Modelling and Simulating the 3D World for Autonomous Driving

Shenlong Wang

June 8, 2024

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Toward building autonomy that everyone trusts

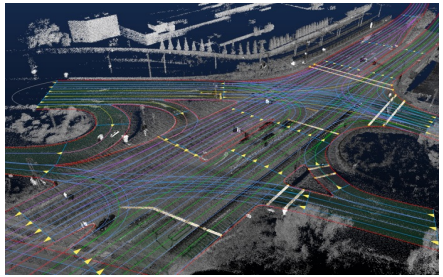
Autonomy

Flexibility

Interact with humans
Handle uncertain future

Robustness

Handle long-tails events
Being failsafe



Scalability

Enlarge operational domain
Reducing the cost

Verifiable Safety

Certifiable correctness
Measurable metrics

Realistic Interaction | Safety-Critical Events | Scalable Evaluation | Realistic Environments

Training, Evaluation and Verification

Image credit: Google, Volvo, Uber


Not safe


Costly operation


MANUAL
Angle
-61.4°
Speed
20.9 MPH
9.32 M/S
Middle Front Roof
Not closed-loop


Too rare

Not safe

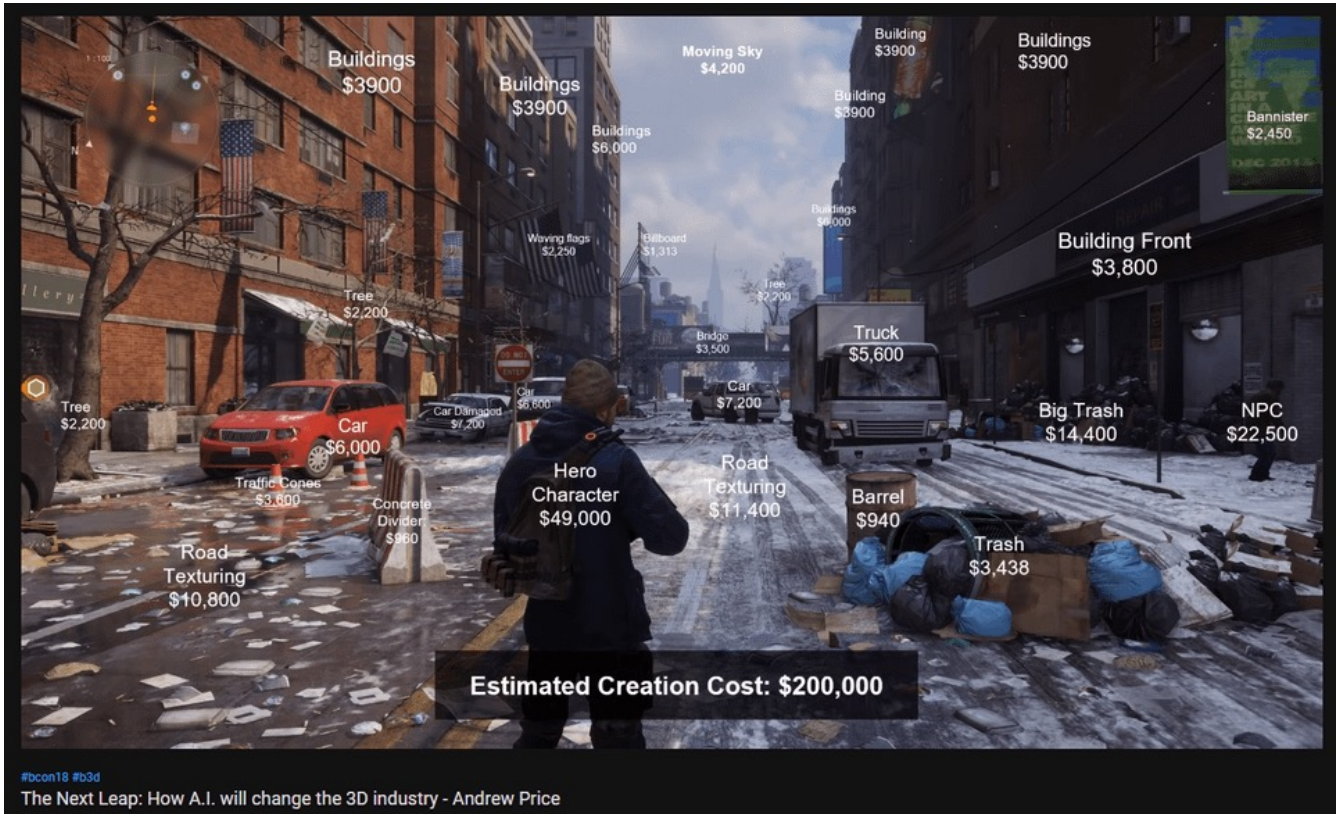
Costly operation

Simulation to rescue!

Not closed-loop

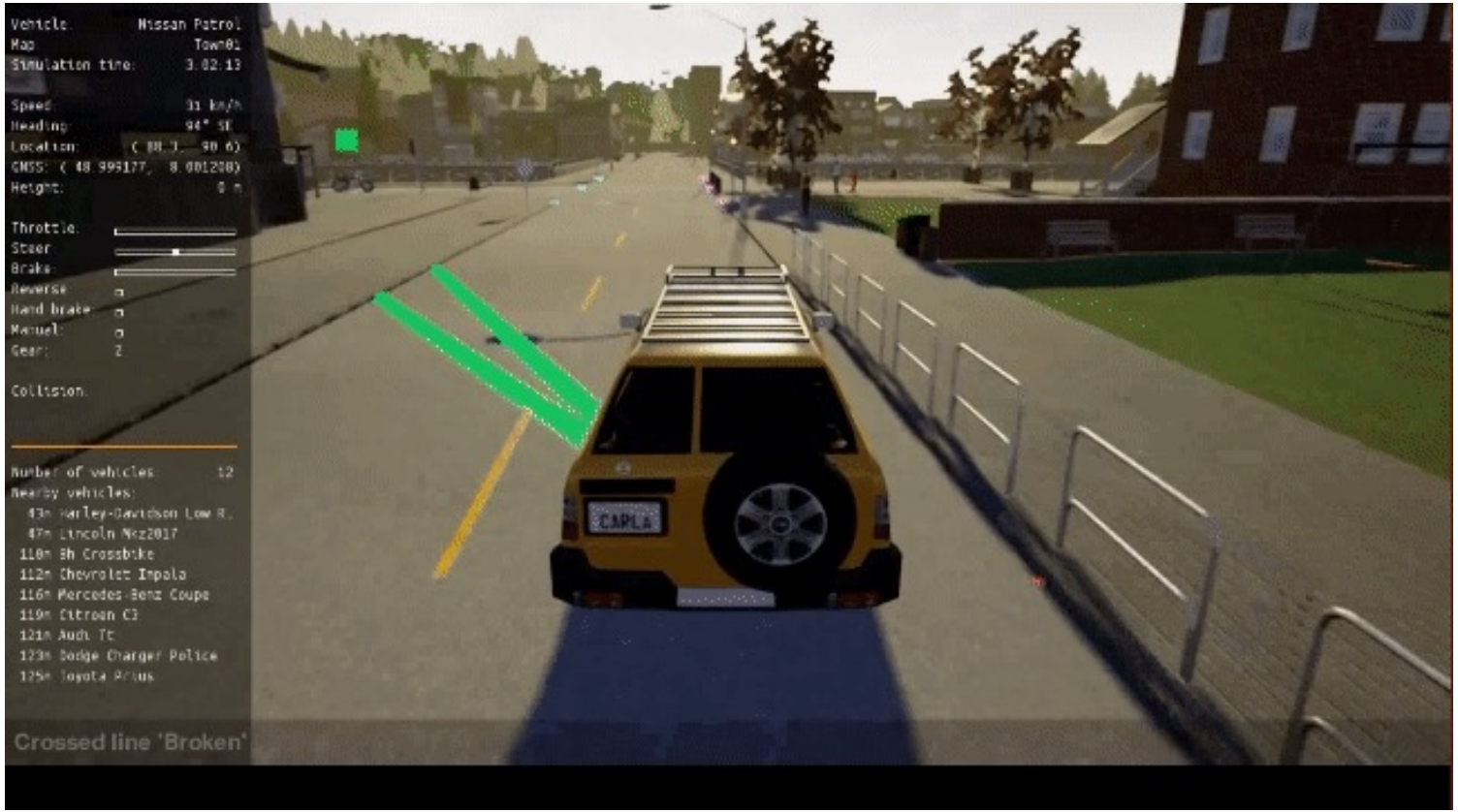
Too rare

Simulation: everything comes with a price tag



https://www.reddit.com/r/gamedev/comments/9zdn7a/putting_a_price_tag_on_game_assets_in_a_screenshot/

… and is not realistic enough



Carla

Combine the best?

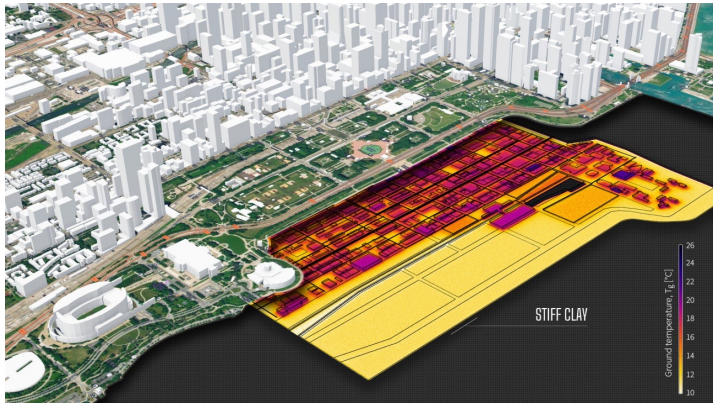
Real-World

?

Simulation

Realistic, **unsafe, costly in operation, slow**

Less realistic, **safe, costly in design**, **fast**



1: An ideal simulator should be
realistic and ***cost efficient in operation and design***

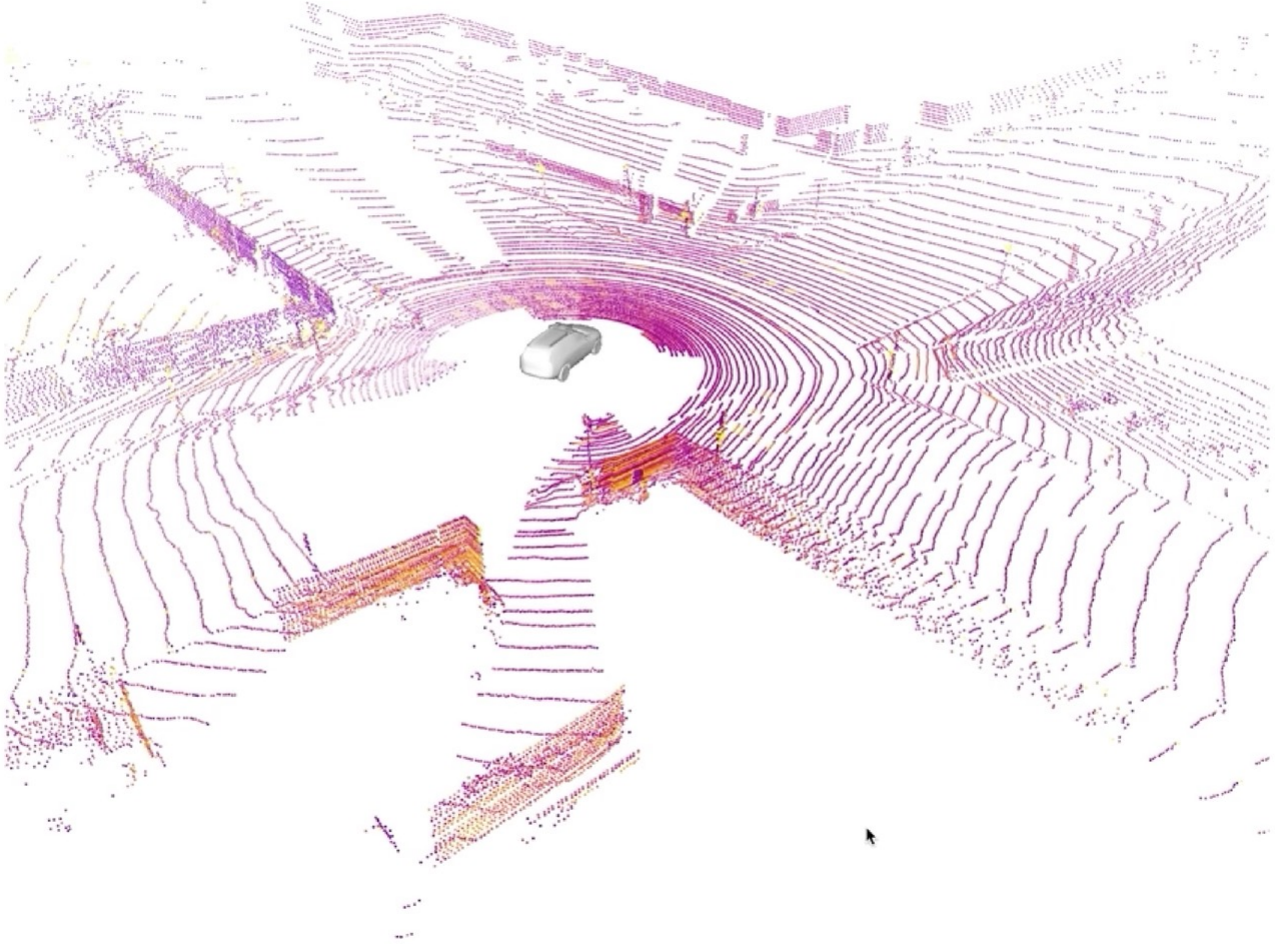
Key Approach: Modeling and Recreation

Model and Perceive the Physical World

Digital Twin World

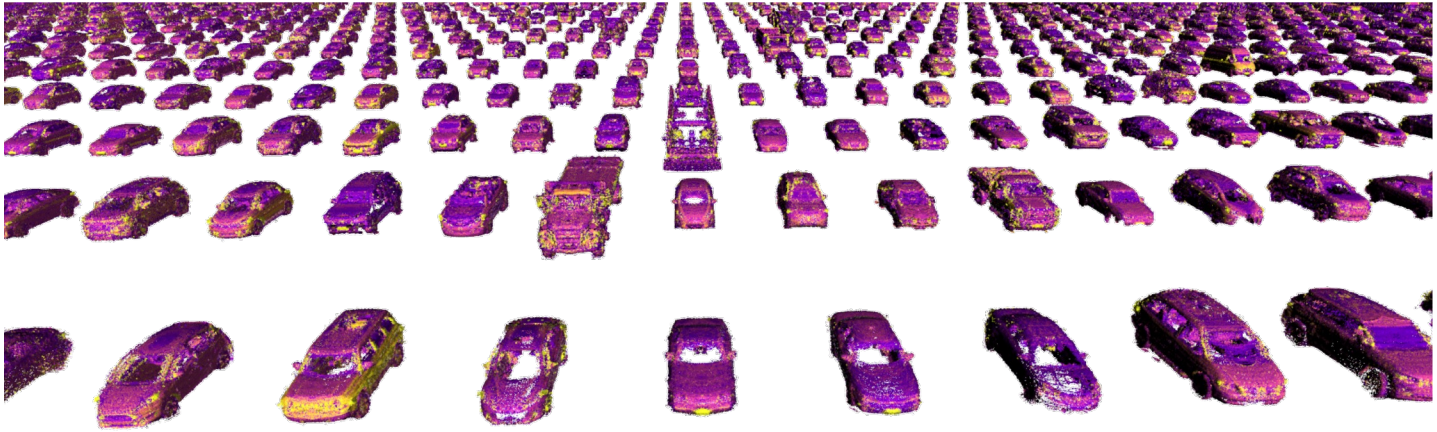
Recreate Experiences

Harness *real-world* data for *simulation*



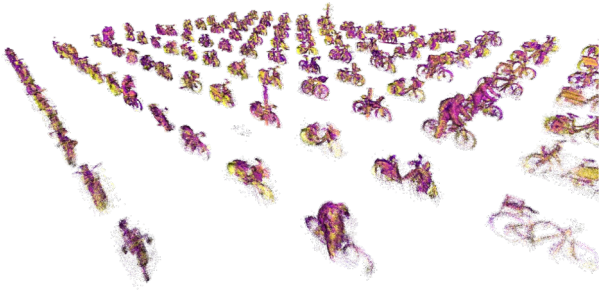
Harness *real-world* data for *simulation*

Vehicles

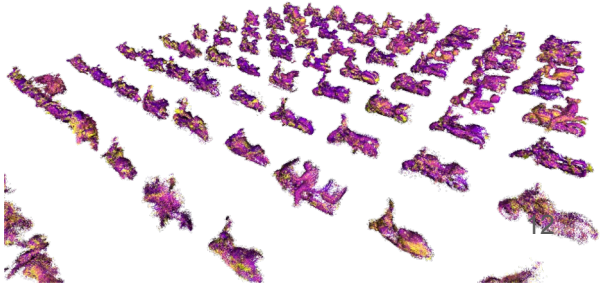


Pedestrian

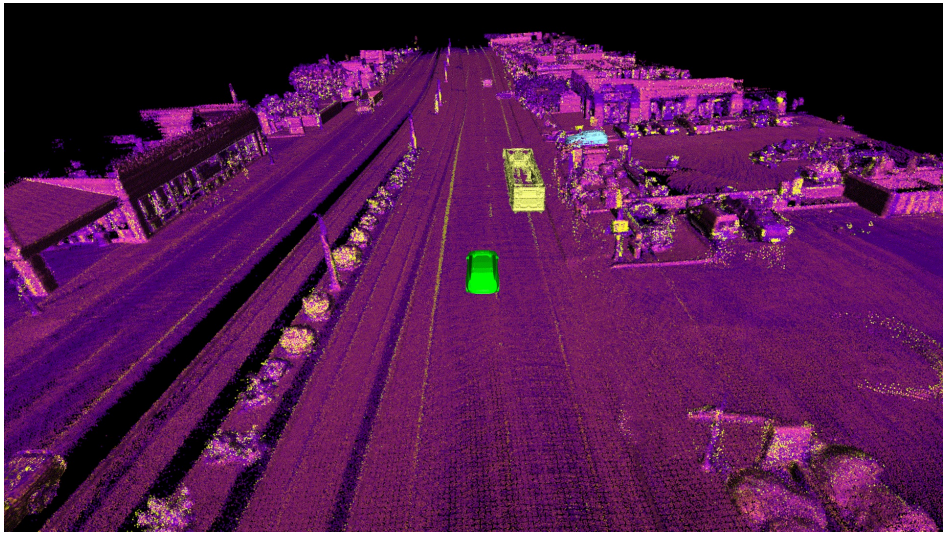
Bicyclist



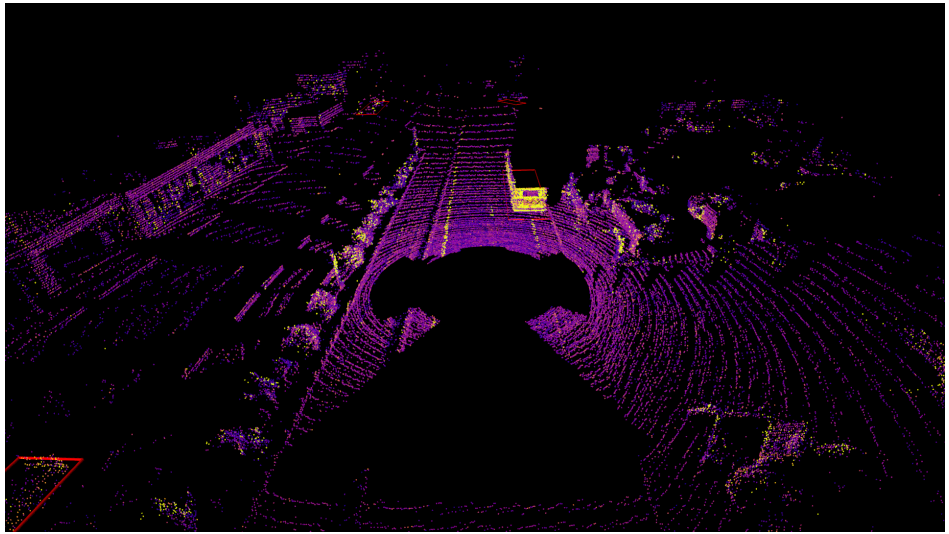
Motorcyclist



Harness *real-world* data for *simulation*



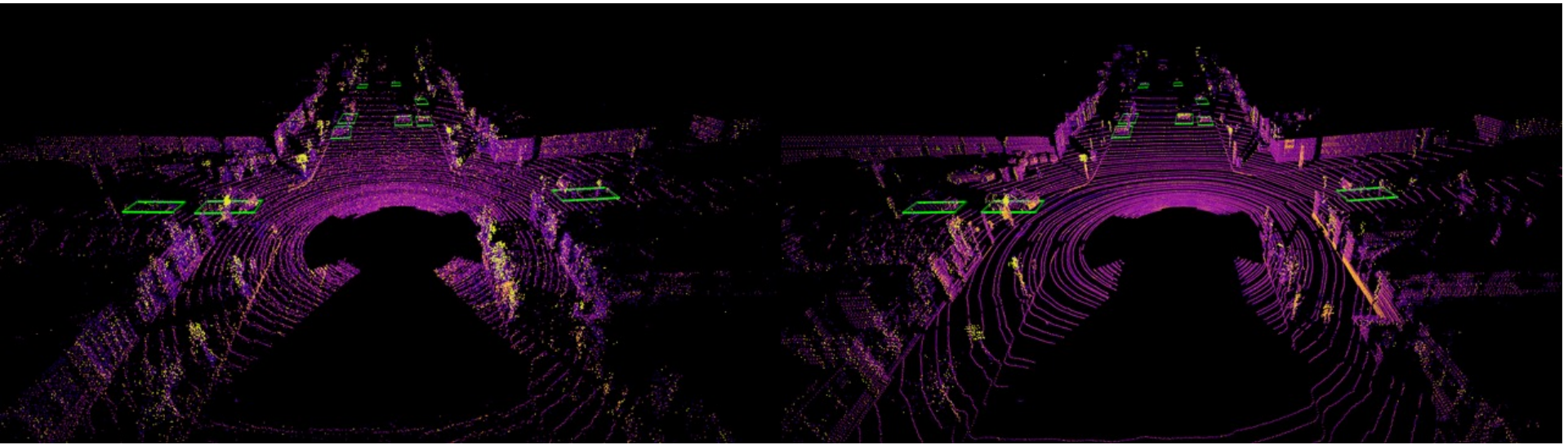
Safety-Critical Case



LiDARSim + Close-Loop

Manivasagam, **Wang**, Wong, Zeng, Ma, Urtasun, CVPR 2020

Harness *real-world* data for *simulation*

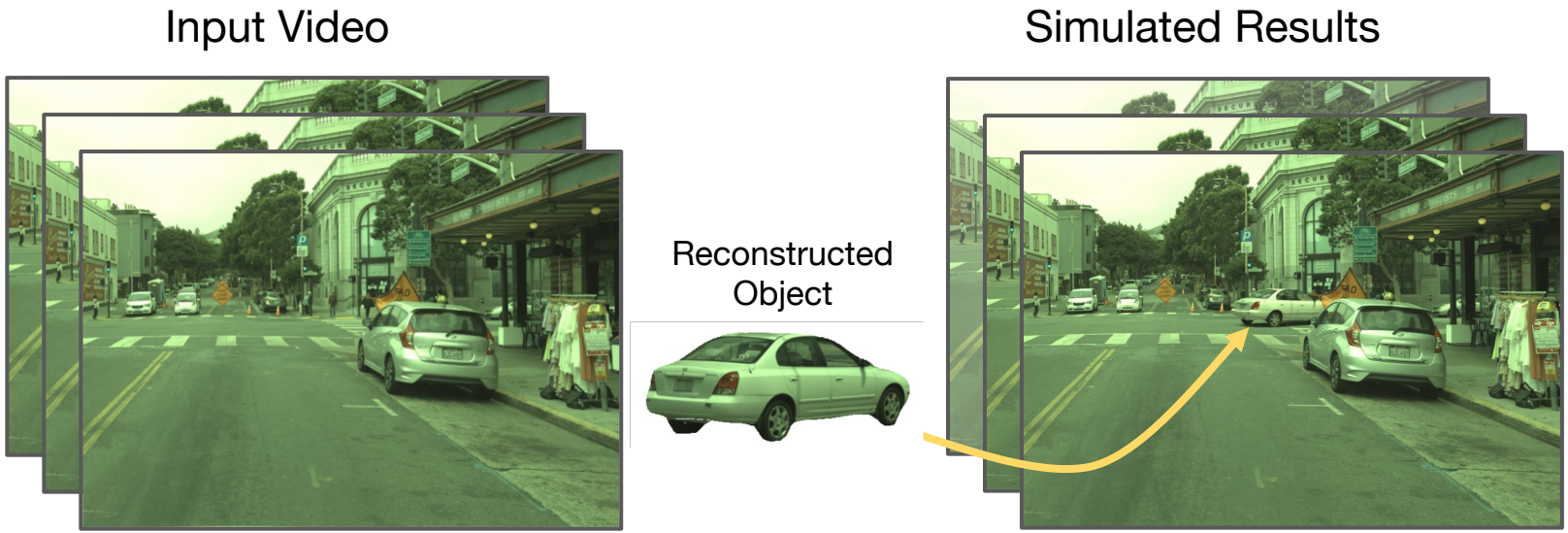


LidarSim

Real LiDAR

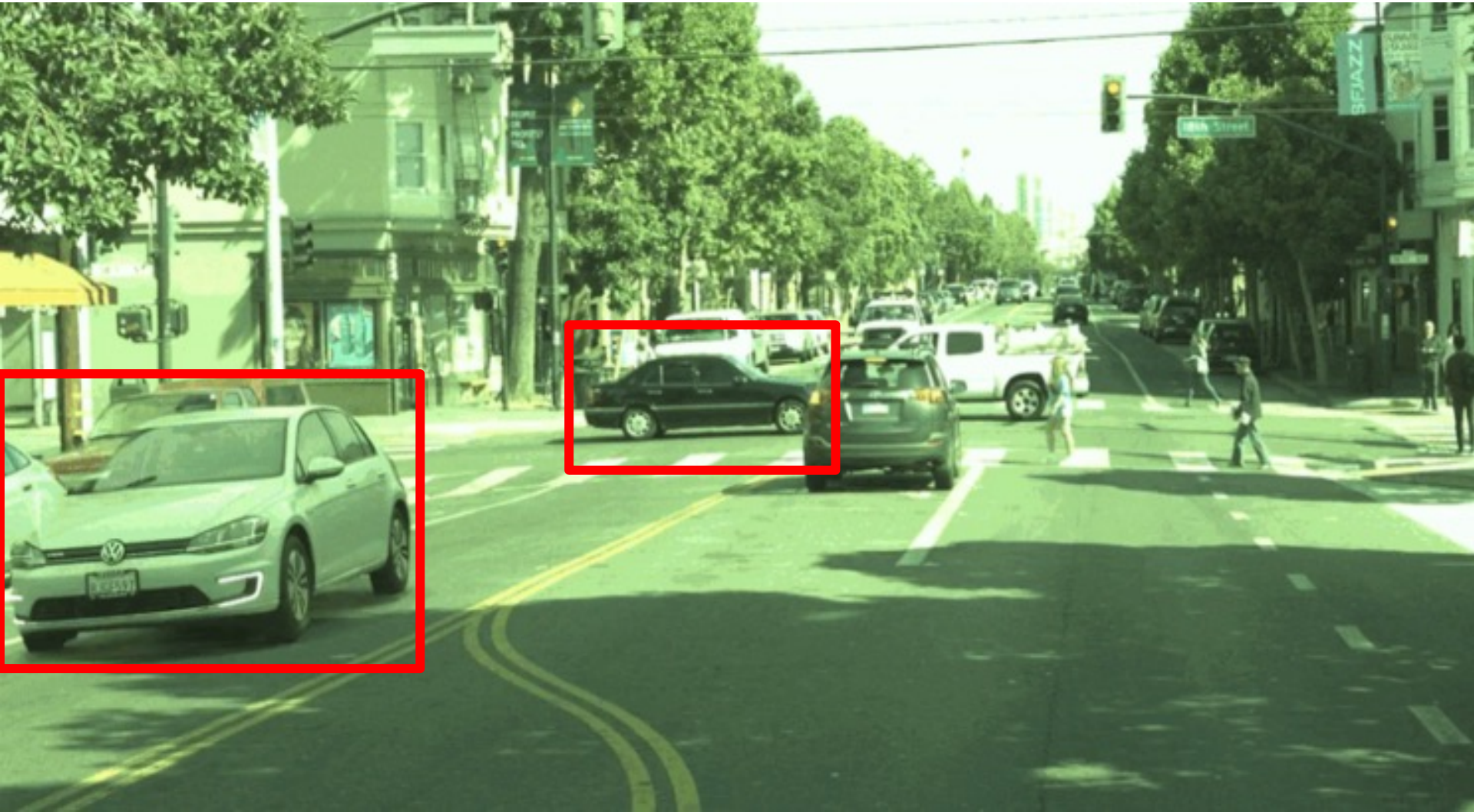
Manivasagam, **Wang**, Wong, Zeng, Ma, Urtasun, CVPR 2020

Harness *real-world* data for *simulation*



Chen et al.. GeoSim: Realistic Video Simulation via Geometry-Aware Composition for Self-Driving, CVPR 2021 (best paper award candidate)


COOK
COMPANY
FedEx
0.5x


SFJAZZ


Eleventh St
0.5x

1: An ideal simulator should be
realistic and ***cost efficient in operation and design***

Harness ***real-world data*** and
recreate novel experiences

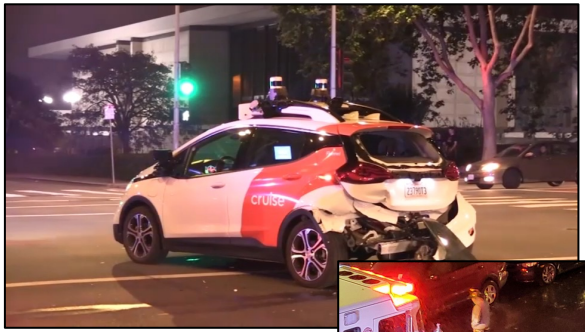
Adversarial factors beyond actors exist in driving

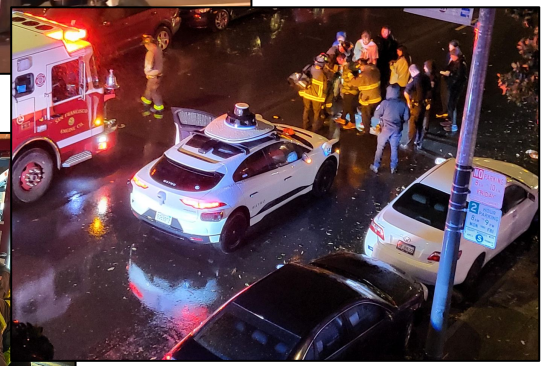
Fatal Motor Vehicle Crashes

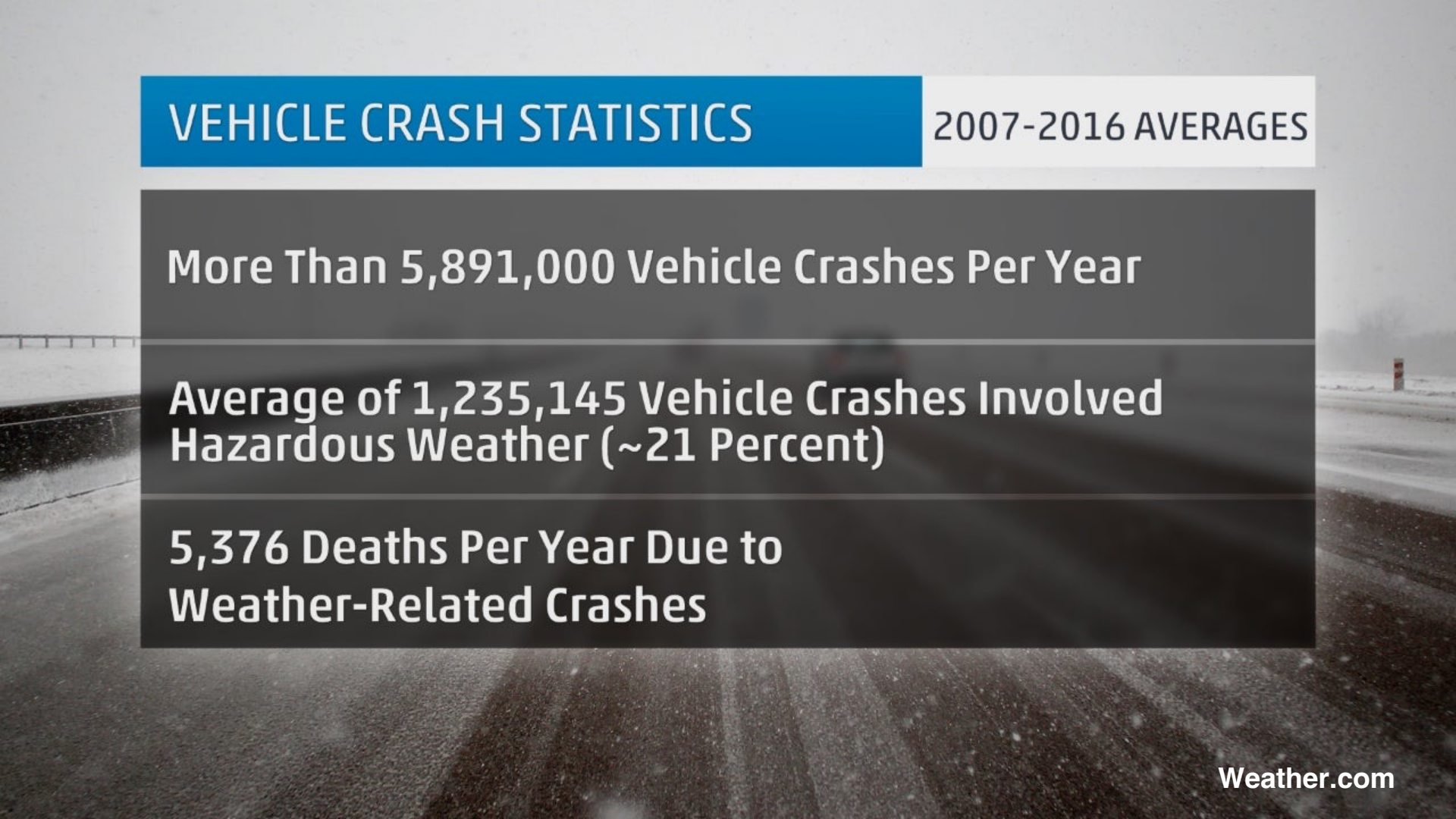
49% occurred during the day

51% occurred at night

20% occurred on a weekend






VEHICLE CRASH STATISTICS
2007-2016 AVERAGES
More Than 5,891,000 Vehicle Crashes Per Year
Average of 1,235,145 Vehicle Crashes Involved Hazardous Weather (~21 Percent)
5,376 Deaths Per Year Due to Weather-Related Crashes
Weather.com

2: An ideal simulator should simulate ***all possible factors*** that matter for driving

Immersive experience for “what if” questions.

What if…

Andreas Geiger, Philip Lenz, Christoph Stiller and Raquel Urtasun, Vision meets Robotics: The KITTI Dataset, IJRR 2013.
Yiyi Liao, Jun Xie Andreas Geiger, KITTI-360: A Novel Dataset and Benchmarks for Urban Scene Understanding in 2D and 3D. PAMI 2022

Immersive experience for “what if” questions.

What if… driving at night?

https://urbaninverserendering.github.io/

Immersive experience for “what if” questions.

What if… driving on a smoggy day?

https://climatenerf.github.io/

Immersive experience for “what if” questions.

What if… the street is flooded?

https://climatenerf.github.io/

Key Approach: Modeling and Recreation

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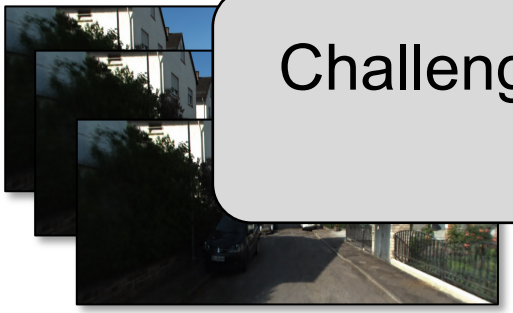
Recreate Experiences



Challenge: physical effects in lighting and dynamics.

Extreme Weather Synthesis in NeRF

Snow

Climate Impact

Style image

Multi-view Input Images

Yuan Li*, Zhi-Hao Lin*, David Forsyth, Jia-Bin Huang, Shenlong Wang, "ClimateNeRF: Physically-based Neural Rendering for Extreme Climate Synthesis", ICCV 2023.

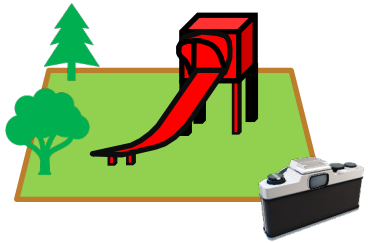
Extreme Weather Synthesis in NeRF

Snow

Climate Impact

Style image

Multi-view Input Images



3D Scene Modeling

Yuan Li*, Zhi-Hao Lin*, David Forsyth, Jia-Bin Huang, Shenlong Wang, "ClimateNeRF: Physically-based Neural Rendering for Extreme Climate Synthesis", ICCV 2023.

Extreme Weather Synthesis in NeRF

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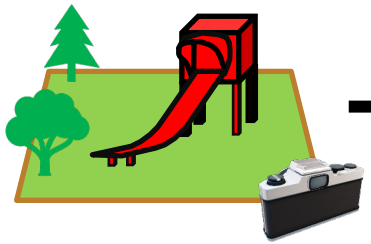
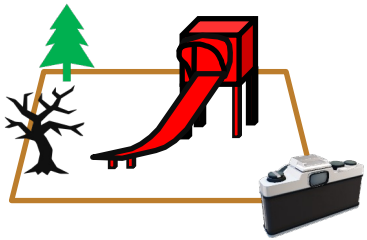


3D Scene Modeling



Neural Scene Stylization

Yuan Li*, Zhi-Hao Lin*, David Forsyth, Jia-Bin Huang, Shenlong Wang, "ClimateNeRF: Physically-based Neural Rendering for Extreme Climate Synthesis", ICCV 2023.

Extreme W

Snow

Climate Impact

Sty

Multi-view Input Imag

Yuan Li*, Zhi-Hao Lin*, David Forsyth, Jia-Bin Huang, Shenlong Wang, "ClimateNeRF: Physically-based Neural Rendering for Extreme Climate Synthesis", ICCV 2023.

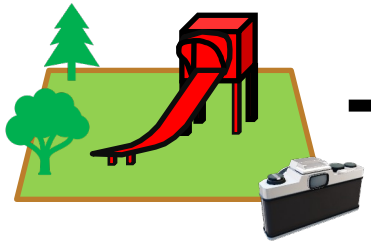
Extreme Weather Synthesis in NeRF

Snow

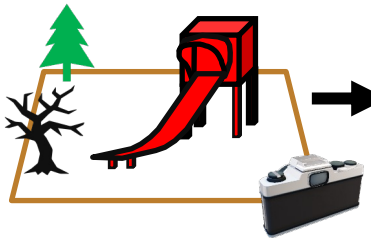
Climate Impact

Style image

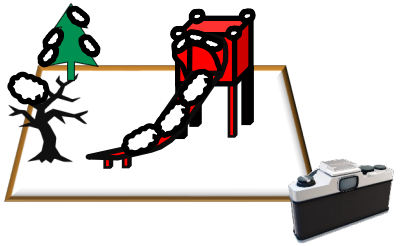
Multi-view Input Images



3D Scene Modeling



Neural Scene Stylization



Physical-Inspired Simulation

Yuan Li*, Zhi-Hao Lin*, David Forsyth, Jia-Bin Huang, Shenlong Wang, "ClimateNeRF: Physically-based Neural Rendering for Extreme Climate Synthesis", ICCV 2023.

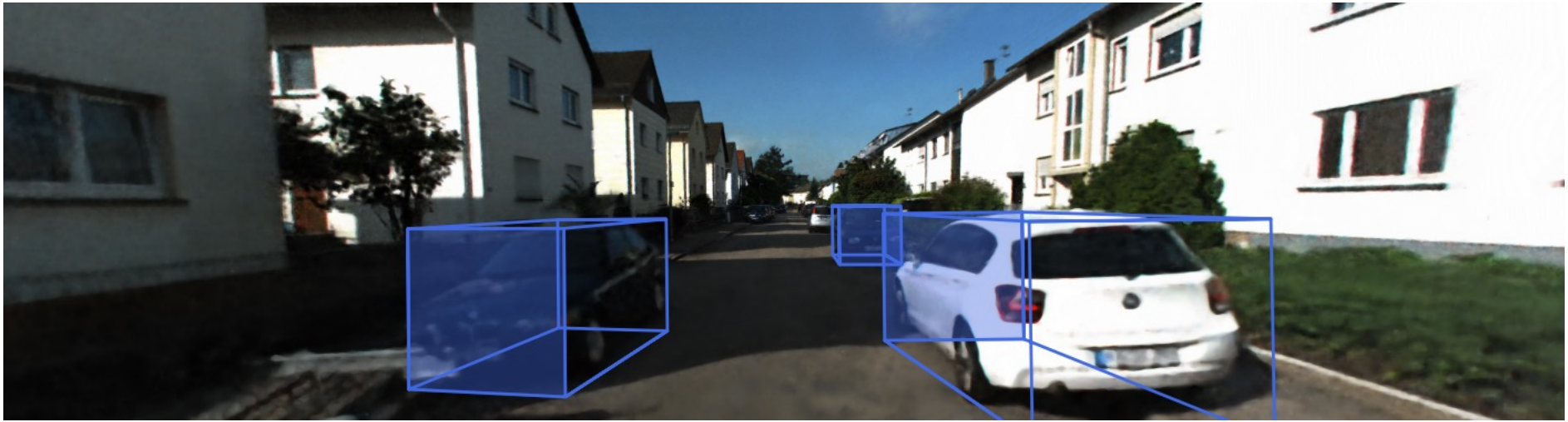

WESTERN
PACIFIC
713

Controllability

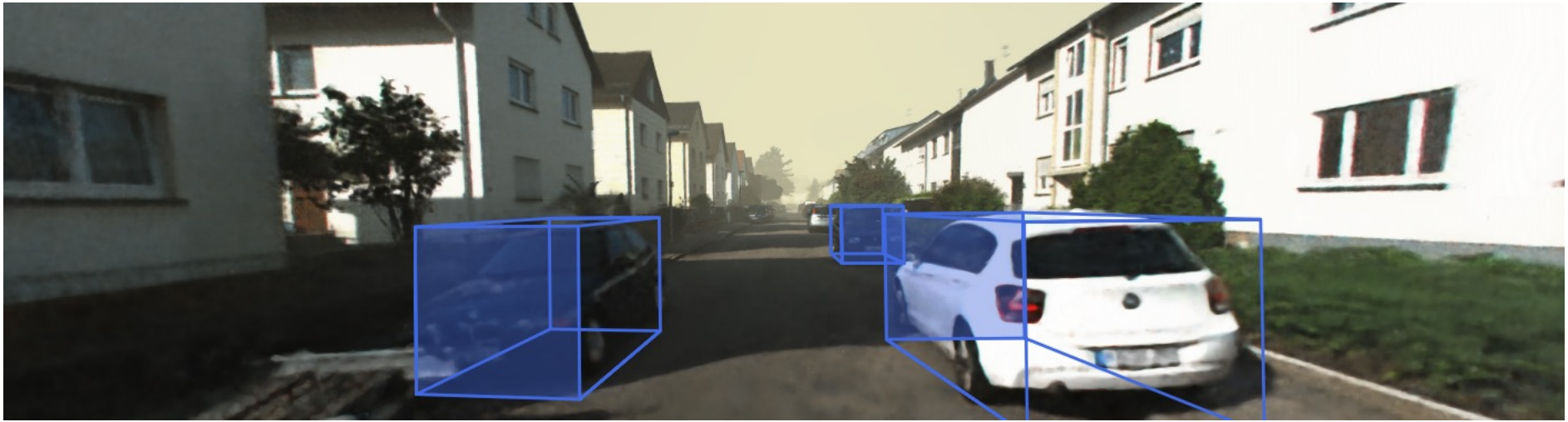
Possible to incorporate realistic weather projection

Yuan Li*, Zhi-Hao Lin*, David Forsyth, Jia-Bin Huang, Shenlong Wang, "ClimateNeRF: Physically-based Neural Rendering for Extreme Climate Synthesis", ICCV 2023.

Extreme weather for self-driving perception



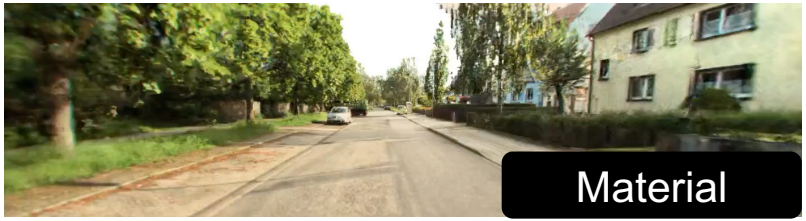
Extreme weather for self-driving perception

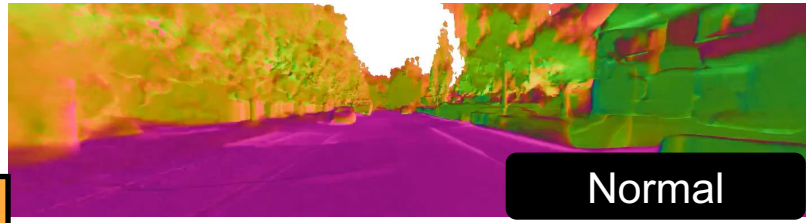


Extreme weather for self-driving perception

Extreme weather for self-driving perception

UrbanIR





Zhi-Hao Lin, Bohan Liu, YI-Ting Hu, Anand Bhattad, David Forsyth, Jia-Bin Huang, Shenlong Wang. UrbanIR: Large-Scale Urban Scene Inverse Rendering from a Single Video, arXiv. 2023


Reconstruction (Day)


Night simulation


Reconstruction (Day)


Night simulation


Reconstruction

2: An ideal simulator should simulate ***all possible factors*** that matter for driving

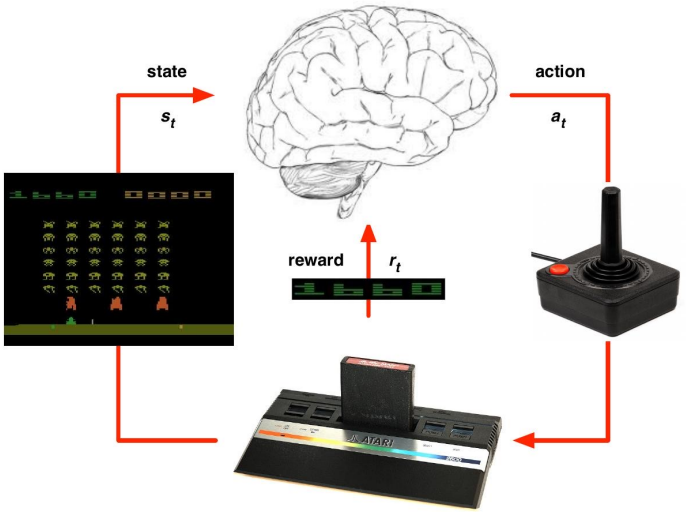
2: An ideal simulator should simulate ***all possible factors*** that matter for driving

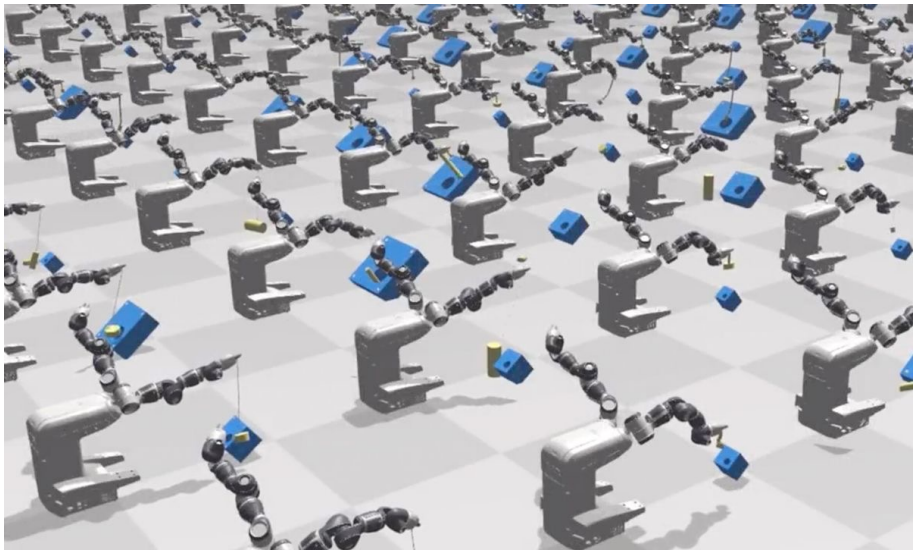
Combine ***generative*** and ***physics-based*** models to simulate physical phenomenon

That said, simulation hasn't yet replace real data in training autonomous agents.

100x acceleration

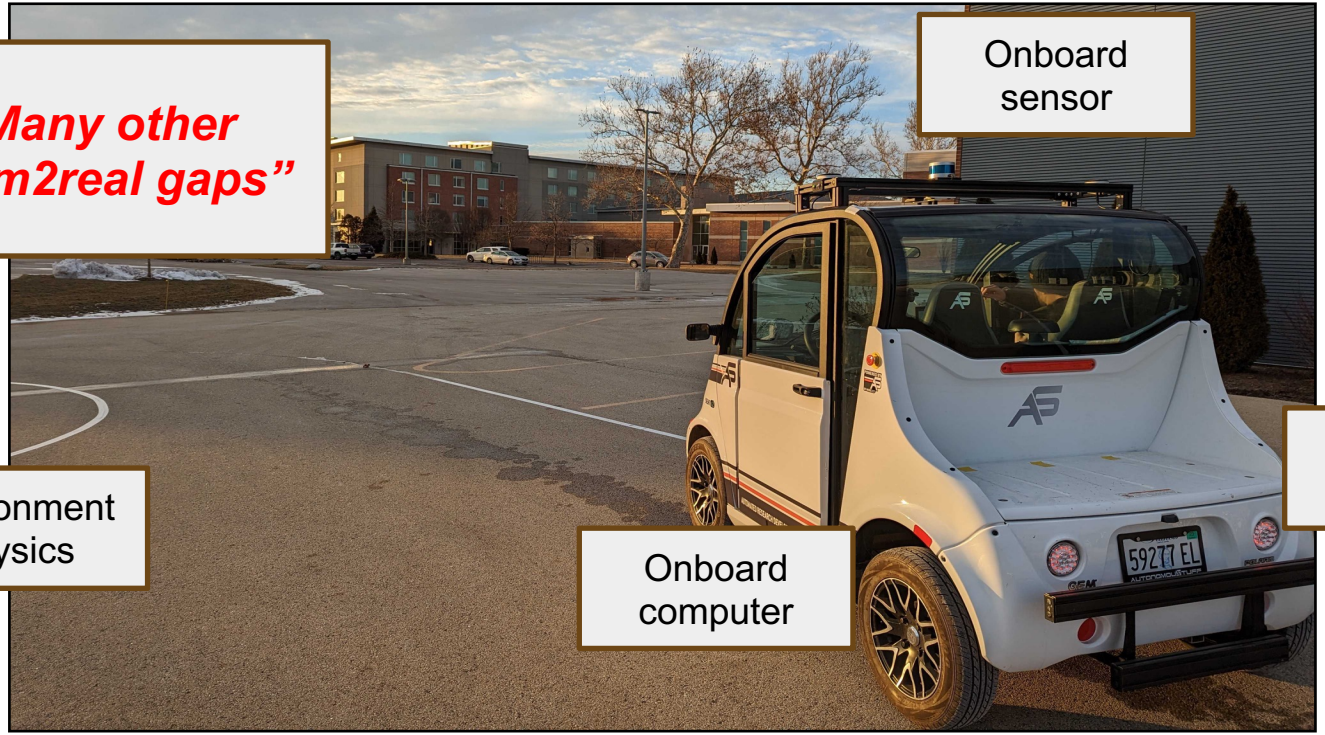
Reinforcement Learning in Atari





DeepMind, Nvidia

That said, simulation hasn't yet replace real data in testing autonomous agents.

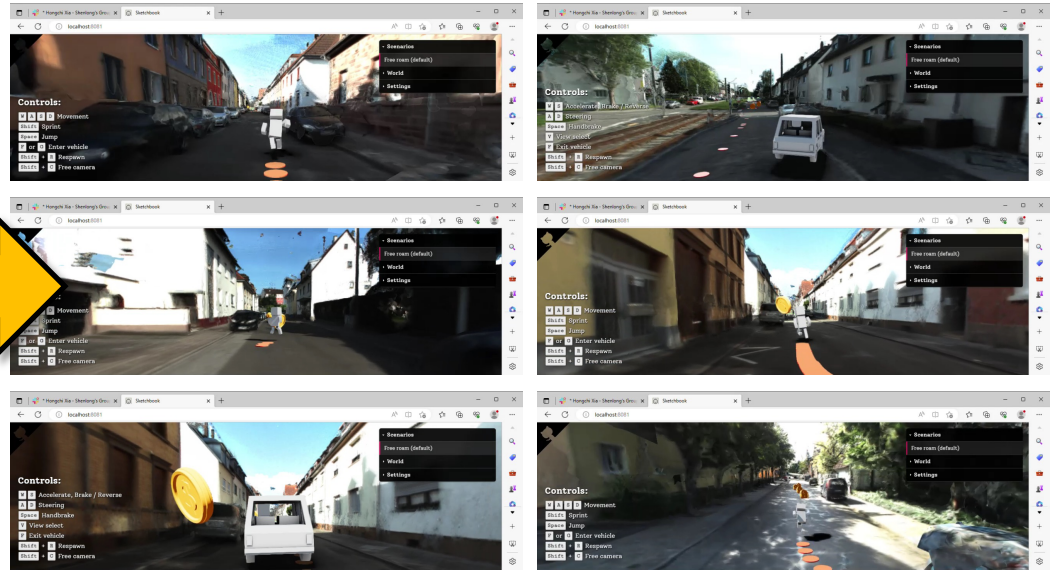


3: An ideal simulator should ***run faster than reality*** and/or ***incorporate as many real components as possible***.

Can we turn a video to an interactive environment?

Input: single video

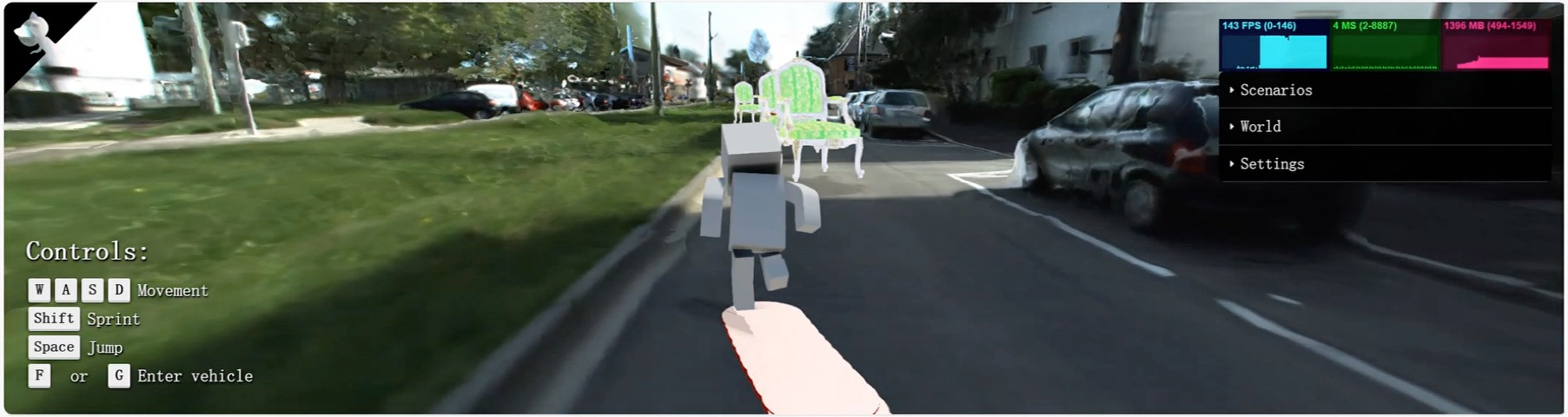
Output: real-time, realistic, interactive environment

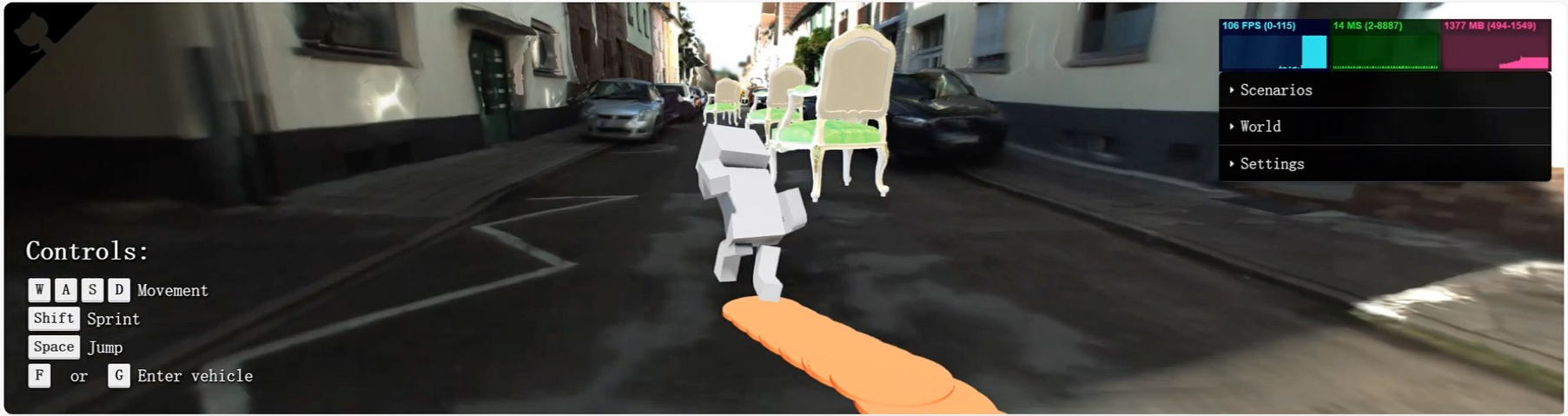


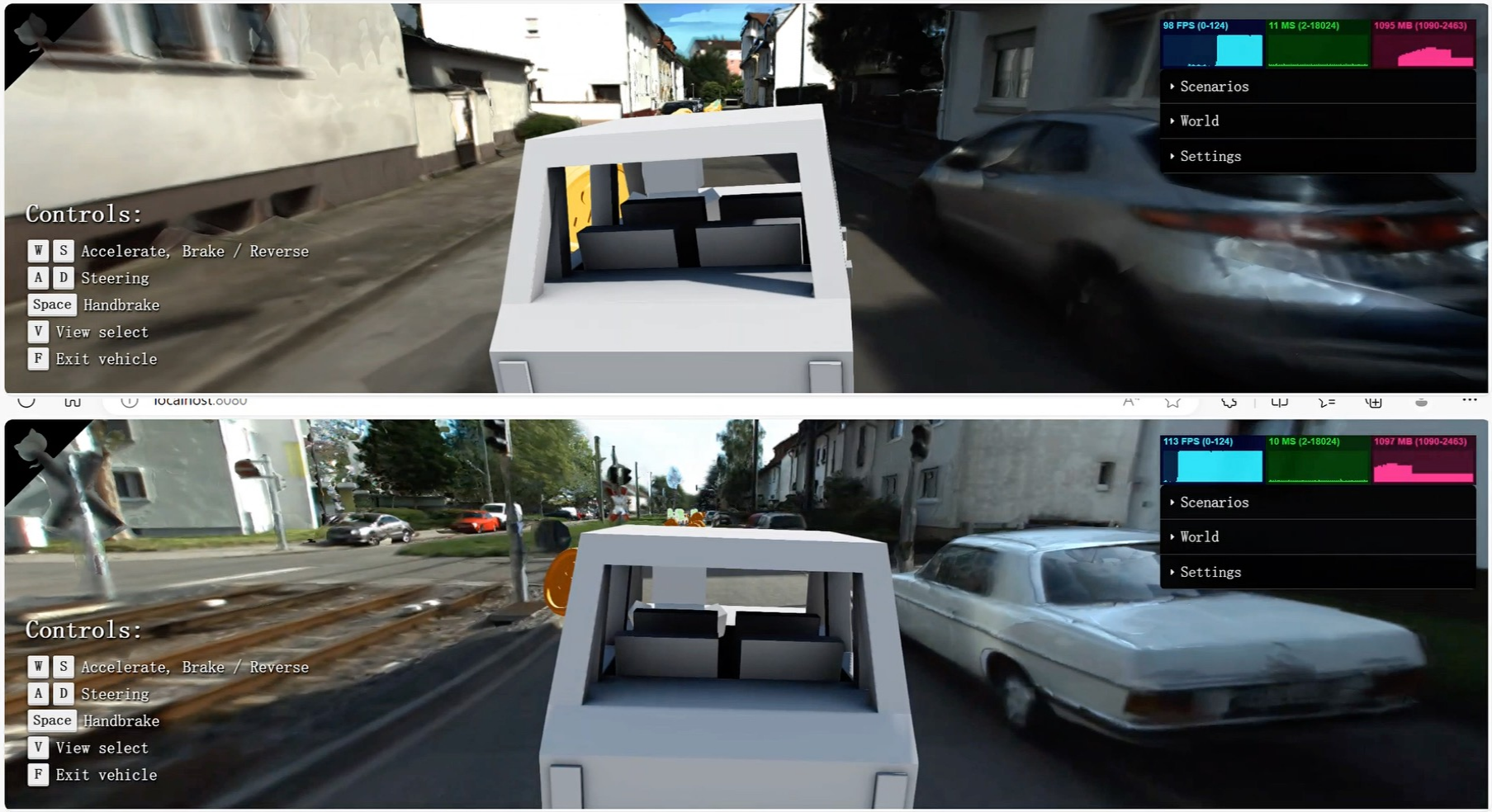
Hongchi Xia, Zhi-Hao Lin, Wei-Chiu Ma, Shenlong Wang, Video2Game: Real-time, Interactive, Realistic and Browser-Compatible Environment from a Single Video, CVPR 2024

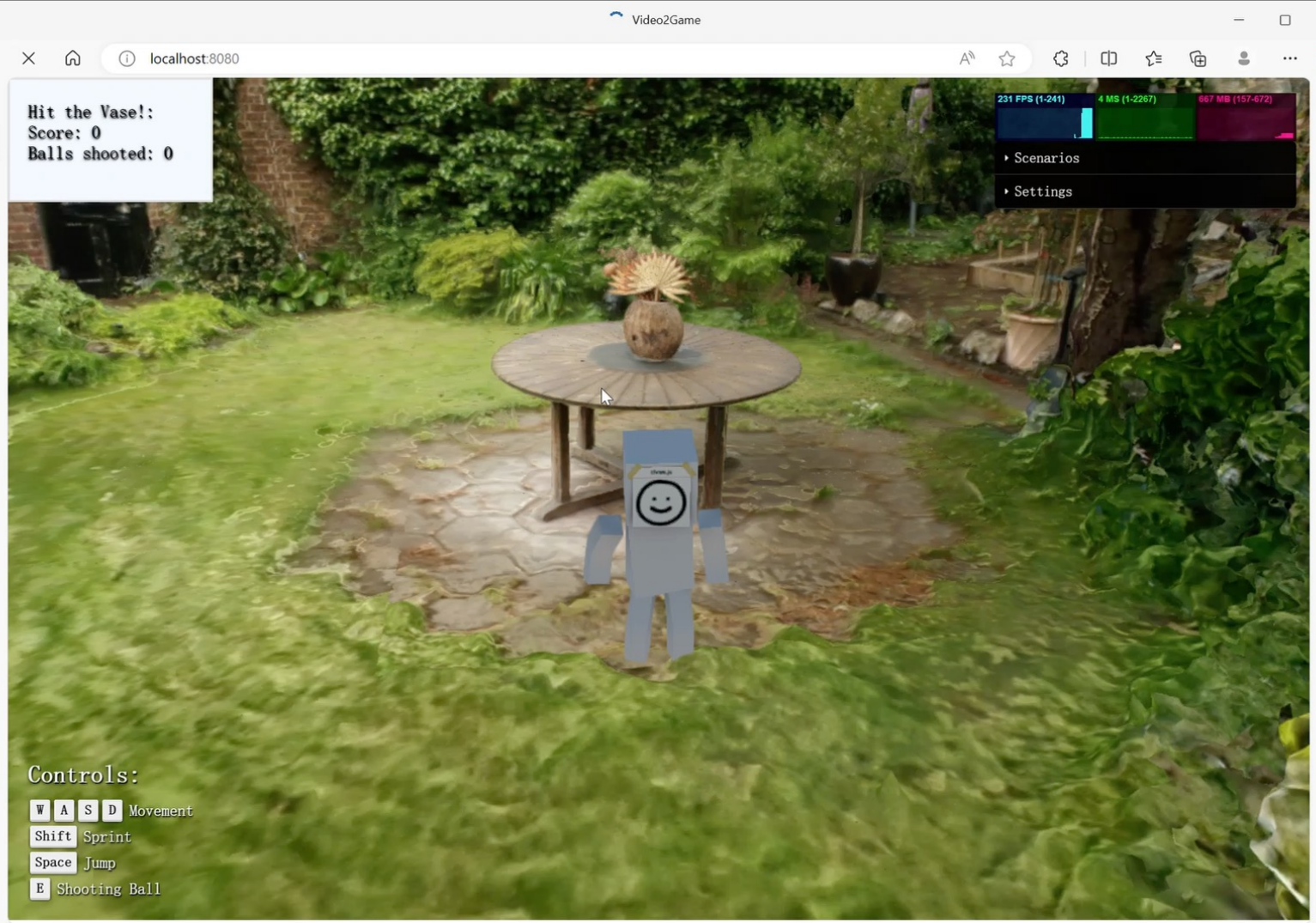
Video2Game

localhost:8080

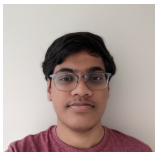




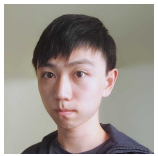

Video2Game
localhost:8080
98 FPS (0-124)
11 MS (2-18024)
1095 MB (1090-2463)
Scenarios
World
Settings
Controls:
W S Accelerate, Brake / Reverse
A D Steering
Space Handbrake
V View select
F Exit vehicle
113 FPS (0-124)
10 MS (2-18024)
1097 MB (1090-2463)
Scenarios
World
Settings
Controls:
W S Accelerate, Brake / Reverse
A D Steering
Space Handbrake
V View select
F Exit vehicle


Video2Game
localhost:8080
Hit the Vase!:
Score: 0
Balls shooted: 0
231 FPS (1-241)
4 MS (1-2267)
667 MB (157-672)
Scenarios
Settings
Controls:
W A S D Movement
Shift Sprint
Space Jump
E Shooting Ball

Can we bring simulation back to reality?


Bhargav Chandaka


Yuan Shen


Albert Zhai


Zhi-Hao Lin

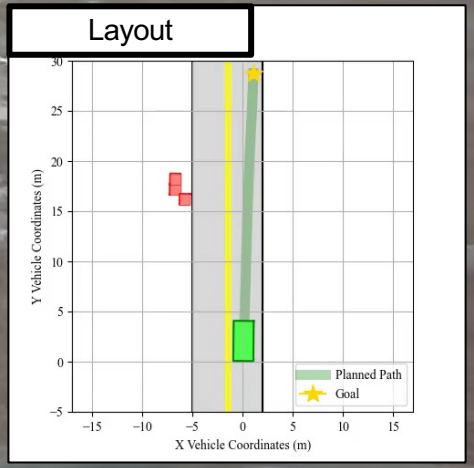
Sim-on-Wheels
Simulation with Real World Physics
and Hardware in the loop

https://sim-on-wheels.github.io/

Sim-on-Wheels: Physical World in the Loop Simulation for Autonomous Driving Yuan Shen*, Bhargav Chandaka*, Zhi-Hao Lin, Albert Jianqiao Zhai, Hang Cui, David Forsyth, Shenlong Wang Robotics and Automation Letters (RAL), 2023

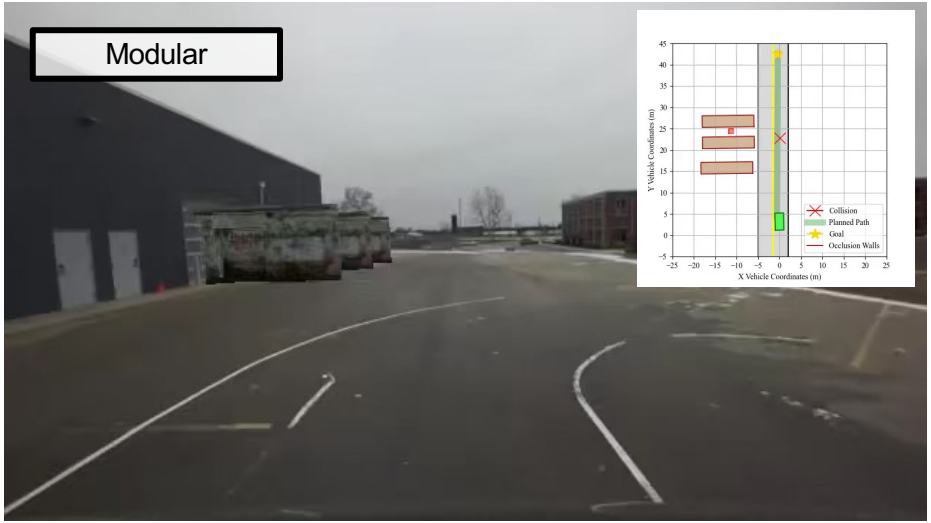

In-Cabin
Third-Person
Layout

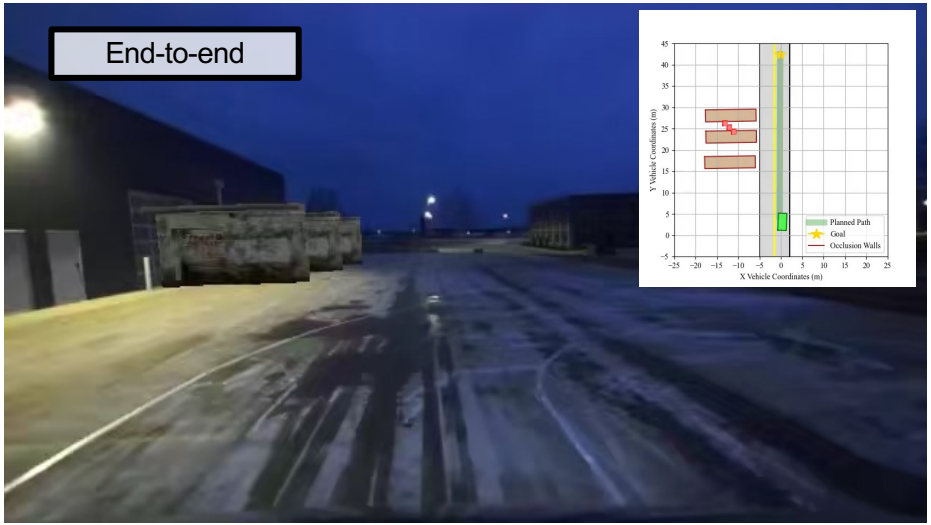
Sim-on-Wheels Simulation



Autonomy Evaluation Experiment

Qualitative Result – Jaywalker with Occlusion

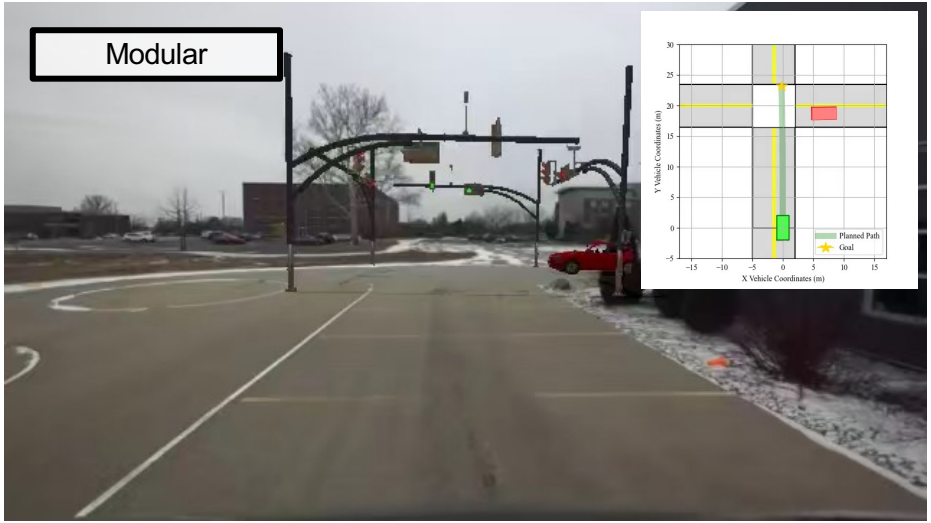


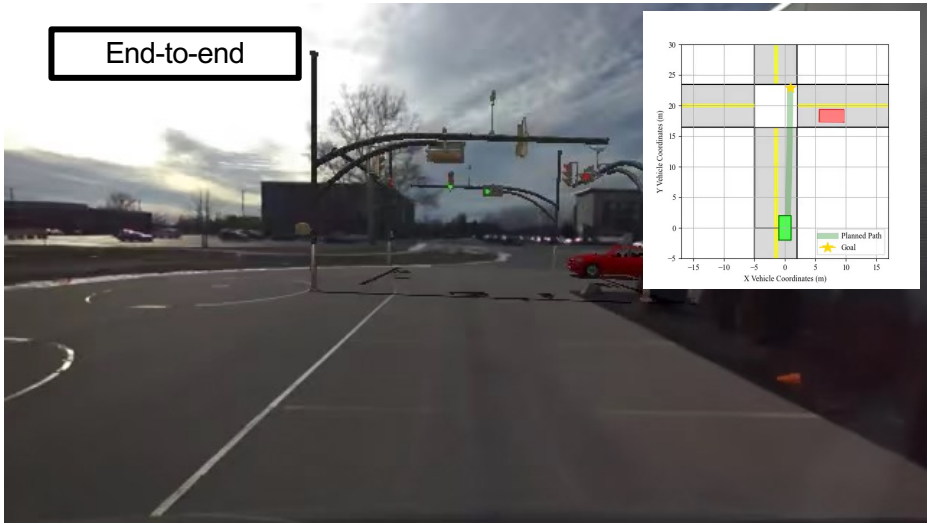


Sim-on-Wheels: Physical World in the Loop Simulation for Autonomous Driving Yuan Shen*, Bhargav Chandaka*, Zhi-Hao Lin, Albert Jianqiao Zhai, Hang Cui, David Forsyth, Shenlong Wang Robotics and Automation Letters (RAL), 2023

Autonomy Evaluation Experiment

Qualitative Result – Traffic Light Violation





Sim-on-Wheels: Physical World in the Loop Simulation for Autonomous Driving Yuan Shen*, Bhargav Chandaka*, Zhi-Hao Lin, Albert Jianqiao Zhai, Hang Cui, David Forsyth, Shenlong Wang Robotics and Automation Letters (RAL), 2023

Reality Gap Experiment

Image Level Comparison

Sim-on-Wheels: Physical World in the Loop Simulation for Autonomous Driving Yuan Shen*, Bhargav Chandaka*, Zhi-Hao Lin, Albert Jianqiao Zhai, Hang Cui, David Forsyth, Shenlong Wang Robotics and Automation Letters (RAL), 2023

Reality Gap Experiment

Image Level Comparison

Sim-on-Wheels: Physical World in the Loop Simulation for Autonomous Driving Yuan Shen*, Bhargav Chandaka*, Zhi-Hao Lin, Albert Jianqiao Zhai, Hang Cui, David Forsyth, Shenlong Wang Robotics and Automation Letters (RAL), 2023

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Reality Gap Experiment

Action Level Comparison

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3: An ideal simulator should ***run faster than real-time*** and/or ***incorporate as many real components as possible***.

Game engine compatible and **hardware-in-the-loop** simulation

Modeling and Recreation

Model and Perceive the Physical World

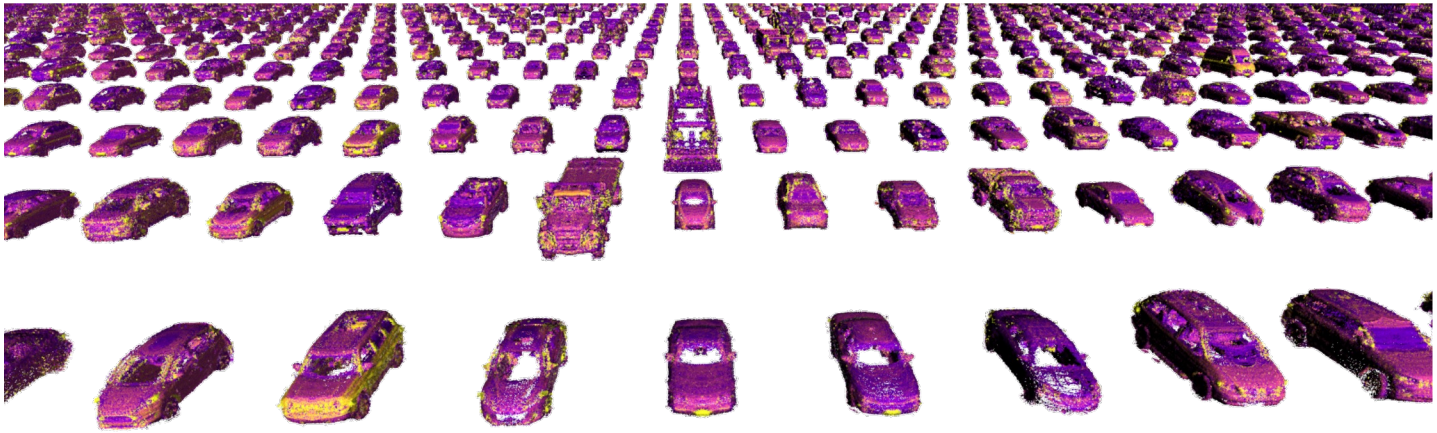
Recreate Experiences

Challenge: scale is limited by the # observed real-world scenes.

4: An ideal simulator should ***scale up to infinitely possible scenarios***.

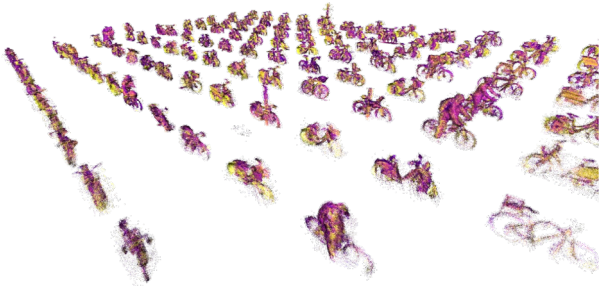
Recap: *real-world simulation is limited in diversity*

Vehicles

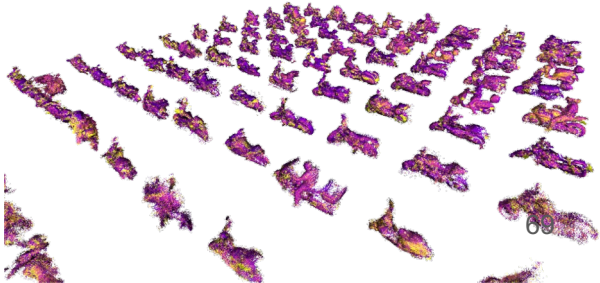


Pedestrian

Bicyclist



Motorcyclist

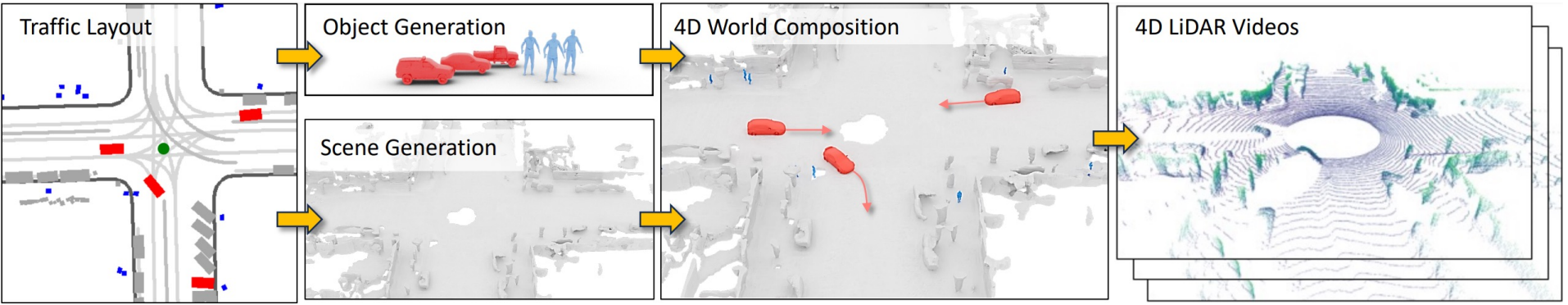


Can we generate digital twin world for driving?

Vlas Zyrianov

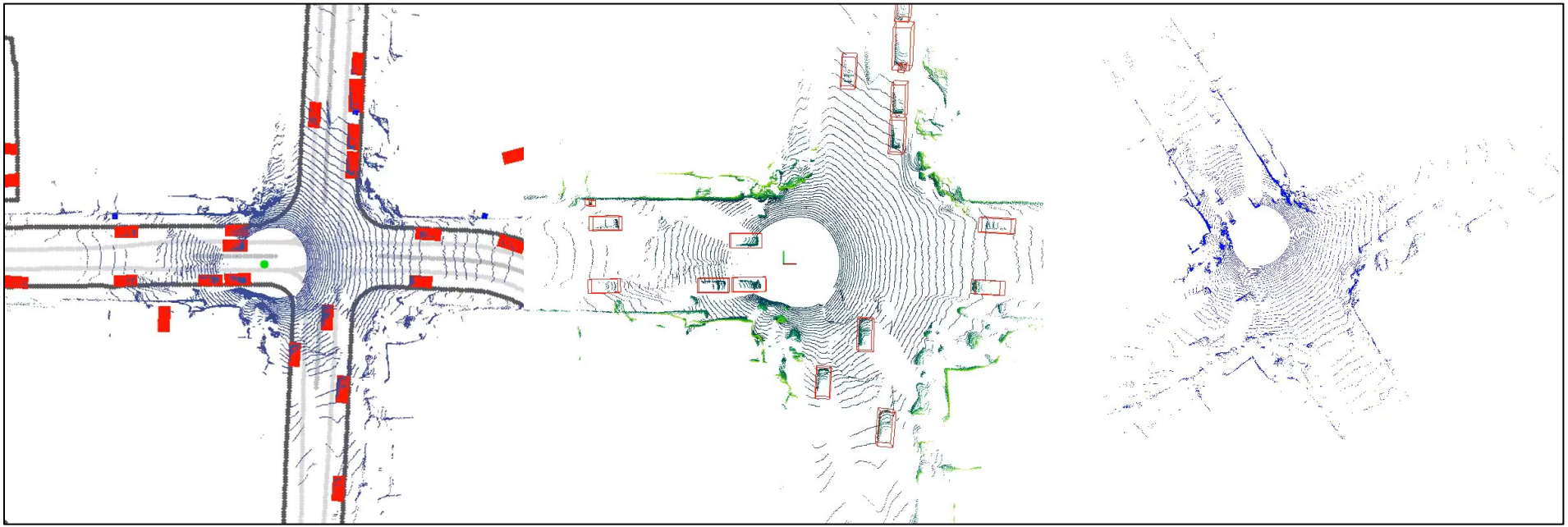
Henry Che

Key insights: Generate a 4D world, then make continuous observations within it.



LidarDM, https://www.zyrianov.org/lidardm/

Can we generate digital twin world for driving?



Layout-aware

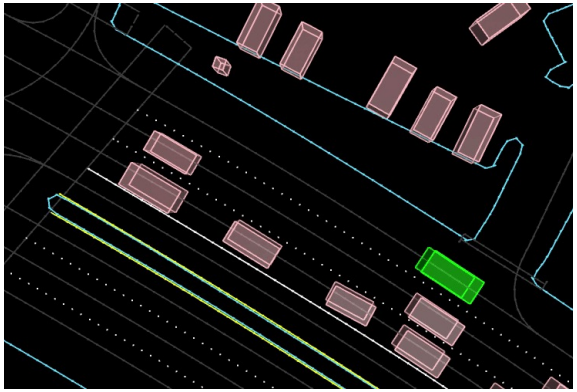
Realistic

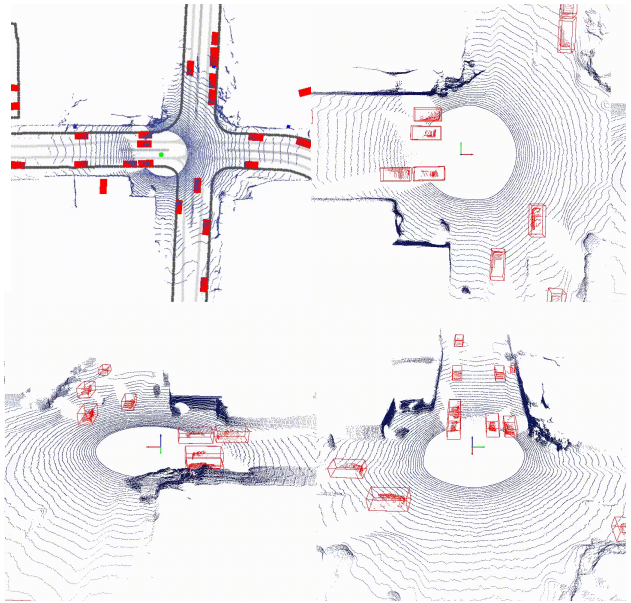
Coherent in space & time

LidarDM, https://www.zyrianov.org/lidardm/

Waymax + LidarDM = *Asset Free Simulator!*

- 2D Traffic Simulator Scenarios are fed into LidarDM





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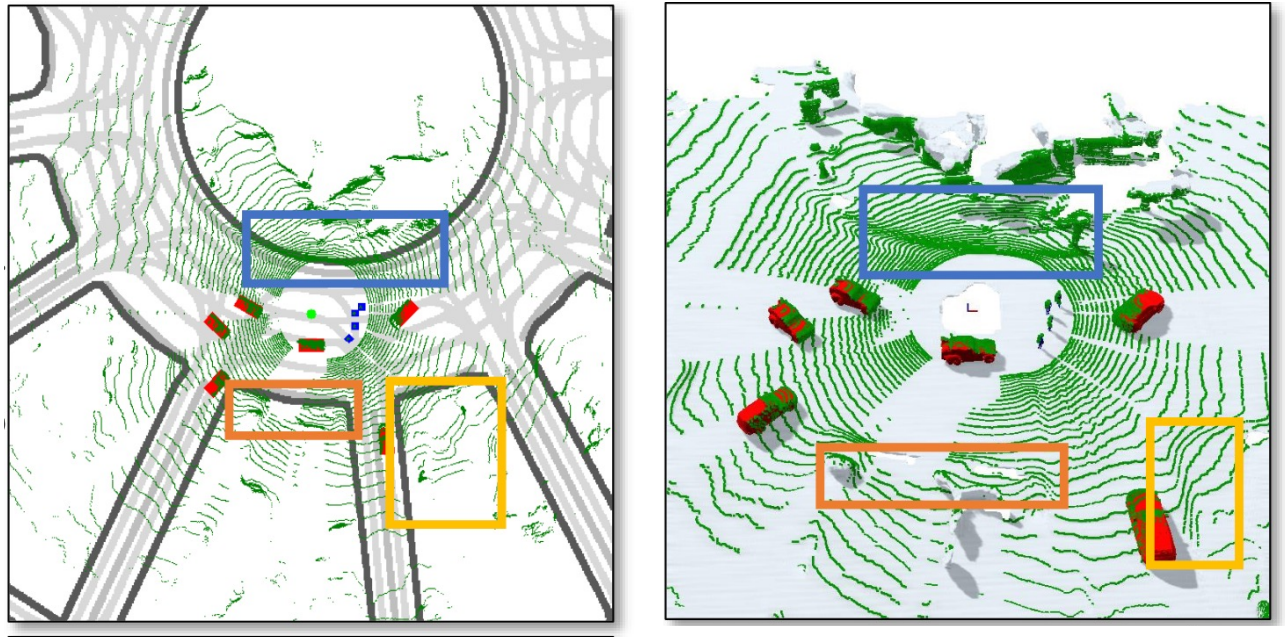
Waymax + LidarDM = *Asset Free Simulator!*

- Generate Champs Élysées without visiting France



LidarDM, https://www.zyrianov.org/lidardm/

4: An ideal simulator should ***scale up to infinitely possible scenarios***.

Generate many ***digital worlds*** and run simulations

Today’s talk

A desired driving simulator should

1. *Use **real-world data** to reduce costs and sim2real gap.*
2. *Cover **all possible real-world scenarios** that matter for driving.*
3. *Simulate at **super-real-time** speeds with **embodiment**.*
4. *Scale with **generative AI** for endless possibilities.*

How much do I trust my simulation results?

Today's talk

A desired driving simulator should

1. *Use **real-world data** to reduce costs and sim2real gap.*
2. *Cover **all possible real-world scenarios** that matter for driving.*
3. *Simulate at **super-real-time** speeds with **embodiment**.*
4. *Scale with **generative AI** for endless possibilities.*
5. ***Provide trust-worthy evaluation results with certificates / guarantees***

Projects summary

- LidarSim (CVPR 2020):
- GeoSim (CVPR 2021):
- SceneGen (CVPR 2021):
- ClimateNeRF (ICCV 2023): https://climatenerf.github.io/
- UrbanIR (arXiv 2024): https://urbaninverserendering.github.io/
- Video2Game (CVPR 2024): https://video2game.github.io/
- Sim-on-Wheels (RA-L 2023): https://sim-on-wheels.github.io/
- NeRF2Physics (CVPR 2024): https://ajzhai.github.io/nerf2physics/
- LidarDM (arXiv 2024): https://lidardm.github.io/
- PhysGen (arXiv soon)

Acknowledgement

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