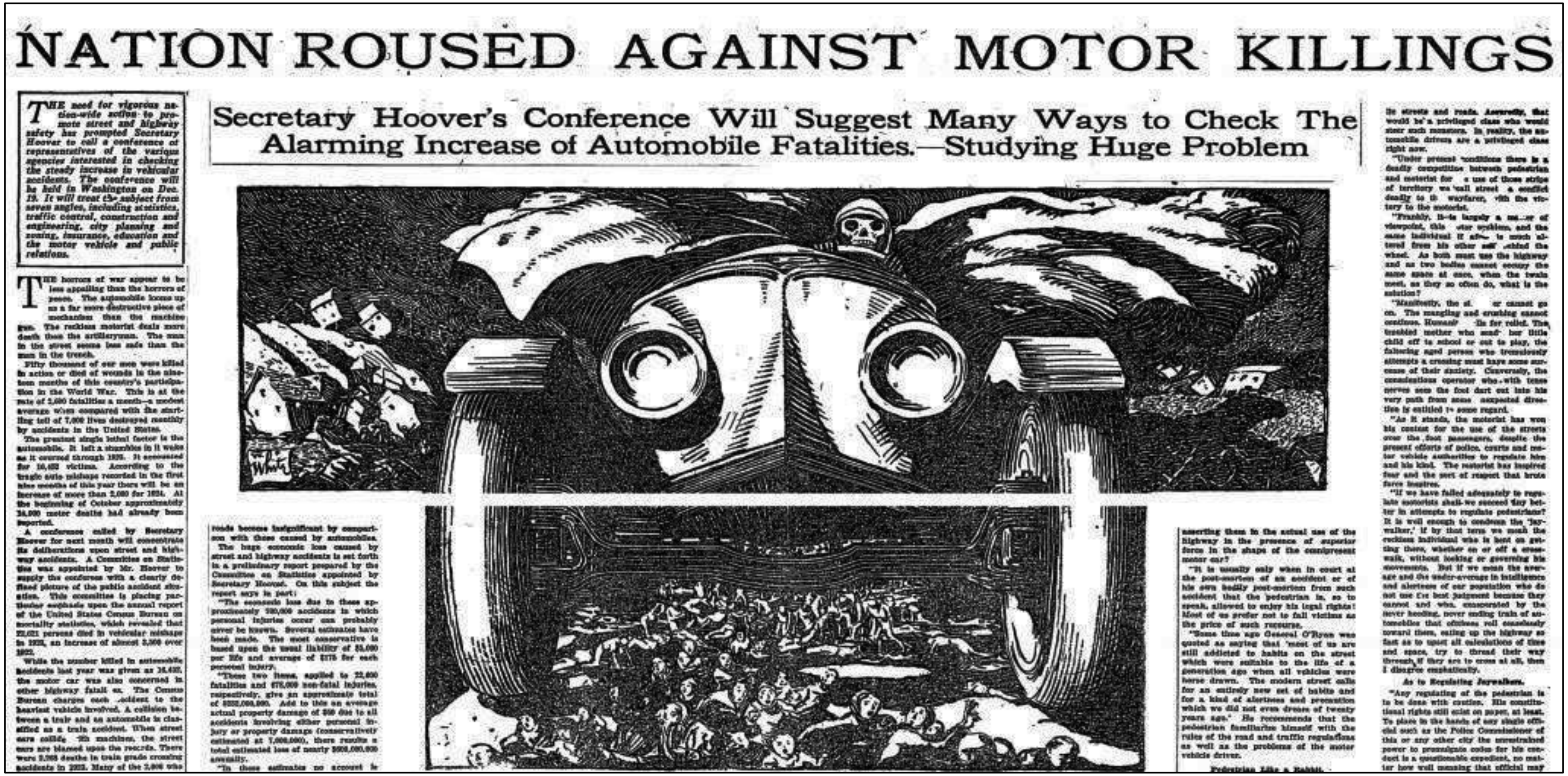
MULTI-AGENT SYSTEMS FOR EMERGENCY RESPONSE

Ayan Mukhopadhyay

WHY CARE ABOUT EMERGENCY RESPONSE?



NATION ROUSED AGAINST MOTOR KILLINGS

Secretary Hoover's Conference Will Suggest Many Ways to Check The Alarming Increase of Automobile Fatalities.—Studying Huge Problem

THE need for vigorous nation-wide action to promote street and highway safety has prompted Secretary Hoover to call a conference of representatives of the various agencies interested in checking the steady increase in vehicular accidents. The conference will be held in Washington on Dec. 15. It will treat the subject from seven angles, including statistics, traffic control, construction and engineering, city planning and zoning, insurance, education and the motor vehicle and public relations.

THE horrors of war appear to be less appalling than the horrors of peace. The automobile looms up as a far more destructive piece of mechanism than the machine gun. The reckless motorist deals more death than the artilleryman. The man in the street seems less safe than the man in the trench.

Fifty thousand of our men were killed in action or died of wounds in the nineteen months of this country's participation in the World War. This is at the rate of 2,600 fatalities a month—a modest average when compared with the startling toll of 7,000 lives destroyed monthly by accidents in the United States.

The greatest single lethal factor is the automobile. It left a shambles in its wake as it coursed through 1923. It accounted for [illegible] victims. According to the tragic auto mishaps recorded in the first nine months of this year there will be an increase of more than 2,000 for 1924. At the beginning of October approximately [illegible] motor deaths had already been reported.

A conference called by Secretary Hoover for next month will concentrate its deliberations upon street and highway accidents. A Committee on Statistics was appointed by Mr. Hoover to supply the conference with a clearly defined picture of the public accident situation. This committee is placing particular emphasis upon the annual report of the United States Census Bureau on mortality statistics, which revealed that [illegible] persons died in vehicular mishaps in 1923, an increase of almost 2,300 over 1922.

While the number killed in automobile accidents last year was given as [illegible], the motor car was also concerned in other highway fatalities. The Census Bureau charges each accident to the heaviest vehicle involved. A collision between a train and an automobile is classified as a train accident. When street cars collide with machines, the street cars are blamed upon the records. There were [illegible] deaths in train grade crossing accidents in 1923. Many of the [illegible] who

...

roads become insignificant by comparison with those caused by automobiles.

The huge economic loss caused by street and highway accidents is set forth in a preliminary report prepared by the Committee on Statistics appointed by Secretary Hoover. On this subject the report says in part:

"The economic loss due to these approximately [illegible] accidents in which personal injuries occur can probably never be known. Several estimates have been made. The most conservative is based upon the usual liability of $5,000 per life and average of $175 for each personal injury.

"These two items, applied to 22,600 fatalities and 678,000 non-fatal injuries, respectively, give an approximate total of $[illegible]. Add to this an average actual property damage of $50 due to all accidents involving either personal injury or property damage (conservatively estimated at 7,000,000), there results a total estimated loss of nearly $[illegible] annually.

"In these estimates no account is

...

asserting them in the actual use of the highway in the presence of superior force in the shape of the omnipresent motor car?

"It is usually only when in court at the post-mortem of an accident or of his own bodily post-mortem from such accident that the pedestrian is, so to speak, allowed to enjoy his legal rights! Most of us prefer not to fall victims as the price of such recourse.

"Some time ago General O'Ryan was quoted as saying that 'most of us are still addicted to habits on the street which were suitable to the life of a generation ago when all vehicles were horse drawn. The modern street calls for an entirely new set of habits and for a kind of alertness and precaution which we did not even dream of twenty years ago.' He recommends that the pedestrian familiarize himself with the rules of the road and traffic regulations as well as the problems of the motor vehicle driver.

Pedestrian Like a Rabbit.

...

its streets and roads. Assuredly, that would be a privileged class who would steer such monsters. In reality, the automobile drivers are a privileged class right now.

"Under present conditions there is a deadly competition between pedestrian and motorist for the use of those strips of territory we call street, a conflict deadly to the wayfarer, with the victory to the motorist.

"Frankly, it is largely a matter of viewpoint, this motor problem, and the same individual is often much altered from his other self behind the wheel. As both must use the highway and as two bodies cannot occupy the same space at once, when the twain meet, as they so often do, what is the solution?

"Manifestly, the [illegible] cannot go on. The mangling and crushing cannot continue. Humanity [illegible] for relief. The troubled mother who sends her little child off to school or out to play, the faltering aged person who tremulously attempts a crossing must have some surcease of their anxiety. Conversely, the conscientious operator who with tense nerves sees the fool dart out into his very path from some unexpected direction is entitled to some regard.

"As it stands, the motorist has won his contest for the use of the streets over the foot passengers, despite the present efforts of police, courts and motor vehicle authorities to regulate him and his kind. The motorist has inspired fear and the sort of respect that brute force inspires.

"If we have failed adequately to regulate motorists shall we succeed any better in attempts to regulate pedestrians? It is well enough to condemn the 'jay-walker,' if by that term we mean the reckless individual who is bent on getting there, whether on or off a crosswalk, without looking or governing his movements. But if we mean the average and the under-average in intelligence and alertness of our population who do not use the best judgment because they cannot and who, exasperated by the never heeding, never ending train of automobiles that oftimes roll ceaselessly toward them, eating up the highway so fast as to upset all calculations of time and space, try to thread their way through if they are to cross at all, then I disagree emphatically.

As to Regulating Jaywalkers.

"Any regulating of the pedestrian is to be done with caution. His constitutional rights still exist on paper, at least. To place in the hands of any single official such as the Police Commissioner of this or any other city the unrestrained power to promulgate codes for his conduct is a questionable expedient, no matter how well meaning that official may

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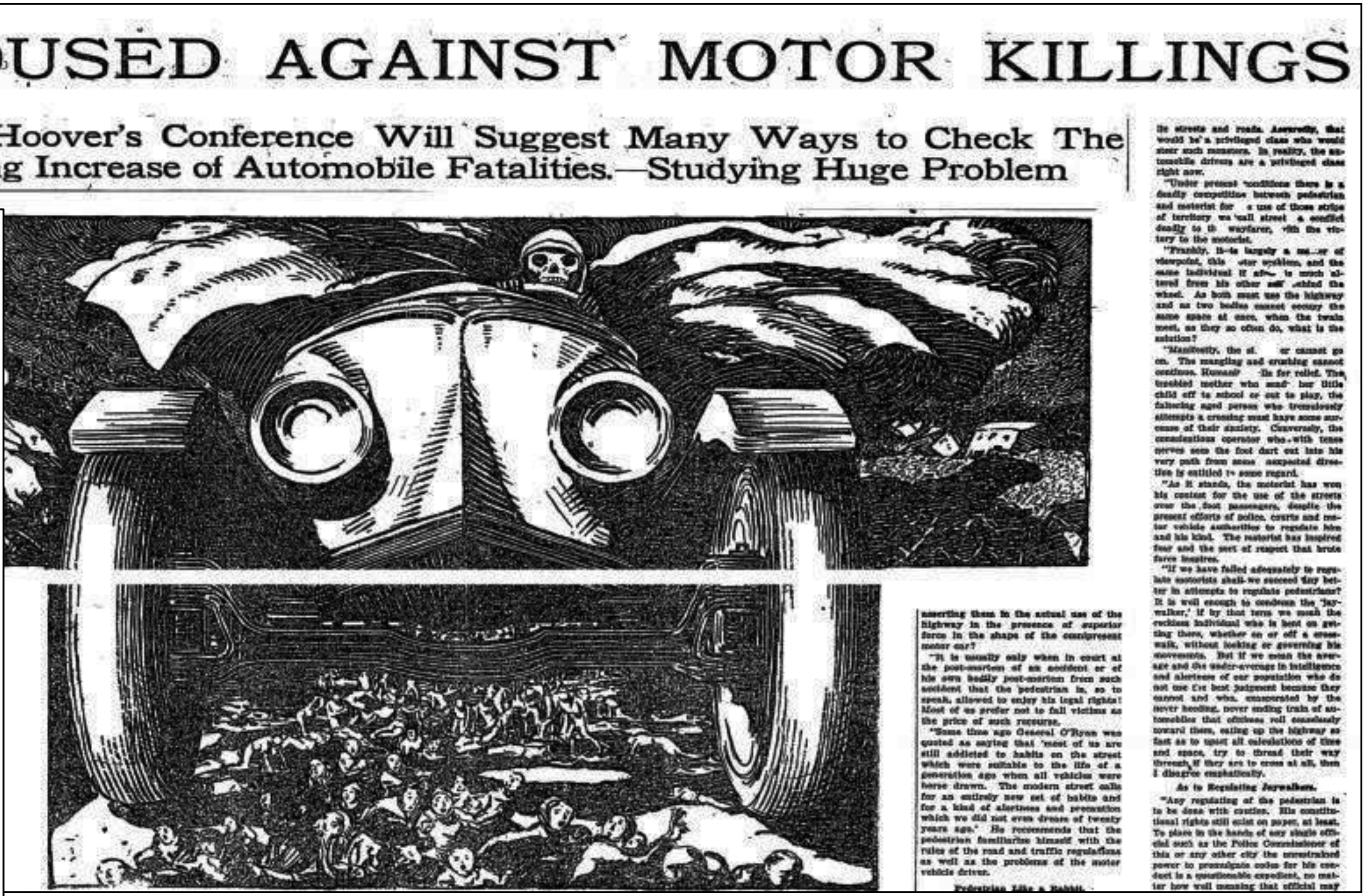
WHY CARE ABOUT EMERGENCY RESPONSE?



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Murder Machines: Why Cars Will Kill 30,000 Americans This Year

By Hunter Oatman-Stanford — March 10th, 2014 | Share 82 | Tweet

There's an open secret in America: If you want to kill someone, do it with a car. As long as you're sober, chances are you'll never be charged with any crime, much less manslaughter. Over the past hundred years, as automobiles have been woven into the fabric of our daily lives, our legal system has undermined public safety, and we've been collectively trained to think of these deaths as unavoidable "accidents" or acts of God. Today, despite the efforts of major public-health agencies and grassroots safety campaigns, few are aware that car crashes are the number one cause of death for Americans under 35. But it wasn't always this way.

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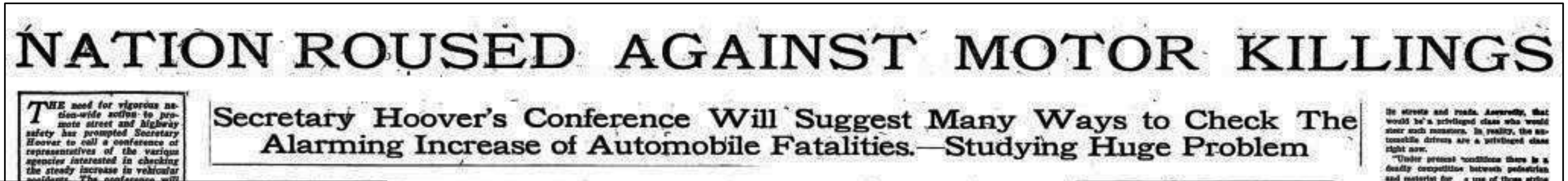

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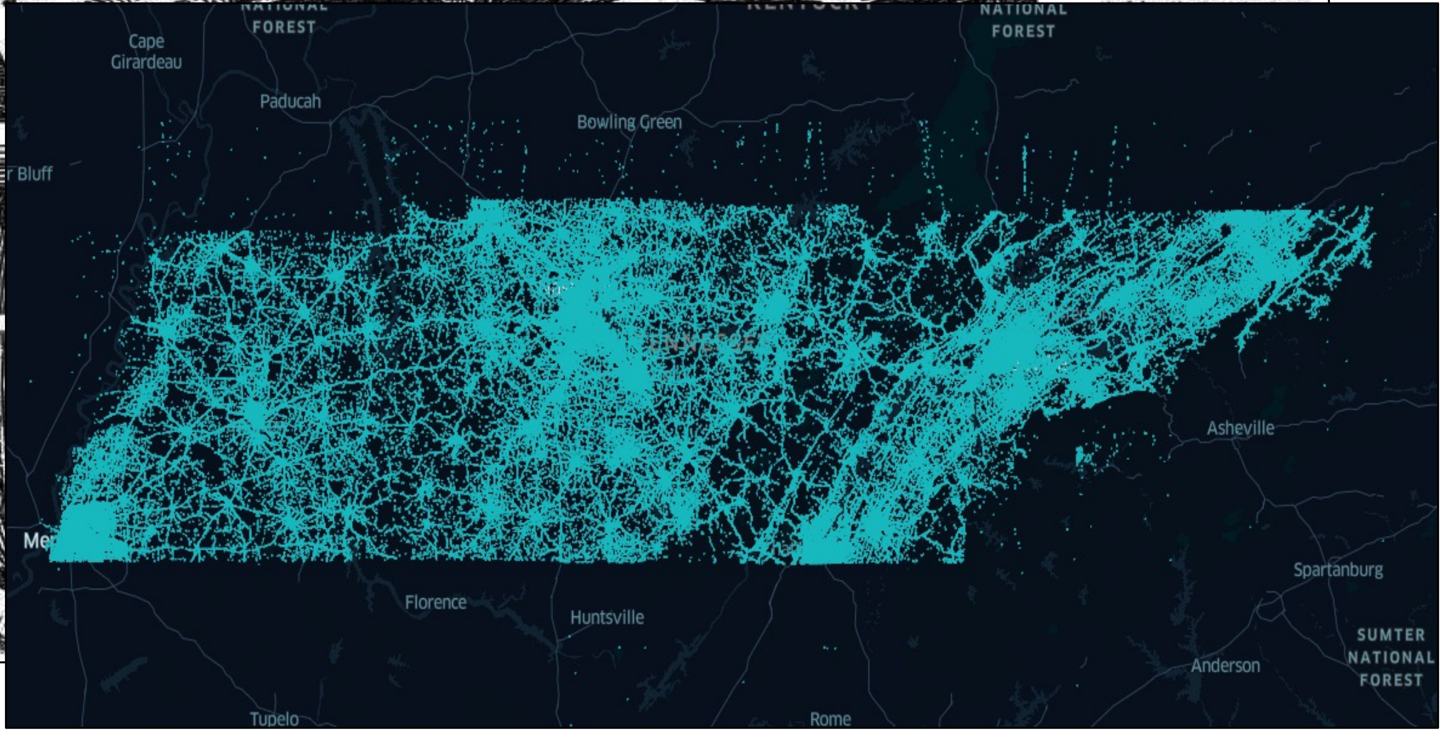

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WHY CARE ABOUT EMERGENCY RESPONSE?

Giants Club: African leaders to gather in Kenya to tackle elephant poaching crisis

In the past three years, 100,000 elephants have been killed in Africa to supply ivory to illegal markets

Alex Dymoke | Friday 26 February 2016 12:00 |

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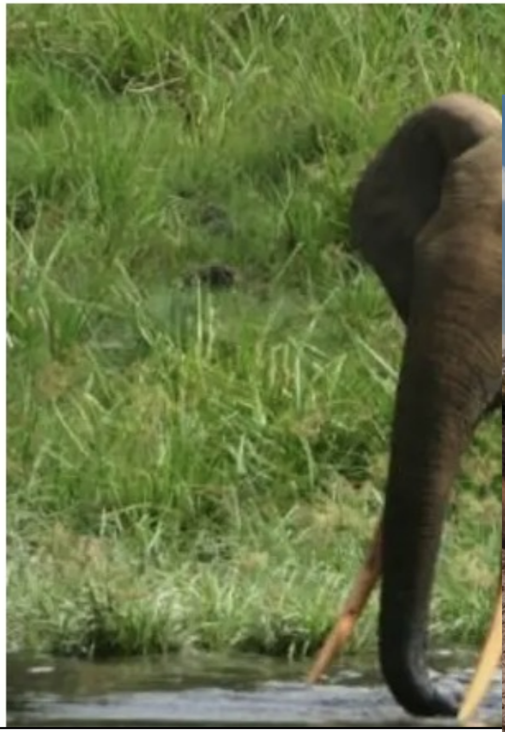

MAGAZINE | WILDLIFE WATCH

Poaching is sending the shy, elusive pangolin to its doom

The small animals, whose scales are coveted for use in Chinese medicine, are now among the world's most trafficked mammals.

WHY CARE ABOUT EMERGENCY RESPONSE?

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SMART EMERGENCY RESPONSE

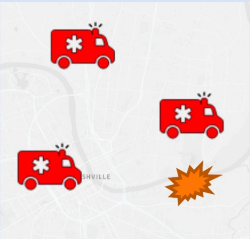
Proactive Resource Management

Sense → Detect → Predict → Plan → Act

<u>Research Objective</u>: framework for *proactive* resource allocation and dispatch that optimizes the expected long-term utility of the system

<u>Challenges</u>:

Large multi-agent systems with complex agent interactions



Environmental Dynamics

Short Term


Traffic


Weather


Events

Long-term


Construction


Population Shifts

Resilience

Communication infrastructure failures

Equipment Breakdowns

SMART EMERGENCY RESPONSE: PROBLEMS

- Extremely large and multi-modal data – the analysis of wildfires uses billions of data points created from satellite imagery; accident prediction uses granular traffic data (think of a measurement coming from every road segment of a city every 30 seconds)

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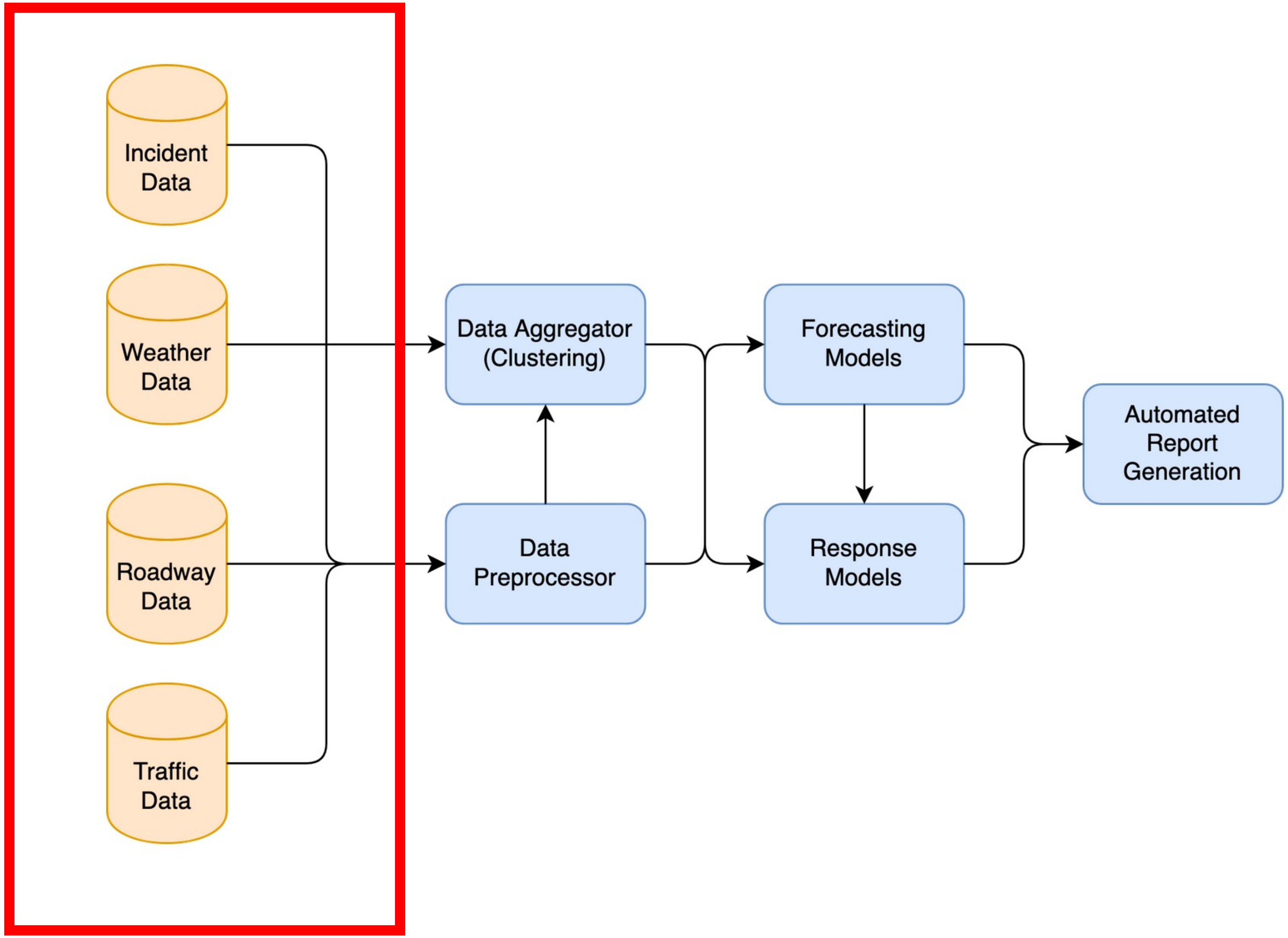
- Adversarial effects – if we know where poaching is expected to occur and deploy rangers, poachers will move. How can we solve interactions that take the form of games?
- Dynamic environments – what if we manage to learn complex models for emergency response and deploy them, but an event changes the dynamics of the problem?

PROBLEMS

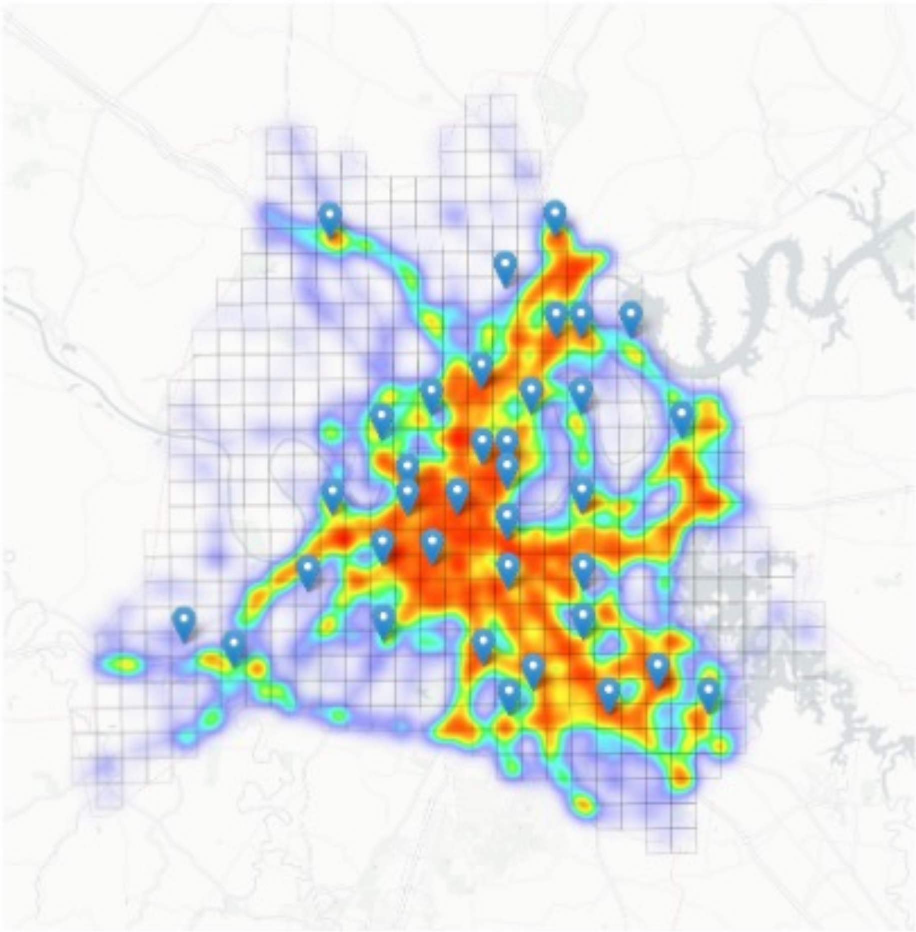
- **Forecasting**: AAMAS 16, GameSec 16, AAMAS 18
- **Allocation**: AAMAS 17, ADVERSE 17, ICCPS 19, AAMAS 20, ICCPS 21
- **Dispatch**: AAMAS 18, ICCPS 19
- **Robustness**: UAI 20
- **Online Modeling**: ICCPS 19
- **Deployment**: ICDE 2021

FORECASTING SPATIAL-TEMPORAL INCIDENTS



AAMAS 2021, ICCPS 2021, ICCPS 2020

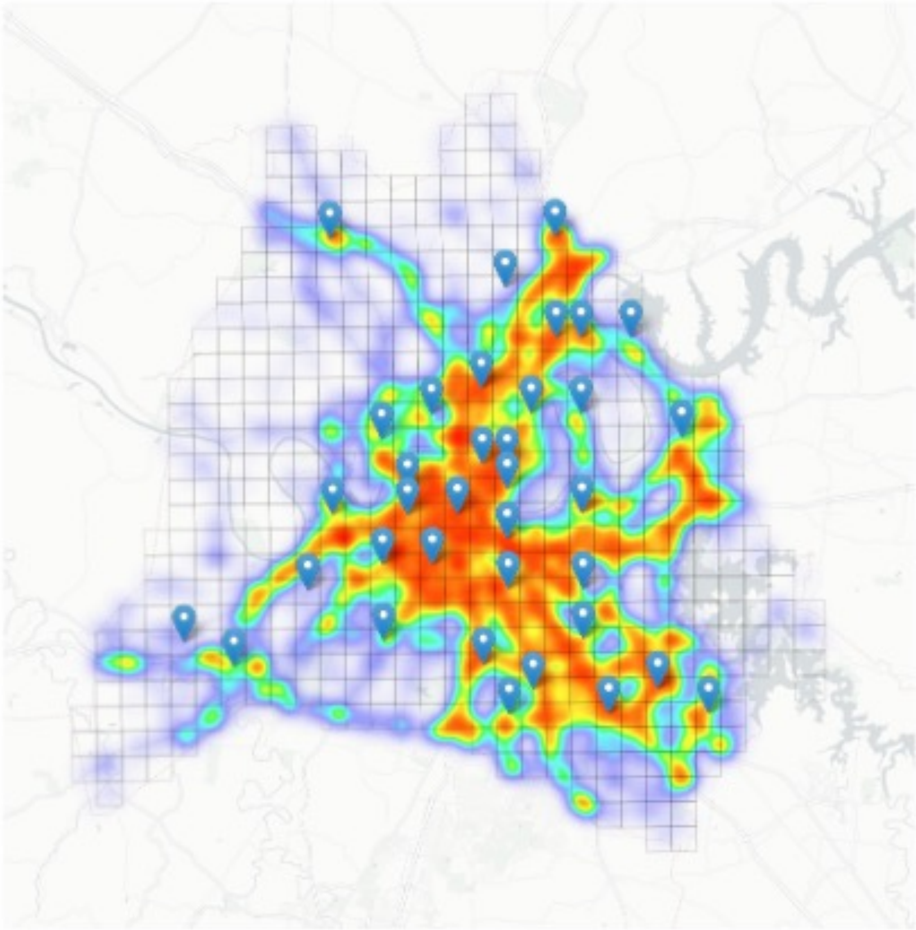
HANDLING COMPLEX EVENTS



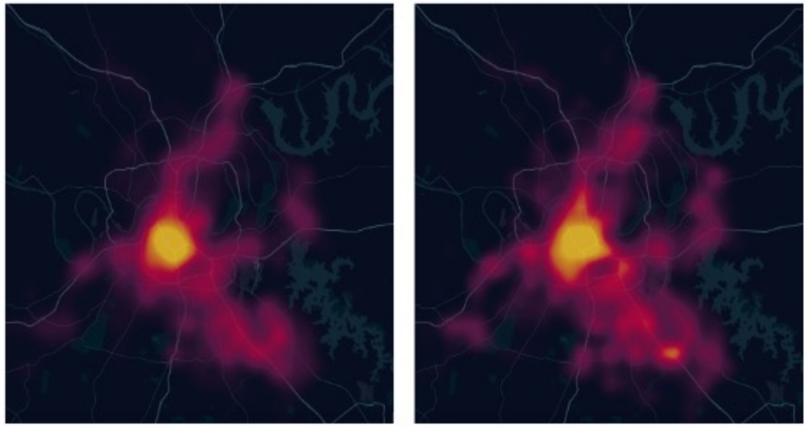
- D: For a given spatial area, incidents happen at specific coordinates and times, with some severity. Let the set of all incident be represented by D.
- G: Consider the entire spatial area to be divided into a set of cells.
- X: For each cell, consider a distribution F, that models the distribution of incident occurrence in the cell, measured by a random variable.

AAMAS 2021, ICCPS 2021, ICCPS 2020

HANDLING COMPLEX EVENTS



- We have shown how a combination of non-spatial clustering, synthetic resampling, and conditioning on carefully chosen features can be used to learn accurate predictive models.



Predicted Incidents vs Actual Incidents

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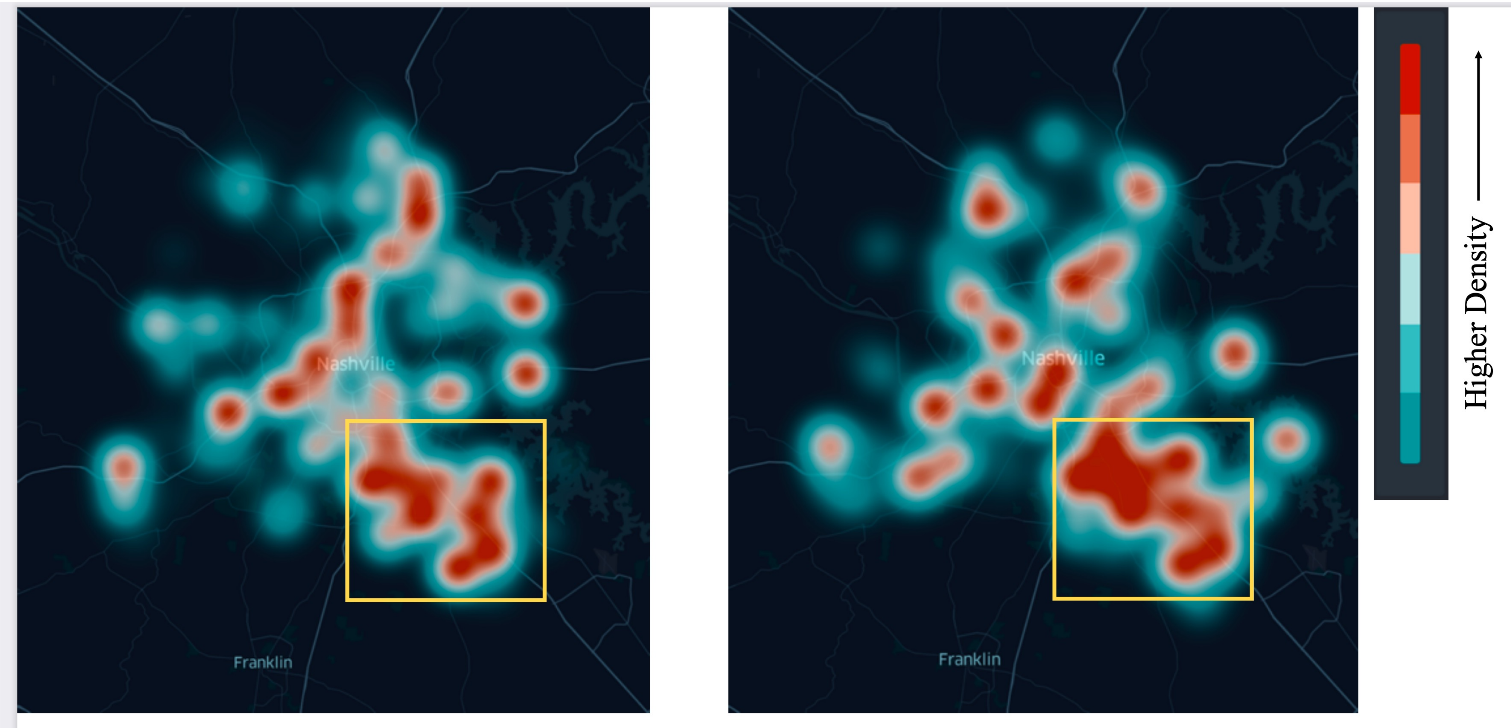
AAMAS 2021, ICCPS 2021, ICCPS 2020

HANDLING DYNAMIC ENVIRONMENTS

Technical Challenge:

What if we deploy a model but the environment changes?

Create online models that adapt to changing dynamics.



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THE SPECTRUM OF MULTI-AGENT SYSTEMS

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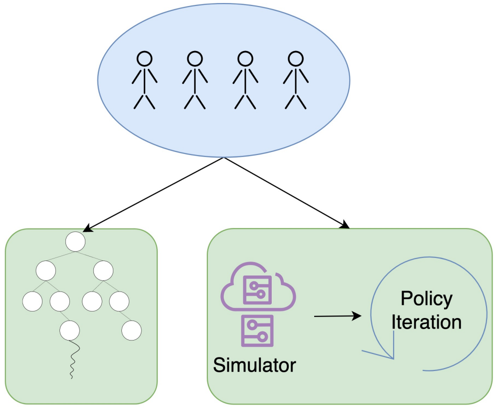

Centralized Planning

Relatively small state space
Complete communication
Unsuitable for dynamic environments

Scalability →

Problem with Coordination →

← Optimality

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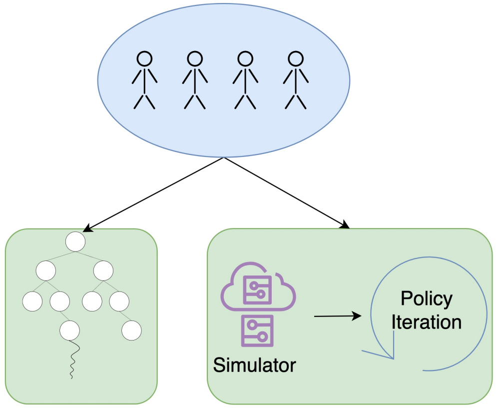

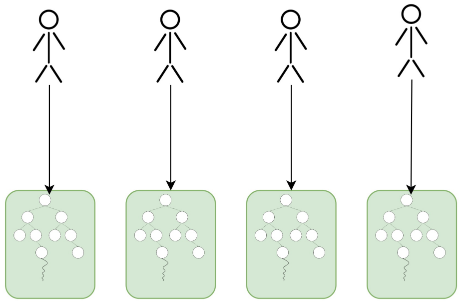

Centralized Planning

Decentralized Planning

Relatively small state space
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Tractable for large state spaces
Limited communication
Can adapt to dynamic environments

Scalability →

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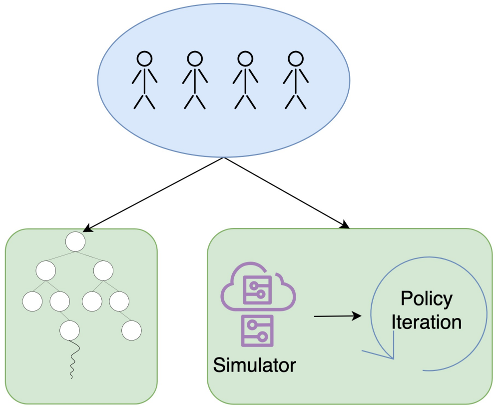
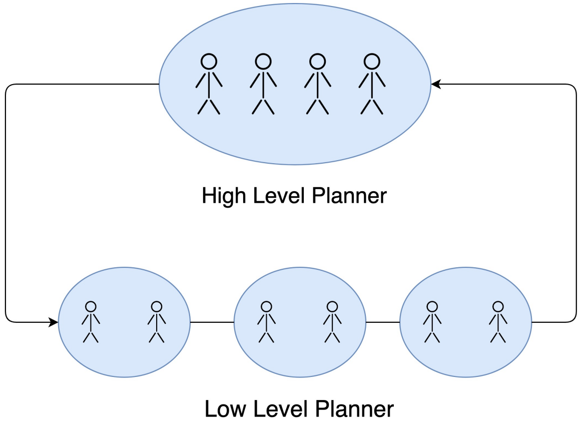
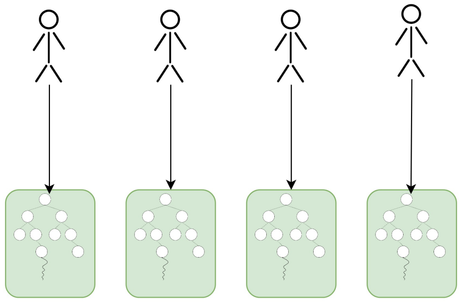






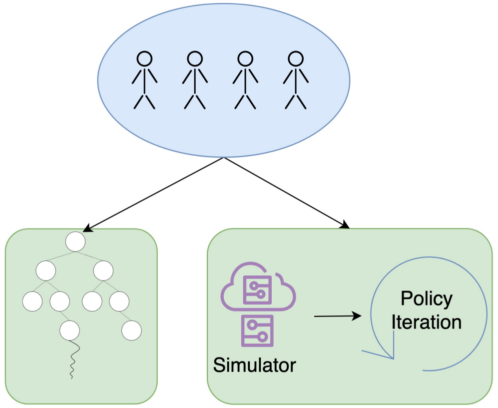
Centralized Planning	Hierarchical Planning	Decentralized Planning
Relatively small state space Complete communication Unsuitable for dynamic environments	Tractable for large state spaces Complete communication within sub-problems Can adapt to dynamic environments	Tractable for large state spaces Limited communication Can adapt to dynamic environments

Scalability →

Problem with Coordination →

← Optimality

THE SPECTRUM OF MULTI-AGENT SYSTEMS



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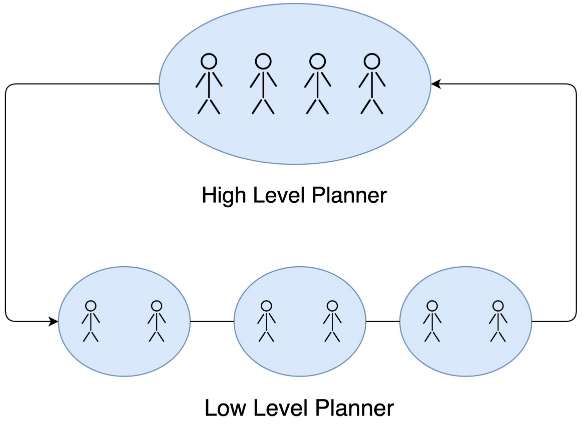
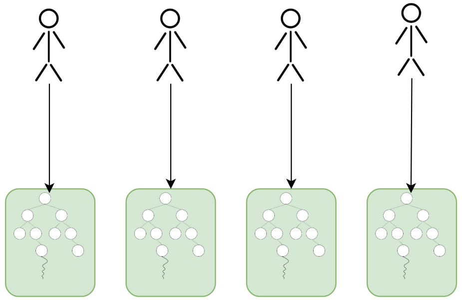


Hierarchical Planning

Tractable for large state spaces
Complete communication within sub-problems
Can adapt to dynamic environments



Decentralized Planning

Tractable for large state spaces
Limited communication
Can adapt to dynamic environments

Scalability

Problem with Coordination

Optimality

HOW CAN LARGE-SCALE MULTI-AGENT SYSTEMS BE SOLVED TRACTABLY?

Problem: Dynamically re-balance the spatial distribution of responders to account for incident distribution shifts and coverage gaps

*In practice, emergency dispatchers *must* send the closest responder to an incident[1]

This can lead to coverage gaps when responders become busy

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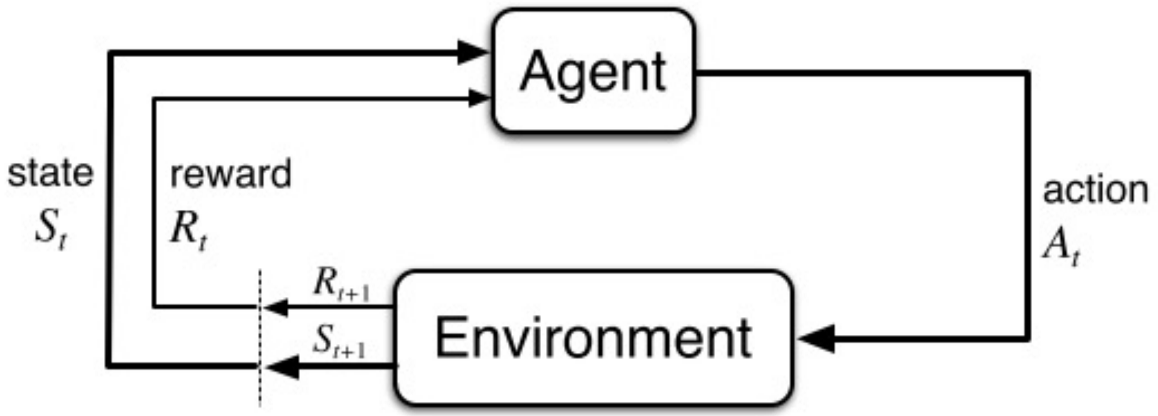
SYSTEM MODEL : SEMI-MARKOV DECISION PROCESSES

A natural modeling framework for control problems in which a decision agent interacts with an uncertain environment and actions have future consequences is the *(Semi)-Markov Decision Process* (SMDP)*



State: Responder and incident information	
Action: Directing responders to valid locations	
Transitions: Environment evolution depends on incident arrival model and responder travel times	
Cost: Incident response times	

Goal: minimize long term cost incurred by the decision agent

* *Semi-Markov because process evolves in continuous time and transitions are not memoryless*

SYSTEM MODEL : SEMI-MARKOV DECISION PROCESSES

Find a *policy:* a general mapping from states to actions

Methods: Reinforcement Learning

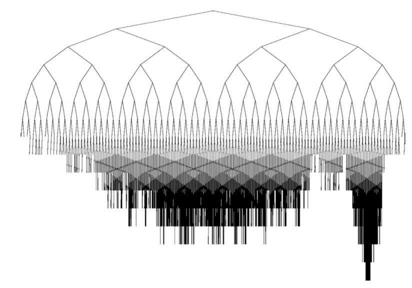
Approximate Dynamic Programming

Barriers:

- Long time to learn a policy due to large state-action space
- Must re-learn models to account for non-stationary environment
- Not resilient to failures and unexpected environmental shifts (disasters)

Evaluate potential actions for a given state using generative models

- Focuses computation on one relevant state
- Adaptable – if environment changes or there is a failure, simply update the underlying models



Monte Carlo Tree Search

Heuristic planning algorithm which balances exploration and exploitation to efficiently navigate a decision tree, focusing computation on promising action trajectories

SYSTEM MODEL : SEMI-MARKOV DECISION PROCESSES

Challenge: How to scale MCTS to practical problem instances?

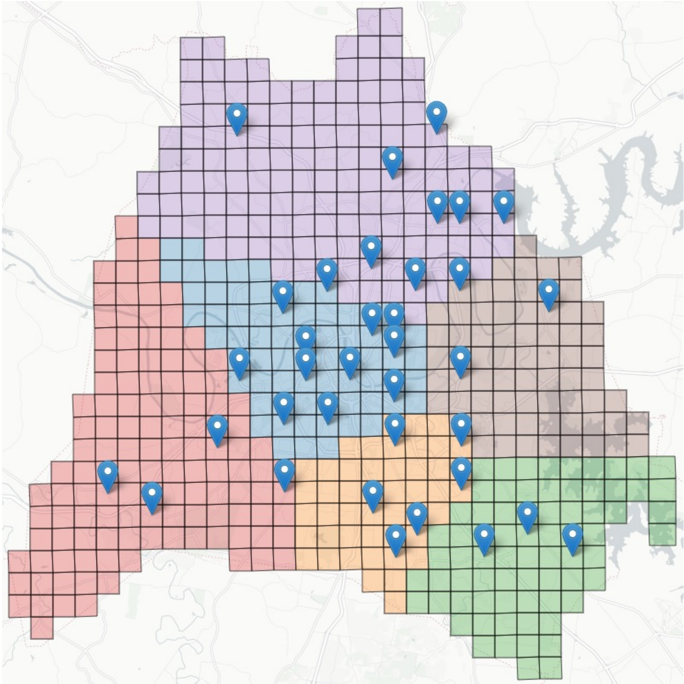
Example: 20 responders and 30 possible waiting locations (depots):

P(30, 20) = 30! / (30-20)! = **7.31 x 10^25** possible allocations!

Approach: Hierarchical Planning

- Split urban area into regions, similar to jurisdictions already used by response agencies. Assume each region is largely independent
- Significantly reduces complexity: splitting the above example into 5 evenly sized sub-problems gives us

  5 * P(6, 4) = 5 * 360 = **1800** possible allocations
- Within each region, can tractably solve the sub-problem using MCTS

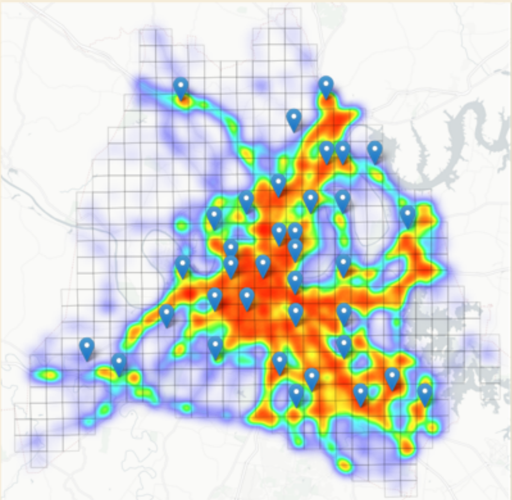


Davidson County, TN, with the locations of ambulance depots shown as pins. Colors represent a possible segmentation into 6 regions

HIERARCHICAL PLANNING

How to create regions?

- Use incident density to create clusters using standard approaches like k-means



How to allocate responders across regions?

- Approximate waiting times within a region using a multi-server queue model (M/M/c queue)
- Solve optimization problem to minimize the queue *waiting time*[1]

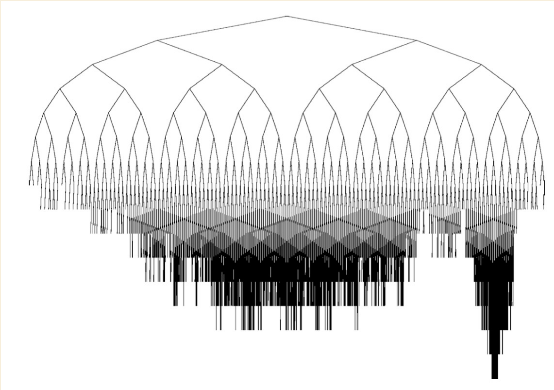
$$\min_{x} \sum_{j=1}^{k} w_j(x_j)$$

$$\text{s.t.} \quad \sum_{i=1}^{k} x_i = |\Lambda|$$

$$x_i \in \mathbb{Z}^{0+} \; \forall i \in \{1, \ldots, k\}$$

How to dynamically reallocate responders within each region?

- Use Monte-Carlo Tree Search combined with a generative incident prediction model to find best allocations.

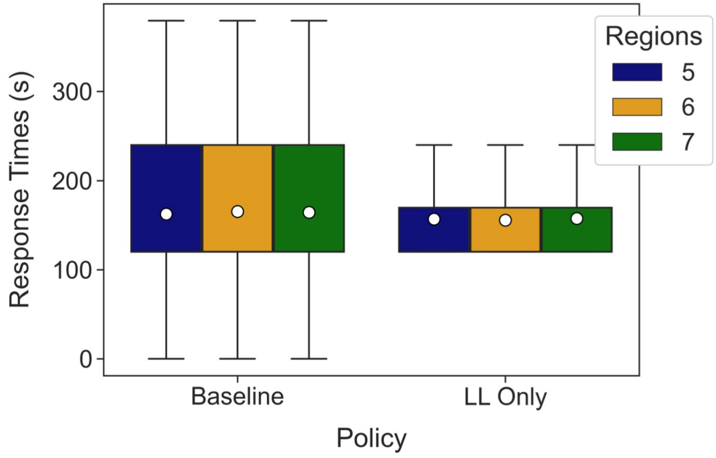


High Level Planner

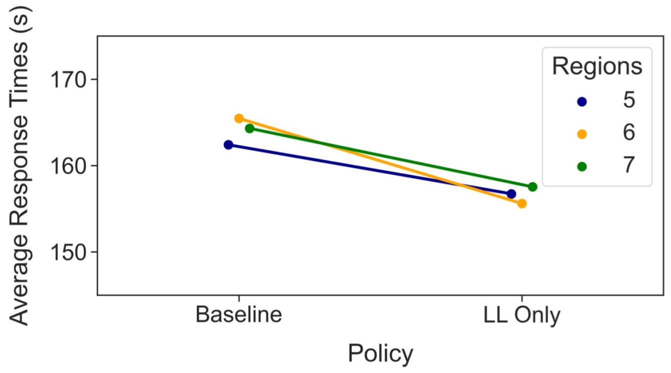
Low Level Planner

EXPERIMENTAL RESULTS

Stationary Experiments

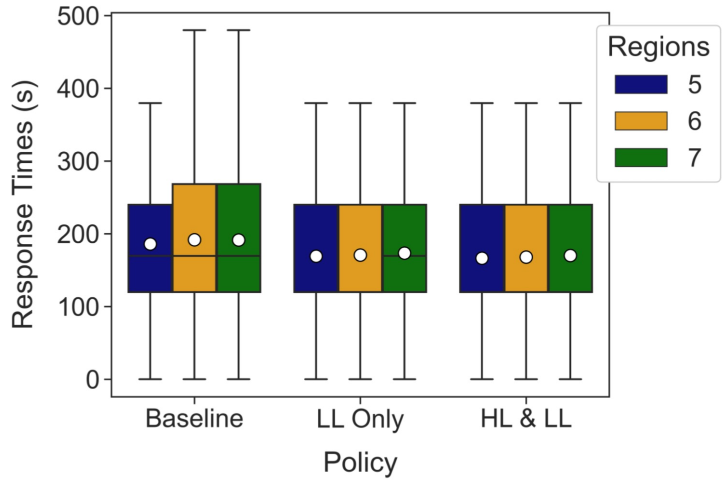


Dynamic allocation reduces upper quartile of response times by **71 seconds**

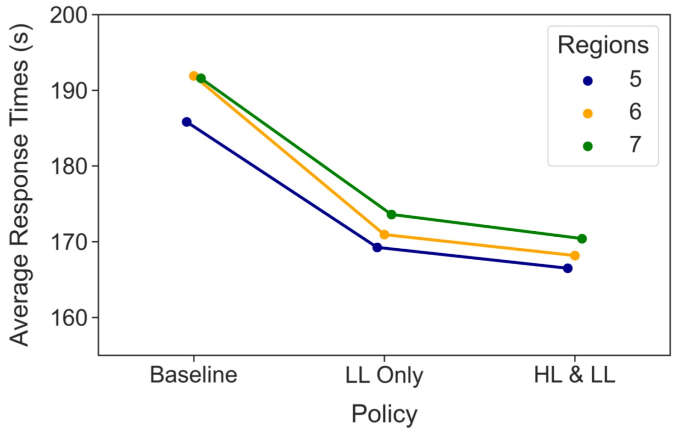


7.5 second reduction in mean response times

Non-Stationary Experiments



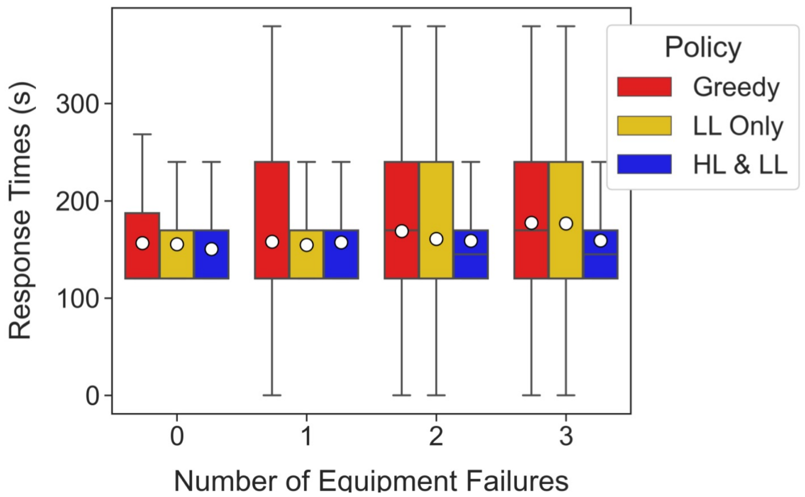
When incident spikes are introduced, the low-level planner alone reduces mean response times by **18.6 seconds**

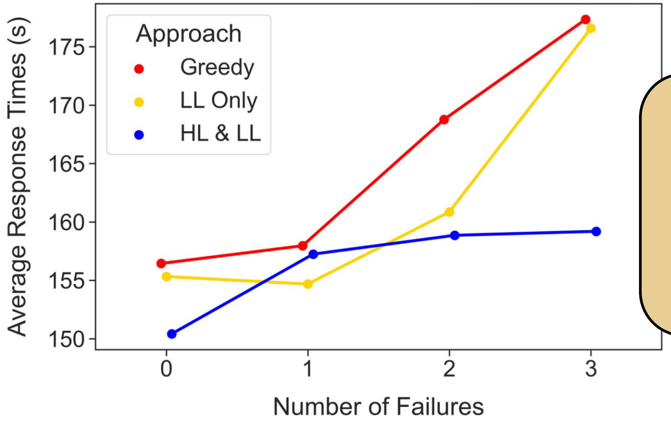


Adding high-level region rebalancing further improves response times – a **21.6 second** reduction

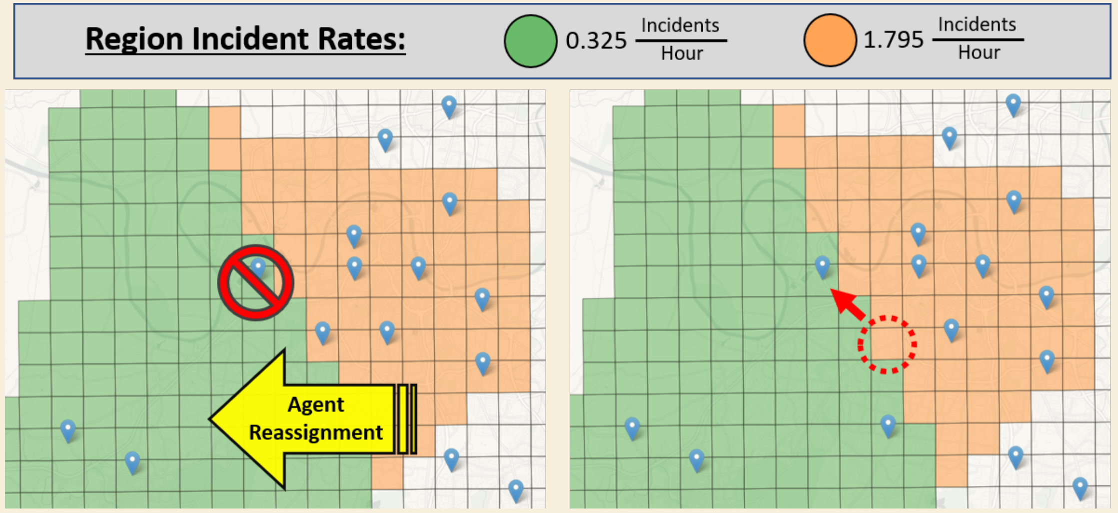
EXPERIMENTAL RESULTS

Ambulance Failure Experiments



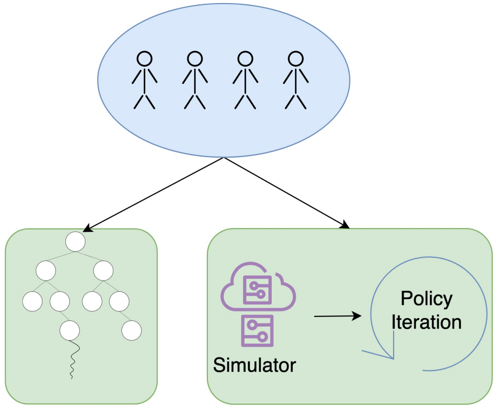


Failure Adaptation Example



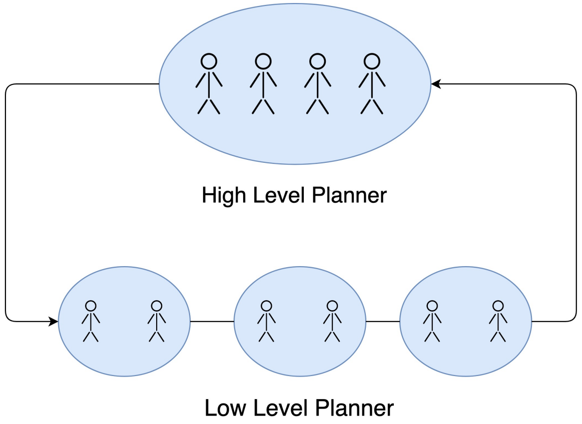
High-level region rebalancing makes the system more resilient to ambulance failure; improves response times by over **20 seconds** on average when 3 failures occur

MULTI-AGENT PLANNING FOR EMERGENCY RESPONSE



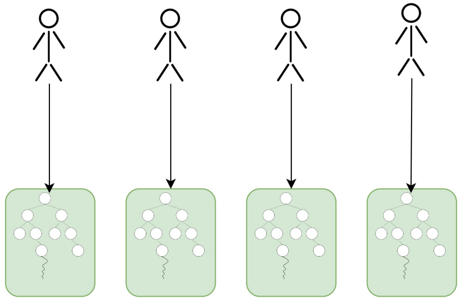
Centralized Planning

Relatively small state space
Complete communication
Unsuitable for dynamic environments



Hierarchical Planning

Tractable for large state spaces
Complete communication within sub-problems
Can adapt to dynamic environments



Decentralized Planning

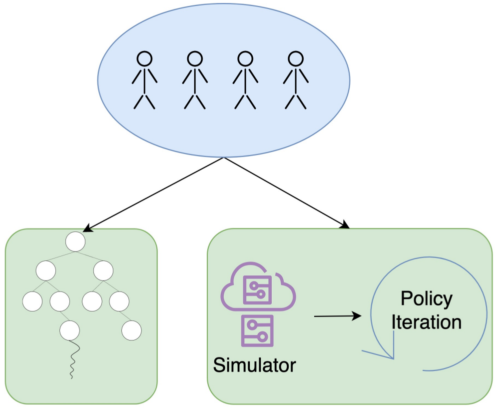
Tractable for large state spaces
Limited communication
Can adapt to dynamic environments

Scalability →

Problem with Coordination →

← Optimality

MULTI-AGENT PLANNING FOR EMERGENCY RESPONSE



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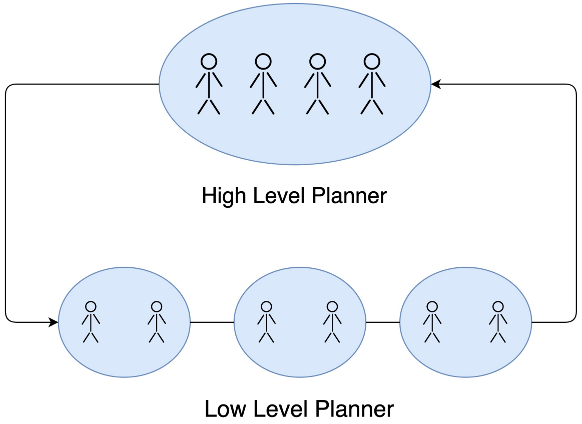

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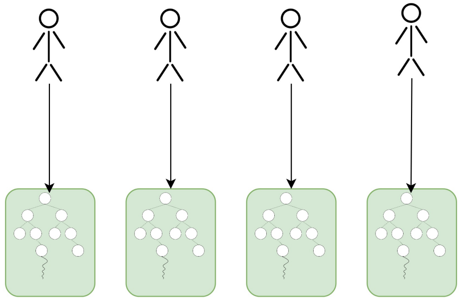

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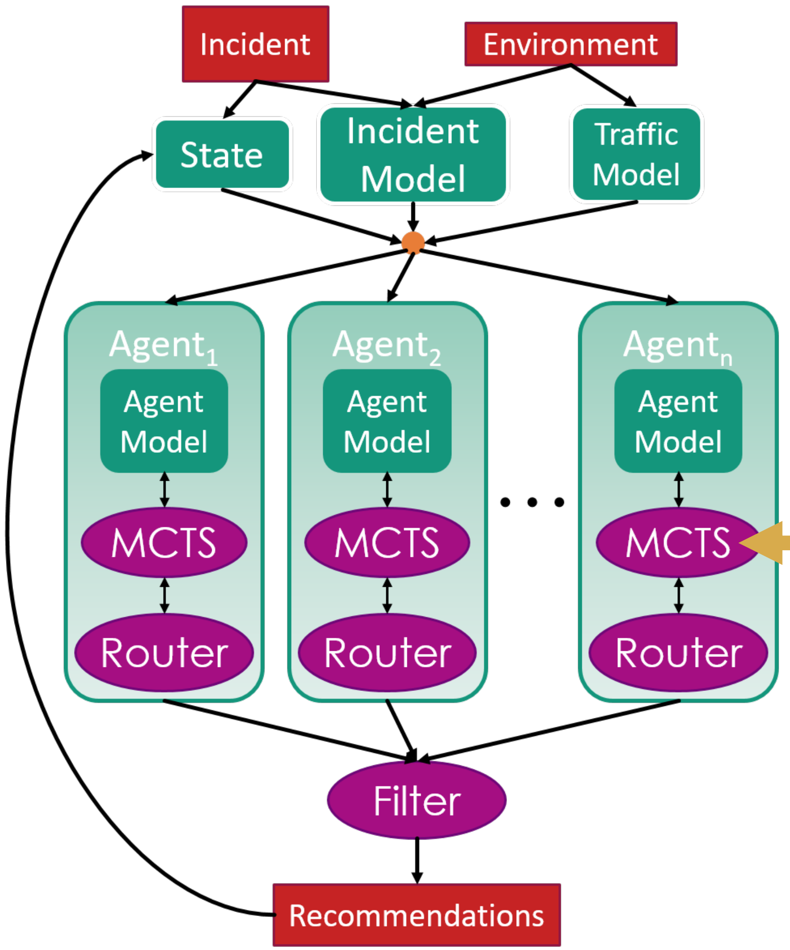
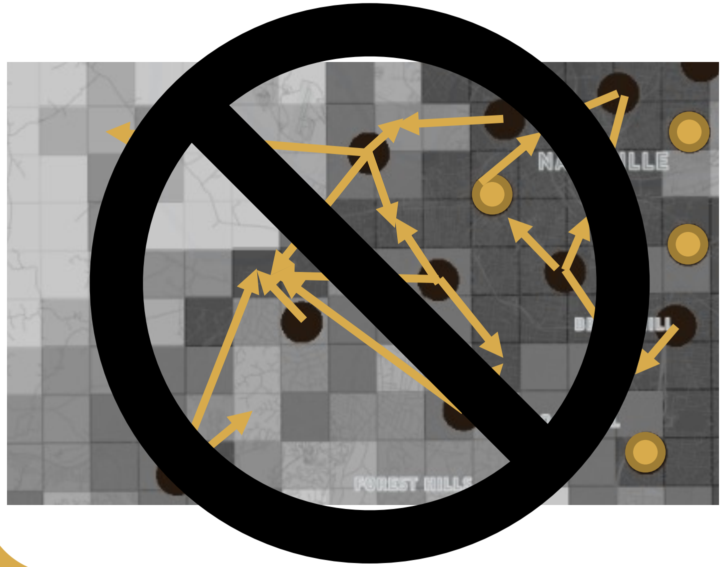
HOW CAN AGENTS PLAN UNDER COMMUNICATION UNCERTAINTY?

- In December 2020, a bomb attack in Nashville downtown destroyed AT&T’s communication infrastructure.
- There were extended outages for 66 public-safety answering points.
- Emergency Response was affected in four states for multiple days.
- Communication also gets hampered during natural disasters like hurricanes.

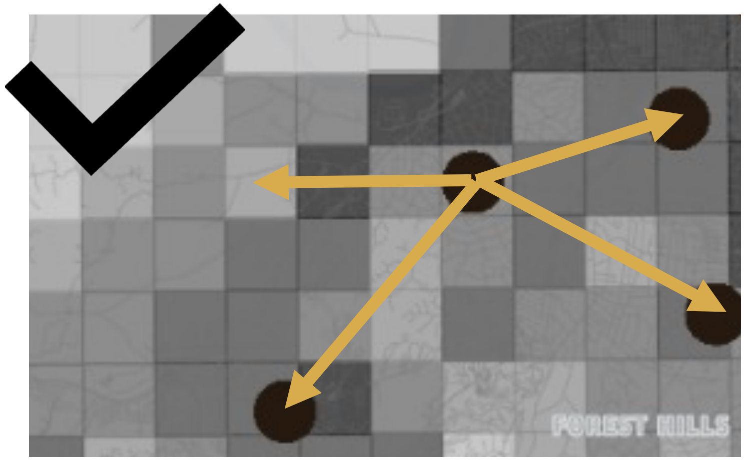
Partially Decentralized Decision Process



Monolithic State Space

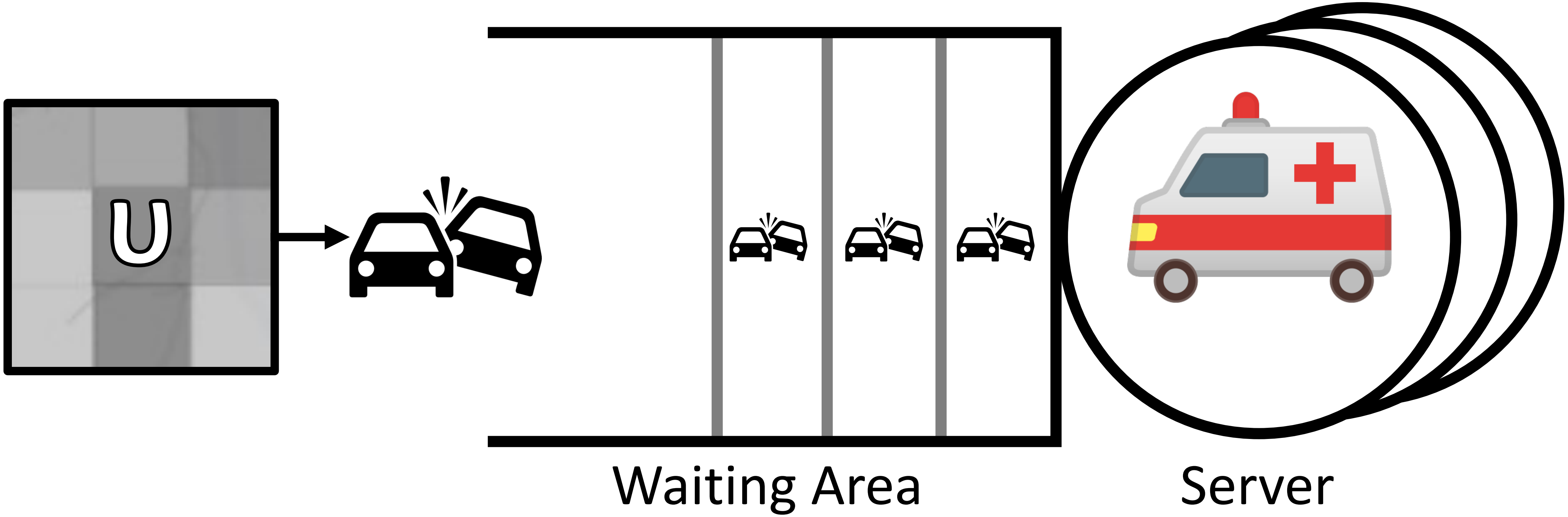


State space split for each agent



Standard MCTS;
Action space limited to relevant actions for the Agent

APPROXIMATE AGENT BEHAVIOR



Grid Cell incident rate := υ → Incidents Placed in Waiting Queue → Ambulances ‘serve’ incidents with mean rate := μ

The “responsibility” of responding to an area is split among several agents. Each agent calculates this responsibility and assumes every agent will do the same.

APPROXIMATE AGENT BEHAVIOR

Distributed MCTS – Takeaways

- ***Pros:***
  - Scales very well as the number of agents increases
  - Resilient to communication failures
- ***Cons***:
  - Requires many assumptions regarding agent behavior – can lead to suboptimal decision making
  - Many hyperparameters that must be tuned

Grid Cell incident rate := **υ** → Incidents Placed in Waiting Queue → ...erve' incidents with mean rate := **μ**

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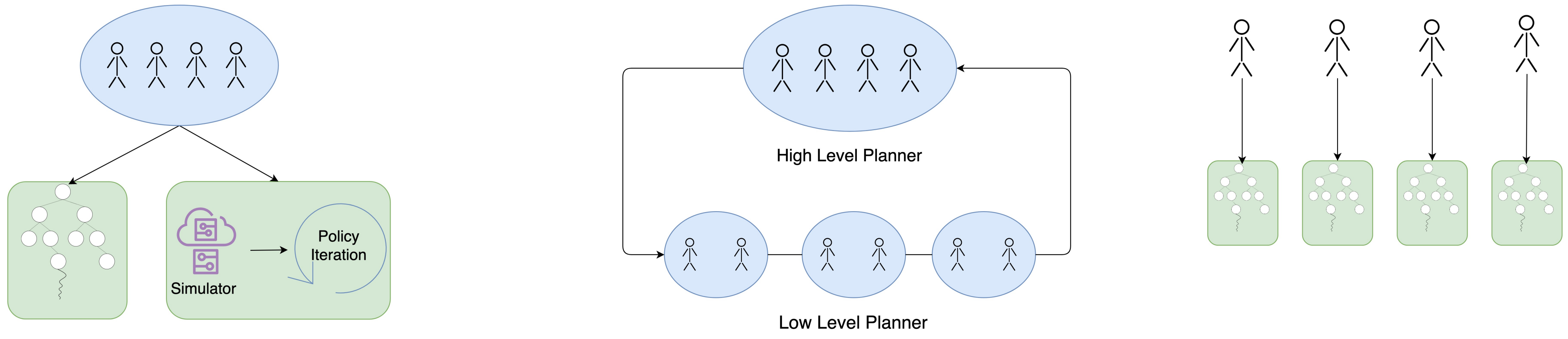

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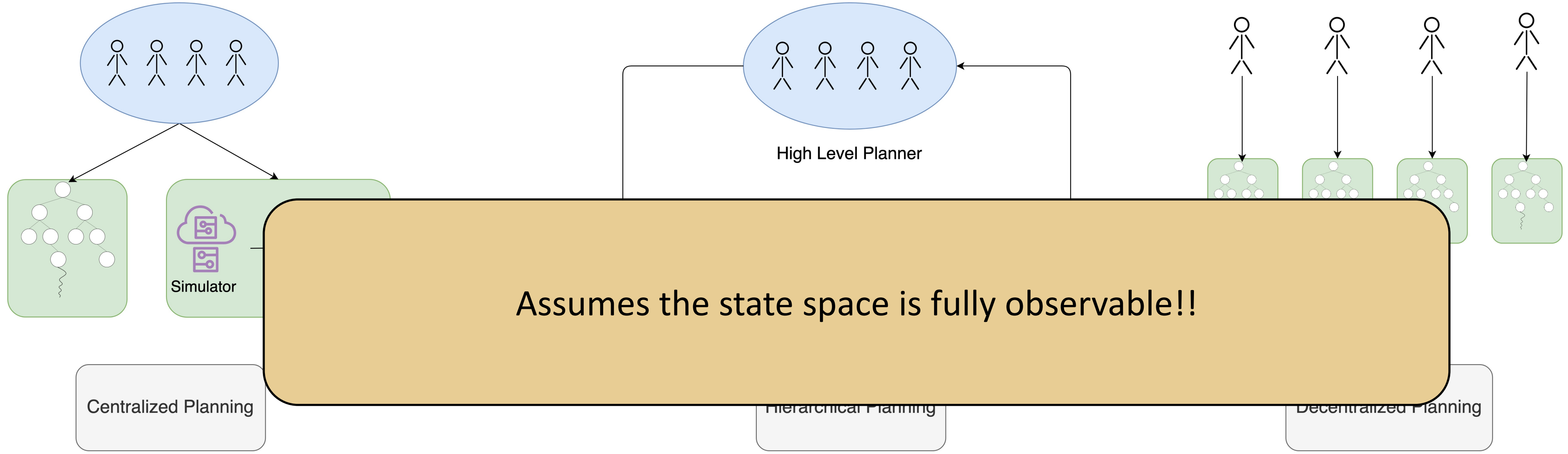

Assumes the state space is fully observable!!

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HOW CAN MULTI-AGENT SYSTEMS OPERATE UNDER STATE UNCERTAINTY?

- In 2018, a large wildfire (named Camp Fire) in California resulted in the loss of 88 lives, displaced countless more, and destroyed more than 18,500 structures.

- Due to the lack of ground surveillance and smoke prohibiting accurate air surveillance, how can agents respond to fires?

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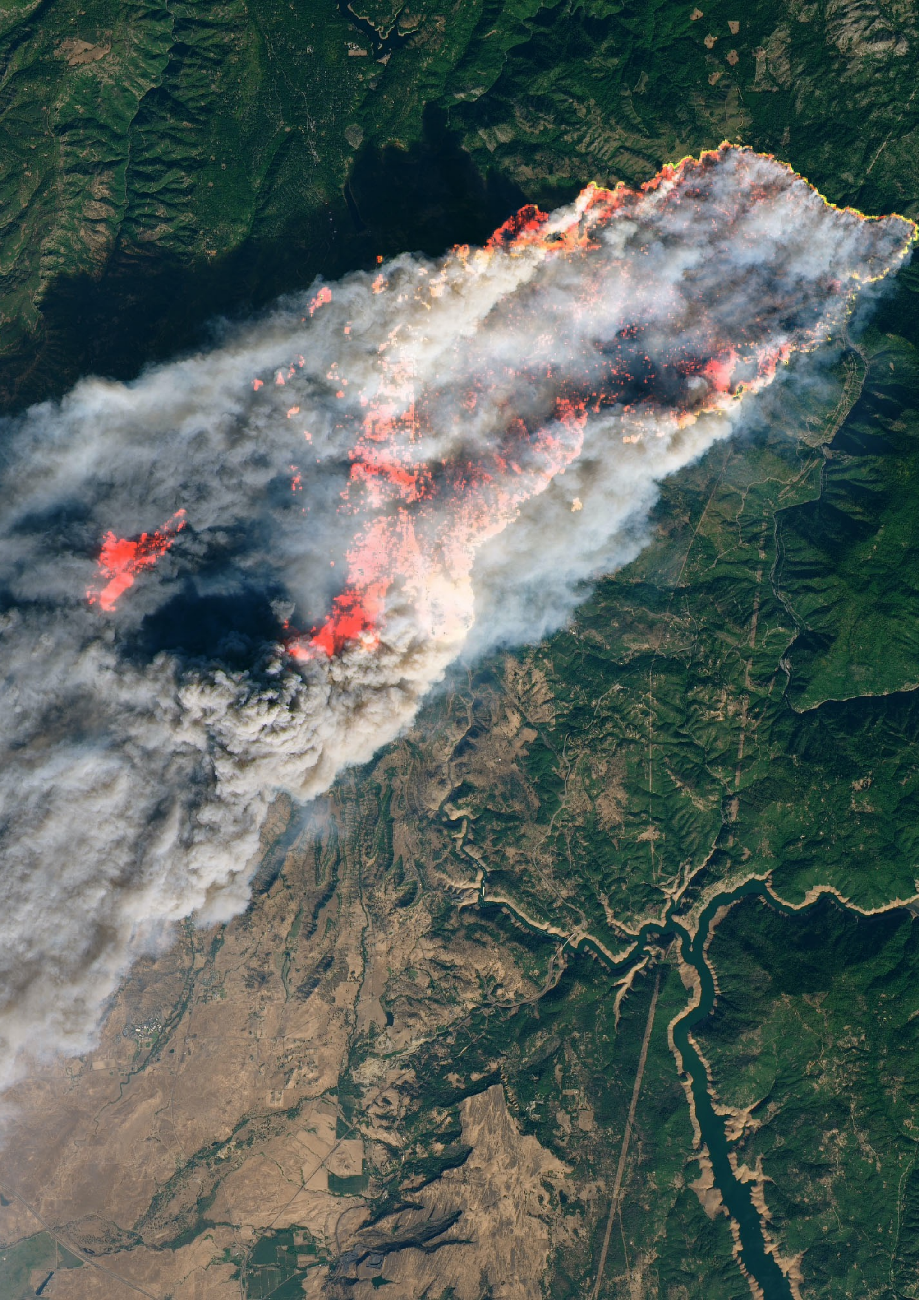
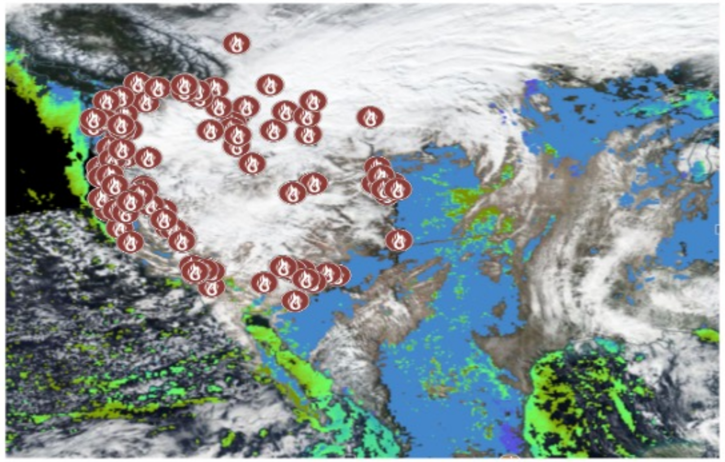


HOW CAN MULTI-AGENT SYSTEMS OPERATE UNDER STATE UNCERTAINTY?

- Unpredictable spread
  - Susceptible to sudden wind changes.
  - Vegetation and fuel dependent.

- Unobservable true state of the fires
  - Smoke covering the fire or otherwise inaccessible areas
  - Delay in communication

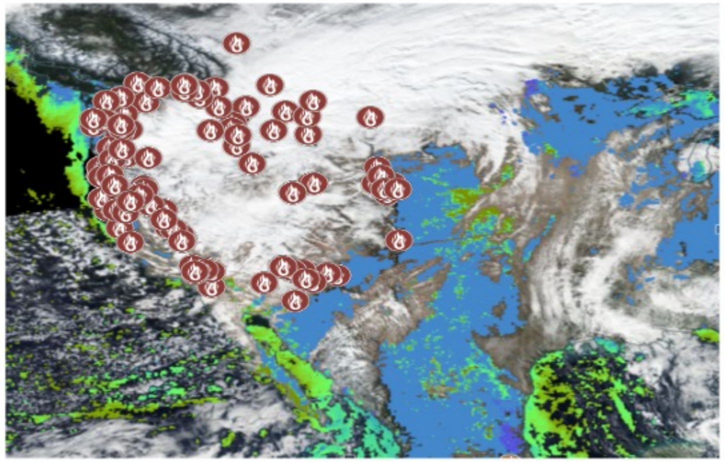
Aggregating Wildfire Data



Fire Occurrence Data

Fire Relevant Geospatial Features Data

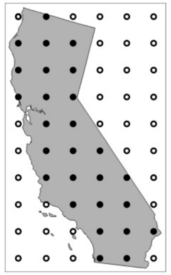
Aggregating Wildfire Data



Fire Occurrence Data

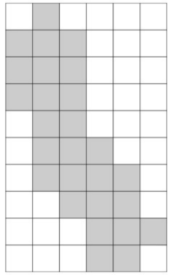
Fire Relevant Geospatial Features Data

Vectorize the raster data



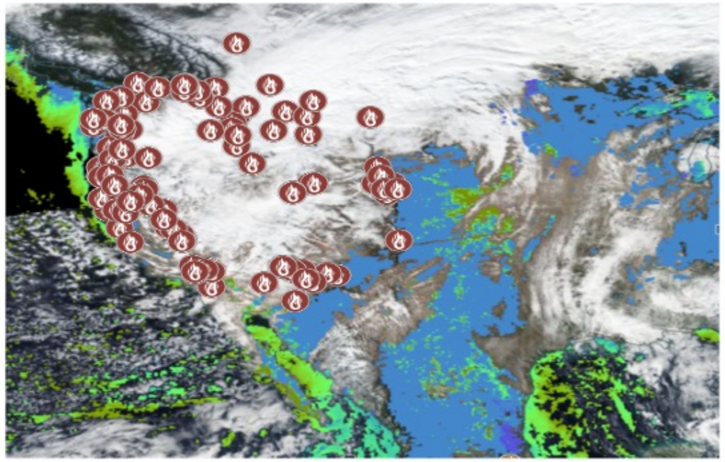
Executes a point in polygon query for each pixel (21 billion pixels)

Rasterize the vector data



Clips each raster layer for each fire cell (3 million polygons)

Aggregating Wildfire Data



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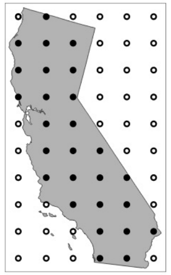

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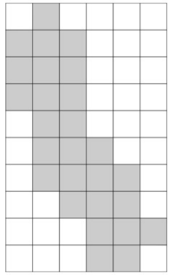
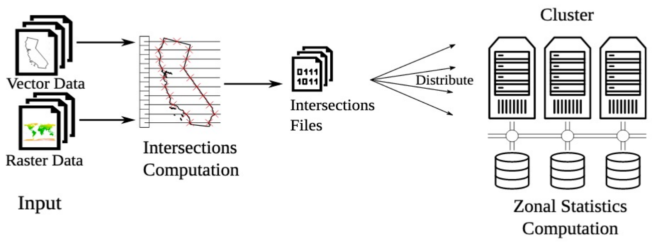


Clips each raster layer for each fire cell (3 million polygons)

We use a novel approach, *Raptor Zonal Statistics*:

- does not convert data from one form to another
- computes an intermediate data structure, *intersection file*
- serves as a map between raster and vector data
- used to leverage parallel computation
- scans the raster dataset only once

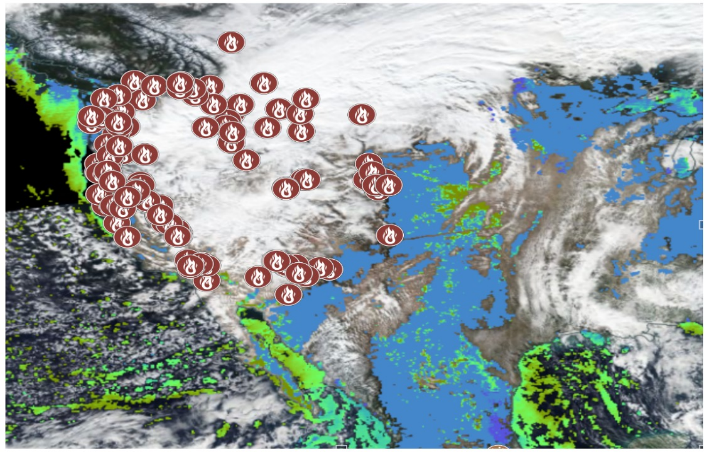


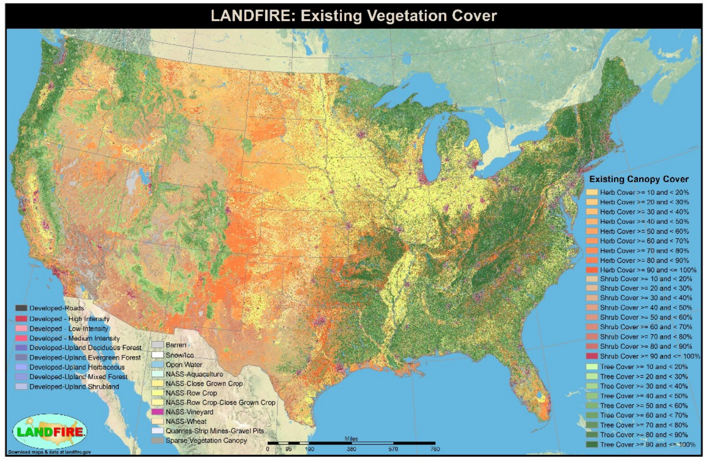
WildfireDB: An Open-Source Wildfire Dataset

- First open-source wildfire database that combines wildfire occurrences, weather, and covariates from satellite imagery.
- > 17 million data points.
- Features – vegetation type, vegetation height, topography, wind direction and strength relative to the spread for all wildfires that occurred in the US since 2012.
- Spatial granularity of 375m x 375m.

Data Example

Polygon ID	Acquisition Date	FRP	Neighbor Polygon ID	Neighbor FRP	Canopy Base Density max.	Canopy Base Density min.	Canopy Base Density median	Canopy Base Density sum	Canopy Base Density mode	Canopy Base Density count	Canopy Base Density mean	...	Neighbor Slope max.	Neighbor Slope min.	Neighbor Slope median	Neighbor Slope sum	Neighbor Slope mode	Neighbor Slope count	Neighbor Slope mean
7234	2012-01-16	3.20	7233	0.0	0.0	13.0	0.0	9.0	1303.0	0.0	156	...	37.0	3.0	17.0	3109.0	24.0	169.0	18.396450





WILDFIRE RESPONSE : SYSTEM MODEL

We formulate the dynamic decision framework as a POMDP (partially observable Markov decision process):

- States $\mathcal{S}$: $s_t = \{X_t, F_t\}$, where
  - $X_t = \{X_t^1, X_t^2, \ldots, X_t^k\}$: the status of the fire (binary) denotes, and
  - $F_t = \{F_t^1, F_t^2, \ldots, F_t^k\}$: the fuel level in each cell in G (integer)
- Actions $\mathcal{A}$: the different permutations of cell indices
  - That suppression efforts may apply to
  - Up to a maximum number as a resource constraint
- State transitions $T(s' \mid s, a)$: the conditional transition probability from state s to s' when action a is taken. It includes:
  1. **Burning**: fuel decrements in previously burning cells
  2. **Action effectiveness**: a probability q that an action was successful
  3. **Fire dynamics**: a generative model to simulate the spread of fire

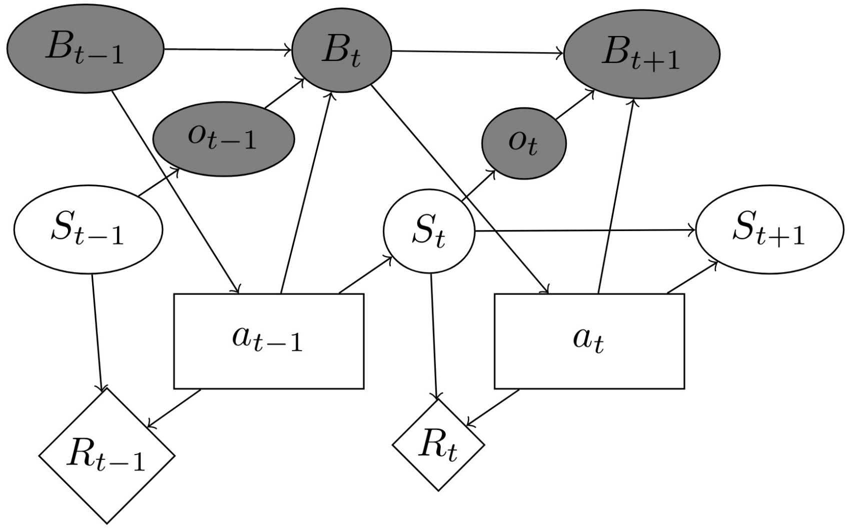
WILDFIRE RESPONSE : SYSTEM MODEL

- Observations $\mathcal{O}$: o_t^i denotes whether cell i is seen burning in time step t.
- Observation transitions $Z(o \mid s, a)$: the probability of receiving observation o at state s when action a is taken.
- Reward function $R : \mathcal{S} \times \mathcal{A} \rightarrow \mathbb{R}$, such that

$$R(s_t, a) = \sum_{g_i \in G} x_t^i U(g_i)$$

where $U(g_i)$ denotes the utility for a cell $g_i \in G$ to be on fire.

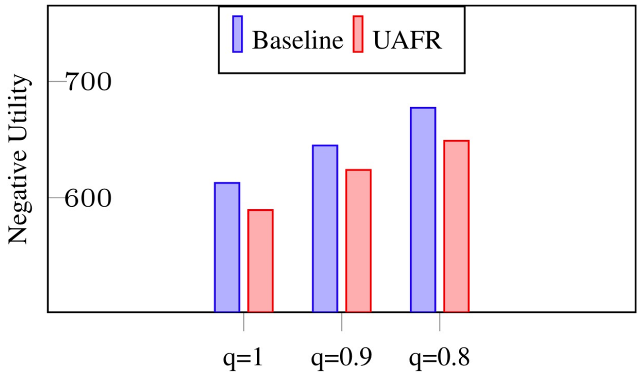
WILDFIRE RESPONSE : APPROACH



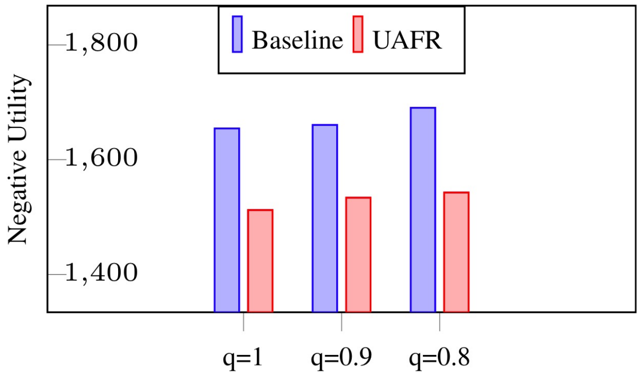
We solve the POMDP using a sampling-based Online Monte Carlo Tree Search (MCTS) algorithm

- Built upon the partially observable Monte Carlo planning algorithm with observation widening (POMCPOW)[1].
- Replaced the weighted particle filter with particle filter without rejection, to combat observation sparsity.

WILDFIRE RESPONSE : RESULTS



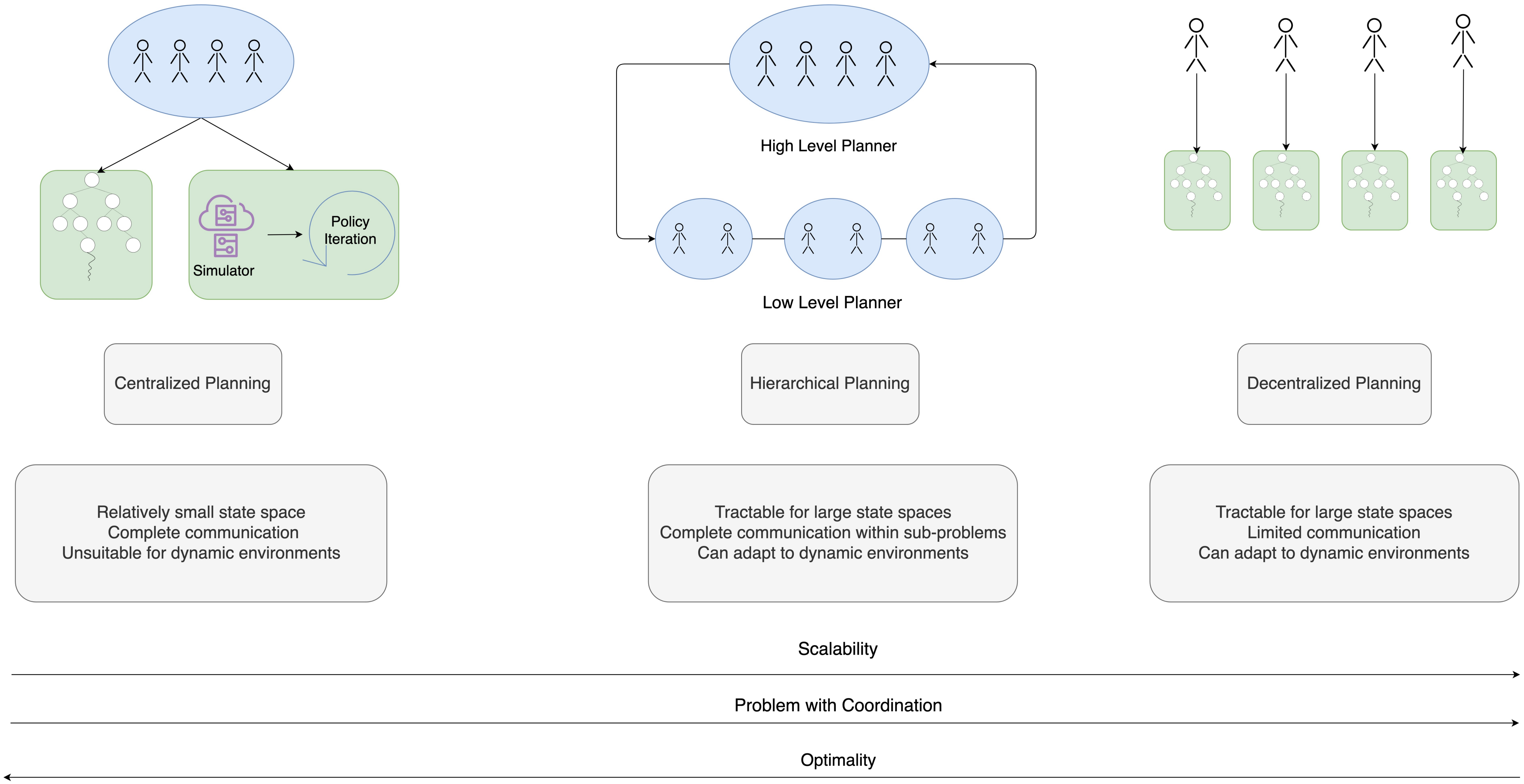
Effectiveness comparison 10 × 10 grid



Effectiveness comparison 12 × 12 grid

- We see that Uncertainty-Aware Fire Response does significantly better than baseline methods.
- q denotes action effectiveness. In the field, every time a fire is responded to, it is not necessarily put out.
- Baseline results : It is hard to scale POMDP solutions to large areas. We are currently exploring how active human-agent collaboration can help scale to larger areas.

MULTI-AGENT PLANNING FOR EMERGENCY RESPONSE



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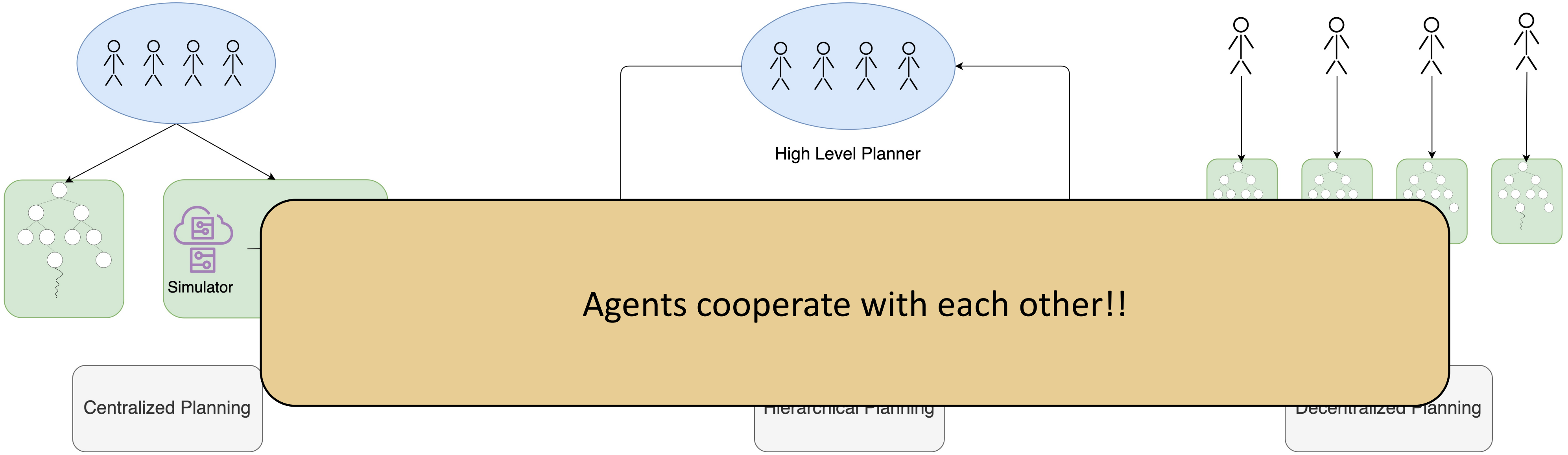

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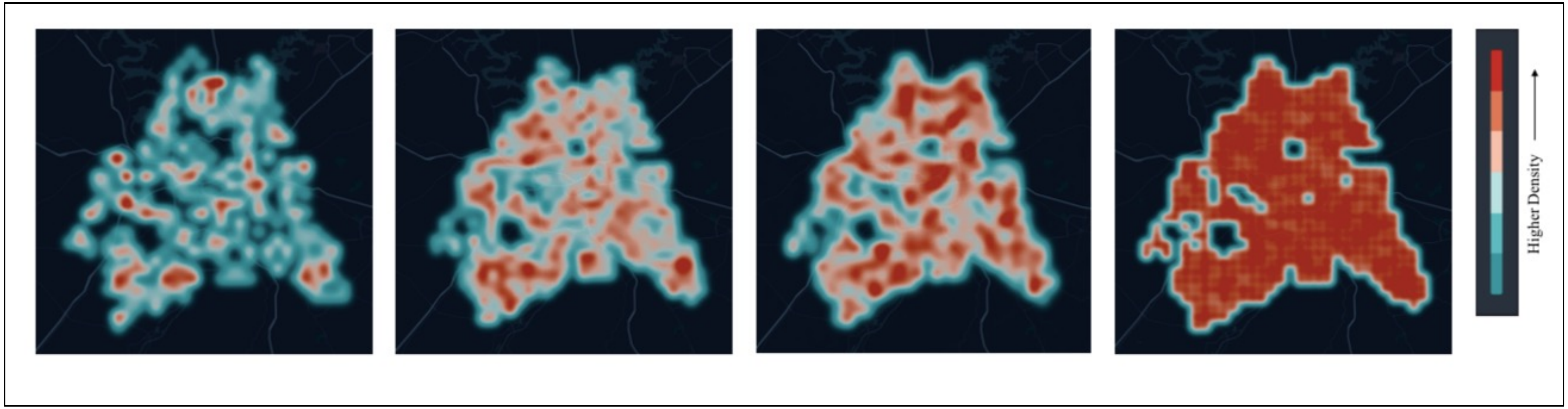
HOW CAN AGENTS PLAN UNDER ADVERSARIAL BEHAVIOR?

- Multi-agent systems are often deployed against adversarial agents.
- Consider poaching; typically, poachers can wait and observe patrols and shift their locations for committing illegal activities.
- How can agents plan if the underlying distribution of incidents “reacts” to the planned agent behavior?

HANDLING ADVERSARIAL INTERACTIONS

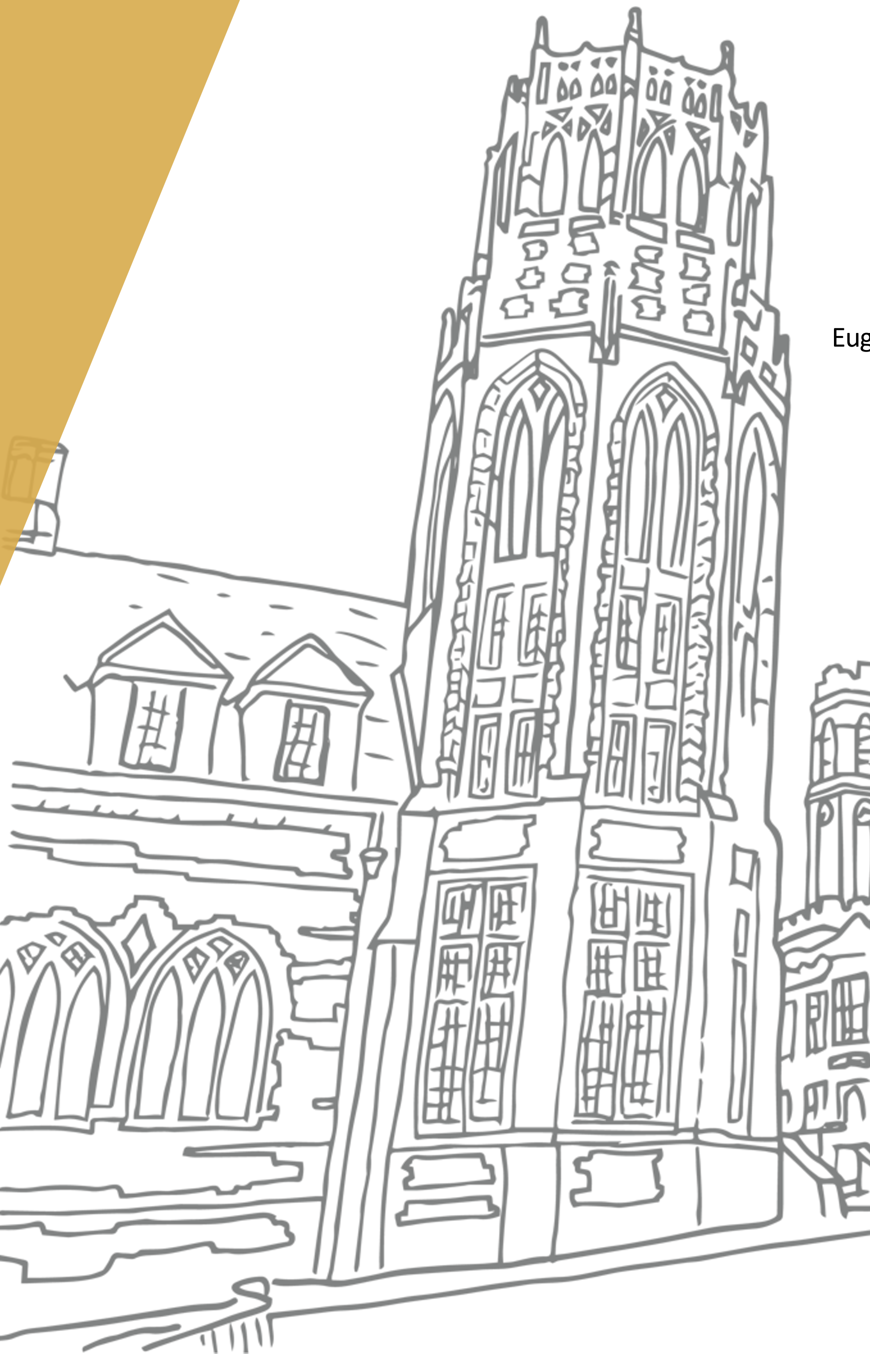
- We created two algorithmic approaches, one optimal and relatively slow and another that trades optimality for efficiency.
- Our approach works on any off-the-shelf ML approach and makes it robust to spatial shifts.

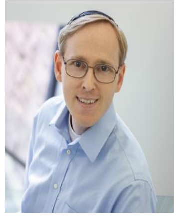
$$\underbrace{\max_{\theta} \min_{s \in S}}_{\text{Hierarchy}} \sum_{d_i \in D} \underbrace{f(x_i(s); \theta, w)}_{\text{Combinatorial + Discrete}}$$



Open Questions/Current Interests

- What if the environment itself is computationally challenging to replicate? Consider the interaction of wildfire and power systems.
- Can learning be integrated into decision-making?
- How can multi-agent POMDPs scale to real-world scenarios concerning emergency response?




Eugene Vorobeychik


Mykel Kochenderfer


Abhishek Dubey

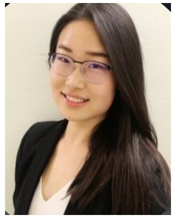

Milind Tambe


Gautam Biswas


Paul Speer


Hendrik Baier


Geoffrey Pettet


Zilin Wang

VANDERBILT UNIVERSITY

Washington University in St. Louis

Stanford University

ISIS Institute for Software Integrated Systems

CRCS Center for Research on Computation and Society at Harvard John A. Paulson School of Engineering and Applied Sciences

CARS

NSF

TN TDOT Department of Transportation

UC RIVERSIDE

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Thank you!

ayan.mukhopadhyay@vanderbilt.edu

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Relevant Publications

- Pettet, Geoffrey, Ayan Mukhopadhyay, Mykel J. Kochenderfer, and Abhishek Dubey. "Hierarchical planning for resource allocation in emergency response systems." In *Proceedings of the ACM/IEEE 12th International Conference on Cyber-Physical Systems*, pp. 155-166. 2021.

- Mukhopadhyay, Ayan, Kai Wang, Andrew Perrault, Mykel Kochenderfer, Milind Tambe, and Yevgeniy Vorobeychik. "Robust Spatial-Temporal Incident Prediction." In *Conference on Uncertainty in Artificial Intelligence*, pp. 360-369. PMLR, 2020.

- Pettet, Geoffrey, Ayan Mukhopadhyay, Mykel Kochenderfer, Yevgeniy Vorobeychik, and Abhishek Dubey. "On algorithmic decision procedures in emergency response systems in smart and connected communities." *arXiv preprint arXiv:2001.07362* (2020).

- Mukhopadhyay, Ayan, Geoffrey Pettet, Chinmaya Samal, Abhishek Dubey, and Yevgeniy Vorobeychik. "An online decision-theoretic pipeline for responder dispatch." In *Proceedings of the 10th ACM/IEEE International Conference on Cyber-Physical Systems*, pp. 185-196. 2019.

- Mukhopadhyay, Ayan, Zilin Wang, and Yevgeniy Vorobeychik. "A decision theoretic framework for emergency responder dispatch." In *International Conference on Autonomous Agents and Multiagent Systems*. 2018.

- Mukhopadhyay, Ayan, and Yevgeniy Vorobeychik. "Prioritized allocation of emergency responders based on a continuous-time incident prediction model." In *International Conference on Autonomous Agents and MultiAgent Systems*. 2017.

- Mukhopadhyay, Ayan, Chao Zhang, Yevgeniy Vorobeychik, Milind Tambe, Kenneth Pence, and Paul Speer. "Optimal allocation of police patrol resources using a continuous-time crime model." In *International Conference on Decision and Game Theory for Security*, pp. 139-158. Springer, Cham, 2016.