Imitative Planning

for Autonomous Vehicles

Nicholas Rhinehart
Carnegie Mellon University

Rowan McAllister
UC Berkeley

Kris Kitani
Carnegie Mellon University

Sergey Levine
UC Berkeley


CARLA

Q: Can robots **safely learn** to drive **suburban roads** in **interpretable** ways to **new goals** ?

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Without learning ?

Behavior cloning ?

Model-based RL ?

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(trains offline)

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Without learning ? ✓

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Model-based RL ? ?

Q: Can robots **safely learn** to drive **suburban roads** in **interpretable** ways to **new goals** ?

(trains offline) (no rewards required)

Without learning ?	✔
Behavior cloning ?	?
Model-based RL ?	?

Q: Can robots **safely learn** to drive **suburban roads** in **interpretable** ways to **new goals** ?

	(trains offline)	(no rewards required)
Without learning ?	✓	✗
Behavior cloning ?	?	✓
Model-based RL ?	?	✗

Q: Can robots **safely learn** to drive **suburban roads** in **interpretable** ways to **new goals** ?

	(trains offline)	(no rewards required)	(plans)
Without learning ?	✓	✗	
Behavior cloning ?	?	✓	
Model-based RL ?	?	✗	

Q: Can robots **safely learn** to drive **suburban roads** in **interpretable** ways to **new goals** ?

	(trains offline)	(no rewards required)	(plans)
Without learning ?	✓	✗	✓
Behavior cloning ?	?	✓	✗
Model-based RL ?	?	✗	✓

Q: Can robots **safely learn** to drive **suburban roads** in **interpretable** ways to **new goals** ?

	(trains offline)	(no rewards required)	(plans)	(dyn. model)
Without learning ?	✓	✗	✓	
Behavior cloning ?	?	✓	✗	
Model-based RL ?	?	✗	✓	

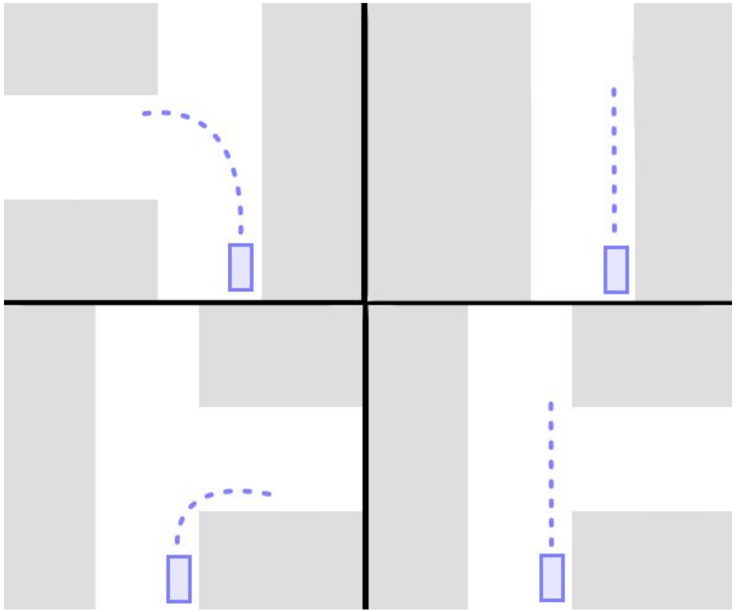
Q: Can robots **safely learn** to drive **suburban roads** in **interpretable** ways to **new goals** ?

	(trains offline)	(no rewards required)	(plans)	(dyn. model)
Without learning ?	✔	✘	✔	✔
Behavior cloning ?	?	✔	✘	✘
Model-based RL ?	?	✘	✔	✔

Q: Can robots **safely learn** to drive **suburban roads** in **interpretable** ways to **new goals** ?

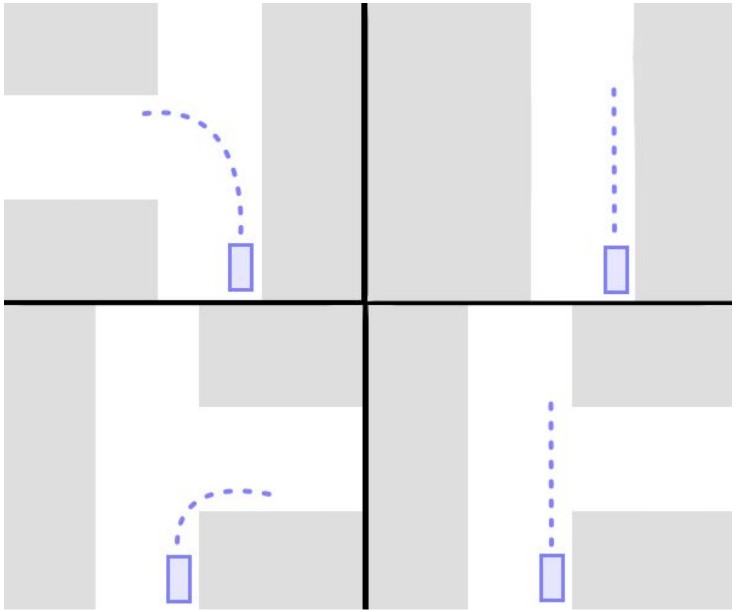
	(trains offline)	(no rewards required)	(plans)	(dyn. model)
Without learning ?	✔	✘	✔	✔
Behavior cloning ?	?	✔	✘	✘
Model-based RL ?	?	✘	✔	✔
Imitative Models (ours)	✔	✔	✔	✔

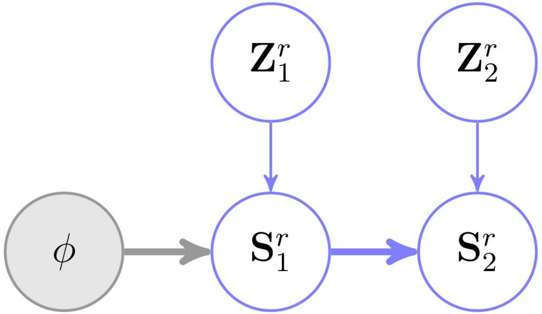
Modelling Expert Drivers



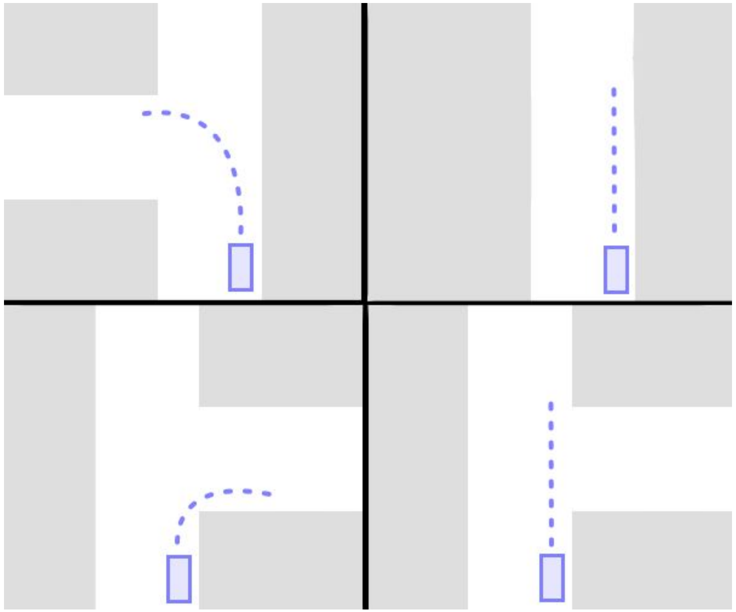
Rhinehart, Kitani, Vernaza **http://r2p2.ml**

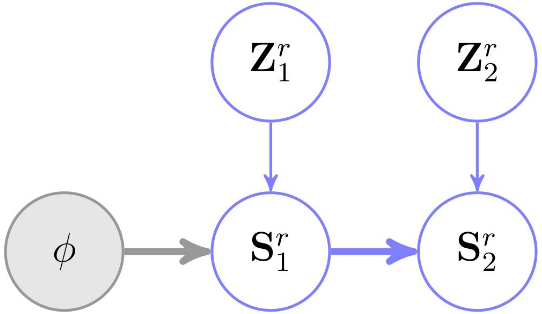
Modelling Expert Drivers





Modelling Expert Drivers

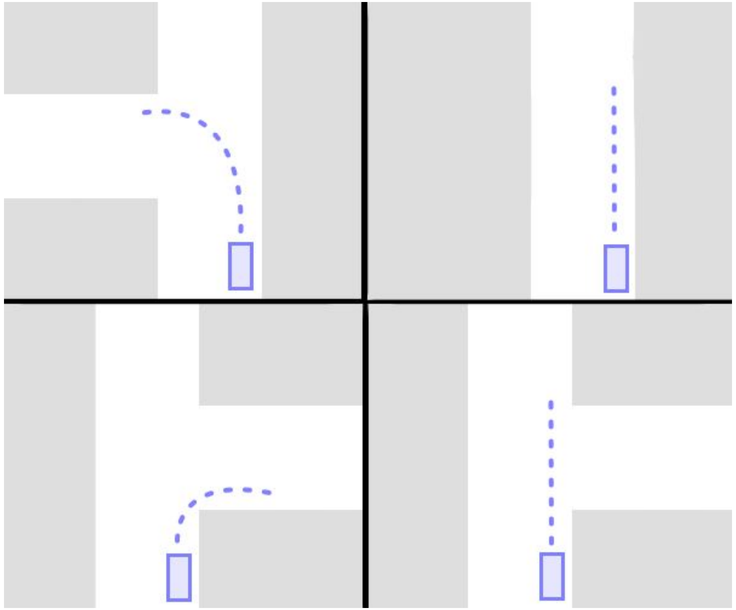


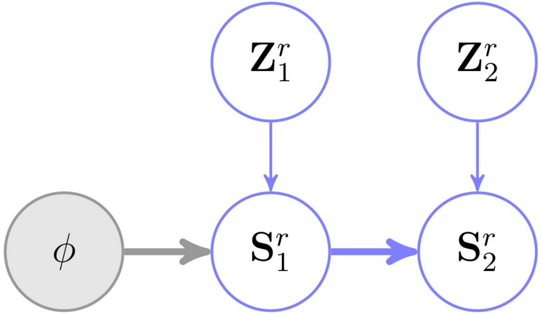


$$\textbf{states} = f\,(\textbf{latents}\,;\textbf{context})$$

Rhinehart, Kitani, Vernaza **http://r2p2.ml**

Modelling Expert Drivers





$$\begin{aligned} \textbf{states} &= f\left(\textbf{latents}\,;\textbf{context}\right) \\ \textbf{latents} &= f^{-1}\left(\textbf{states}\,;\textbf{context}\right) \end{aligned}$$

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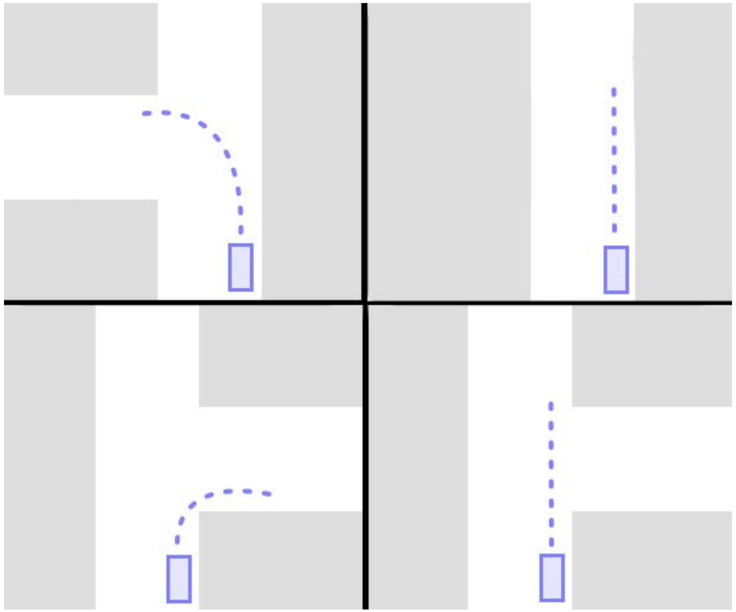
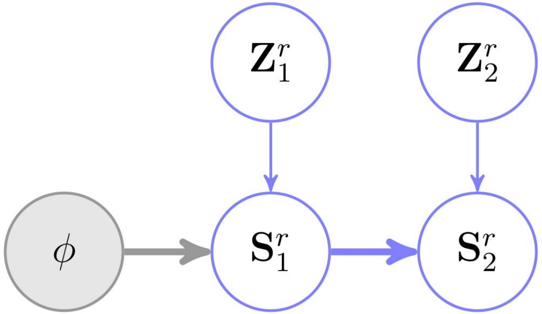
Modelling Expert Drivers





$$\begin{aligned}\textbf{states} &= f\left(\textbf{latents}\,;\textbf{context}\right)\\ \textbf{latents} &= f^{-1}\left(\textbf{states}\,;\textbf{context}\right)\end{aligned}$$

$$q\left(\textbf{states}\,|\,\textbf{context}\right) = \frac{\mathcal{N}\left(\textbf{latents}; 0, I\right)}{\left|\det \frac{\partial f}{\partial\,\textbf{latents}}\right|}$$

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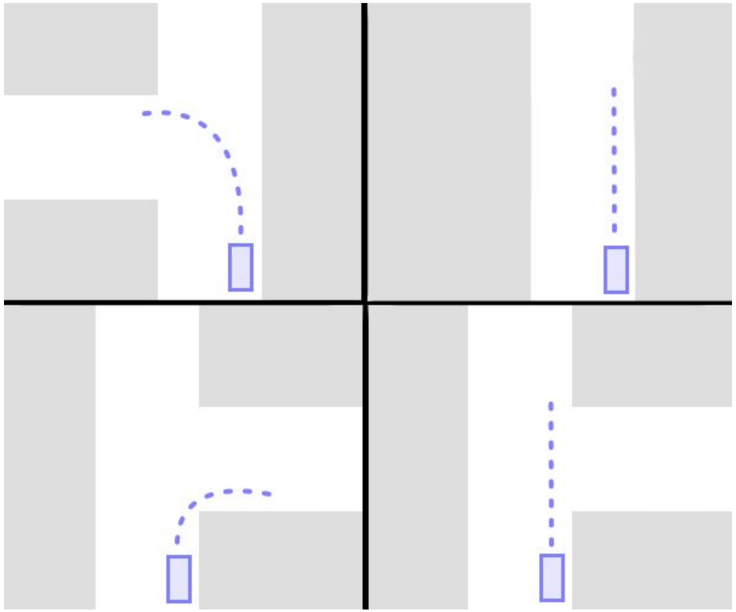
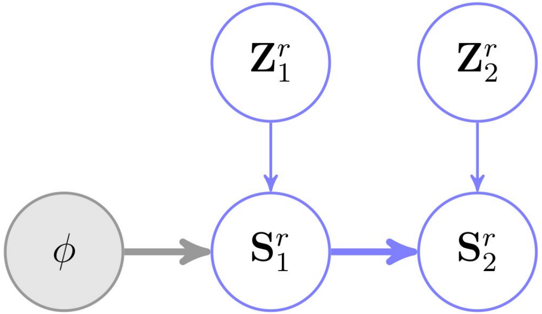
Modelling Expert Drivers





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Can **plan** in this distribution!

new idea

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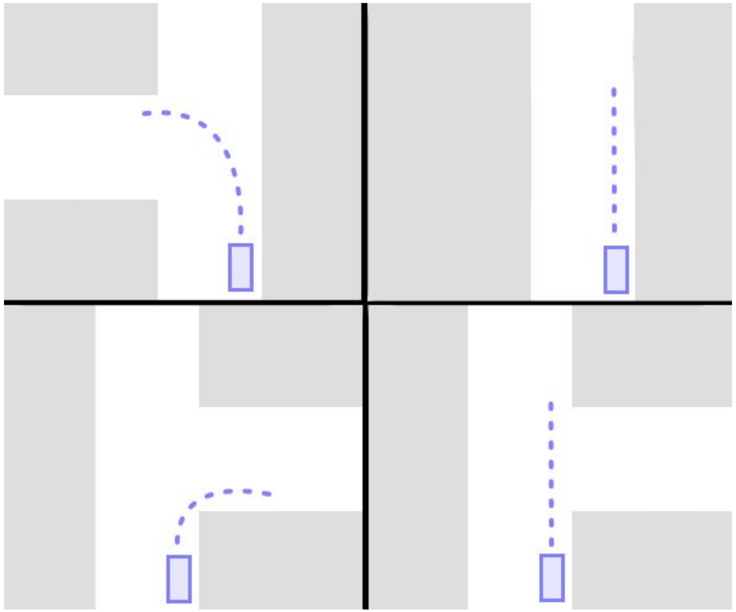
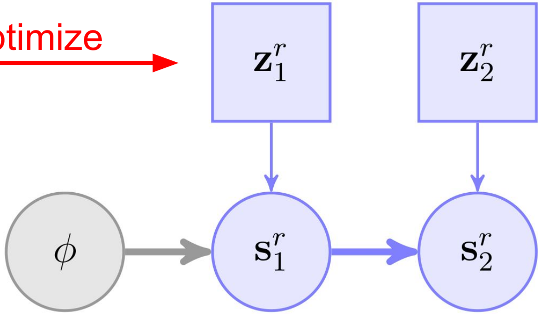
Modelling Expert Drivers



optimize



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Can **plan** in this distribution!

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Planning “Expert-like” Motions to our own Goals

$$\textbf{planned path} = \arg\max_{\textbf{states}} \log p(\textbf{states} \mid \textbf{goal}, \textbf{context})$$

Planning “Expert-like” Motions to our own Goals

$$\textbf{planned path} = \arg\max_{\textbf{states}} \log p(\textbf{states} \mid \textbf{goal}, \textbf{context})$$

$$= \arg\max_{\textbf{states}} \log q(\textbf{states} \mid \textbf{context}) + \log p(\textbf{goal} \mid \textbf{states}, \textbf{context}) - \log p(\textbf{goal} \mid \textbf{context})$$

Planning “Expert-like” Motions to our own Goals

$$\begin{aligned}
\textbf{planned path} &= \underset{\textbf{states}}{\arg\max} \log p(\textbf{states} \mid \textbf{goal}, \textbf{context}) \\
&= \underset{\textbf{states}}{\arg\max} \log q(\textbf{states} \mid \textbf{context}) + \log p(\textbf{goal} \mid \textbf{states}, \textbf{context}) - \log p(\textbf{goal} \mid \textbf{context}) \\
&= \underset{\textbf{states}}{\arg\max} \underbrace{\log q(\textbf{states} \mid \textbf{context})}_{\text{imitation prior}} + \underbrace{\log p(\textbf{goal} \mid \textbf{states}, \textbf{context})}_{\text{goal likelihood}}
\end{aligned}$$

Planning “Expert-like” Motions to our own Goals

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\end{aligned}$$

Drive safely...

Planning “Expert-like” Motions to our own Goals

$$
\begin{aligned}
\text{planned path} &= \arg\max_{\text{states}} \log p(\text{states} \mid \text{goal}, \text{context}) \\
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\end{aligned}
$$

Drive safely...

...and get to our destination!

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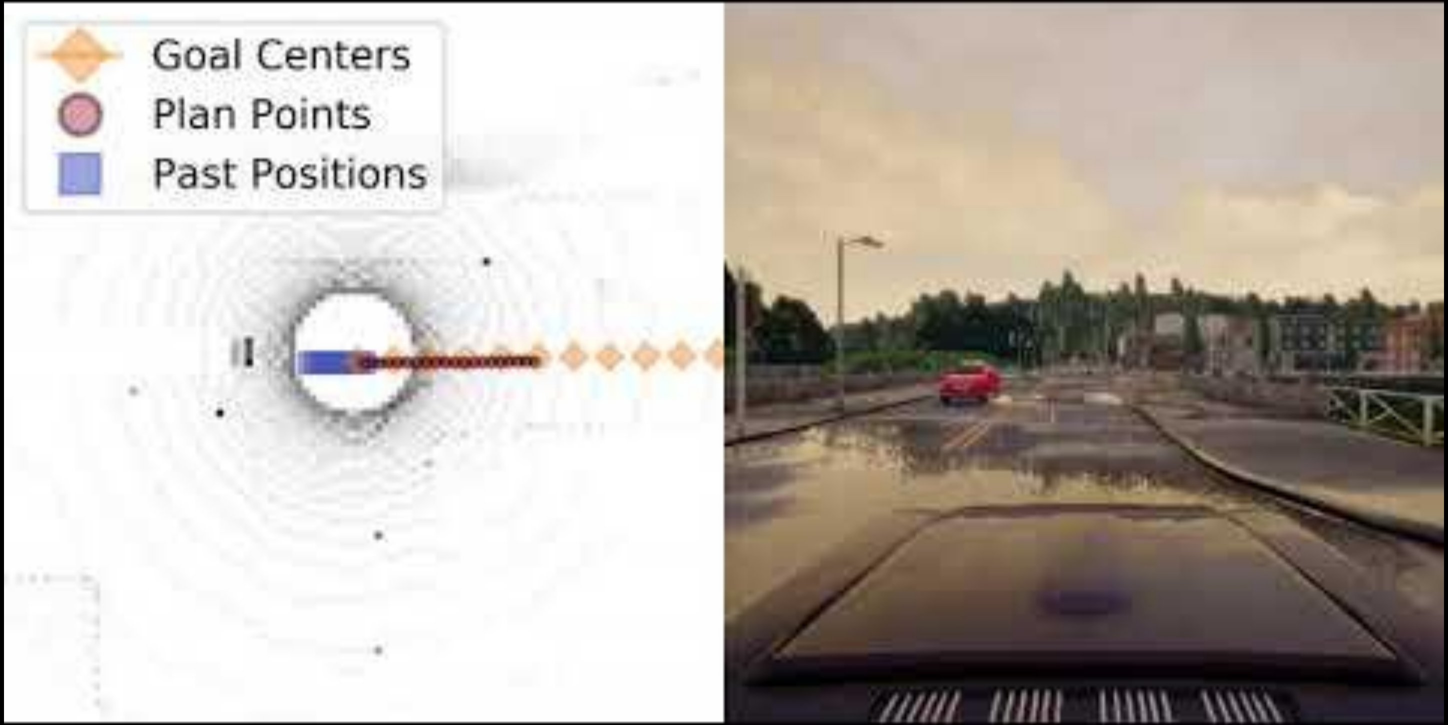
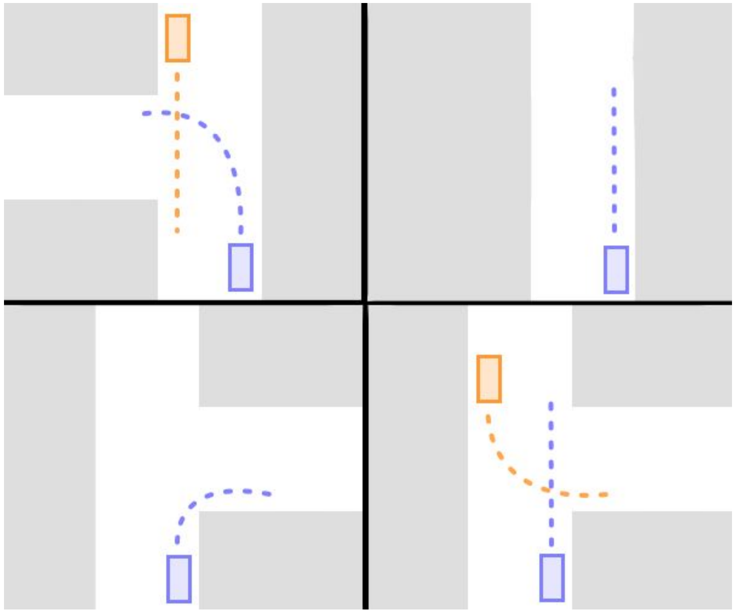
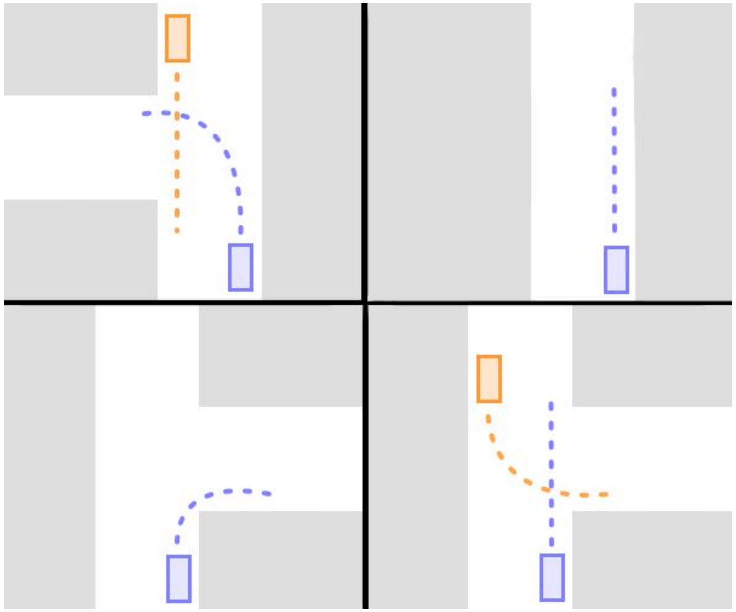

Goal Centers
Plan Points
Past Positions

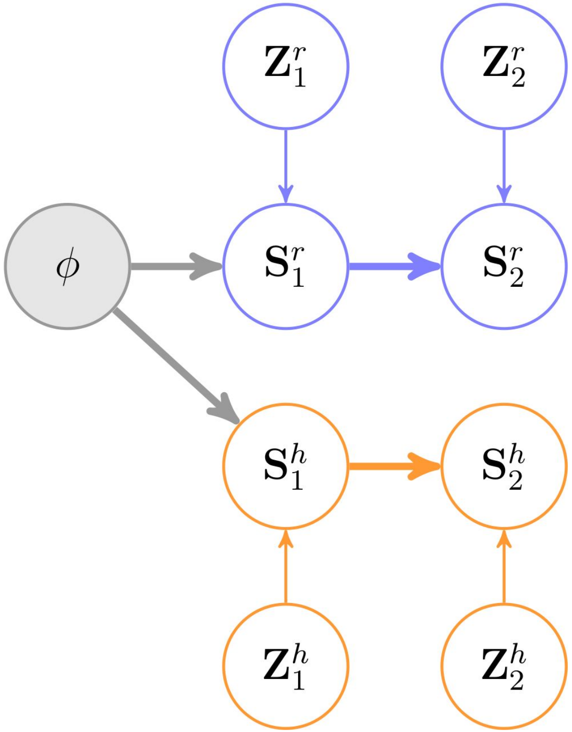
Goal Centers
Plan Points
Past Positions

Modelling Multiple Expert Drivers



Modelling Multiple Expert Drivers





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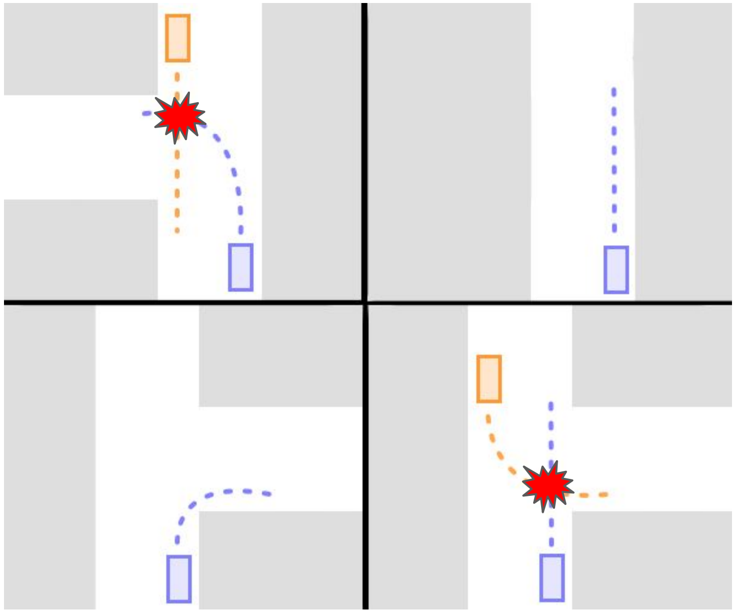

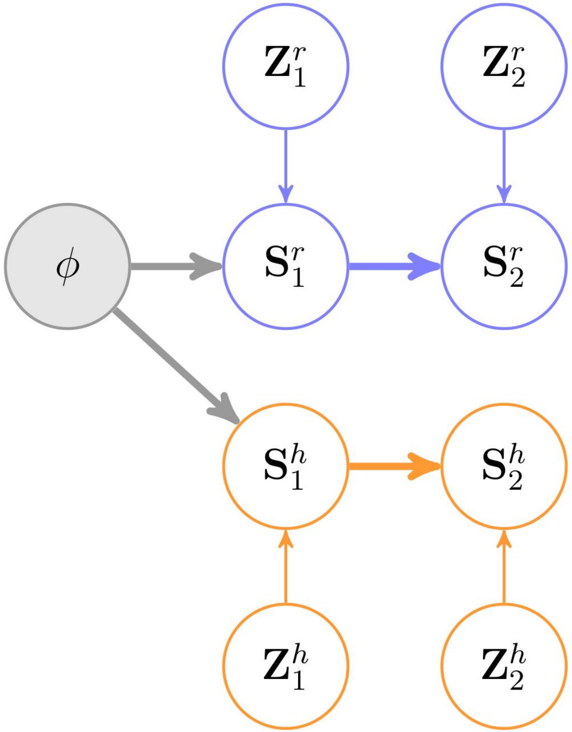

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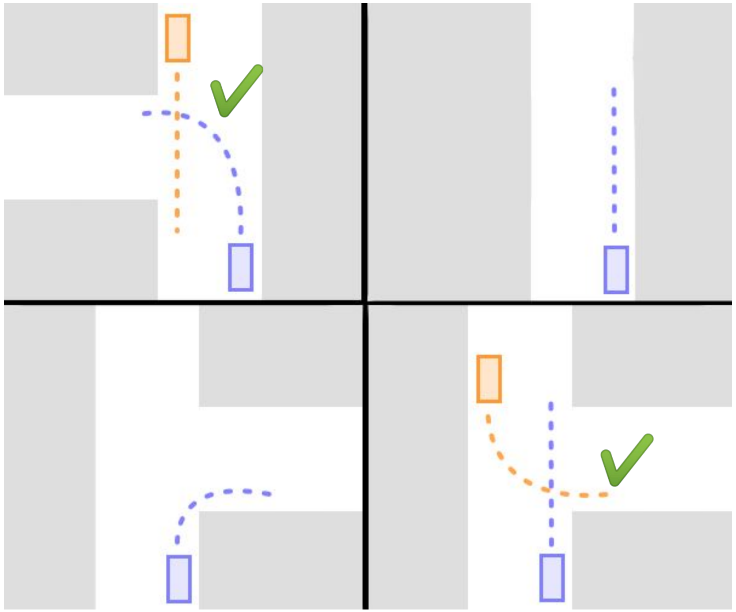

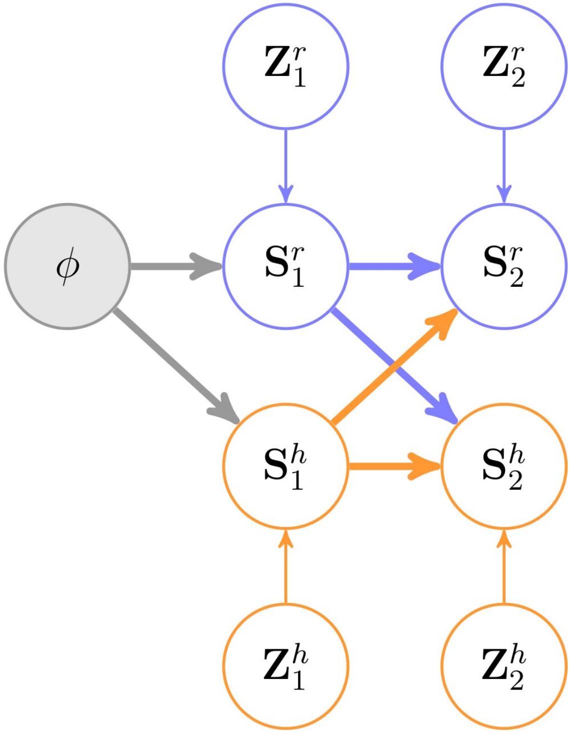

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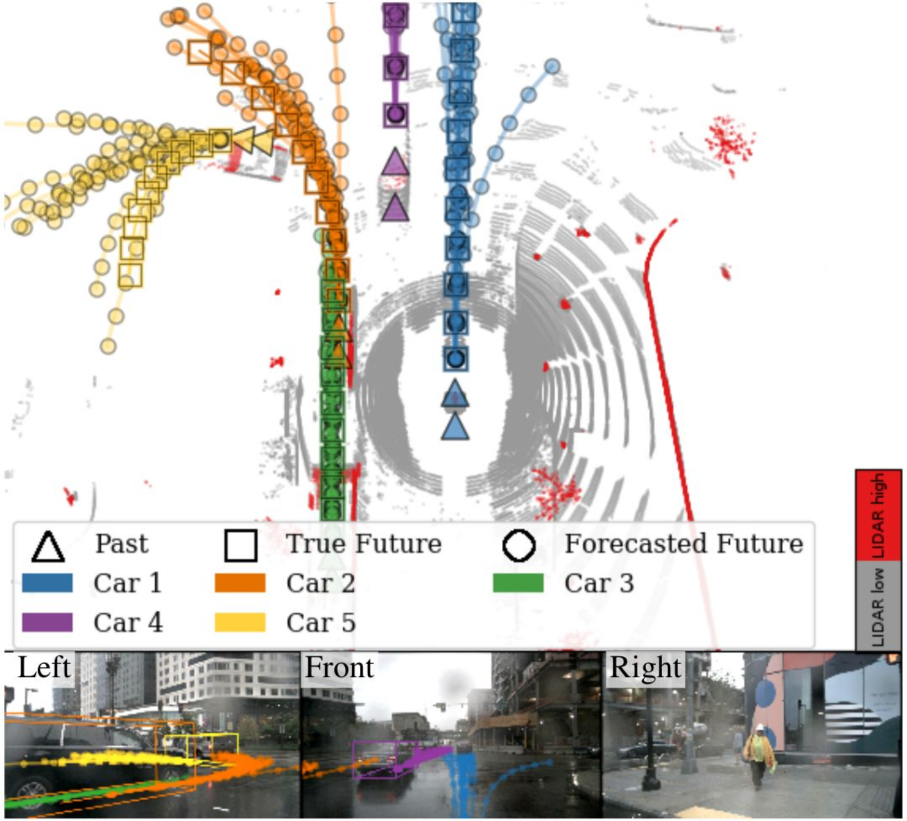
Forecasting with nuScenes data (Singapore + Boston)



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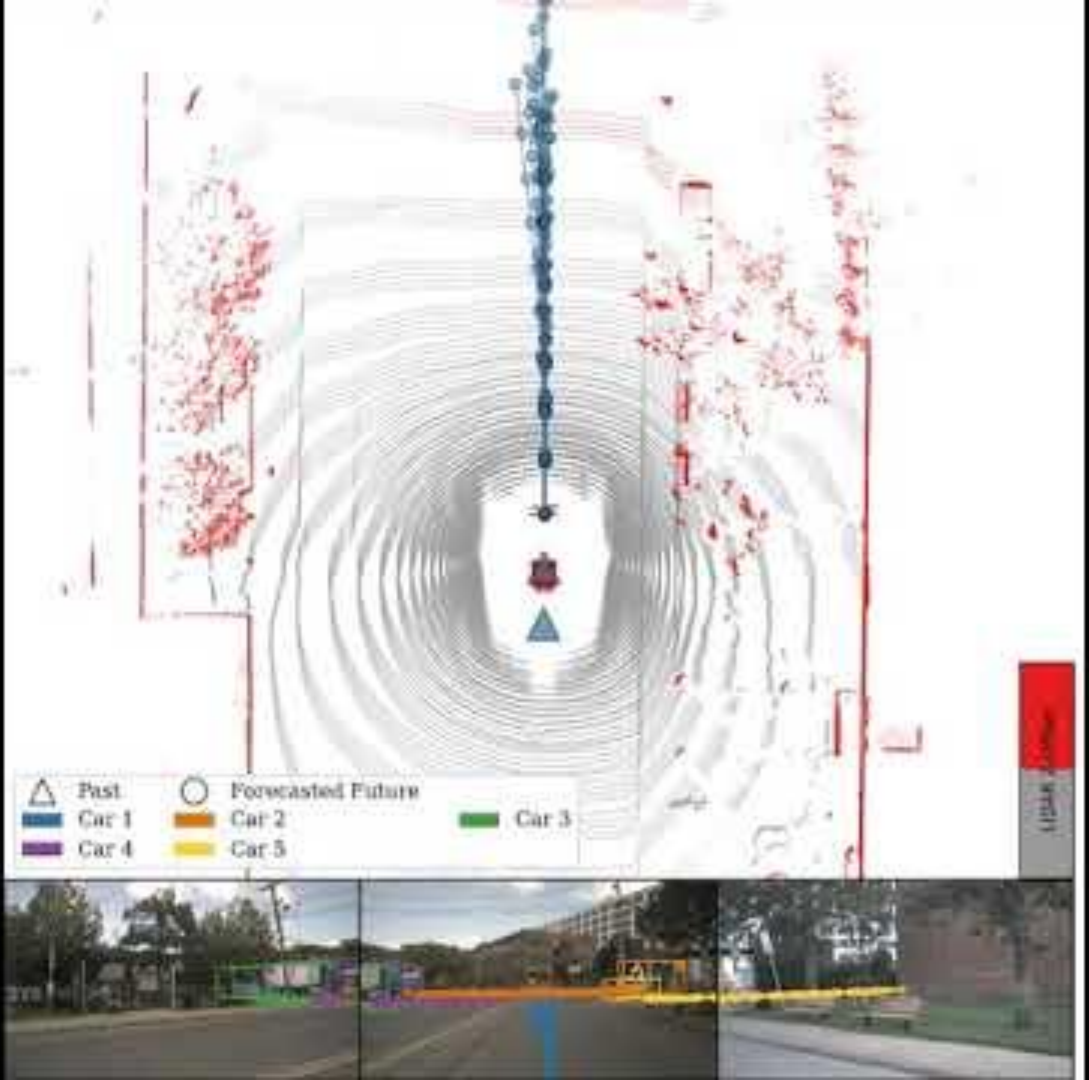
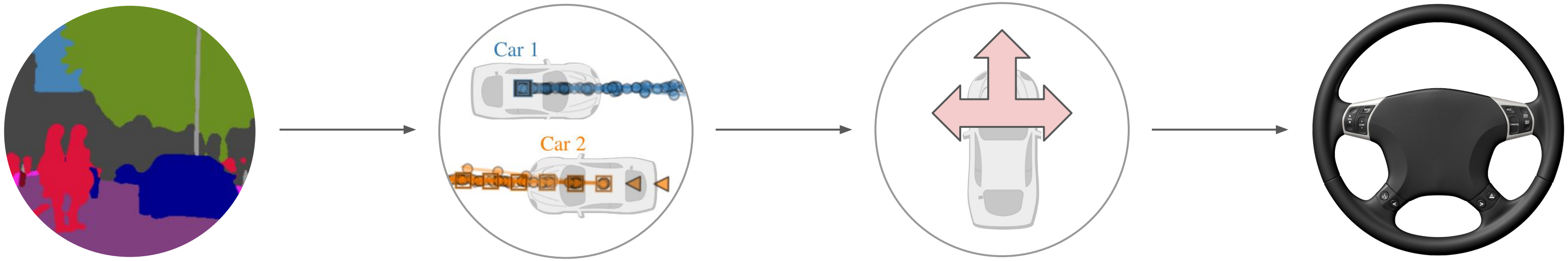

Past
Forecasted Future
Car 1
Car 2
Car 3
Car 4
Car 5

Multi-Agent Planning

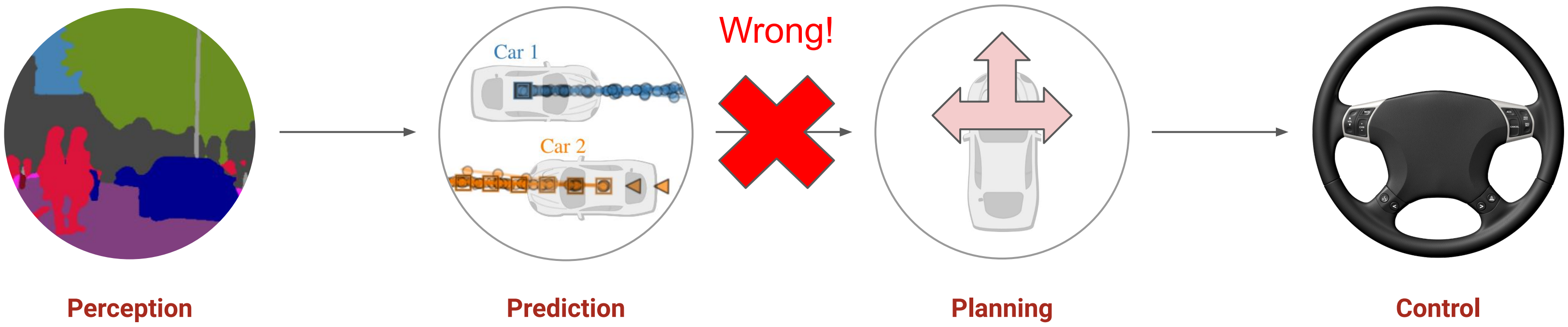
Q: but how should ***autonomous vehicles*** predict other agents...**online**?



Perception **Prediction** **Planning** **Control**

Multi-Agent Planning

Q: but how should ***autonomous vehicles*** predict other agents...**online**?



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Multi-Agent Planning

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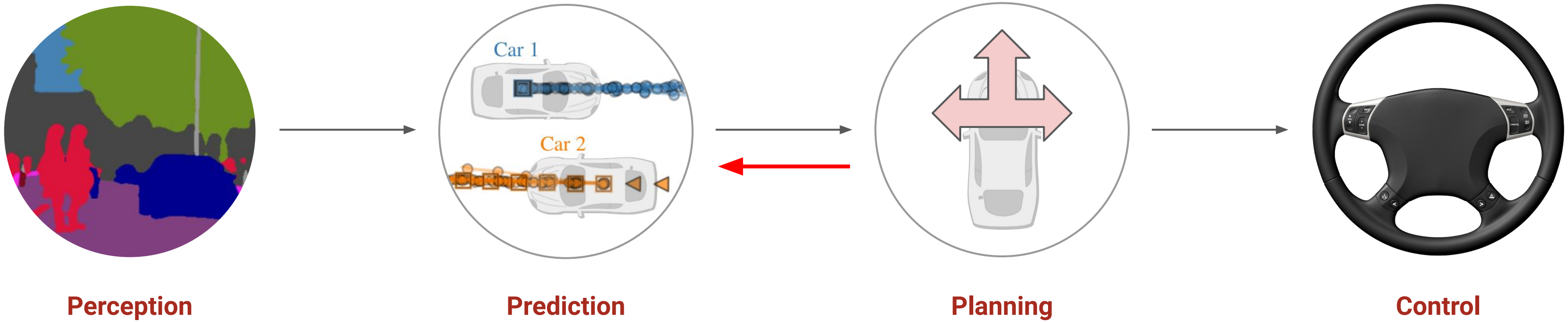

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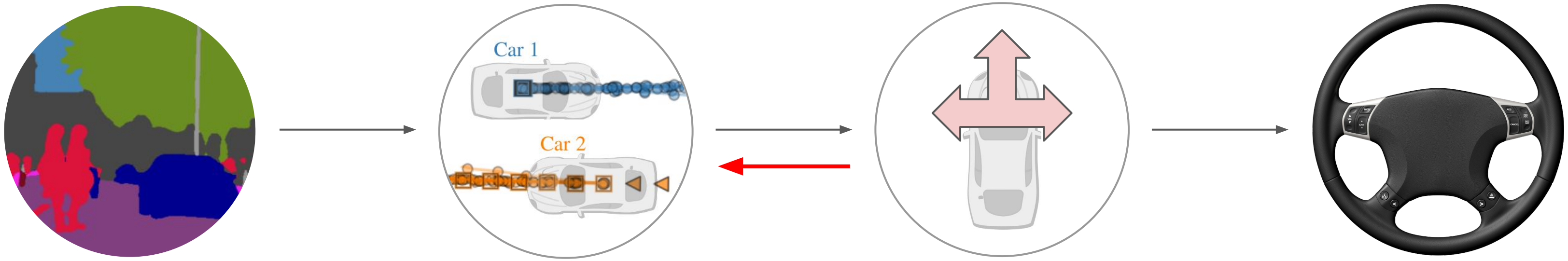
Multi-Agent Planning

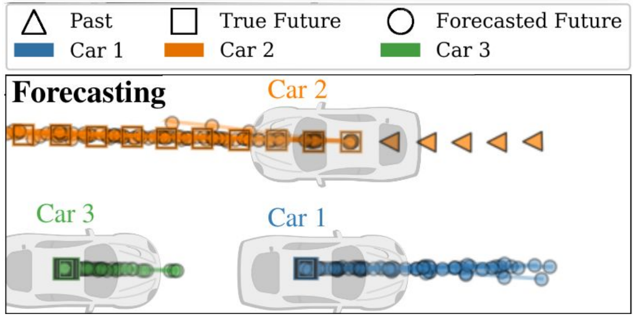
Q: but how should ***autonomous vehicles*** predict other agents...**online**?



Perception **Prediction** **Planning** **Control**

(our actions will affect others)

Goal-Conditioned Multi-Agent Forecasting



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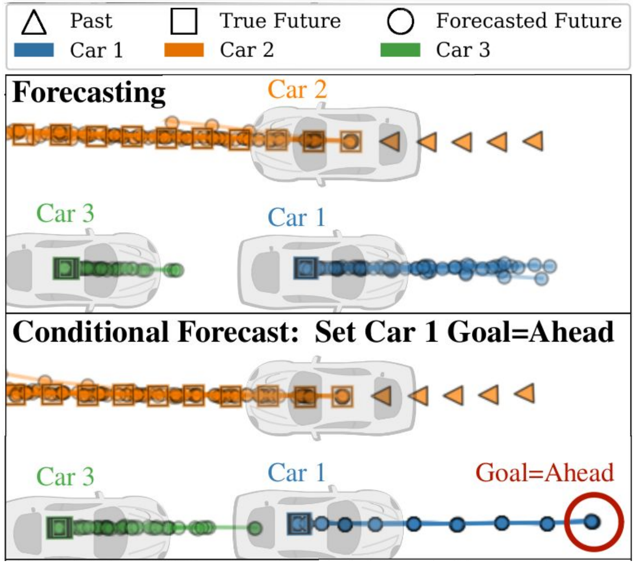
Goal-Conditioned Multi-Agent Forecasting



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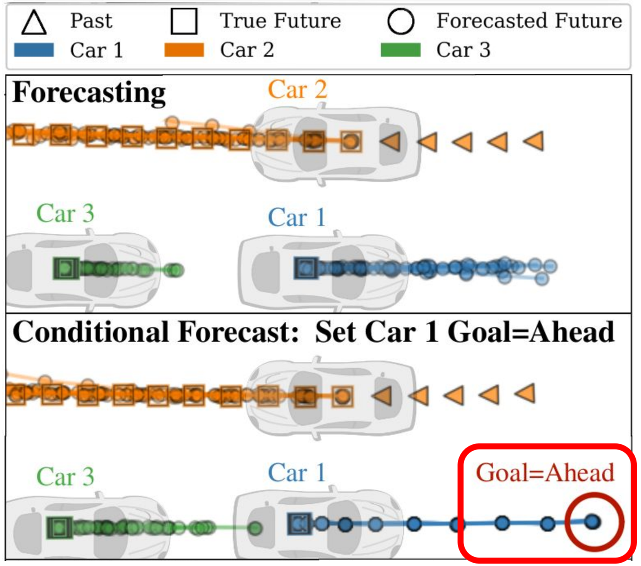

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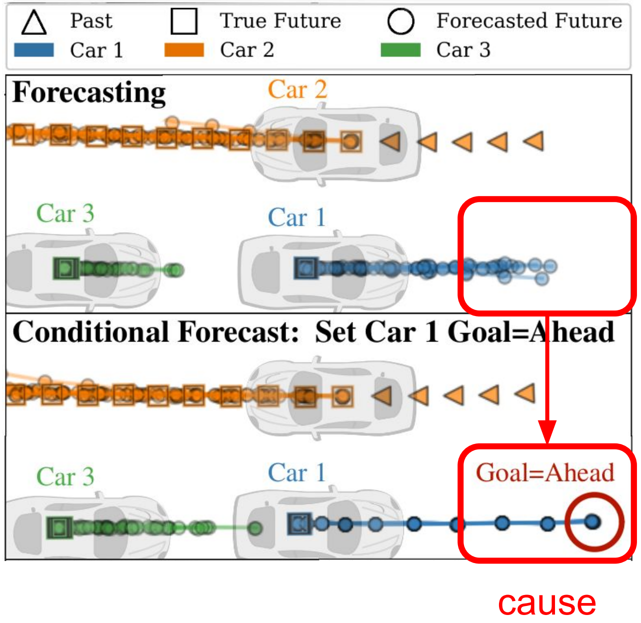

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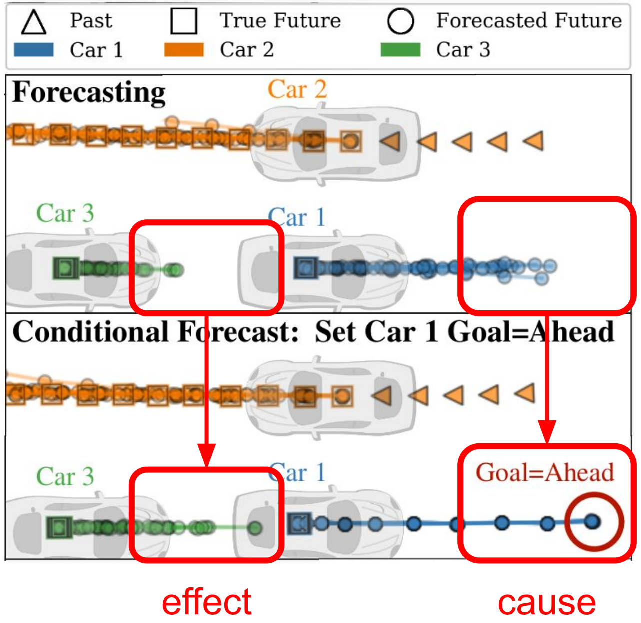

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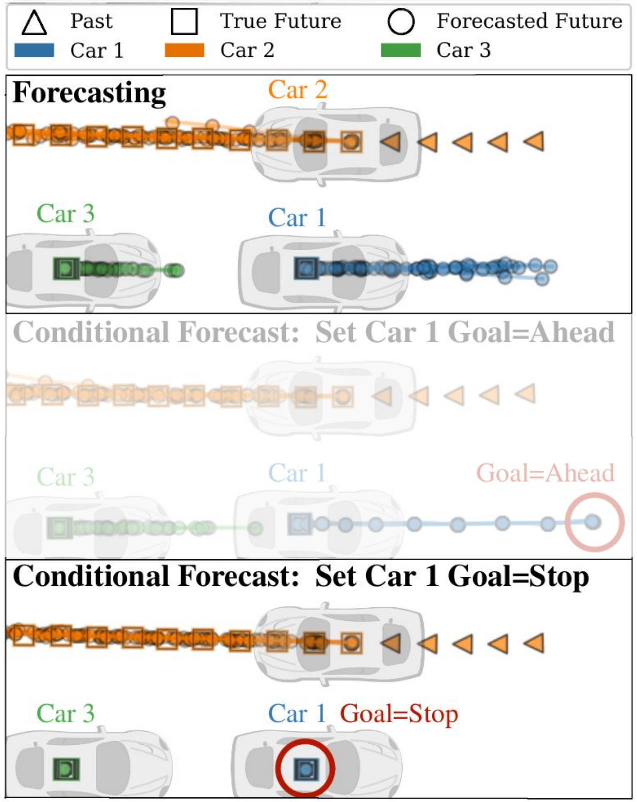

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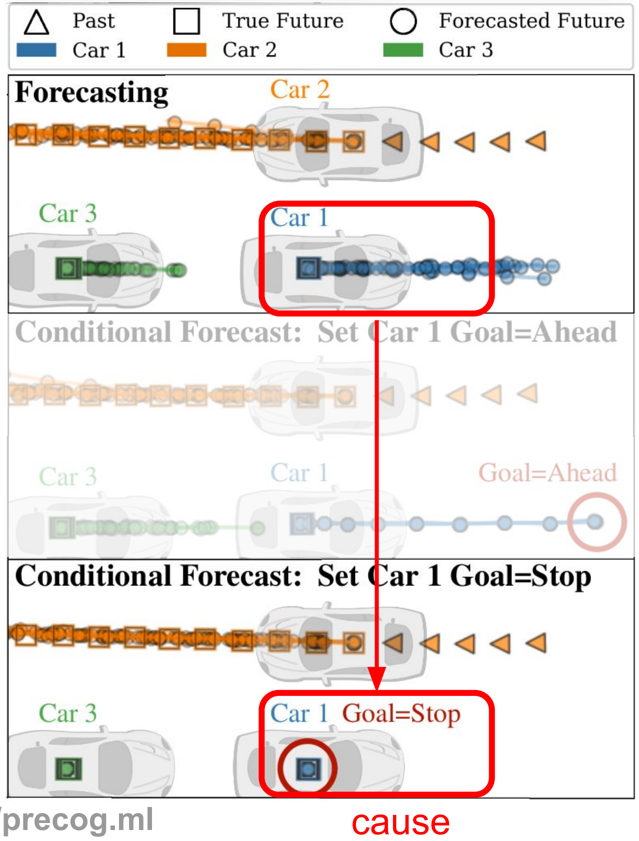

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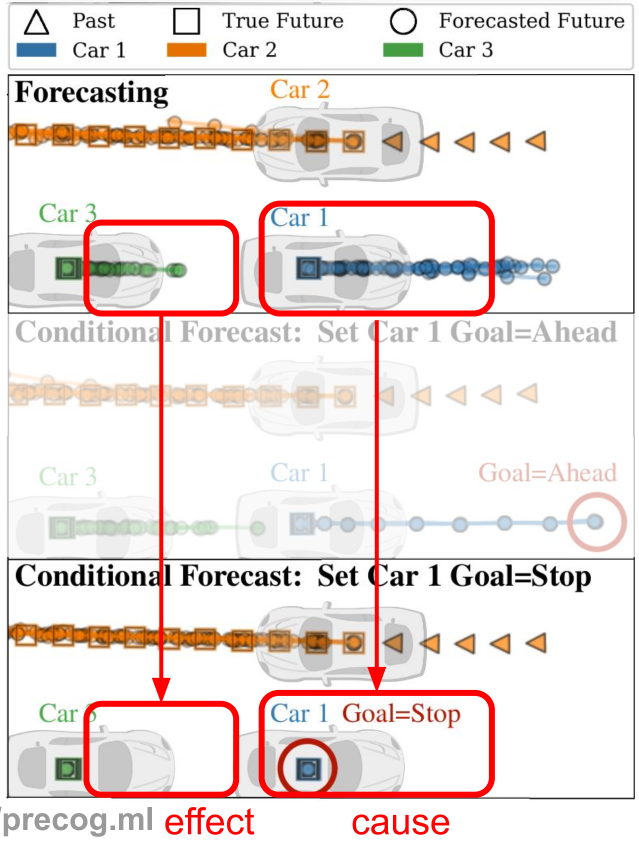
Goal-Conditioned Multi-Agent Forecasting



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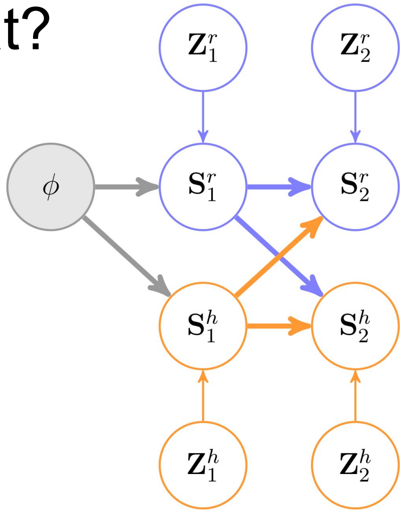
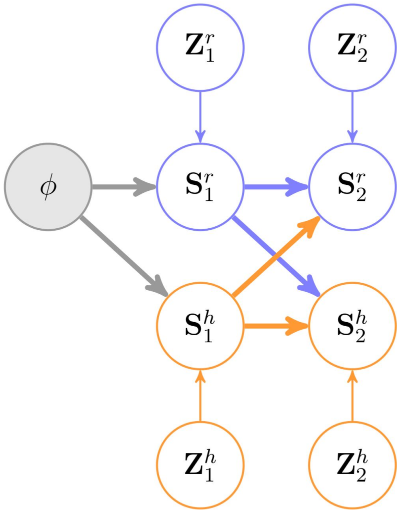
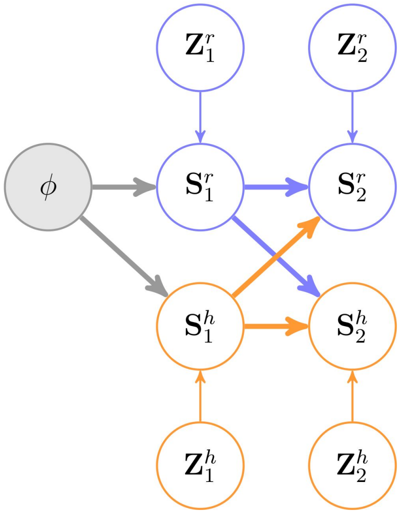
How did we do that?





Generating function:

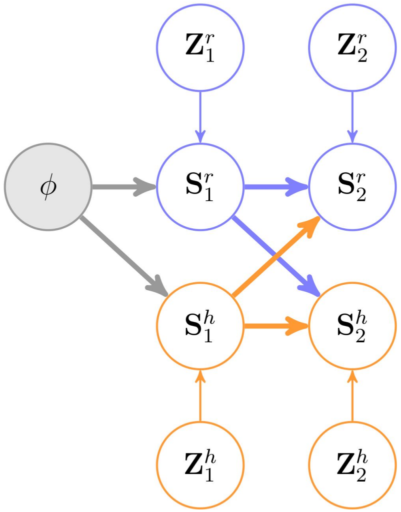
$$\mathbf{states}, \mathbf{states} \;=\; f\left(\mathbf{latents}, \mathbf{latents}\,; \mathbf{context}\right)$$



Generating function:

$$\mathbf{states}, \mathbf{states} = f\left(\mathbf{latents}, \mathbf{latents}\,; \mathbf{context}\right)$$

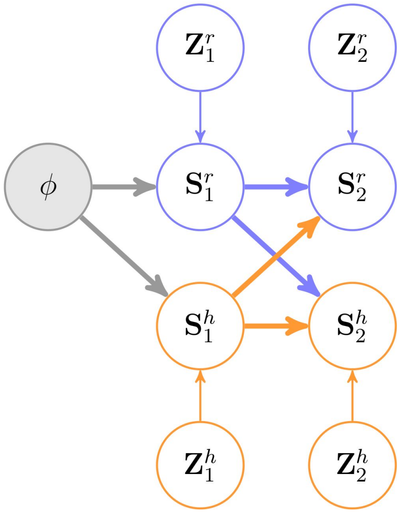
What is our Planning Objective?



$$p\left(\mathbf{states}, \mathbf{states} \,\middle|\, \mathbf{goal}, \mathbf{context}\right)$$

Generating function:

$$\mathbf{states}, \mathbf{states} = f\left(\mathbf{latents}, \mathbf{latents}\,; \mathbf{context}\right)$$

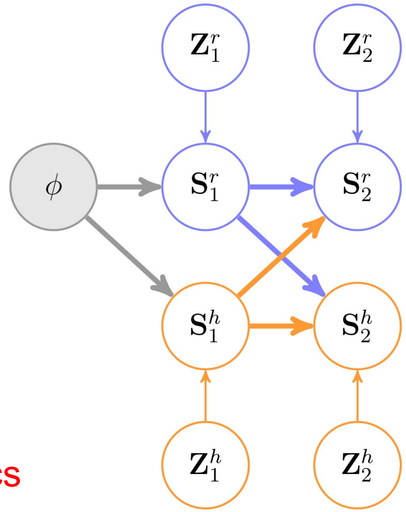


Generating function:

$$\textbf{states}, \textbf{states} = f\left(\textbf{latents}, \textbf{latents}\,; \textbf{context}\right)$$

$$p\left(\textbf{states}, \textbf{states} \,\middle|\, \textbf{goal}, \textbf{context}\right)$$

e.g. desired location



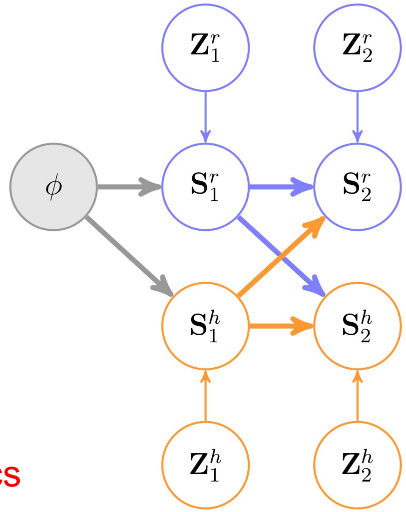
Generating function:

$$\mathbf{states}, \mathbf{states} = f\left(\mathbf{latents}, \mathbf{latents}\,; \mathbf{context}\right)$$

numerics

$$\log p \left(\mathbf{states}, \mathbf{states} \,\middle|\, \mathbf{goal}, \mathbf{context} \right)$$

e.g. desired location



Generating function:

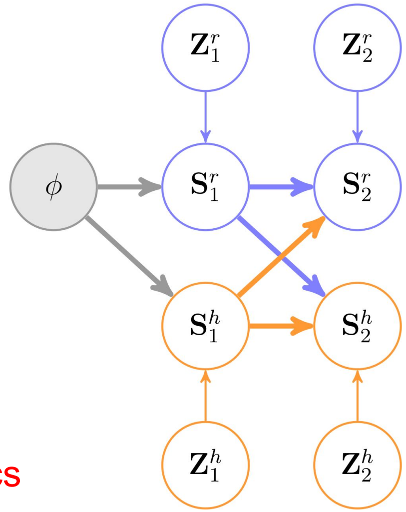
$$\textbf{states}, \textbf{states} = f\left(\textbf{latents}, \textbf{latents}\,; \textbf{context}\right)$$

numerics

$$\mathbb{E}_{\textbf{latents}}\left[\log p\left(\textbf{states}, \textbf{states} \,\middle|\, \textbf{goal}, \textbf{context}\right)\right]$$

cannot control

e.g. desired location



Generating function:

$$\textbf{states}, \textbf{states} = f\left(\textbf{latents}, \textbf{latents}\,; \textbf{context}\right)$$

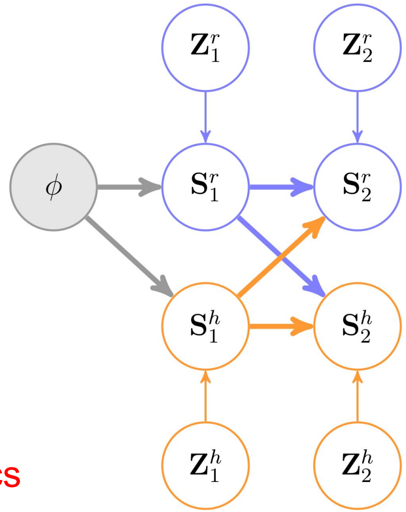
numerics

$$\arg\max_{\textbf{latents}} \mathbb{E}_{\textbf{latents}}\left[\log p\left(\textbf{states}, \textbf{states} \,\middle|\, \textbf{goal}, \textbf{context}\right)\right]$$

cannot control

e.g. desired location

can control



Generating function:

$$\textbf{states}, \textbf{states} = f\left(\textbf{latents}, \textbf{latents}\,; \textbf{context}\right)$$

numerics

$$\textbf{latents}^* = \arg\max_{\textbf{latents}} \mathbb{E}_{\textbf{latents}}\left[\log p\left(\textbf{states}, \textbf{states} \,\middle|\, \textbf{goal}, \textbf{context}\right)\right]$$

cannot control

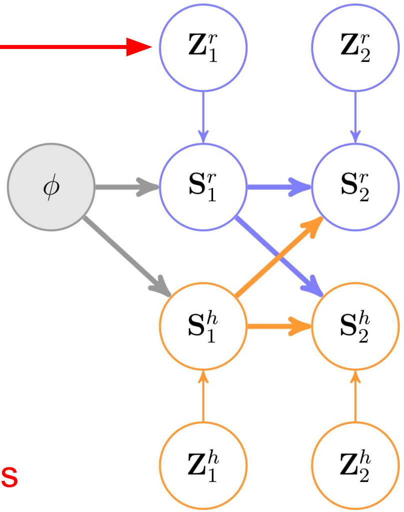
e.g. desired location

our plan

can control

Rhinehart, McAllister, Kitani, Levine **http://precog.ml**

decide



Generating function:

$$\text{states}, \text{states} = f\,(\text{latents}, \text{latents}\,; \text{context})$$

numerics

$$\boxed{\text{latents}^*} = \arg\max_{\text{latents}} \mathbb{E}_{\text{latents}}\left[\log p\left(\text{states}, \text{states} \,\middle|\, \text{goal}, \text{context}\right)\right]$$

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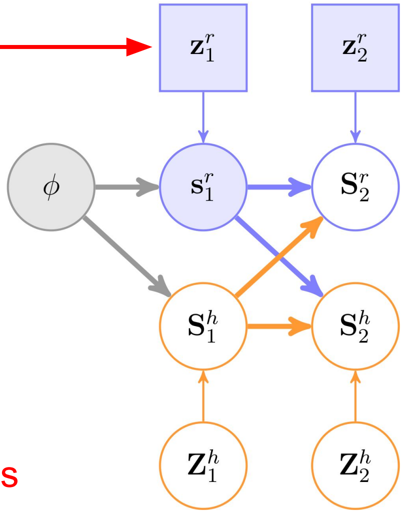

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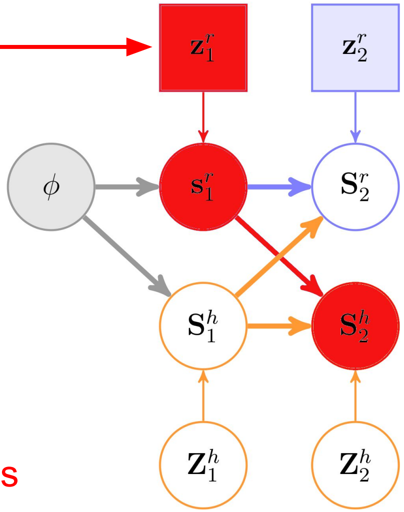

cause, from robot, at t=1

effect, on human, at t=2

Generating function:

$$\text{states}, \text{states} = f\left(\text{latents}, \text{latents}\, ; \text{context}\right)$$

numerics

$$\boxed{\text{latents}^*} = \arg\max_{\text{latents}} \mathbb{E}_{\text{latents}}\left[\log p\left(\text{states}, \text{states} \,\middle|\, \text{goal}, \text{context}\right)\right]$$

our plan

can control

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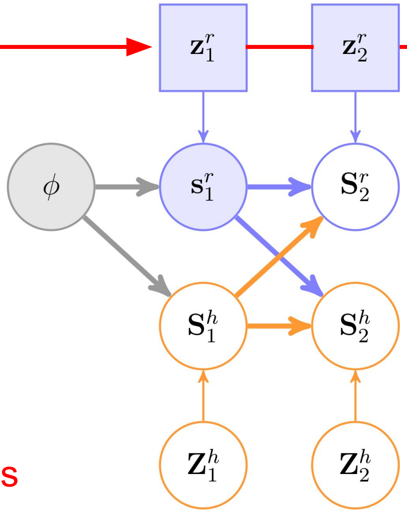


Generating function:

$$\textbf{states}, \textbf{states} = f\left(\textbf{latents}, \textbf{latents}\,; \textbf{context}\right)$$

~ Normal(0,1)

numerics

$$\boxed{\textbf{latents}^*} = \arg\max_{\textbf{latents}} \mathbb{E}_{\textbf{latents}}\left[\log p\left(\textbf{states}, \textbf{states} \,\middle|\, \textbf{goal}, \textbf{context}\right)\right]$$

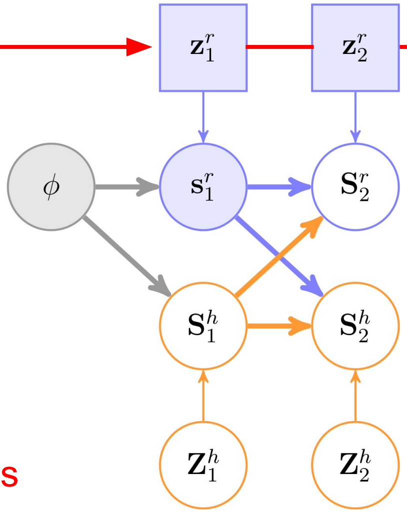
our plan

can control

cannot control

e.g. desired location

decide



Generating function:

$$\text{states}^*, \text{states}^* = f\left(\text{latents}^*, \text{latents}\, ; \text{context}\right)$$

~ Normal(0,1)

numerics

$$\boxed{\text{latents}^*} = \arg\max_{\text{latents}} \mathbb{E}_{\text{latents}}\left[\log p\left(\text{states}, \text{states} \,\middle|\, \text{goal}, \text{context}\right)\right]$$

our plan

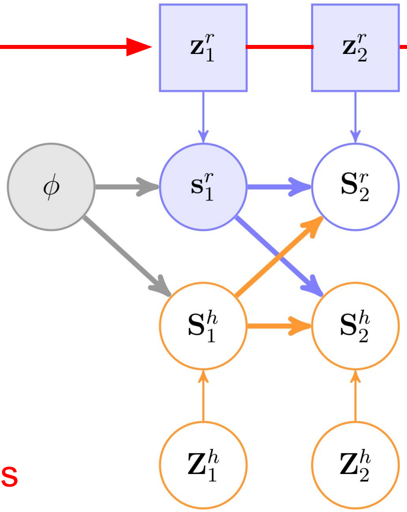
can control

cannot control

e.g. desired location

can control

decide



Generating function:

$$\text{states}^*, \text{states}^* = f\left(\text{latents}^*, \text{latents} \,;\, \text{context}\right)$$

Predictions conditioned on **goal** !

~ Normal(0,1)

numerics

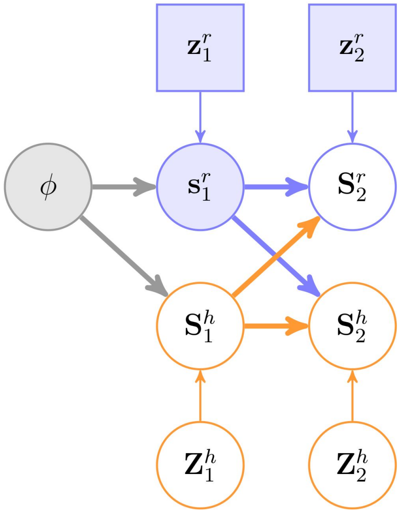
$$\boxed{\text{latents}^*} = \arg\max_{\text{latents}} \mathbb{E}_{\text{latents}}\left[\log p\left(\text{states}, \text{states} \,\middle|\, \text{goal}, \text{context}\right)\right]$$

our plan

can control

cannot control

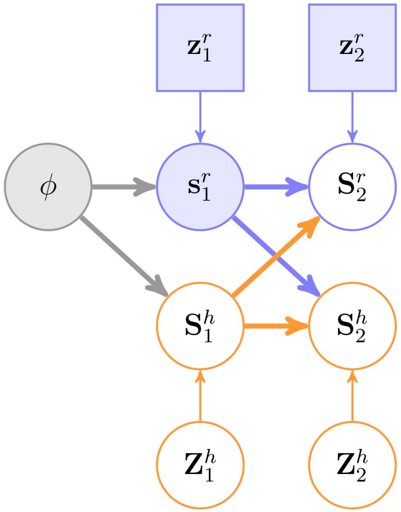
e.g. desired location



Generating function:

$$\textbf{states}, \textbf{states} = f\left(\textbf{latents}, \textbf{latents}\,; \textbf{context}\right)$$

$$\begin{aligned}\textbf{latents}^* &= \underset{\textbf{latents}}{\arg\max}\, \mathbb{E}_{\textbf{latents}}\left[\log p\left(\textbf{states}, \textbf{states} \,\middle|\, \textbf{goal}, \textbf{context}\right)\right] \\ &= \underset{\textbf{latents}}{\arg\max}\, \mathbb{E}_{\textbf{latents}}\left[\log q\left(\textbf{states}, \textbf{states} \,\middle|\, \textbf{context}\right) + \log p(\textbf{goal} \,|\, \textbf{states}, \textbf{states}, \textbf{context}) - \log p\left(\textbf{goal} \,\middle|\, \textbf{context}\right)\right]\end{aligned}$$



Generating function:

$$\textbf{states}, \textbf{states} \; = \; f\,(\textbf{latents}, \textbf{latents}\,; \textbf{context})$$

$$\begin{aligned}
\textbf{latents}^* &= \underset{\textbf{latents}}{\arg\max}\, \mathbb{E}_{\textbf{latents}}\left[\log p\left(\textbf{states}, \textbf{states} \,\middle|\, \textbf{goal}, \textbf{context}\right)\right] \\
&= \underset{\textbf{latents}}{\arg\max}\, \mathbb{E}_{\textbf{latents}}\left[\log q\left(\textbf{states}, \textbf{states} \,\middle|\, \textbf{context}\right) + \log p(\textbf{goal} \,|\, \textbf{states}, \textbf{states}, \textbf{context}) - \log p\left(\textbf{goal} \,\middle|\, \textbf{context}\right)\right] \\
&= \underset{\textbf{latents}}{\arg\max}\, \mathbb{E}_{\textbf{latents}}\left[\underbrace{\log q\left(\textbf{states}, \textbf{states} \,\middle|\, \textbf{context}\right)}_{\text{multi-agent prior}} + \underbrace{\log p\left(\textbf{goal} \,\middle|\, \textbf{states}, \textbf{states}, \textbf{context}\right)}_{\text{goal likelihood}}\right]
\end{aligned}$$

Future work: how to respond to “out-of-distribution” scenes?

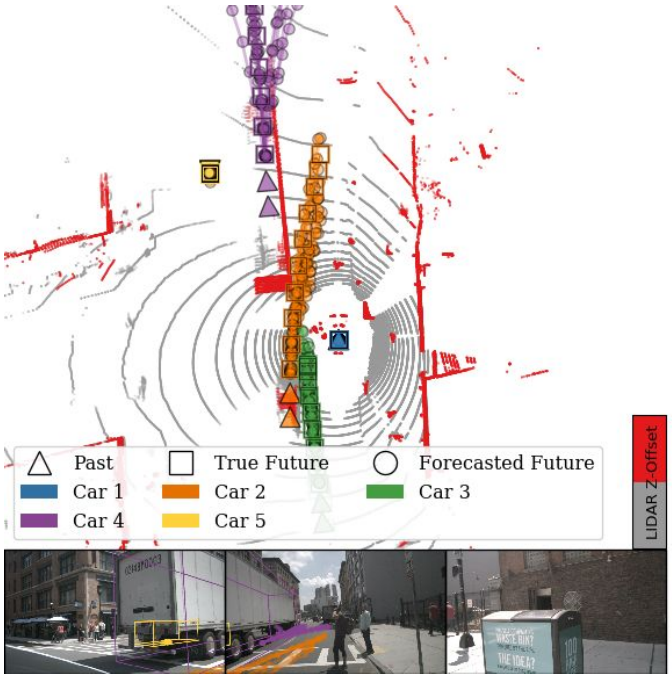
Thank you!

Single-agent forecasting + control
Deep Imitative Models for Flexible Inference, Planning, and Control
Nicholas Rhinehart, Rowan McAllister, Sergey Levine
arXiv 2018 http://imitate.ml

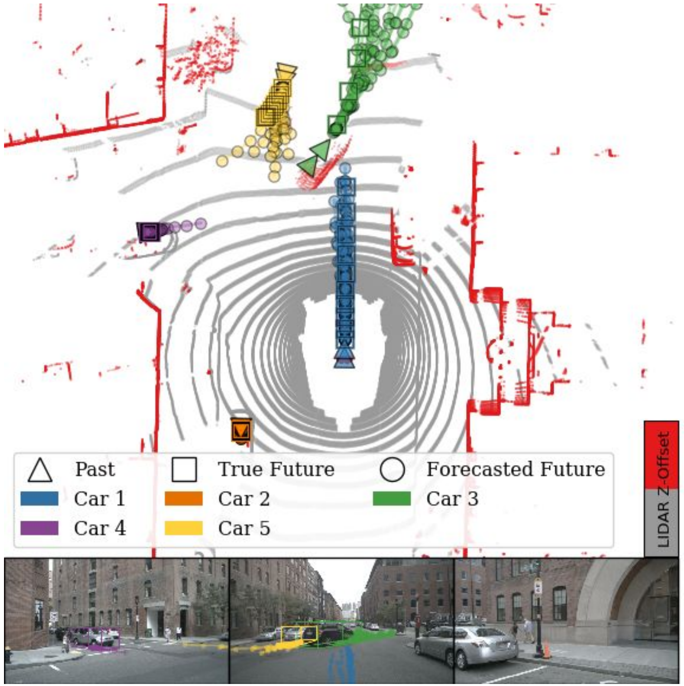
Multi-agent forecasting
PRECOG: PREdiction Conditioned On Goals in Visual Multi-Agent Settings
Nicholas Rhinehart, Rowan McAllister, Kris Kitani, Sergey Levine
ICCV 2019 http://precog.ml

Bayesian single-agent forecasting + control
(in progress)

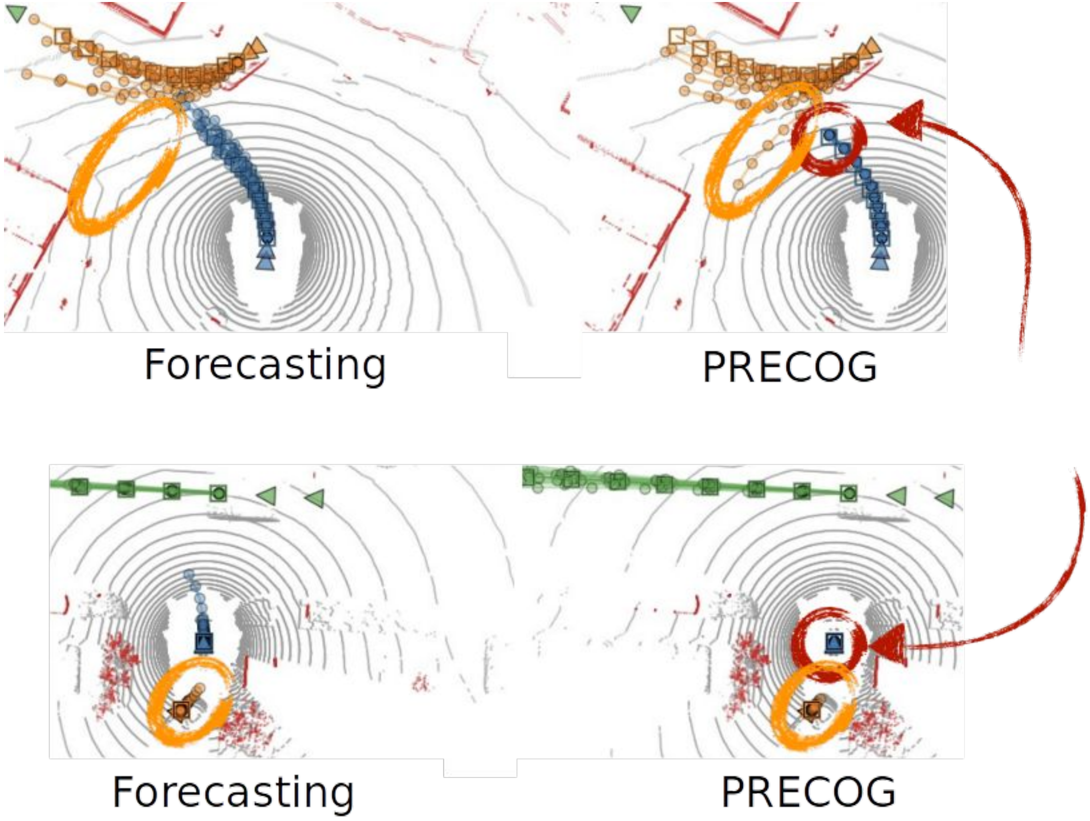
Forecasting with nuScenes data (Singapore + Boston)



Car 2 is predicted to overtake Car 1, which itself is forecasted to continue to wait for pedestrians and Car 2.



Car 4 is predicted to wait for a clear intersection, and Car 5 is predicted to either start turning or continue straight.


Forecasting
PRECOG
Forecasting
PRECOG

Goal-Conditioned Forecasting