Inverse Neural Rendering for Explainable Multi-Object Tracking

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PRINCETON
COMPUTATIONAL IMAGING LAB

* denotes equal contribution

Agenda

- ➔ Prior Work and Motivation
- ➔ Our Method
- ➔ Generalization
- ➔ Failure Cases and Interpretability
- ➔ 3D Interpretation
- ➔ Limitations
- ➔ Key Takeaway

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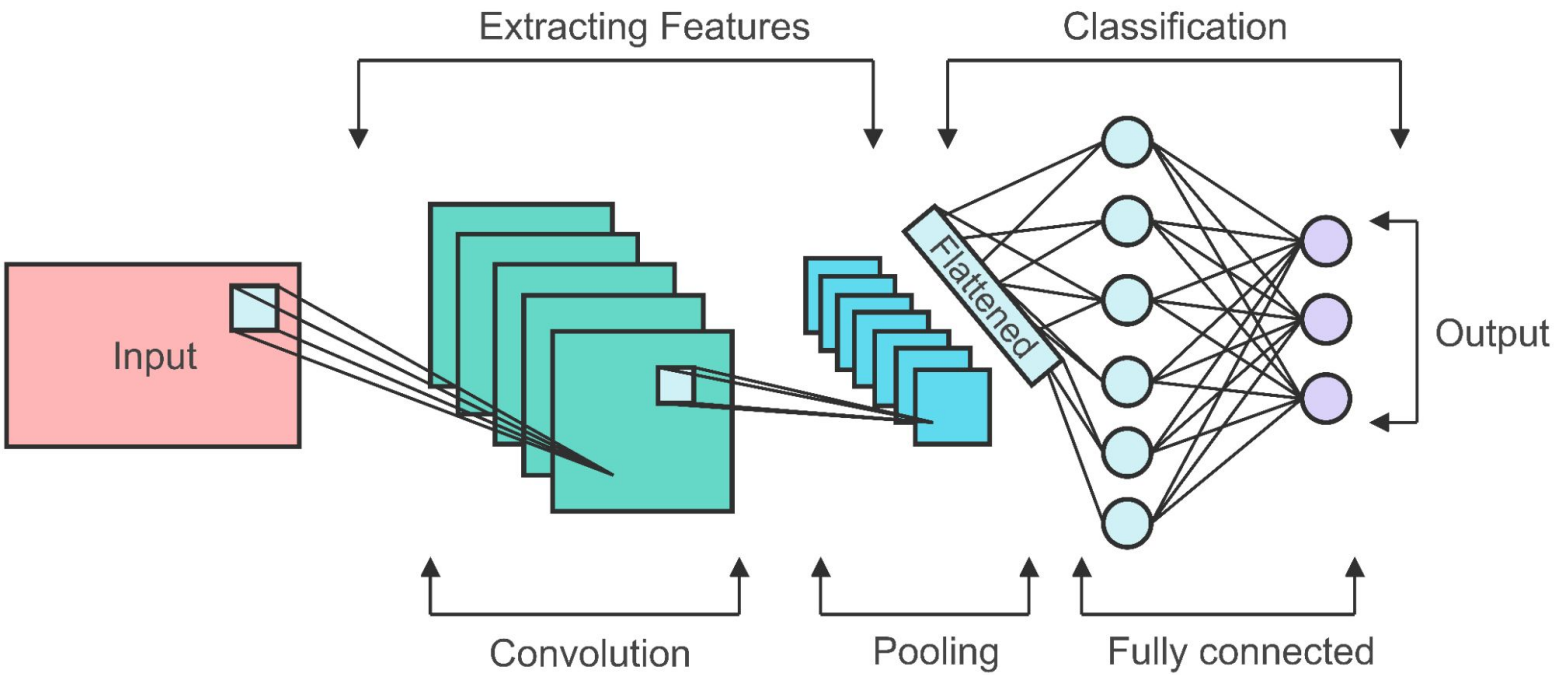

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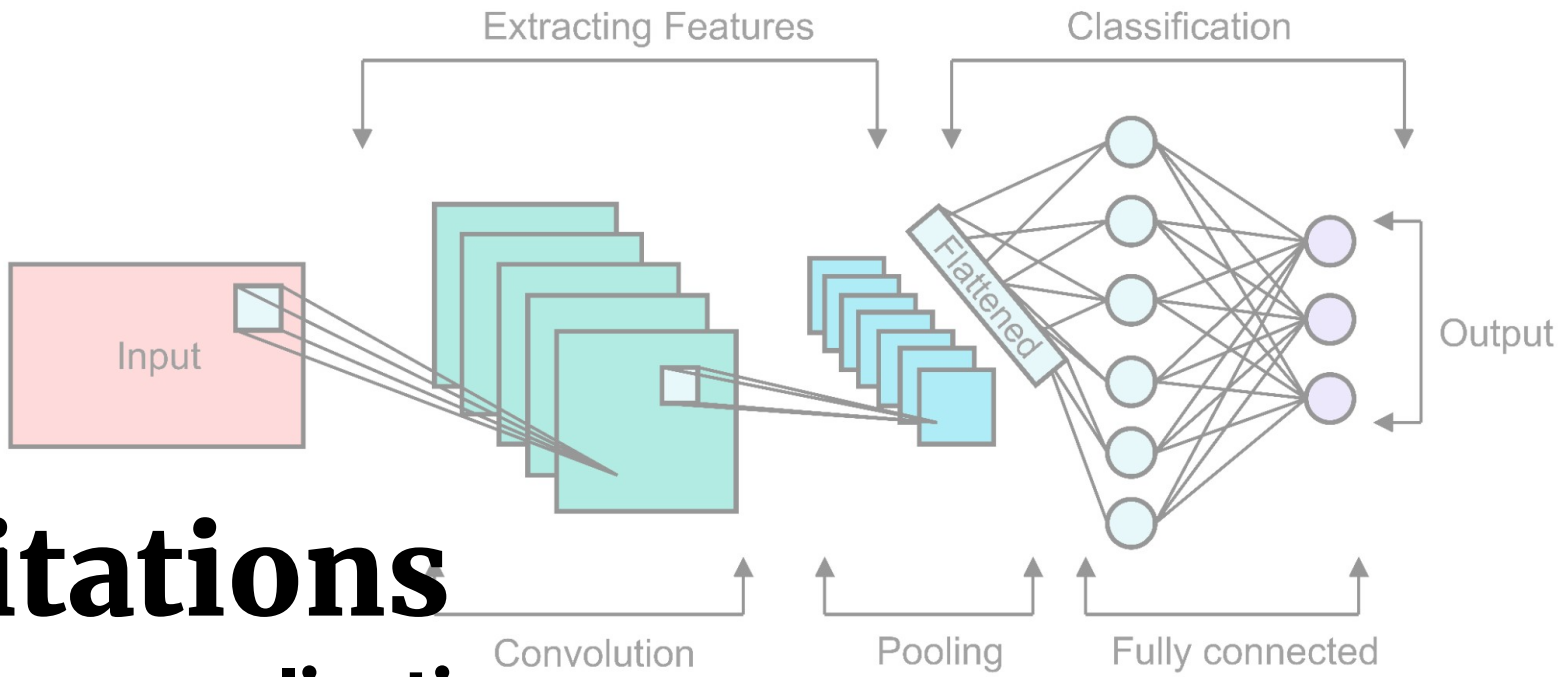


Limitations

1. **Poor generalization**
2. **Not interpretable**
3. **Hard to enforce 3D constraints**

https://www.edrawmax.com/templates/1011715/

Caesar, H., et al. (2020). nuScenes: A multimodal dataset for autonomous driving.

Monocular Tracking

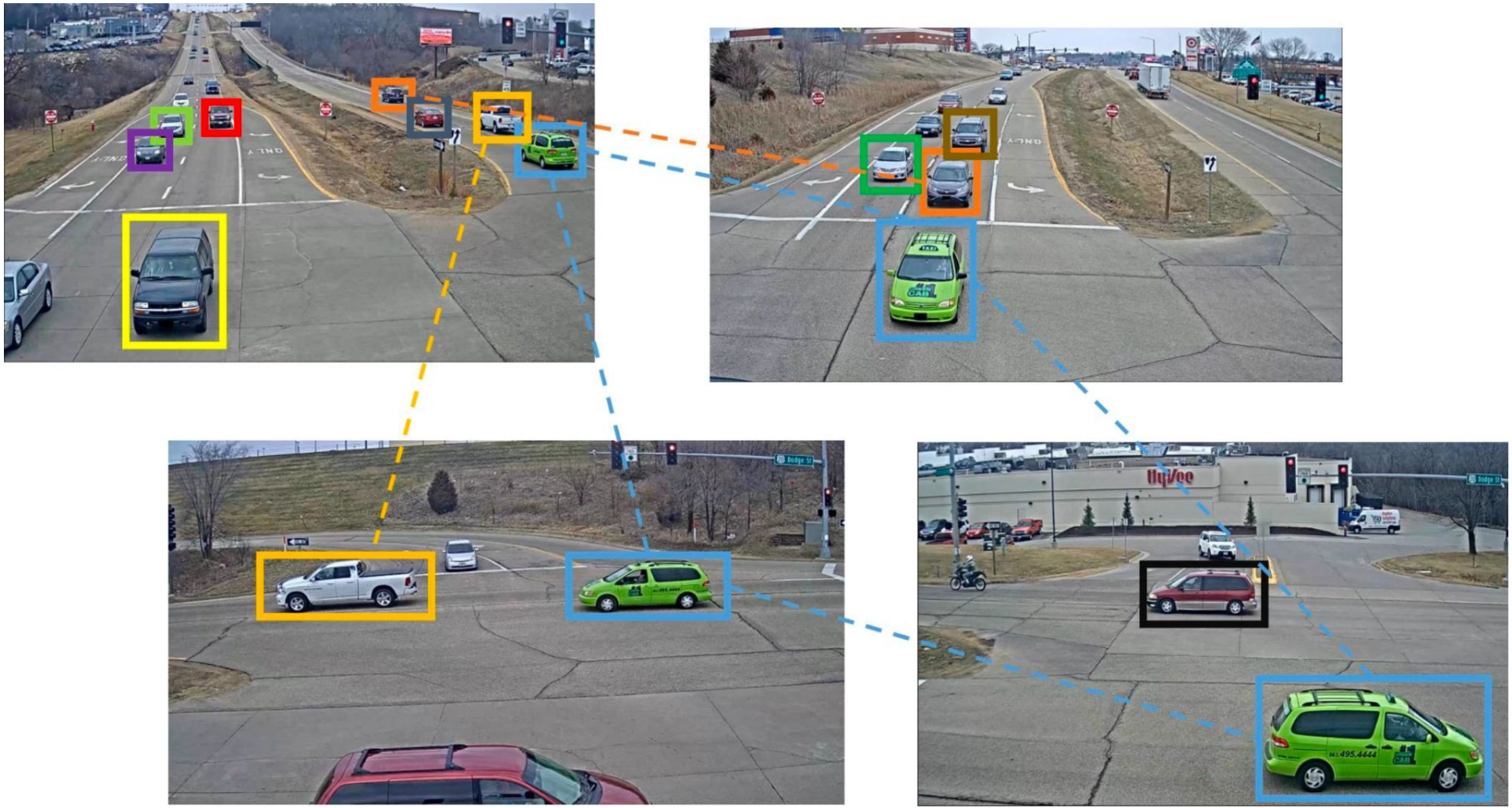
1. **Object Detection**
2. **Motion Prediction**
3. **Object Association**

Monocular Tracking

1. Object Detection

2. Motion Prediction

3. **Object Association**



Li, Yun-Lun, et al. (2022). Multi-Camera Vehicle Tracking Based on Deep Tracklet Similarity Network.

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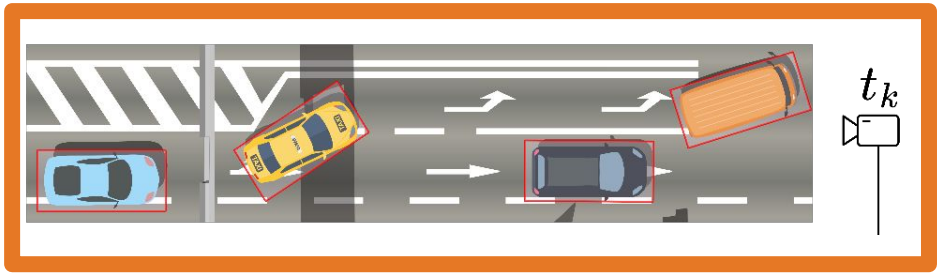
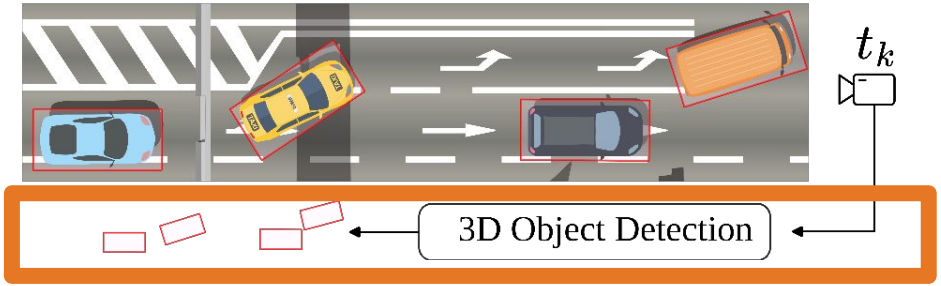
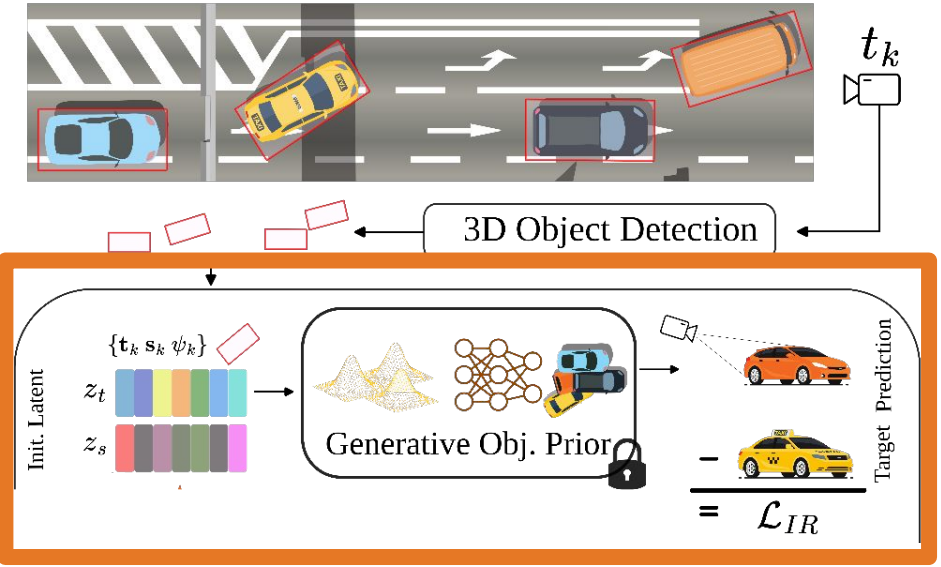
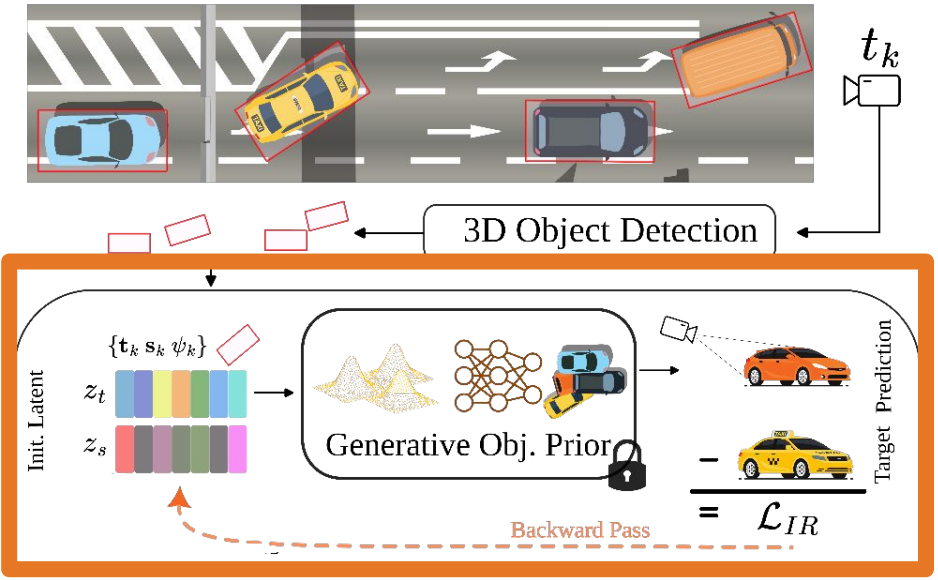
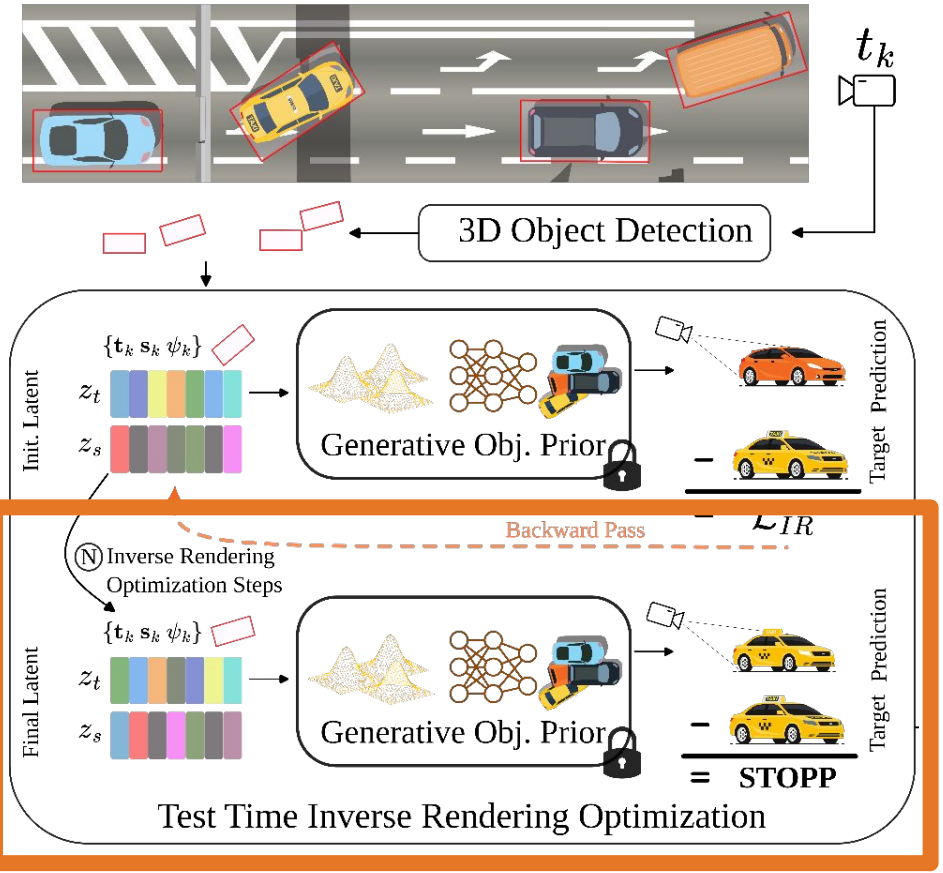
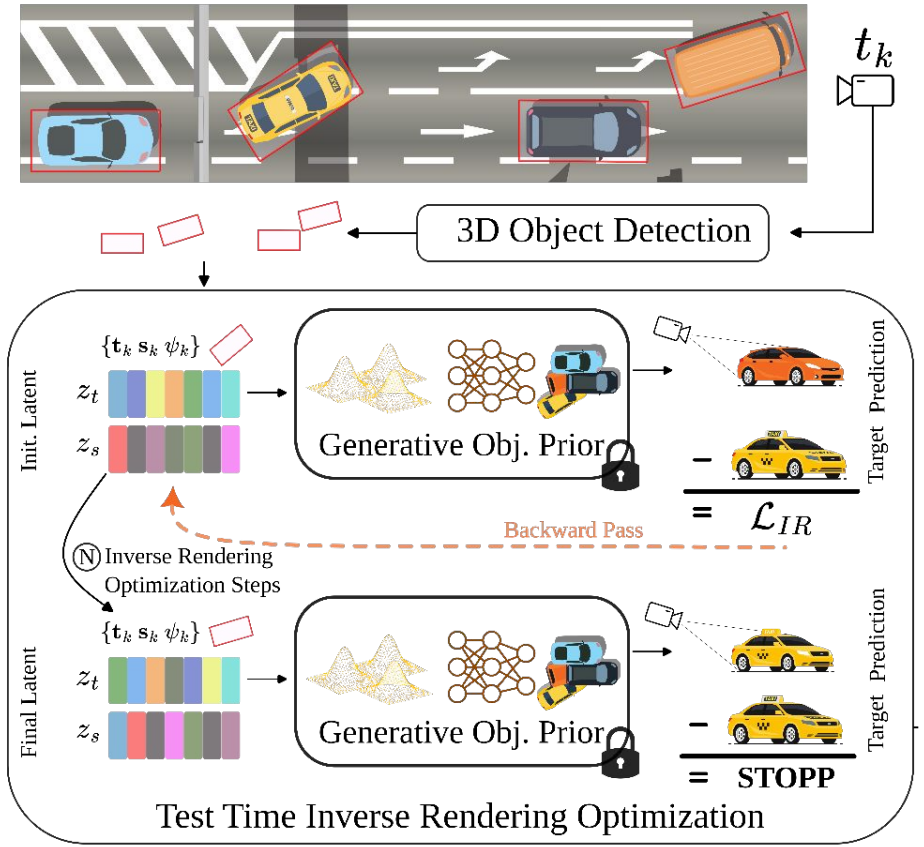

t_k

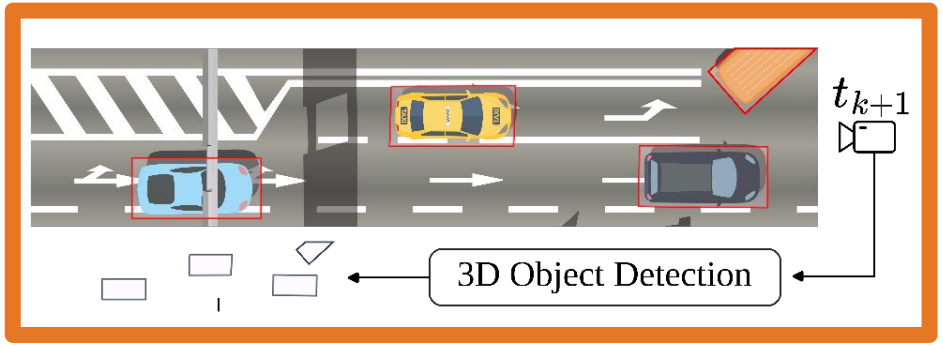

t_k
3D Object Detection

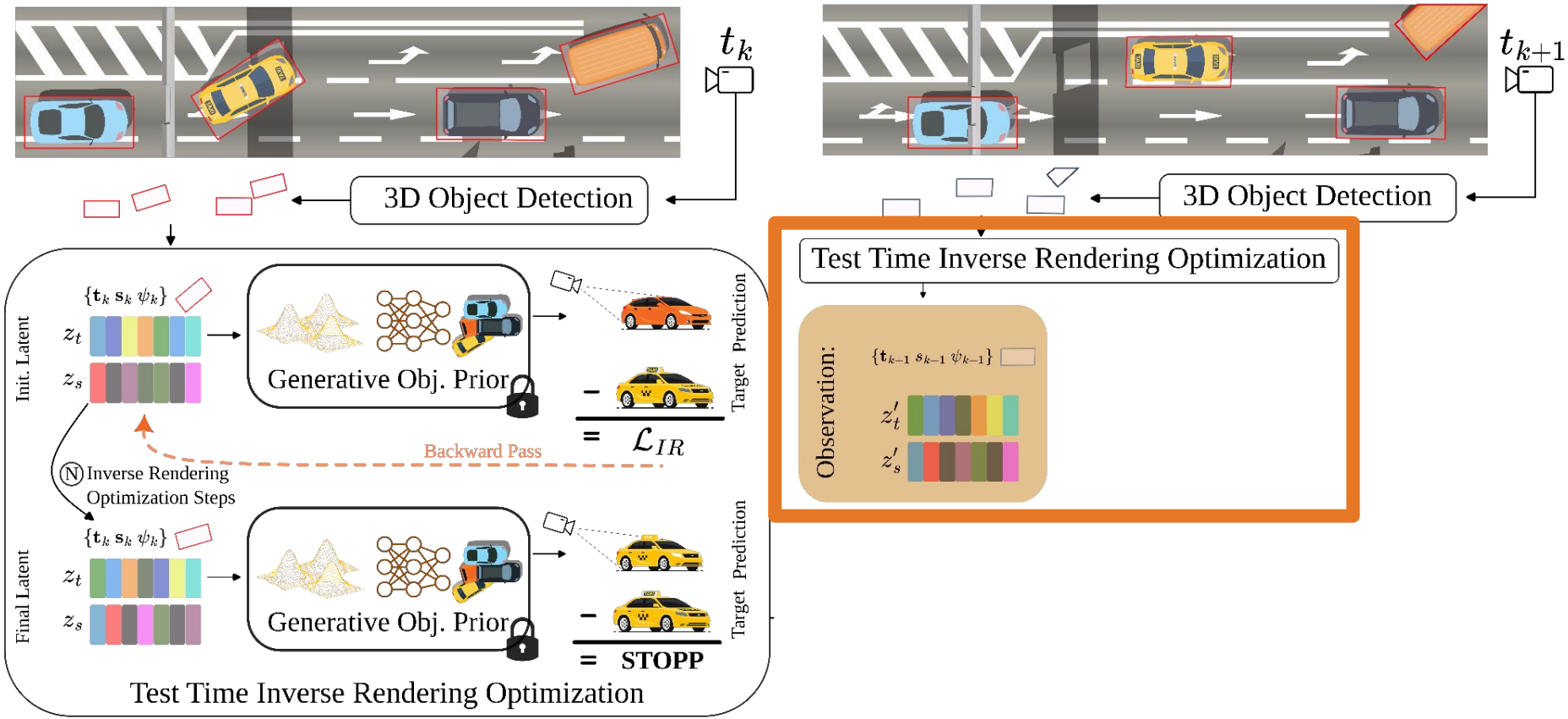

t_k
3D Object Detection
$\{\mathbf{t}_k\ \mathbf{s}_k\ \psi_k\}$
z_t
z_s
Init. Latent
Generative Obj. Prior
Target Prediction
$\mathcal{L}_{IR}$

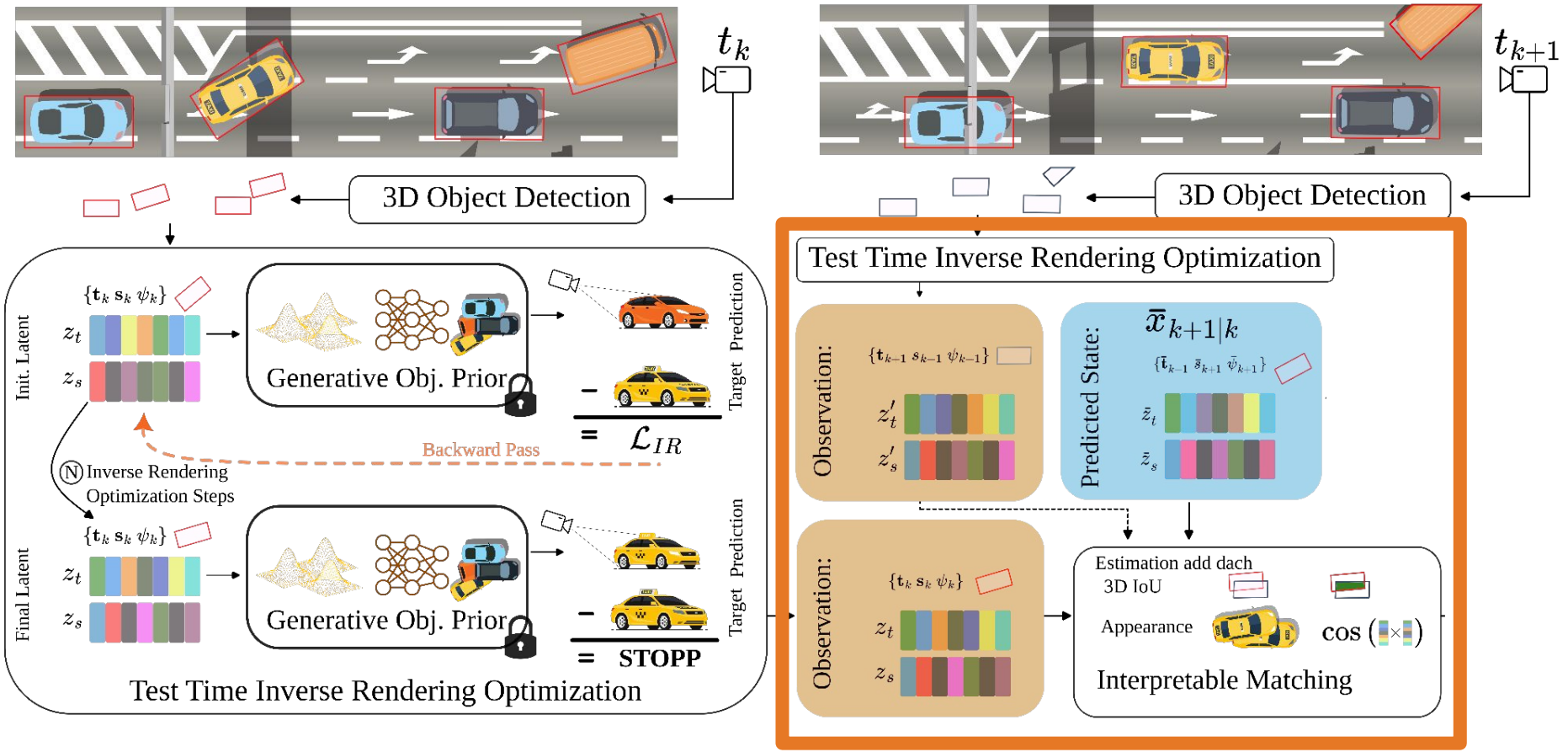

t_k
3D Object Detection
$\{\mathbf{t}_k\ \mathbf{s}_k\ \psi_k\}$
z_t
z_s
Init. Latent
Generative Obj. Prior
Prediction
Target
$\mathcal{L}_{IR}$
Backward Pass

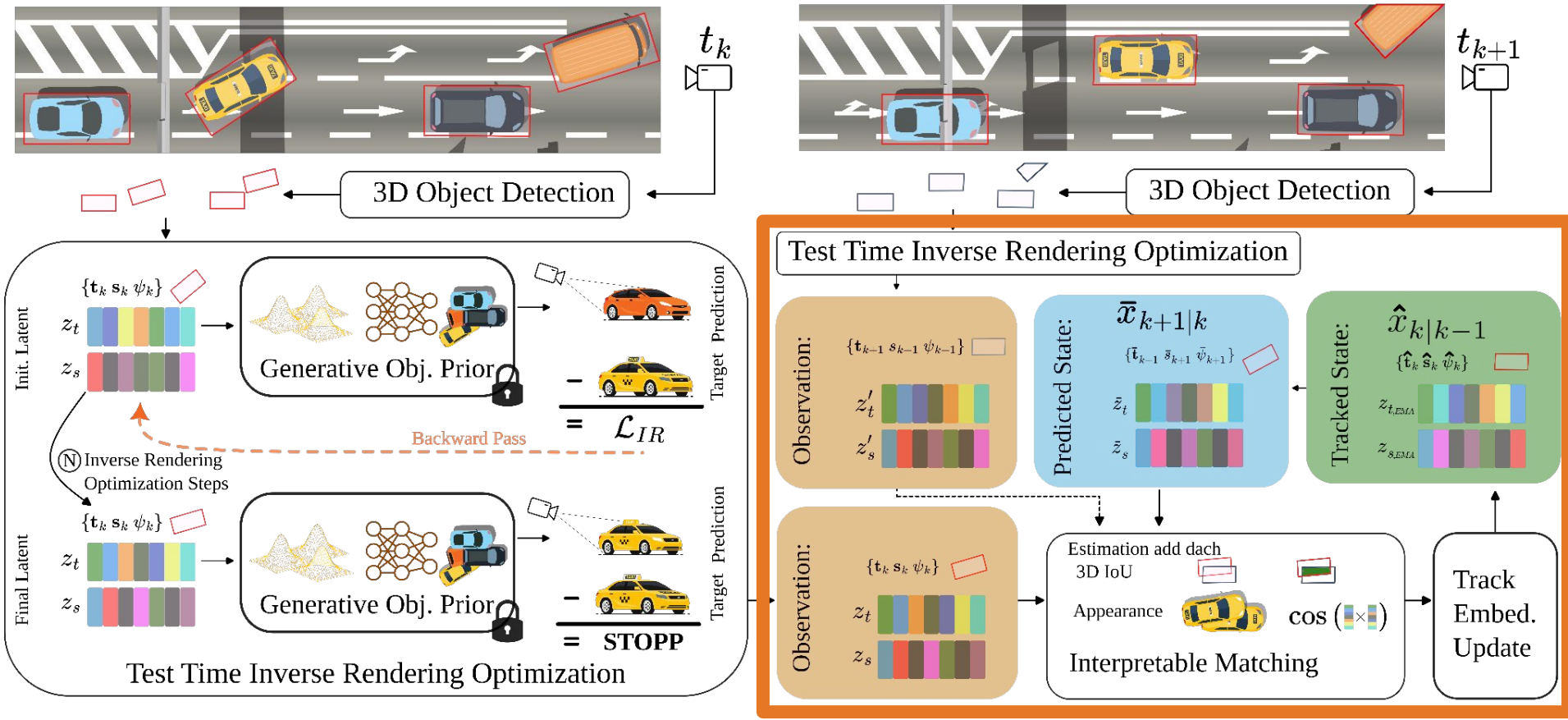

t_k
3D Object Detection
Init. Latent
$\{\mathbf{t}_k\ \mathbf{s}_k\ \psi_k\}$
z_t
z_s
Generative Obj. Prior
Target Prediction
$\mathcal{L}_{IR}$
Backward Pass
N Inverse Rendering Optimization Steps
Final Latent
$\{\mathbf{t}_k\ \mathbf{s}_k\ \psi_k\}$
z_t
z_s
Generative Obj. Prior
Target Prediction
= STOPP
Test Time Inverse Rendering Optimization


t_k
3D Object Detection
$\{\mathbf{t}_k\ \mathbf{s}_k\ \psi_k\}$
z_t
z_s
Init. Latent
Generative Obj. Prior
Prediction
Target
$\mathcal{L}_{IR}$
Backward Pass
N Inverse Rendering Optimization Steps
Final Latent
STOPP
Test Time Inverse Rendering Optimization

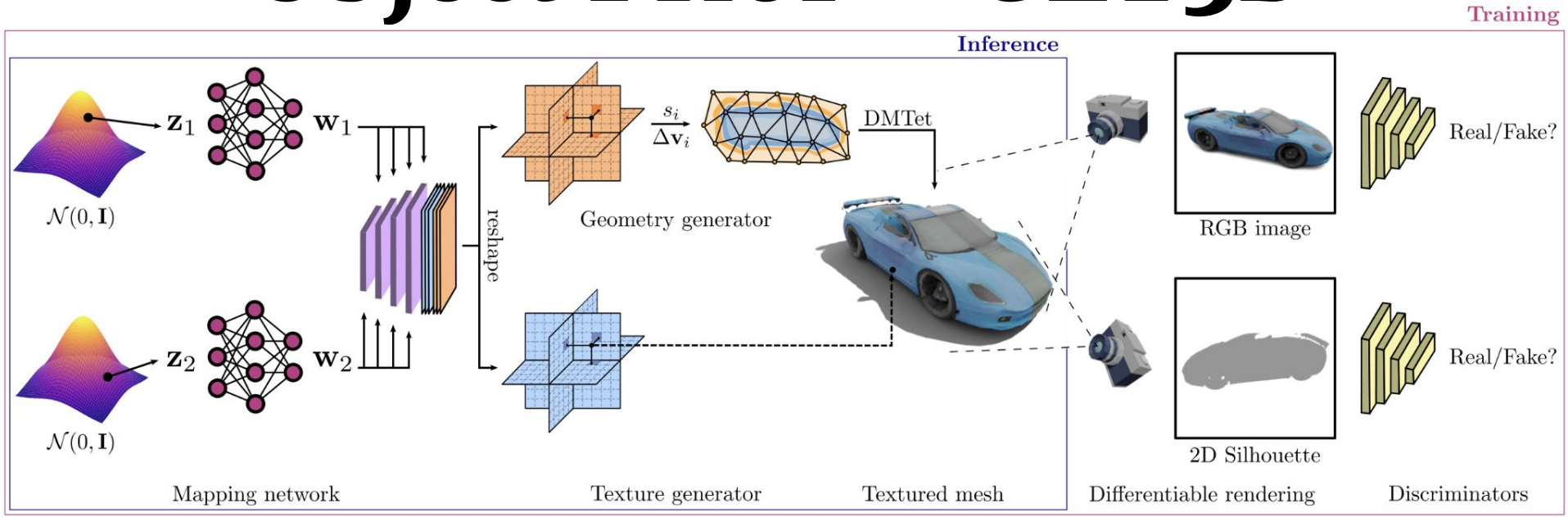

t_{k+1}
3D Object Detection


t_k
t_{k+1}
3D Object Detection
3D Object Detection
Test Time Inverse Rendering Optimization
Observation:
$\{\mathbf{t}_{k-1}\ s_{k-1}\ \psi_{k-1}\}$
z'_t
z'_s
Init. Latent
$\{\mathbf{t}_k\ \mathbf{s}_k\ \psi_k\}$
z_t
z_s
Generative Obj. Prior
Target Prediction
$\mathcal{L}_{IR}$
Backward Pass
N Inverse Rendering Optimization Steps
Final Latent
$\{\mathbf{t}_k\ \mathbf{s}_k\ \psi_k\}$
z_t
z_s
Generative Obj. Prior
Target Prediction
STOPP
Test Time Inverse Rendering Optimization


t_k
t_{k+1}
3D Object Detection
3D Object Detection
Test Time Inverse Rendering Optimization
Init. Latent
Final Latent
$\{\mathbf{t}_k\ \mathbf{s}_k\ \psi_k\}$
z_t
z_s
Generative Obj. Prior
Target Prediction
$\mathcal{L}_{IR}$
Backward Pass
N Inverse Rendering Optimization Steps
STOPP
Test Time Inverse Rendering Optimization
Observation:
$\{\mathbf{t}_{k-1}\ s_{k-1}\ \psi_{k-1}\}$
z'_t
z'_s
Predicted State:
$\bar{x}_{k+1|k}$
$\{\bar{\mathbf{t}}_{k-1}\ \bar{s}_{k+1}\ \bar{\psi}_{k+1}\}$
$\bar{z}_t$
$\bar{z}_s$
Estimation add dach
3D IoU
Appearance
cos
Interpretable Matching


t_k
t_{k+1}
3D Object Detection
3D Object Detection
Test Time Inverse Rendering Optimization
Init. Latent
Final Latent
$\{\mathbf{t}_k\ \mathbf{s}_k\ \psi_k\}$
z_t
z_s
Generative Obj. Prior
Target Prediction
$\mathcal{L}_{IR}$
Backward Pass
N Inverse Rendering Optimization Steps
STOPP
Test Time Inverse Rendering Optimization
Observation:
Predicted State:
Tracked State:
$\bar{x}_{k+1|k}$
$\hat{x}_{k|k-1}$
Estimation add dach
3D IoU
Appearance
cos
Interpretable Matching
Track Embed. Update

Object Prior – GET3D



Our method is <u>independent</u> of the object prior

G. Shen, et al. (2022). GET3D: A Generative Model of High Quality 3D Textured Shapes Learned from Images.

Real Dataset Unseen by Our Method – Generalizability

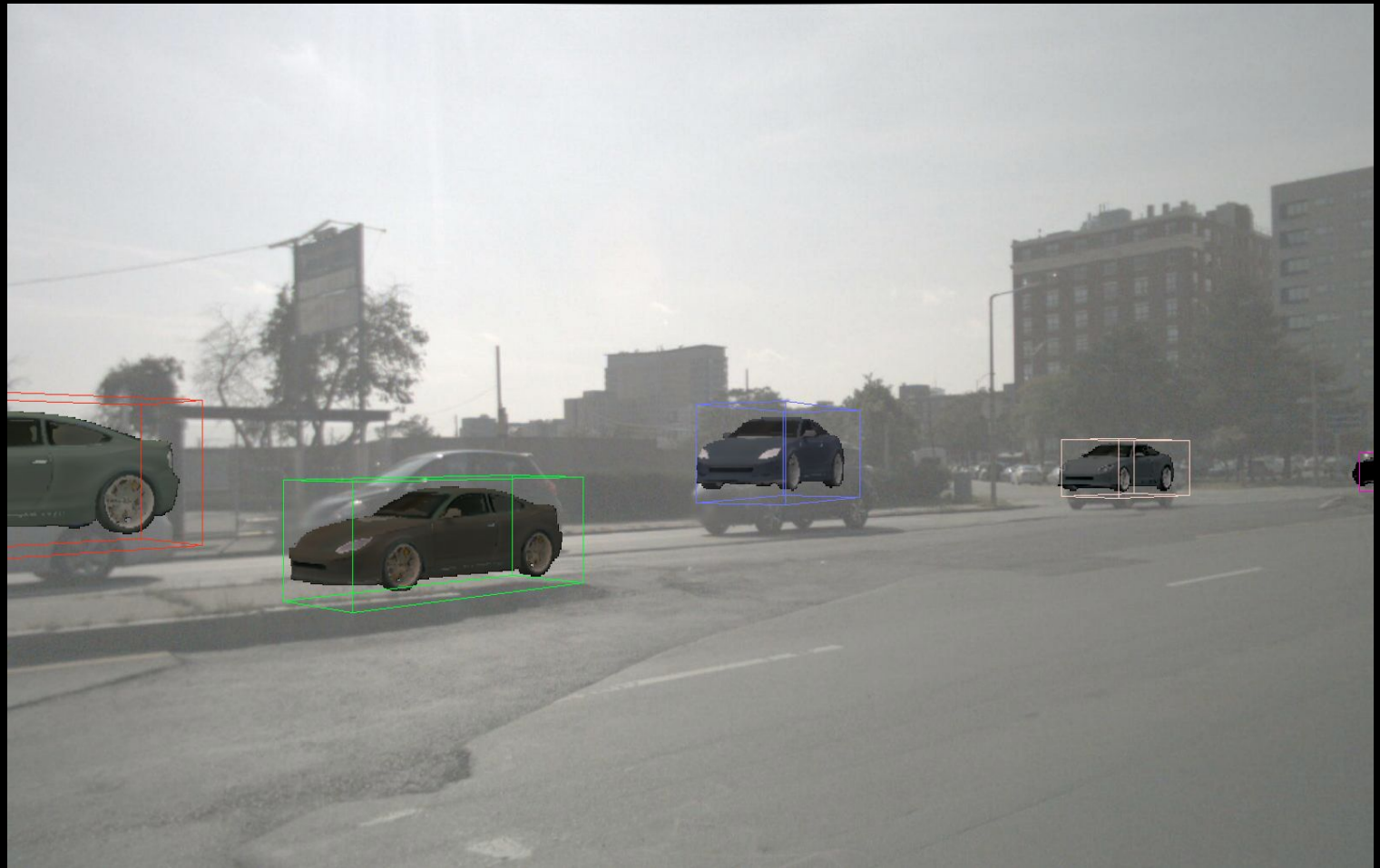
G. Shen, et al. (2022). GET3D: A Generative Model of High Quality 3D Textured Shapes Learned from Images.
Chang, A., et al. (2015). ShapeNet: An Information-Rich 3D Model Repository.

Optimization Process

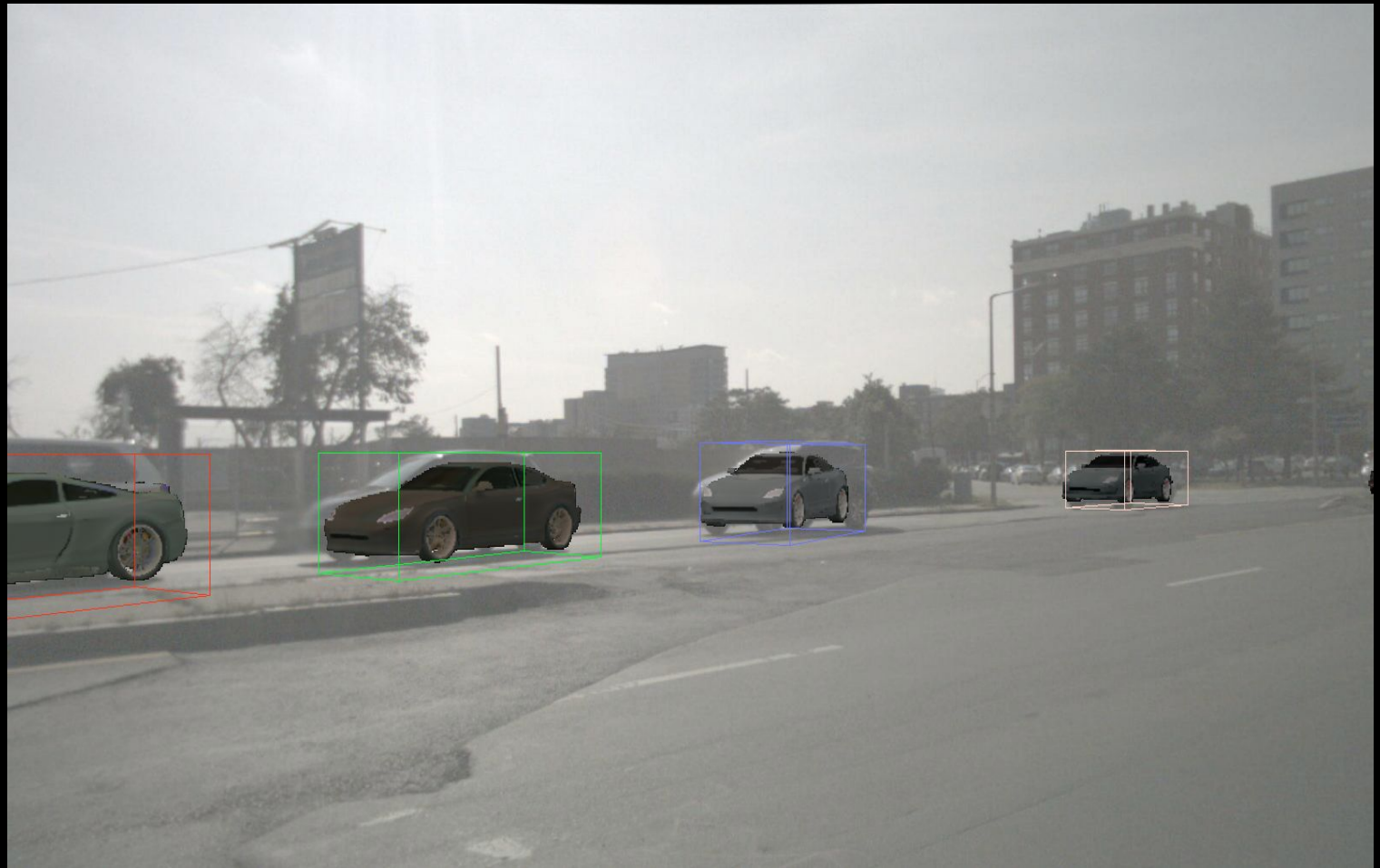
Input Frame

Initial Guess

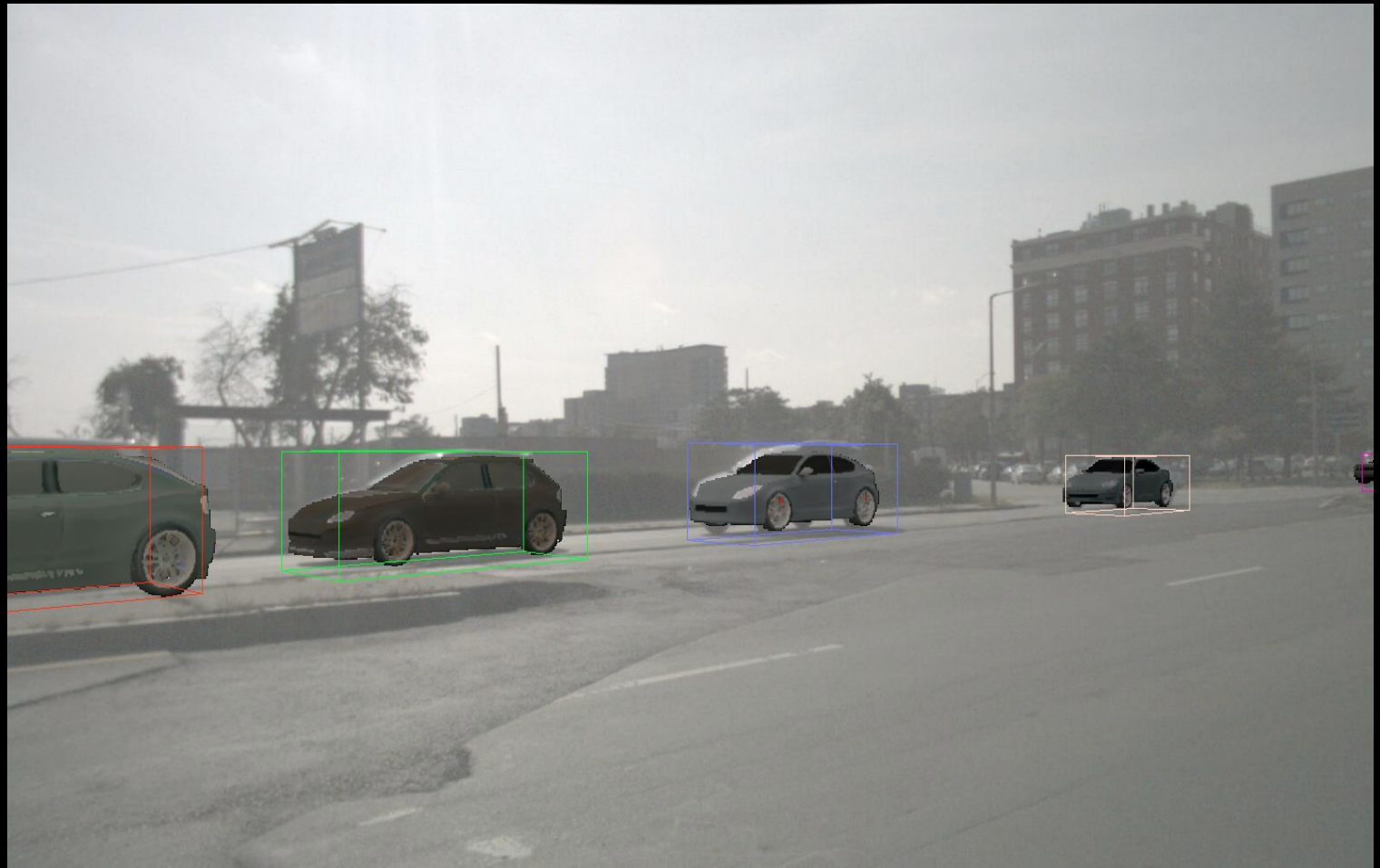
Texture Fit



Pose Fit



Shape Fit



Input

Our Schedule

Initial Guess

No Schedule

Loss Function

$$\mathcal{L}_{IR} = L_{RGB} + \lambda \mathcal{L}_{perceptual}$$

$$\mathcal{L}_{IR} = L_{RGB} + \lambda \mathcal{L}_{perceptual}$$

$$\left(I_c - \hat{I}_c \right) \circ \hat{M}_{I_c} \|_2$$

Ground Truth Image

Rendered Image

Rendered Object Masks

$$\mathcal{L}_{IR} = L_{RGB} + \lambda \mathcal{L}_{perceptual}$$

$$\text{LPIPS}_{patch}\left(I_c, \hat{I}_{c,p}\right)$$

Object-centered patches

Ground Truth Image

Rendered Image

$$\mathcal{L}_{IR} = L_{RGB} + \lambda \mathcal{L}_{perceptual}$$

$$\hat{\mathbf{z}}_{S,p}, \hat{\mathbf{z}}_{T,p}, \hat{s}_p \hat{\mathbf{t}}_p, \hat{\mathbf{R}}_p = \arg\min(\mathcal{L}_{IR})$$

Shape **Texture** **Scale** **Translation** **Rotation**

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Single-Shot Performance

Training Data Unseen	Method	AMOTA ↑	AMOTP (m) ↓	Recall ↑	MOTA ↑
×	PF-Track	0.622	0.916	0.719	0.558
×	QTrack	0.692	0.753	0.760	0.596
×	QD-3DT	0.425	1.258	0.563	0.358
✓	QD-3DT (trained on WOD)	0.000	1.893	0.226	0.000
× (CP)	CenterTrack	0.202	1.195	0.313	0.134
✓ (CP)	AB3DMOT	0.387	**1.158**	0.506	0.284
✓ (CP)	Inverse Neural Rendering (ours)	**0.413**	<u>1.189</u>	**0.536**	**0.321**

Bold denotes best
<u>Underlined</u> denotes second-best

Pang, Z., et al.: Standing between past and future: Spatio-temporal modeling for multi-camera 3d multi-object tracking. (2023).; Yang, J., et al.: Quality matters: Embracing quality clues for robust 3d multi-object tracking.; Hu, H.N., et al.: Monocular quasi-dense 3d object tracking. (2022); Zhou, X., et al.: Tracking objects as points. (2020); Weng, X., et al..: 3d multi-object tracking: A baseline and 677 new evaluation metrics. (2020)

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- → 3D Reasoning
- → Limitations
- → Key Takeaway

Rainy Scene

Reflection

Interpretability “for free”

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- → Key Takeaway
- → Current Project

Input Frame

INR Generation

INR BEV Layout

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Not real-time (yet)

 0.3 seconds / frame

Rendering pipeline not performance-optimized

Solution: Adaptive level-of-detail rendering?

Limited object prior

GET3D does not model shadows, reflectance, environmental conditions, etc.

Solution: Use object model that also models these?

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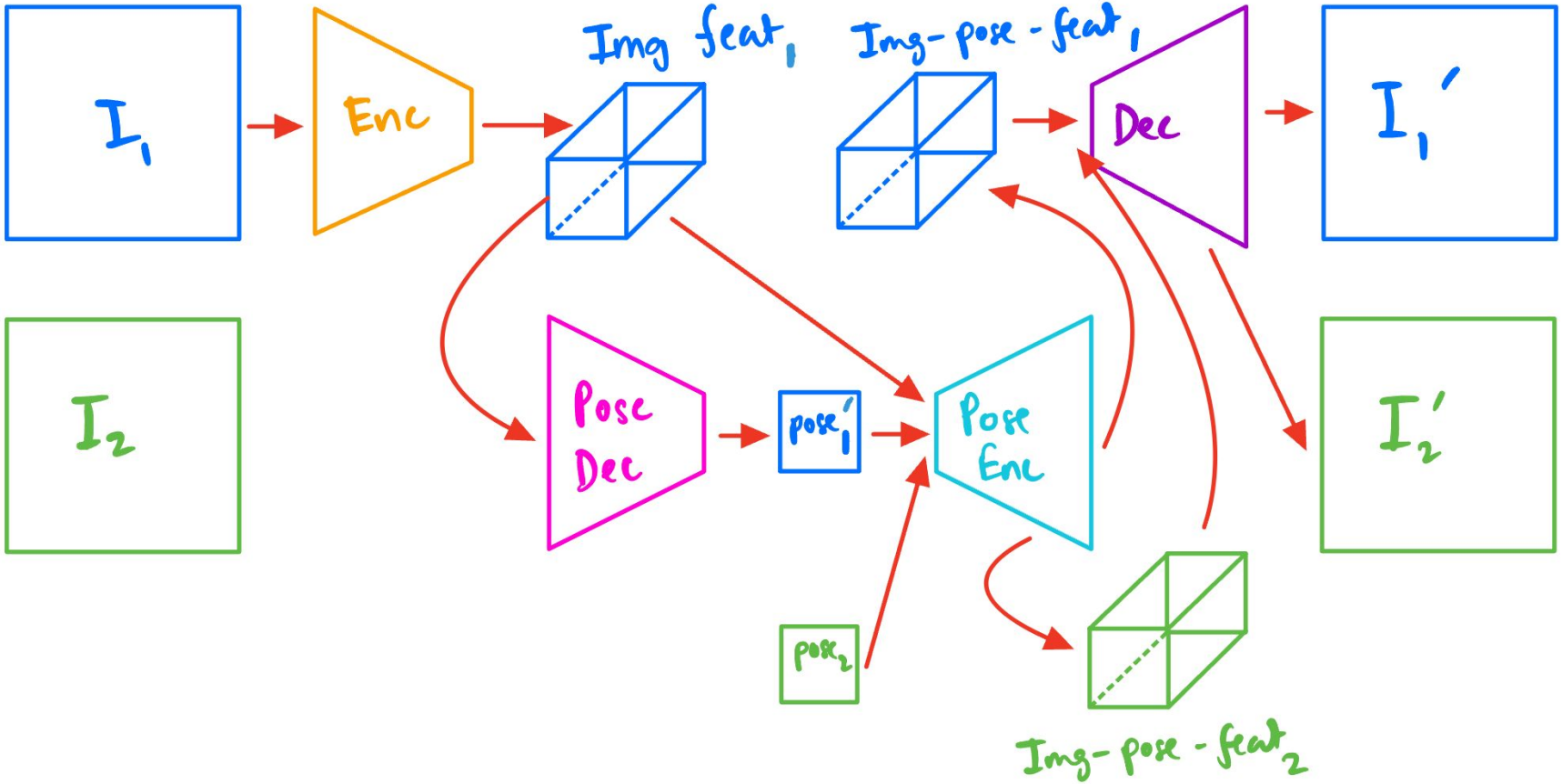
Leveraging 3D object priors can allow for interpretability

Leveraging 3D object priors can allow for generalization

Leveraging 3D object priors can allow for 3D interpretation

Object Detection Using VAEs



Thank you!

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