

China3DV 2025 战略论坛



北京大学
PEKING UNIVERSITY

Physics-Sim Empowered Spatial Intelligence

基于物理仿真的空间智能构建

陈宝权 Baoquan Chen

Beijing, 2025-04-12

Spatial Intelligence & Physical AI



- **Spatial intelligence** refers to the ability of an individual or system to *understand, generate, and act in physical space*, a critical bridge for robots to comprehend the physical world.
- **Physical AI/Embodied AI**, a pivotal frontier in spatial intelligence, bridges the digital and physical worlds, where Real2Sim2Real is the key path.
- Advanced physical simulations are the key to spatial Intelligence



Challenges:

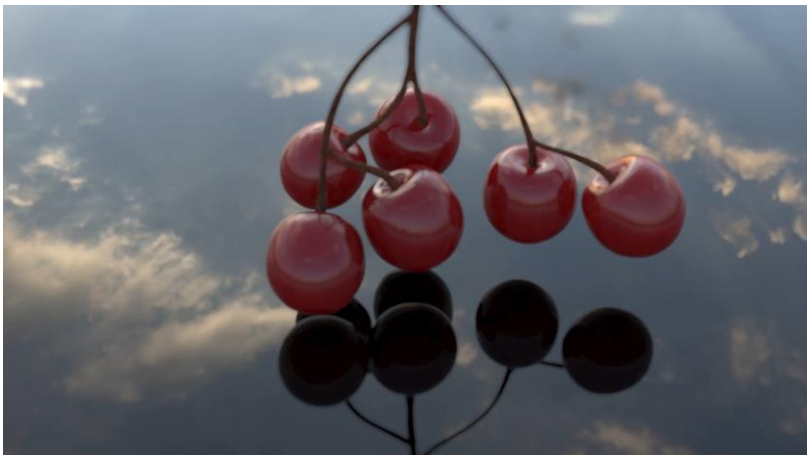
- ① Multiphysics
- ② Fidelity vs. Performance
- ③ Physical Fidelity & Real-World Realism



Towards Multiphysics

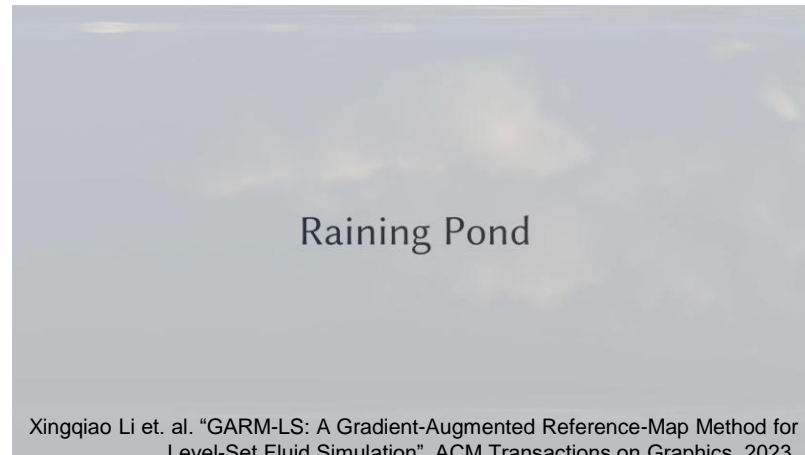


- Surface Tension Coupling (Fluid-Solid/Air Interface)



ACM SIGGRAPH @siggraph · Oct 17
 A visual ASMR treat 🍒 Could they be real or computer generated? 🤔
 (cc: @twominutepapers @NaturePhysics)

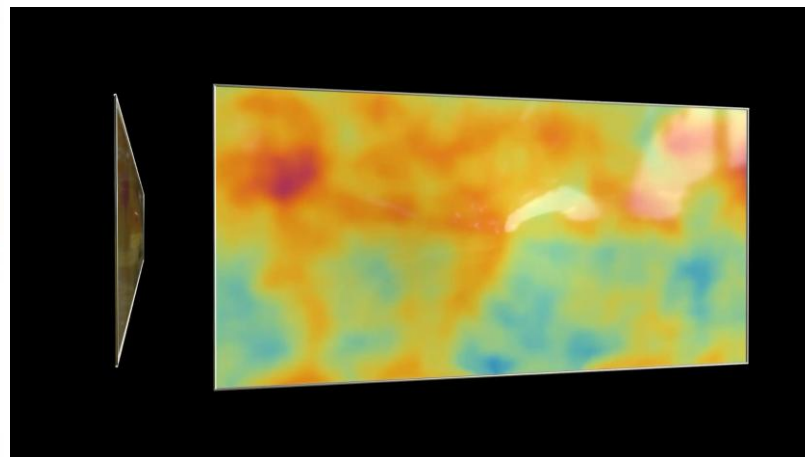
Nature Physics @NaturePhysics · Oct 13
 Are these cherries real? You can find out the answer in a new @nature.physics Comment article about flow simulations by @twominutepapers : rdcu.be/cXtbK
 Check out the video of the cherries being dropped into water or milk in this accompanying... [instagram.com/p/CjpmDd_jyOn/](https://www.instagram.com/p/CjpmDd_jyOn/)



Xingqiao Li et. al. "GARM-LS: A Gradient-Augmented Reference-Map Method for Level-Set Fluid Simulation", ACM Transactions on Graphics, 2023.



Liangwang Ruan et. al. "Solid-fluid interaction with surface-tension-dominant contact", ACM Transactions on Graphics, 2021.



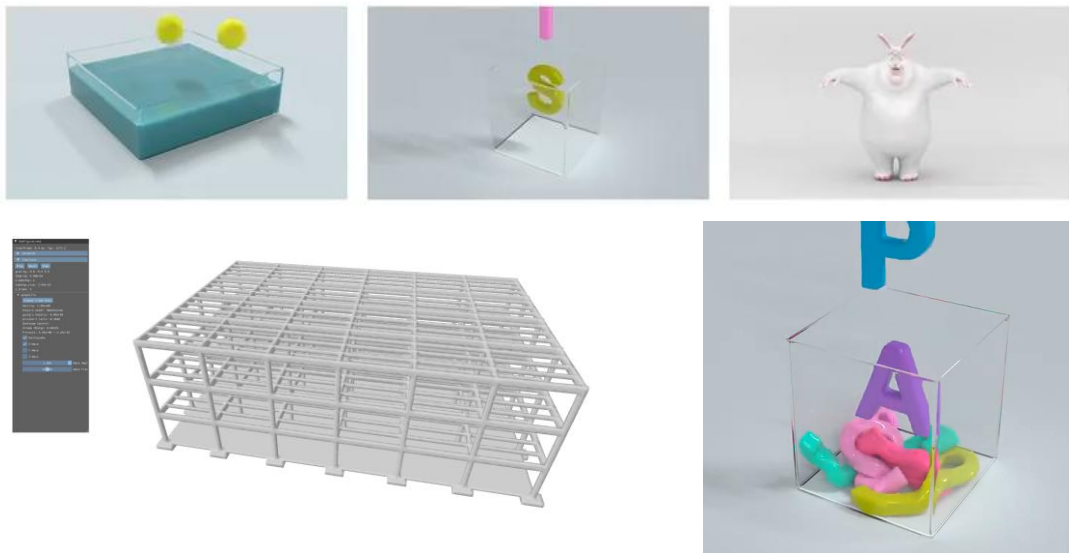
Ningxiao Tao et. al. "A Vortex Particle-on-Mesh Method for Soap Film Simulation", ACM Transactions on Graphics, 2024.



Fidelity v.s. Performance



- Soft-body deformation and collision modeling—critical phenomena in embodied AI
- Being Faster while being more physically accurate



A Time-Dependent Inclusion-Based Method for Continuous Collision Detection between Parametric Surfaces (no audio)

XUWEN CHEN, School of Intelligence Science and Technology, Peking University, China
 CHENG YU, School of Intelligence Science and Technology, Peking University, China
 XINGYU NI, School of Computer Science, Peking University, China
 MENGYU CHU, State Key Laboratory of General Artificial Intelligence, Peking University, China
 BIN WANG*, State Key Laboratory of General Artificial Intelligence, BIGAI, China
 BAOQUAN CHEN*, State Key Laboratory of General Artificial Intelligence, Peking University, China

* corresponding authors

Liangwang Ruan et. al.. “MiNNIE: a Mixed Multigrid Method for Real-time Simulation of Nonlinear Near-Incompressible Elastics”, ACM Transactions on Graphics, 2024.

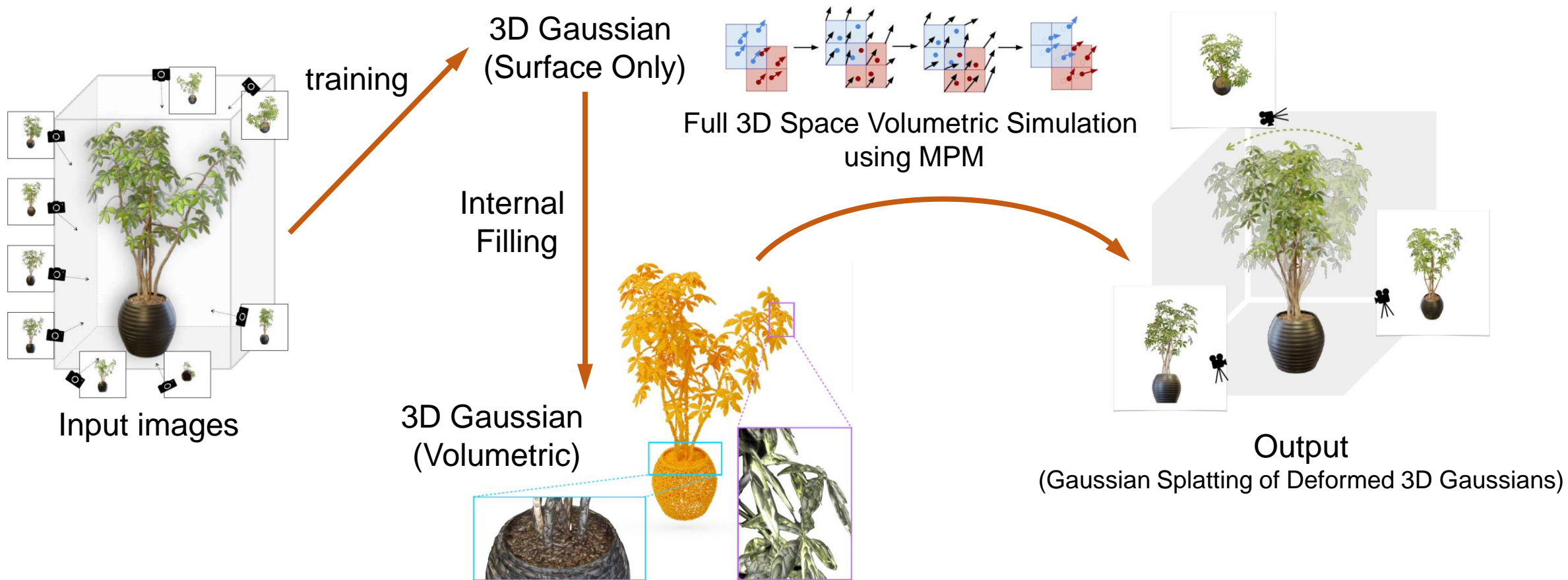
Xuwen Chen et. al.. “A Time-Dependent Inclusion-Based Method for Continuous Collision Detection between Parametric Surfaces”, ACM Transactions on Graphics, 2024.

Real-time Simulation of Near-Incompressible Elastics

A Continuous Collision Detection Method Supporting Parametric Surfaces, x100 Faster Than Previous Work

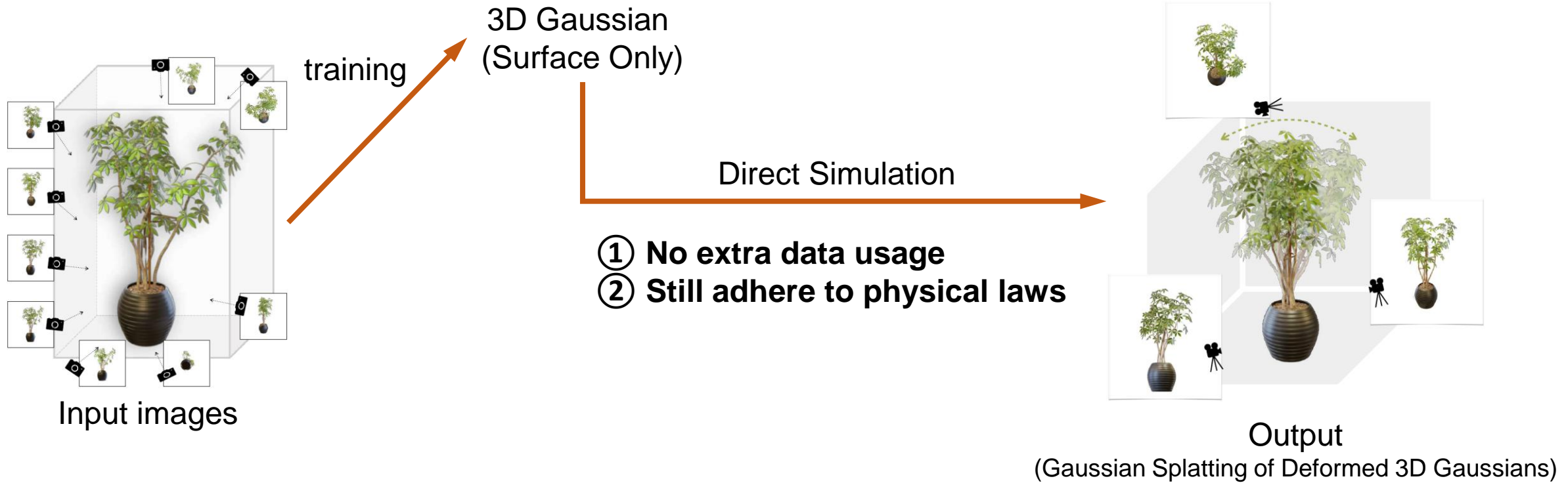


Physical Fidelity & Real-World Realism





Physical Fidelity & Real-World Realism

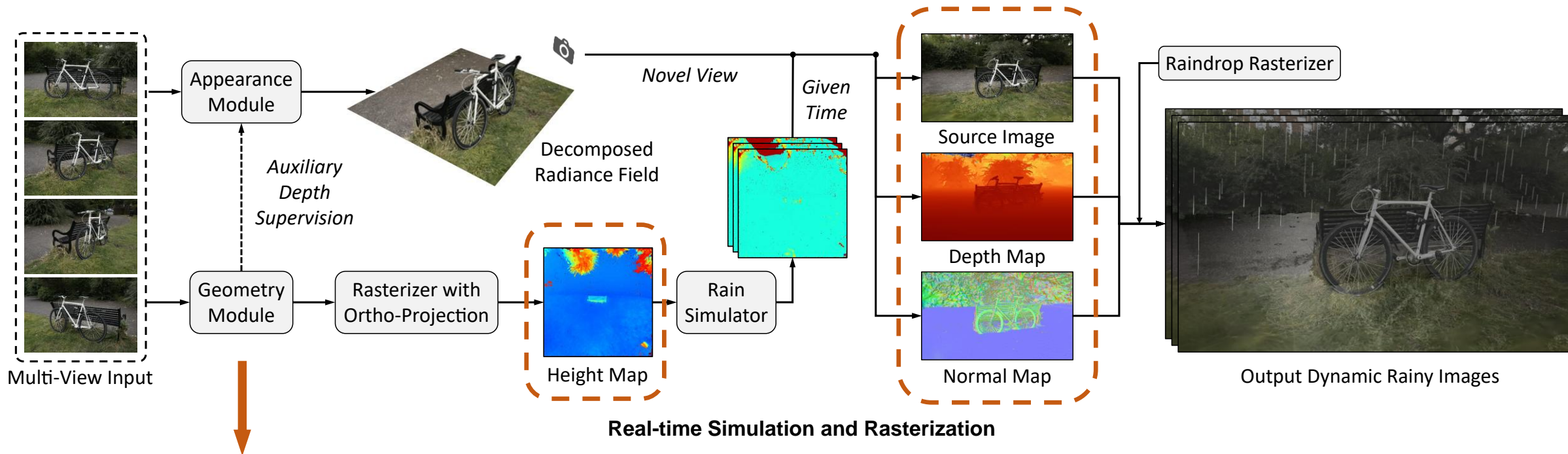




Physical Fidelity & Real-World Realism



Achieved: Real Time Surface Fluid Motion on Physical Scenes Reconstructed by 3D Gaussian



Appearance Module (外观模组): GaussianShader, For rasterization
Geometry Module (几何模组): GOF, For height-based fluid surface

No extra data usage or data conversion

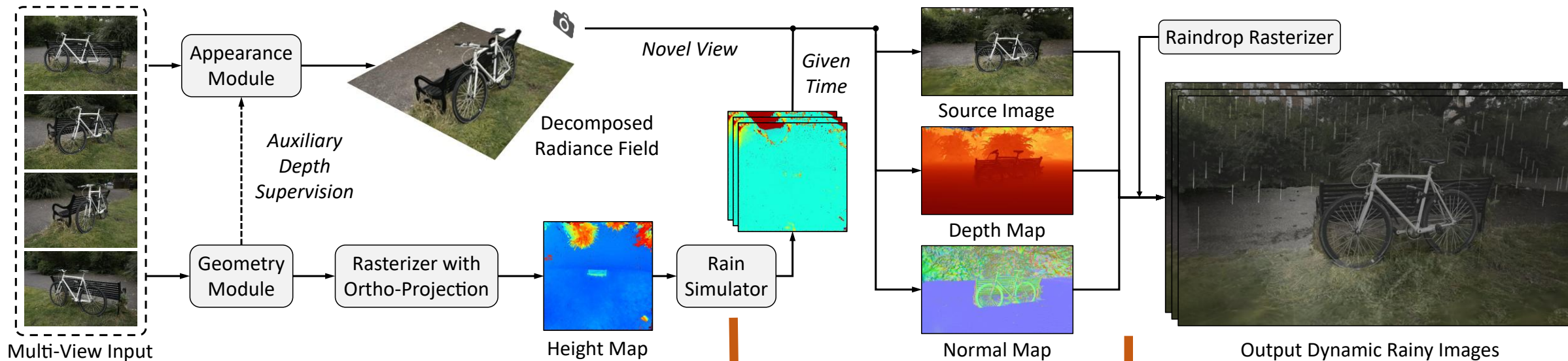
Qiyu Dai*, Xingyu Ni*, Qianfan Shen, Wenzheng Chen, Baoquan Chen, and Mengyu Chu.
 RainyGS: Efficient Rain Synthesis with Physically-Based Gaussian Splatting. *CVPR* 2025.



Physical Fidelity & Real-World Realism



Achieved : Real Time Surface Fluid Motion on Physical Scenes Reconstructed by 3D Gaussian



Shallow Water Equations

$$\frac{\partial h}{\partial t} + (\mathbf{u} \cdot \nabla)h = -h(\nabla \cdot \mathbf{u})$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -g\nabla h$$

Image-Based Rendering

- screen-space reflection
- Fresnel-Slick approximation
- no ray tracing required

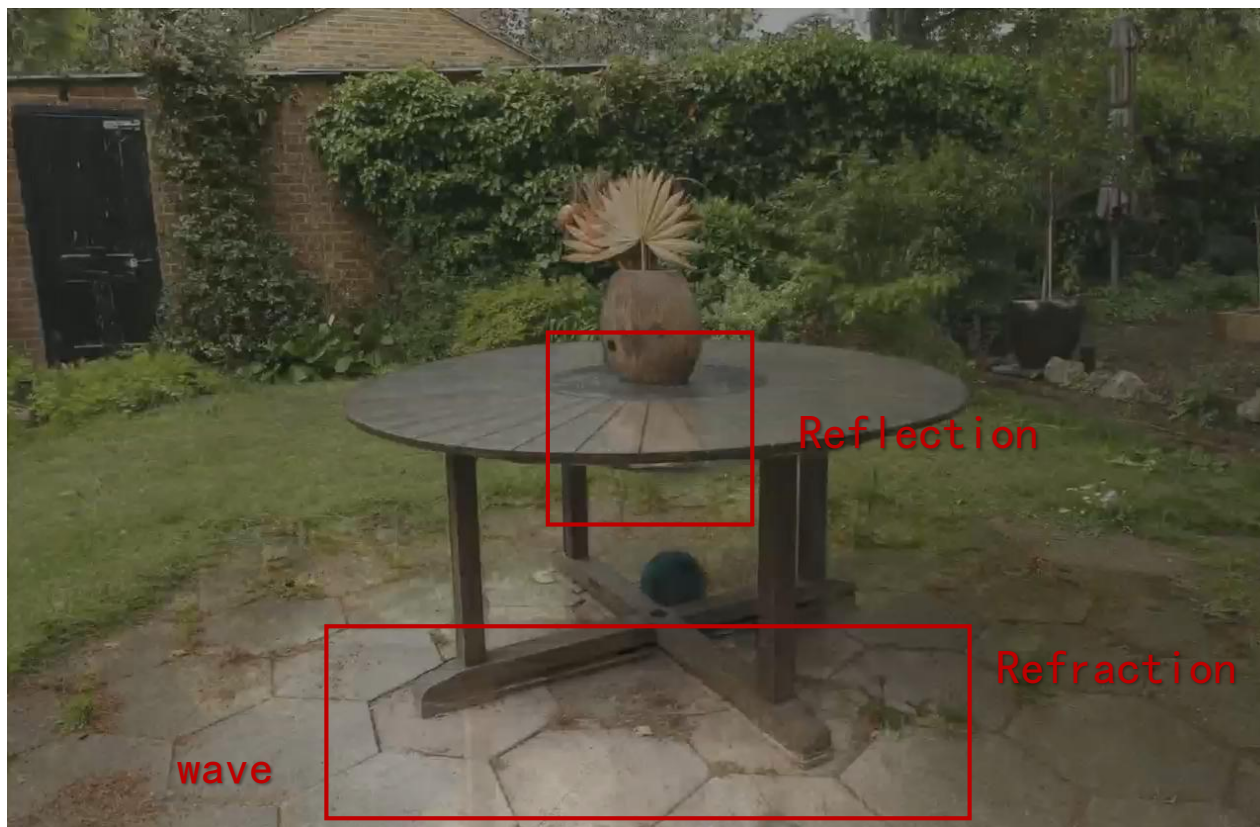
Qiyu Dai*, **Xingyu Ni***, Qianfan Shen, Wenzheng Chen, Baoquan Chen, and Mengyu Chu.
 RainyGS: Efficient Rain Synthesis with Physically-Based Gaussian Splatting. *CVPR* 2025.



Physical Fidelity & Real-World Realism



Results: Real-time Rain Simulation and Rendering on 3D Gaussian





Physical Fidelity & Real-World Realism



Qiyu Dai*, **Xingyu Ni***, Qianfan Shen, Wenzheng Chen, Baoquan Chen, and Mengyu Chu.
RainyGS: Efficient Rain Synthesis with Physically-Based Gaussian Splatting. *CVPR* 2025.



Physical Fidelity & Real-World Realism



Qiyu Dai*, **Xingyu Ni***, Qianfan Shen, Wenzheng Chen, Baoquan Chen, and Mengyu Chu.
RainyGS: Efficient Rain Synthesis with Physically-Based Gaussian Splatting. *CVPR 2025*.



Physical Fidelity & Real-World Realism



Results: Comparing with Generative Models





Physical Fidelity & Real-World Realism



Result of Waymo Scenes (Supporting Auto-Driving Training)



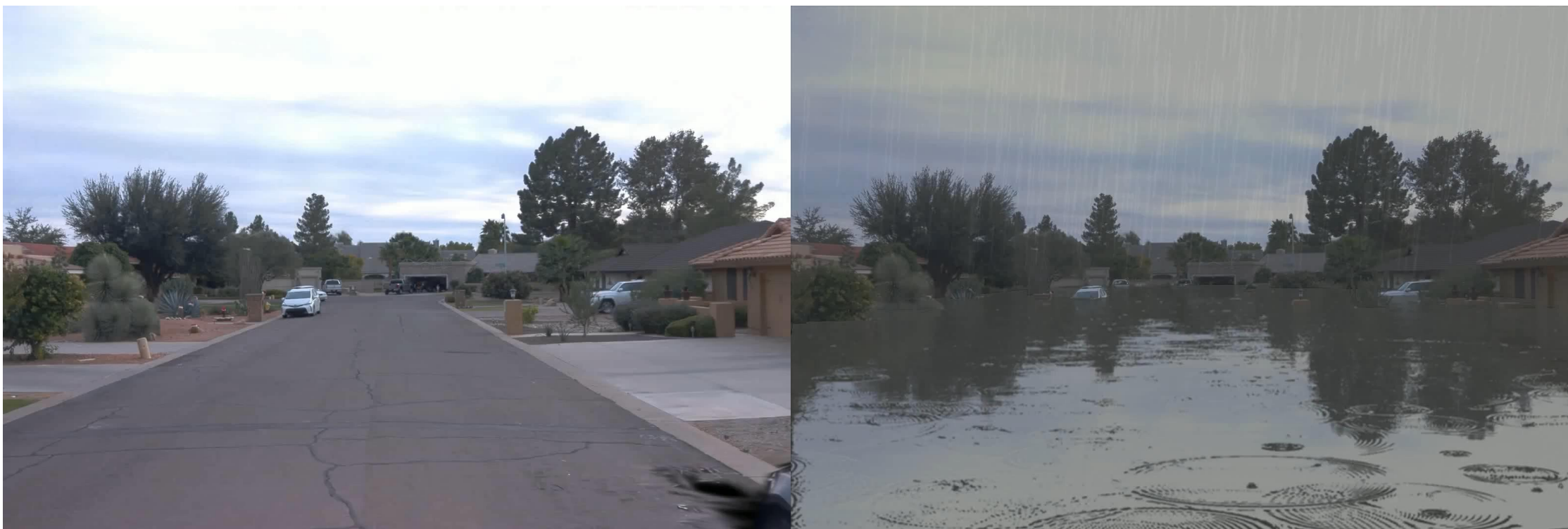
Qiyu Dai*, **Xingyu Ni***, Qianfan Shen, Wenzheng Chen, Baoquan Chen, and Mengyu Chu.
RainyGS: Efficient Rain Synthesis with Physically-Based Gaussian Splatting. *CVPR* 2025.



Physical Fidelity & Real-World Realism



Result of Waymo Scenes (Supporting Auto-Driving Training)



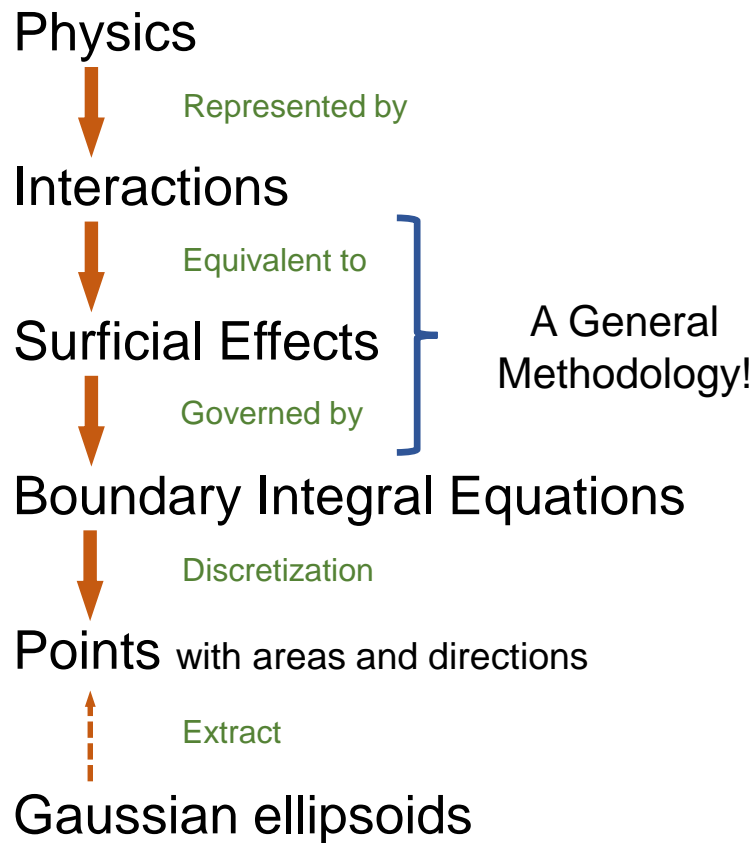
Qiyu Dai*, **Xingyu Ni***, Qianfan Shen, Wenzheng Chen, Baoquan Chen, and Mengyu Chu.
RainyGS: Efficient Rain Synthesis with Physically-Based Gaussian Splatting. *CVPR* 2025.



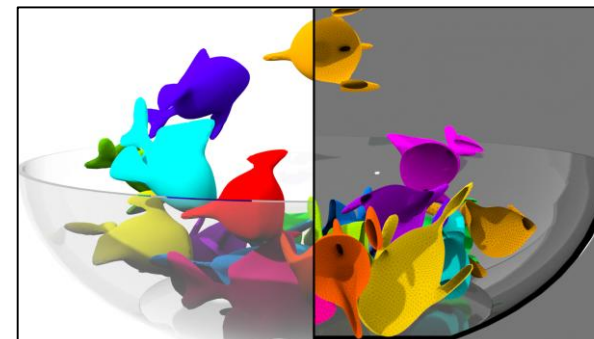
Physical Fidelity & Real-World Realism



Physical Sim on Surfaces



Quasi-Static [James and Pai 1999]

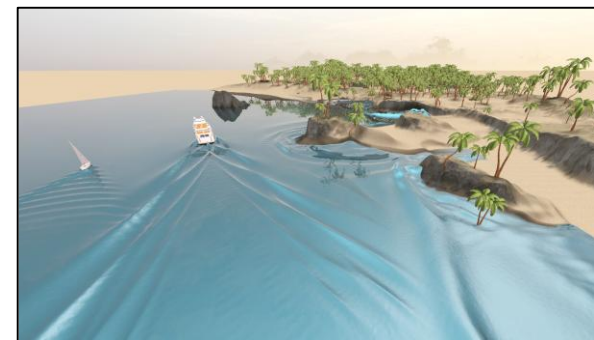


Dynamics [Sugimoto et al. 2022]

Surface-Only Deformables



Splashes [Da et al. 2016]



Waves [Jeschke and Wojtan 2023]

Surface-Only Fluids



Inverse Physics

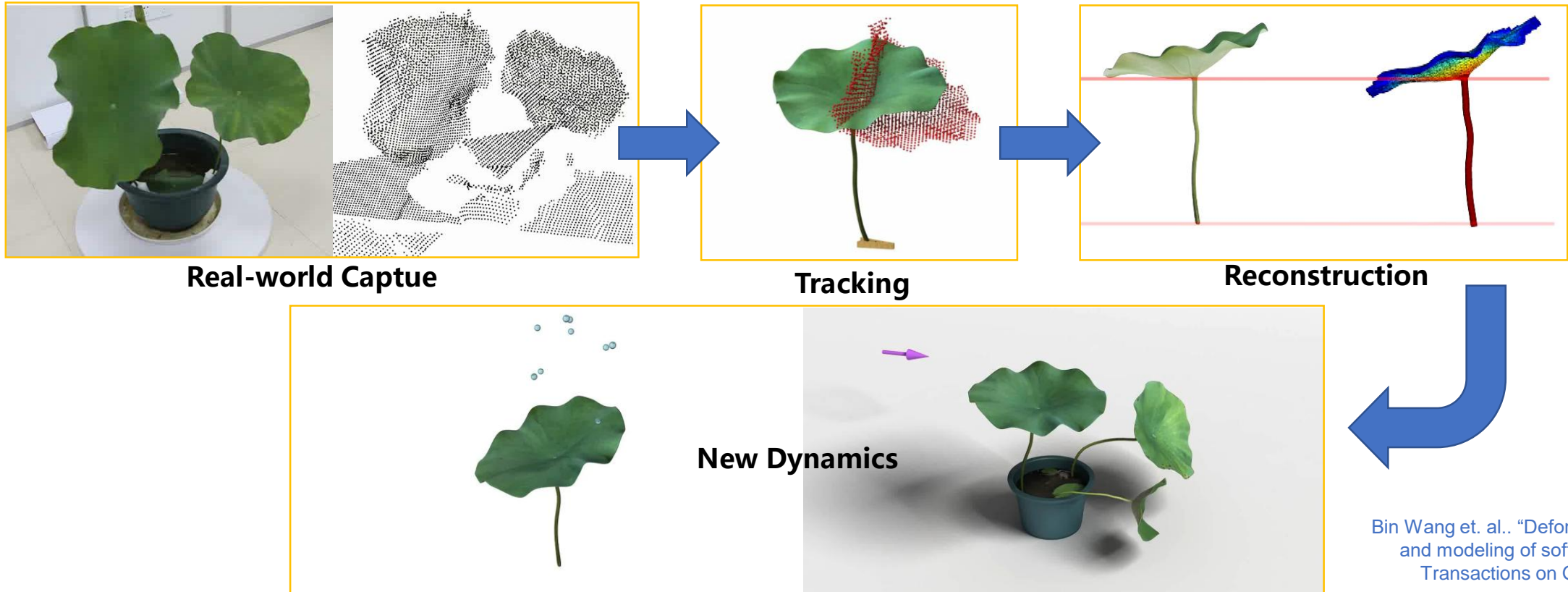


Inverse Physics Provides:

- **Understanding, Prediction & Control**
- **Training Supervision**



Inverse Physics for Understanding/Prediction/Control



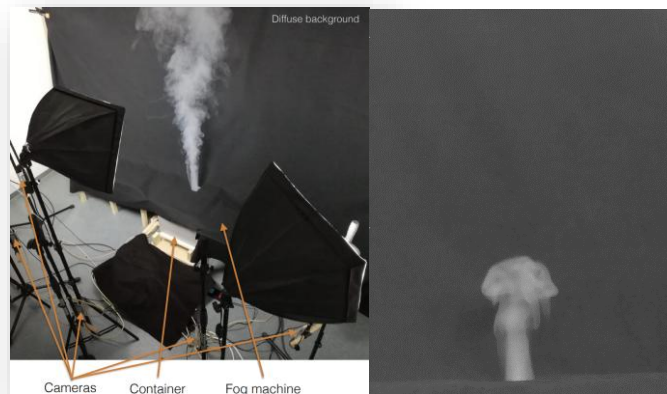
Bin Wang et. al.. "Deformation capture and modeling of soft objects", ACM Transactions on Graphics, 2015.



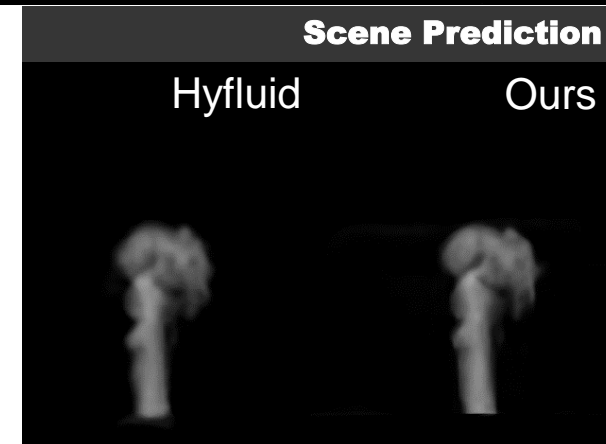
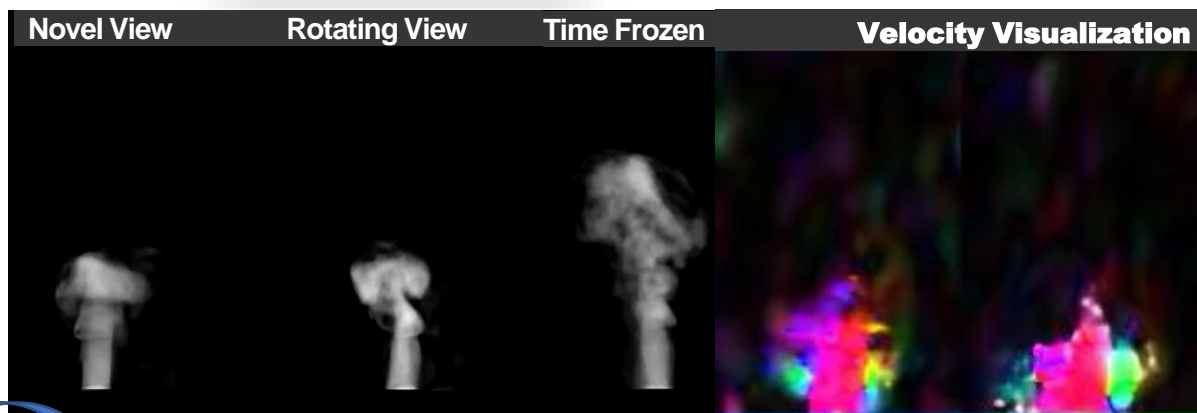
Inverse Physics for Understanding/Prediction/Control



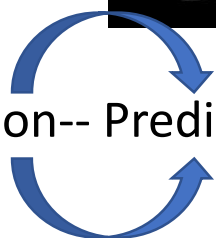
Real-Capture



Dynamic Reconstruction



- Reconstruction-- Prediction, A Closed Loop Enabled by Differentiable Physics



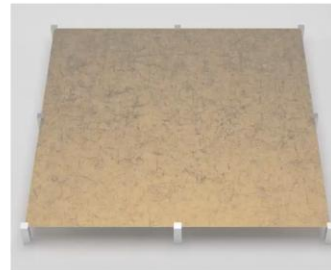
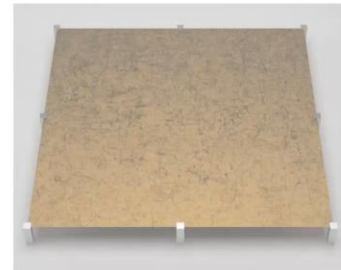
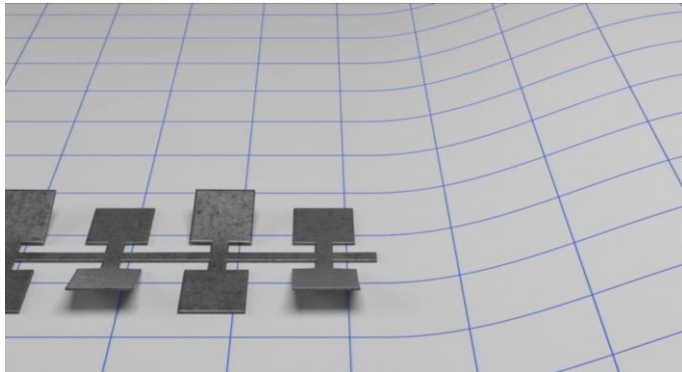
Mengyu Chu et al. "Physics Informed Neural Fields for Smoke Reconstruction with Sparse Data", ACM Transactions on Graphics, 2022
 Ningxiao Tao et al. "FlowCapX: Physics-Grounded Flow Capture with Long-Term Consistency", Under Review



Inverse Physics for Understanding/Prediction/Control



- **Differential Physics** allows gradient-based control of physics system



Letter 'A'

Letter 'S'

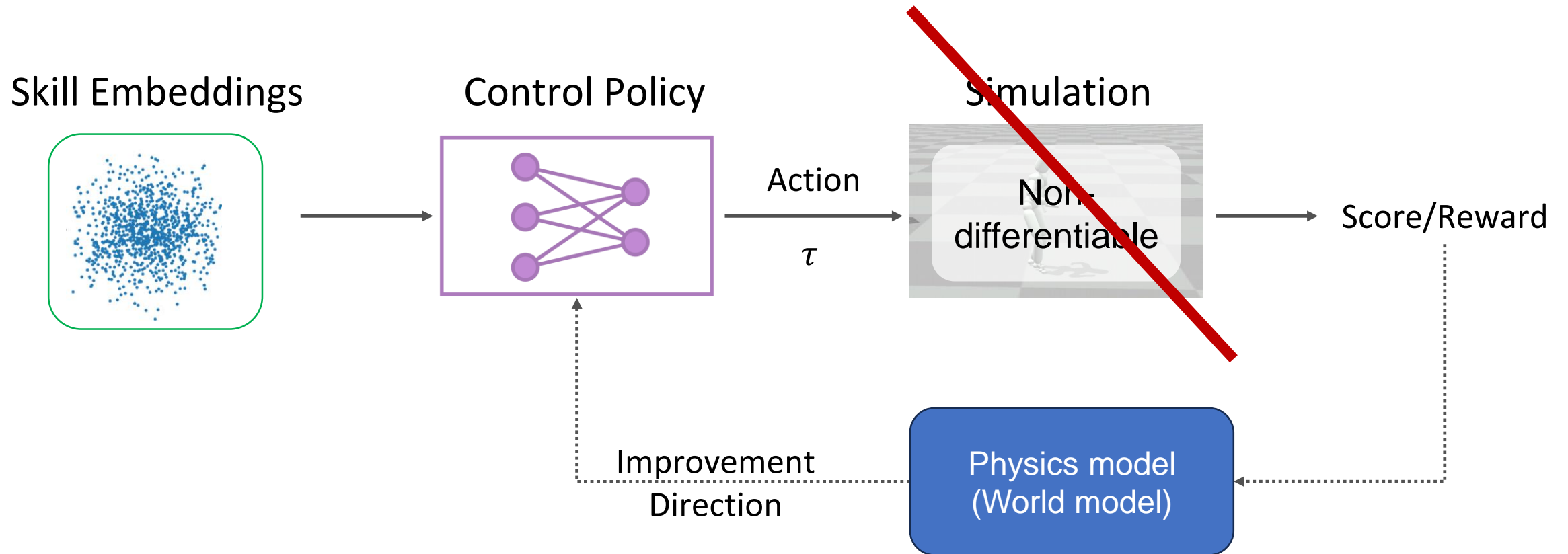


Xuwen Chen et. al.. "Simulation and optimization of magnetoelastic thin shells", ACM Transactions on Graphics, 2022.

Differential/Gradients for Training Supervision



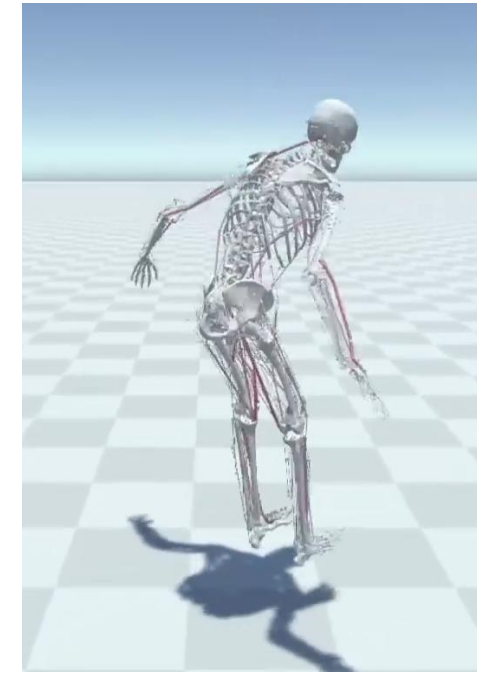
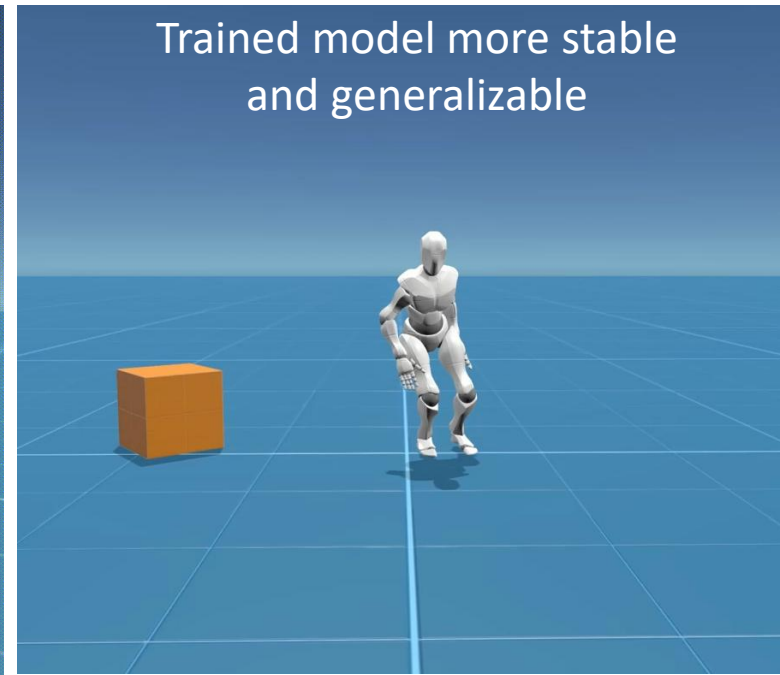
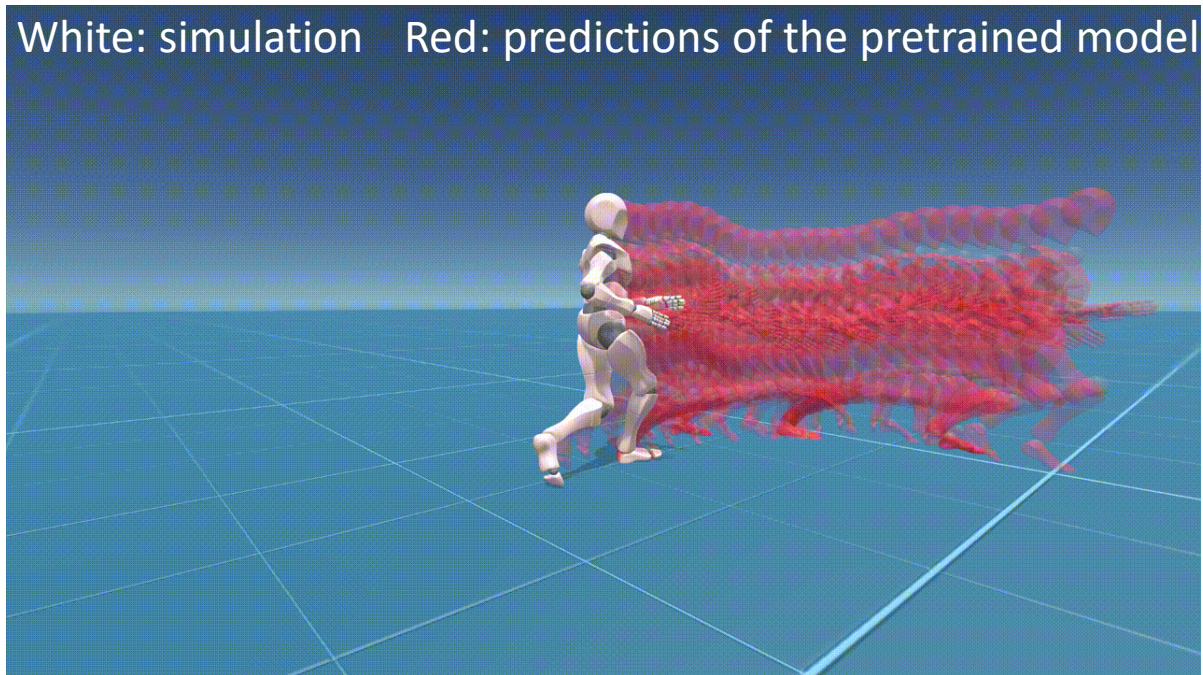
- Apply Simulation-Enhanced Gradients in Training:



Differential/Gradients for Training Supervision



- Apply Simulation-Enhanced Gradients in Training:
 - for e.g., train human motion using gradients of learned physics models:

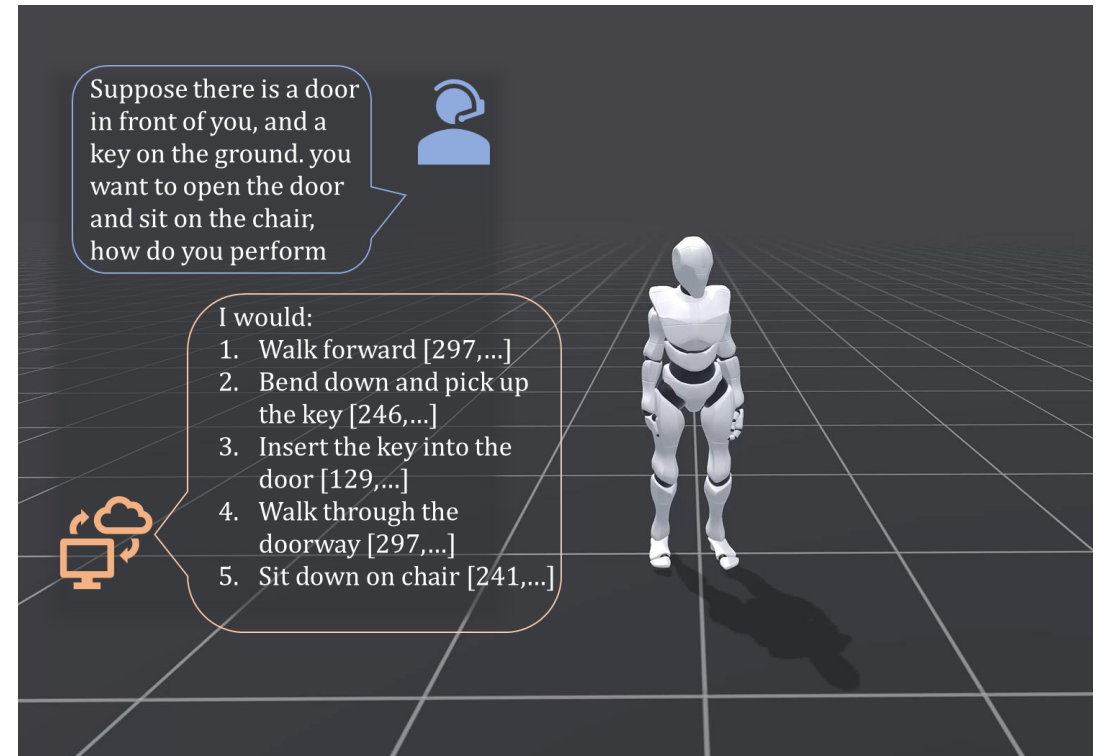
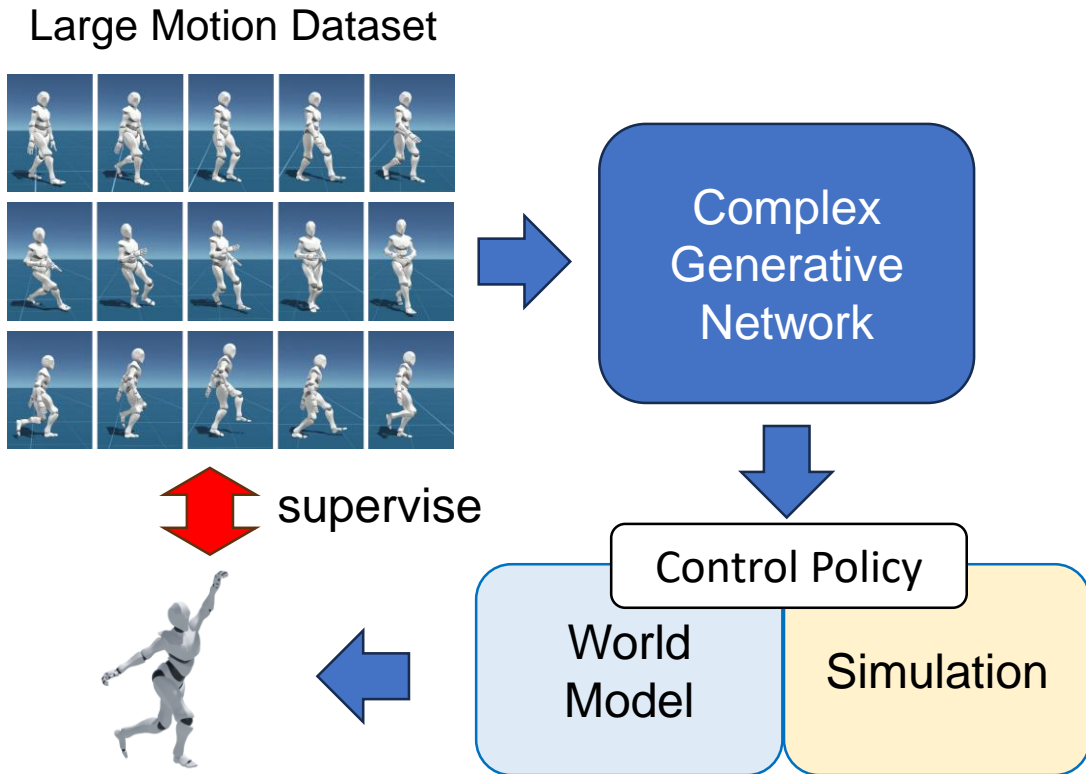


Heyuan Yao et al., “Control VAE: Model-Based Learning of Generative Controllers for Physics-Based Characters”. ACM Transactions on Graphics 2022
Yusen Feng et al., “MuscleVAE: Model-Based Controllers of Muscle-Actuated Characters”, ACM Transactions on Graphics 2023

Differential/Gradients for Training Supervision



- Apply Simulation-Enhanced Gradients in Training:
 - for e.g., enable training of large model using learned physics models:





Future Outlook



- 3D is becoming a commodity





Future Outlook



- Differential physics offers a path to spatial intelligence

将世界知识可微化，高效建模动态世界的结构和演化规律，嵌入数据驱动的大模型，为空间智能学习提供强有力的基础设施



可微仿真
Differential Physics



大模型
LLMs



空间智能
Spatial Intelligence



北京大學
PEKING UNIVERSITY

Thanks!

Spatial Intelligence Empowered by Physical Intelligence

Baoquan Chen

2025-04-12



VISUAL
COMPUTING AND
LEARNING