framing fluid flows — a perspective on fluid mechanical environments for challenges in reinforcement learning

Shruti Mishra[1] Michael Chang[2] Vamsi Spandan[1] Shmuel M. Rubinstein[3]

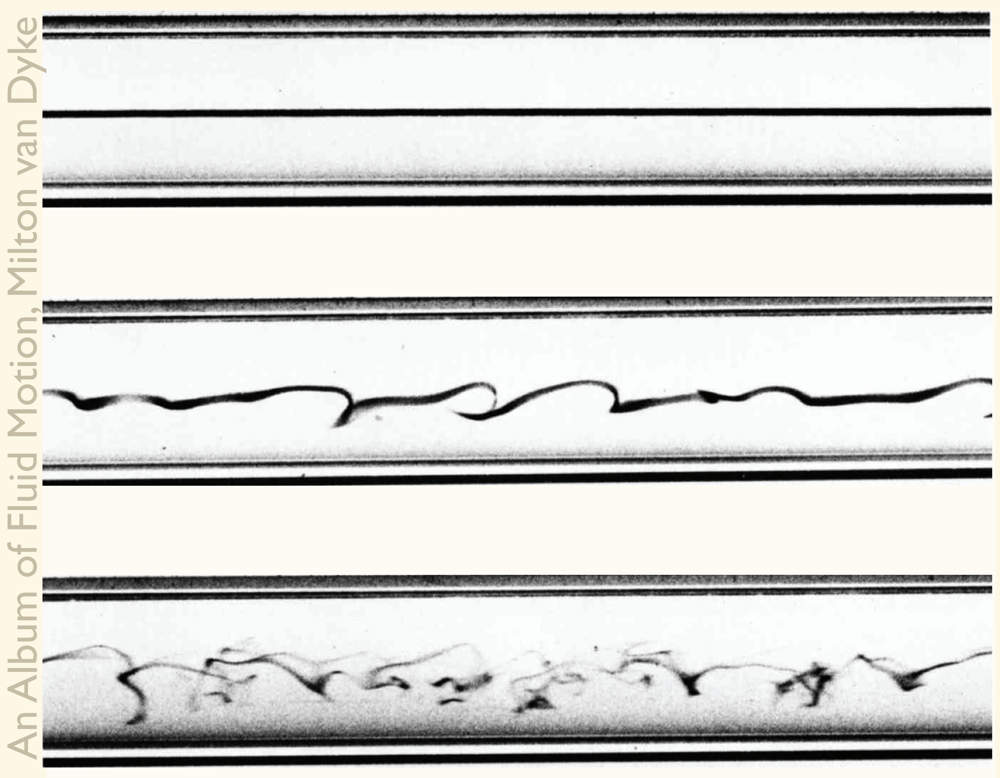
[1]Sony AI [2]Cohere Labs Community [3]Hebrew University of Jerusalem

Challenges in reinforcement learning and features of fluid mechanical environments

- Interacting with large environments: Examples include ocean waves and aircraft contrails.
- Learning efficiently from limited samples: Fluid flows have condensed descriptions through conservation equations.
- Interacting with high-dimensional environments: Fluid flows are high-dimensional, with continuously varying quantities.

Framing a pipe flow

- As the speed of fluid flowing through a pipe increases, flow patterns change from smooth to chaotic.



An Album of Fluid Motion, Milton van Dyke

Snapshots of dark colored dye in a pipe flow: As the flow velocity increases from top to bottom, small disturbances to the background flow evolve into increasingly unpredictable chaotic patterns, while the governing equations remain preserved.

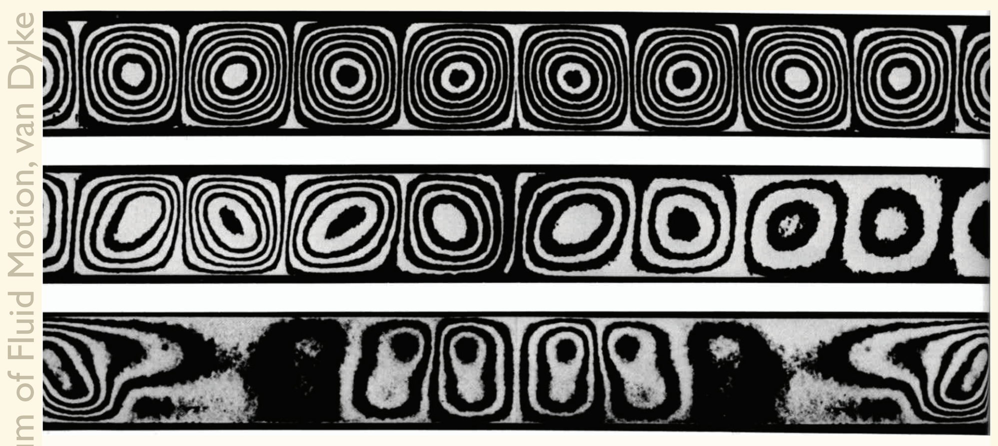
- Across the smooth and chaotic regimes, the flow is described by a mathematical model, the Navier–Stokes equations, $\boldsymbol{\nabla} \cdot \boldsymbol{u} = 0$, and

$$\boldsymbol{u}_t + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\,\boldsymbol{u} = -{}^{\nabla p}/_{\rho} + \nu \nabla^2 \boldsymbol{u}\,.$$

Disturb the dye: An agent might be tasked with creating a disturbance that grows the most within a particular time window. The choice of such a disturbance is non-trivial. The agent is thus trying to create a highly nonstationary environment, while mathematical descriptions remain preserved.

Navigating an evolving cellular flow

- Natural and engineering flows can have cellular flow structures that evolve spatially and temporally.



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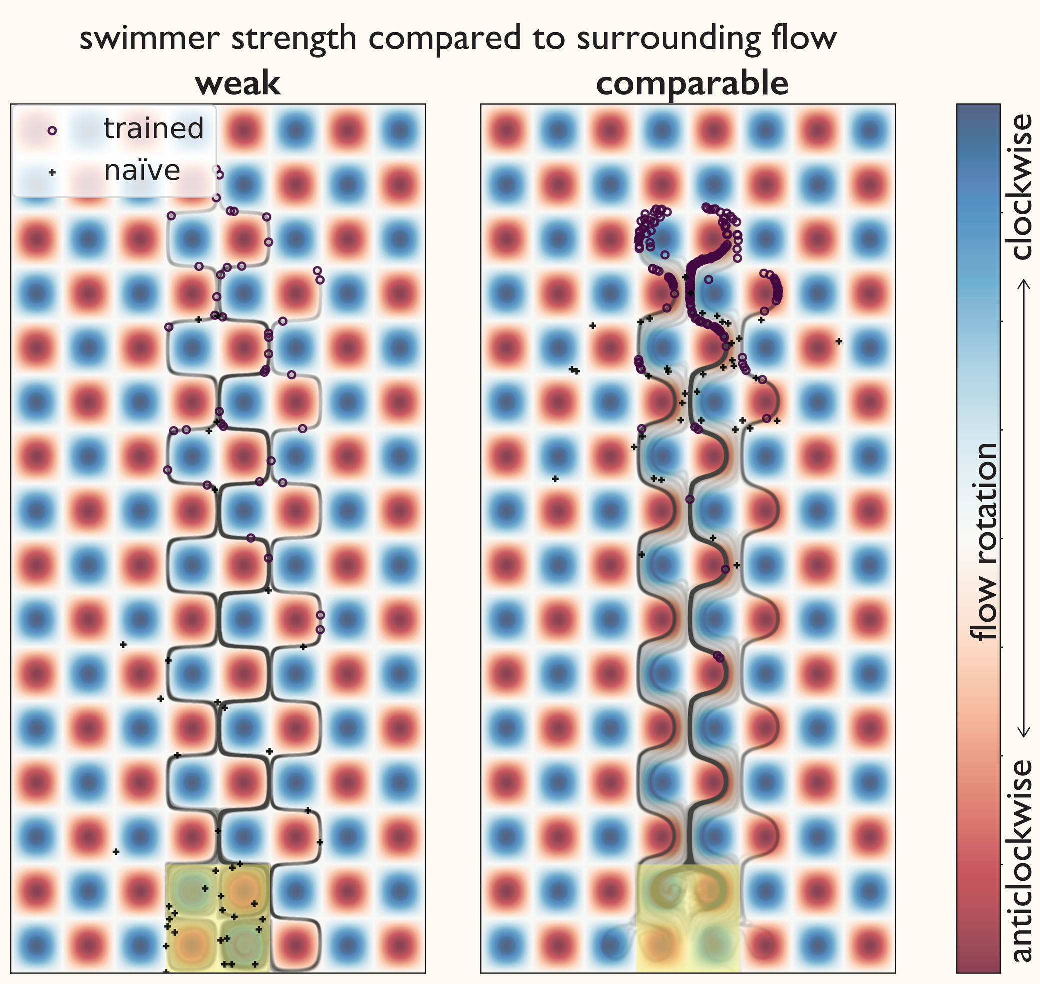
Snapshots of cellular flow structures: A flow evolves into convection rolls under the influence of spatial temperature gradients.

- As the flow structures change, optimal navigation strategies also change.



Swimmers move through a cellular flow: As the swimmers become stronger from the left panel to the right panel, the learned strategy for moving upwards from the initial location, in the yellow square, changes. The naïve swimmers always orient upwards. Markers indicate the final locations of the swimmers. Flow simulators such as Dedalus and JAX-CFD have been used in supervised learning problems, and may analogously be considered for reinforcement learning.

Open problems

- How do fluids mix?
- How does a liquid jet break up into drops?
- How can we simulate elastic turbulence?
- How can we navigate oceans with evolving conditions and rogue waves?