Learning general-purpose CNN-based simulators for astrophysical turbulence

Alvaro Sanchez–Gonzalez, Kimberly Stachenfeld, Drummond Fielding, Dmitrii Kochkov, Miles Cranmer, Tobias Pfaff, Jonathan Godwin, Can Cui, Shirley Ho, Peter Battaglia

Introduction

- Turbulence simulation is important to understanding astrophysical phenomena like galaxy formation.
- Numerical solvers (like Athena++) are computationally expensive at high resolution, and very inaccurate at low resolution.
- **Question:** To what extent can learned models supplement or replace traditional simulators for astrophysics?

**Highlights:**

- Domain-general, fully-learned convolutional models for simulation
- Same architecture can learn to predict different types of turbulence
- Comparisons to coarsened numerical solvers in terms of spatial and temporal resolution, numerical stability, and generalization performance

Model

We train a general-purpose model to learn the transition function between pairs of states for 1D, 2D, or 3D grids. At test time, we apply the model multiple times from an initial state.

Datasets and domain generality

- **1D Kuramoto-Sivashinsky (KS) Equation**
  - Chaotic, unstable, nonlinear dynamics
- **2D Incompressible Turbulence**
  - Relevant to planet, star, black hole, and galaxy formation
- **3D Uniform Compressible Decaying Turbulence**
- **3D Mixing Layer Turbulence with Radiative Cooling**

Models trained without noise can be unstable

Using training noise helps fixing stability

Stability

The learned model can operate at coarser discretizations of the problem more effectively than the ground truth solver

**Spatial coarsening**

**Constraint preservation**

Training without noise does not preserve constraints

Training with noise helps... sometimes.

**Generalization to different states**

Generalization to longer trajectories:

Does not generalize to more developed turbulence

Generalization to different initial conditions:

Generalizes to higher solenoidal components

Fails to generalize to higher compressive components

**Generalization to larger boxes**

The model requires training on multiple box sizes to be able to produce plausible predictions for larger box sizes

**Running time**

- Athena++
  - Scalable (resolution\(^n\))
  - CPU only
- Learned model:
  - Up to 1000x faster than Athena at 128

**Datasets and domain generality**

- **1D Kuramoto-Sivashinsky (KS) Equation**
  - Chaotic, unstable, nonlinear dynamics
- **2D Incompressible Turbulence**
  - Relevant to planet, star, black hole, and galaxy formation
- **3D Uniform Compressible Decaying Turbulence**
- **3D Mixing Layer Turbulence with Radiative Cooling**

**Models trained without noise** can be unstable

Using training noise helps fixing stability

**Temporal coarsening**

Unlike the ground truth solver, the learned model is not very sensitive to the specific integration timestep, and can operate well on many timesteps

**Running time**

- Athena++
  - Scalable (resolution\(^n\))
  - CPU only
- Learned model:
  - Up to 1000x faster than Athena at 128

**Datasets and domain generality**

- **1D Kuramoto-Sivashinsky (KS) Equation**
  - Chaotic, unstable, nonlinear dynamics
- **2D Incompressible Turbulence**
  - Relevant to planet, star, black hole, and galaxy formation
- **3D Uniform Compressible Decaying Turbulence**
- **3D Mixing Layer Turbulence with Radiative Cooling**

**Models trained without noise** can be unstable

Using training noise helps fixing stability

**Temporal coarsening**

Unlike the ground truth solver, the learned model is not very sensitive to the specific integration timestep, and can operate well on many timesteps

**Running time**

- Athena++
  - Scalable (resolution\(^n\))
  - CPU only
- Learned model:
  - Up to 1000x faster than Athena at 128

**Datasets and domain generality**

- **1D Kuramoto-Sivashinsky (KS) Equation**
  - Chaotic, unstable, nonlinear dynamics
- **2D Incompressible Turbulence**
  - Relevant to planet, star, black hole, and galaxy formation
- **3D Uniform Compressible Decaying Turbulence**
- **3D Mixing Layer Turbulence with Radiative Cooling**

**Models trained without noise** can be unstable

Using training noise helps fixing stability

**Temporal coarsening**

Unlike the ground truth solver, the learned model is not very sensitive to the specific integration timestep, and can operate well on many timesteps

**Running time**

- Athena++
  - Scalable (resolution\(^n\))
  - CPU only
- Learned model:
  - Up to 1000x faster than Athena at 128

**Datasets and domain generality**

- **1D Kuramoto-Sivashinsky (KS) Equation**
  - Chaotic, unstable, nonlinear dynamics
- **2D Incompressible Turbulence**
  - Relevant to planet, star, black hole, and galaxy formation
- **3D Uniform Compressible Decaying Turbulence**
- **3D Mixing Layer Turbulence with Radiative Cooling**

**Models trained without noise** can be unstable

Using training noise helps fixing stability

**Temporal coarsening**

Unlike the ground truth solver, the learned model is not very sensitive to the specific integration timestep, and can operate well on many timesteps

**Running time**

- Athena++
  - Scalable (resolution\(^n\))
  - CPU only
- Learned model:
  - Up to 1000x faster than Athena at 128

**Datasets and domain generality**

- **1D Kuramoto-Sivashinsky (KS) Equation**
  - Chaotic, unstable, nonlinear dynamics
- **2D Incompressible Turbulence**
  - Relevant to planet, star, black hole, and galaxy formation
- **3D Uniform Compressible Decaying Turbulence**
- **3D Mixing Layer Turbulence with Radiative Cooling**

**Models trained without noise** can be unstable

Using training noise helps fixing stability

**Temporal coarsening**

Unlike the ground truth solver, the learned model is not very sensitive to the specific integration timestep, and can operate well on many timesteps

**Running time**

- Athena++
  - Scalable (resolution\(^n\))
  - CPU only
- Learned model:
  - Up to 1000x faster than Athena at 128

**Datasets and domain generality**

- **1D Kuramoto-Sivashinsky (KS) Equation**
  - Chaotic, unstable, nonlinear dynamics
- **2D Incompressible Turbulence**
  - Relevant to planet, star, black hole, and galaxy formation
- **3D Uniform Compressible Decaying Turbulence**
- **3D Mixing Layer Turbulence with Radiative Cooling**

**Models trained without noise** can be unstable

Using training noise helps fixing stability

**Temporal coarsening**

Unlike the ground truth solver, the learned model is not very sensitive to the specific integration timestep, and can operate well on many timesteps

**Running time**

- Athena++
  - Scalable (resolution\(^n\))
  - CPU only
- Learned model:
  - Up to 1000x faster than Athena at 128

**Datasets and domain generality**

- **1D Kuramoto-Sivashinsky (KS) Equation**
  - Chaotic, unstable, nonlinear dynamics
- **2D Incompressible Turbulence**
  - Relevant to planet, star, black hole, and galaxy formation
- **3D Uniform Compressible Decaying Turbulence**
- **3D Mixing Layer Turbulence with Radiative Cooling**

**Models trained without noise** can be unstable

Using training noise helps fixing stability

**Temporal coarsening**

Unlike the ground truth solver, the learned model is not very sensitive to the specific integration timestep, and can operate well on many timesteps

**Running time**

- Athena++
  - Scalable (resolution\(^n\))
  - CPU only
- Learned model:
  - Up to 1000x faster than Athena at 128

**Datasets and domain generality**

- **1D Kuramoto-Sivashinsky (KS) Equation**
  - Chaotic, unstable, nonlinear dynamics
- **2D Incompressible Turbulence**
  - Relevant to planet, star, black hole, and galaxy formation
- **3D Uniform Compressible Decaying Turbulence**
- **3D Mixing Layer Turbulence with Radiative Cooling**

**Models trained without noise** can be unstable

Using training noise helps fixing stability

**Temporal coarsening**

Unlike the ground truth solver, the learned model is not very sensitive to the specific integration timestep, and can operate well on many timesteps

**Running time**

- Athena++
  - Scalable (resolution\(^n\))
  - CPU only
- Learned model:
  - Up to 1000x faster than Athena at 128

**Datasets and domain generality**

- **1D Kuramoto-Sivashinsky (KS) Equation**
  - Chaotic, unstable, nonlinear dynamics
- **2D Incompressible Turbulence**
  - Relevant to planet, star, black hole, and galaxy formation
- **3D Uniform Compressible Decaying Turbulence**
- **3D Mixing Layer Turbulence with Radiative Cooling**

**Models trained without noise** can be unstable

Using training noise helps fixing stability

**Temporal coarsening**

Unlike the ground truth solver, the learned model is not very sensitive to the specific integration timestep, and can operate well on many timesteps

**Running time**

- Athena++
  - Scalable (resolution\(^n\))
  - CPU only
- Learned model:
  - Up to 1000x faster than Athena at 128