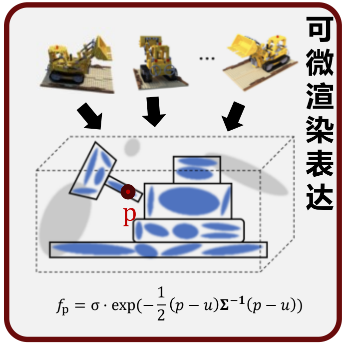
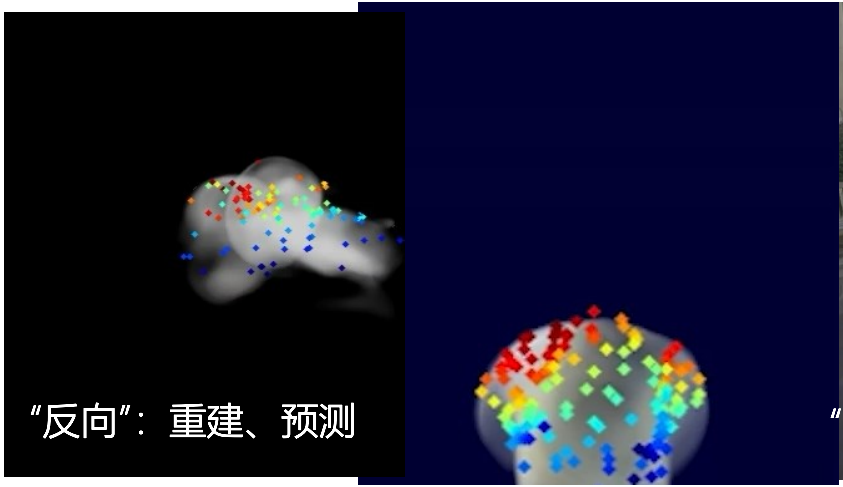


可微渲染表达

$f_p = \sigma \cdot \exp(-\frac{1}{2}(p-u)\Sigma^{-1}(p-u))$

3DGS and NeRF



“反向”：重建、预测

“前向”：仿真、编辑

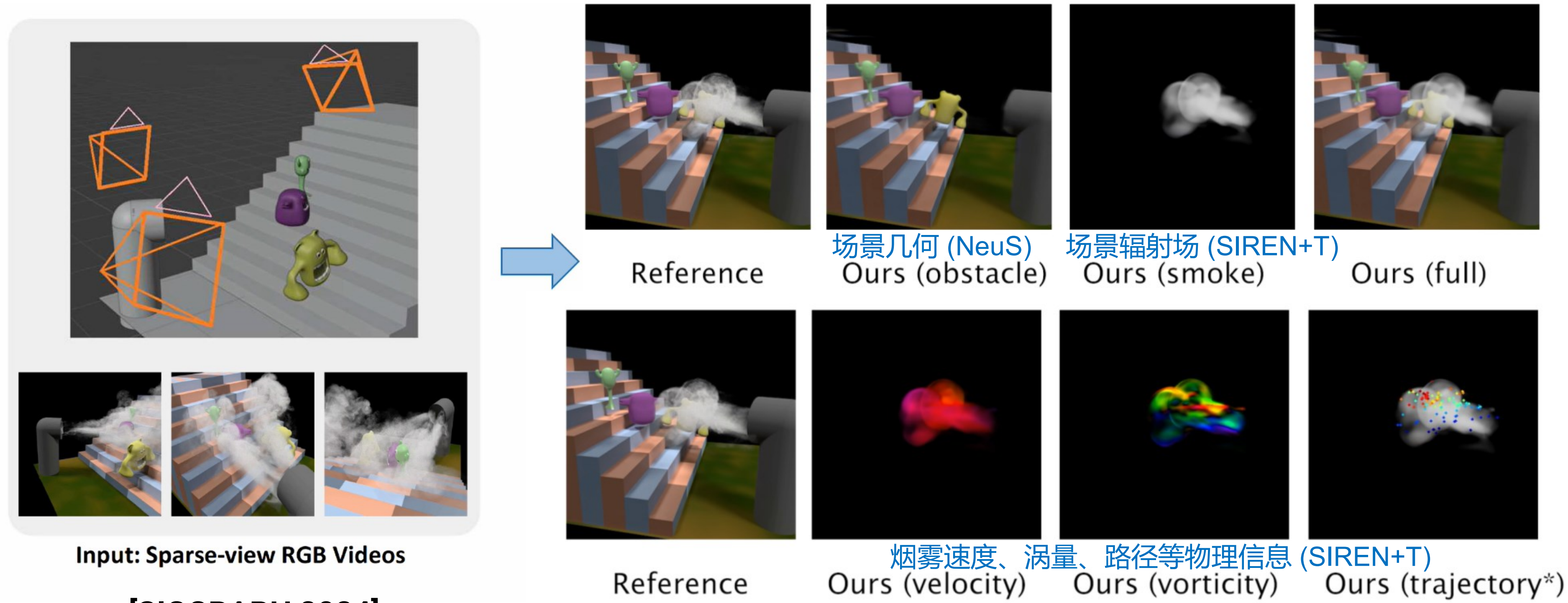
RainyGS

Physics Simulation on New Representations like **3DGS and NeRF**

基于新型表达的物理动态仿真及重建

北京大学 楚梦渝

准确动态重建：基于神经表达的路径场重建,优化物理约束



场景几何 (NeuS)

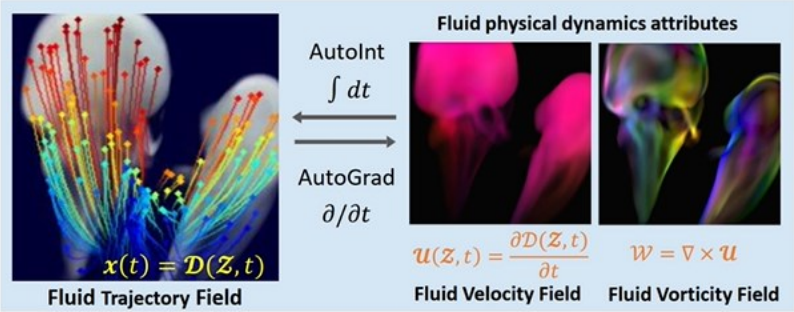
场景辐射场 (SIREN+T)

烟雾速度、涡量、路径等物理信息 (SIREN+T)

[SIGGRAPH 2024]

Yiming Wang, Siyu Tang, **Mengyu Chu**. “Physics-Informed Learning of Characteristic Trajectories for Smoke Reconstruction”, SIGGRAPH 2024

准确动态重建：基于神经表达的路径场重建,优化物理约束

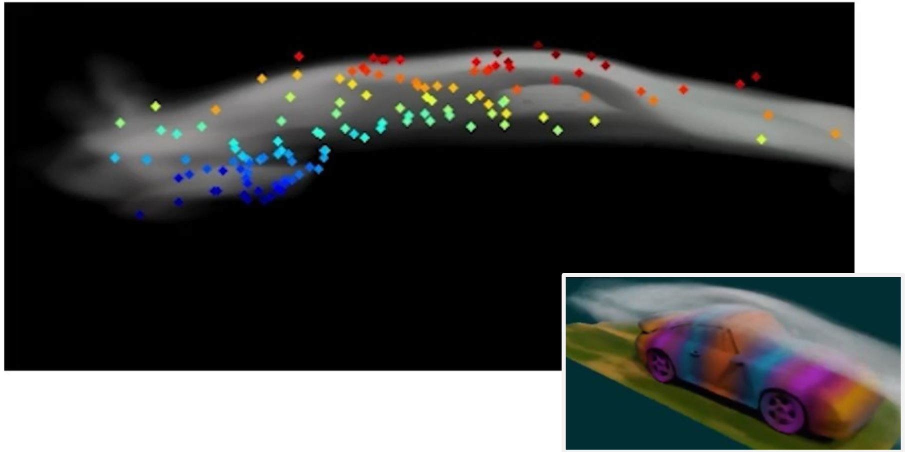


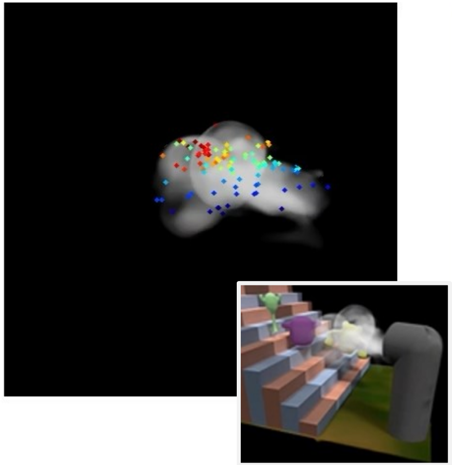
- 提出基于路径的表达：$\mathrm{x}(t) = D(z,t) = D(E(\mathrm{x},t),t)$
- 联合优化短时序的物理约束和长时序的守恒约束

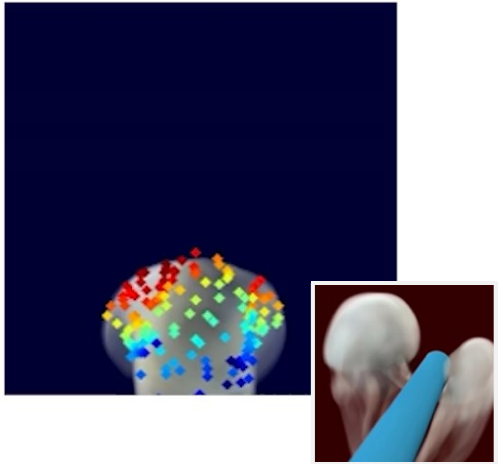
短程PDE约束：$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \nu \nabla \cdot \nabla \mathbf{u} + \mathbf{f}$ and $\nabla \cdot \mathbf{u} = 0$

长程守恒约束：$\mathbf{u}_a = (M_{a \to b})^T \mathbf{u}_b$ and $M_{a \to b} = \frac{\partial \mathcal{D}(\mathcal{E}(\mathbf{x}_a, t_a), t_b)}{\partial \mathbf{x}_a}$

- 重建物理准确的动态







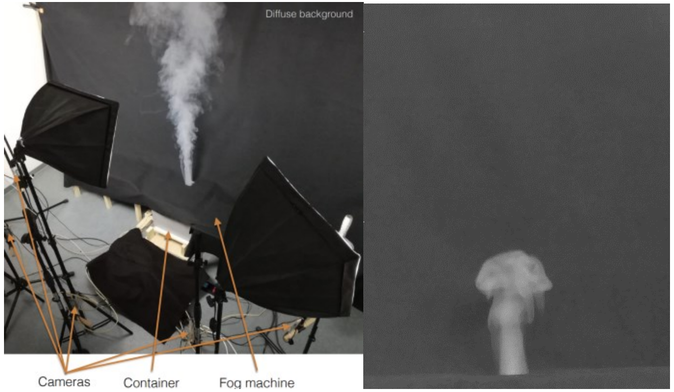
Yiming Wang, Siyu Tang, **Mengyu Chu**. “Physics-Informed Learning of Characteristic Trajectories for Smoke Reconstruction”, SIGGRAPH 2024

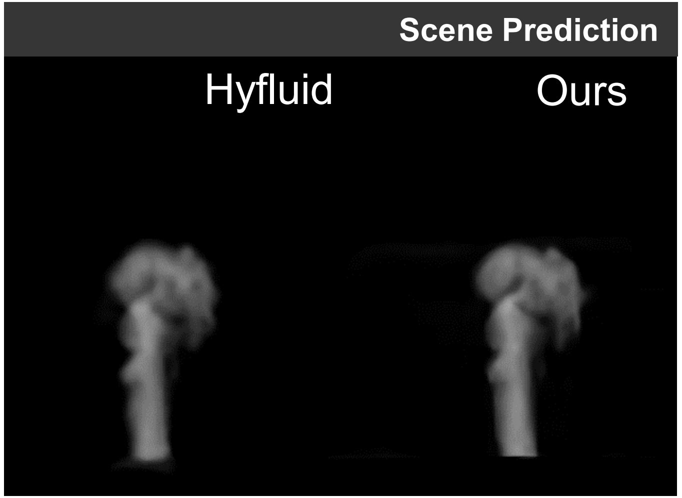
准确动态重建：支持动态重现和预测

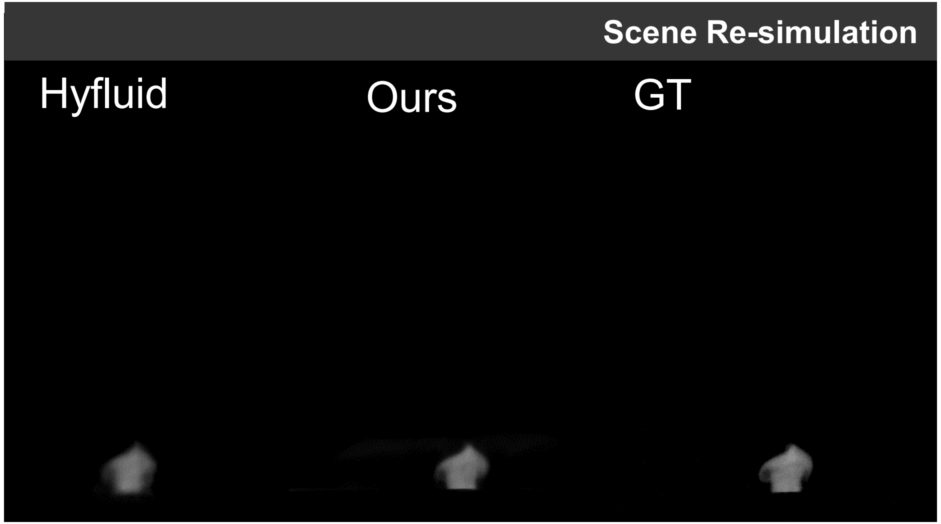
- 准确重建的物理信息，可以：
  - ✓ 复现场景运动

    使用重建的速度和第一帧数据，完整重现场景动态
  - ✓ 预测未来动态

    从任意时刻的重建开始仿真，预测未来时刻动态







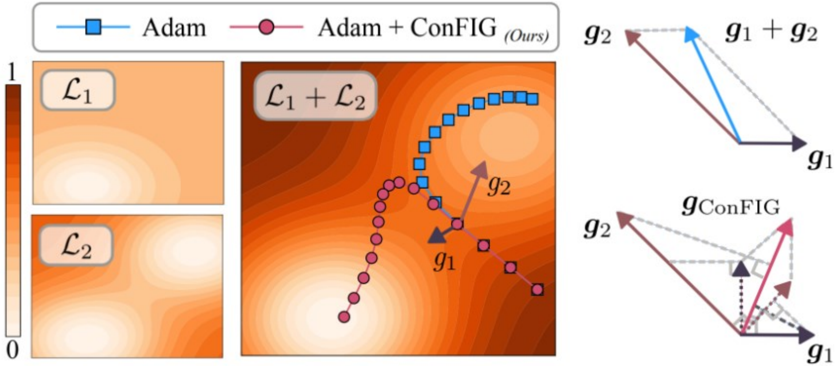
Ningxiao Tao et al. “FlowCapX: Physics-Grounded Flow Capture with Long-Term Consistency”, Under Review

高效优化物理：提出梯度投影策略，联合优化数据和物理约束

ConFIG

Conflict-Free Inverse Gradients

[ICLR2025 Spotlight]



- ○ 联合优化 数据 & 物理约束 是广泛存在的难题，典型例子：PINN常因梯度冲突难以高效收敛
- ○ ConFIG, 无冲突逆梯度方法(Conflict-Free Inverse Gradients), 具备特性:

$$\mathbf{g}_u = \mathcal{U}\left[[\mathcal{U}(\mathbf{g}_1),\mathcal{U}(\mathbf{g}_2),\cdots,\mathcal{U}(\mathbf{g}_m)]^{\underset{1}{\boxed{-\top}}}\ \underset{2}{\boxed{\mathbf{1}_m}}\right],$$

$$\mathbf{g}_{\text{ConFIG}} = \mathcal{G}(\mathbf{g}_1,\mathbf{g}_2,\cdots,\mathbf{g}_m) := \underset{3}{\boxed{\left(\sum_{i=1}^{m} \mathbf{g}_i^\top \mathbf{g}_u\right)}}\ \mathbf{g}_u.$$

① 最终更新梯度 $\mathbf{g}_{\text{ConFIG}}$ 与所有损失项的优化梯度**均不冲突。**

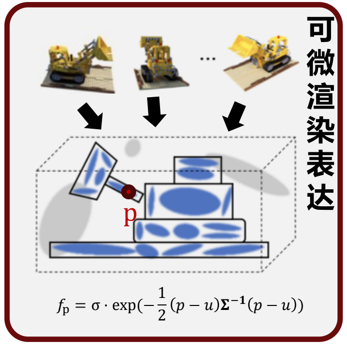
② 每个特定损失的梯度投影均匀，确保所有损失项以**相同速率优化。**

③ $\mathbf{g}_{\text{ConFIG}}$ 步长可以根据损失项之间的冲突程度**自适应**调整。

④ ConFIG 还介绍了更高效的**基于动量的优化**模式。

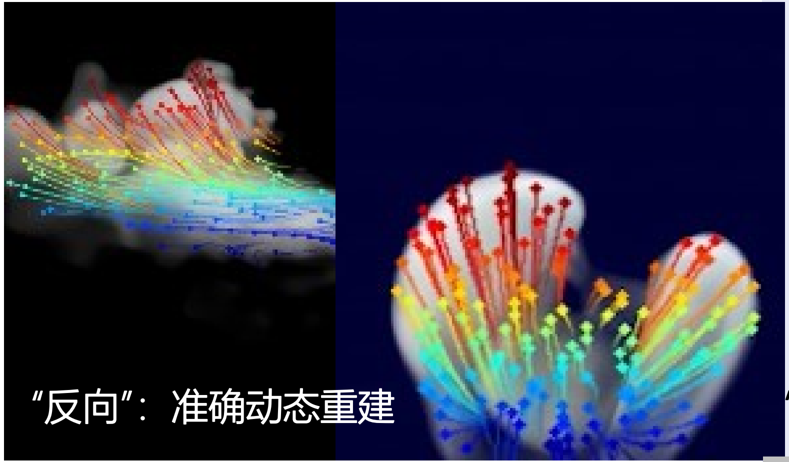
Qiang Liu, **Mengyu Chu,** Nils Thuerey. “ConFIG: Towards Conflict-free Training for Physics Informed Neural Networks”, ICLR 2025

基于新型表达的物理动态仿真及重建



$f_p = \sigma \cdot \exp(-\frac{1}{2}(p-u)\mathbf{\Sigma}^{-1}(p-u))$

3DGS and NeRF



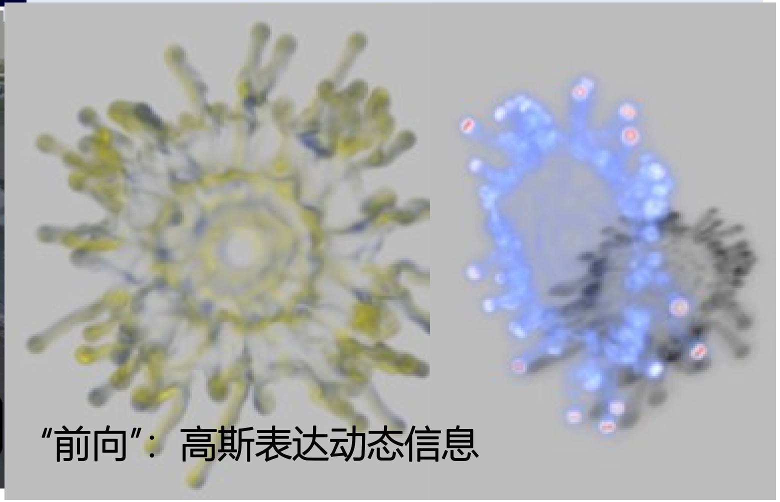
“反向”：准确动态重建

$$\mathbf{g}_u = \mathcal{U}\left[[\mathcal{U}(\mathbf{g}_1),\mathcal{U}(\mathbf{g}_2),\cdots,\mathcal{U}(\mathbf{g}_m)]^{\underset{①}{\boxed{-\top}}}\underset{②}{\boxed{\mathbf{1}_m}}\right],$$

$$\mathbf{g}_{\mathrm{ConFIG}} = \mathcal{G}(\mathbf{g}_1,\mathbf{g}_2,\cdots,\mathbf{g}_m) := \underset{③}{\boxed{\left(\sum_{i=1}^{m}\mathbf{g}_i^{\top}\mathbf{g}_u\right)}}\,\mathbf{g}_u.$$

“反向”：高效优化物理

“前向”：高斯表达几何信息

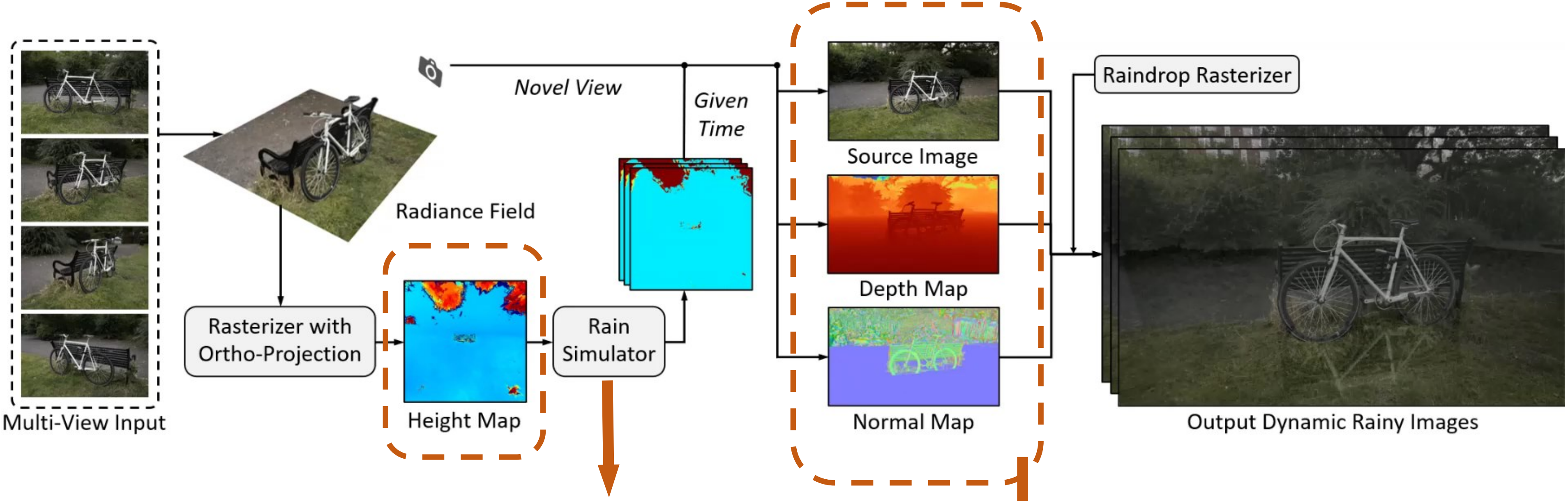


“前向”：高斯表达动态信息

高效动态仿真：RainyGS 孪生场景的实时降雨呈现

Multi-View Input

高效动态仿真：RainyGS 孪生场景的实时降雨呈现



Shallow Water Equations

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

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

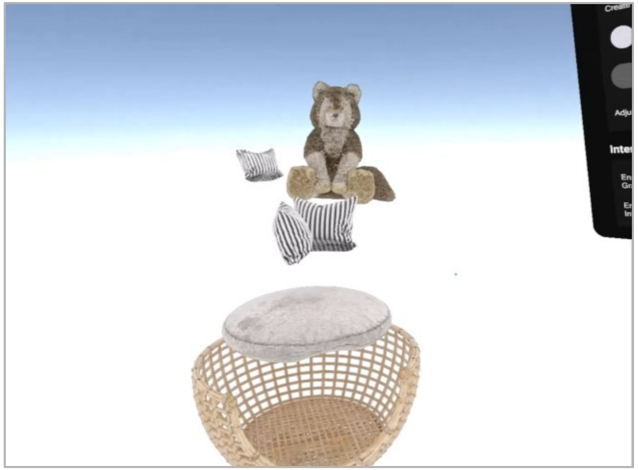
Image-Based Rendering

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

高效动态仿真：RainyGS 孪生场景的实时降雨呈现

高效动态仿真：RainyGS 孪生场景的实时降雨呈现

高效动态仿真：孪生物体的实时造型设计



Luo, Z., Cui, Z., Luo, S., **Chu, M.**, & Li, M. (2025). VR-Doh: Hands-on 3D Modeling in Virtual Reality. Under Review

Gaussian Fluids: 以高斯场表达动态信息，求解物理方程

We present a grid-free fluid solver featuring a novel Gaussian representation.

- 精度具备自适应的特性
- 更好的保持流体细节、流体涡量

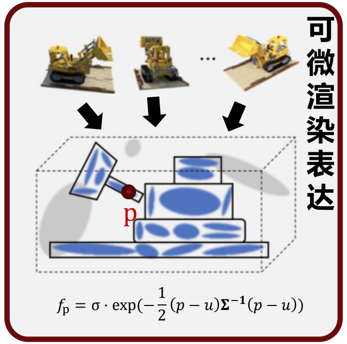
Xing, J., Wang, B., Chu, M., & Chen, B. (2025). Gaussian Fluids: A Grid-Free Fluid Solver based on Gaussian Spatial Representation. Under Review

Gaussian Fluids: 以高斯场表达动态信息，求解物理方程

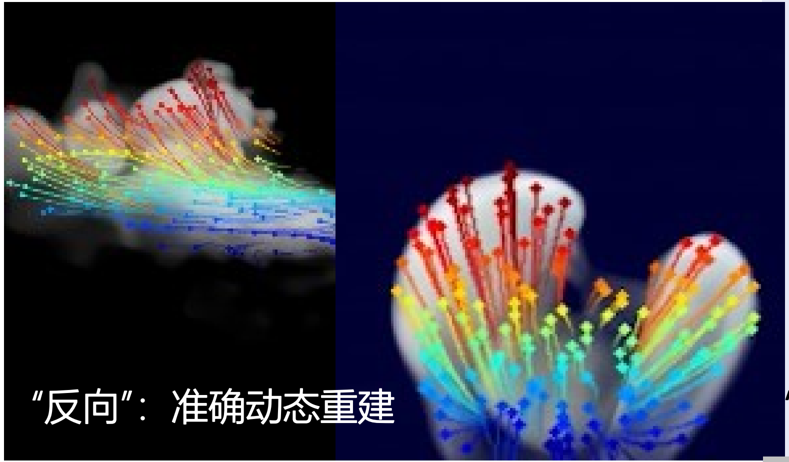
3D Leapfrog

Xing, J., Wang, B., Chu, M., & Chen, B. (2025). Gaussian Fluids: A Grid-Free Fluid Solver based on Gaussian Spatial Representation. Under Review

总结：基于新型表达，统一前向方向仿真，统一几何动态表达



3DGS and NeRF



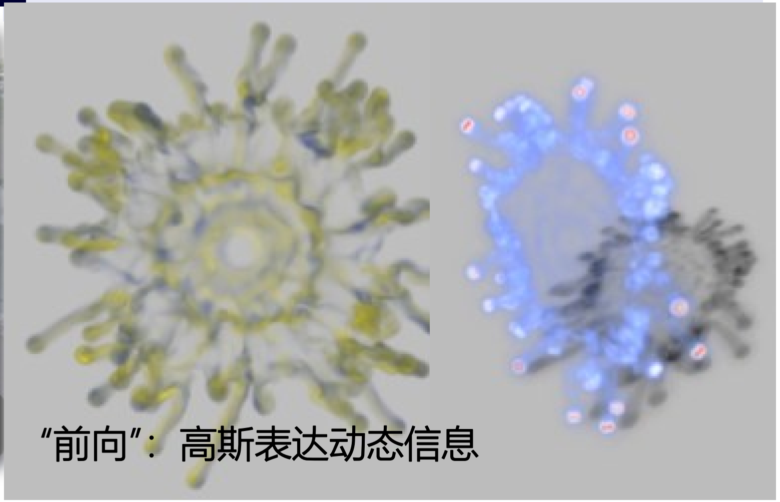
“反向”：准确动态重建

$$\mathbf{g}_u = \mathcal{U}\left[[\mathcal{U}(\mathbf{g}_1),\mathcal{U}(\mathbf{g}_2),\cdots,\mathcal{U}(\mathbf{g}_m)]^{\underset{\textcircled{1}}{\boxed{-\top}}}\underset{\textcircled{2}}{\boxed{\mathbf{1}_m}}\right],$$

$$\mathbf{g}_{\mathrm{ConFIG}} = \mathcal{G}(\mathbf{g}_1,\mathbf{g}_2,\cdots,\mathbf{g}_m) := \underset{\textcircled{3}}{\boxed{\left(\sum_{i=1}^{m}\mathbf{g}_i^\top\mathbf{g}_u\right)}}\mathbf{g}_u.$$

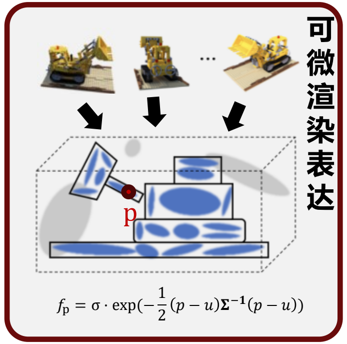
“反向”：高效优化物理

“前向”：高斯表达几何信息



“前向”：高斯表达动态信息

总结：基于新型表达，统一前向方向仿真，统一几何动态表达



3DGS and NeRF

新型表达:

- 统一前向、反向仿真任务
- 统一渲染、几何、和仿真
- 统一虚拟和现实，支持编辑交互

应用：

- 支撑真实世界仿真环境的构建
- 更紧密结合图象、语言信息，与大模型技术接轨
- 支撑具身智能、空间智能训练

Thanks

楚梦渝

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http://rachelcmy.github.io/