DiffCloth: Differentiable Cloth Simulation with Dry Frictional Contact

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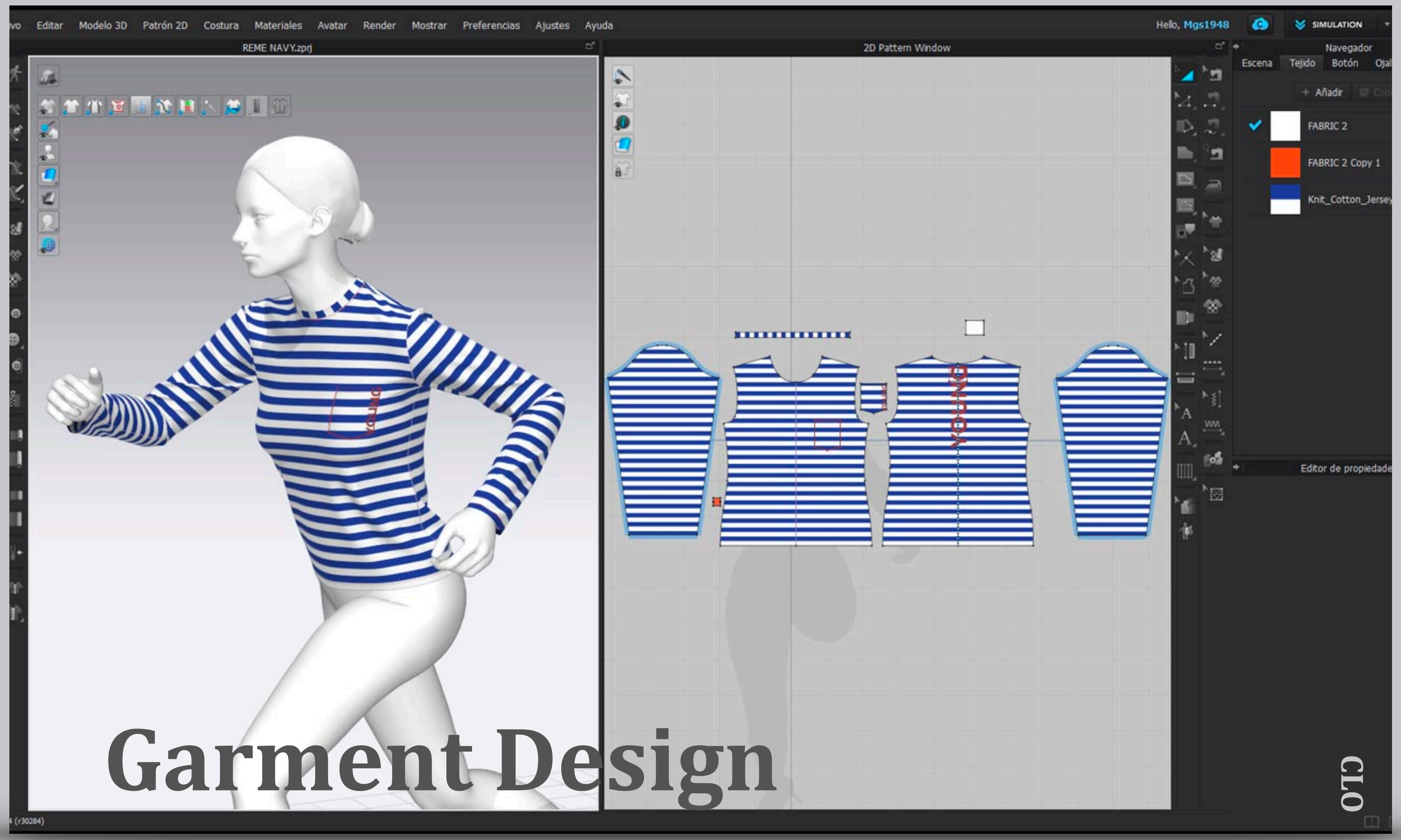
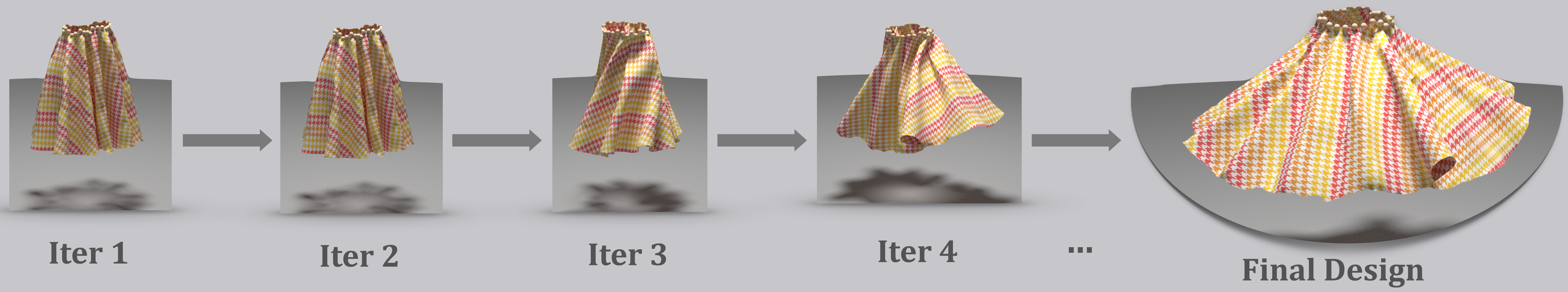
Cloth simulation has wide applications…



Slow & Tedious Manual Workflow



Differentiable Cloth Simulation

Goal: Optimize θ (e.g. cloth material) to perform a task (e.g. garment design)

Dress Design

Differentiable Cloth Simulation

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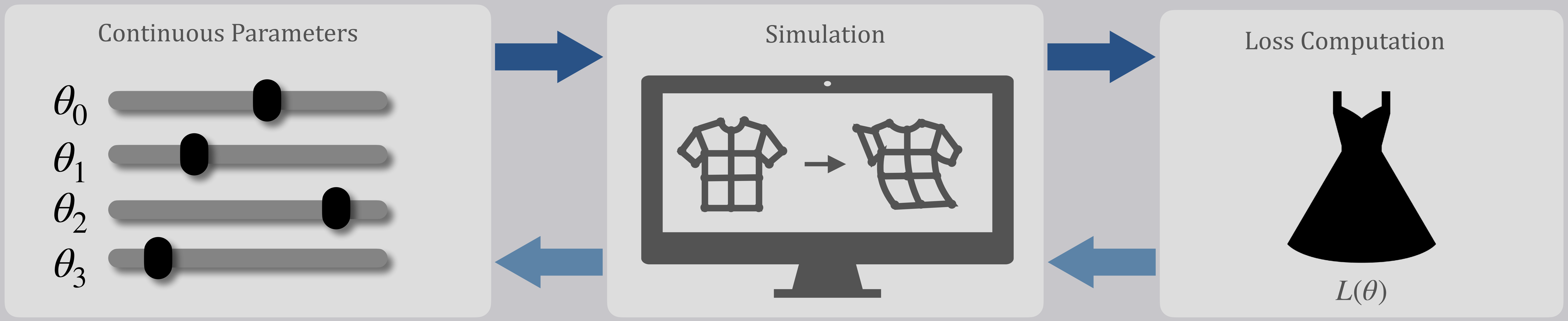
Dress Design

1 **Forward Simulation through time to obtain $L(\theta)$**

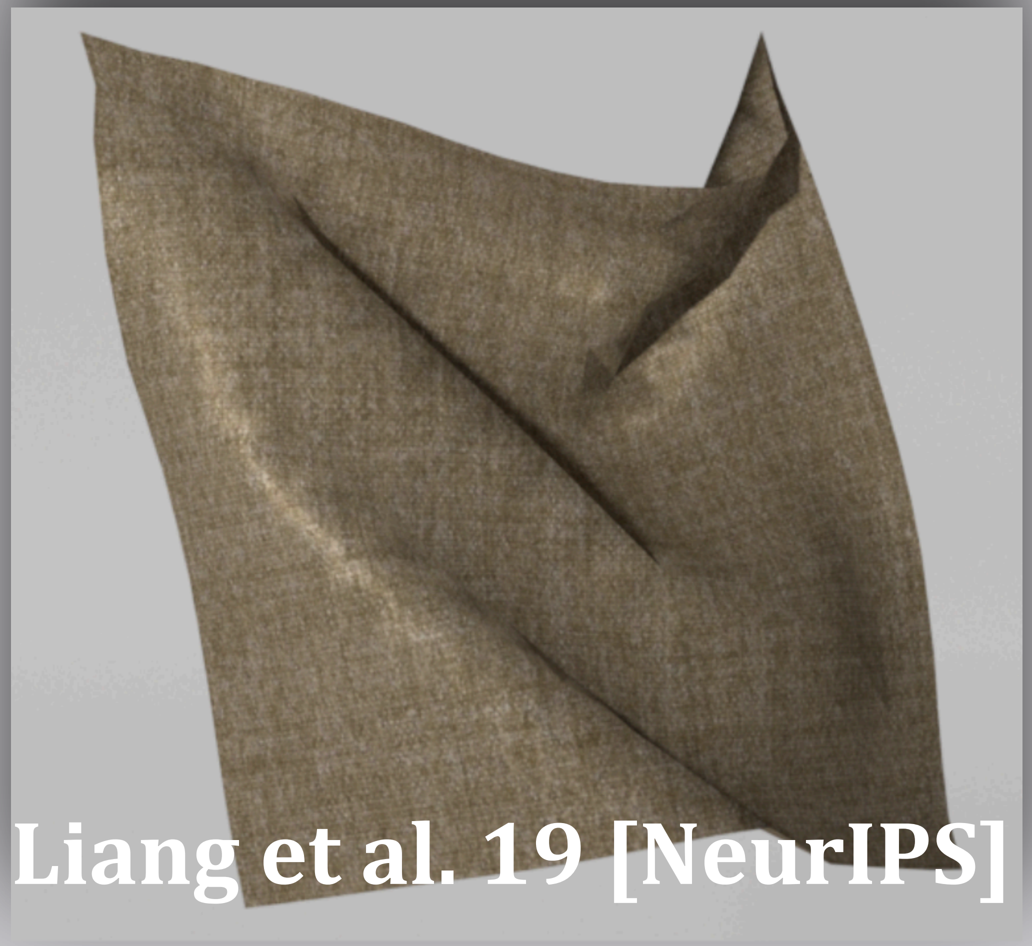


2 **Gradient Back Propagation $\frac{\partial L}{\partial \theta} \leftarrow L$ to obtain $\frac{\partial L}{\partial \theta}$**

3 **Use gradient-based optimizer to update θ**

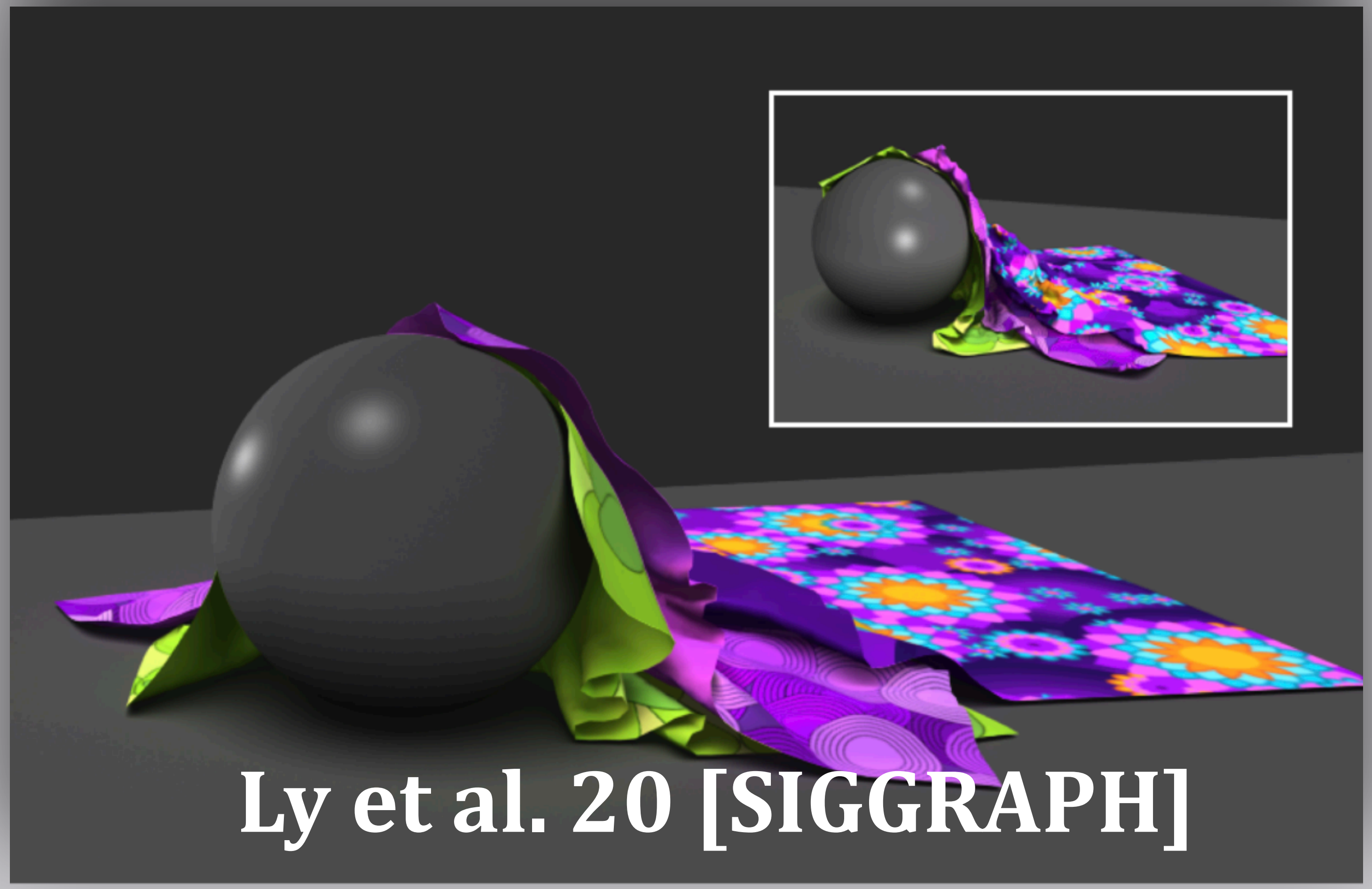
$$\theta_{new} \leftarrow \theta_{old} - \frac{\partial L}{\partial \theta} \cdot k$$

Related Works



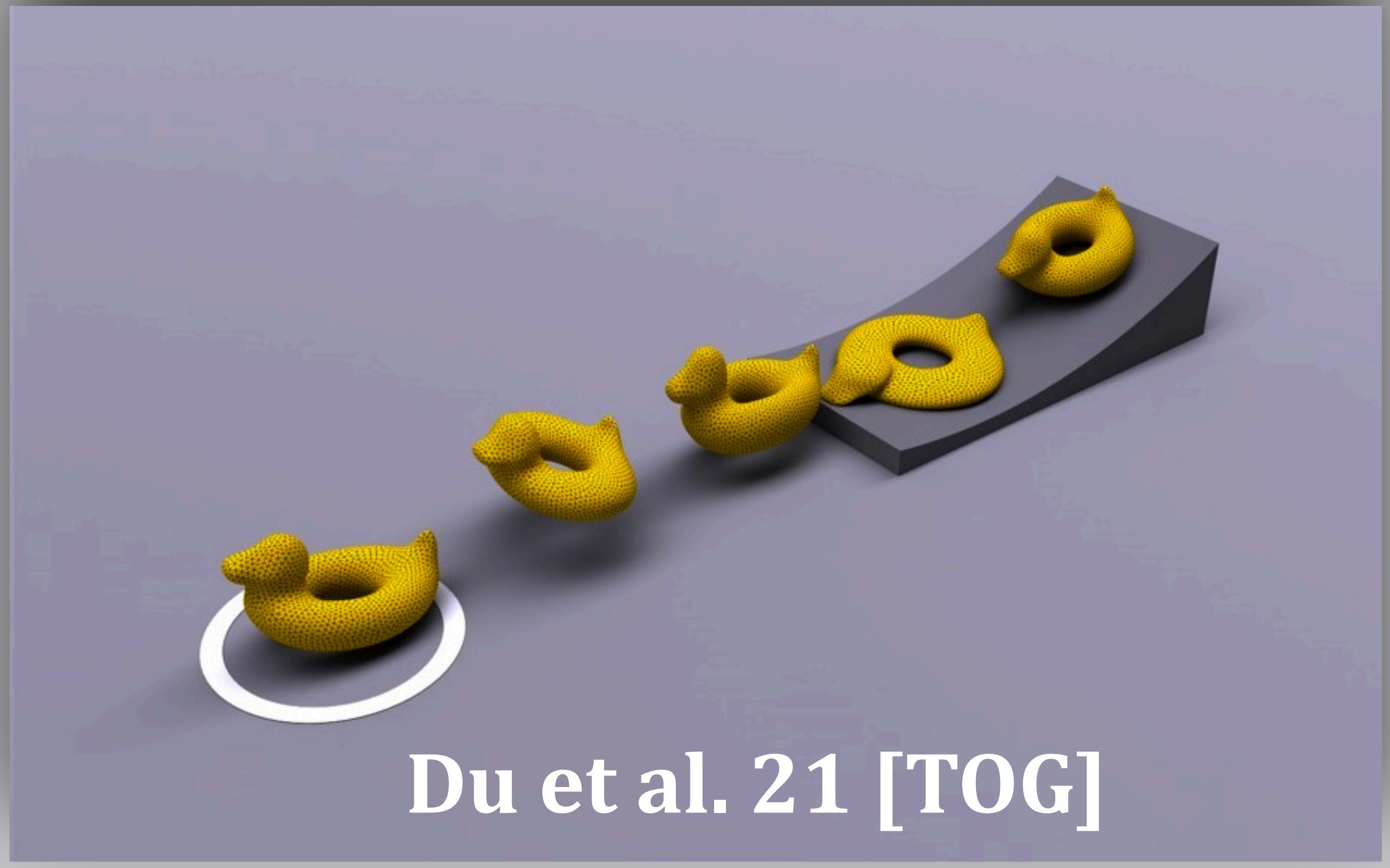
Liang et al. 19 [NeurIPS]

Differentiable cloth simulation for inverse problems



Ly et al. 20 [SIGGRAPH]

Projective Dynamics with dry frictional contact



Du et al. 21 [TOG]

DiffPD: Differentiable Projective Dynamics

Contributions of DiffCloth

Fast Simulation + Gradient Derivation

- Projective-Dynamics-based forward simulation
- Novel gradient computation to speed up back-propagation

Accurate Contact Modeling

Dry-frictional contact

Effective in Inverse Tasks

- Trajectory Optimization
- Closed-Loop Control
- Inverse Design
- System Identification
- Real-to-Sim

Simulating Cloth Dynamics

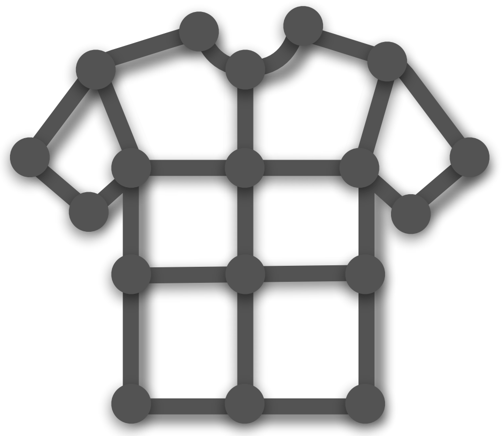
Implicit Euler integration is robust

Newton's 2nd Law with Implicit Euler

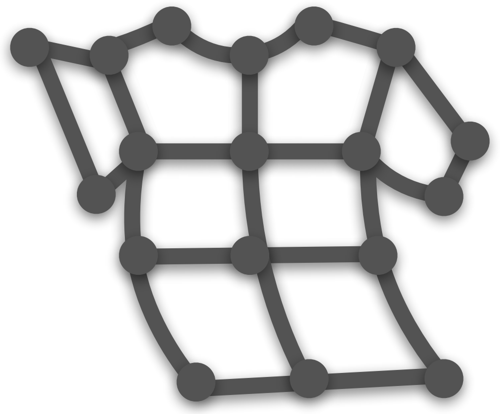
Forward Simulation

$$x_{t+1} - h^2 M^{-1} f(x_{t+1}) = x_t + h v_t$$

. . .



x_t



x_{t+1}

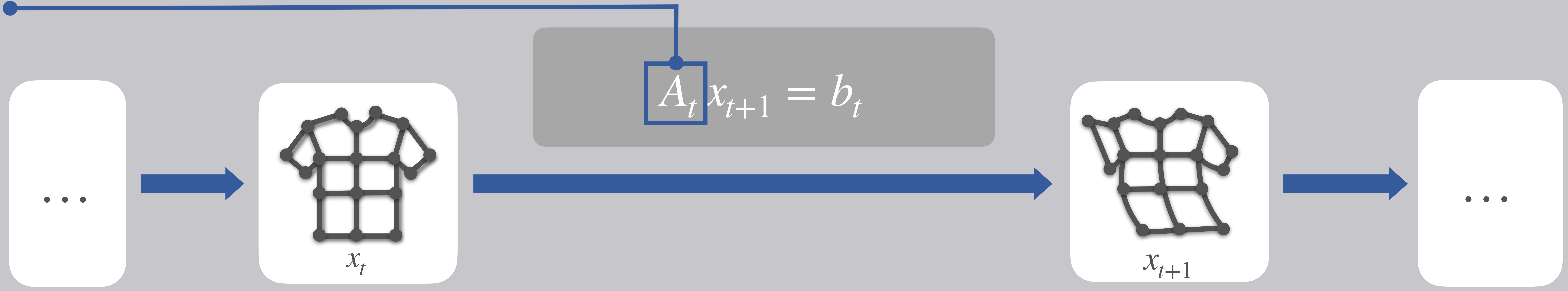
. . .

x_t, v_t **postion,velocity** h **timestep** M **mass matrix** f **force**

Simulating Cloth Dynamics

Implicit Euler integration is robust but expensive

Using Newton's method requires costly Hessian matrix computation and factorization of A_t at *every timestep* **(slow)**



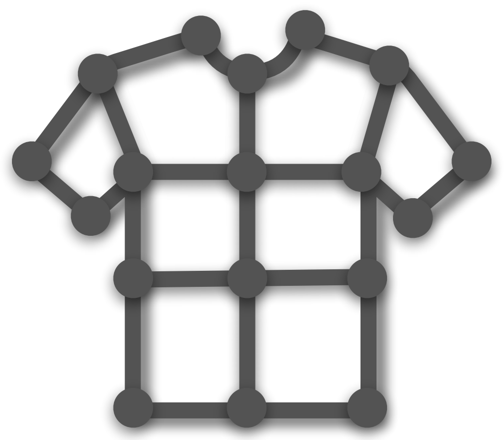
Fast Simulation with Projective Dynamics

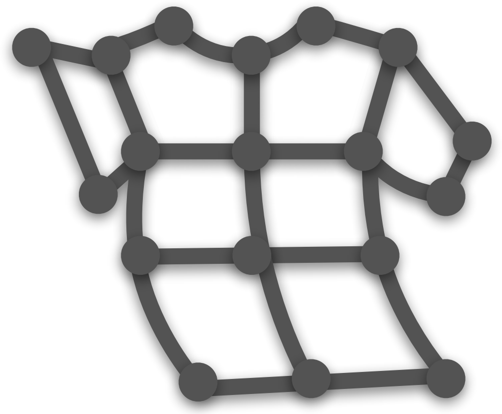
local/global iterative scheme [Bouaziz et al. 14]

Global: Same system matrix P at every timestep

$$P\,x_{t+1}^{k+1} = b(p)_{t+1}^{k}$$

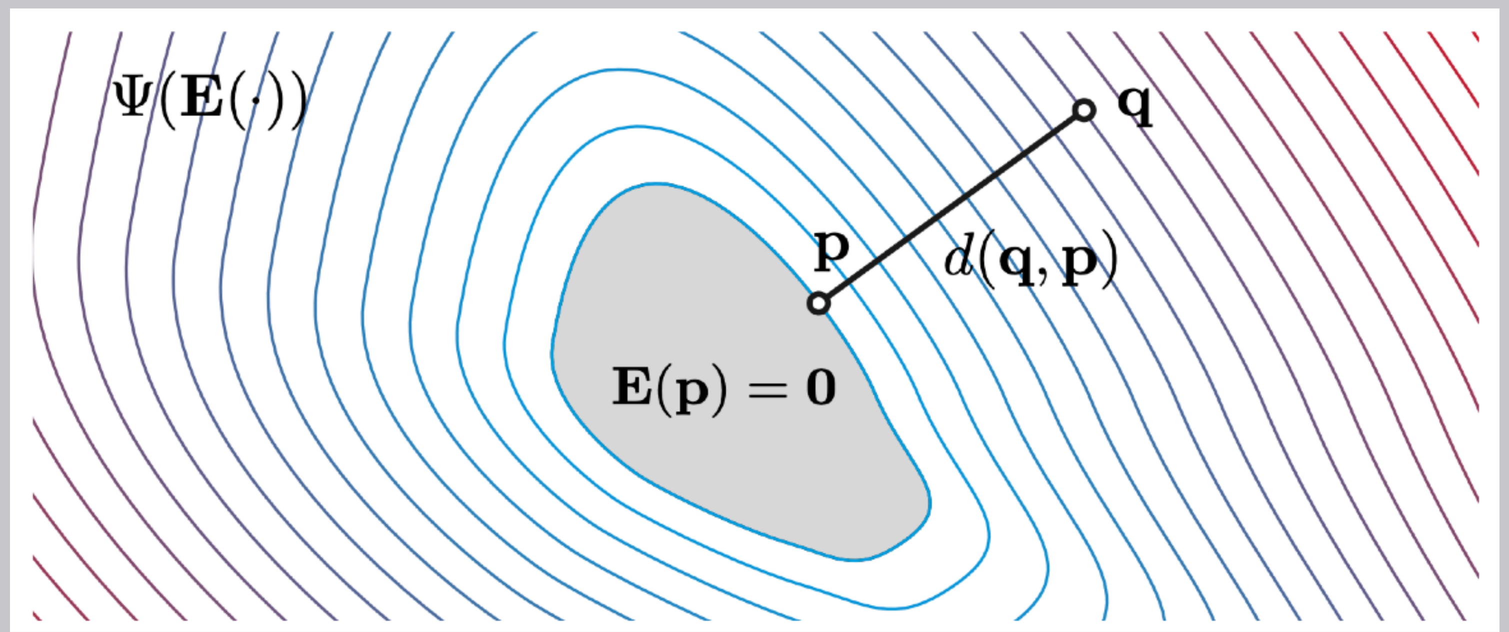
...


x_t


x_{t+1}

...

Local: parallel local projections p



Sofien Bouaziz, Sebastian Martin, Tiantian Liu, Ladislav Kavan, and Mark Pauly. 2014. Projective dynamics: fusing constraint projections for fast simulation. ACM Trans. Graph.

PD with Dry Frictional Contact [Ly et al. 20]

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enforce vertex-vertex frictional contact semi-implicitly to satisfy Signorine-Coulomb condition

$$P\, v^{k+1} = b(p)^k$$

$$:= f(p)^k + r^k$$

impulse contact impulse

Mickaël Ly, Jean Jouve, Laurence Boissieux, and Florence Bertails-Descoubes. 2020. Projective dynamics with dry frictional contact. ACM Trans. Graph

PD with Dry Frictional Contact [Ly et al. 20]

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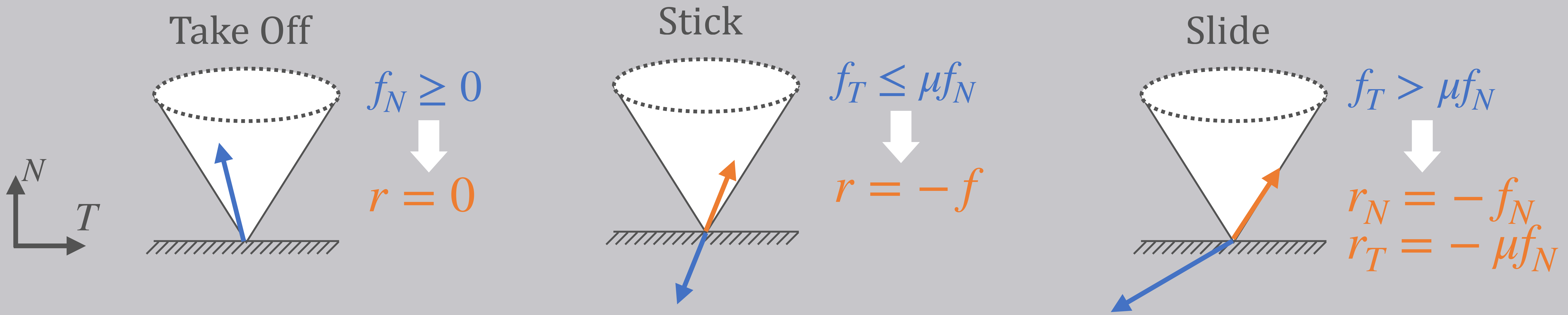

Signorini Condition $r = 0, v_N > 0$ $||r_T|| < \mu r_N, v = 0$ $||r_T|| = \mu r_N, v_N = 0, r_T || v_T, r_T \cdot u_t \leq 0$

Mickaël Ly, Jean Jouve, Laurence Boissieux, and Florence Bertails-Descoubes. 2020. Projective dynamics with dry frictional contact. ACM Trans. Graph

Slow Gradient Computation

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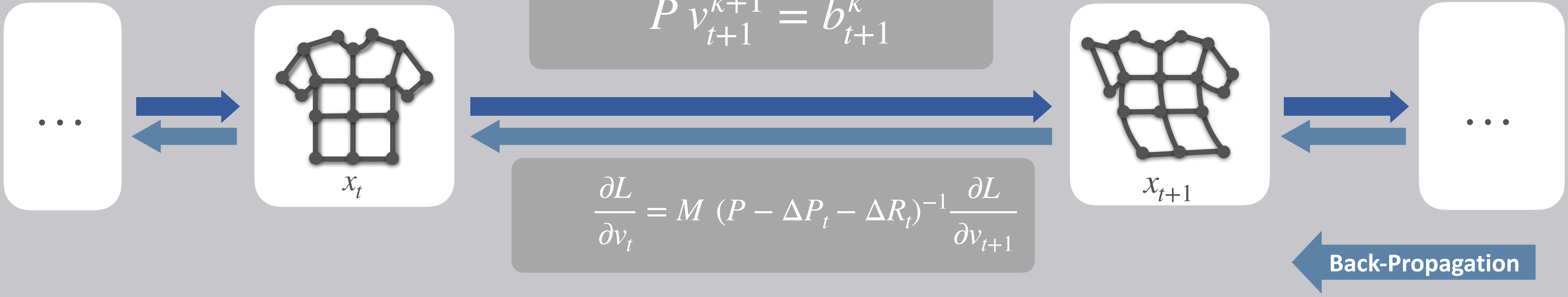
gradient computation via adjoint method



$$P\, v_{t+1}^{k+1} = b_{t+1}^{k}$$

$$\frac{\partial L}{\partial v_t} = M\ (P - \Delta P_t - \Delta R_t)^{-1} \frac{\partial L}{\partial v_{t+1}}$$

ΔP Gradient for the projection vector p

ΔR Gradient for the contact impulse response vector r

Slow Gradient Computation

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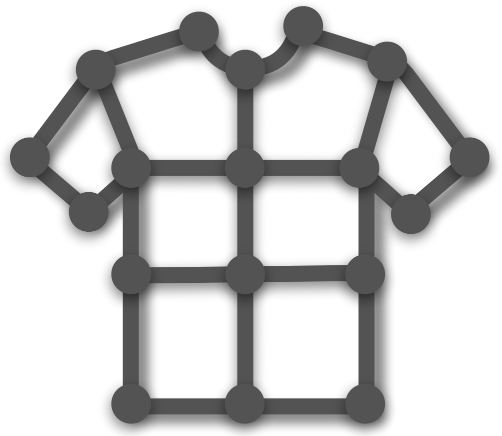
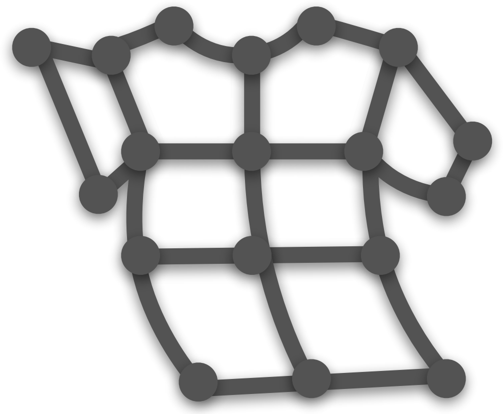
…





…

$$\frac{\partial L}{\partial v_t} = M \boxed{(P - \Delta P_t - \Delta R_t)^{-1} \frac{\partial L}{\partial v_{t+1}}}$$

$:= z_t$ adjoint vector

Slow Gradient Computation

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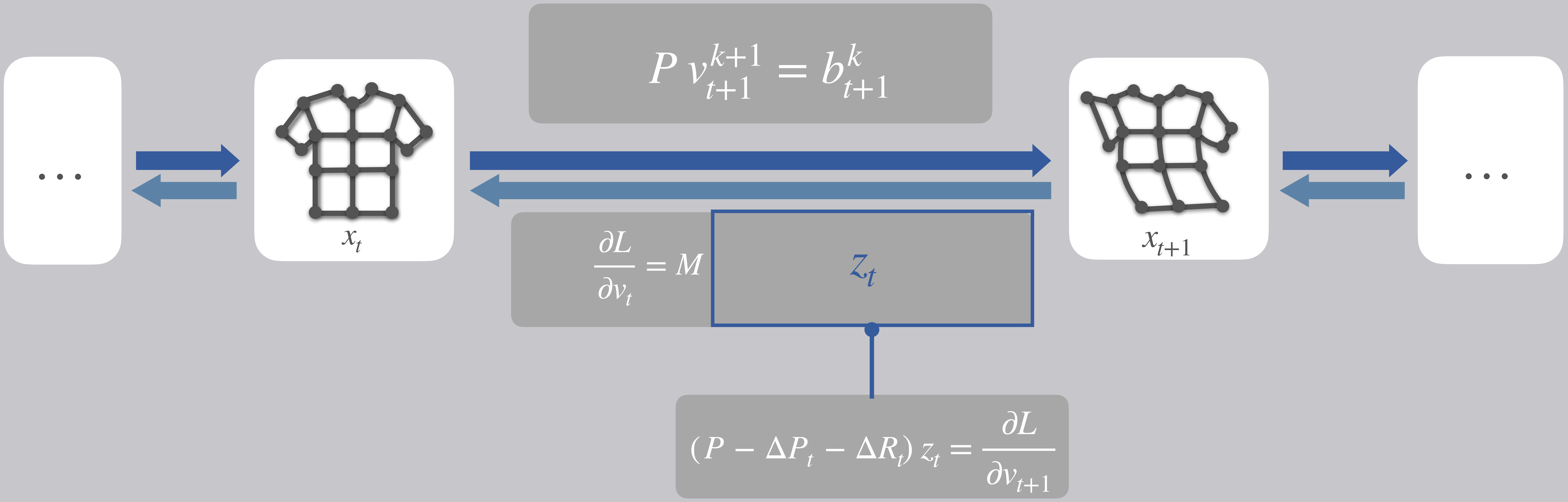
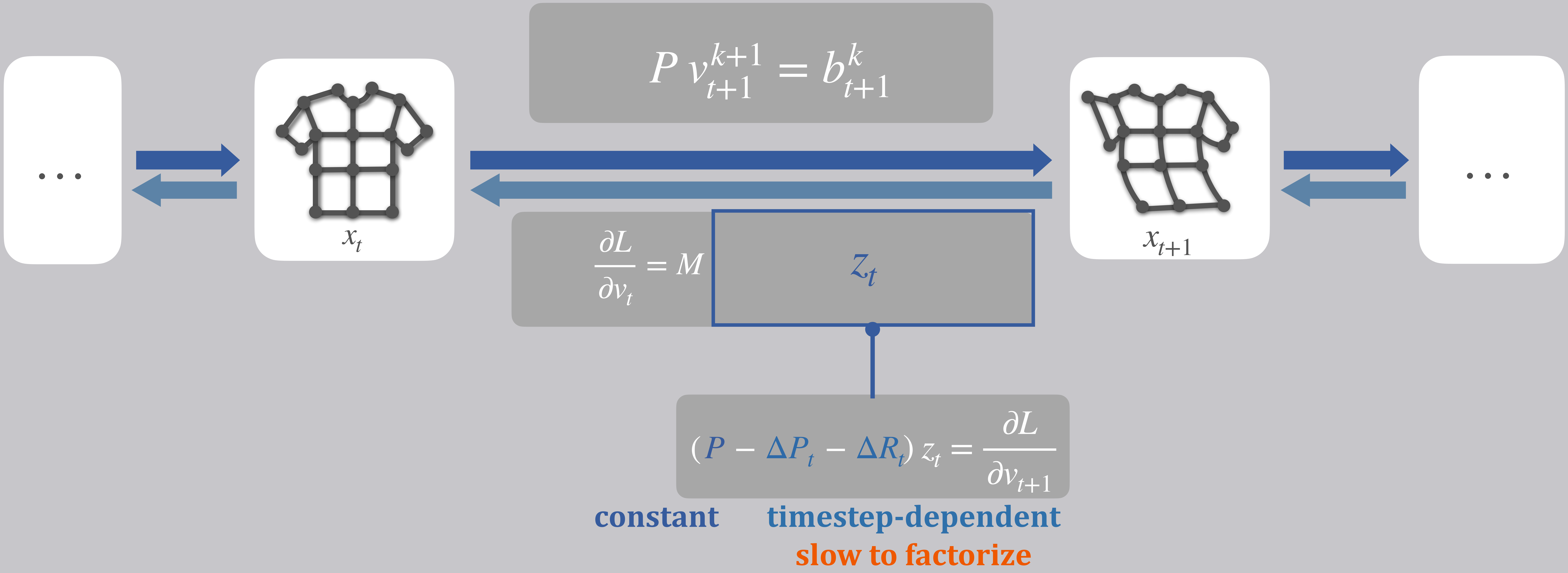


Slow Gradient Computation

Can we exploit the source of efficiency in forward solve for backward solve?



Fast Gradient Computation

constant — timestep-dependent

$$\left(P - \Delta P_t - \Delta R_t\right) z_t = \frac{\partial L}{\partial v_{t+1}}$$

Direct Solve

Matrix Splitting →

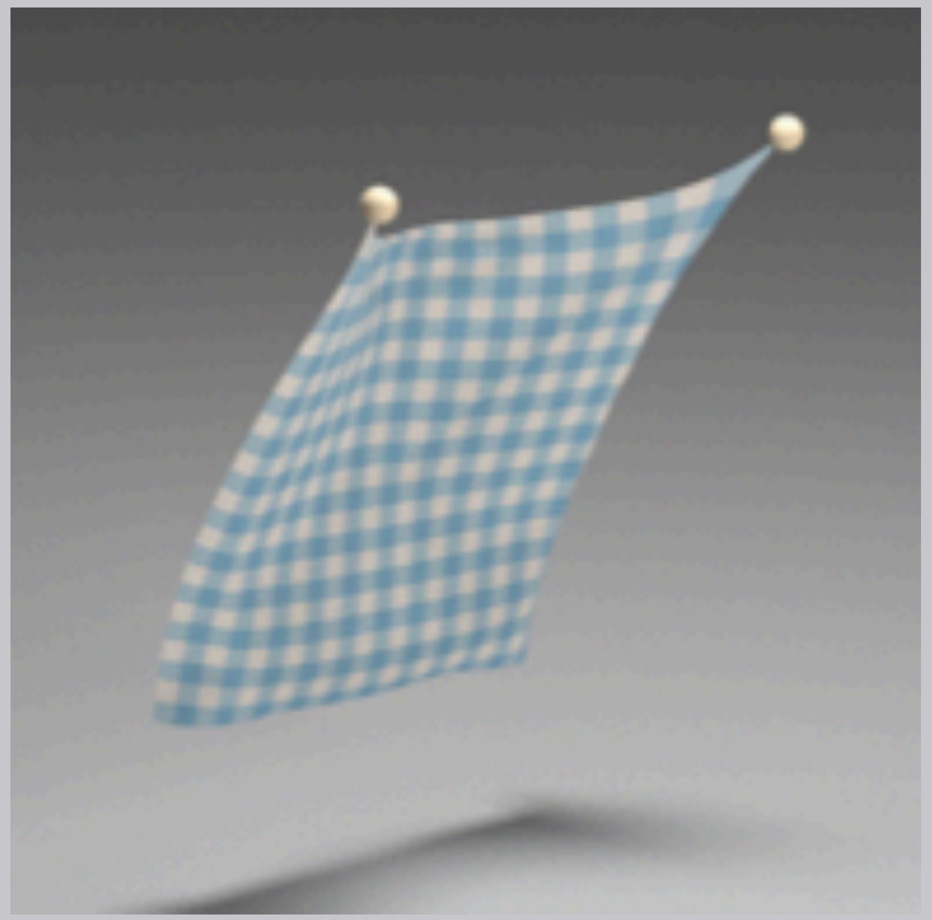
constant: pre-factorize

$$P z_t^{k+1} = (\Delta P_t + \Delta R_t) z_t^k + \frac{\partial L}{\partial v_{t+1}}$$

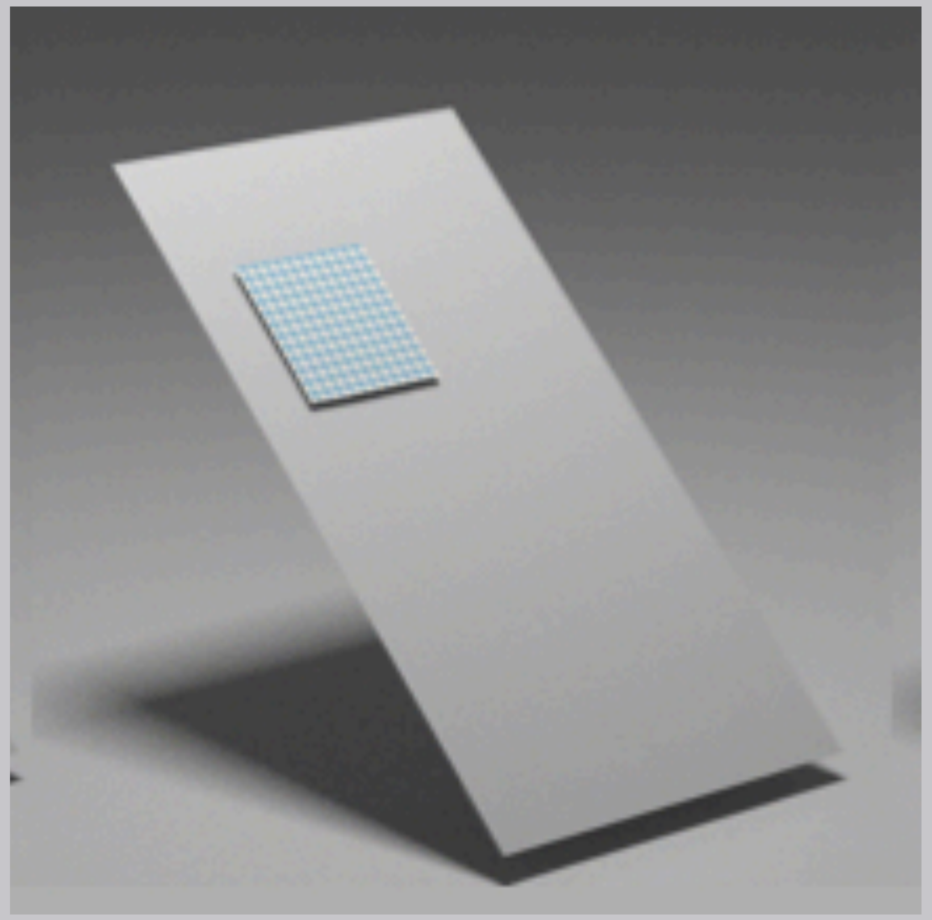
Iterative Solve: Good convergence in practice

Fast Differentiable Cloth Simulation (Backward)

Iterative Solver Speedup (convergence $\epsilon = $ 1e-4): 3x - 12x



Wind: minimal contact



Slope: maximal contact

	Cloth Grid Resolution		
	12x12	24x24	48x48
Wind	2.9x	5.7x	10.6x
Slope	3.1x	6.8x	12.0x

Iterative Solver Speedup

Inverse Task Comparison with Gradient-Free Methods

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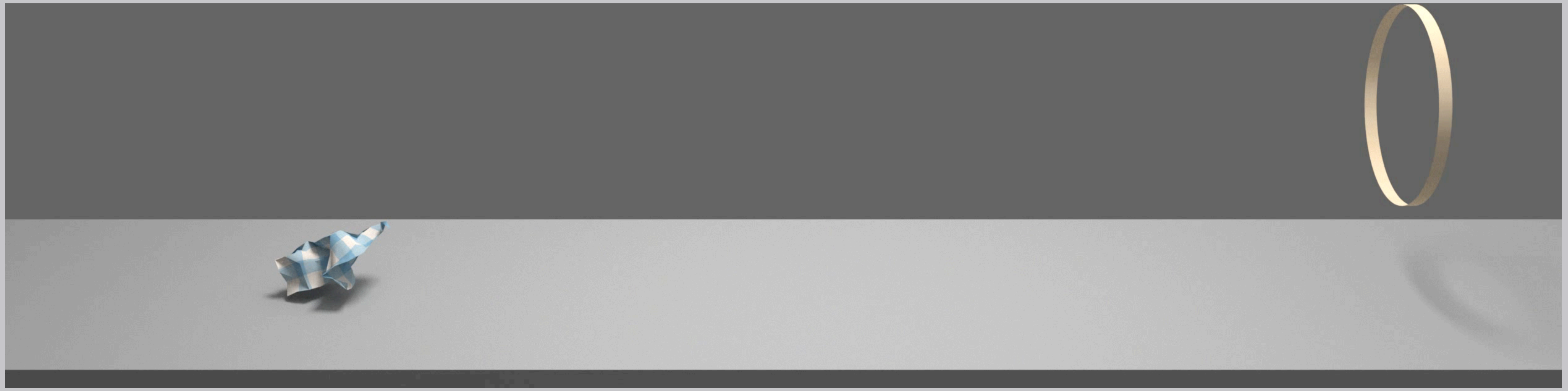
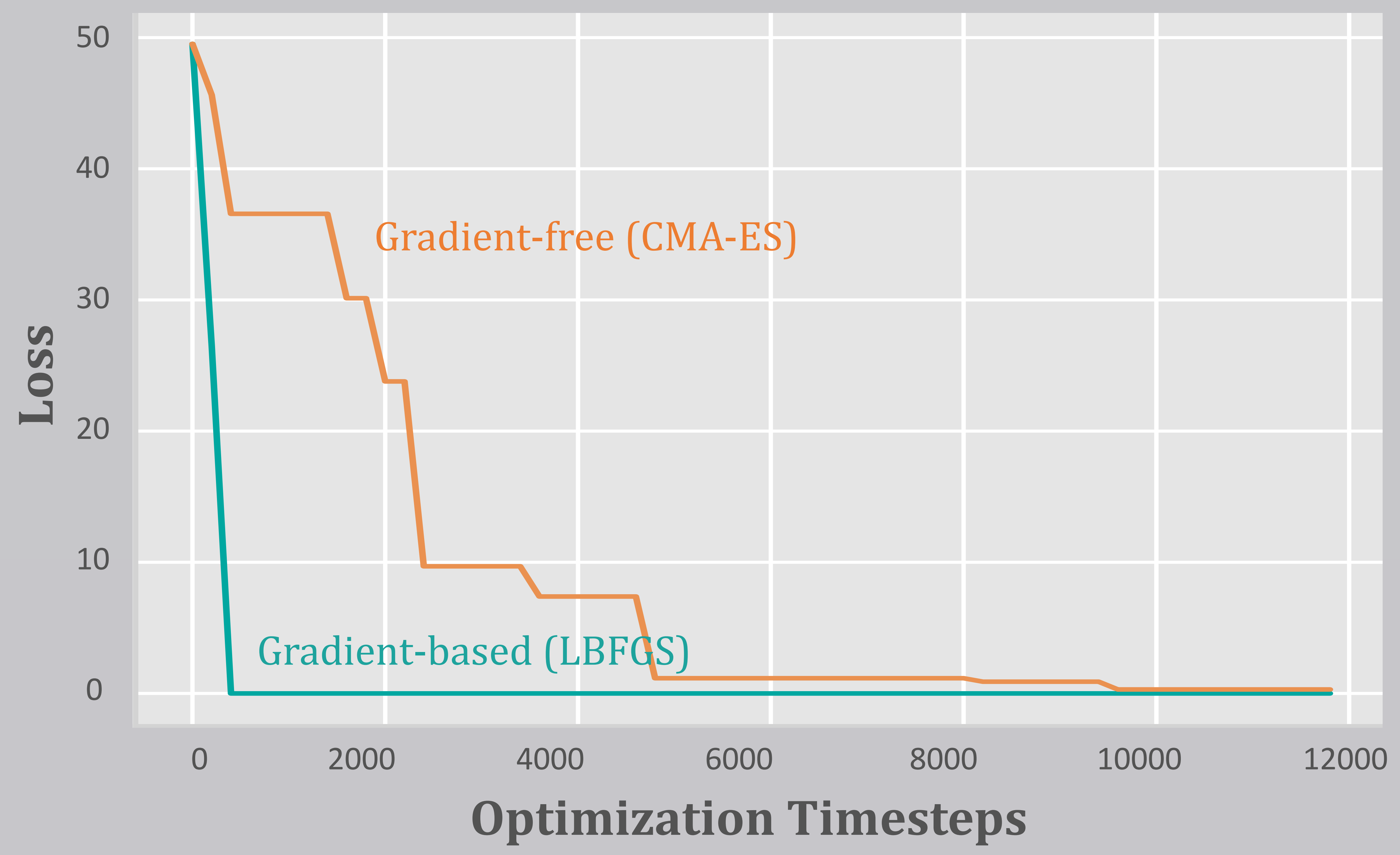
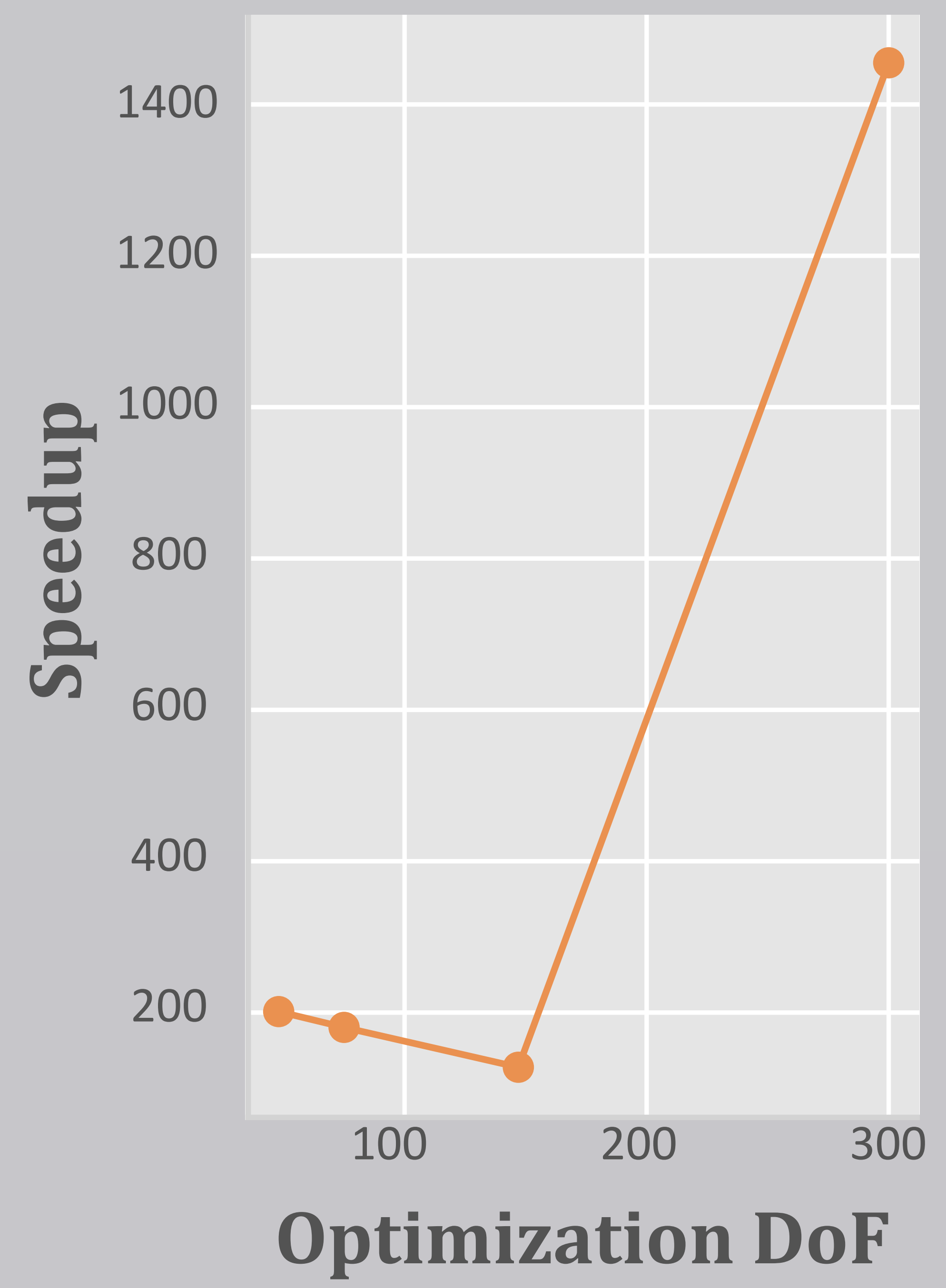
Benchmark Test: Optimize force field on the cloth to reach the ring







Task: Identify wind model and material parameters to match target trajectory

4300 DoF | 250 Timesteps | Δt = 1/90s
6 Design Parameters: cloth stretching stiffness and sinusoidal wind model parameters

Trajectory Optimization

Task: Optimize manipulator end effector trajectories to pull a sock on the foot model

1700 DoF | 400 Timesteps | Δt = 1/100s
36 Design Parameters: Tangents and endpoints of the 4 Hermite Splines

Inverse Design

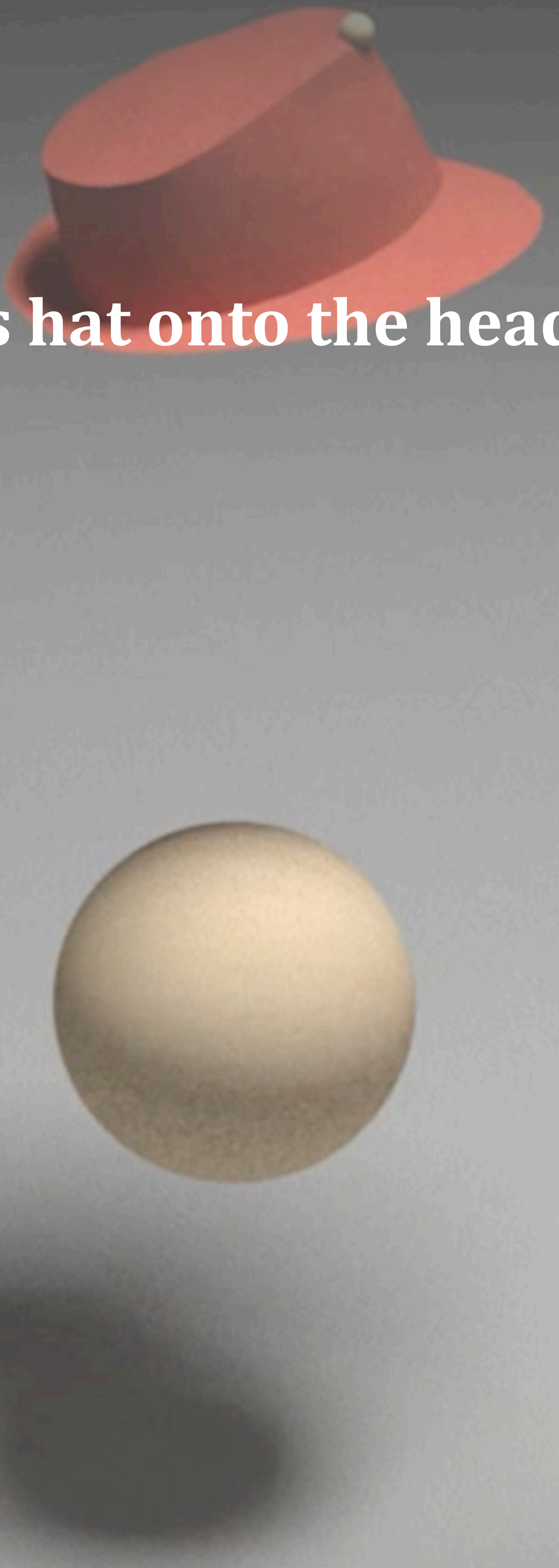
Task: Optimize dress material parameters so that the spinning angle of the dress is 50 degrees

Initial Guess

Optimized

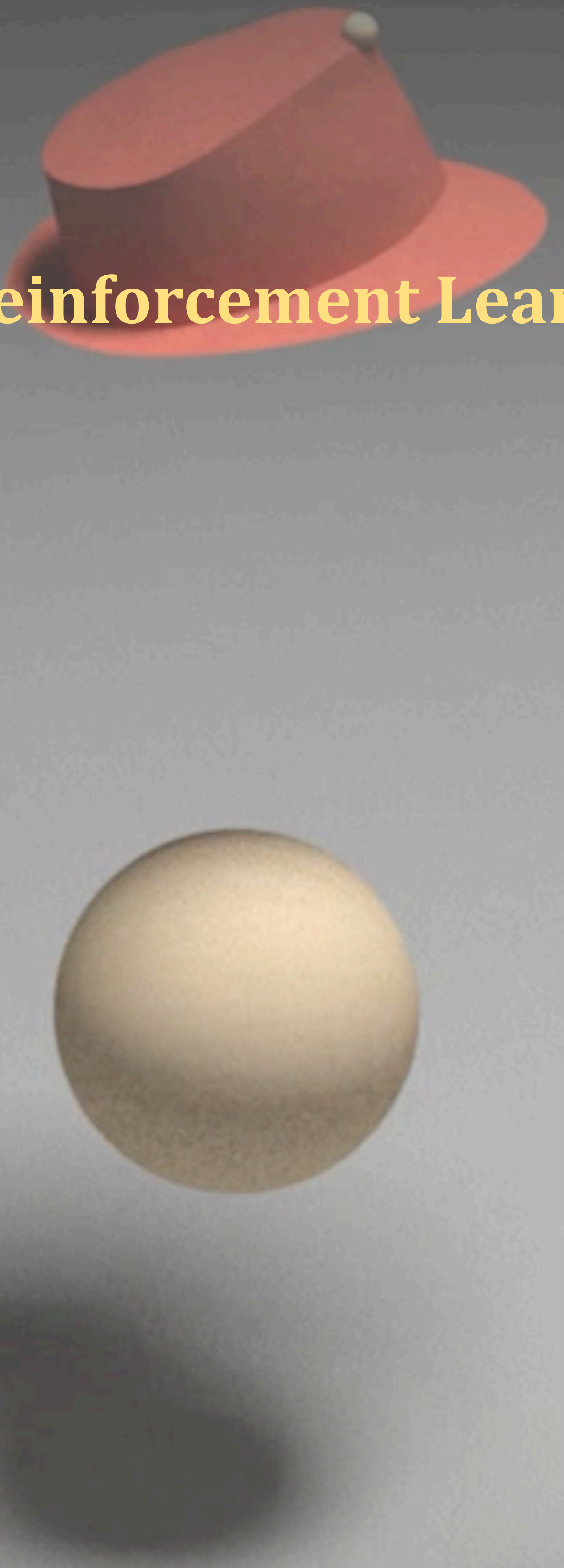
19000 DoF | 125 Timesteps | Δt = 1/120s
2 Design Parameters: density and bending stiffness

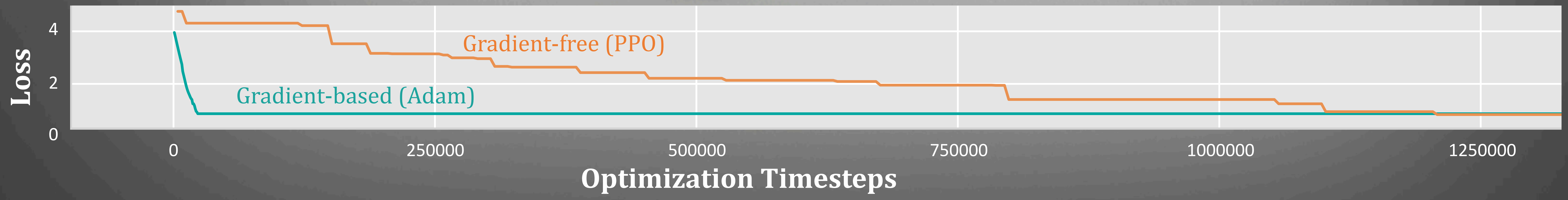
Task: A generalizable NN controller that puts hat onto the head from any initial positions around the upper hemisphere



1700 DoF | 400 Timesteps | Δt = 1/100s
117000 Design Parameters: Network parameters of the 2-layer MLP

85x more sampling efficient compare with Reinforcement Learning baseline

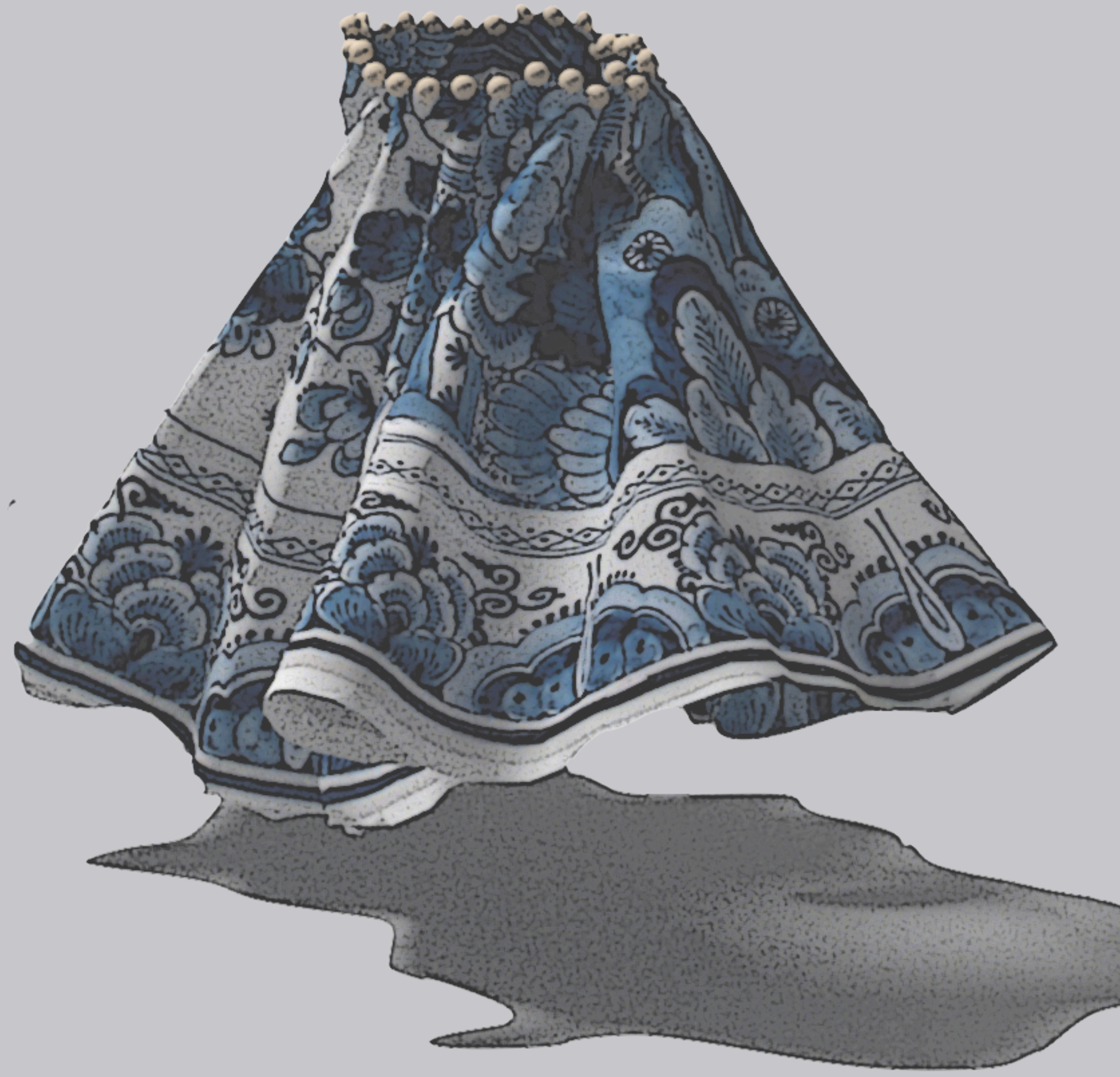




Summary & Takeaway

A differentiable cloth simulator with dry frictional contact

- Fast simulation with Projective Dynamics & fast back-propagation with iterative solver
- More sampling efficient than gradient-free methods
- Effective in a wide range of inverse tasks



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