pointers:
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The vision of automated system co-design

minimize
(resources usage)
subject to
(functionality constraints)

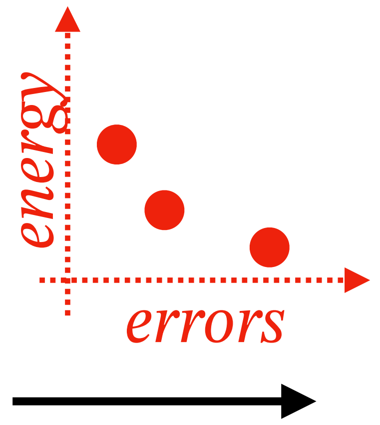
task specification →
multi-domain knowledge →
design options →

"automated designer"

→ **optimal design(s)**

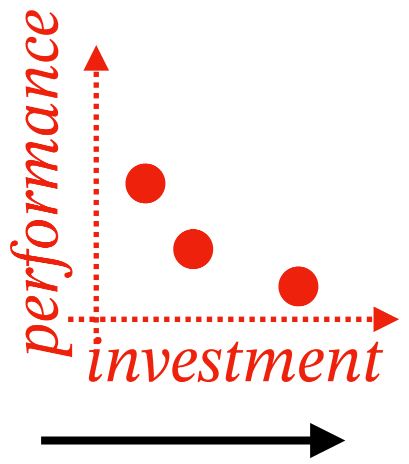
Autonomy co-design

task →
robot autonomy, physics →
components, algorithms →



Mobility co-design

demand →
networks, operations, infrastructure →
mobility services, policies →



Autonomy as the frontier of complexity for the co-design of complex systems

A fleet of autonomous vehicles

=

software behavior coordination hardware actuation localization planning invasivity sensing control interaction learning liability computation perception mapping regulations energetics communication infrastructure

OMG!

So many **components** (hardware, software, ...), and **choices** to make!

Nobody understands the **whole** thing!

We forget why we made **choices**, and we are afraid to make **changes** (high failure cost).

We need **faster** design cycles, **nimbler** execution.

anthropomorphization of 21st century engineering malaise

"My dear, it's simple: you lack a theory of **co-design**!"

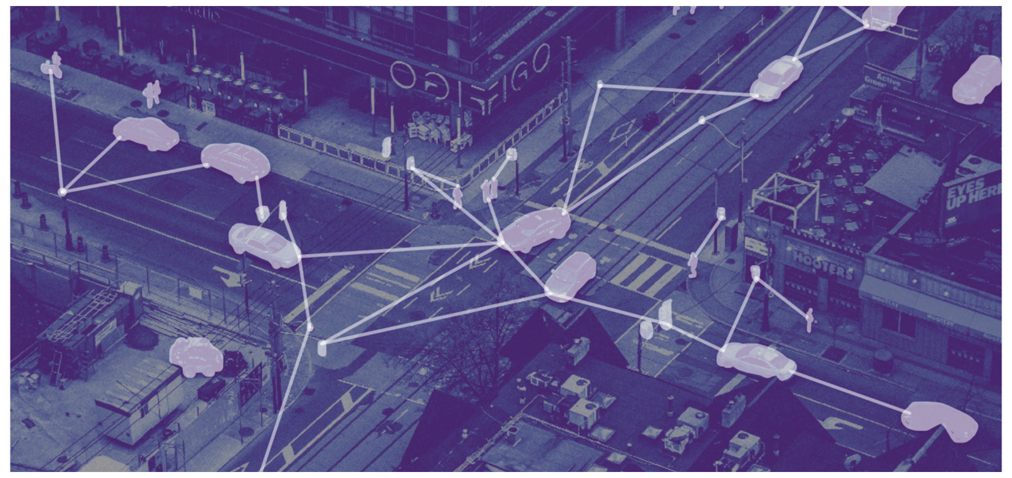
Formal
Quantitative
Intellectually tractable

Your system is just a component in another person's system

Infrastructure level

Optimal infrastructure choices

Service level



Optimal deployment

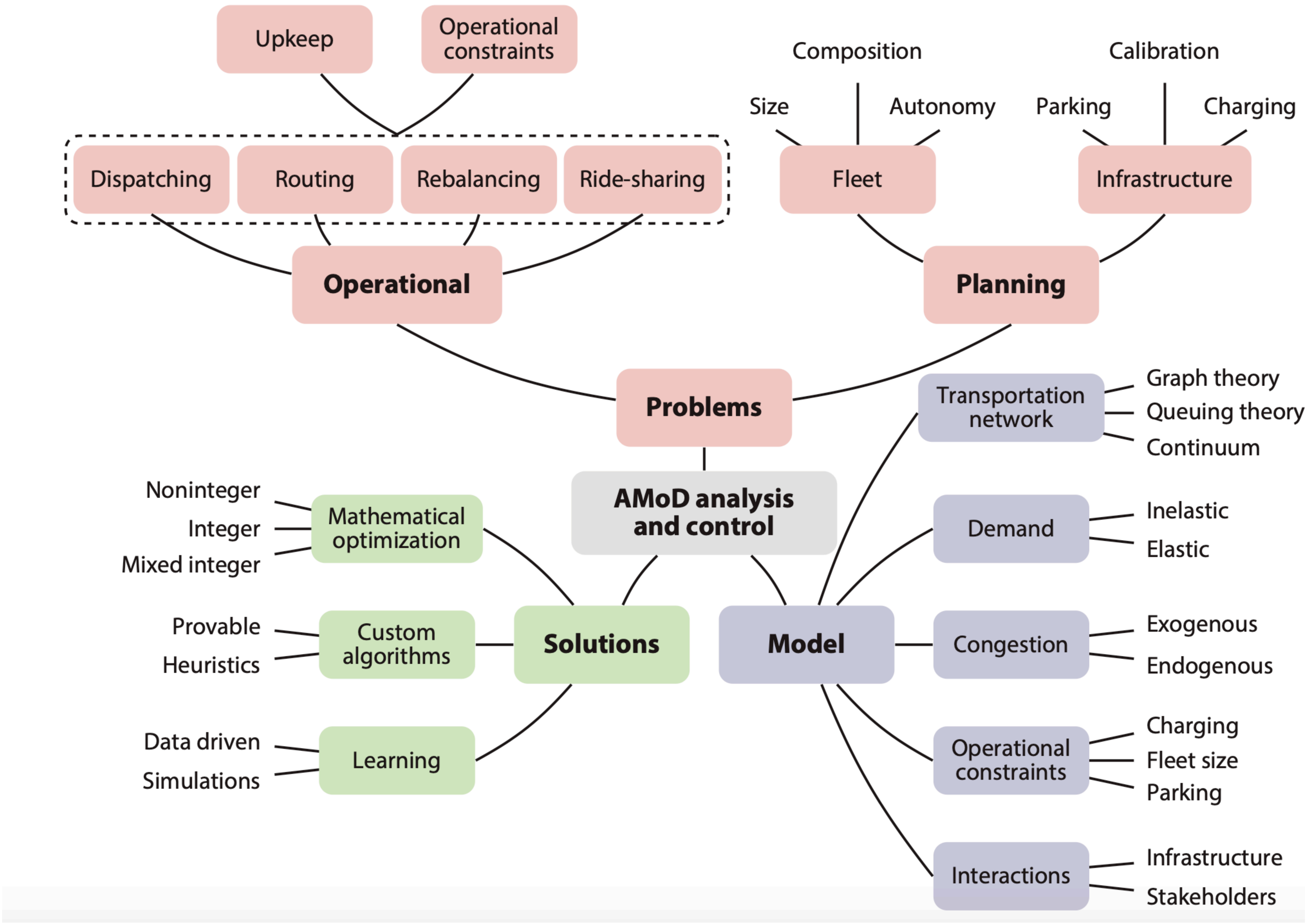
Platform level

Choice of components

Subsystem level

Single component design

Your system is just a component in another person's system



[AnnuRev'22]

Complex systems typically feature multi-stakeholders interactions

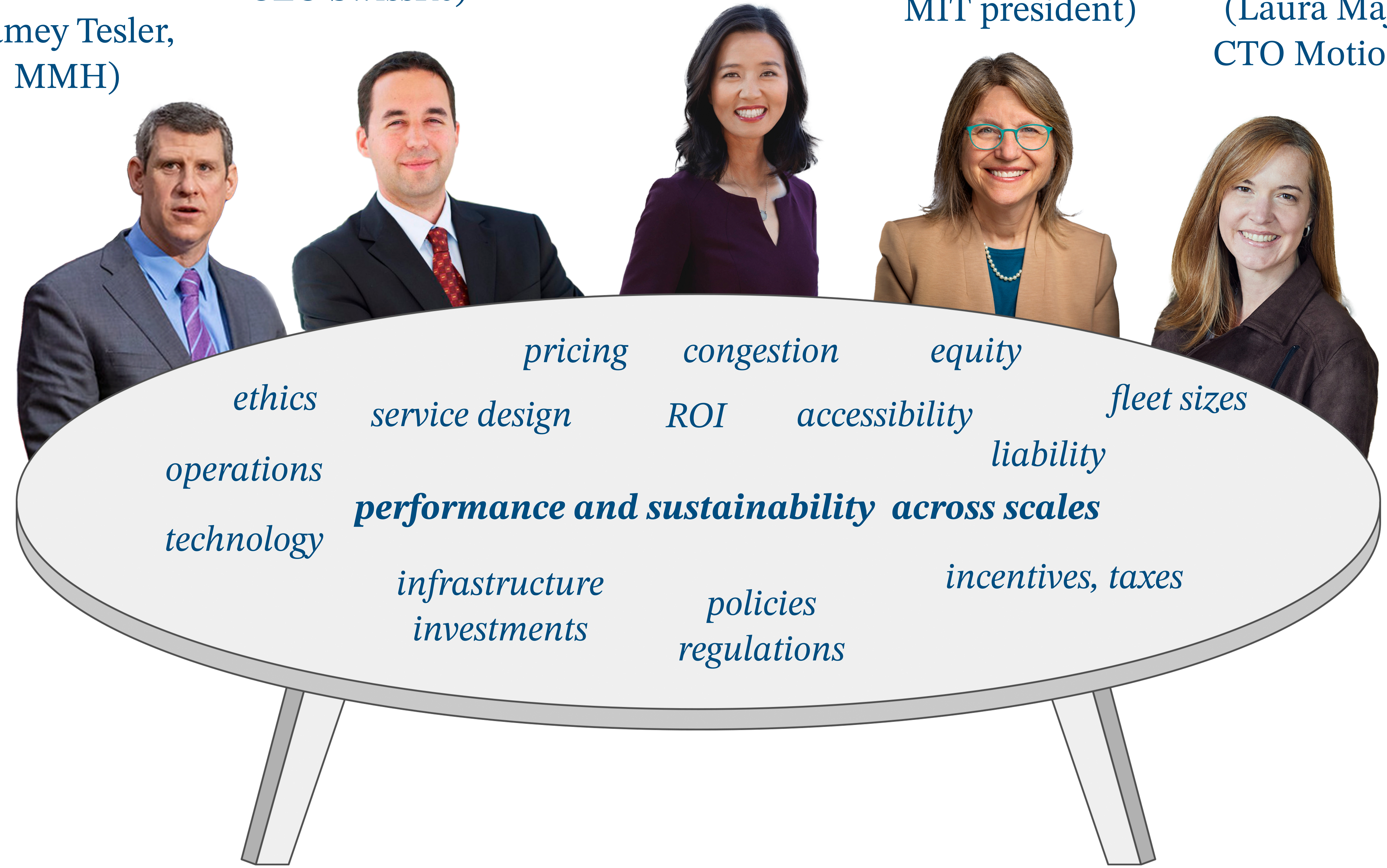
Mobility providers
(Jamey Tesler, MMH)

Liability
(Christian Mumenthaler, CEO SwissRe)

Policy makers
(Michelle Wu, Mayor Boston)

Academia Tech Developers
(Sally Kornbluth, MIT president)

Industry
(Laura Major, CTO Motional)



Challenges for automated co-design of complex systems

Complexity when designing complex systems

Large systems
- Many components, scales
- Heterogeneous natures
- Multiple objectives

Strategic interactions
- Many agents
- Heterogeneous interactions
- Conflicts/collaborations

A fleet of autonomous vehicles

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software hardware behavior coordination actuation sensing localization planning invasivity control interaction learning computation perception mapping regulations energetics communication infrastructure

Desiderata for the automation of complex systems co-design

- **Formal, domain-independent**
- **Computationally tractable**
  - Need to compute solutions efficiently
- **Compositional, hierarchical**
  - My system is a component of somebody else's system
- **Collaborative**
  - Pooling knowledge from experts across fields.
- **Intellectually tractable**
  - Not exclusively accessible to system architects
- **Continuous**
  - Design is not static: it should be reactive to changes in goals and contexts

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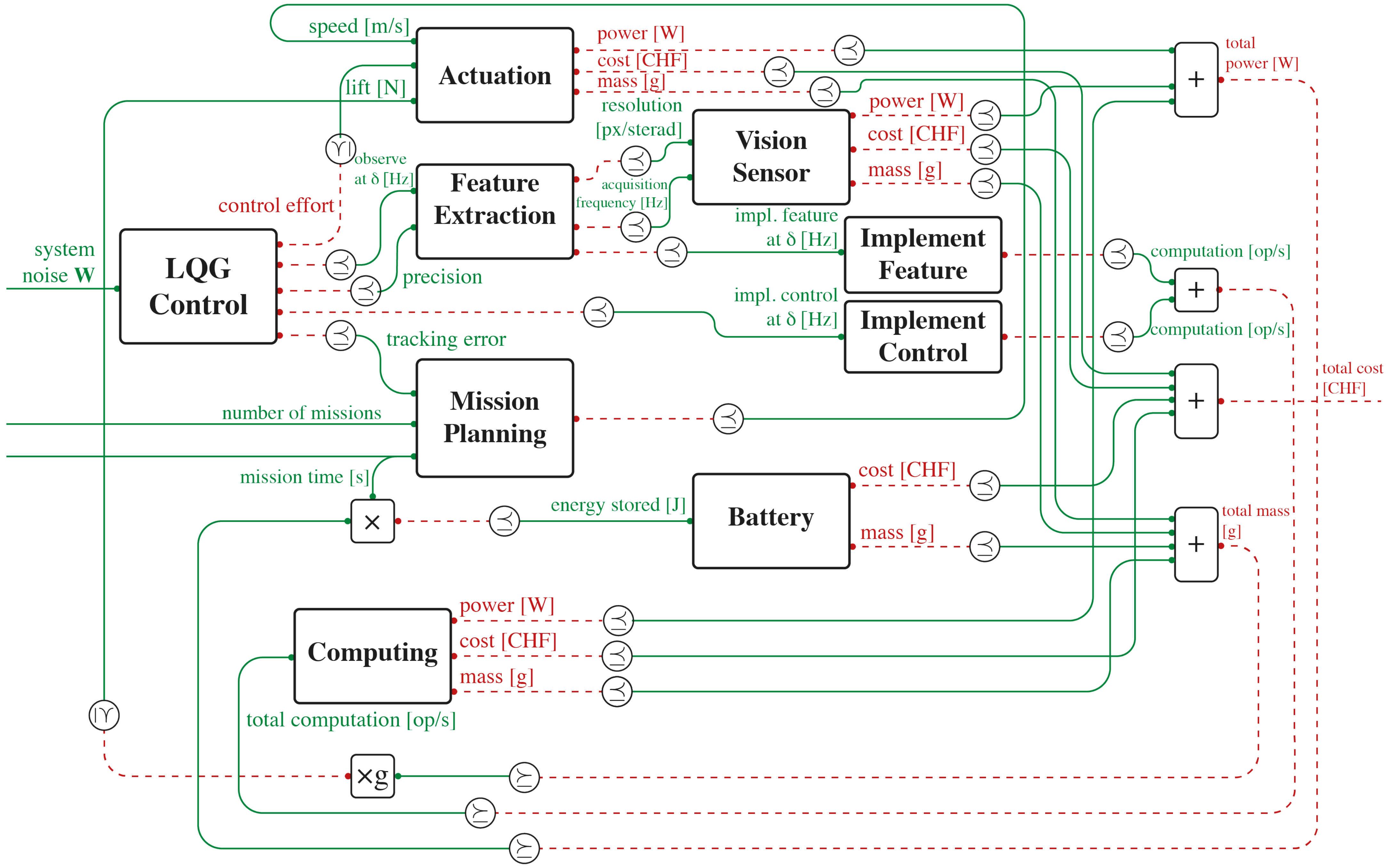
A new approach to multi-disciplinary engineering “co”-design

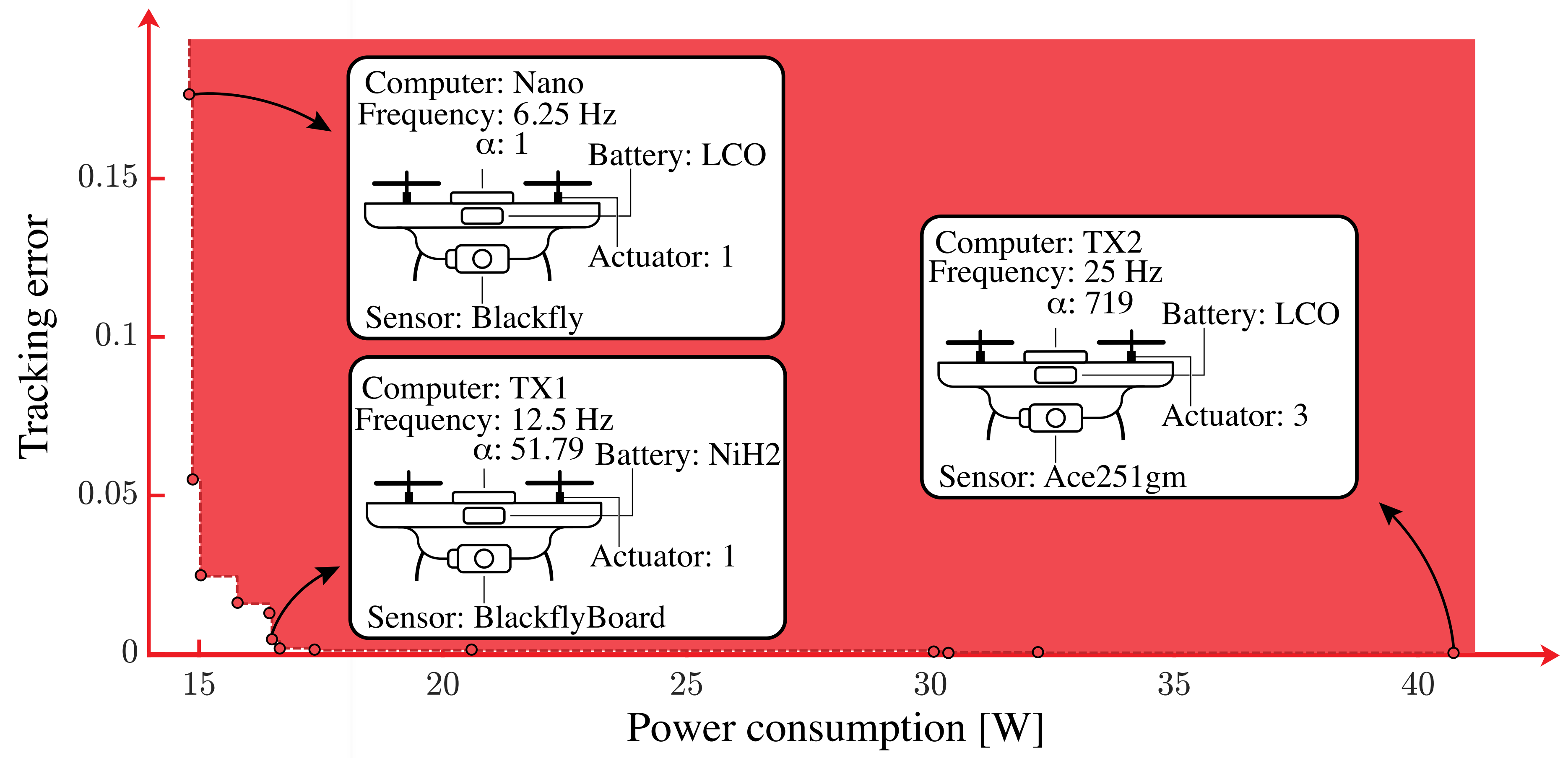
- A new approach to **<u>co</u>llaborative**, **<u>co</u>mputational**, **<u>co</u>mpositional**, **<u>co</u>ntinuous** design designed to work **across fields** and **across scales**.
- Leverages **domain theory**, **applied category theory**, and **optimization**
- Roadmap:
  - Defining **“design problems”** for **components.**
  - Modeling **co-design constraints** in a complex **system**.
  - **Efficient** solution to design queries.

“Co-design diagram”



optimization for a task

Pareto front of optimal designs



A new approach to multi-disciplinary engineering “co”-design

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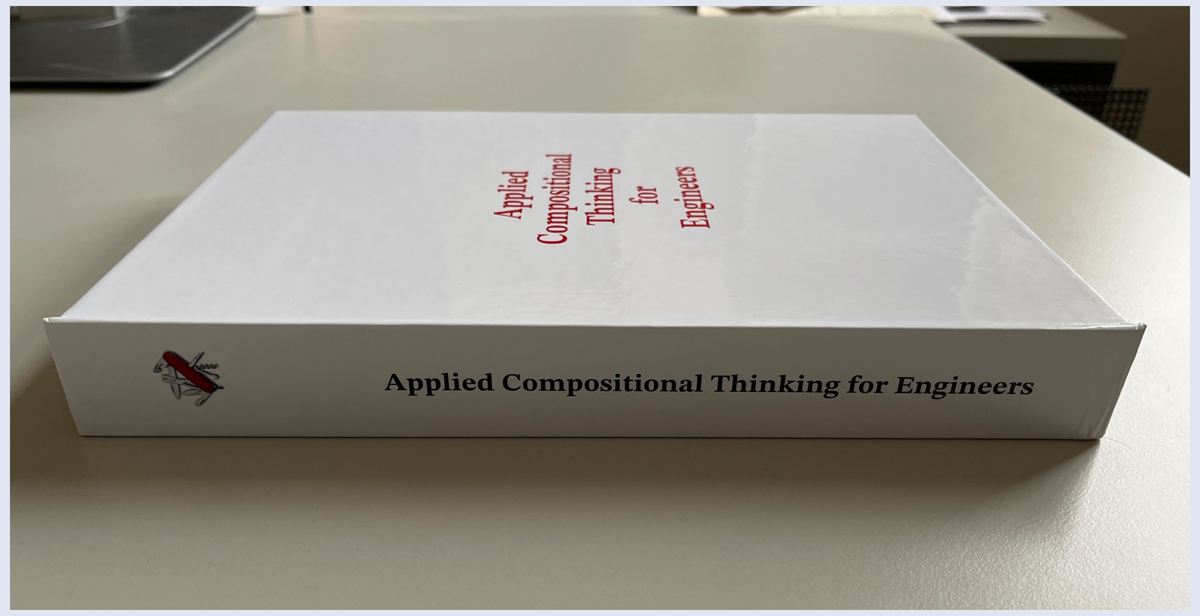
a “pro” box



Access the book at:
https://bit.ly/3qQNrdR

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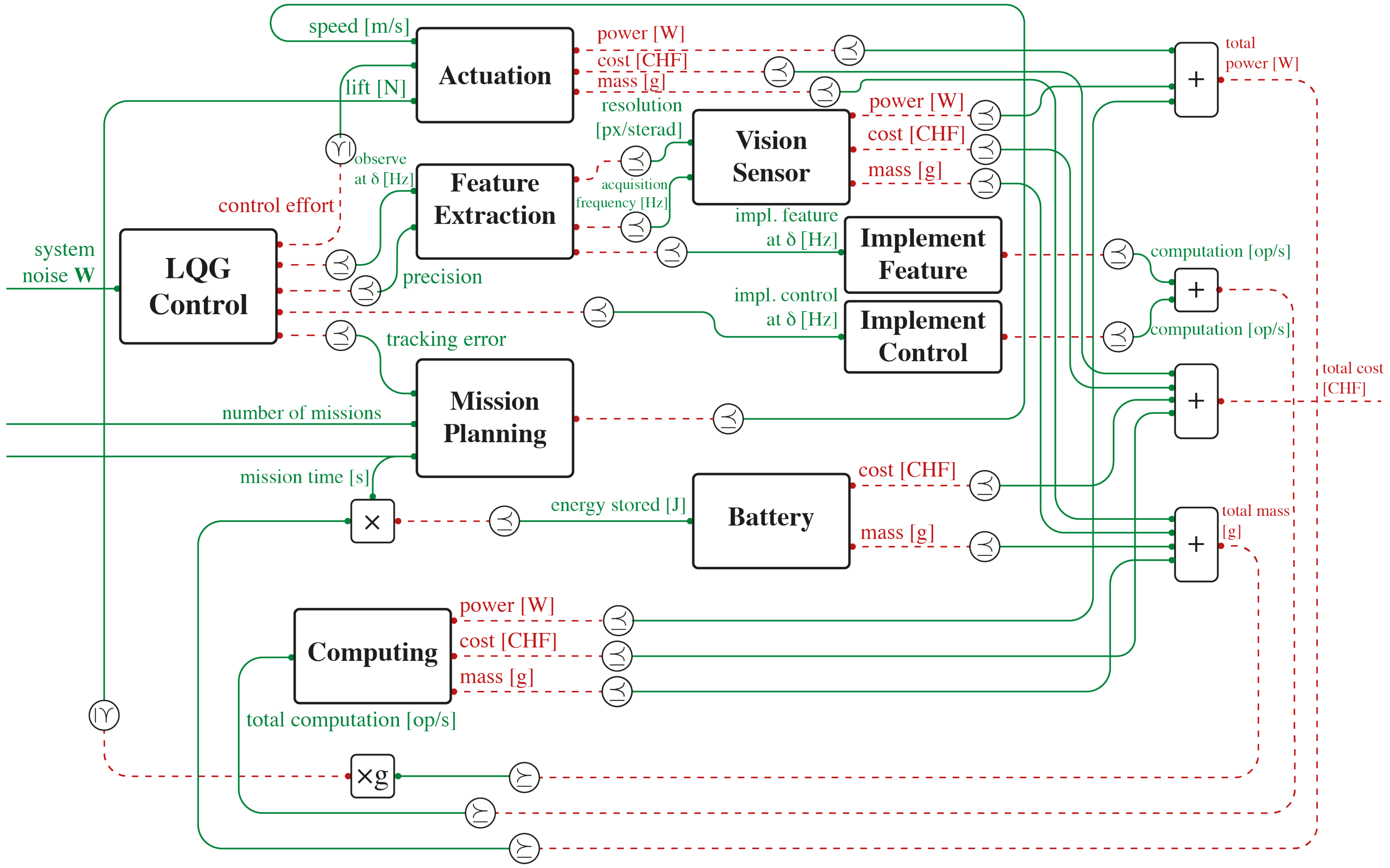

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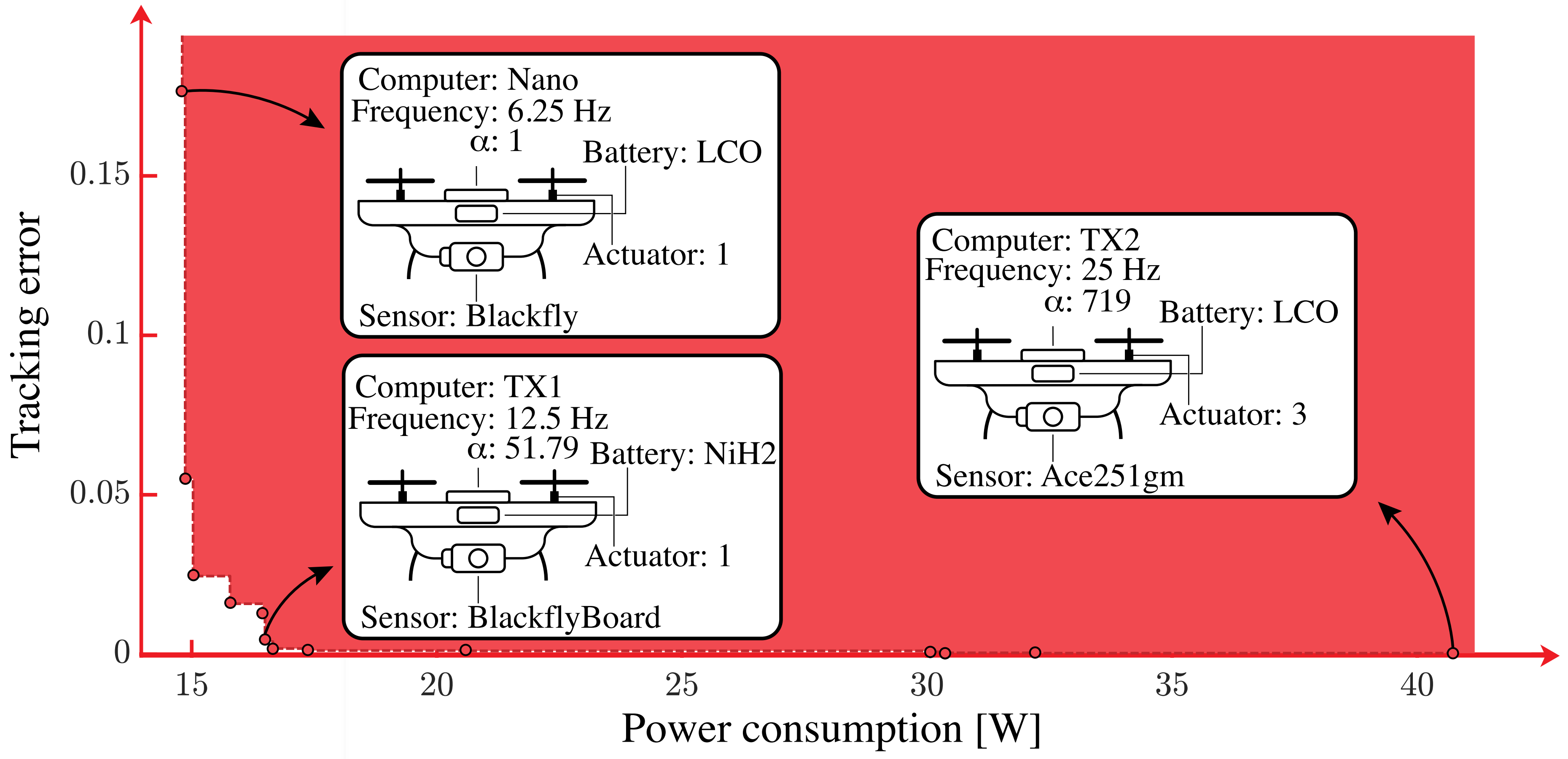
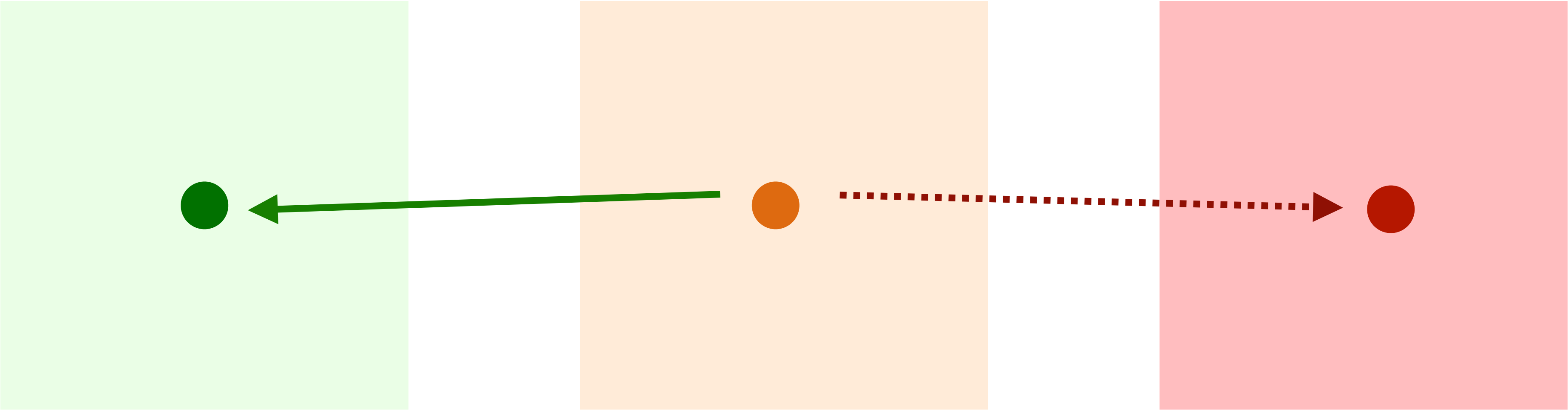


An abstract view of design problems

- Across fields, design or synthesis problems are defined with **three spaces**:
  - **implementation space**: the **options** we can choose from;
  - **functionality space**: what we need to **provide**/**achieve**;
  - **requirements/costs space**: the **resources** we need to have available;

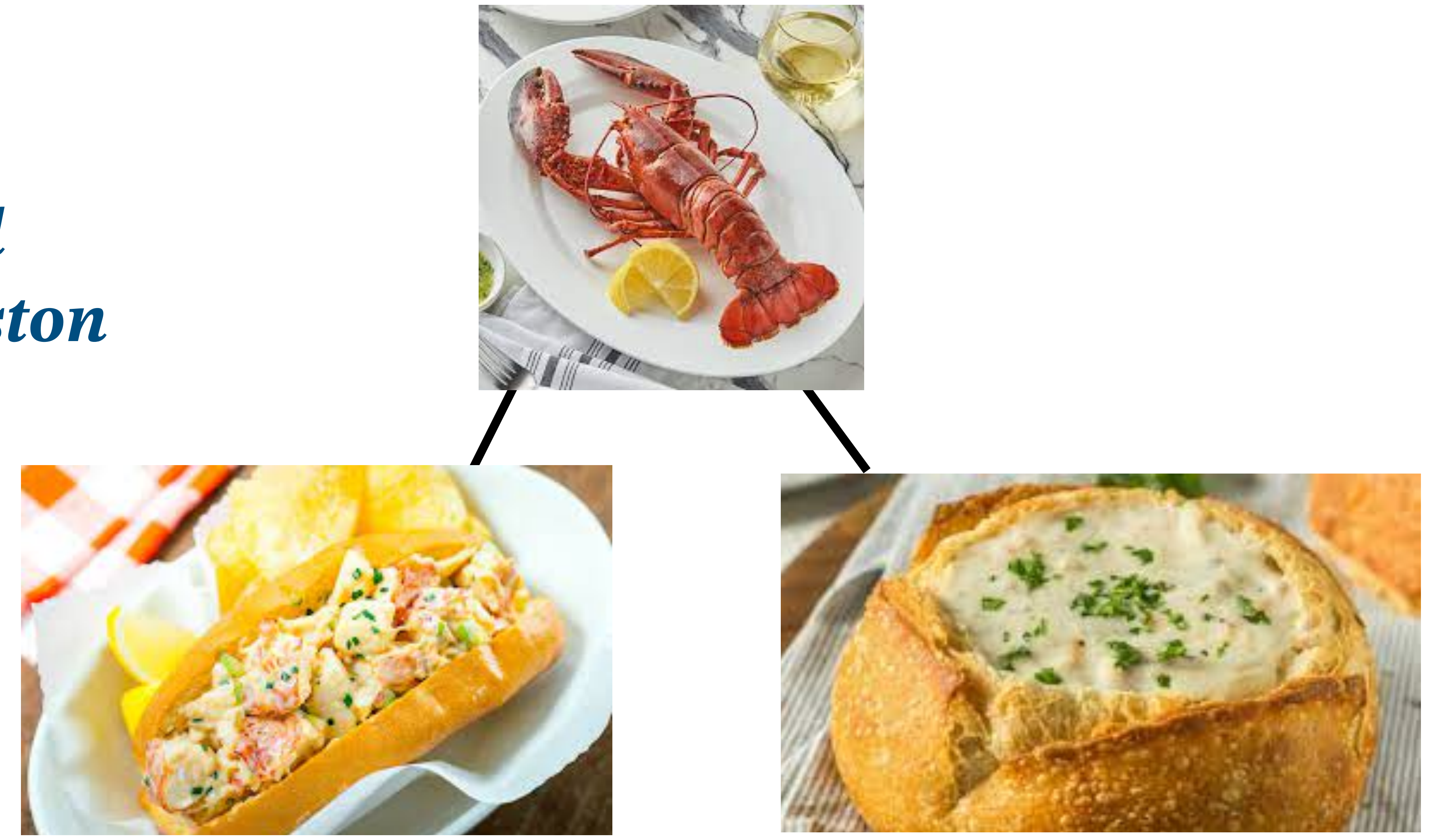


functionality *(provided)*	***implementations***	***costs, resources*** *(required)*
desired behavior	*choices*	*budget*
specifications	*plans*	*requirements*
objectives	*blueprints*	*dependencies*
guarantees	*decision variables*	*assumptions*
conclusions		
“function”	*“form”*	*“function”*

Partially ordered sets model trade-offs, across fields

- Posets model standard costs in engineering $\langle \mathbb{R}_{\geq 0}, \leq \rangle$, $\langle \mathbb{N}, \leq \rangle$
- ... but also enable **richer** cost structures, with **incomparable** elements

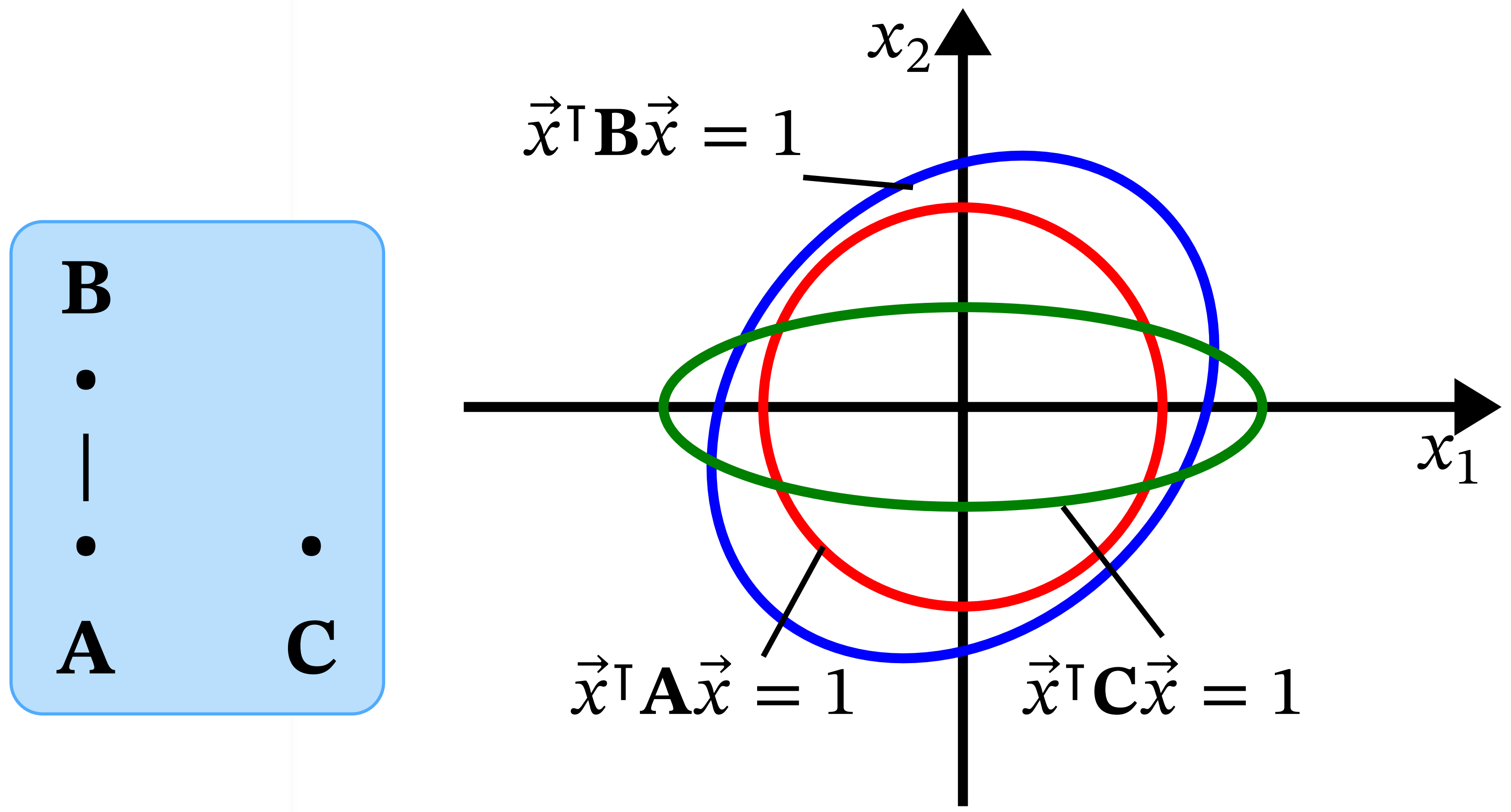
A poset of food preferences in Boston



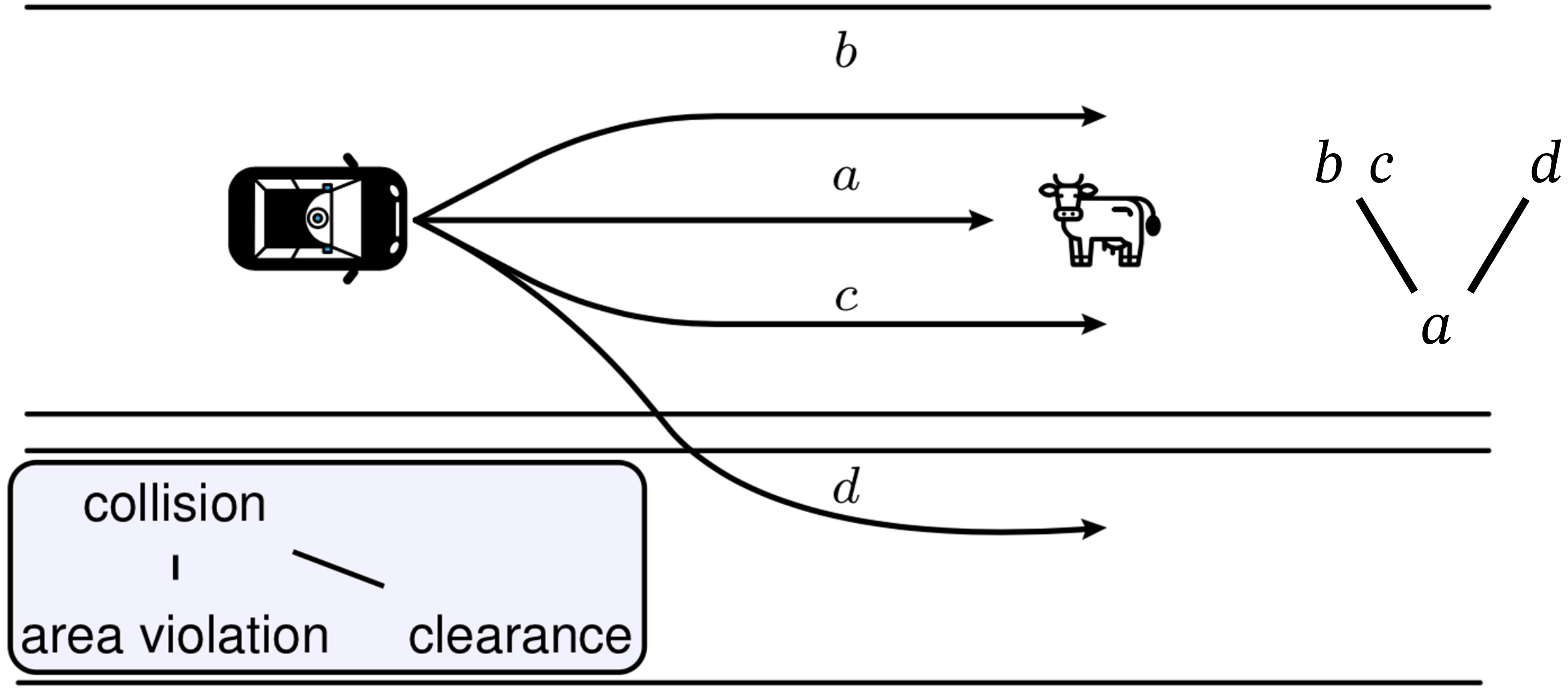
A poset of positive-definite matrices

$$\frac{\mathbf{A} \preceq_{\mathsf{PDM}(n)} \mathbf{B}}{\vec{x}^\intercal \mathbf{A} \vec{x} \leq \vec{x}^\intercal \mathbf{B} \vec{x} \quad \forall \vec{x} \in \mathbb{R}^n}$$

$$\mathbf{A} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 3/4 & -1/8 \\ -1/8 & 3/4 \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} 1/2 & 0 \\ 0 & 2 \end{bmatrix}$$



Posets of rules, which induce priorities over behaviors



[RAL'22, CDC'22, IROS'21, ECC'21]

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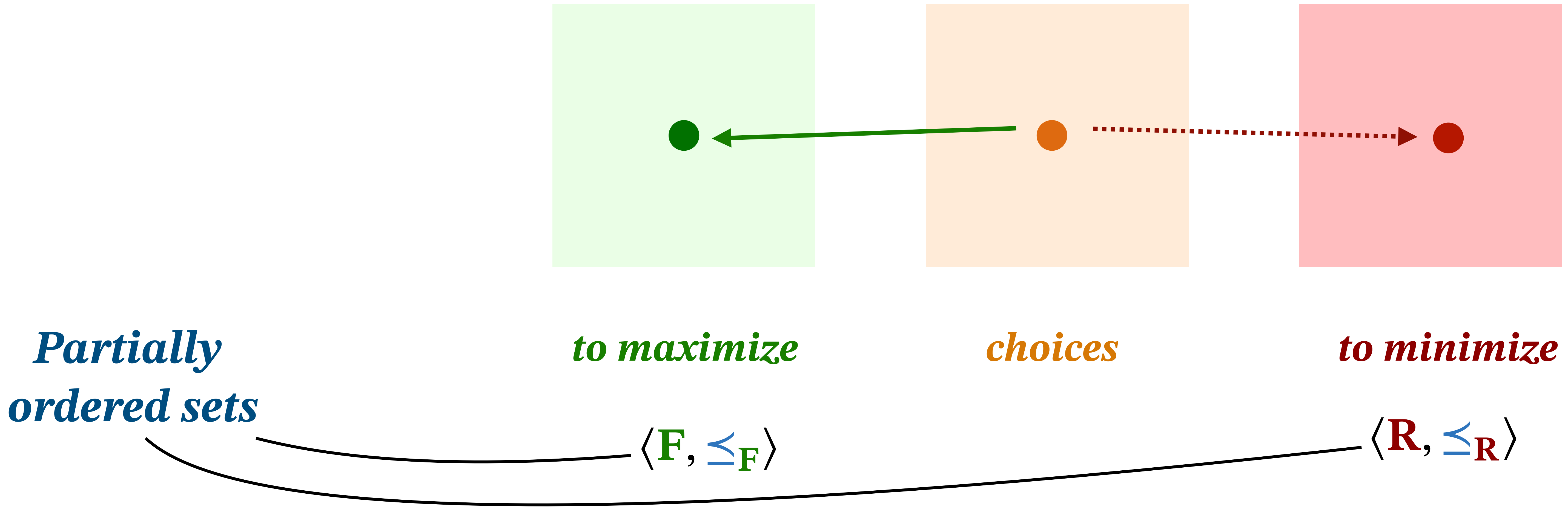
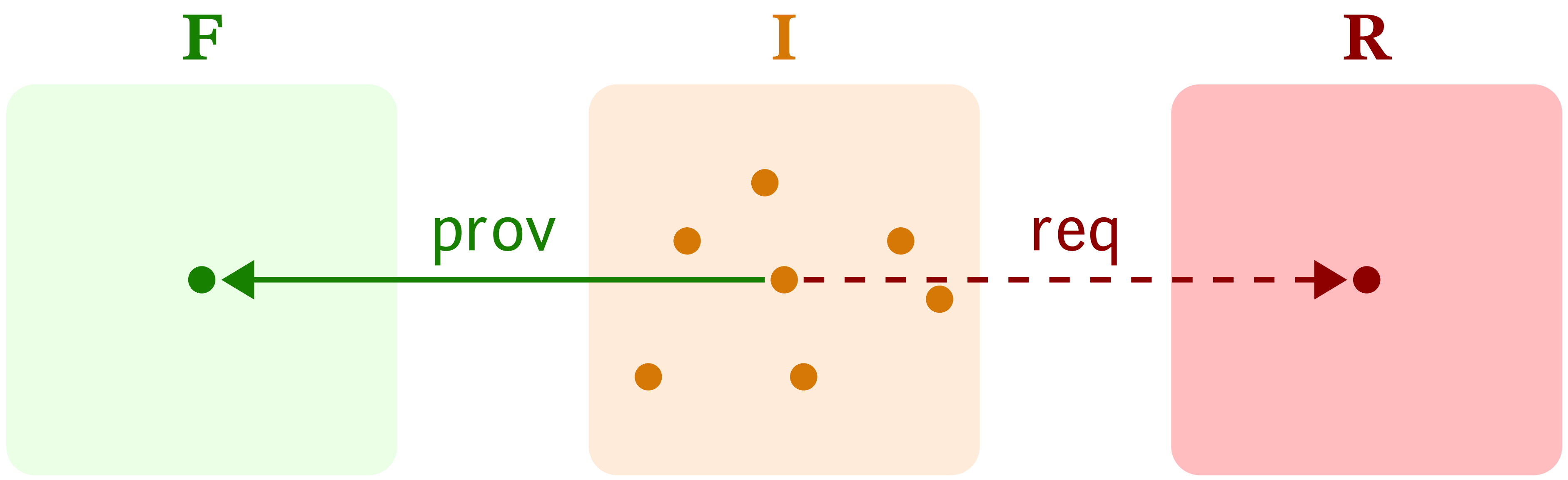


Transparent vs black-box models

- The **"Design Problems with Implementations" model** is a **"transparent" model:**



- **DP** model: **direct feasibility relation** between functionality and resources ("black box") as a monotone map:

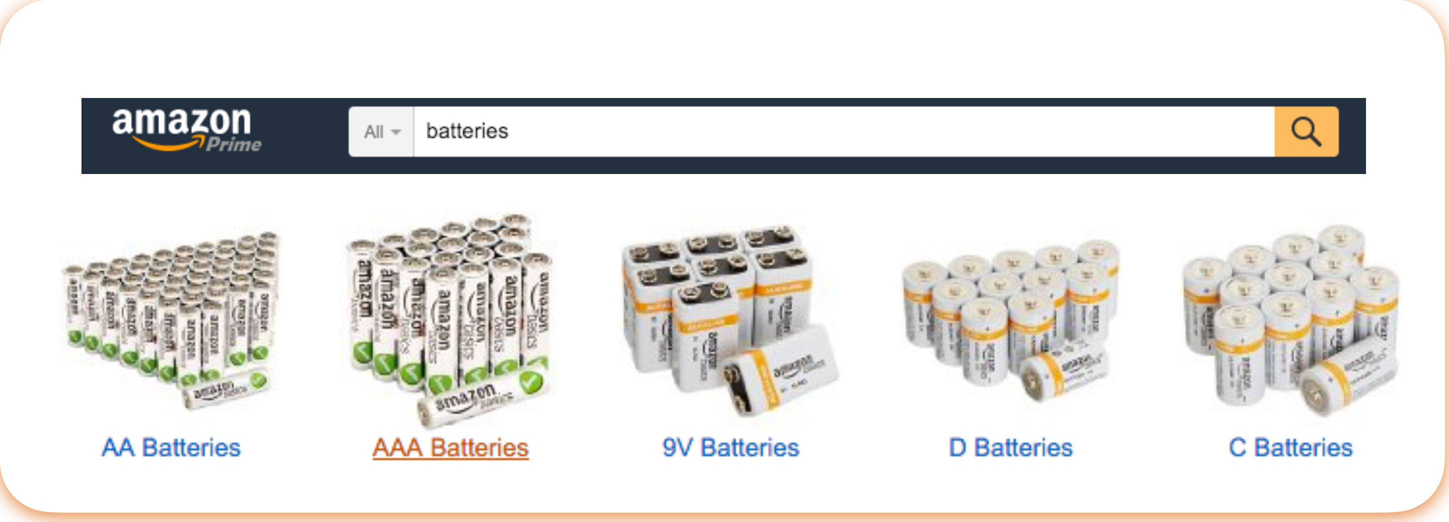
$$\mathbf{d} : \mathbf{F}^{\mathrm{op}} \times \mathbf{R} \to_{\mathbf{Pos}} \mathbf{Bool}$$
$$\langle f^*, r \rangle \mapsto \exists i \in \mathbf{I} : (f \preceq_{\mathbf{F}} \mathsf{prov}(i)) \wedge (\mathsf{req}(i) \preceq_{\mathbf{R}} r)$$

… a "boolean profunctor"

- **Monotonicity**:
  - **Lower functionality** does **not** require **more resources**;
  - More **resources** do not provide **less functionality.**

Co-design enables a rich class of model population techniques

- “**Catalogues**”: off-the-shelf designs.



	Spark	Phantom 3 Std	Phantom 4 Adv	Phantom 4 Pro	Mavic	Inspire
Flight time	16 mins	25 mins	30 mins	30 mins	27 mins	27 mins
Top Speed	31 mph (50 km/h)	36 mph (58 km/h)	45 mph (72 km/h)	45 mph (72 km/h)	40 mph (65 km/h)	58 mph (94 km/h)
Range	1.2 miles (2 km)	0.6 miles (1 km)	4.3 miles (7 km)	4.3 miles (7 km)	4.3 miles (7 km)	4.3 miles (7 km)
Camera	12-MP stills 1080p video	12-MP stills 2704 x 1520p video	20-MP stills 4K 60fps video	20-MP stills 4K 60fps video	12-MP stills 4K video	20.8-MP stills 4K/5K video
Size	5.6 x 5.6 x 2.1 in (14.3 x 14.3 x 5.5 cm)	13.8 in diagonal (350 mm)	13.8 in diagonal (350 mm)	13.8 in diagonal (350 mm)	13.2 in diagonal (350 mm)	16.8 x 12.5 x 16.7 in (42.7 x 31.7 x 42.5 cm)
Takeoff weight	11.6 oz (330 g)	2.6 lb (1.2 kg)	3 lb (1.4 kg)	3 lb (1.4 kg)	1.6 lb (743 kg)	8.8 lb (4 kg)
Other features	Follow me, Return home, Obstacle avoidance, FPV	Follow me, Return home	Follow me, Return home, Obstacle avoidance	Follow me, Return home, 3 Direction Obstacle avoidance	Follow me, Return home, Obstacle avoid-ance, folding arms	Obstacle avoidance, Spotlight Pro/Broadcast/ Composition mode
Price	US$499	US$499	US$1,349	US$1,499	US$999	US$2,999 ($6,198 with camera/gimbal)

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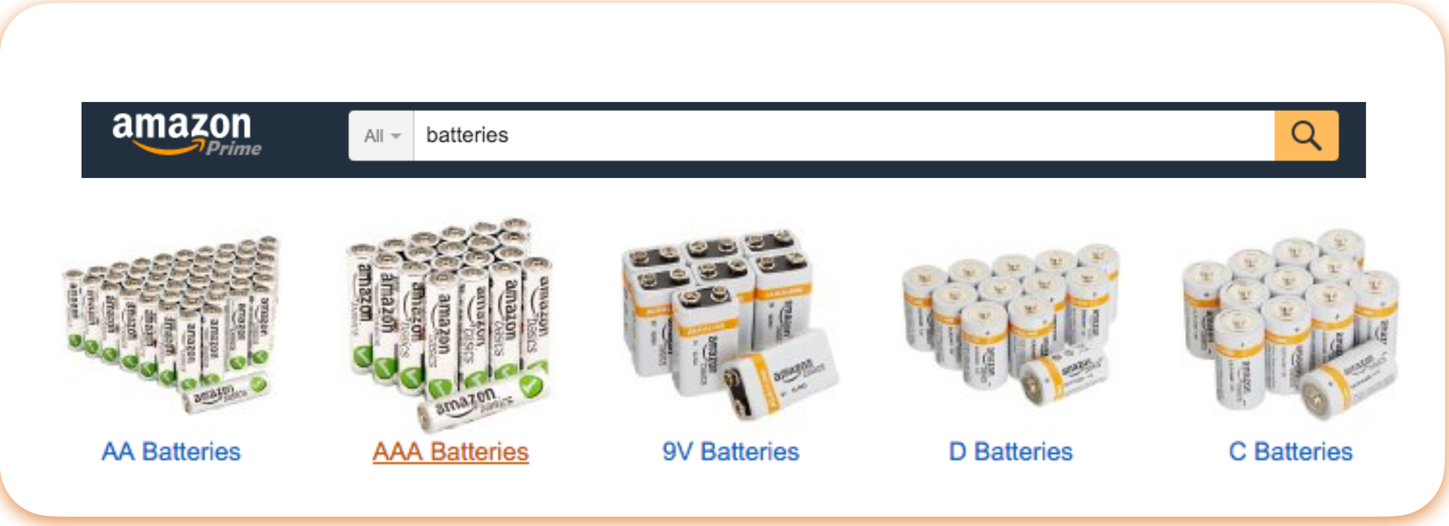

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- “**First-principles**”: analytical relations.

mission energy ≥ mission duration x *power consumption*

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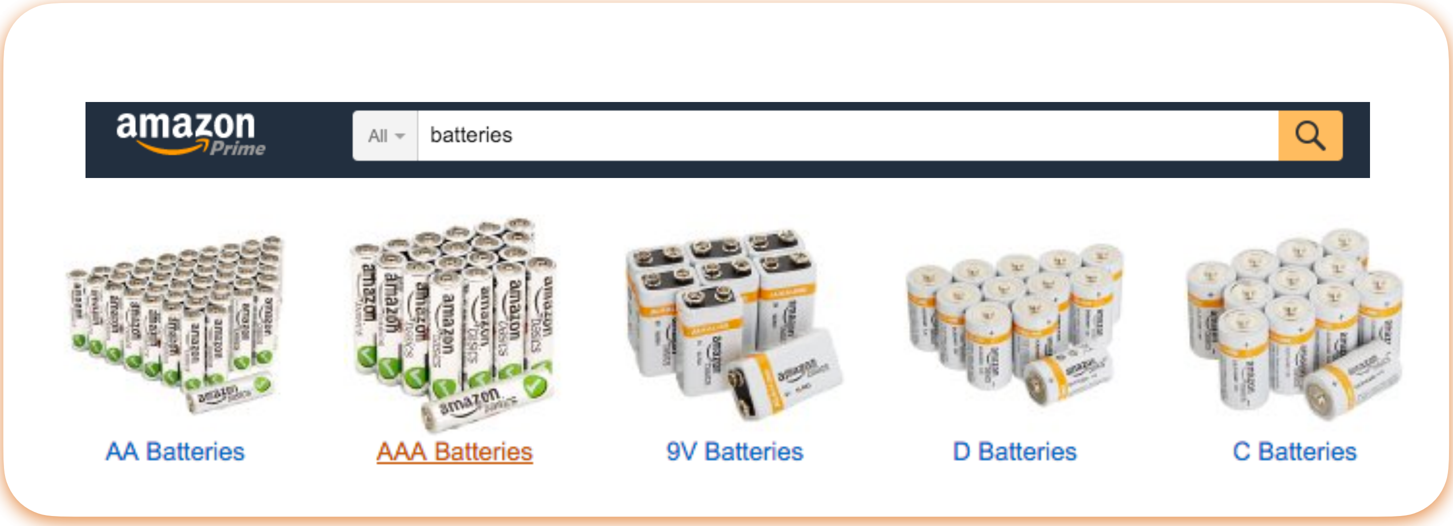

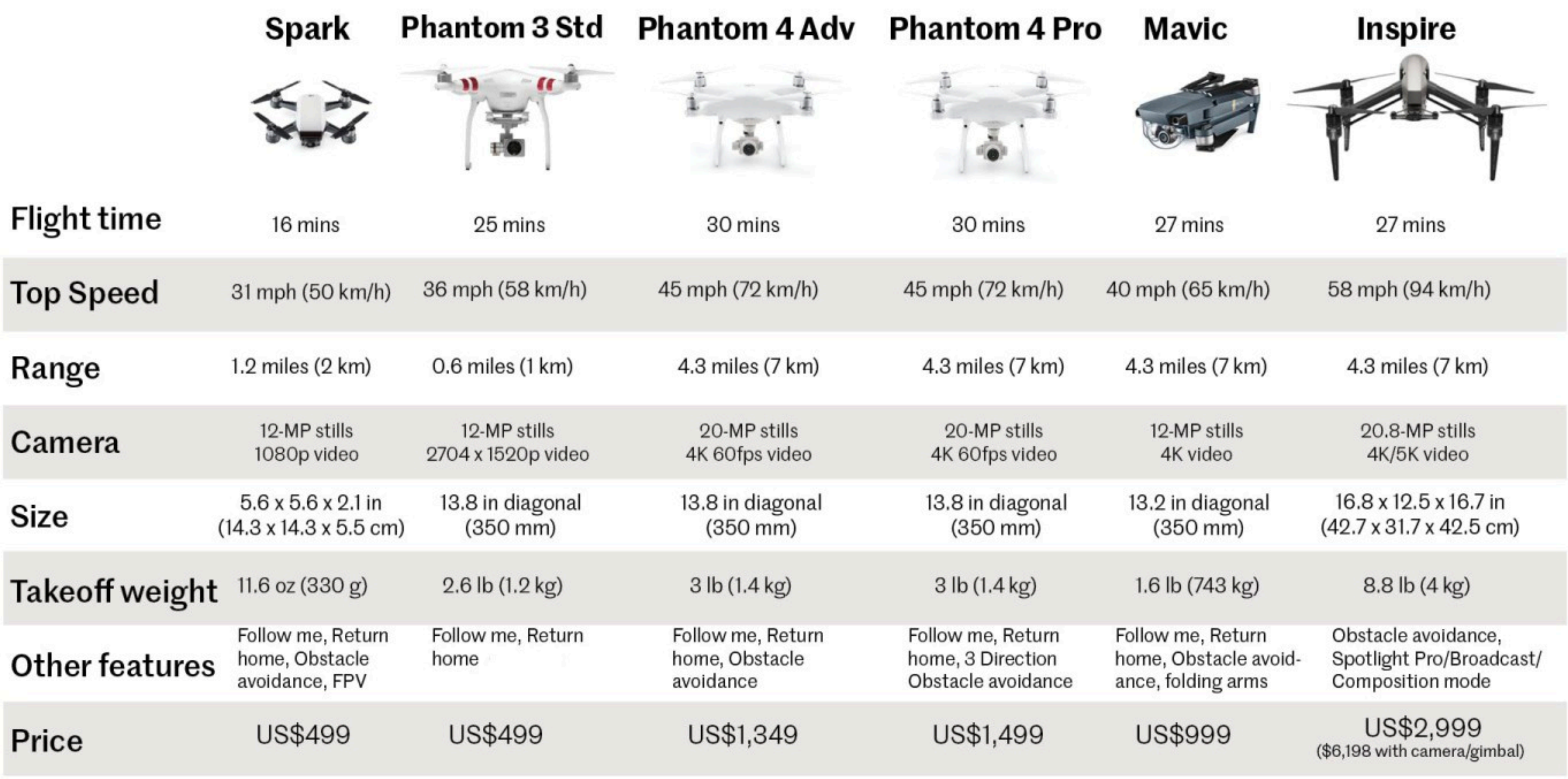

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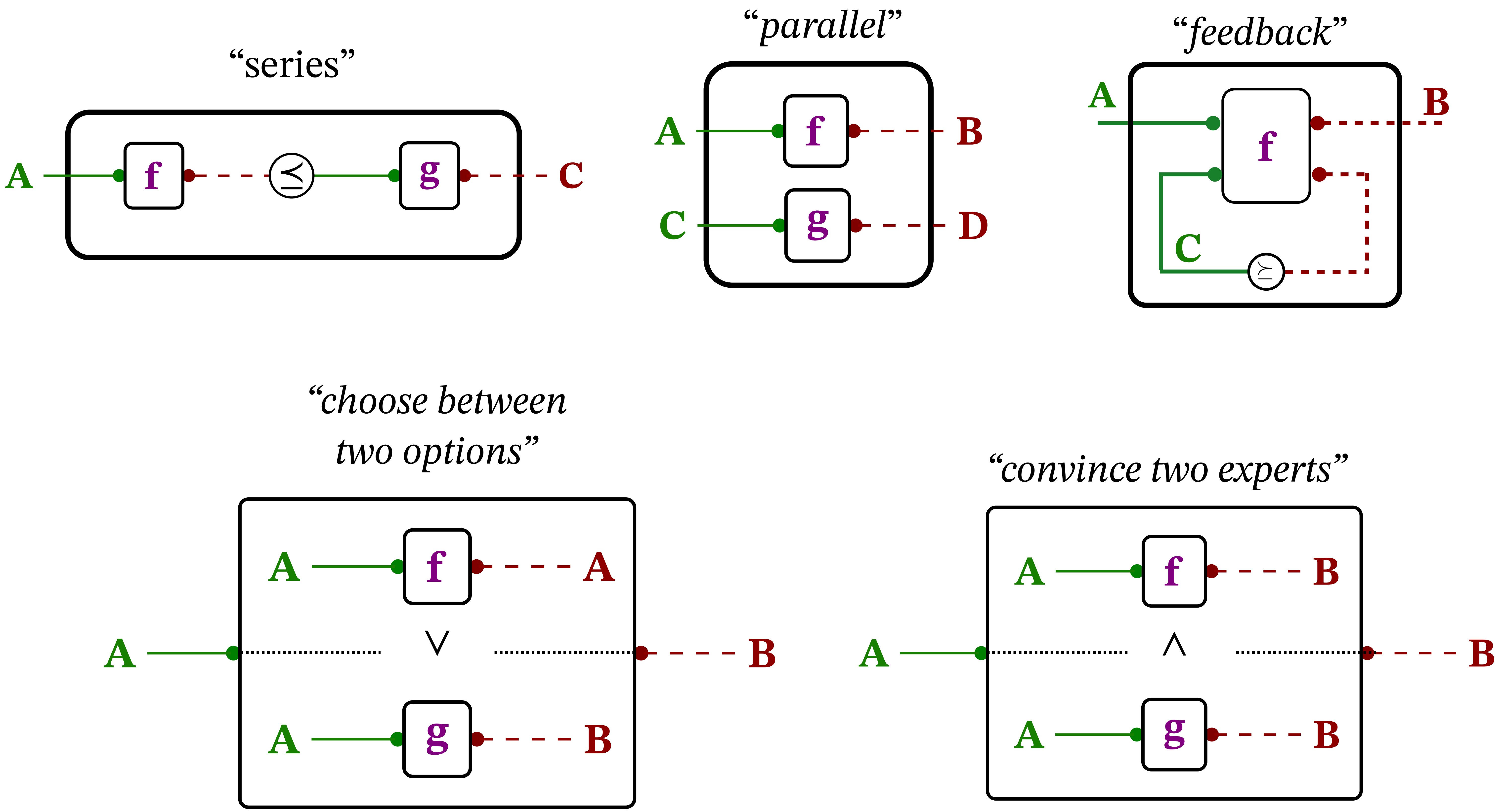
- “**First-principles**”: analytical relations.

mission energy ≥ mission duration x *power consumption*

- “**Data-driven**”, “**on-demand**”
  - The optimization will only ask for a **sequence** of data points. The model is constructed **incrementally**.
  - Opens the door to **experiments**, black-box **simulations**, solutions of **optimization problems**.

Design problems can be composed in various ways, preserving properties



- The **composition** of any two **DPs** returns a **DP** (closure)
- Very practical tool to **decompose** large **problems** into **subproblems**

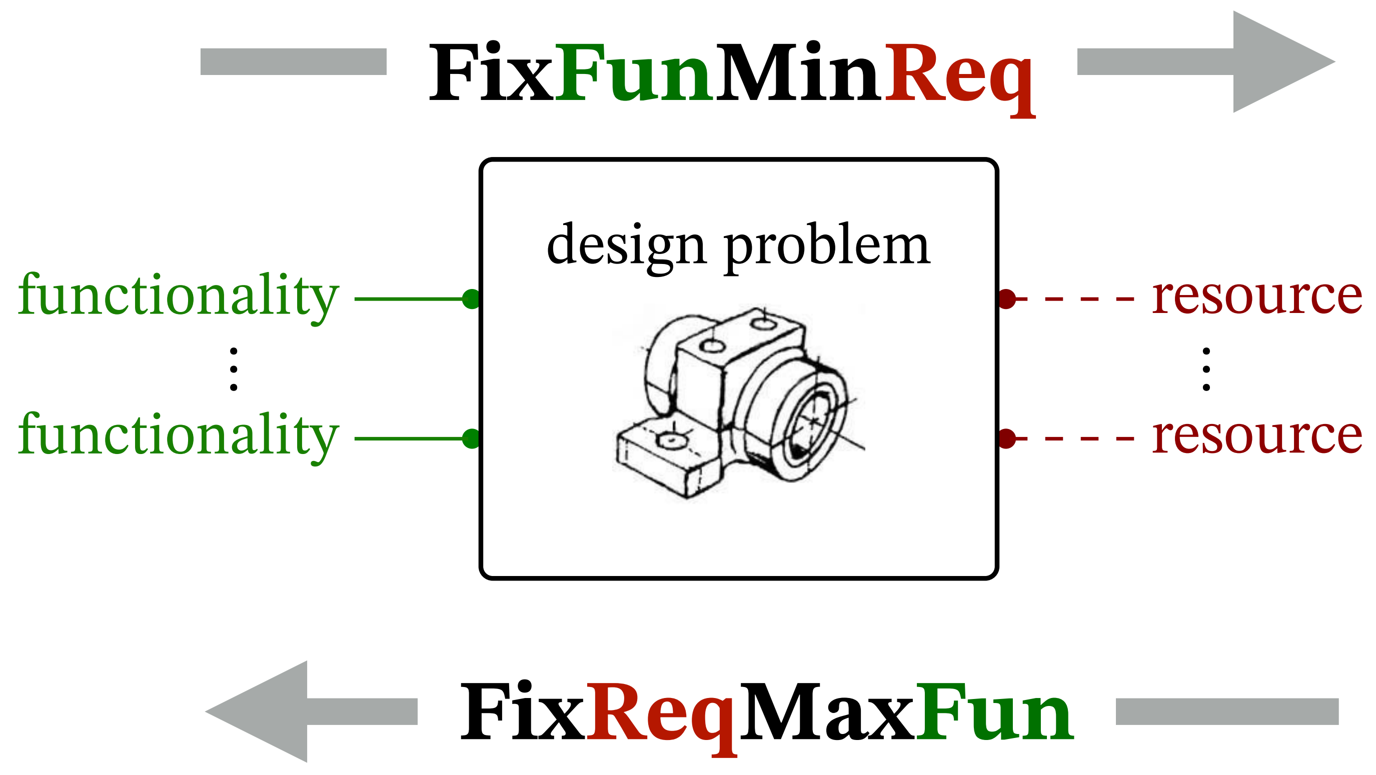
*There is a category **DP** which is traced monoidal, and locally posetal*

✔ ***Formal Compositional/hierarchical***

Multiple queries from the same design problem

- Two basic design queries are:

Given the functionality to be provided,
what are the **minimal resources** required?



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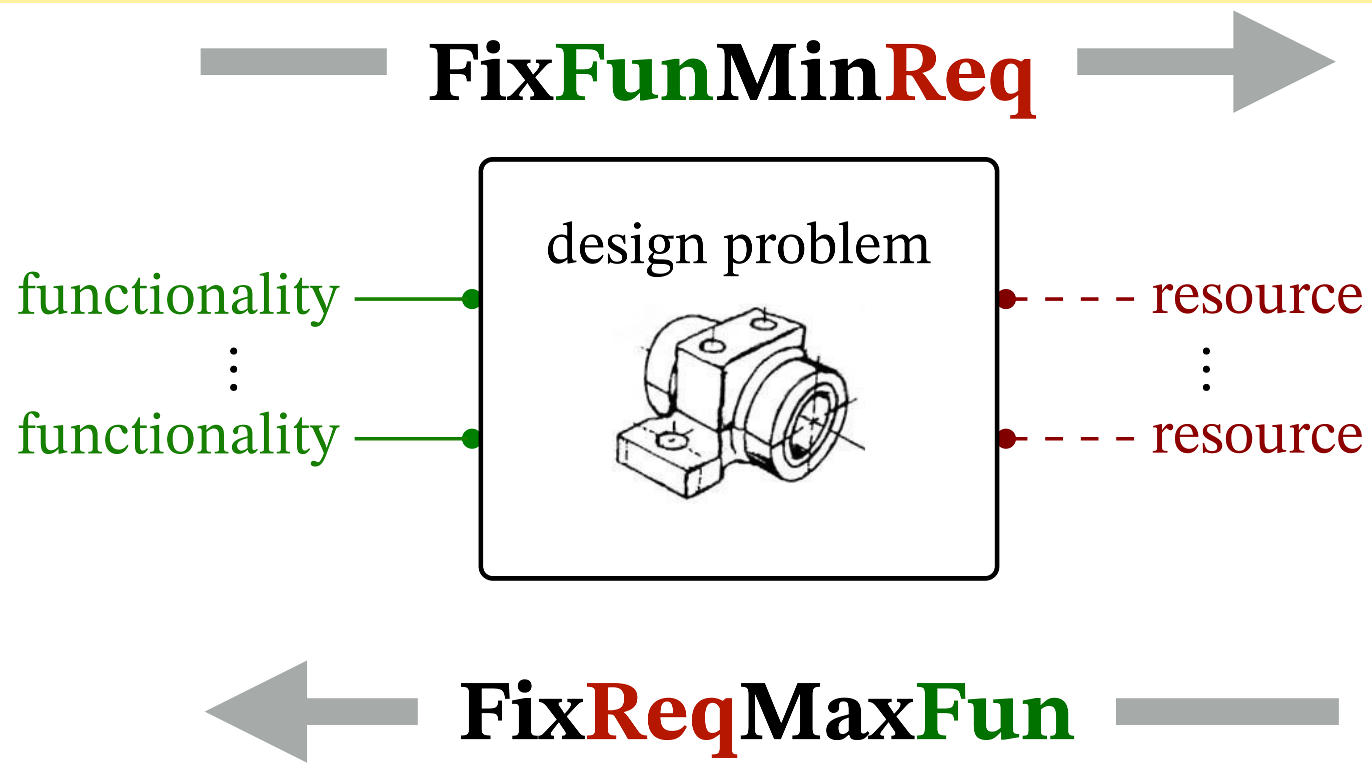

Given the resources that are available, what is the **maximal functionality** that can be provided?

- The two problems are **dual**

Multiple queries from the same design problem

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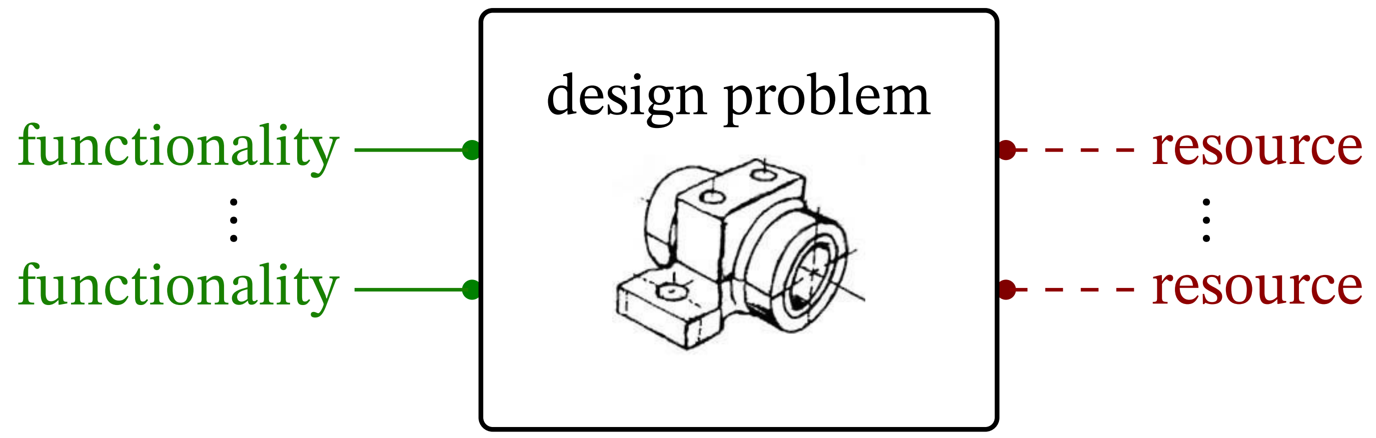
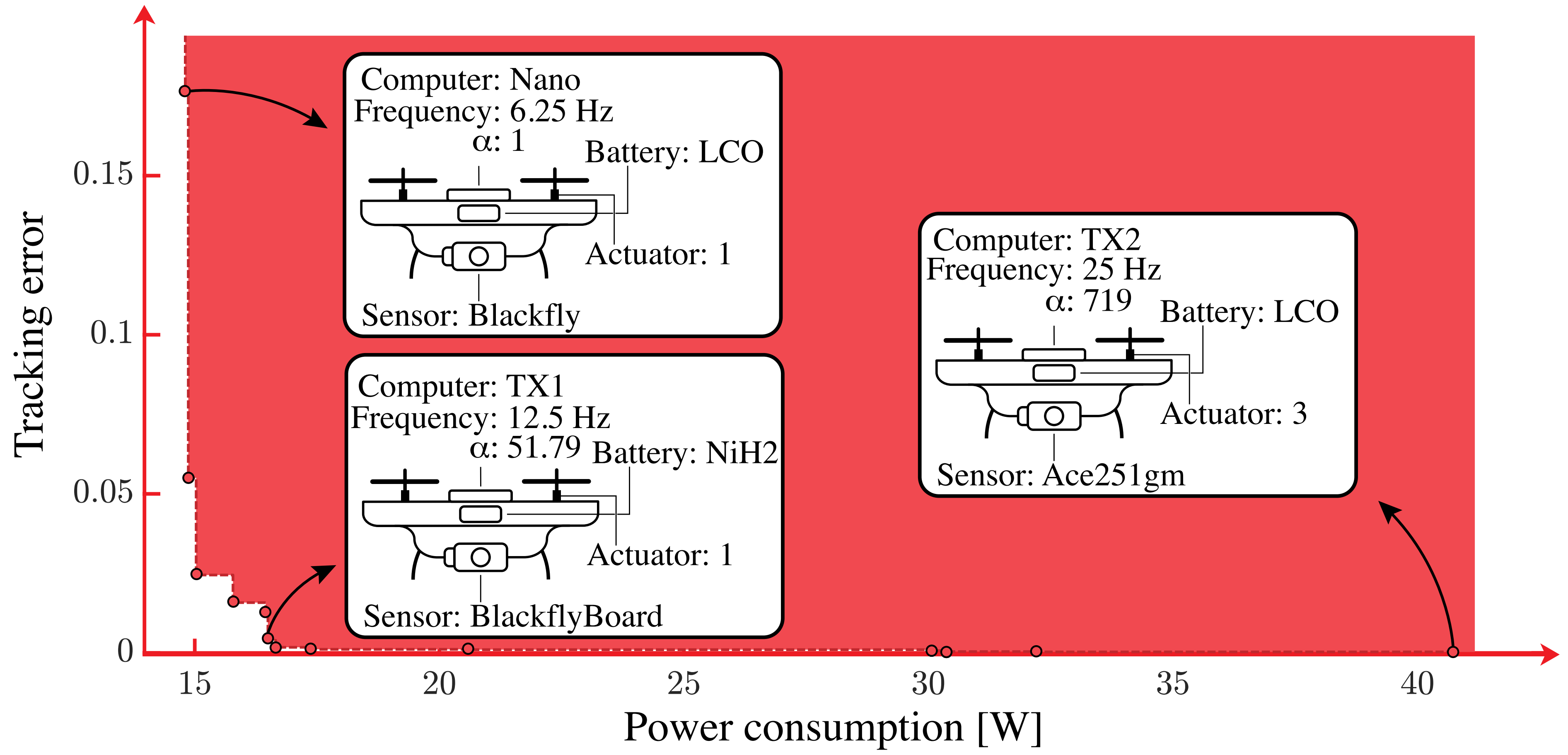
FixFunMinReq →



← **FixReqMaxFun**

Given the resources that are available, what is the **maximal functionality** that can be provided?

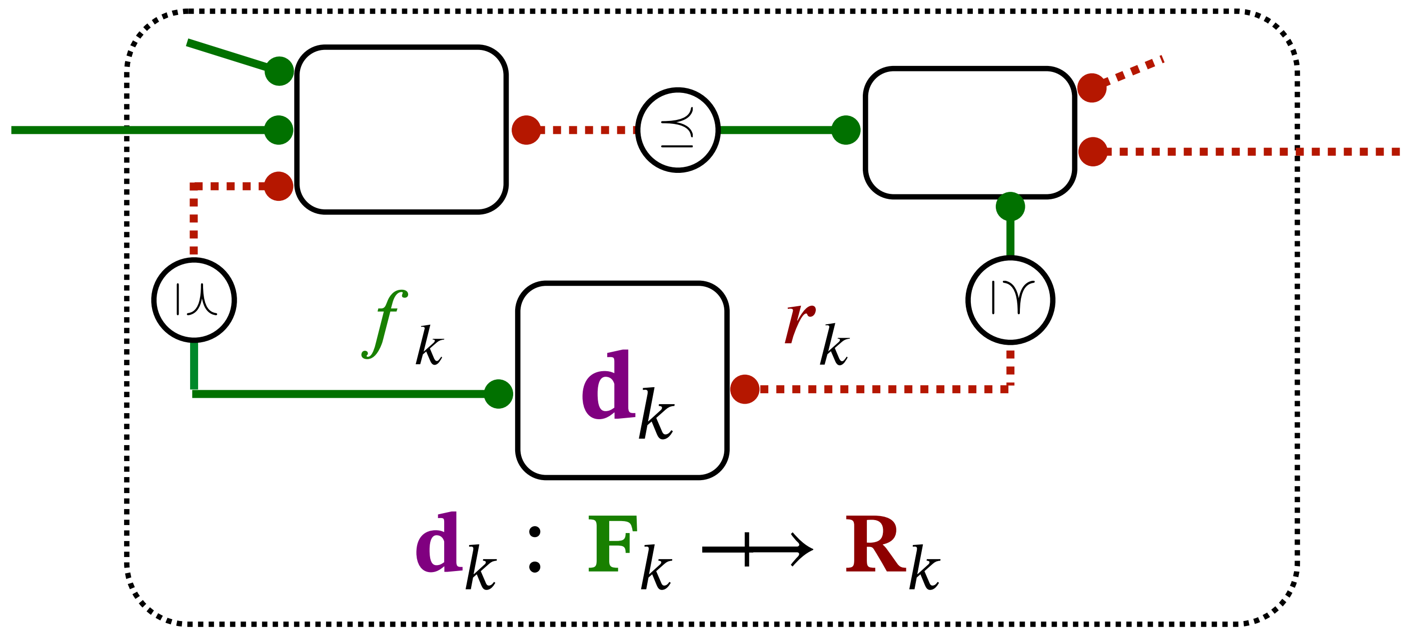
- We are looking for:
  - A map from functionality to **upper sets** of feasible resources: $h : \mathbf{F} \to \mathcal{U}\mathbf{R}$
  - A map from functionality to **antichains** of minimal resources: $h : \mathbf{F} \to \mathcal{A}\mathbf{R}$



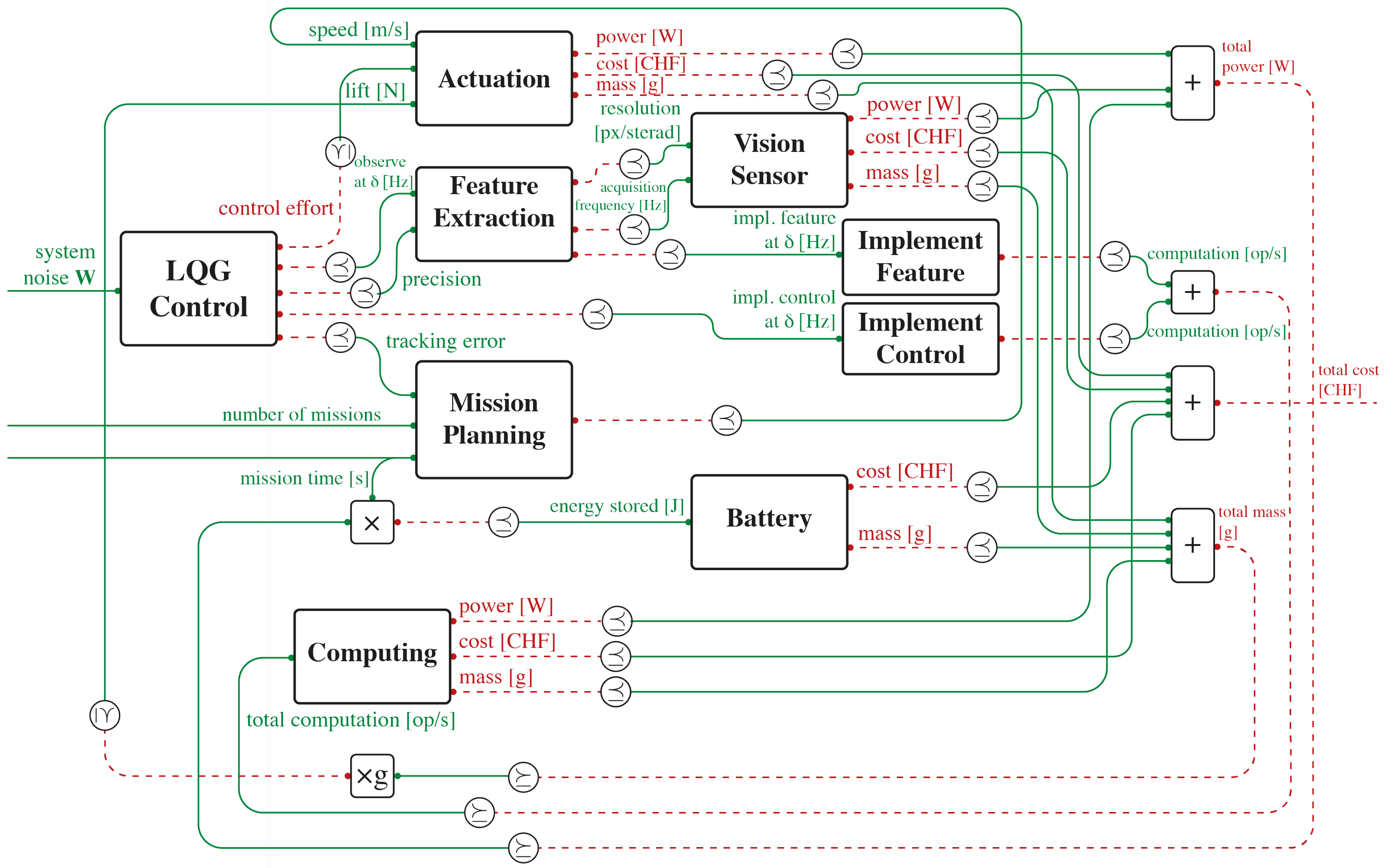
Optimization semantics

- This is the semantics of **FixFunMinReq** as a **family of optimization problems.**

chosen by user $\bar{f}$

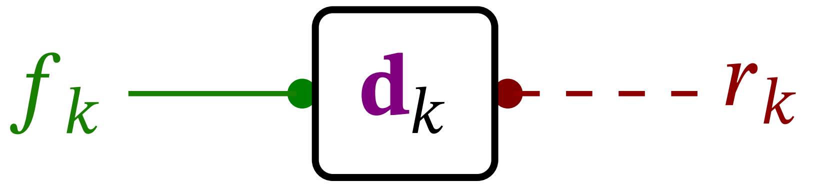


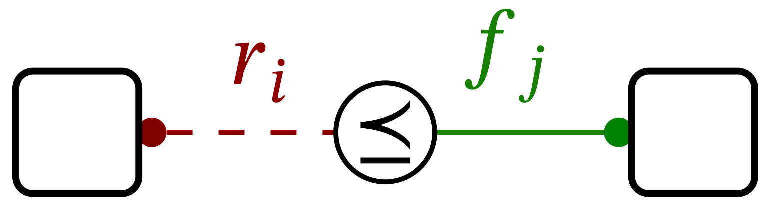
$\bar{r}$ **to minimize**



variables $f_k \in \langle \mathbf{F}_k, \preceq_{\mathbf{F}_k} \rangle$ $r_k \in \langle \mathbf{R}_k, \preceq_{\mathbf{R}_k} \rangle$

constraints *for each node:* *for each edge:*





$\mathbf{d}_k(f_k^*, r_k) = \top$

component feasibility

$r_i \preceq f_j$

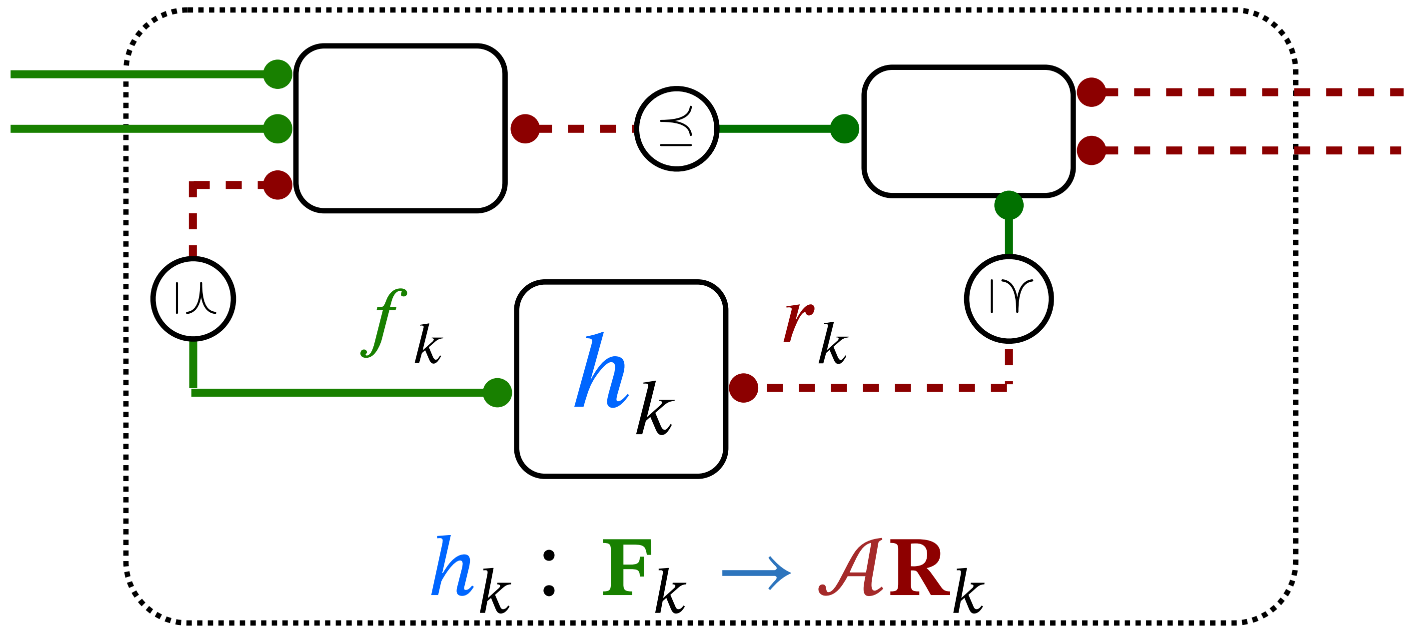
co-design constraint

objective $\operatorname{Min}_{\preceq} \bar{r}$

! **not convex**
! **not differentiable**
! **not continuous**
! **not even defined on continuous spaces**

Compositional solution of design problem queries

- Suppose that we are given the map $h_k : \mathbf{F}_k \to \mathcal{A}\mathbf{R}_k$ for all nodes in the co-design graph



- Can we find the map $h : \mathbf{F} \to \mathcal{A}\mathbf{R}$ for the entire graph?

Computationally tractable

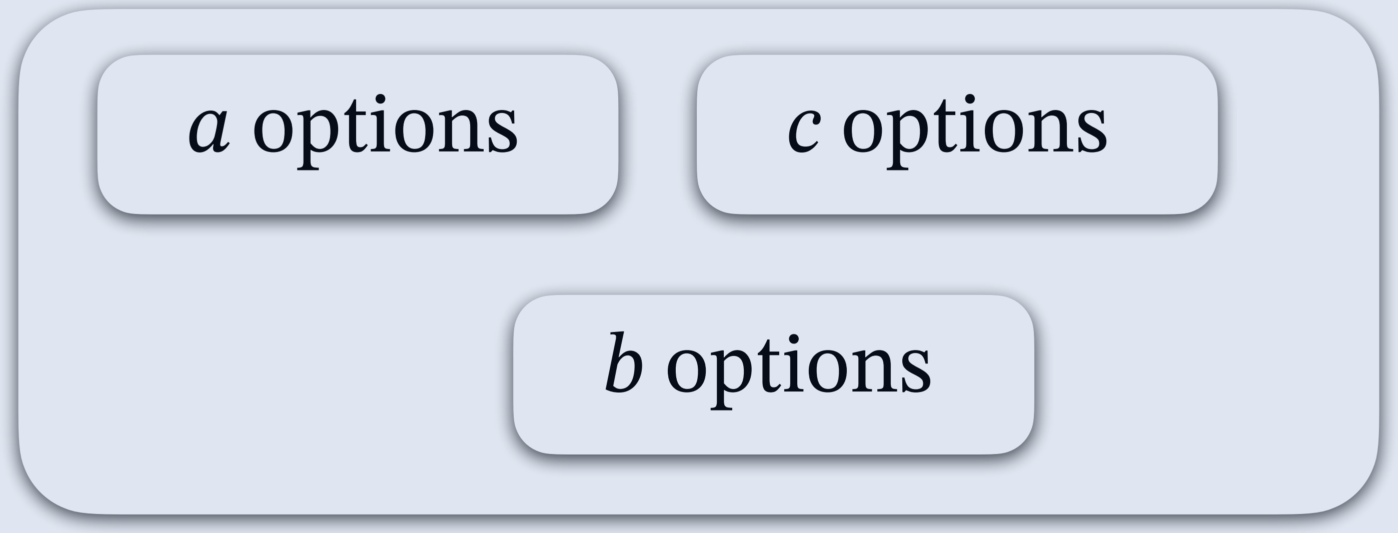
- **Compositional approach**: just need to work out the composition formulas for all operations

solution(**composition**(a, b)) = **composition**(**solution**(a), **solution**(b))

... a functor between a category of problems and one of solutions

- The set of **minimal** feasible resources can be obtained as the **least fixed point** of a monotone function in the space of anti-chain

- We have a **complete solution**: guaranteed to find the set of **all** optimal solutions (if empty, **certificate of infeasibility**)

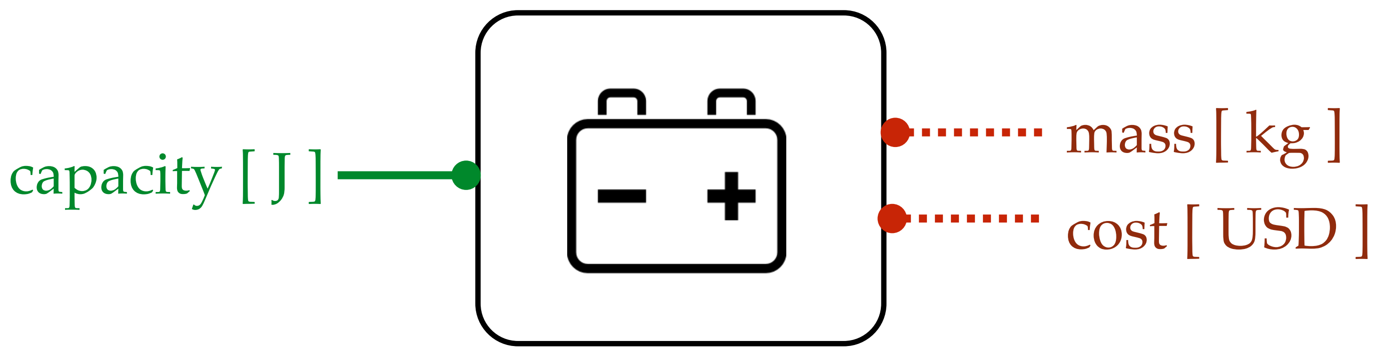


- The complexity is **not combinatorial in the number of options** for each component
- The complexity depends on the **complexity of the interactions**: the co-design **constraints**

$O(a + b + c)$

User-friendly interfaces

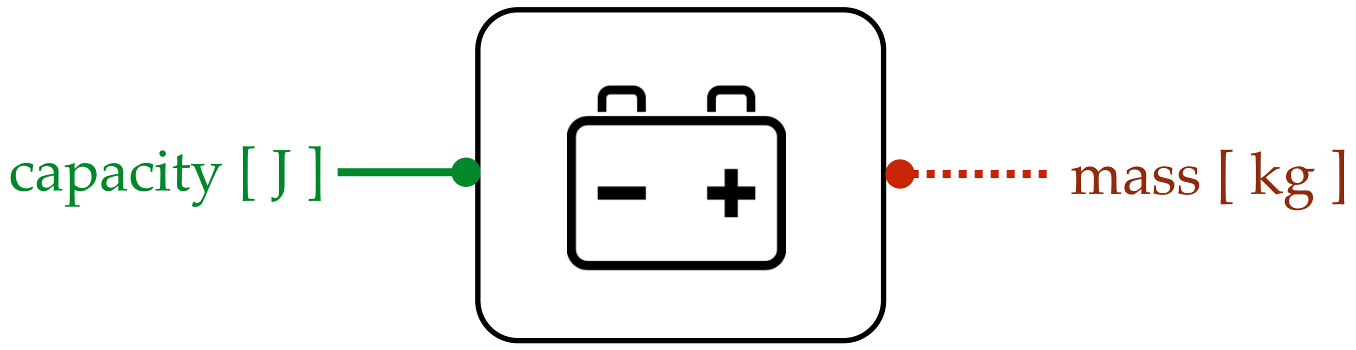
- “**Catalogues**”: already available designs




```
catalogue {
    provides capacity [J]
    requires mass [g]
    requires cost [USD]

    500 kWh ⟻ model1 ⟼ 100 g, 10 USD
    600 kWh ⟻ model2 ⟼ 200 g, 200 USD
    600 kWh ⟻ model3 ⟼ 250 g, 150 USD
    700 kWh ⟻ model4 ⟼ 400 g, 400 USD
}
```

... and a solver

- “**First-principles**”: analytical relations.



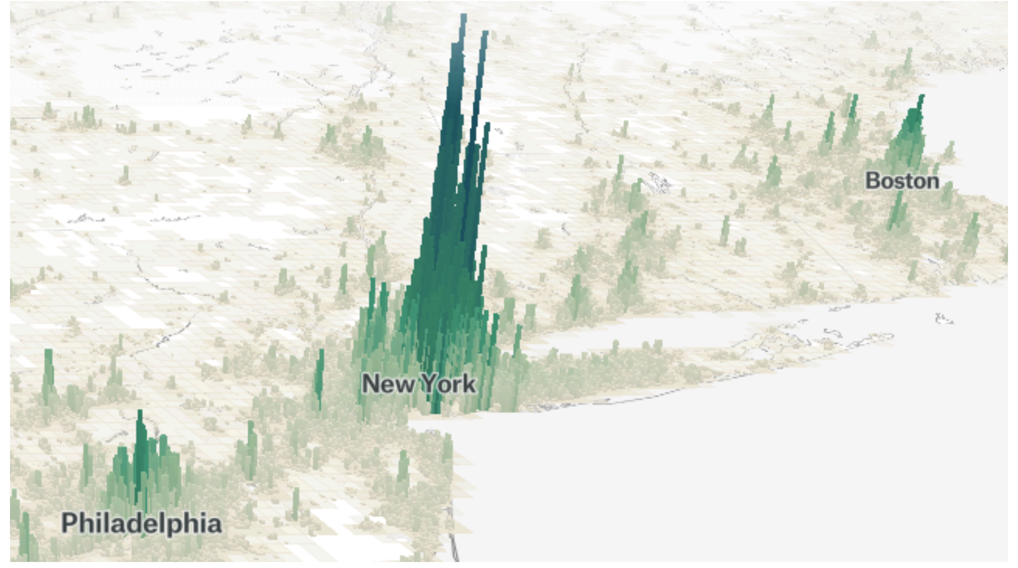

```
mcdp {
    provides capacity [J]
    requires mass [kg]

    specific_energy_Li_Ion = 500 Wh / kg

    required mass >= provided capacity / specific_energy_Li_Ion
}
```


```
mcdp {
    provides lift [N]
    requires power [W]
    c = 10.0 W/N²
    required power ≽ c · provided lift²
}
```

Co-design across scales: from autonomy to mobility systems

- Mobility systems are **under pressure**

Travel demand is changing
By 2050, 68% of population in cities



Need for **service design** and **regulations**
Over 1,000% ride-hailing increase in 2012-22

Need to meet **sustainability goals**
Cities cause 60% of GHGs, 30% from mobility

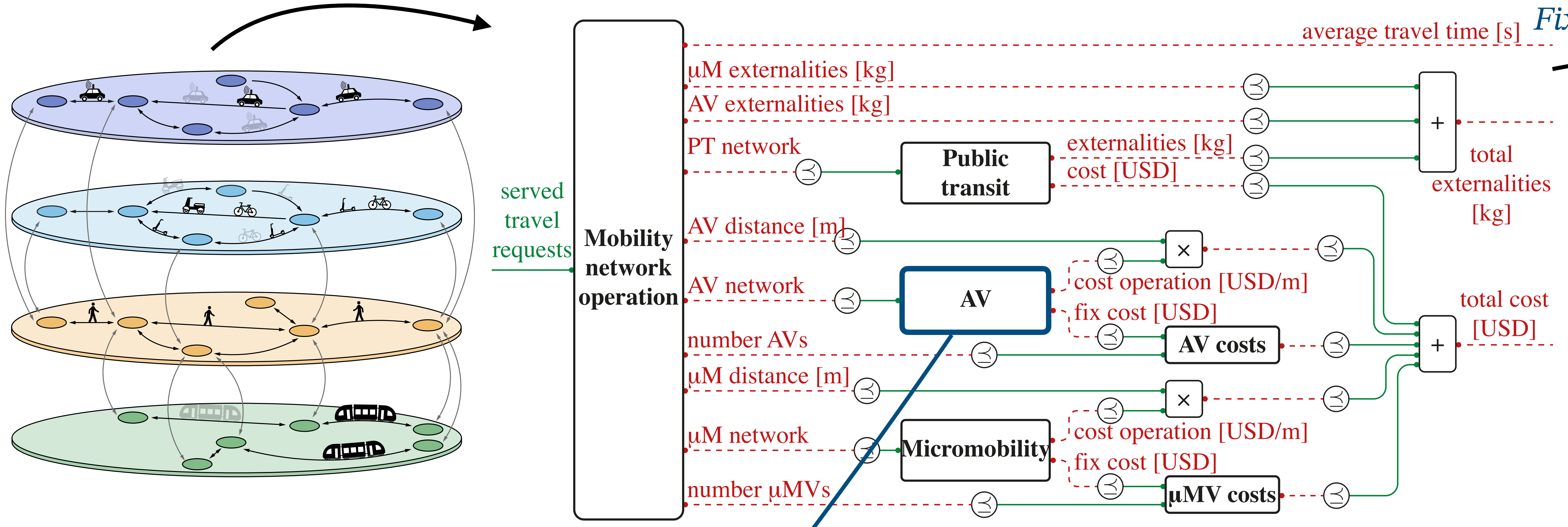
- We look at the problem from the perspective of **municipalities** and **policy makers**

How many vehicles should we allow?
Which infrastructure investments?
How performant?
Which services to encourage?

- Need for **demand-driven** co-design of **mobility solutions** and the **intermodal network** they enable

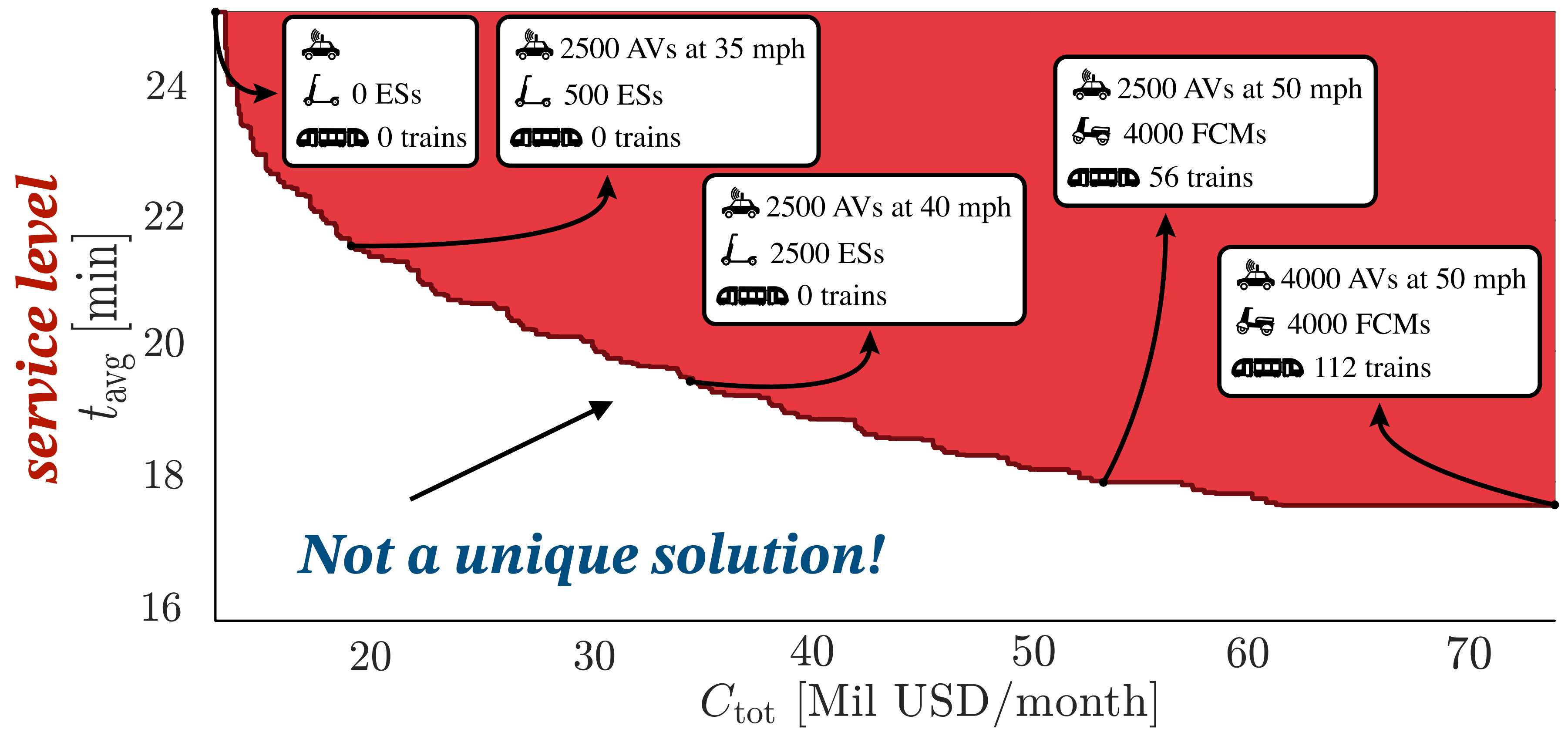
- Several **disciplines** involved (transportation science, autonomy, economics, policy-making)

Co-design to enable user-friendly tools to assess the impact of future mobility solutions



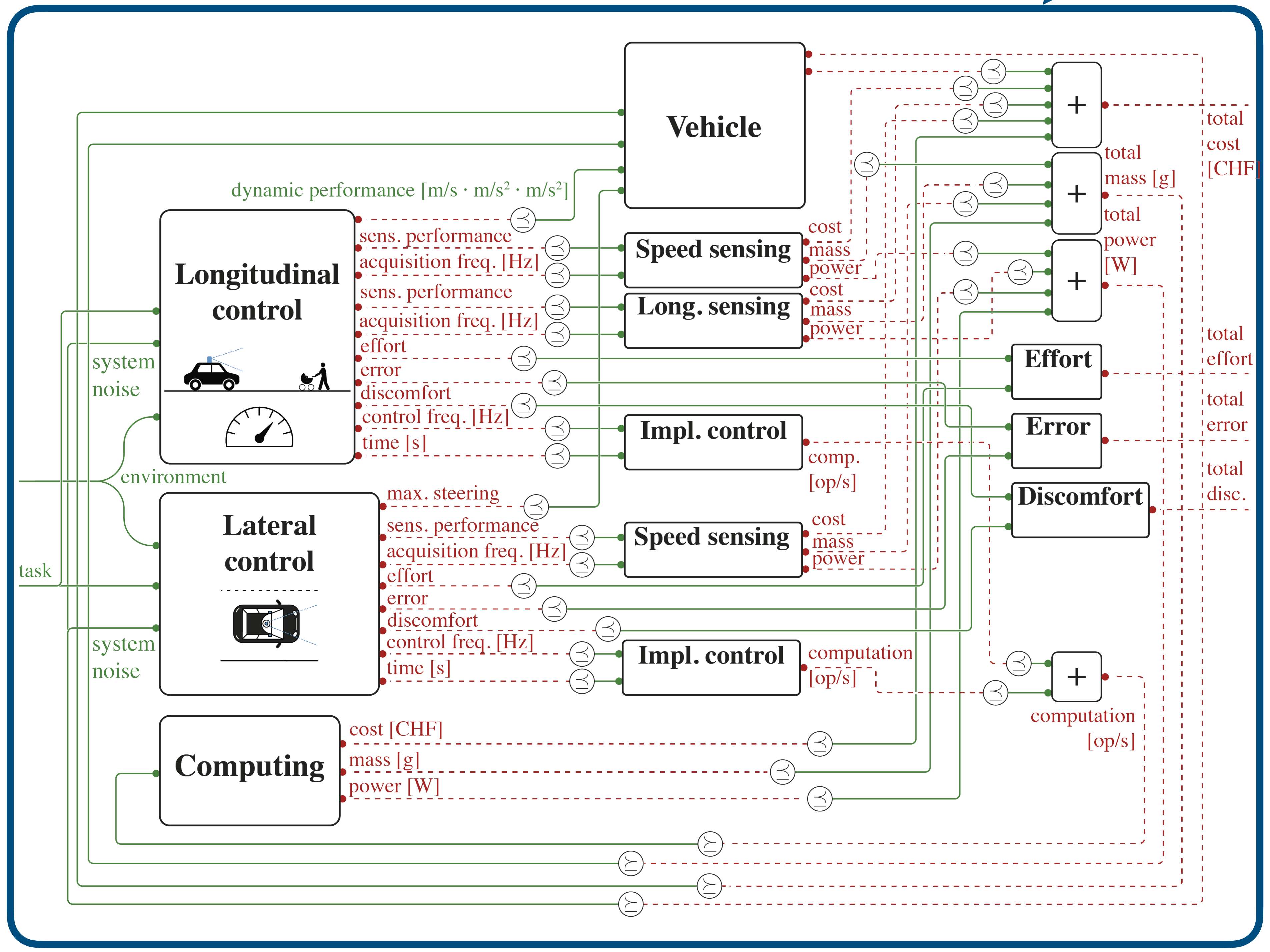
Fix demand, minimize costs

Washington D.C. in 2030

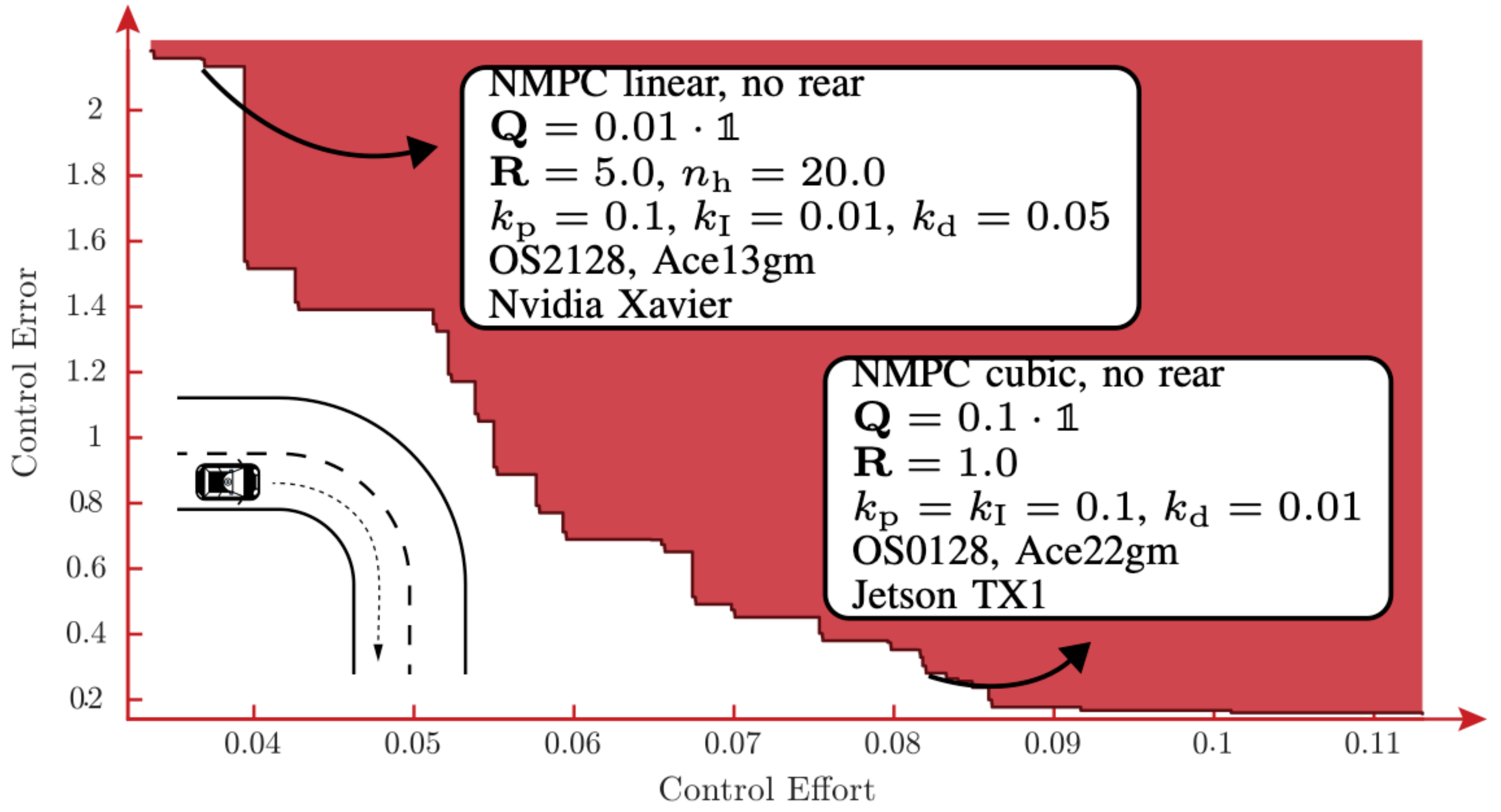


investments

compositionality (vertical composition)



Fix environment, task



Details about software and hardware implementations, in a way that was not possible before

Continuous
Collaborative
Intellectually tractable

[TNSE'22, CDC'22, IROS'21, ECC'21, ITSC'20]

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  - *Game theory to deal with strategic interactions*
  - *Hierarchical interactions in mobility systems*
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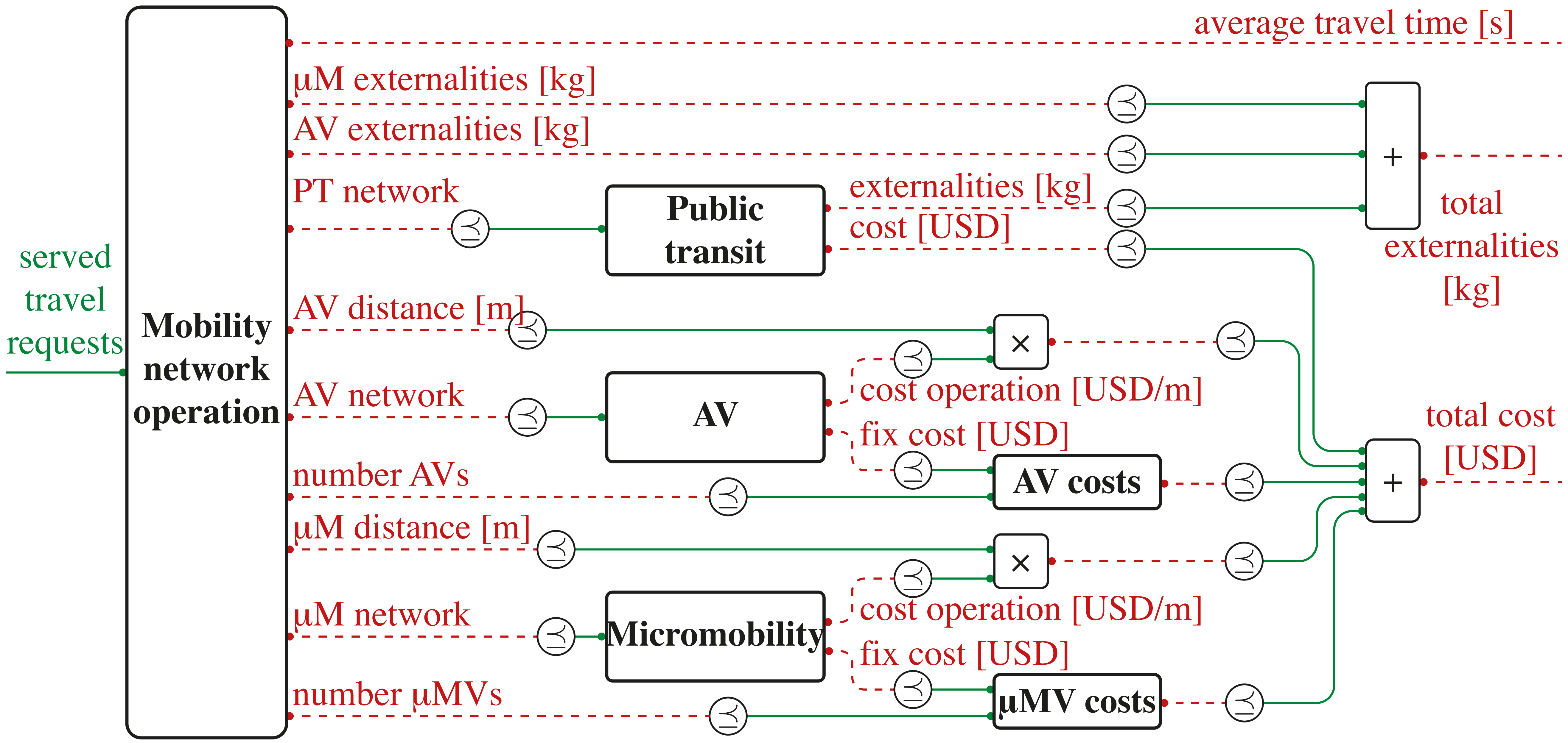
Complexity when designing complex systems

Large systems
- Many components
- Heterogeneous natures
- Multiple objectives

Strategic interactions
- Many agents
- Heterogeneous interactions
- Conflicts/collaborations

Explicitly accounting for strategic interactions: towards co-design games



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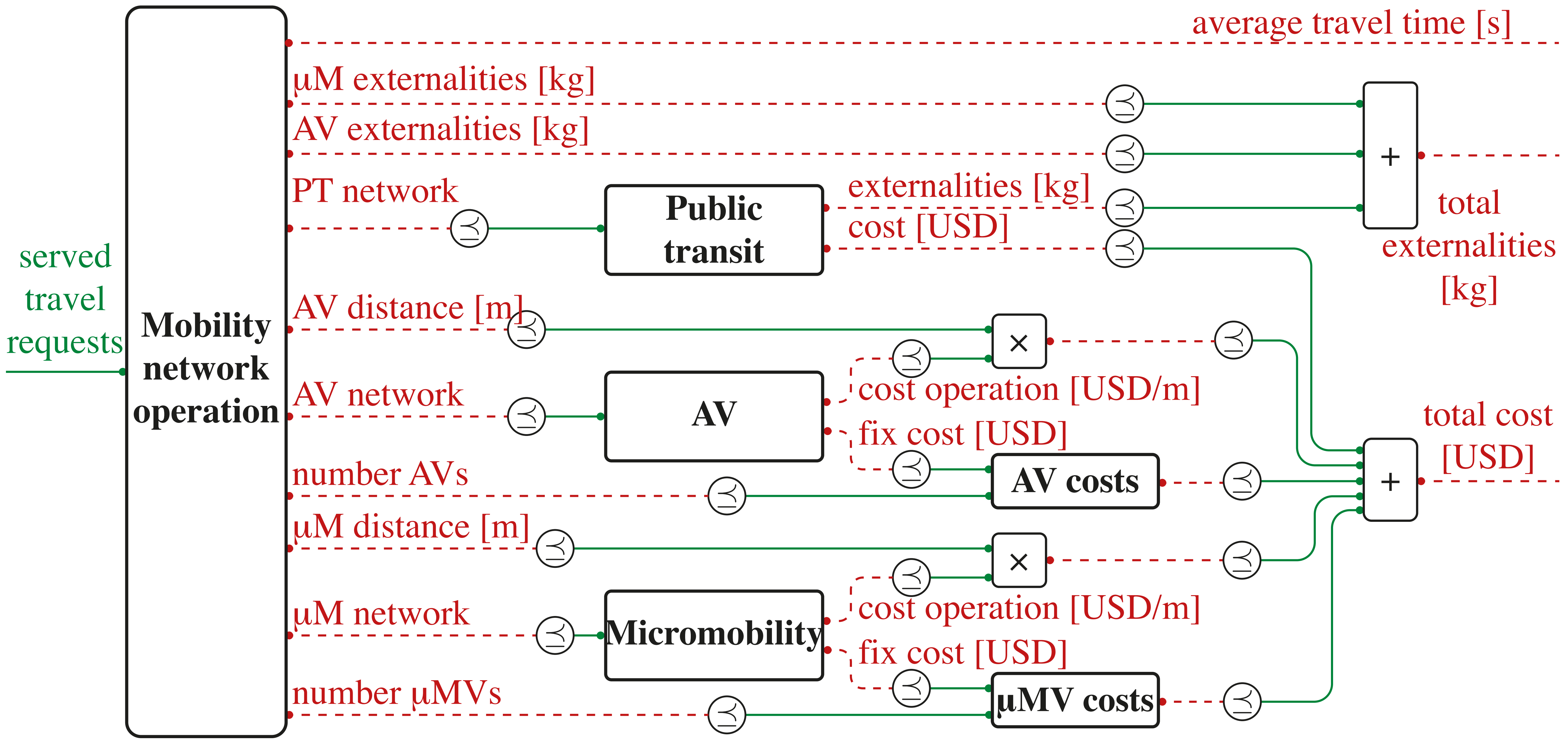

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- Game theory: Multi-agent **strategic** decision making
  Allows one to **model interactions**
- The notion of **optimal designs** extends to **equilibria of designs**
- Towards a theory of **co-design games**

- Two **milestones** towards **co-design games**:

Co-design features **rich cost structures** (posets):

- **"Posetal Games"** (games with posetal preferences)

[RA-L' 22]

Interactions are naturally **hierarchical**:

- **Mobility games** via Stackelberg

[ITSC'21 (***Best Paper Award***), ITSC'23]

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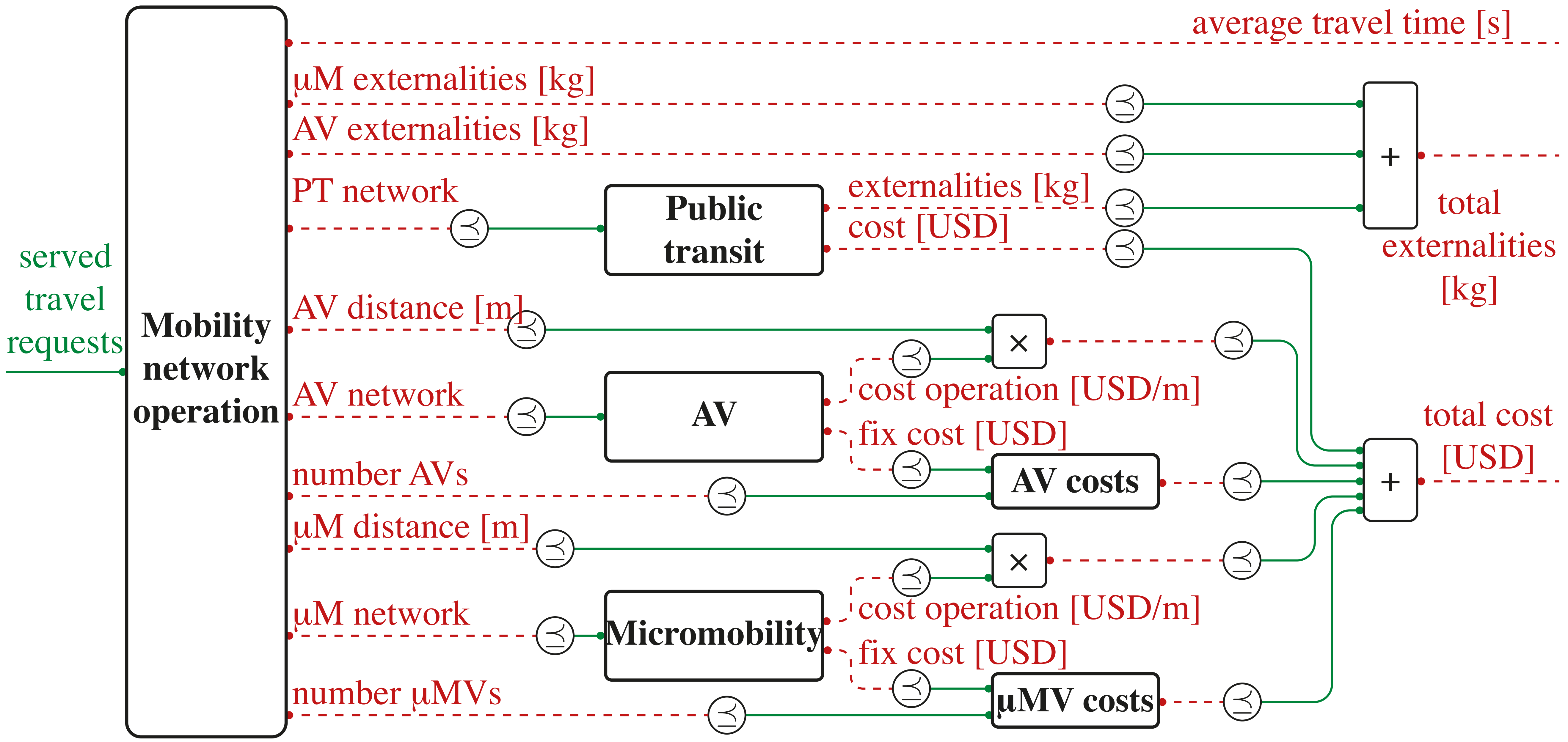

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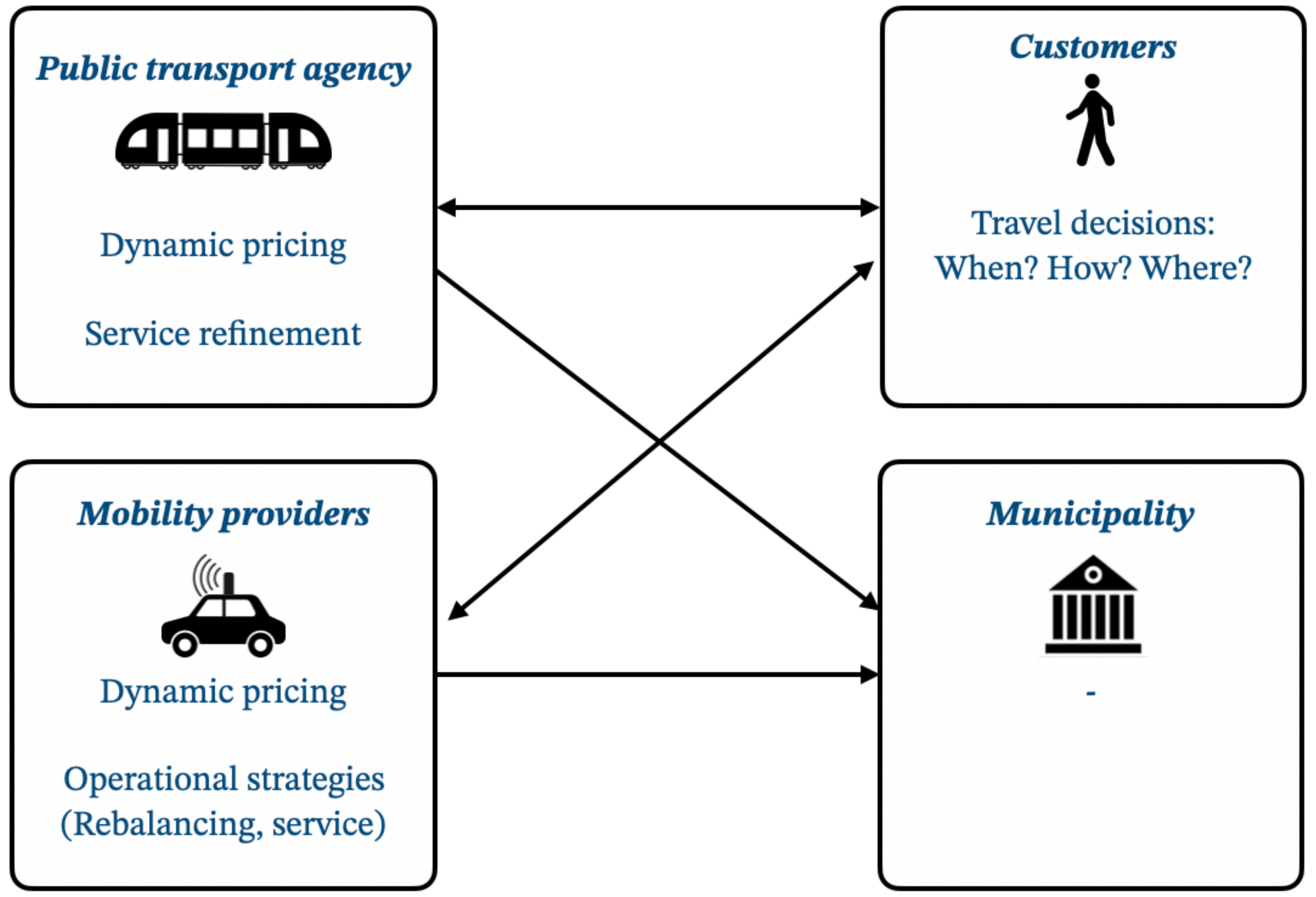
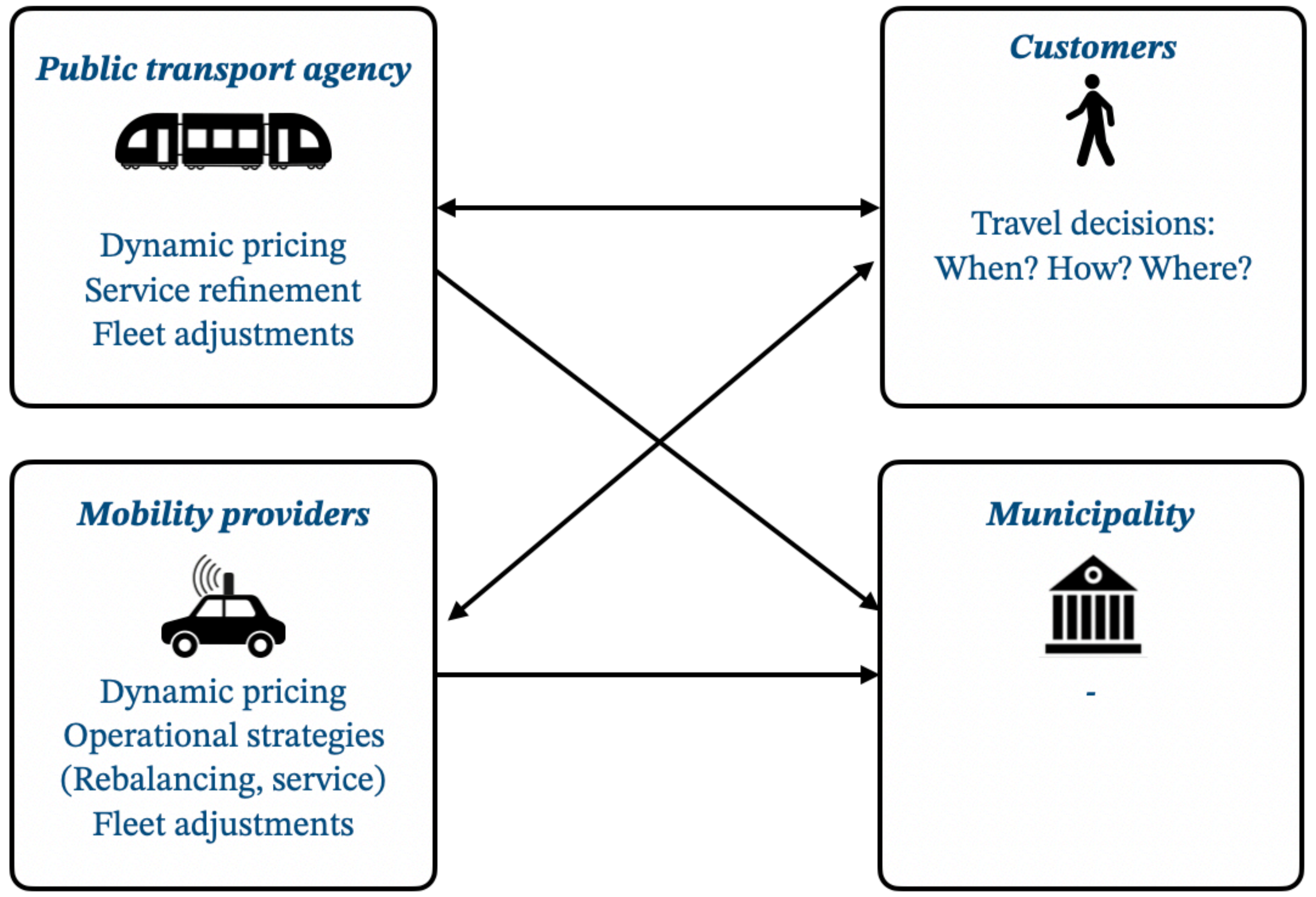
[ITSC'21 (***Best Paper Award***), ITSC'23]

Interactions between stakeholders are characterized by different time horizons

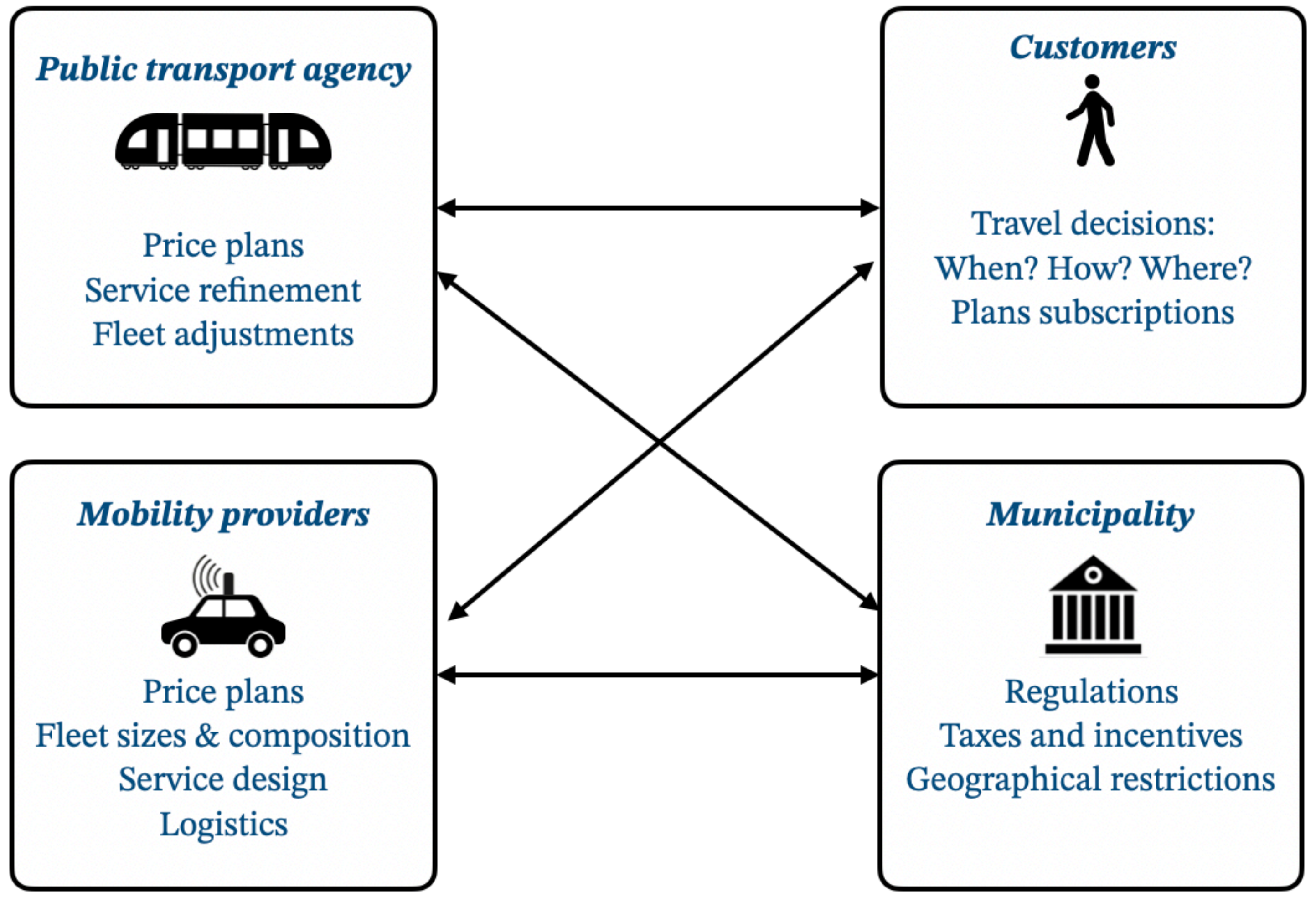
Daily



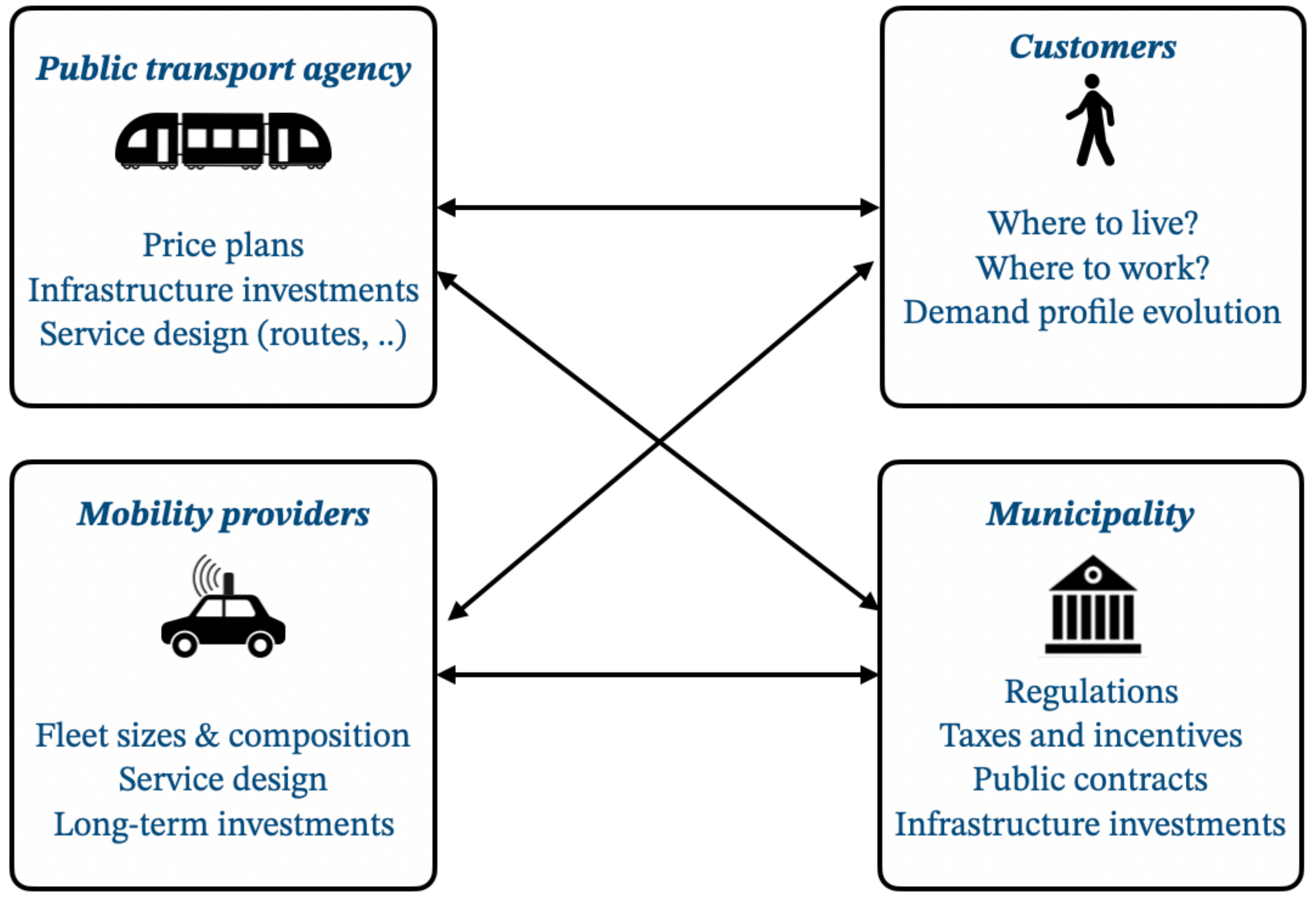
Monthly



Yearly

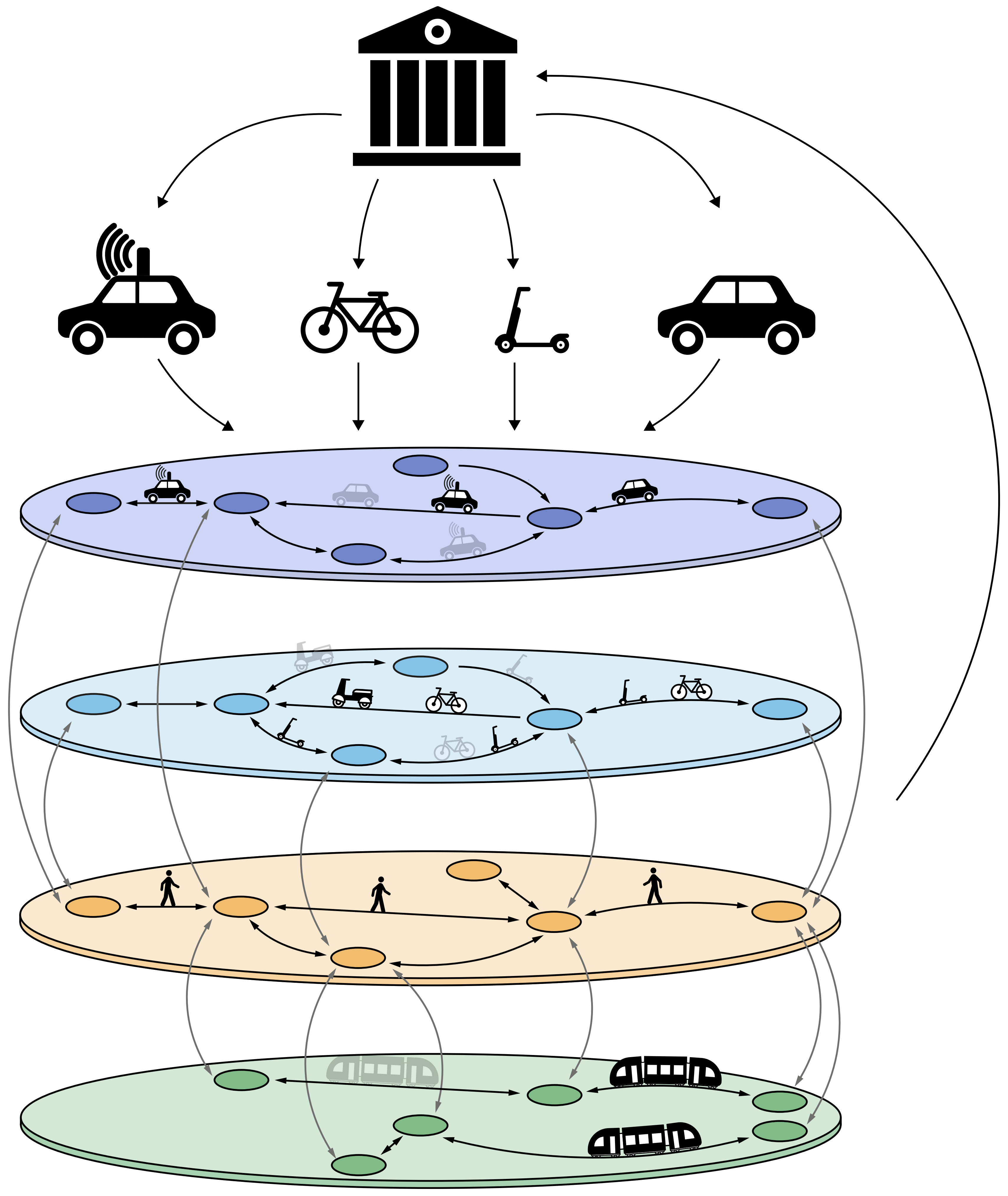


Every five years



Hierarchical nature of interactions can be modeled via Stackelberg games

- We model **sequential** interactions as a **game**:
  - **Municipality** plays **first** (choosing public transport **prices**, **taxes**)
  - The **mobility providers** interact **simultaneously** after the municipality (choosing **prices**, **fleet sizes**)
  - Customers **react** accordingly (choosing their **trip**)



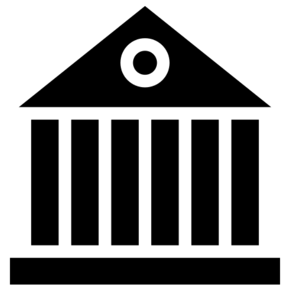
- For instance:
  - **Municipalities** want to **minimize** *emissions,* and **maximize** *social welfare*, *performance*
  - **Mobility providers** want to **maximize** *return on investment*
- The payoff depends on a **low-level model** of the mobility system (e.g., a **simulator**, an **optimization problem**)
- We can compute equilibria via **backward induction**

[ITSC'21 (**Best Paper Award**), ITSC'23]

Considering strategic interactions for the city of Berlin, Germany

- We consider the city of **Berlin**, including:

Municipality

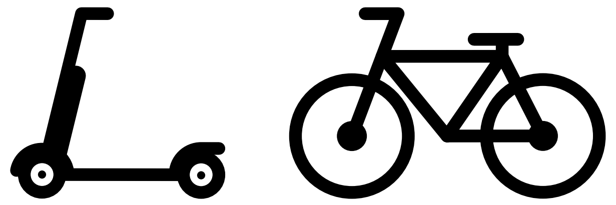


***Actions*:**
- *Short-distance PT price*
- *Long-distance PT price*
- *Cutoff distance*
- *Distance-based tax for AVs*
- *Distance-based tax for empty AVs*

AMoD operator

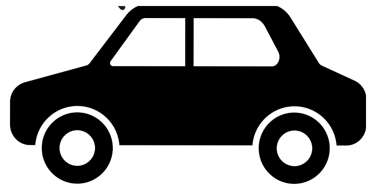
***Actions*:**
- *Propulsion*
- *Automation level*
- *Fleet size*

Micro-mobility operator



***Actions*:**
- *Base price*
- *Mileage-dependent price*
- *Vehicle type*

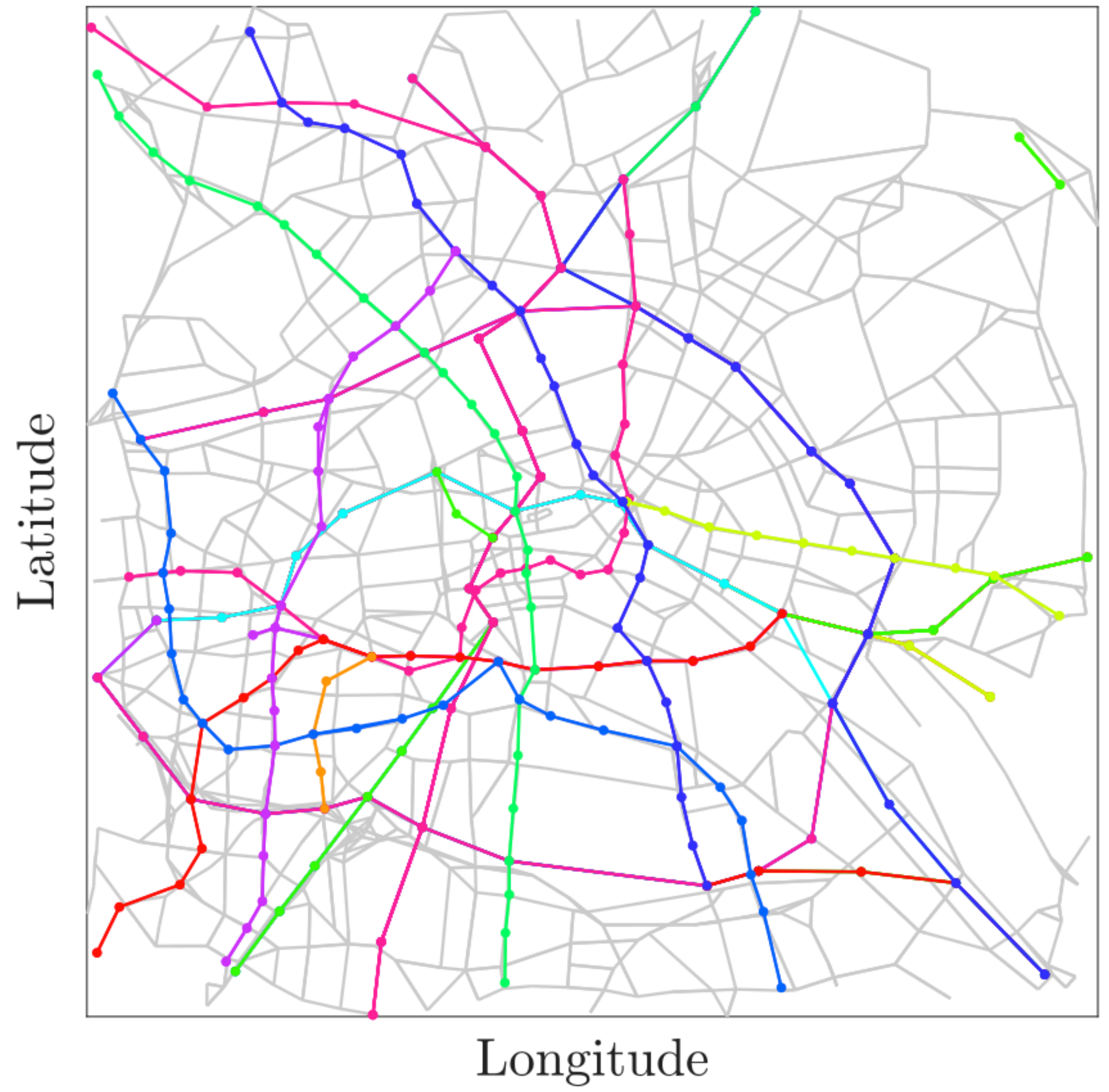
Taxi company



***Actions*:**
- *Base price*
- *Mileage-dependent price*

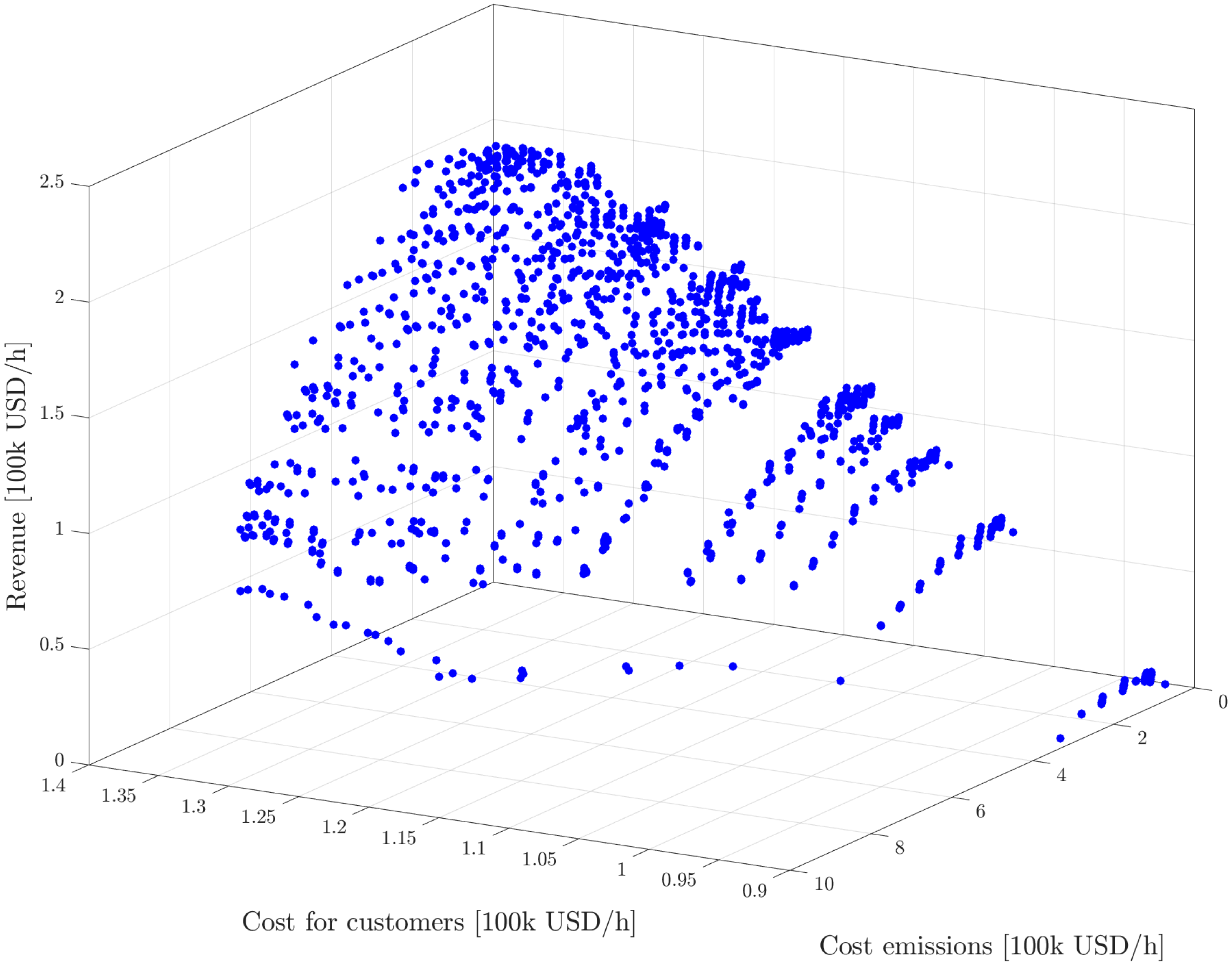
- Customers choose options by **minimizing** their **cost** (including **fare** and **value of time**)
- We consider 129,560 **real travel requests** and account for **congestion effects**
- We derive **vehicle-related parameters** and **costs** from **catalogues** and **official reports**

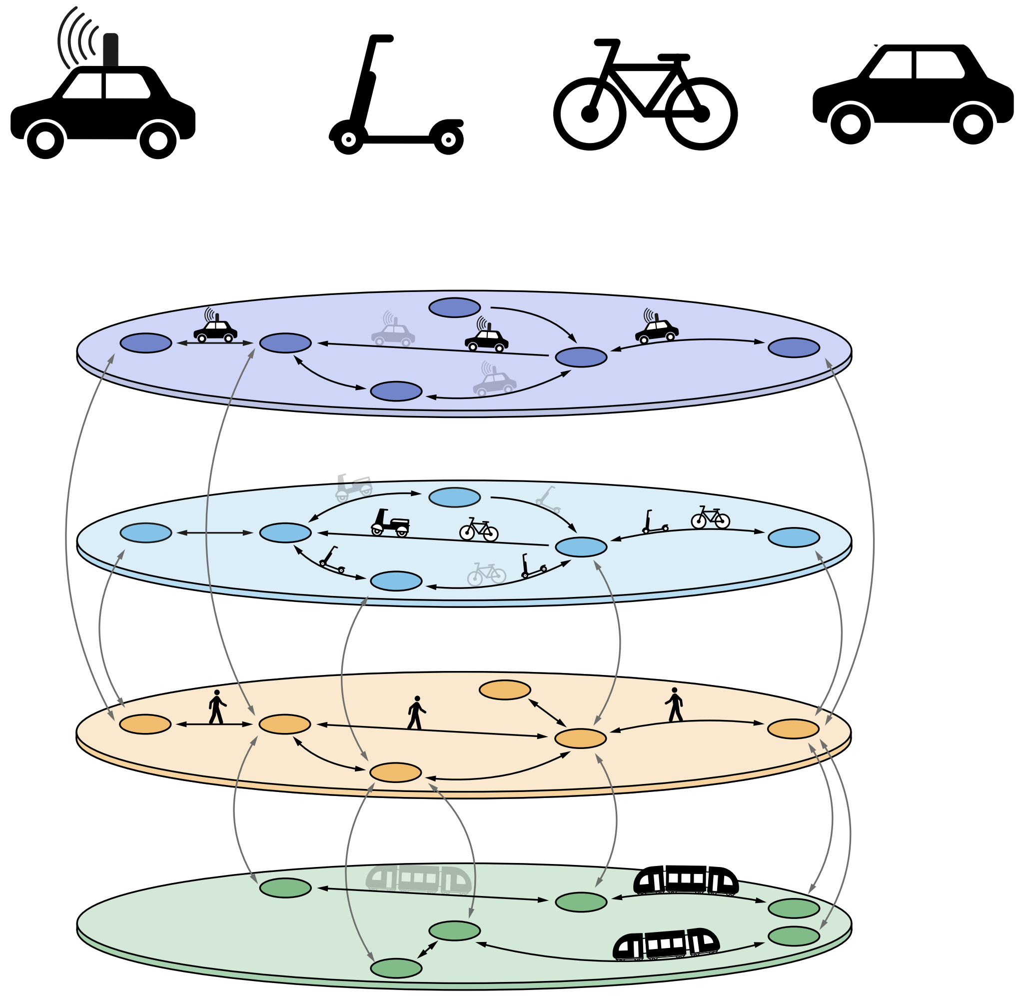
Intermodal network in Berlin



Looking for equilibria of the simultaneous game between MSPs

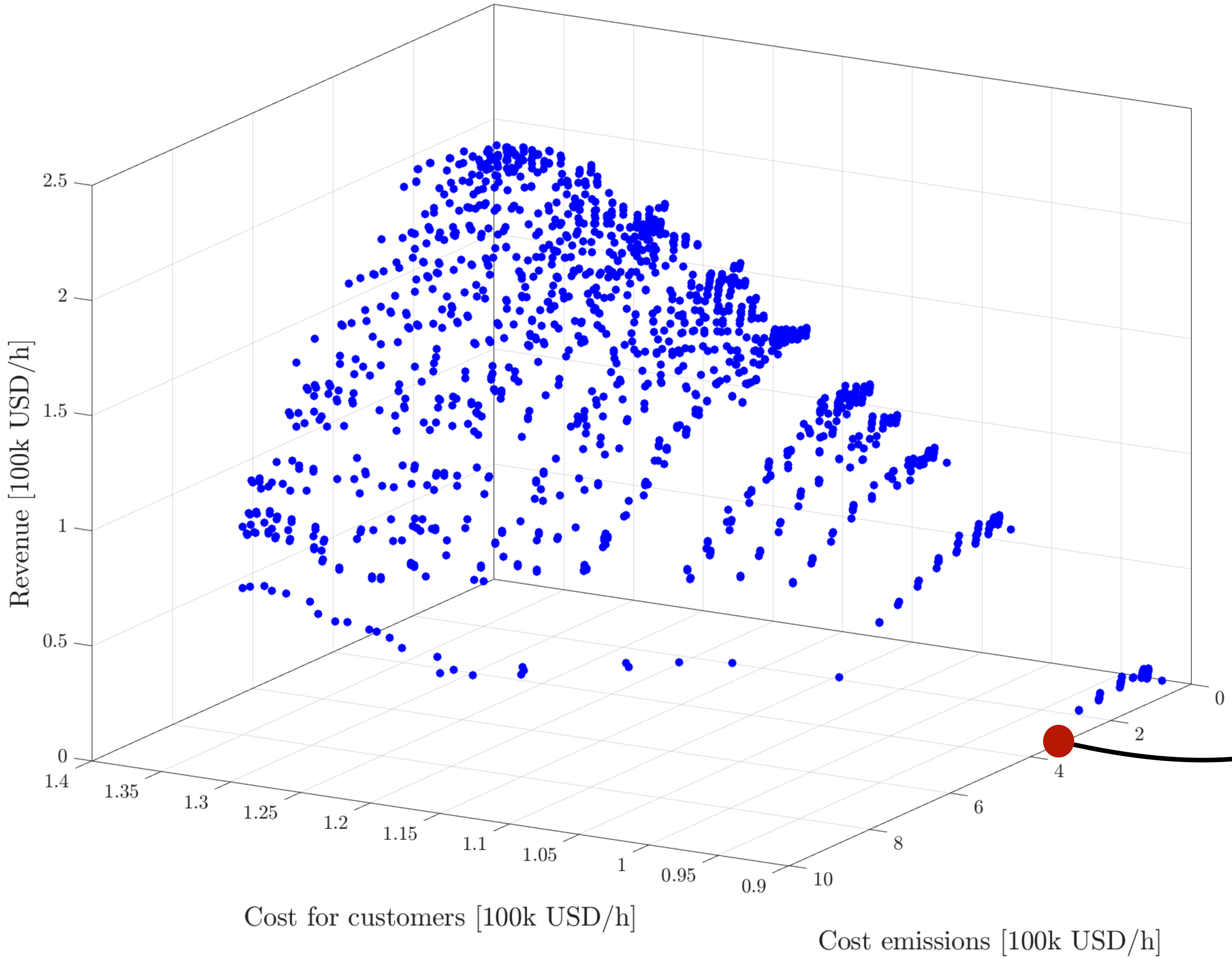
- First, we compute **equilibria** of the **simultaneous** game between mobility providers:





Looking for equilibria of the sequential game

- We then compute the **equilibria** of the **sequential game**
- The **objective** of the **municipality** is pure *political* matter. For each choice, we produce **actionable information:**



Customers-oriented City

AMoD:
5,000 AVs, ICEV
Micromobility:
E-scooters, with fares:
- Base: 1.20 USD
- Variable 1.21 USD/mile

Municipality:
Public transit fares:
- SDP: 0 USD
- LDP: 0 USD

Taxes:
- 0 USD/mile both on full and empty vehicles

Looking for equilibria of the sequential game

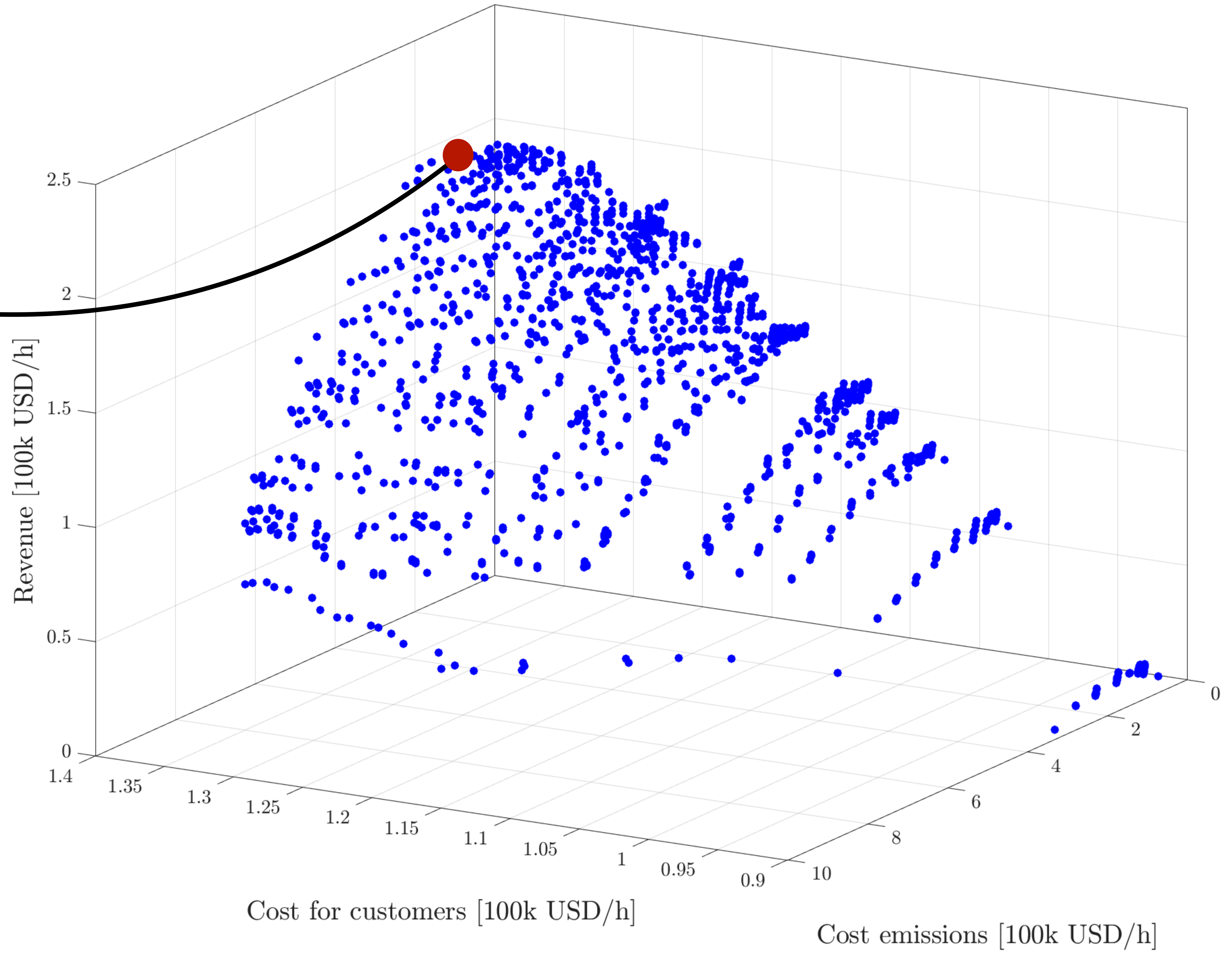
- We then compute the **equilibria** of the **sequential game**
- The **objective** of the **municipality** is pure *political* matter. For each choice, we produce **actionable information:**

Revenue-oriented City

AMoD:
5,000 AVs, ICEV
Micromobility:
E-scooters, with fares:
- Base: 1.20 USD
- Variable 0.96 USD/mile

Municipality:
Public transit fares:
- SDP: 3 USD
- LDP: 5 USD
- Cutoff: 1.55 miles

Taxes:
- 1.28 USD/mile both on full and empty vehicles



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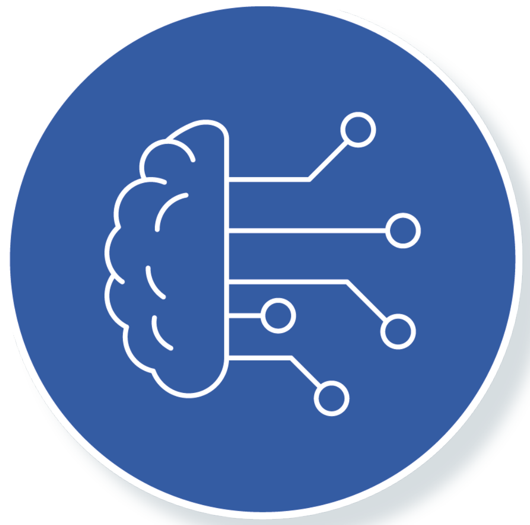

Modeling & Algorithmic Foundations

Societal Applications

User-friendly Tools

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My lab will be building the next generation tools for systems design optimization

Modeling and Algorithmic Foundations

Leveraging **optimization**, **control theory, game theory, domain theory**, and **applied category theory**:

- Extend and improve current **modeling** & **solution algorithms** for **multi-objective** design optimization
- Promote **interdisciplinarity** by bridging the gap between **standard optimization** and **co-design**
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Societal Applications

Mobility, networks, infrastructure
Strategic interactions at all levels

Mission-driven autonomy

Aerospace, automotive, production chains, energy and data networks

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User-friendly Tools

Collaborative, intellectually tractable

Authorities & Industry

Literature, workshops, classes

Take-aways

- A new approach to **co-design** designed to work **across fields** and **scales**.
- It is:
  - **Compositional** horizontally and hierarchically.
  - Supports both **data-driven** and **model-based** components.
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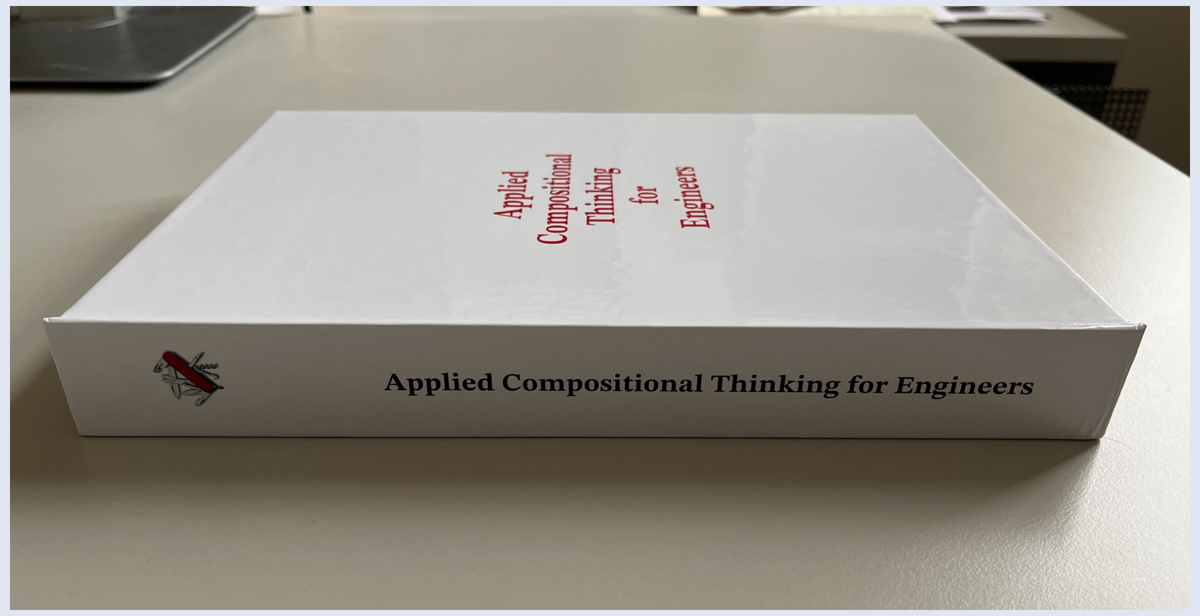
  - **Intellectually tractable.**
- Future: extend **modeling** and **algorithmic** capabilities



Access the book at:
https://bit.ly/3qQNrdR

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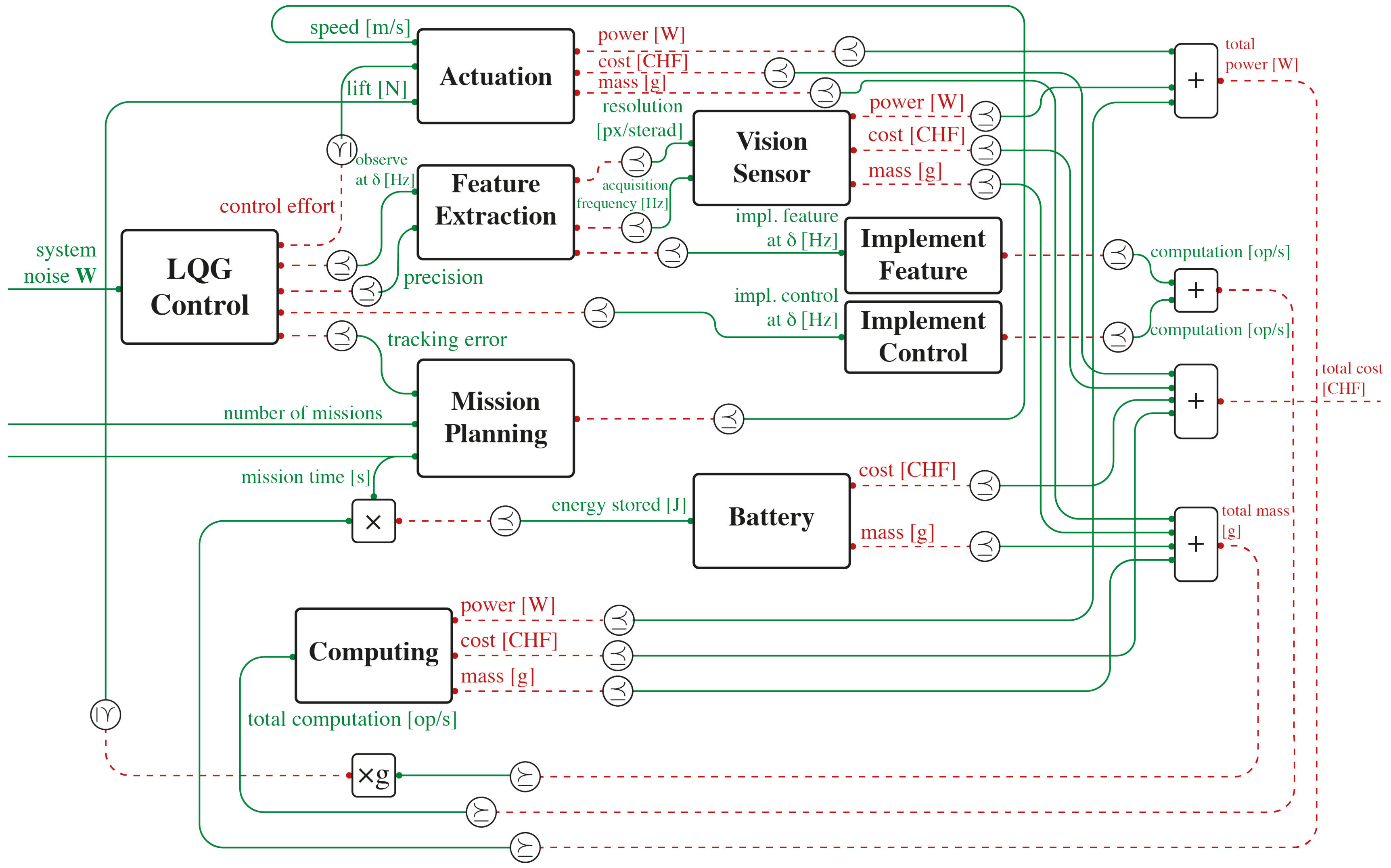
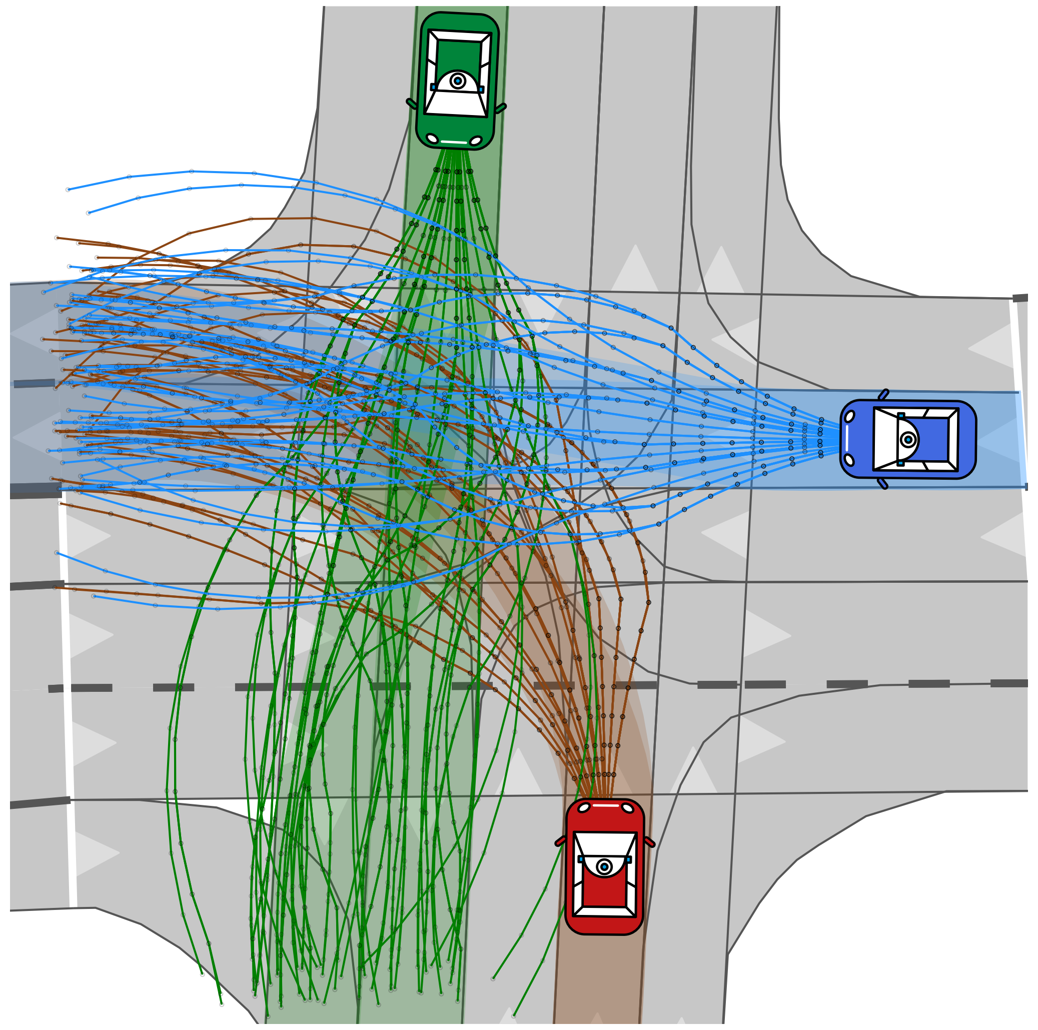
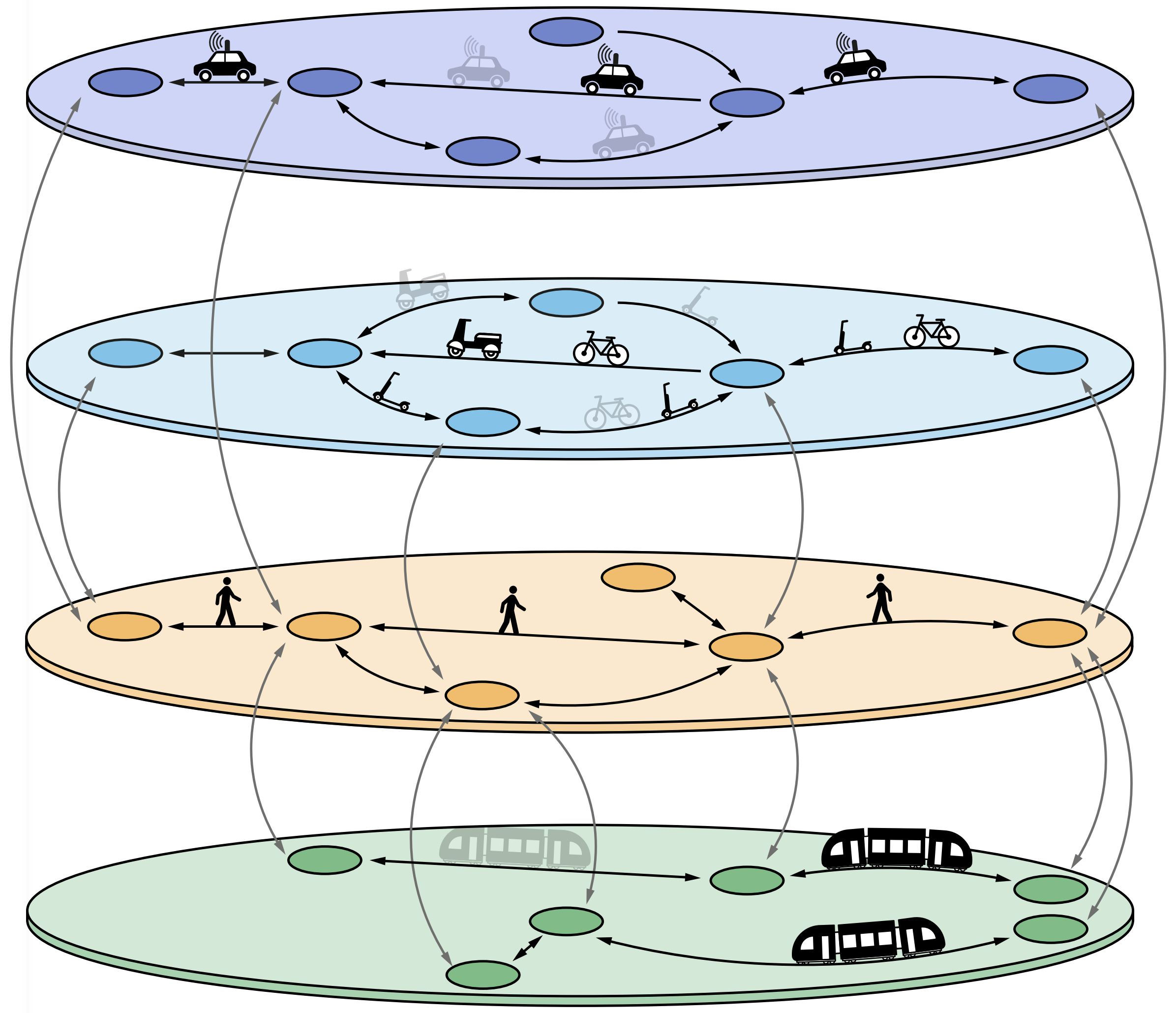
  - **Posetal games**: A new class of games, where **utilities** are **posets**
- Future: **uncertainty** and **computational** schemes







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- A. Censi, J. Lorand, G. Zardini, “Applied Compositional Thinking for Engineers”, *work-in-progress book*, 2023.

Co-Design basics

- G. Zardini, D. Milojevic, A. Censi, E. Frazzoli, “Co-Design of Embodied Intelligence: A Structured Approach”, *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2021.
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- G. Zardini, Z. Suter, A. Censi, E. Frazzoli, “Task-driven Modular Co-Design of Vehicle Control Systems”, *IEEE Conference on Decision and Control (CDC)*, 2022.
- G. Zardini, N. Lanzetti, A. Censi, E. Frazzoli, M. Pavone, “Co-Design to Enable User-Friendly Tools to Assess the Impact of Future Mobility Solutions”, *IEEE Transactions on Network Science and Engineering*, 2023.
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Co-Design of autonomy, mobility

- A. Zanardi*, G. Zardini*, S. Srinivasan, S. Bolognani, A. Censi, F. Dörfler, E. Frazzoli, “Posetal Games: Efficiency, existence, and refinement of equilibria in games with prioritized metrics”, *IEEE Robotics and Automation Letters*, 2022.
- G. Zardini, N. Lanzetti, L. Guerrini, S. Bolognani, E. Frazzoli, F. Dörfler, “Game Theory to Study Interactions Between Mobility Stakeholders”, *IEEE International Intelligent Transportation Systems Conference (ITSC)*, **Best Paper Award**, 2021.

Strategic Interactions

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- **Collaborators** for the presented works

Zelio Suter
Laura Guerrini
Dejan Milojevic
Nicolas Lanzetti
Alessandro Zanardi

Dr. Jonathan Lorand
Dr. Saverio Bolognani
Dr. Andrea Censi
Prof. Florian Dörfler
Prof. Marco Pavone
Prof. Emilio Frazzoli

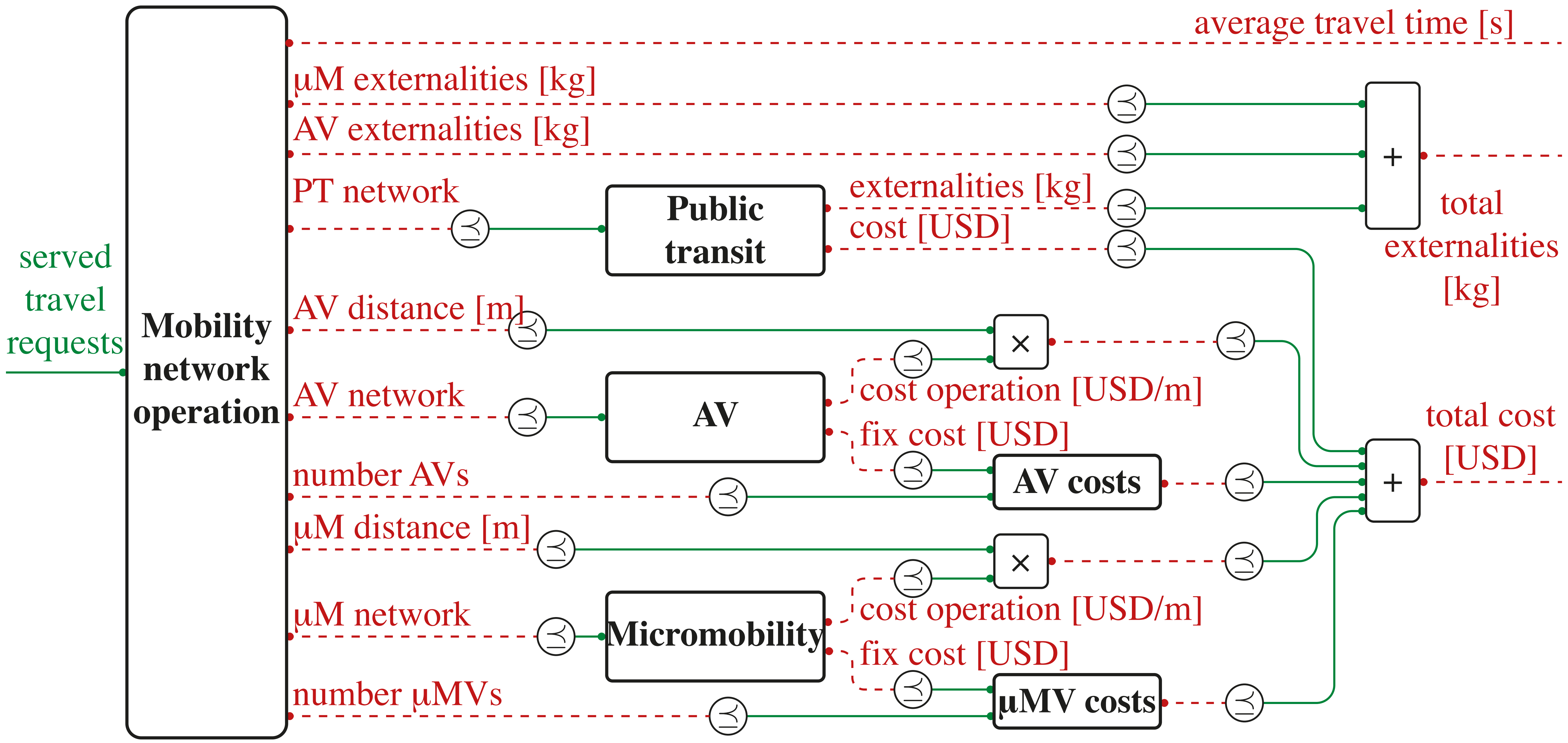
ETH zürich

Stanford University

Questions?

I'm hiring!

Explicitly accounting for strategic interactions: towards co-design games



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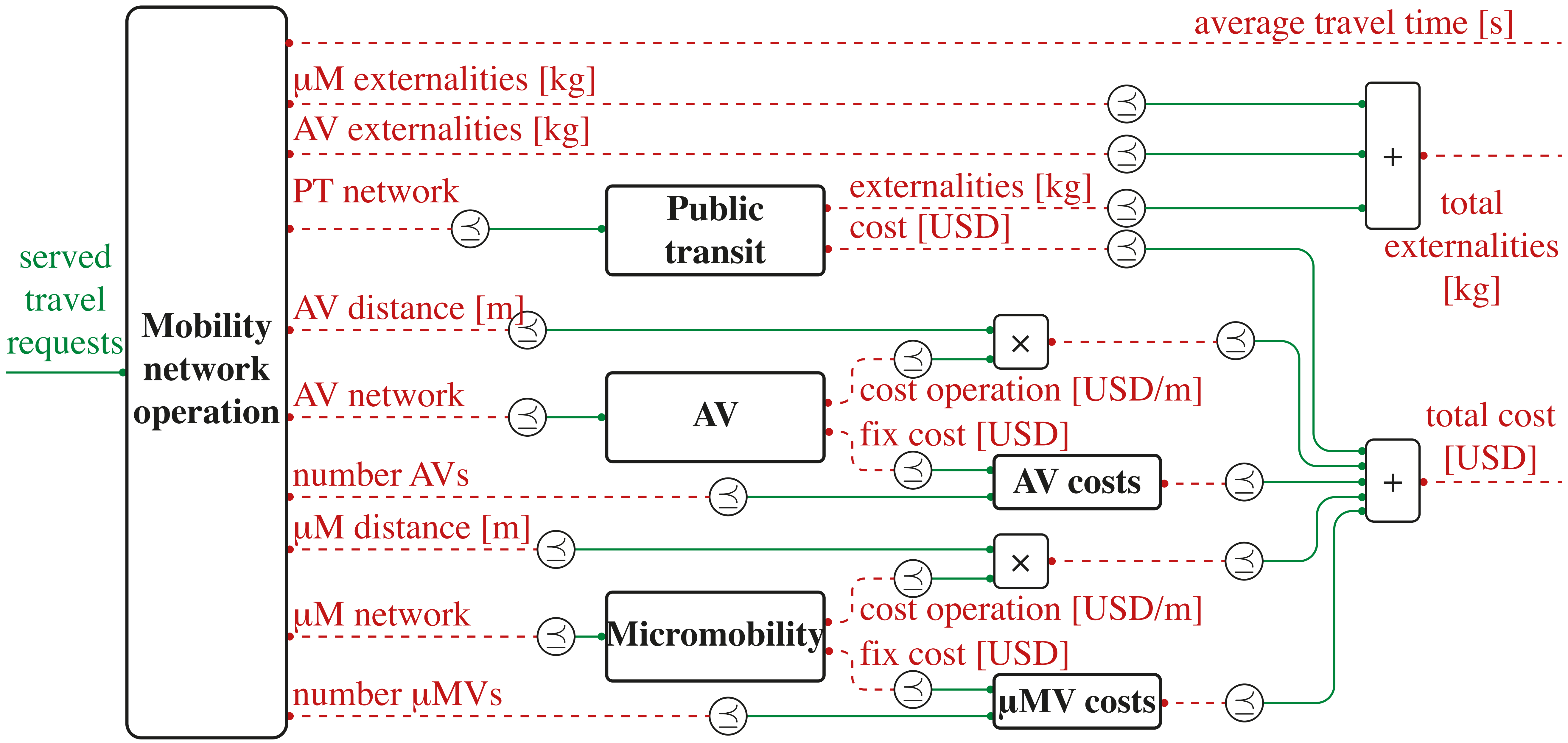

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- **Mobility games** via Stackelberg

Next time!

[ITSC'21 (***Best Paper Award***), ITSC'23]

Technology is evolving fast

- Autonomous systems (are?) will be ubiquitous in our lives

- As engineers, we are getting **closer to the natural sciences:**

We create things that we do not fully understand, and then we study our creations

- In this talk — Two important **challenges** for decision making.
  - Existing rules are written **by** humans **for** humans, and require **context** to be **interpreted**
  - Designed systems need to be **robust** to **complex**, **unconstrained environments**, featuring **interactions**

Behavior requirements for robots are numerous, vague, and conflicting

Ethics

Safety

Liability

Compliance to traffic rules

Extensive & diverse
written by humans for humans

Function

"Does your car have any idea why my car pulled it over?"

Courtesy

Culture

Example: Boston left

Comfort

Safety for human-driven vehicles

- Safety (i.e., prevention of *unreasonable risks of driving*) is typically ensured by a mix of:
  - **Certification** of vehicles and drivers
  - **Rules** of the road
  - **Enforcement** by authorities and legal system

- Typically, **rules** rely on fundamental **axioms**, which require **interpretation**

Fundamental norm in Switzerland:
All road users must behave in such a way not to pose an obstacle or a danger to other road users

- No clear specification of **safety**
- It is **legal** to break the law to ensure **safety**

Things that do <u>not</u> work well for AV behavior specification

- **Hard constraints**
  - What do you do with **infeasibility**?
  - Whenever you consider other actors, hard to find **guarantees**

- **Case analysis, finite state machines, …**
  - "IF statements kill people"

- **Just relax!**

$$J = \alpha J_1 + \beta J_2 + \gamma J_3 + \dots$$

  - Hard to re-tune, prone to **overfitting**
  - Lack of **transparency**

What should we do instead?

- Throw the ball at **other stakeholders**
- Incorporate our **own beliefs** in our algorithms

- Create **transparent** systems
- Create **customizable** systems
- **Explain** issues to the public
- **Engage** with **stakeholders** of the problem (e.g., regulators, liability companies, etc.)

Minimum violation planning

- Assume that constraints will be violated, and find the alternative that ***least*** violates them
- Define **rules** as a **total order** over realizations
- **Order rules** according to priority
- This is practical:
  - Allows **modular definition of behavior**
  - **Easy to predict** what the car will do
  - **Easy to understand** why the car did something
  - One can introduce **tolerances**

Taxi	**Race car**
Safety	*Compliance*
↑	↑
Compliance	*Performance*
↑	↑
Comfort	*Safety*
↑	↑
Performance	*Comfort*

What if rules are incomparable, or indifferent?

See seminal work by Tumova, Karaman, Frazzoli

We capture the richness of robot behavior requirements via partial orders

- We can use **pre-orders over rules** to express preferences

"Rule A is more important than rule B"

A
|
B

"Rule A and B are not comparable"

A *B*

"Rule A and B are indifferent"

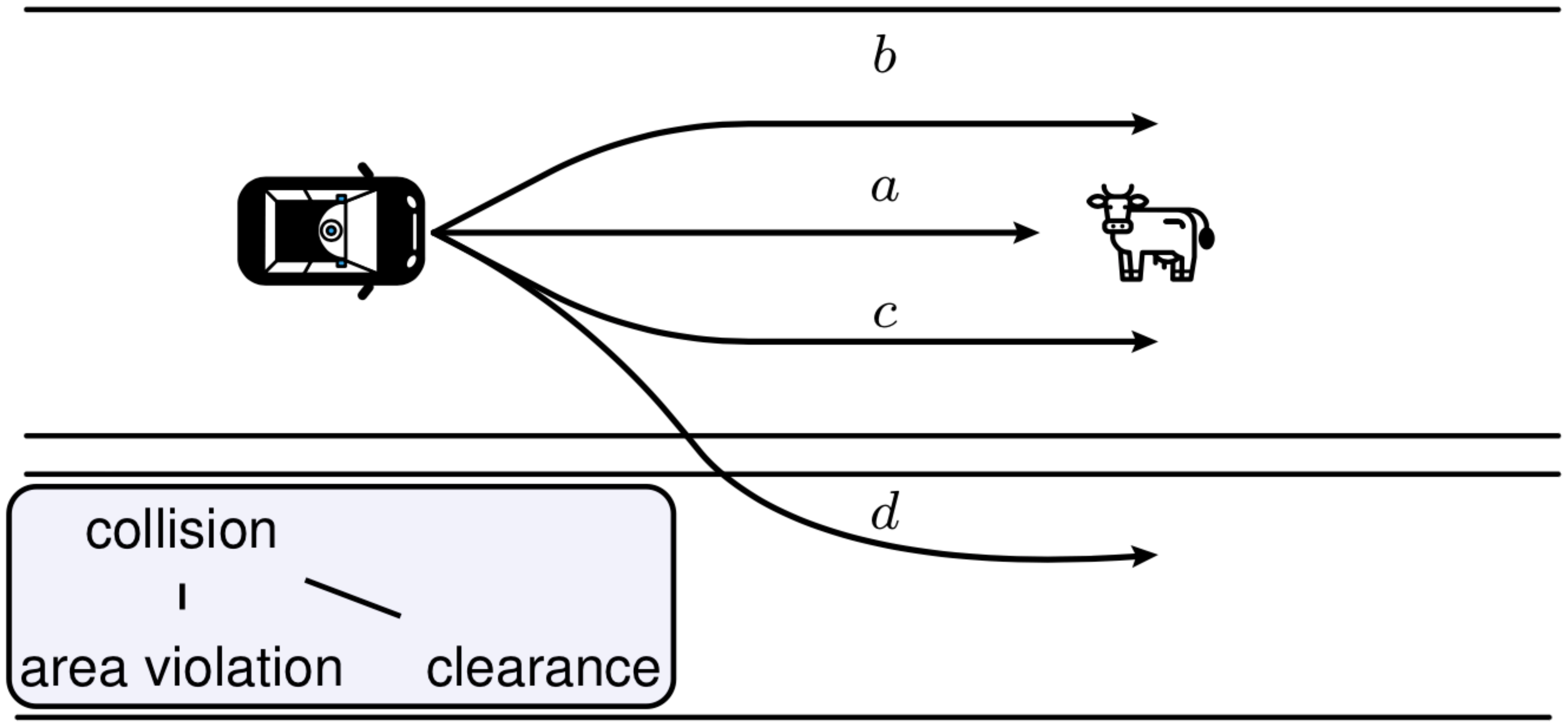
A ⟷ *B*

- Pre-order over rules induces pre-order over outcomes

b and *c* are **indifferent**

b, c, d are **preferred** over *a*

b, c are **incomparable** with *d*



Minimum violation planning using partial orders, unbridled creativity and good taste

"The way to get good ideas is to get lots of ideas, and throw the bad ones away." — Linus Pauling

creativity

good taste

See Rulebooks work by Censi, Frazzoli, and others

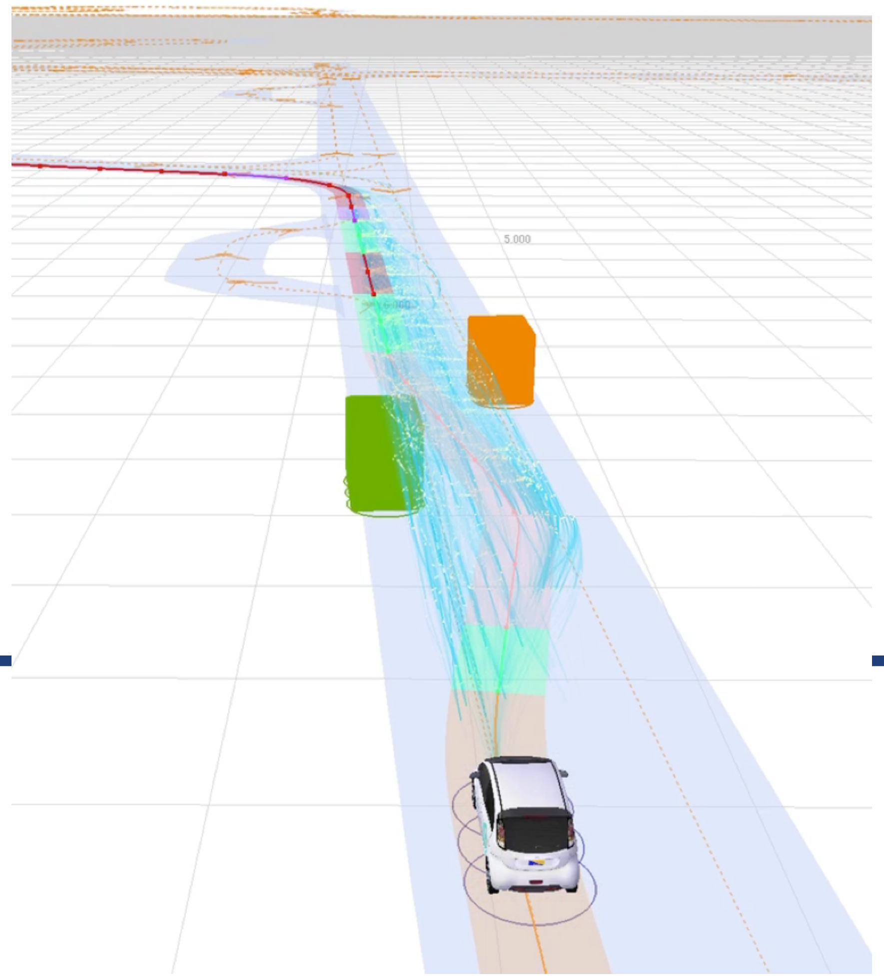
Minimum violation planning using partial orders, unbridled creativity and good taste

observations *world state* *plan* *commands*

sensors → **perception** → **planning** → **control** → actuators

planning

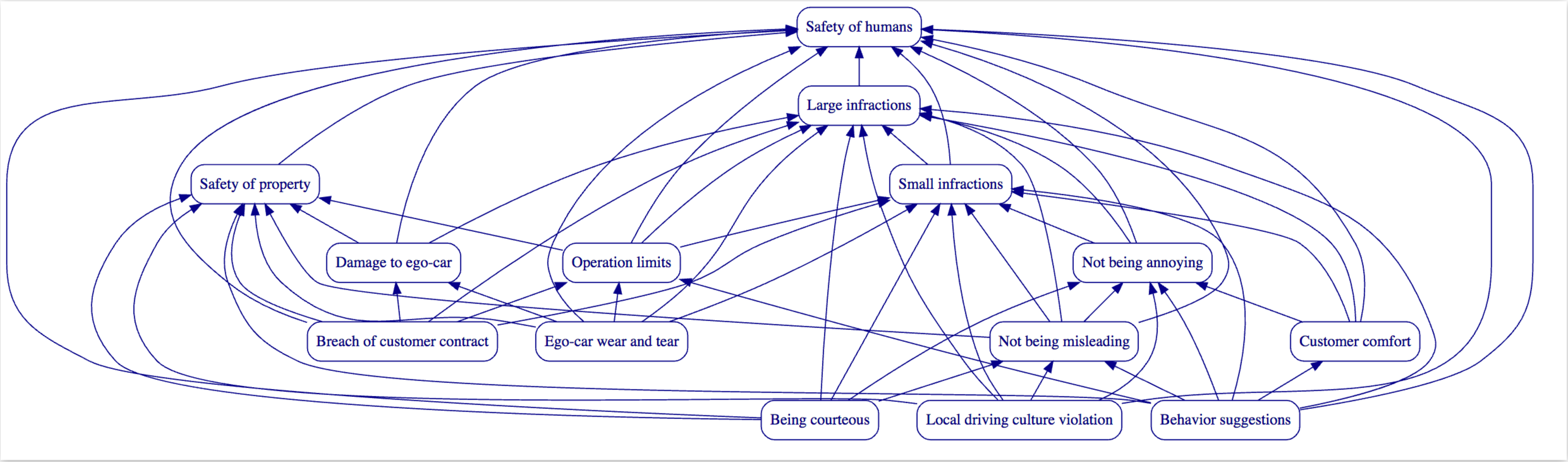
world state → trajectory proposers ↕ prediction models → extractors ↕ scorers → *plan*



“creativity” “good taste”

Defining and ordering rule groups for realistic scenarios

- Estimate: urban driving requires ~200 **rules**, ~20 **rule groups**



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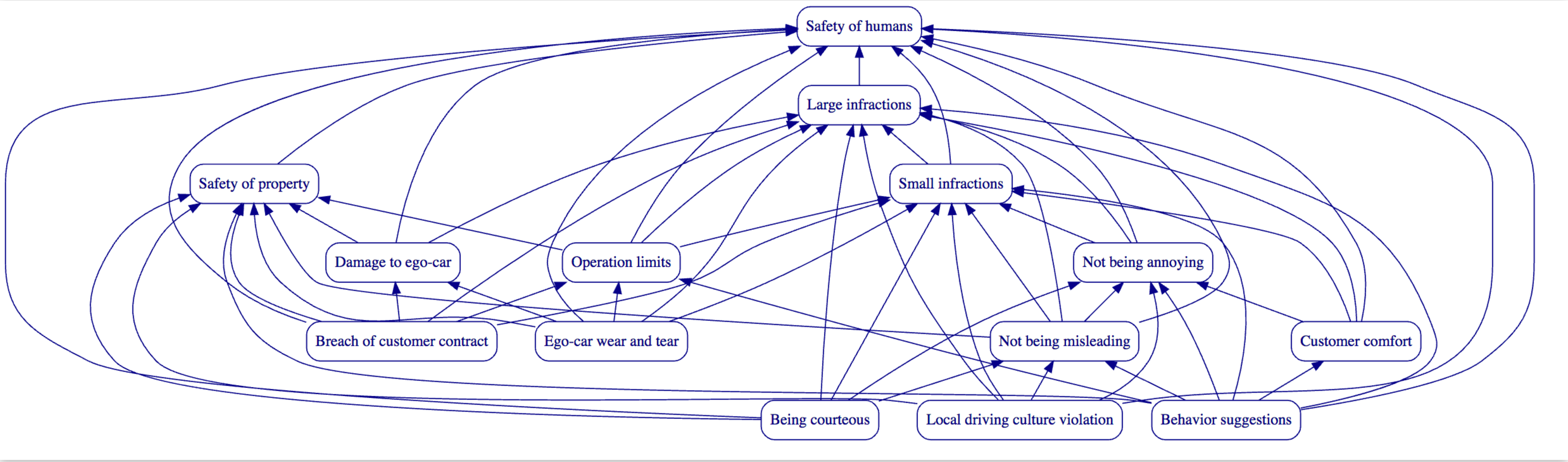


All of this is considering ego agents…
How do these specifications work with multiple, interacting agents?

Posetal Games to deal with highly interactive multi-objective nature of decisions

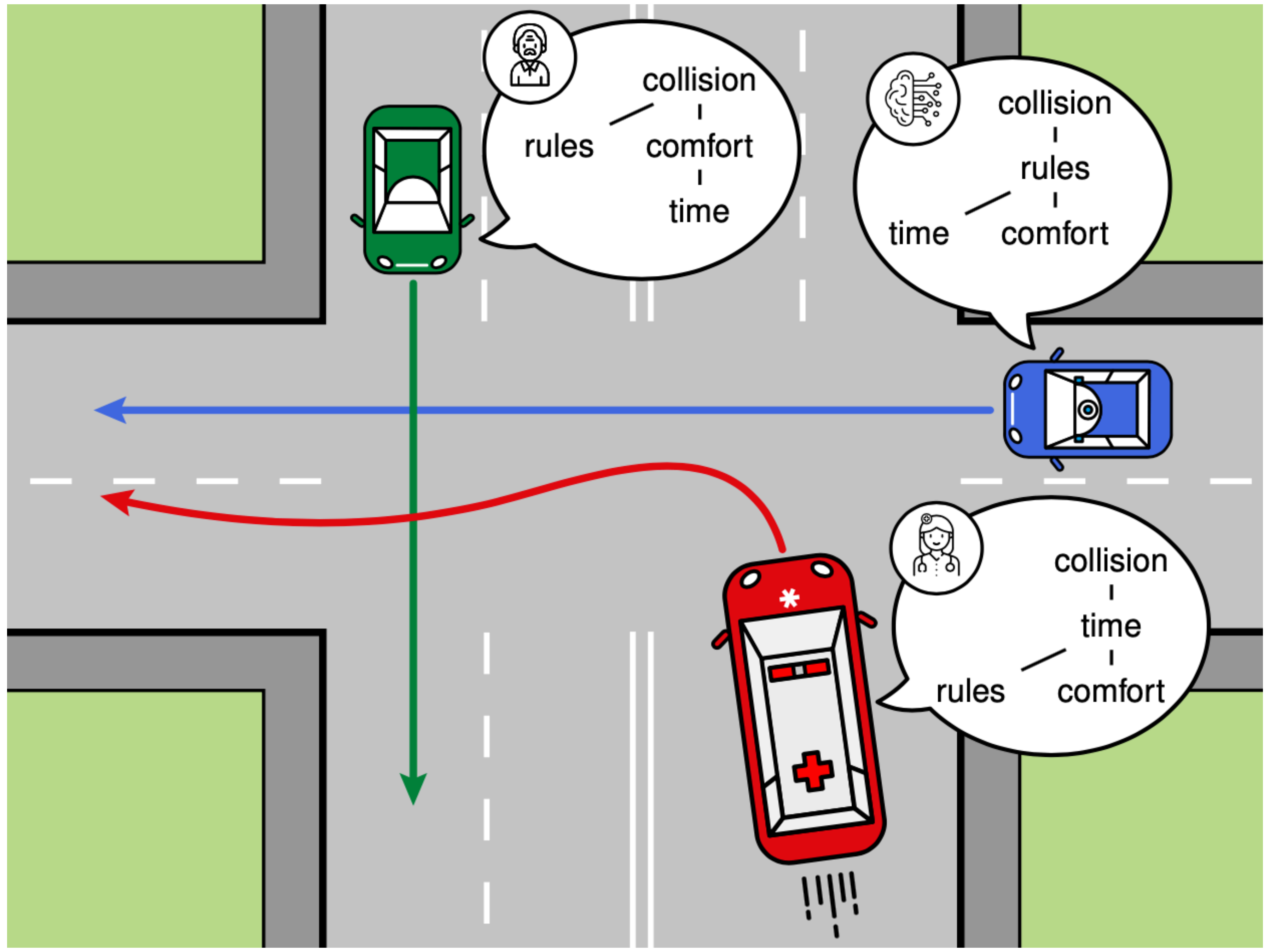
- **Games** in short:
  - Each **player** has a **scalar utility function**
  - Based on **preferences**, players select an **action** from decision space
  - Given joint **action profile** of players, we obtain a **game outcome** for each player via a *deterministic* **metric function**
  - **Equilibria** are joint action profiles from which **no player** has **interest to deviate**

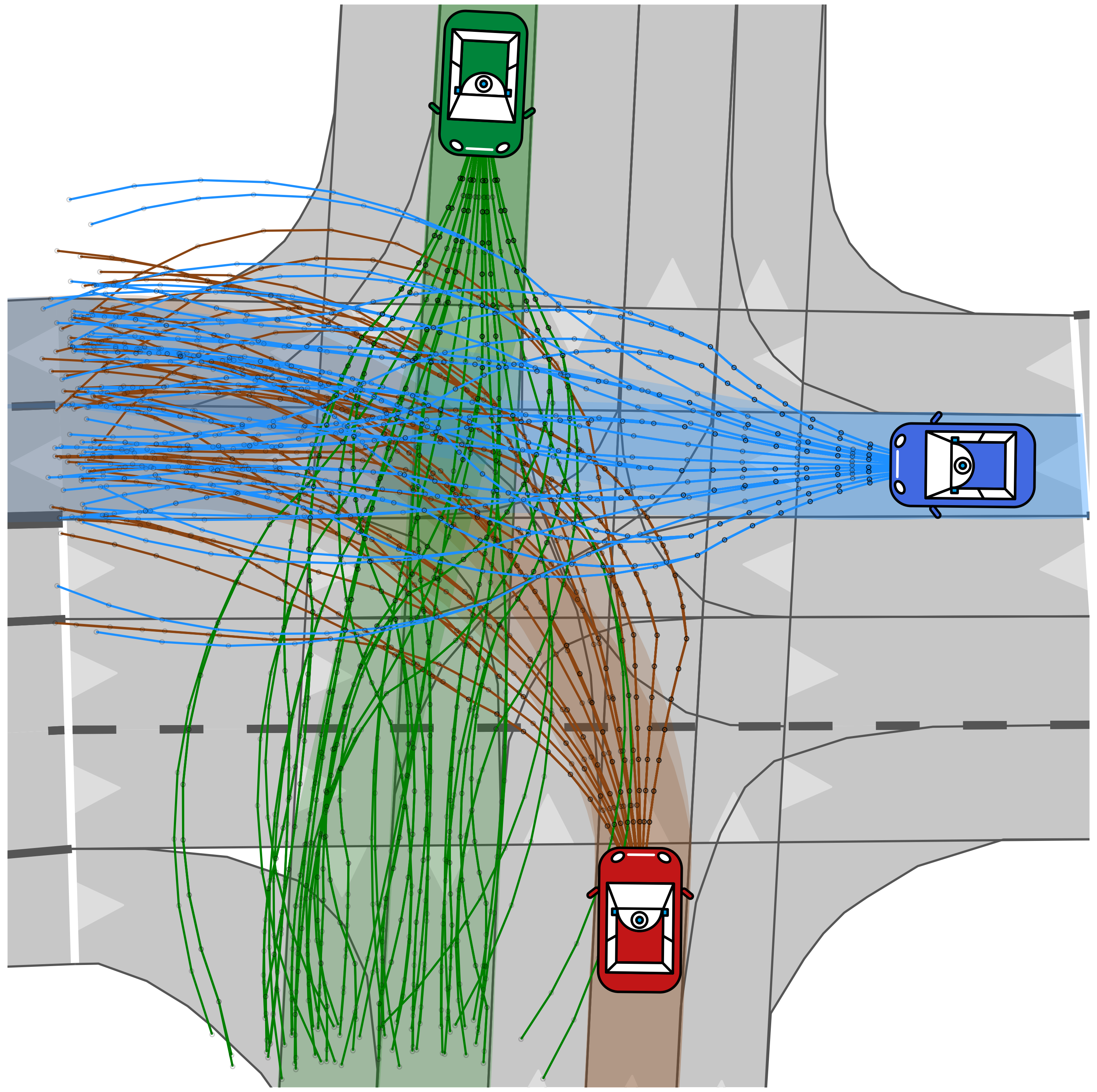
Related work: V.V. Rozen'18, S. Le Roux'08

Posetal Games to deal with highly interactive multi-objective nature of decisions

- **Posetal games** in short:
  - Each **player** has a ~~scalar utility function~~ *partially ordered* **preference** over a set of metrics (scores, costs)
  - Based on **preferences**, players select an **action** from decision space
  - Given joint **action profile** of players, we obtain a **game outcome** for each player via a *deterministic* **metric function**
  - **Equilibria** are joint action profiles from which **no player** has **interest to deviate**

Technical results instantiated in trajectory driving games for urban scenarios





[RA-L' 22]

Posetal Games to deal with highly interactive multi-objective nature of decisions

- Posetal games **extend standard notions in game theory**, and
  - Provide **sufficient** conditions for the existence of **Nash equilibria** (via **potential games**)
  - Characterize **efficiency** of **admissible equilibria**
  - Design a **formal, systematic** way to leverage **preference refinement** (e.g., via *estimation*) to **refine equilibria**