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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(trains offline) (no rewards required)

Without learning ?	✓	✗
Behavior cloning ?	?	✓
Model-based RL ?	?	✗

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(trains offline) (no rewards required) (plans)

Without learning ?	✓	✗
Behavior cloning ?	?	✓
Model-based RL ?	?	✗

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	(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** ?

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Without learning ?	✓	✗	✓	
Behavior cloning ?	?	✓	✗	
Model-based RL ?	?	✗	✓	

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Behavior cloning ?	?	✓	✗	✗
Model-based RL ?	?	✗	✓	✓

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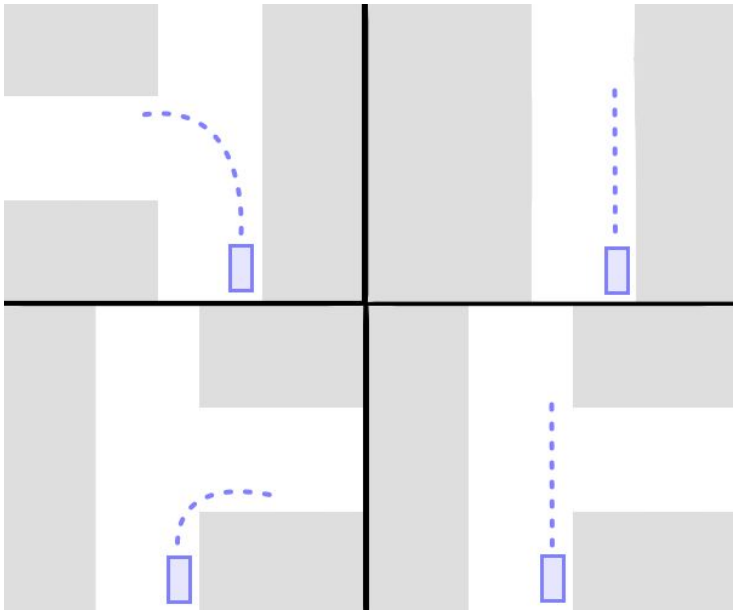
Without learning ?	✓	✗	✓	?
Behavior cloning ?	?	✓	✗	✗
Model-based RL ?	?	✗	✓	✓
Imitative Models (ours)	✓	✓	✓	✓

Modelling Expert Drivers



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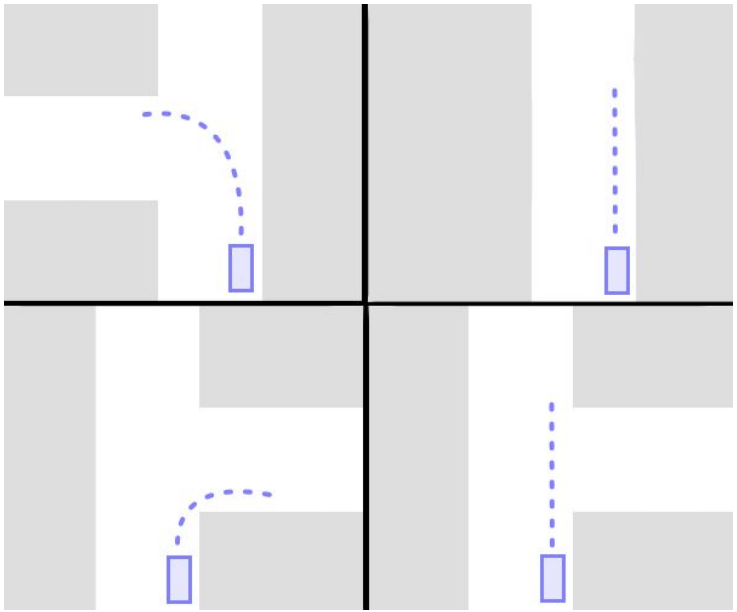

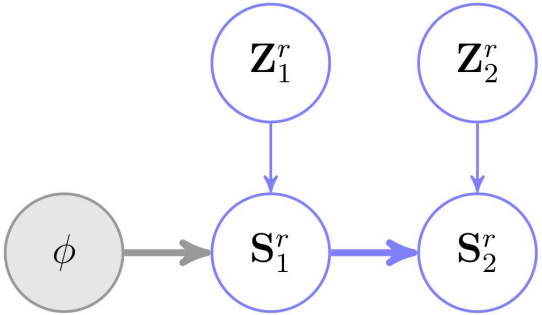

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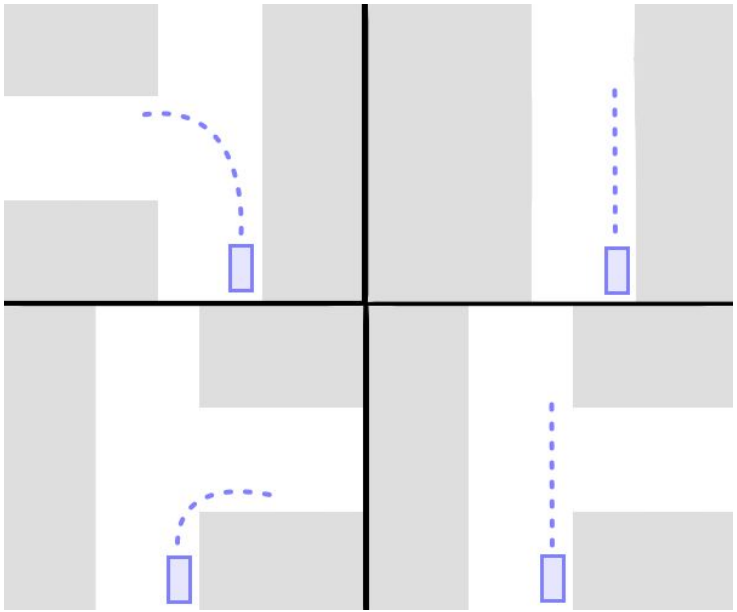
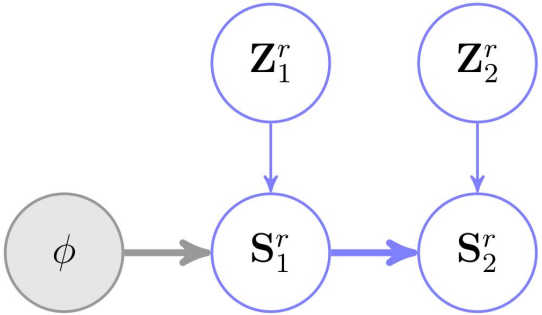
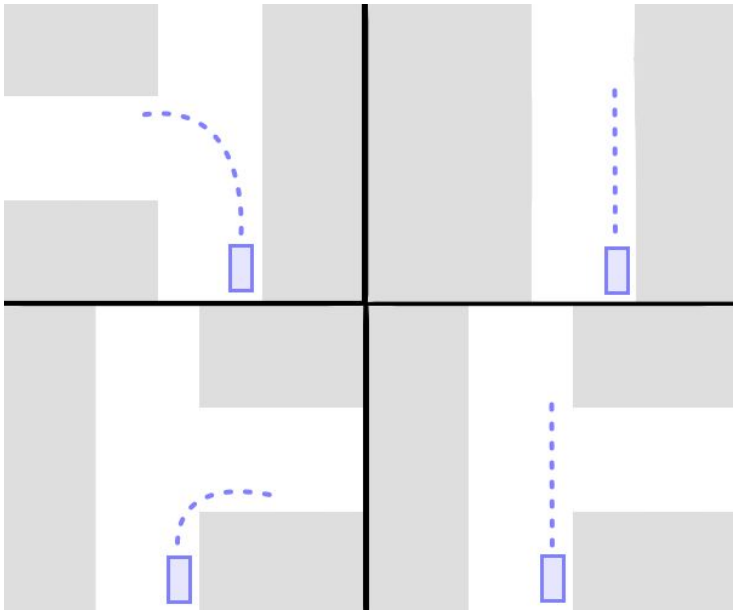
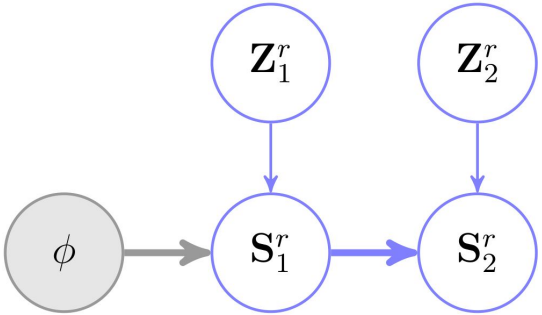




$$\textbf{states} = f\,(\textbf{latents}\,;\textbf{context})$$

Modelling Expert Drivers





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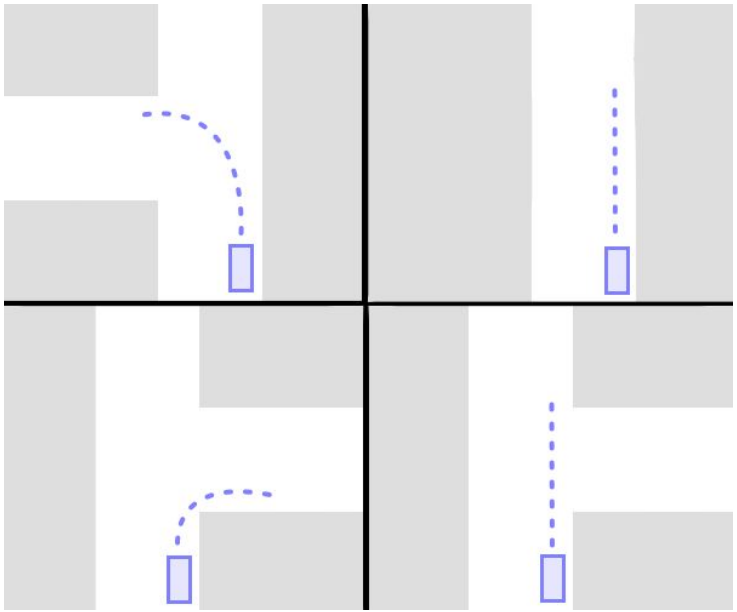

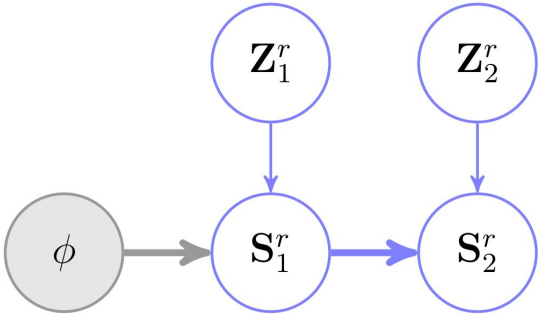

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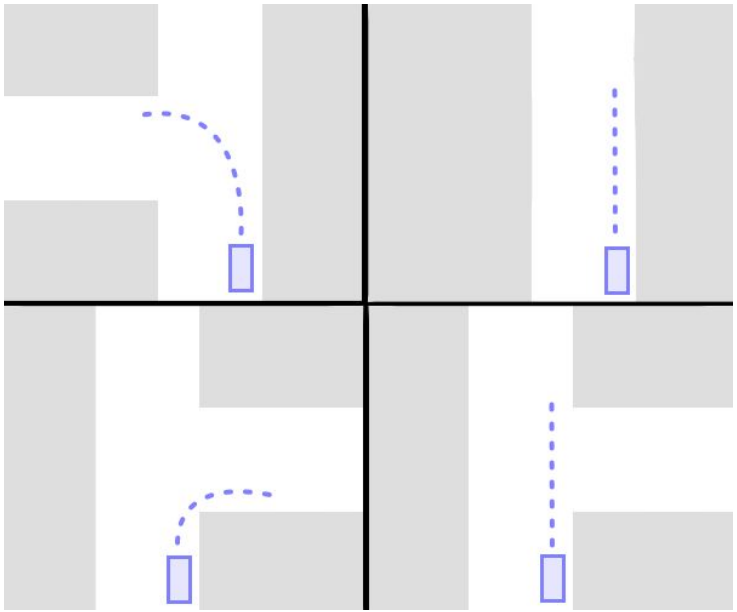
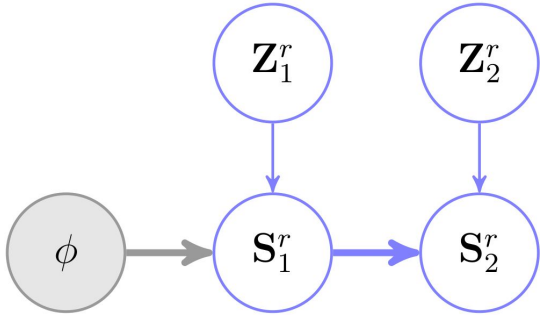
Modelling Expert Drivers





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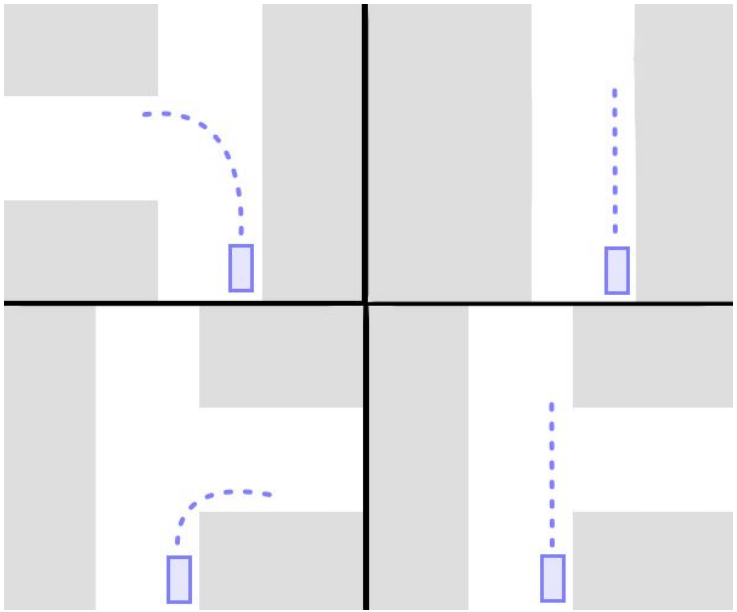
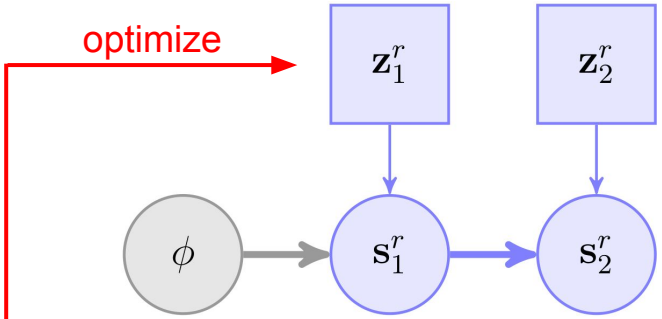
Can **plan** in this distribution!

new idea

Rhinehart, McAllister, Levine **http://imitate.ml**

Modelling Expert Drivers





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Planning “Expert-like” Motions to our own Goals

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

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Planning “Expert-like” Motions to our own Goals

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&= \arg\max_{\textbf{states}} \log \underbrace{q(\textbf{states} \mid \textbf{context})}_{\text{imitation prior}} + \log \underbrace{p(\textbf{goal} \mid \textbf{states}, \textbf{context})}_{\text{goal likelihood}}
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Drive safely...

Rhinehart, McAllister, Levine **http://imitate.ml**

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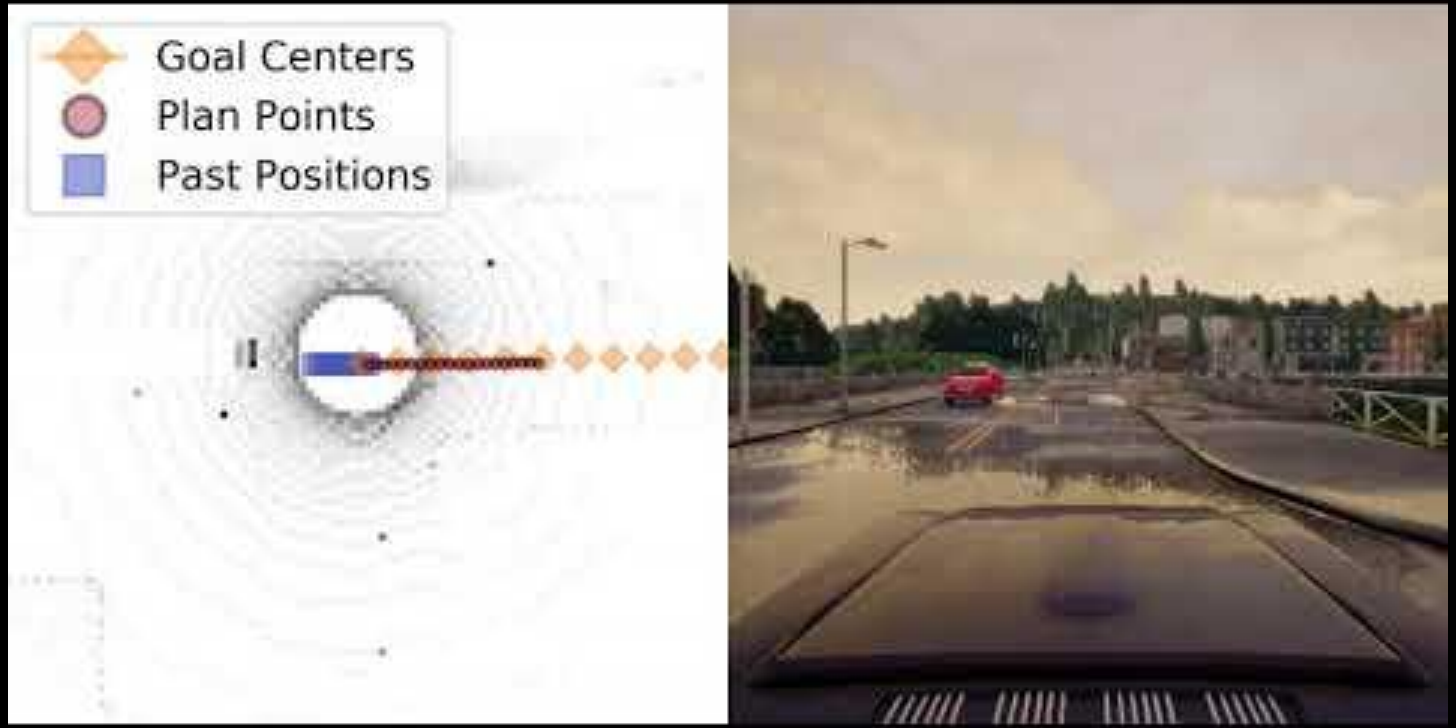
Drive safely...

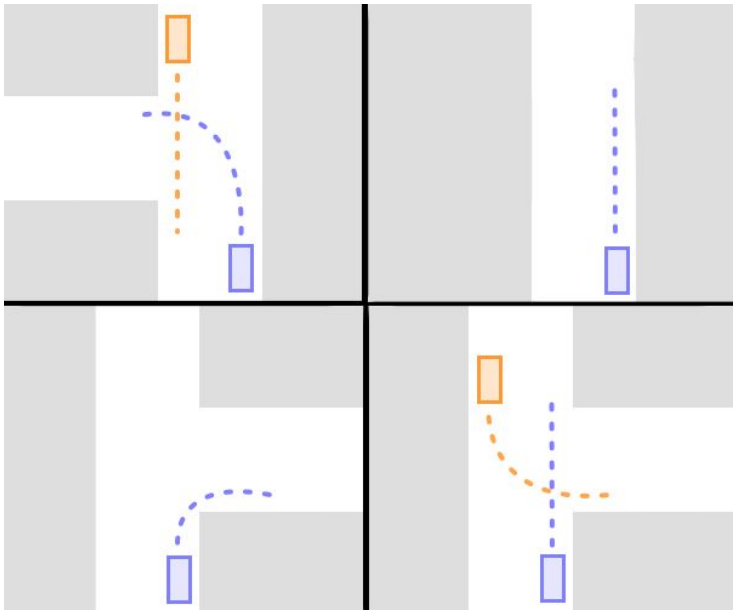
...and get to our destination!

Rhinehart, McAllister, Levine **http://imitate.ml**


Goal Centers
Plan Points
Past Positions

Goal Centers
Plan Points
Past Positions

Modelling Multiple Expert Drivers



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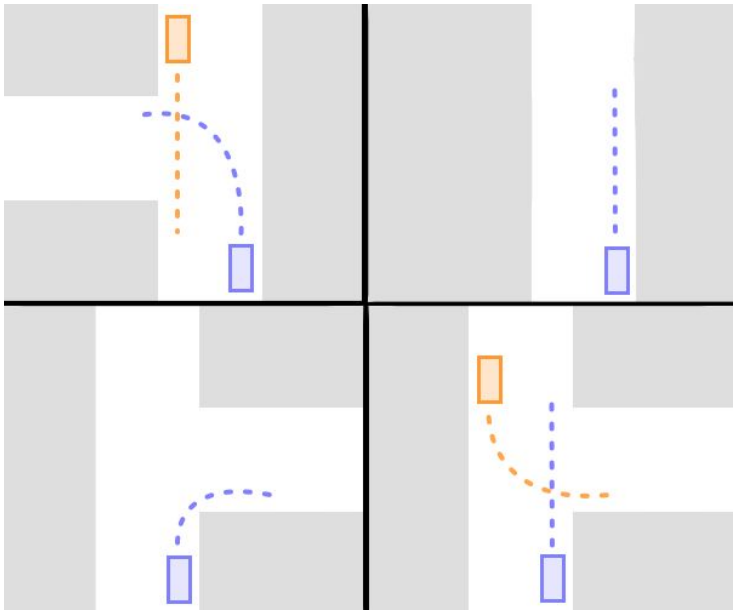

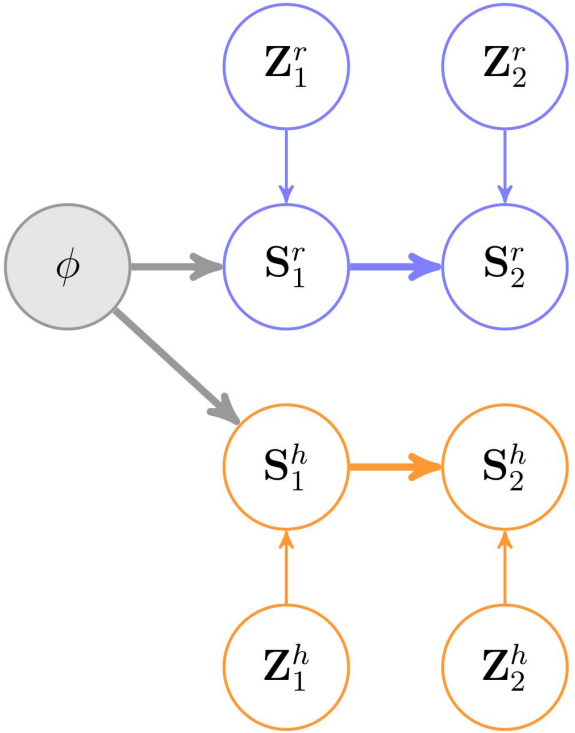

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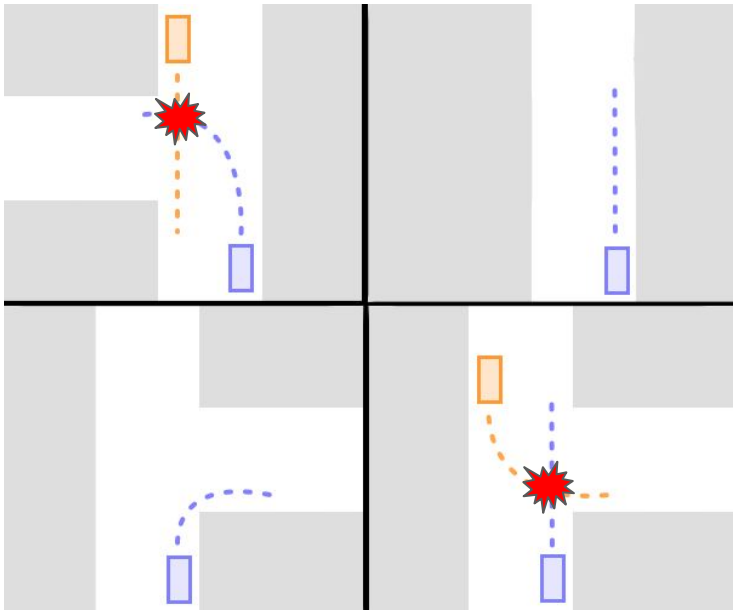
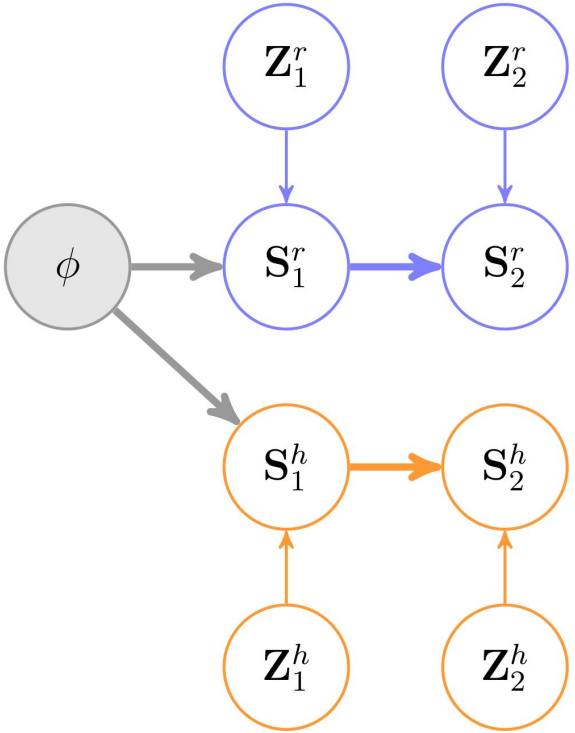
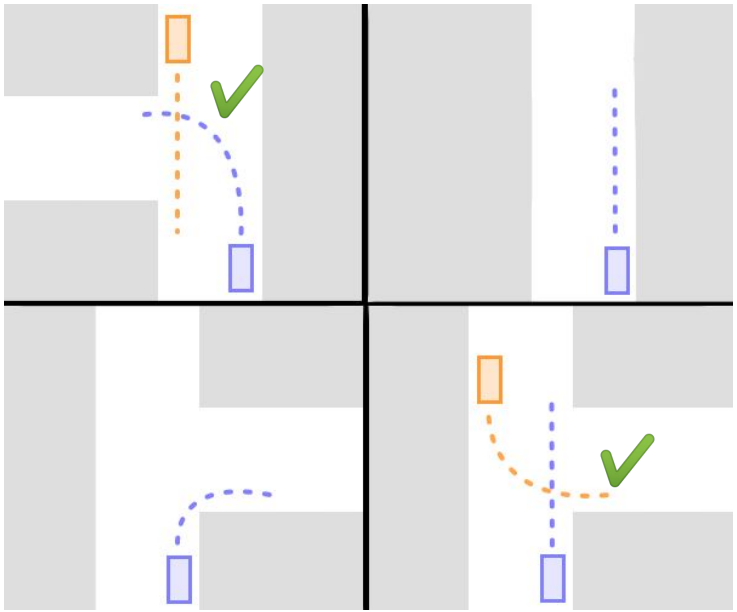
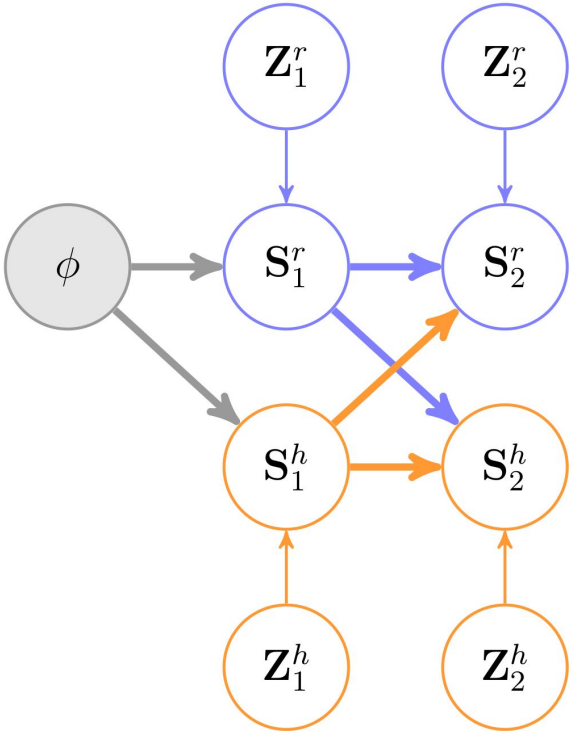


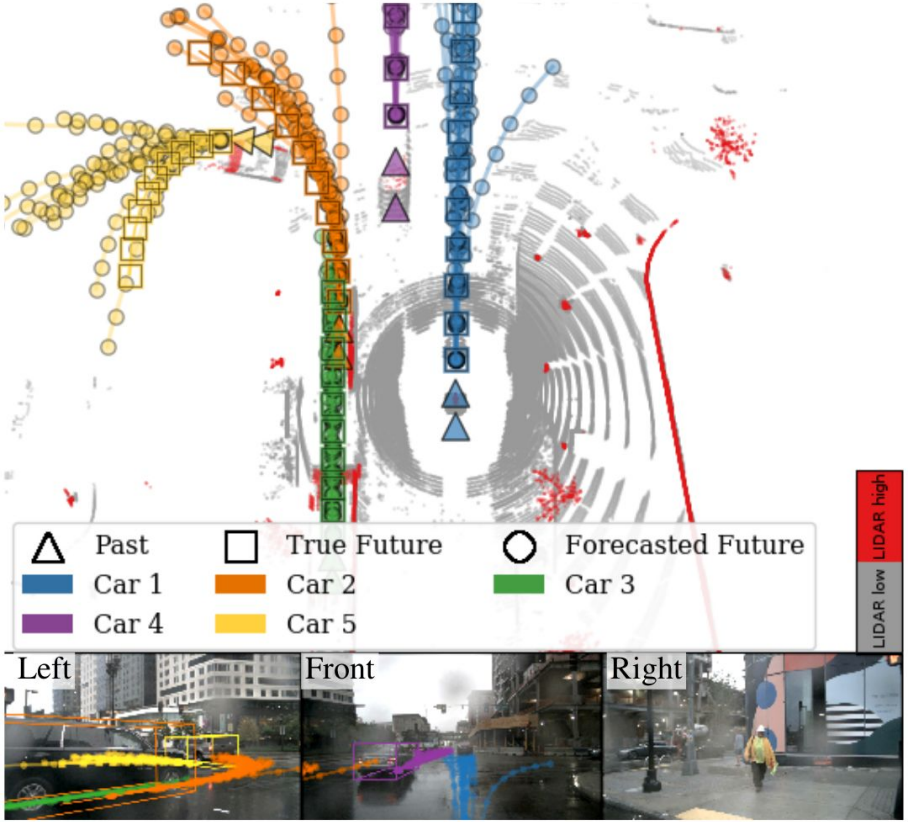


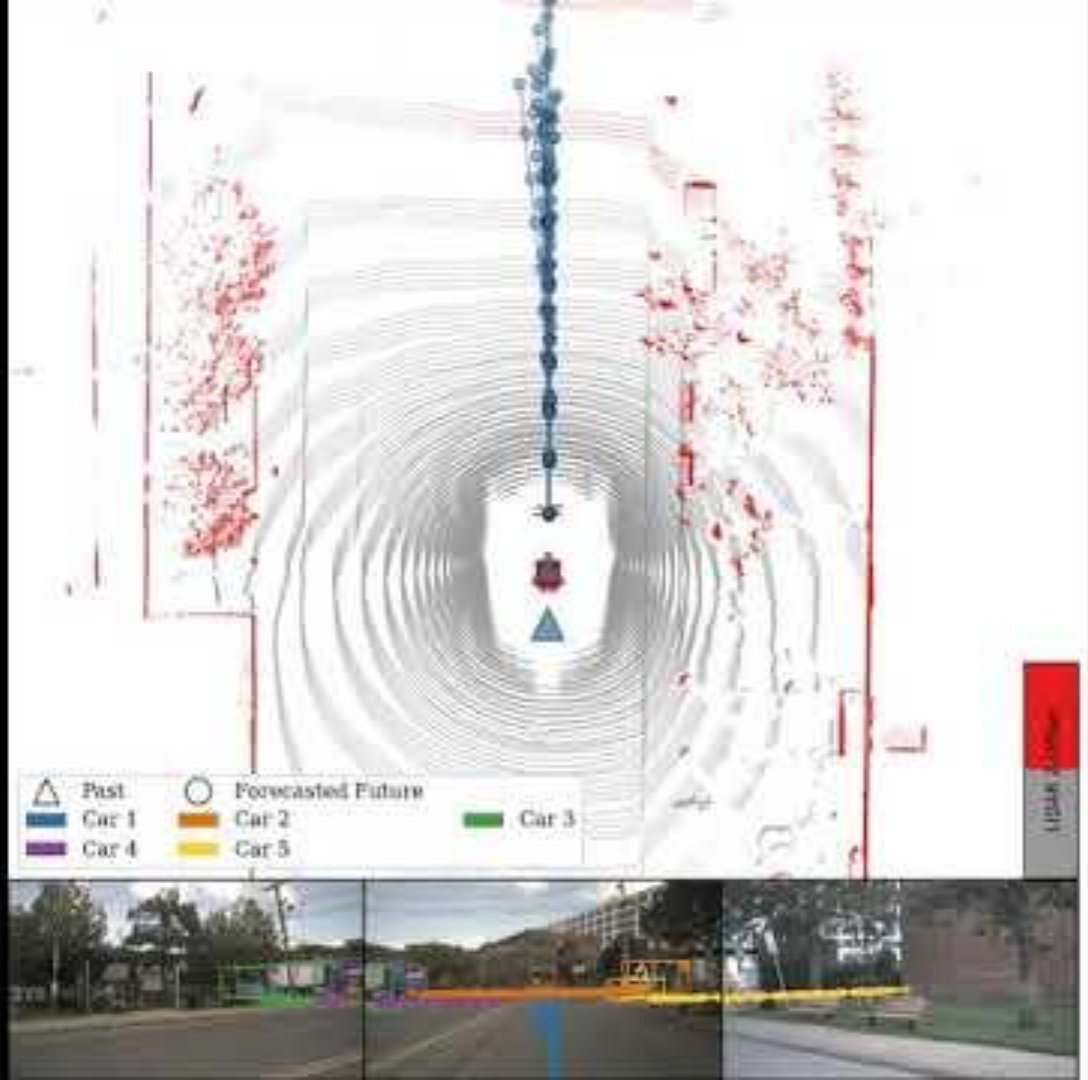
Modelling Multiple Expert Drivers





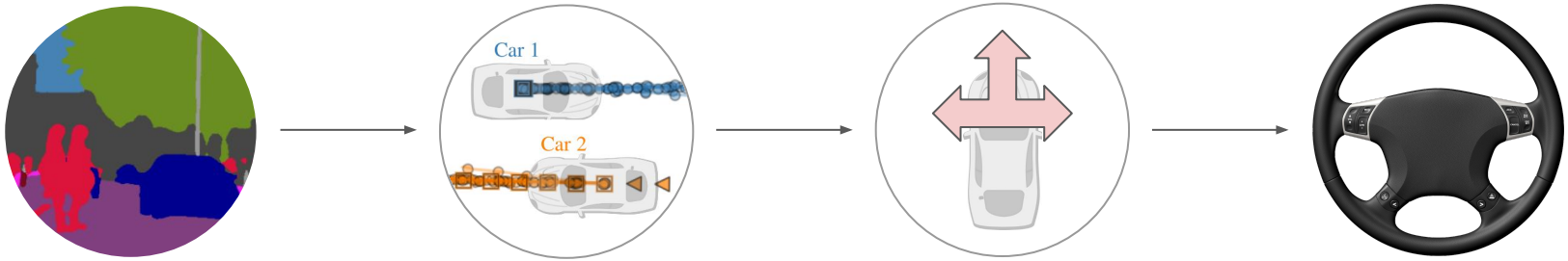
Forecasting with nuScenes data (Singapore + Boston)




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**?



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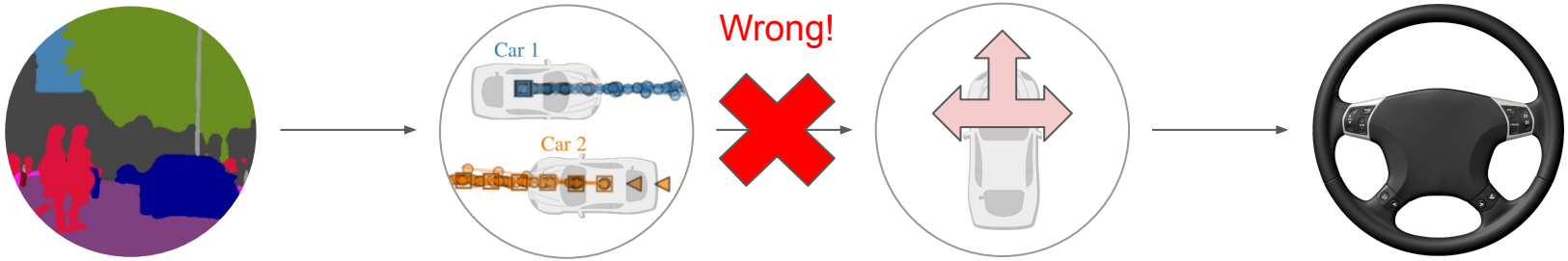

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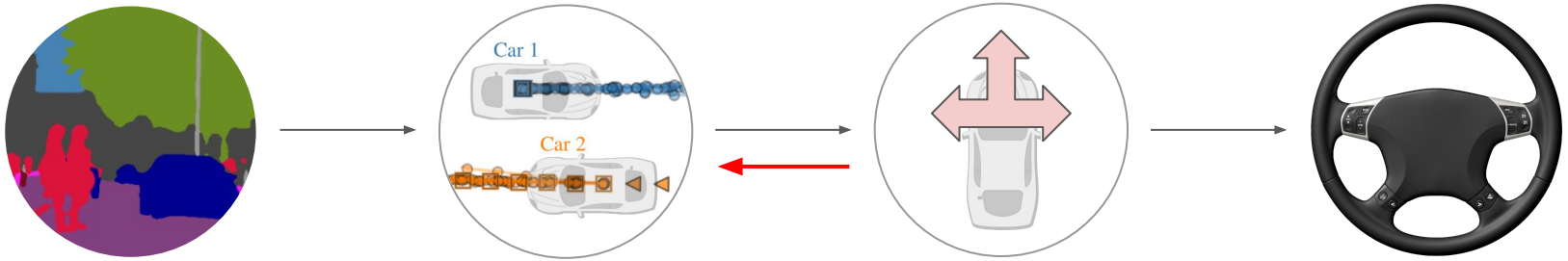
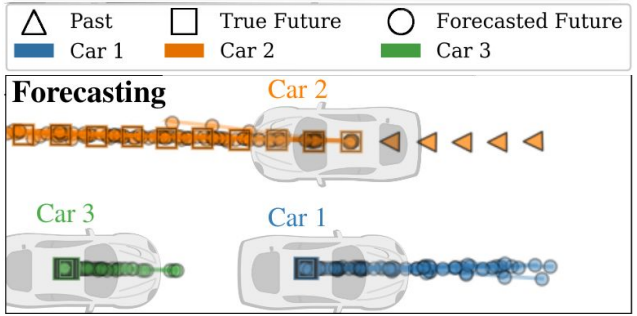


Goal-Conditioned Multi-Agent Forecasting



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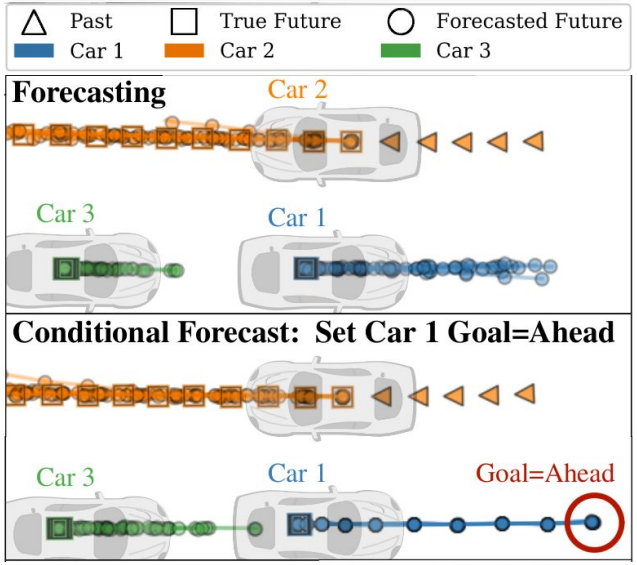

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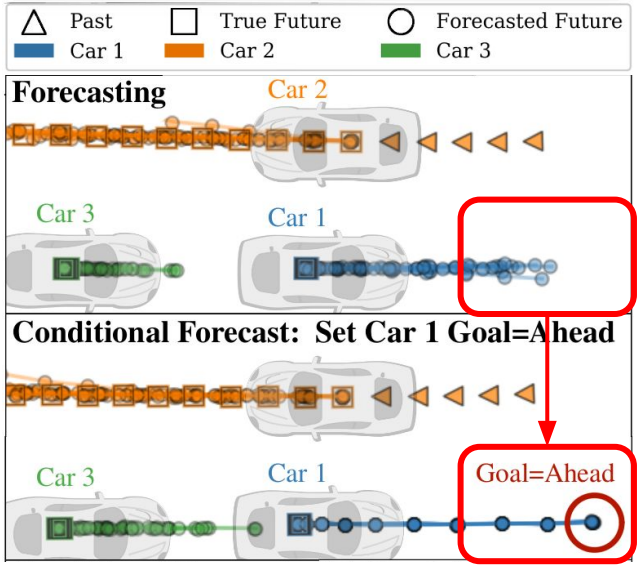

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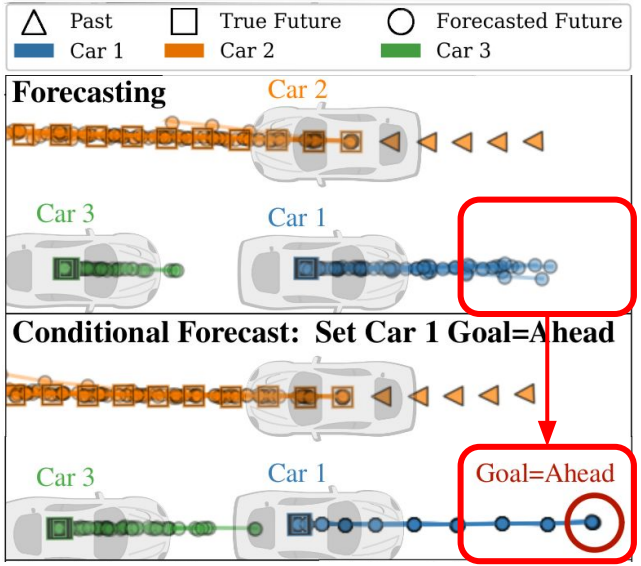
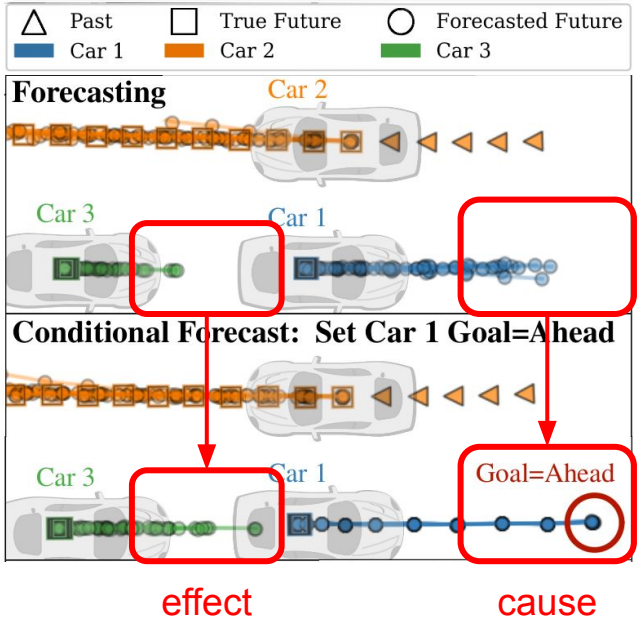


cause

Goal-Conditioned Multi-Agent Forecasting



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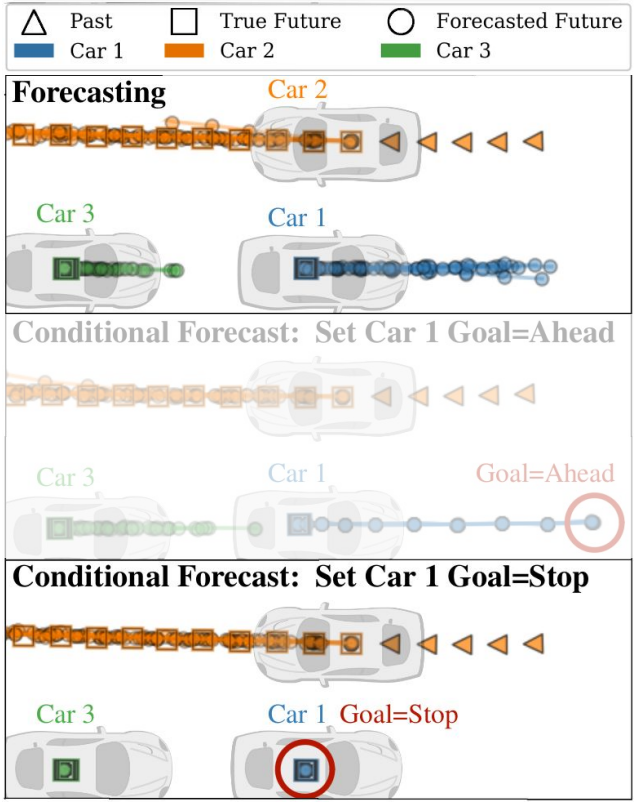

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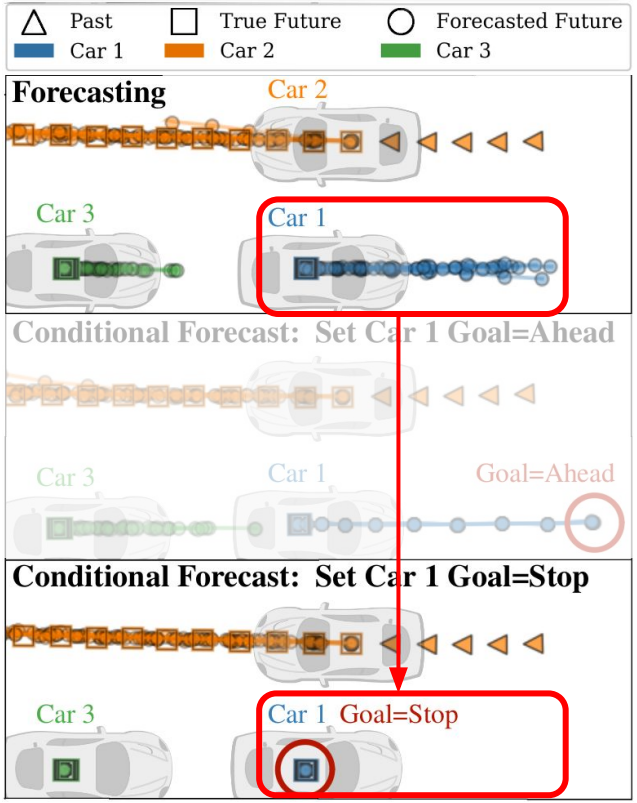

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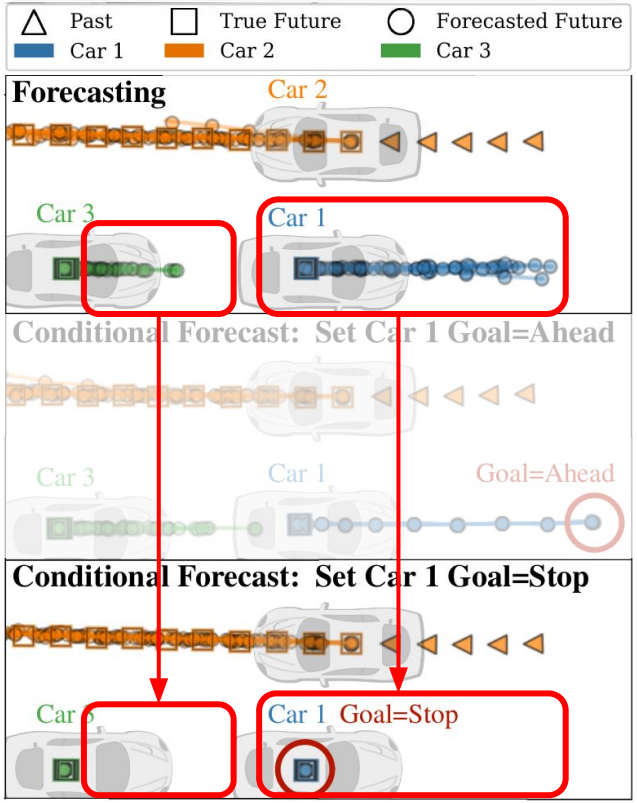
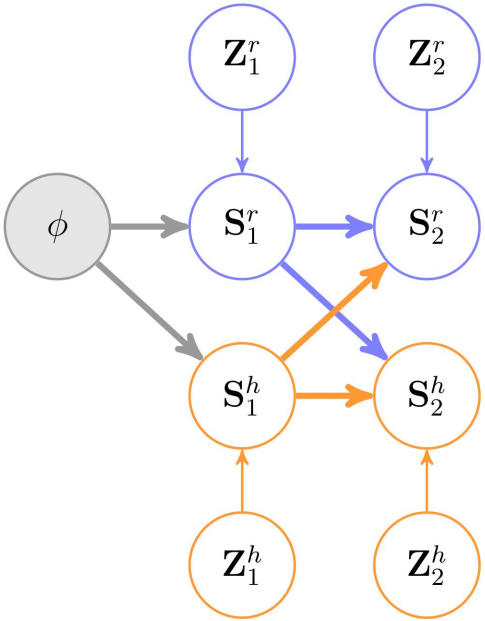
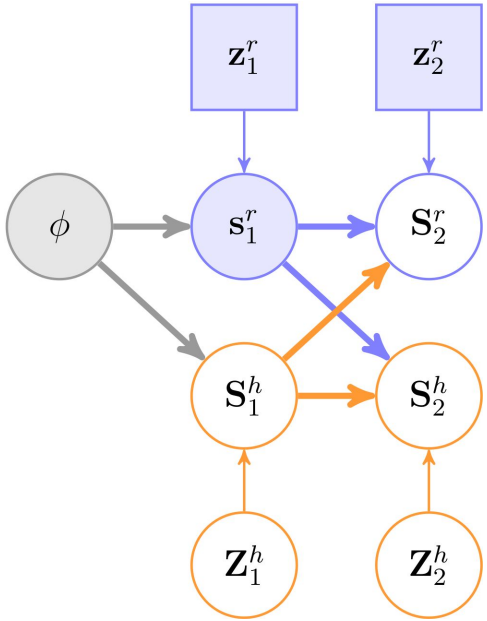


Goal-Conditioned Multi-Agent Forecasting

Forecasting



Conditional forecasting



Goal-Conditioned Multi-Agent Forecasting

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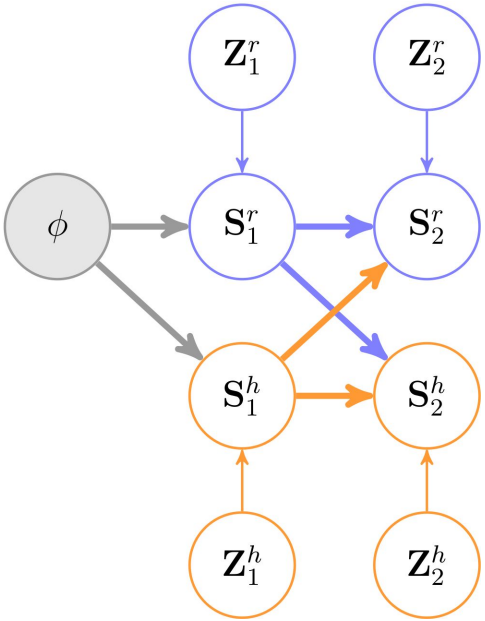

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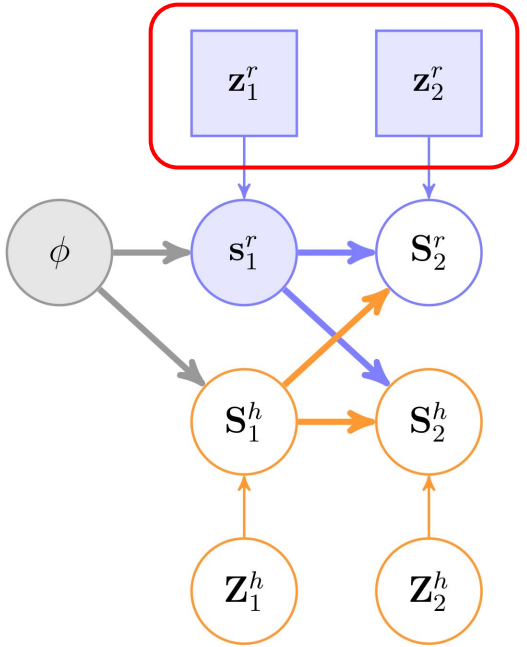
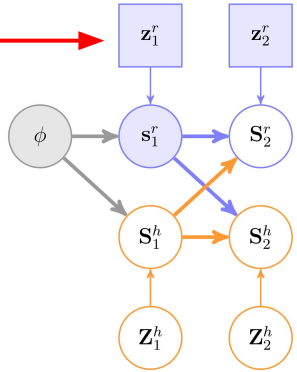


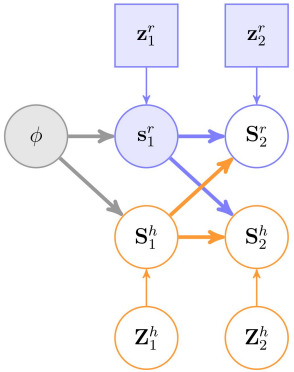
How to decide?

Goal-Conditioned Multi-Agent Forecasting

How to decide ?

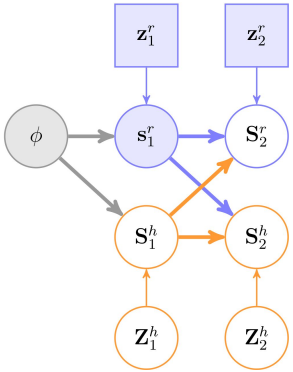


Goal-Conditioned Multi-Agent Forecasting



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

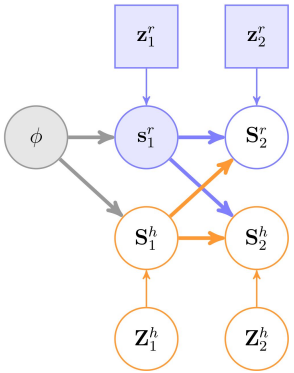
Goal-Conditioned Multi-Agent Forecasting



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

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

Goal-Conditioned Multi-Agent Forecasting

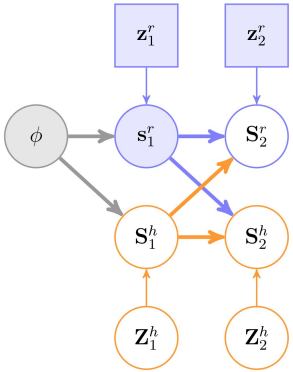


$$\textbf{states}, \textbf{states} \;=\; f\left(\textbf{latents}, \textbf{latents}\,;\, \textbf{context}\right)$$

numerics

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

Goal-Conditioned Multi-Agent Forecasting



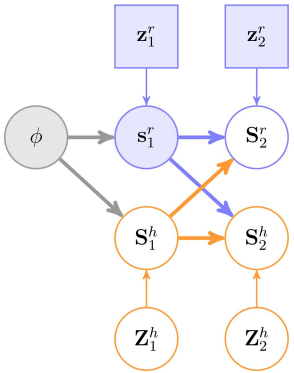
$$\mathbf{states}, \mathbf{states} = f\left(\mathbf{latents}, \mathbf{latents}\,;\, \mathbf{context}\right)$$

numerics

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

cannot control

Goal-Conditioned Multi-Agent Forecasting



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

numerics

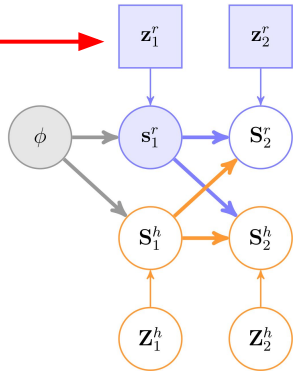
$$\arg\max_{\text{latents}} \mathbb{E}_{\text{latents}}\left[\log p\left(\text{states}, \text{states} \,\middle|\, \text{goal}, \text{context}\right)\right]$$

cannot control

can control

Goal-Conditioned Multi-Agent Forecasting

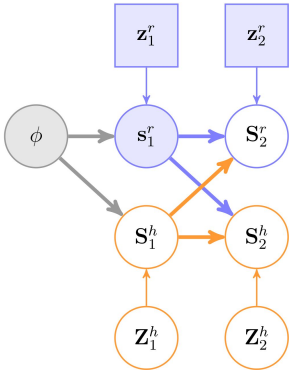
How we decide



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

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

Goal-Conditioned Multi-Agent Forecasting

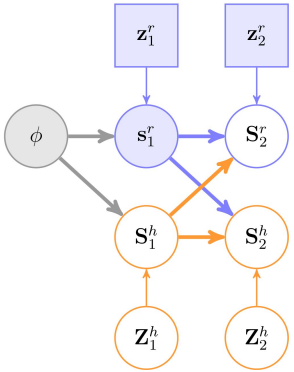


$$\textbf{states}, \textbf{states} = f\left(\textbf{latents}, \textbf{latents}\,;\, \textbf{context}\right)$$

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

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

Goal-Conditioned Multi-Agent Forecasting



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

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

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

$$= \arg\max_{\textbf{latents}} \mathbb{E}_{\textbf{latents}}\Big[\underbrace{\log q\left(\textbf{states}, \textbf{states} \,\middle|\, \textbf{context}\right)}_{\text{multi-agent prior}} + \underbrace{\log p\left(\textbf{goal} \,\middle|\, \textbf{states}, \textbf{states}, \textbf{context}\right)}_{\text{goal likelihood}}\Big]$$

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

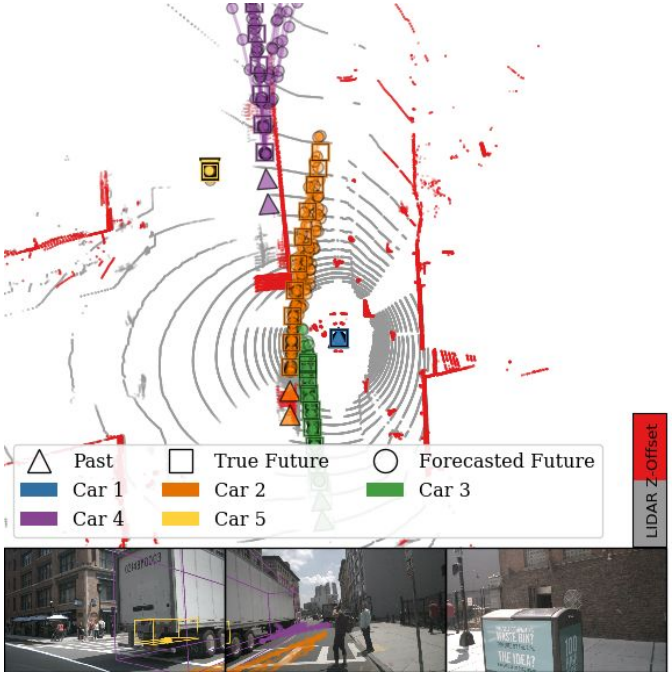
Thank you!

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

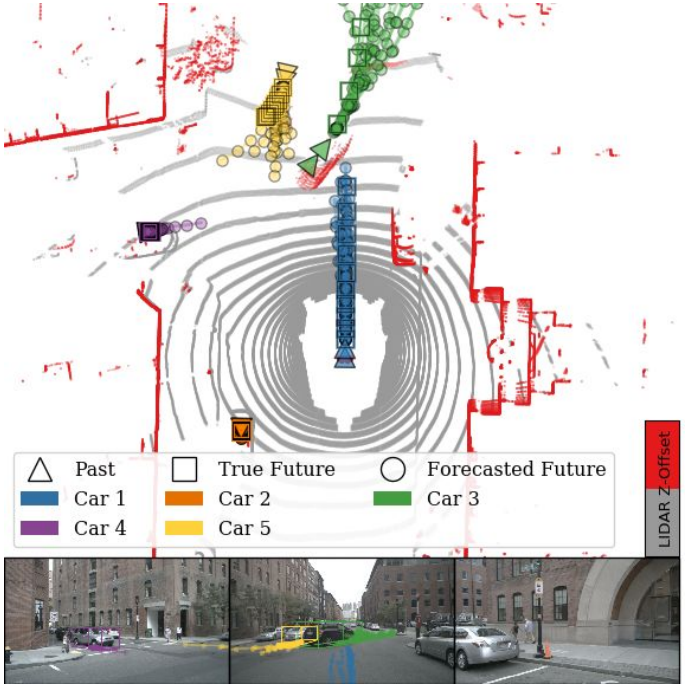
Multi-agent forecasting
PRECOG: PREdiction Conditioned On Goals in Visual Multi-Agent Settings
Nicholas Rhinehart, Rowan McAllister, Kris Kitani, Sergey Levine
http://precog.ml

Bayesian single-agent forecasting + control
(in progress)

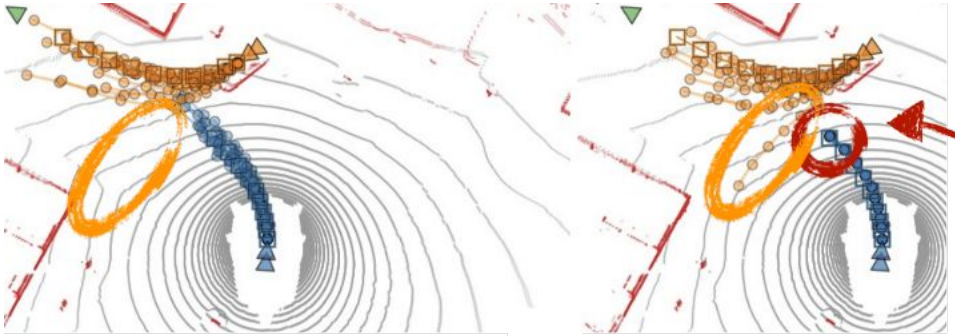
Forecasting with nuScenes data (Singapore + Boston)



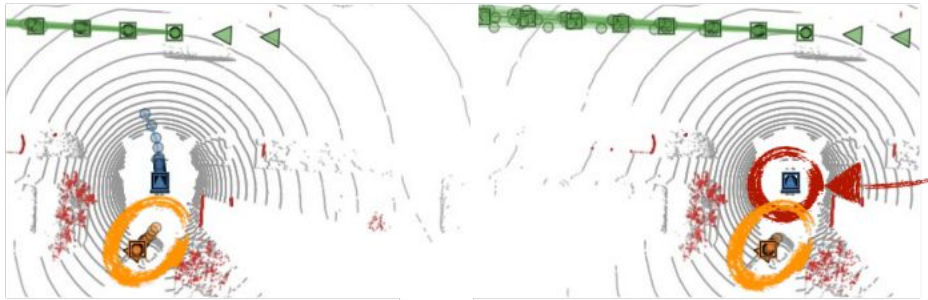
Car 2 is predicted to overtake **Car 1**, which itself is forecasted to continue to wait for pedestrians and **Car 2**.



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



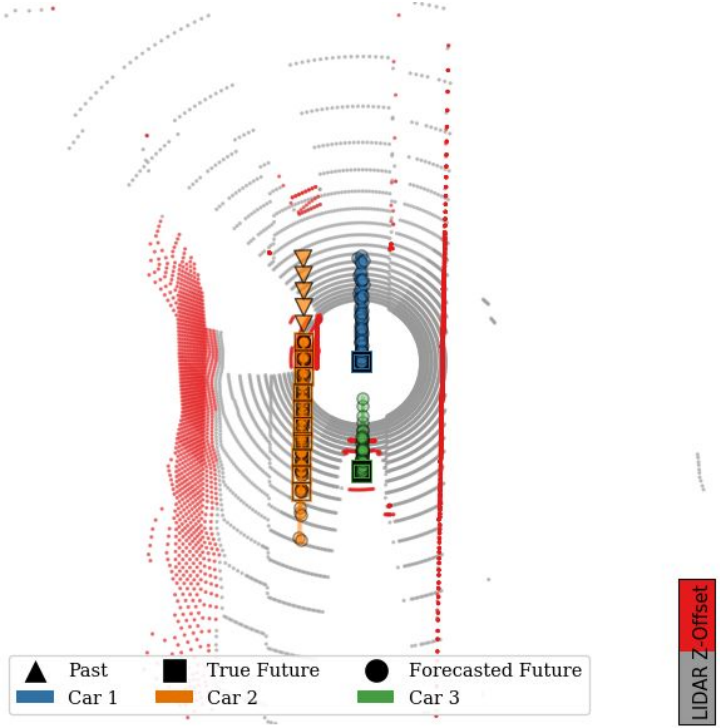
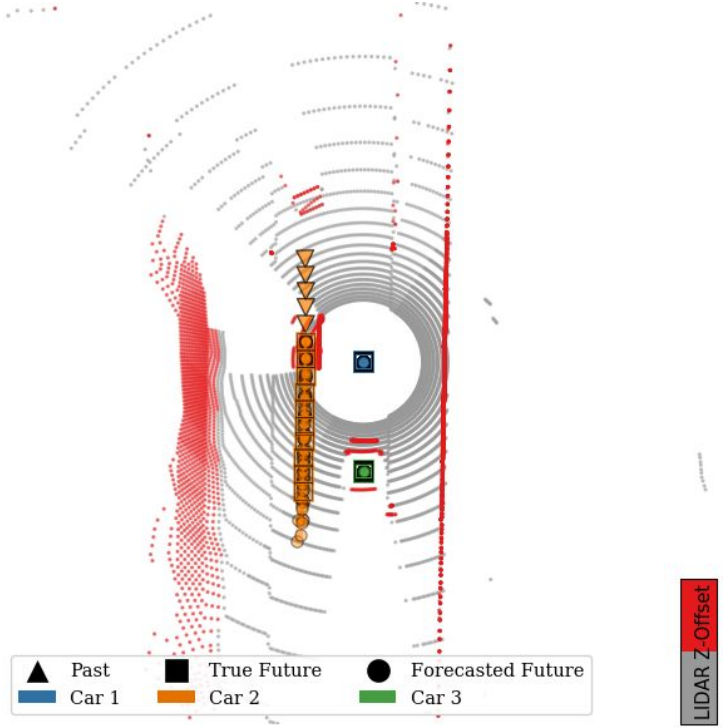
Forecasting PRECOG



Forecasting PRECOG

Goal-Conditioned Forecasting

Forecasting



Car 1 Forecasts Stopping