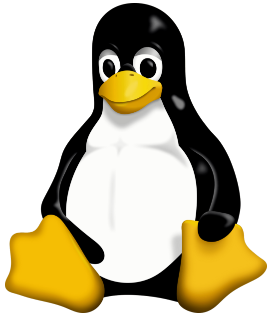
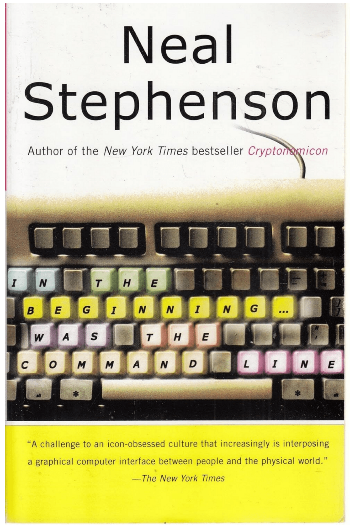
A bit about me



Linux



Teaching is only half of my job...

Autonomous Decision and Control Laboratory

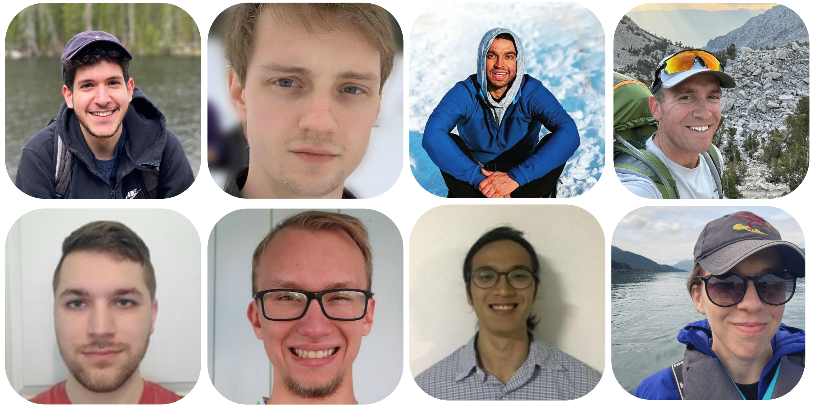
cu-adcl.org

University of Colorado **Boulder**

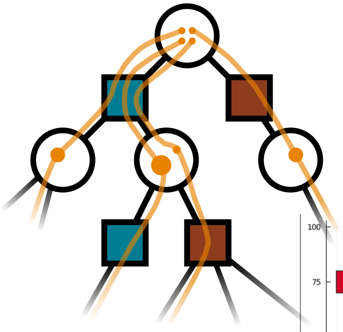
PI: Prof. Zachary Sunberg

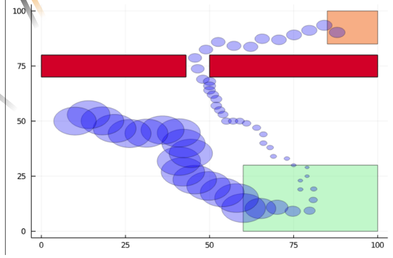
Postdoc

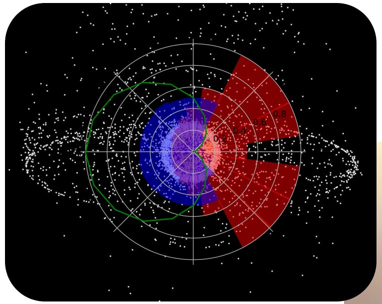
PhD Students

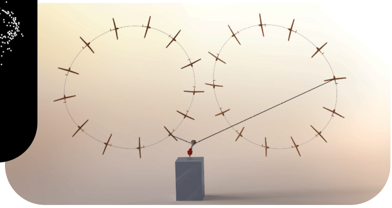


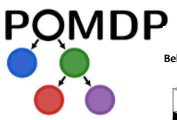
- **Algorithmic Contributions**
  - Scalable algorithms for partially observable Markov decision processes (POMDPs)
  - Motion planning with safety guarantees
  - Game theoretic algorithms
- **Theoretical Contributions**
  - Particle POMDP approximation bounds
- **Applications**
  - Space Domain Awareness
  - Autonomous Driving
  - Autonomous Aerial Scientific Missions
  - Search and Rescue
  - Space Exploration
  - Ecology
- **Open Source Software**
  - POMDPs.jl Julia ecosystem

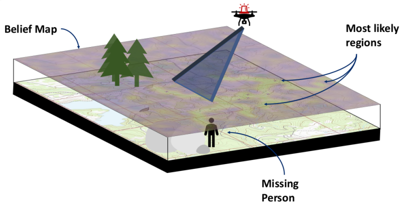


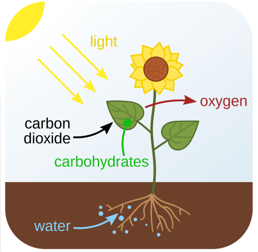










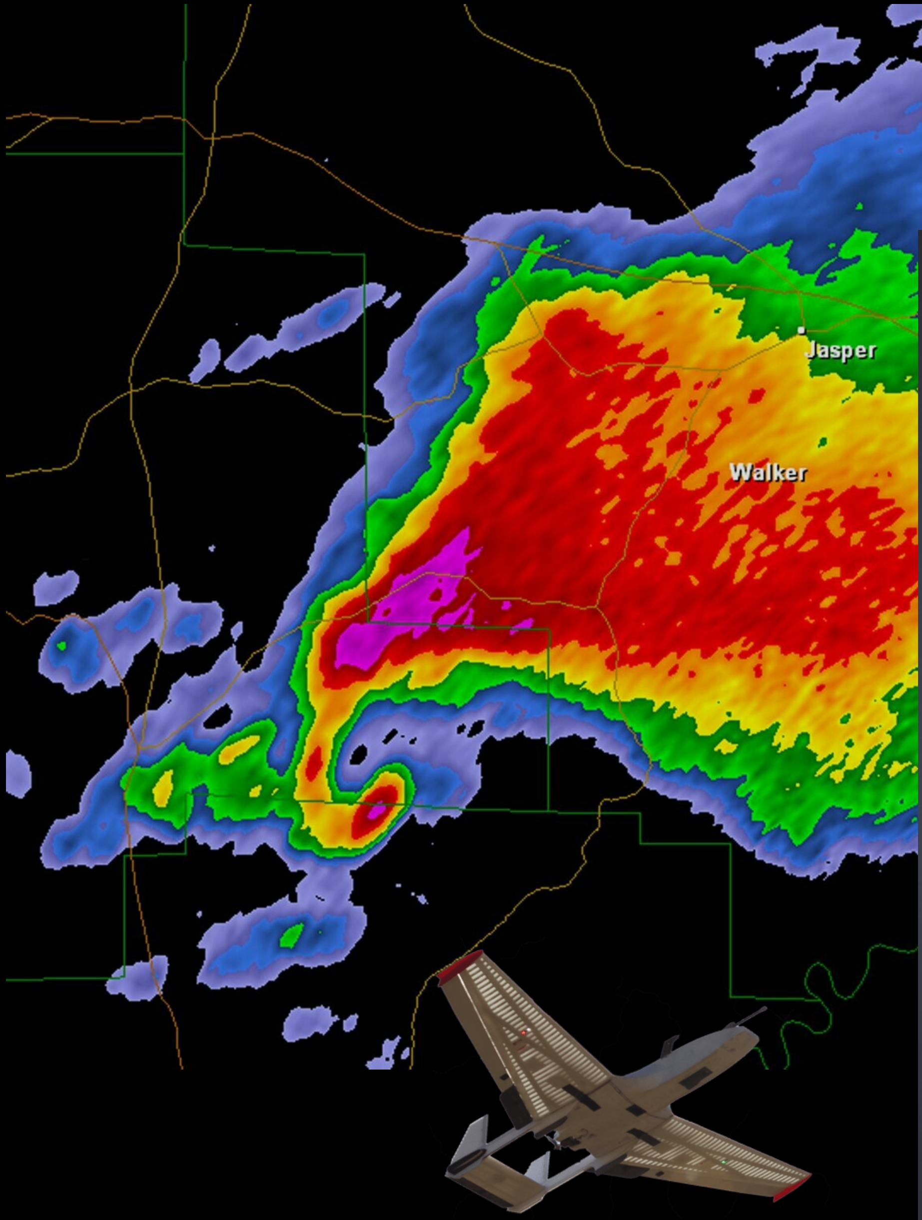


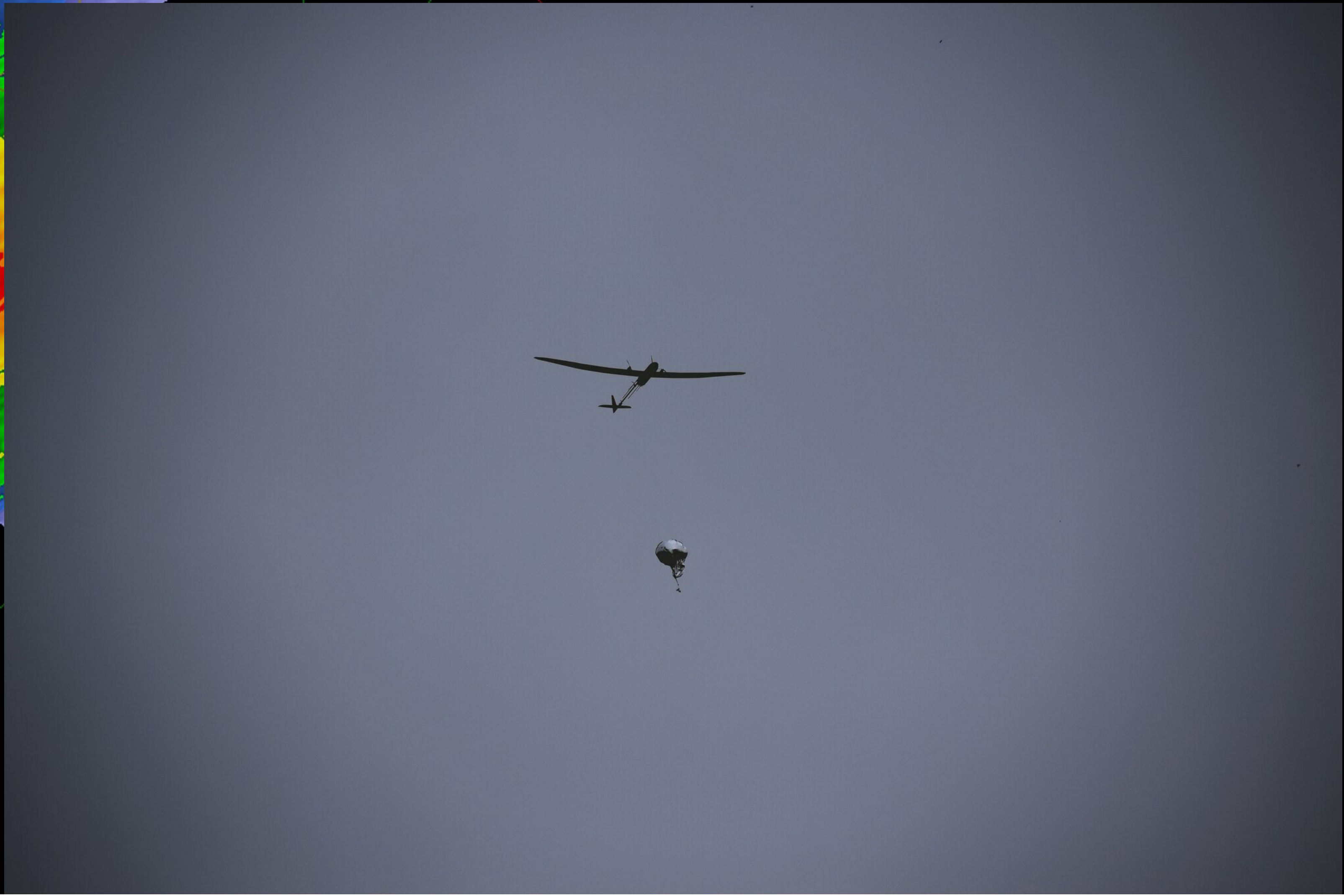
Example 1: Autonomous Driving

Tweet by Nitin Gupta
29 April 2018
https://twitter.com/nitguptaa/status/990683818825736192

Video: Eric Frew

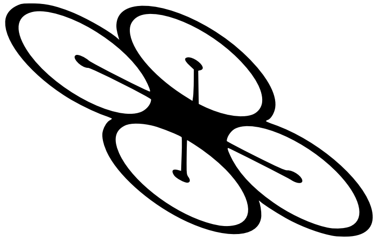
Example 2: Tornados





Example 3: Search and Rescue

What do they have in common?



All are sequential decision-making problems with uncertainty!

Driving: what are the other road users going to do?

Tornado Forecasting: what is going on in the storm?

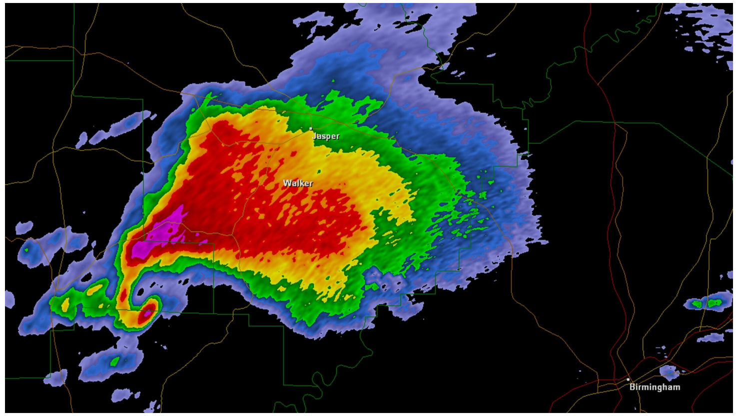
Search and Rescue: where is the lost person?

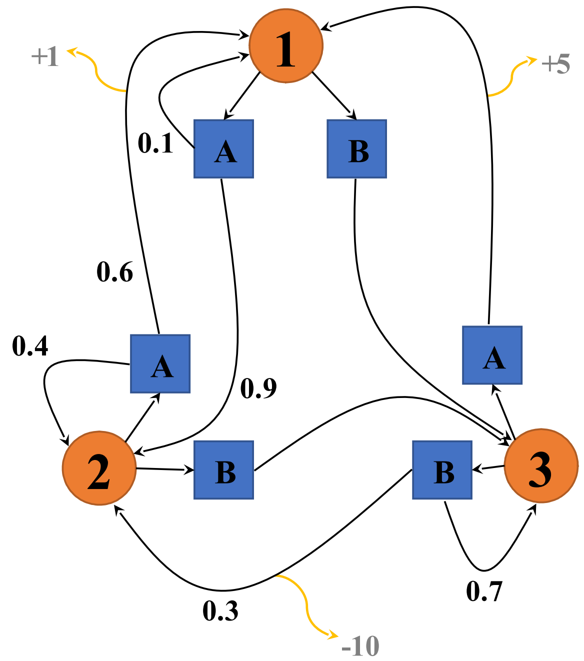
All can be modeled as a **POMDP** (with a very large state and observation spaces).

Markov Decision Process (MDP)

$$[x, y, z, \quad \phi, \theta, \psi, \quad u, v, w, \quad p, q, r]$$

$$\mathcal{S} = \mathbb{R}^{12} \times \mathbb{R}^{\infty}$$





- $\mathcal{S}$ - State space
- $T : \mathcal{S} \times \mathcal{A} \times \mathcal{S} \to \mathbb{R}$ - Transition probability distribution
- $\mathcal{A}$ - Action space
- $R : \mathcal{S} \times \mathcal{A} \to \mathbb{R}$ - Reward

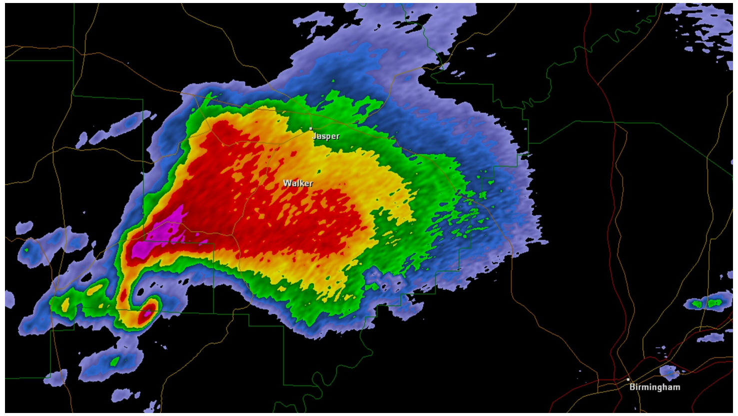
$$\underset{\pi : \mathcal{S} \to \mathcal{A}}{\text{maximize}} \quad \mathrm{E}\left[\sum_{t=0}^{\infty} R(s_t, a_t)\right]$$

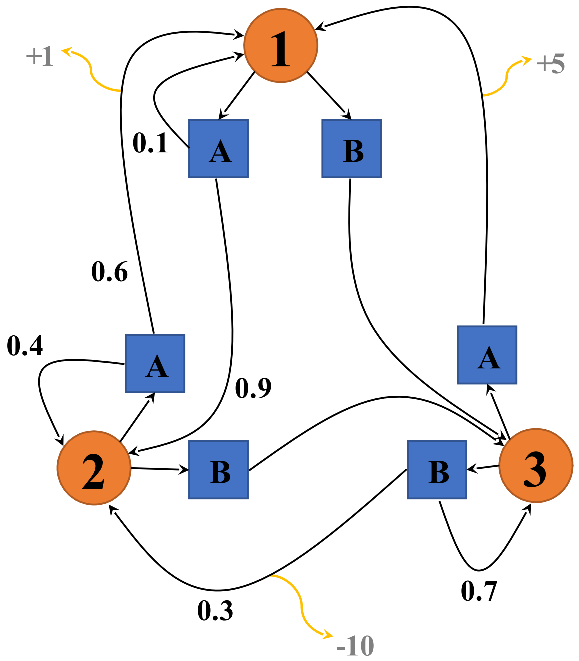
Aleatory

Reinforcement Learning

$$[x, y, z, \quad \phi, \theta, \psi, \quad u, v, w, \quad p, q, r]$$

$$\mathcal{S} = \mathbb{R}^{12} \times \mathbb{R}^{\infty}$$





- $\mathcal{S}$ - State space
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- $\mathcal{A}$ - Action space
- $R : \mathcal{S} \times \mathcal{A} \to \mathbb{R}$ - Reward

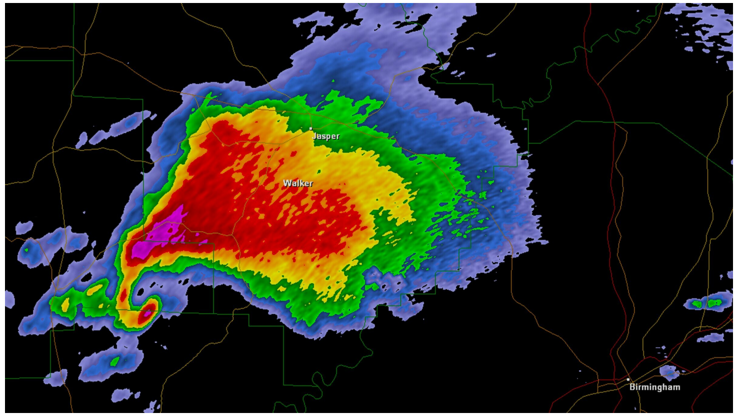
Aleatory

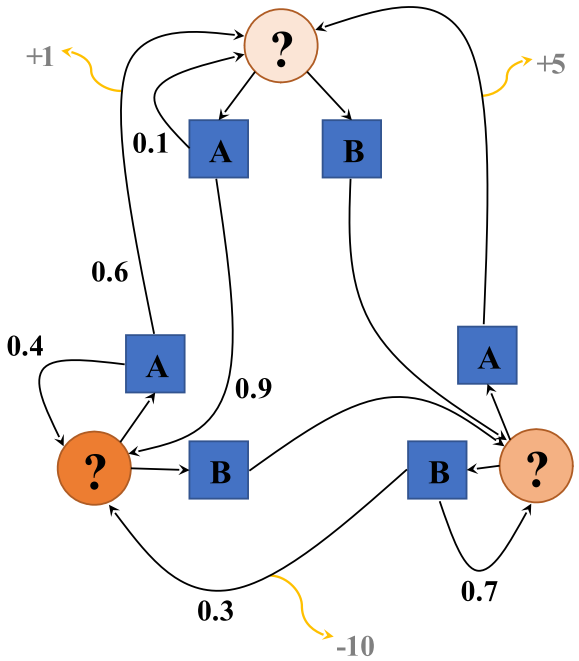
Epistemic (Static)

Partially Observable Markov Decision Process (POMDP)

$$[x, y, z, \quad \phi, \theta, \psi, \quad u, v, w, \quad p, q, r]$$

$$\mathcal{S} = \mathbb{R}^{12} \times \mathbb{R}^{\infty}$$





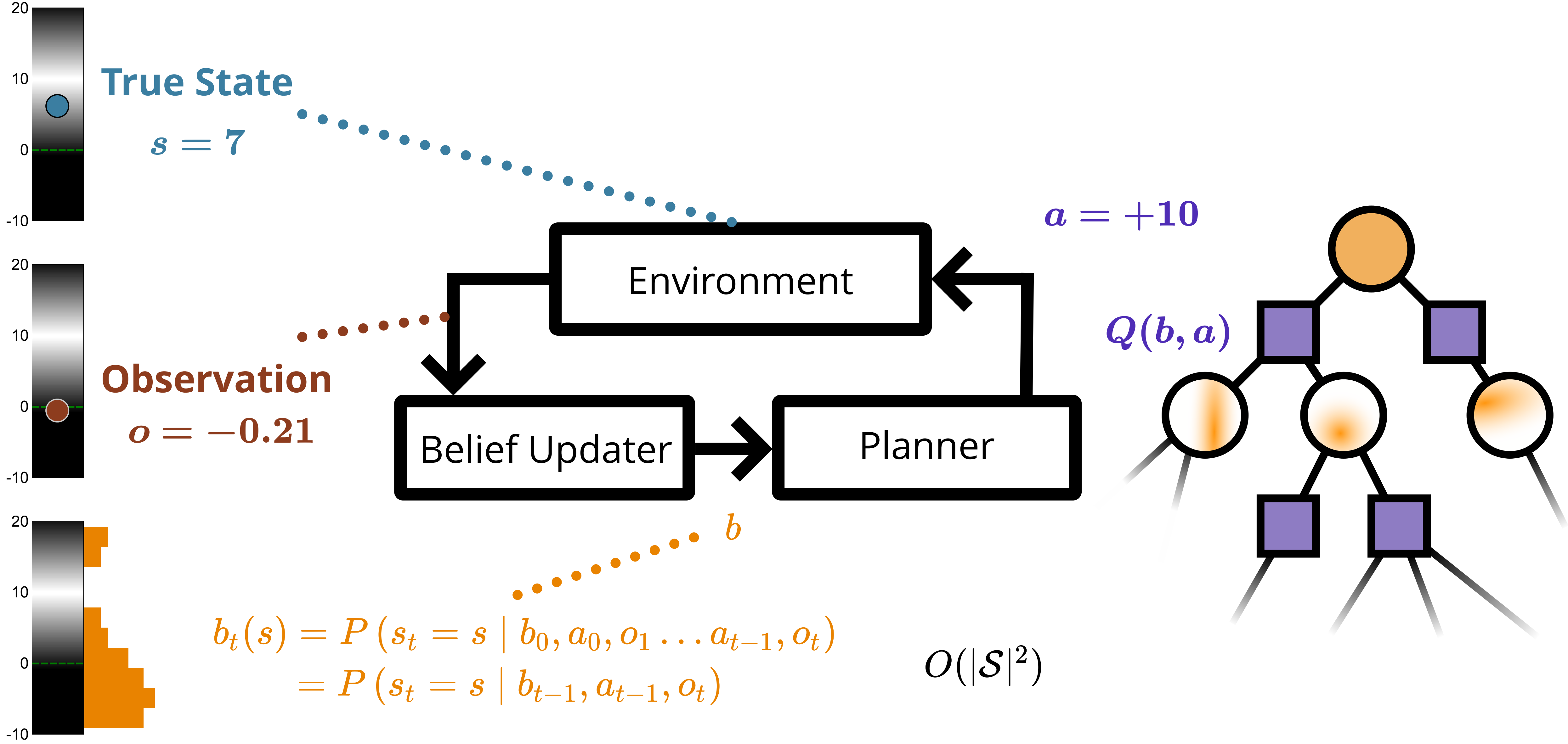
- $\mathcal{S}$ - State space
- $T : \mathcal{S} \times \mathcal{A} \times \mathcal{S} \rightarrow \mathbb{R}$ - Transition probability distribution
- $\mathcal{A}$ - Action space
- $R : \mathcal{S} \times \mathcal{A} \rightarrow \mathbb{R}$ - Reward
- $\mathcal{O}$ - Observation space
- $Z : \mathcal{S} \times \mathcal{A} \times \mathcal{S} \times \mathcal{O} \rightarrow \mathbb{R}$ - Observation probability distribution

Aleatory

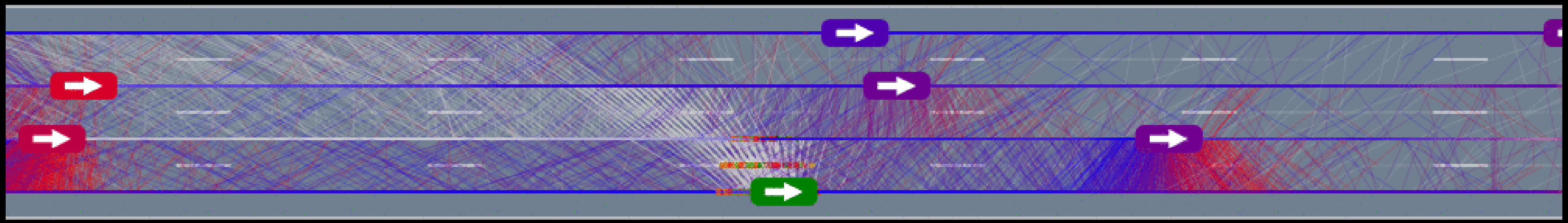
Epistemic (Static)

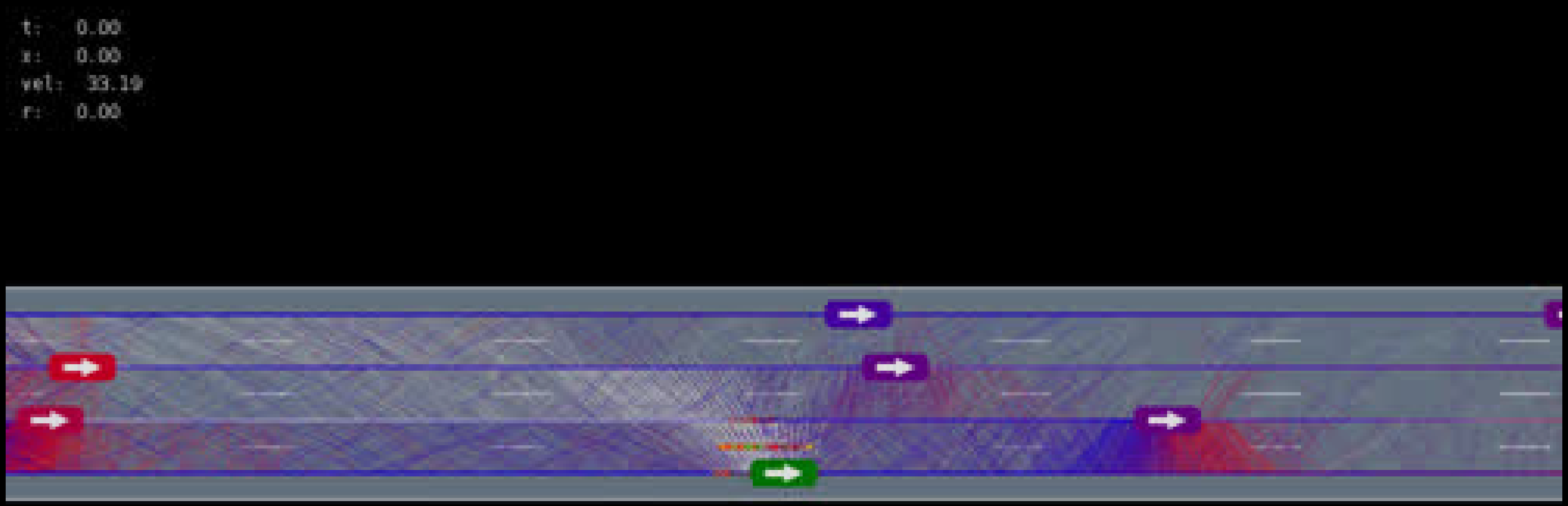
Epistemic (Dynamic)

Solving a POMDP



t: 0.15
x: 4.87
vel: 32.89
r: 0.00



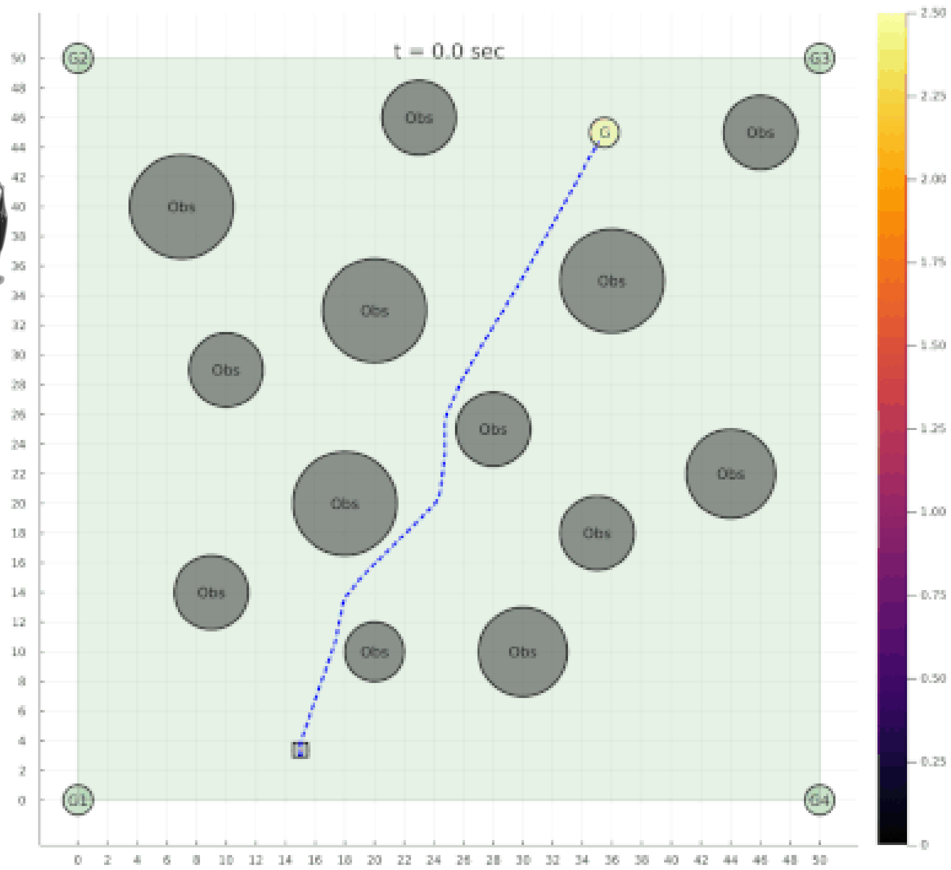

t: 0.00
x: 0.00
vel: 33.19
r: 0.00

Navigation among Pedestrians

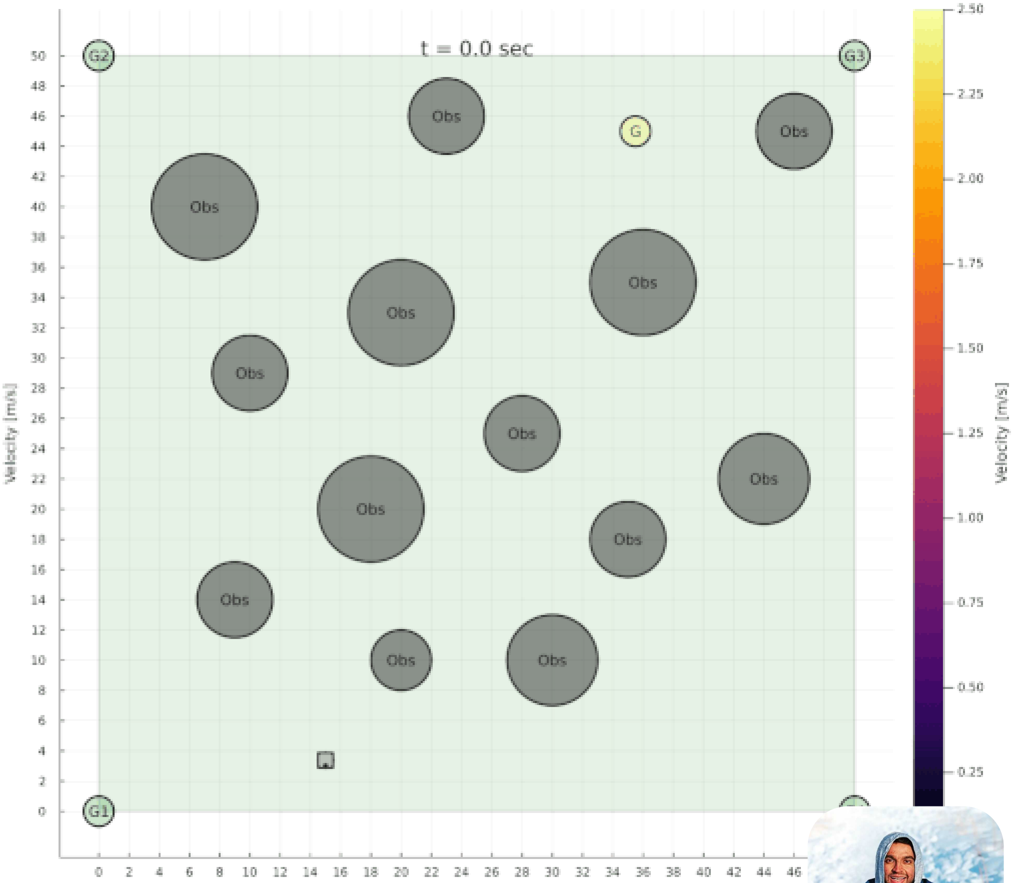
State:

- Vehicle physical state
- Human physical state
- Human intention

Previous solution: 1-D POMDP (92s avg)

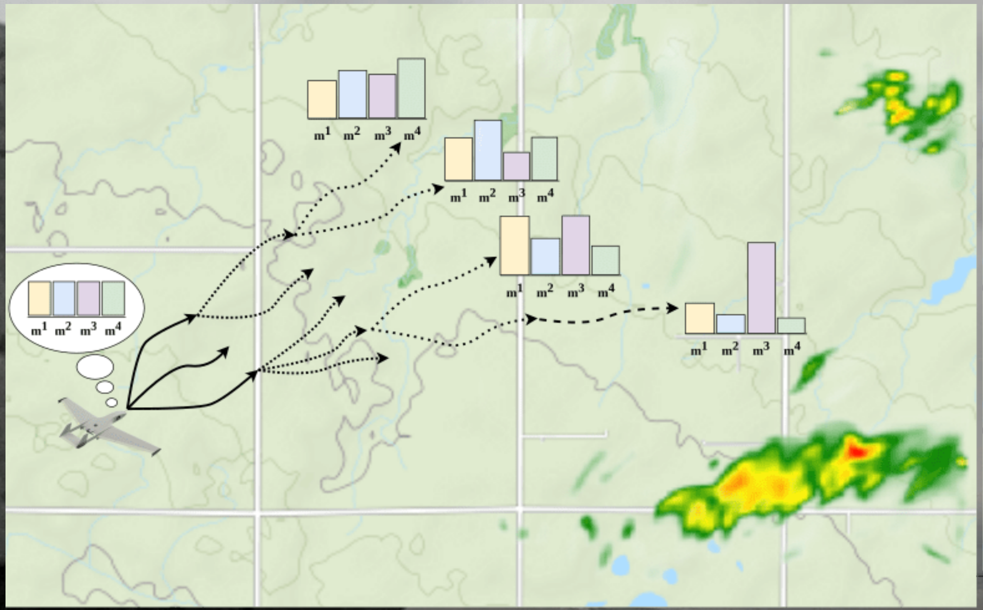


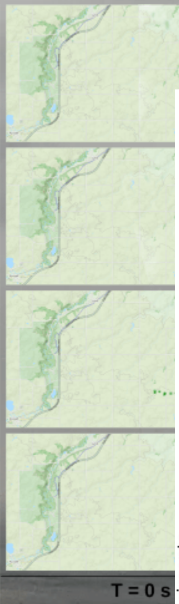
Our solution (65s avg)

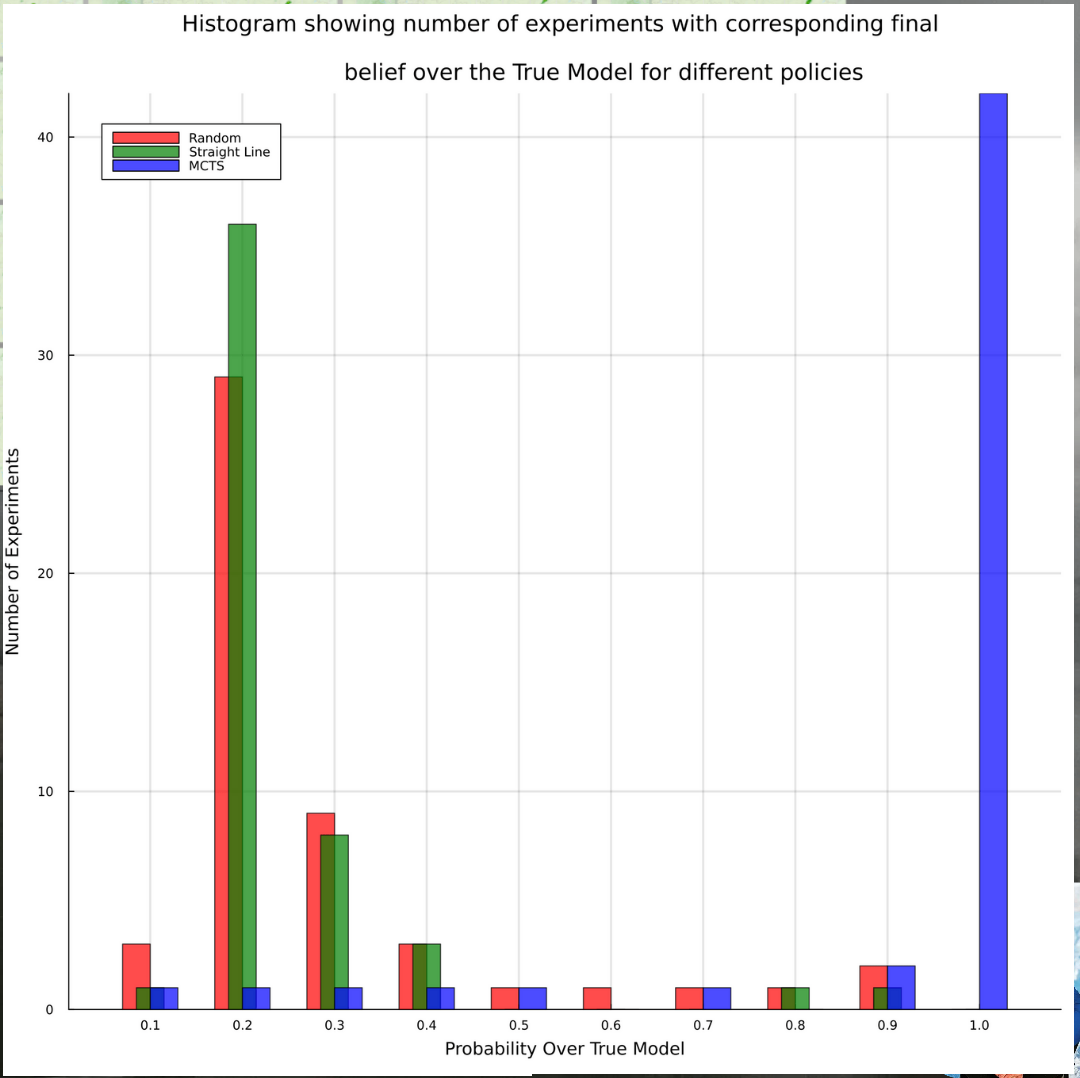


[Gupta, Hayes, & Sunberg, AAMAS 2022]

Meteorology

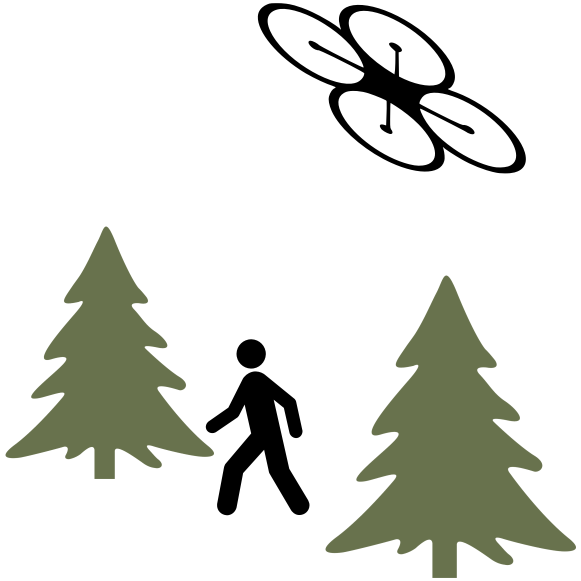




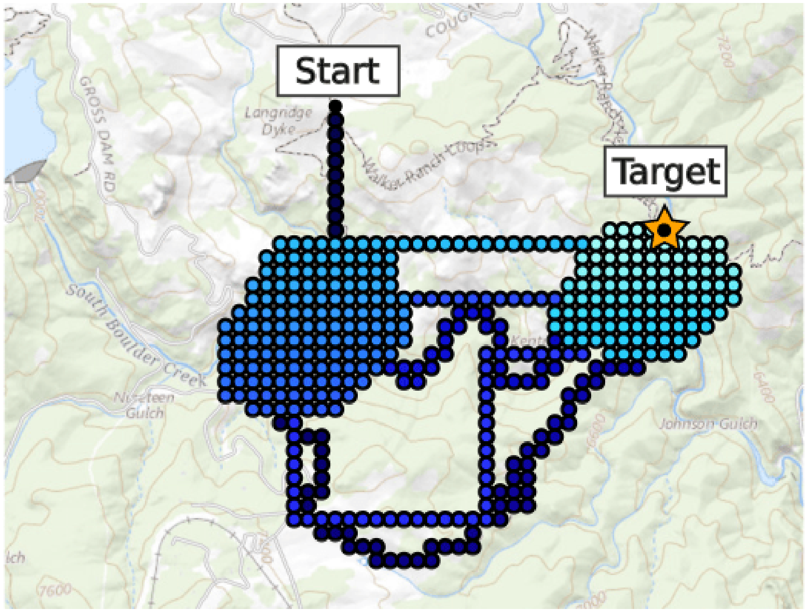


- State: (physical state of aircraft, which forecast is the truth)
- Action: (flight direction, drifter deploy)
- Reward: Terminal reward for correct weather prediction

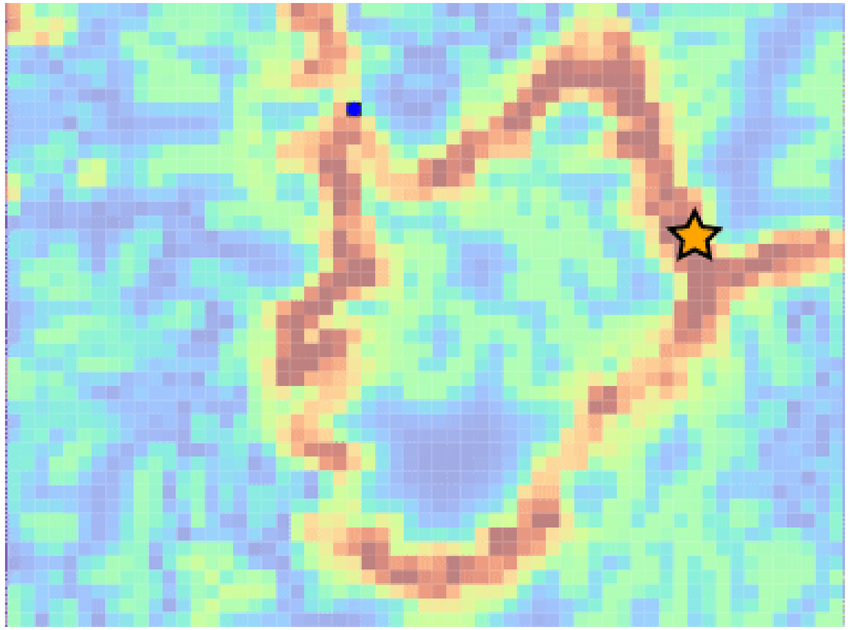
Drone Search and Rescue



Baseline



Our POMDP Planner

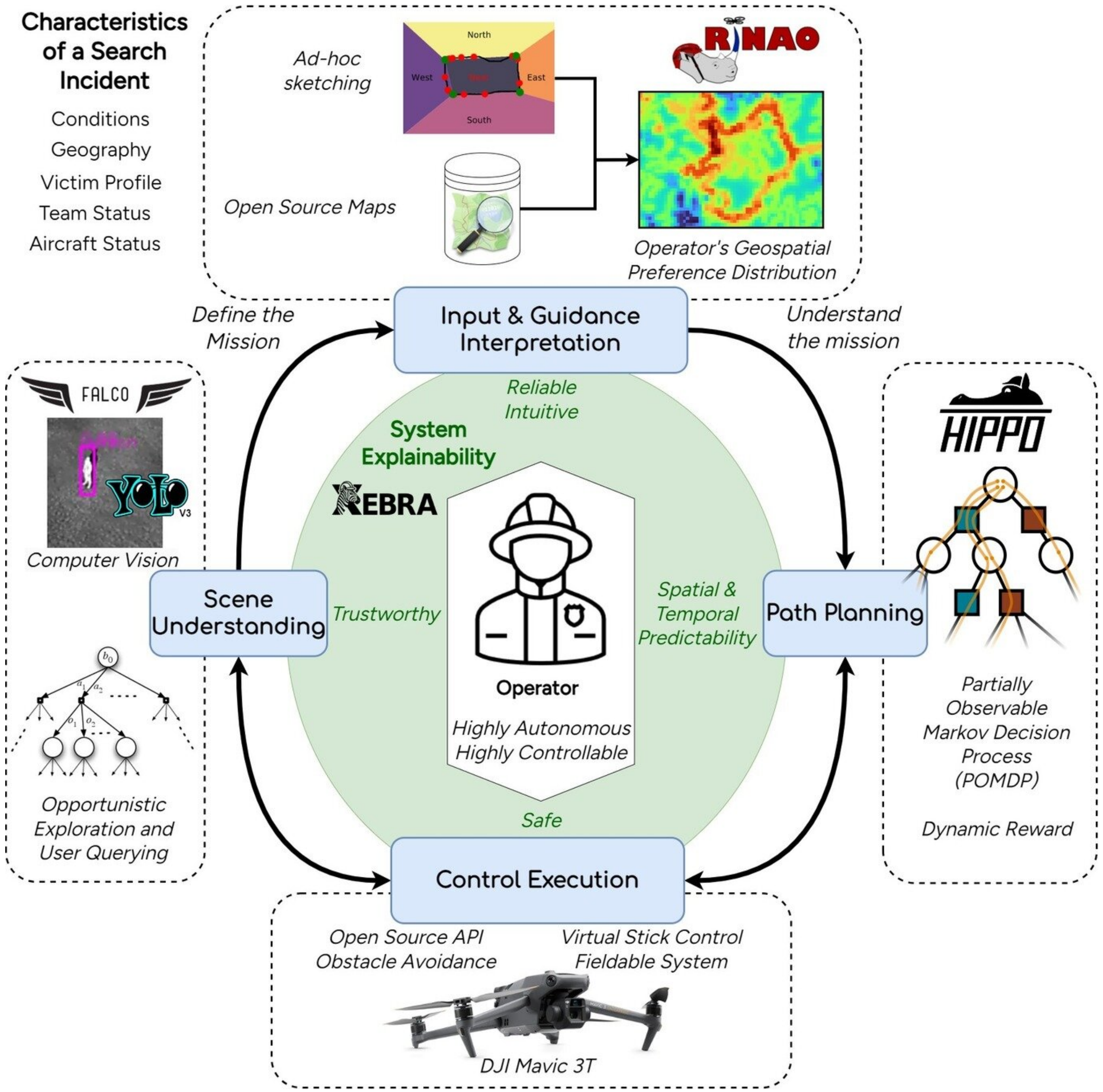


State:

- Location of Drone
- Location of Human

[Ray, Laouar, Sunberg, & Ahmed, ICRA 2023]

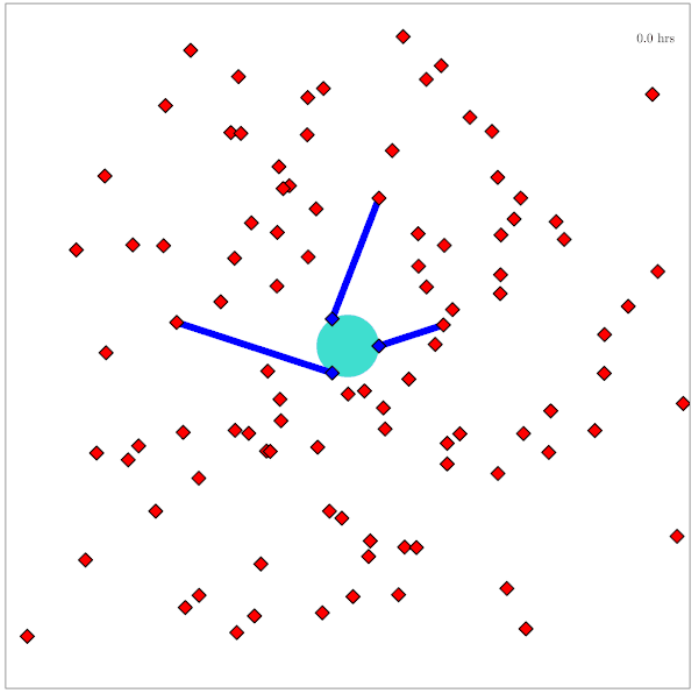
Drone Search and Rescue

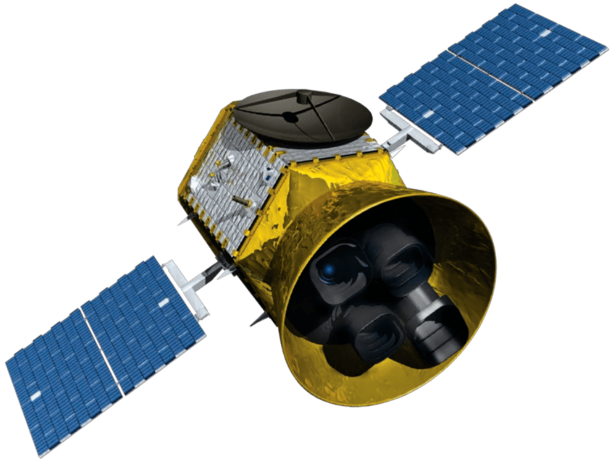


[Ray, Laouar, Sunberg, & Ahmed, ICRA 2023]

Space Domain Awareness

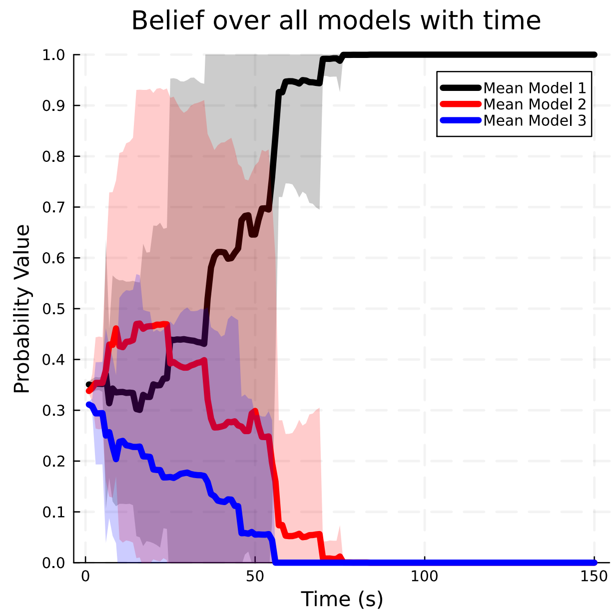
Catalog Maintenance Plan





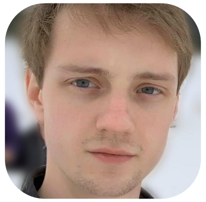
State:

- Position, velocity of object-of-interest
- Anomalies: navigation failure, suspicious maneuver, thruster failure, etc.

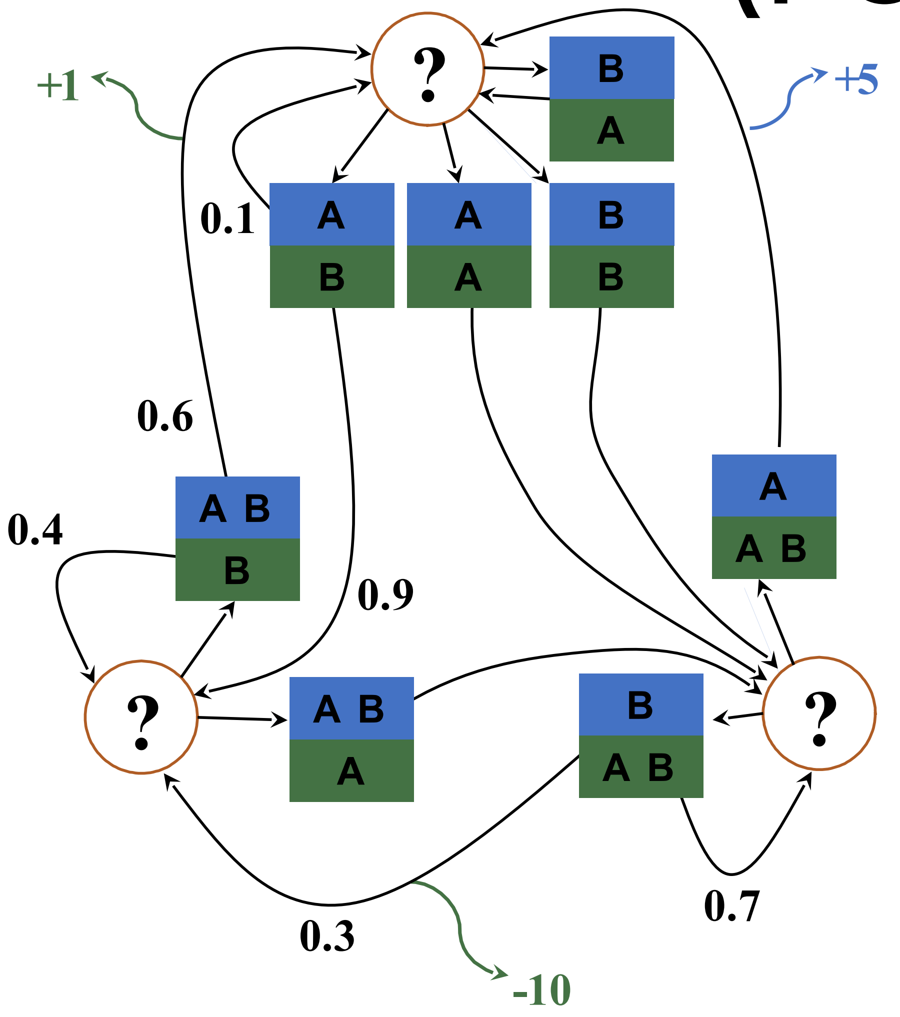


(Result for simplified dynamical system)

Innovation: Large language models allow analysts to quickly specify anomaly hypotheses



Partially Observable Stochastic Game (POSG)



- $\mathcal{S}$ - State space
- $T(s' \mid s, \boldsymbol{a})$ - Transition probability distribution
- $\mathcal{A}^i,\ i \in 1..k$ - Action spaces
- $R^i(s, \boldsymbol{a})$ - Reward function (cooperative, opposing, or somewhere in between)
- $\mathcal{O}^i,\ i \in 1..k$ - Observation spaces
- $Z(o^i \mid \boldsymbol{a}, s')$ - Observation probability distributions

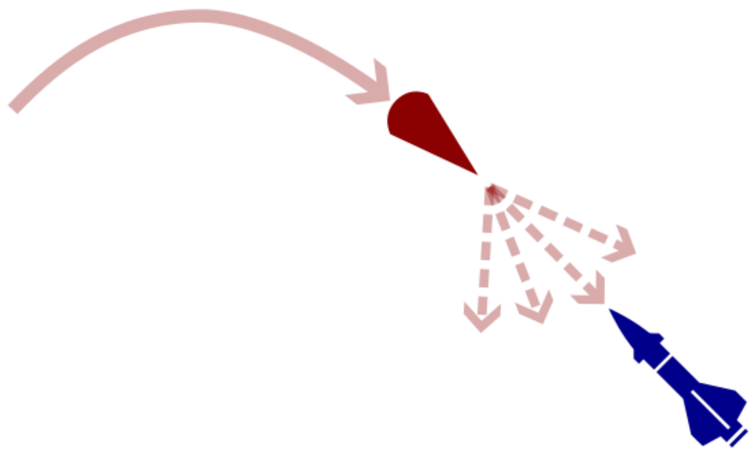
Aleatory

Epistemic (Static)

Epistemic (Dynamic)

Interaction

POSG Example: Missile Defense



POMDP Solution:

1. Assume a distribution for the missile's actions
2. Update belief according to this distribution
3. Use a POMDP planner to find the best defensive action

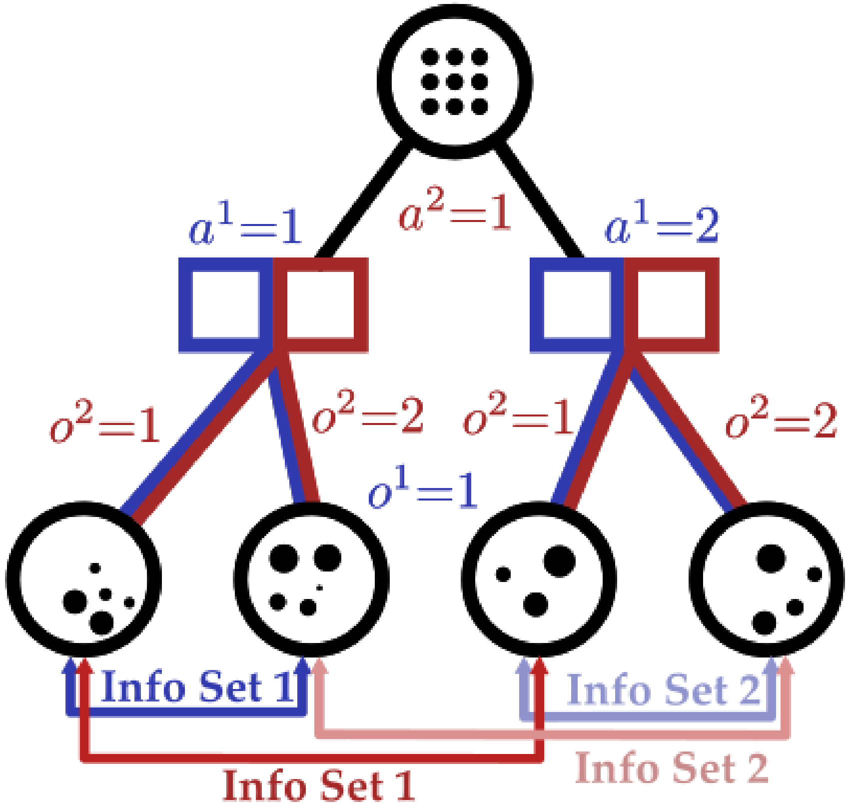
A shrewd missile operator will use different actions, invalidating our belief

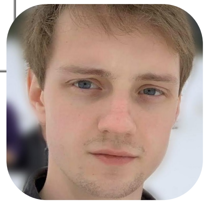
Nash equilibrium: All players play a best response to the other players

May include stochastic behavior (bluffing)

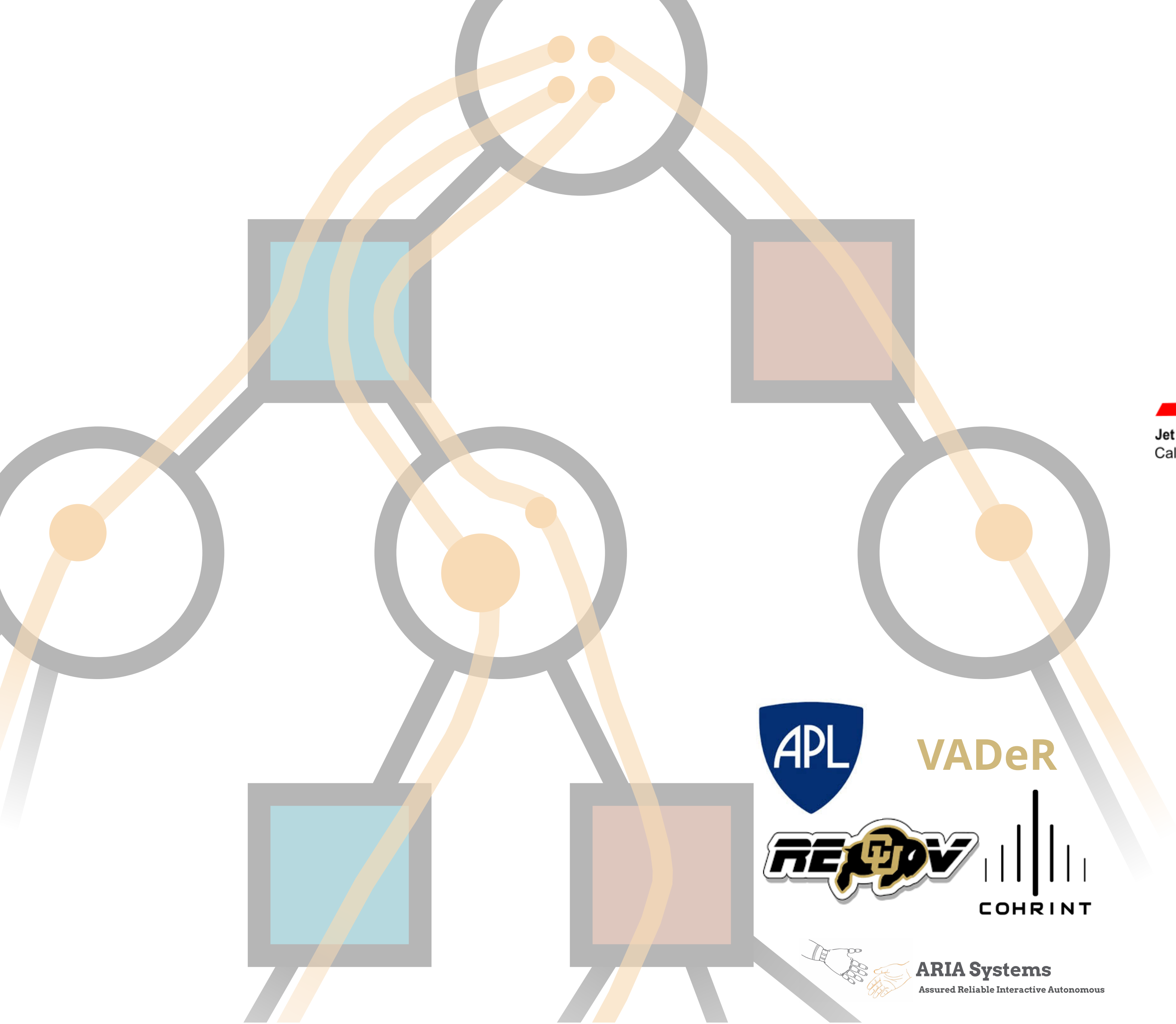
Fundamentally impossible for POMDP solvers to compute.

Tree Search Algorithms for POSGs





[Becker & Sunberg, NeurIPS 2024 (Under Review)]



Thank You!

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Jet Propulsion Laboratory
California Institute of Technology

NSF

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ONR
Science & Technology

APL

VADeR

COHRINT

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Assured Reliable Interactive Autonomous