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# Cloth Simulation

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KAIST (Korea Advanced Institute of Science and Technology)

**KAIST**



# Overview

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- Introduction
- Three Parts of Cloth Simulation
  - Cloth Model System
  - Numerical Solver
  - Collision Handling
- Sketch of Recently Developed Methods
- Challenging Problem
- Conclusion

# Introduction

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- Cloth Simulation is widely used in the world



Shrek the Third(2007)

["http://www.shrek3.co.kr"](http://www.shrek3.co.kr)



King kong(2005)

["http://www.kingkong2005.co.kr"](http://www.kingkong2005.co.kr)

# Introduction

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- The Goal of Cloth Simulation

**Reality**

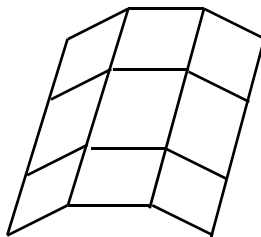


**Efficiency**

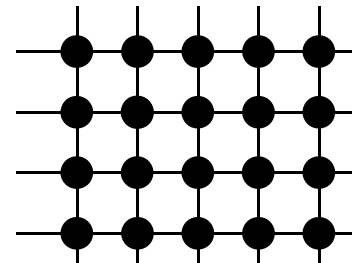
Get realistic results  
by calculating intensive  
computation

Get fast results  
by calculating efficient  
computation

**Continuum Model**



**Particle System Model**



# Introduction

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- Steps of Cloth Simulation

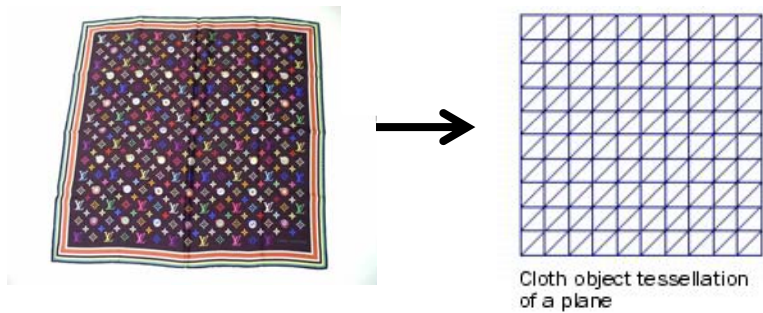


# Introduction

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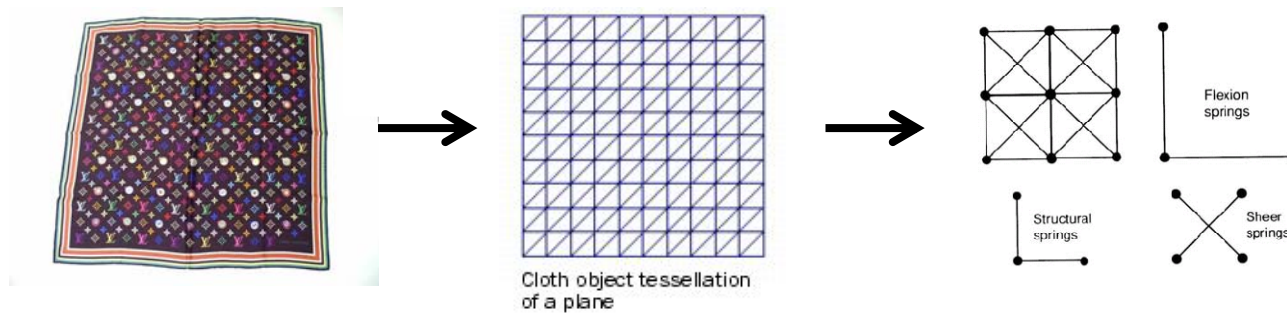
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- Steps of Cloth Simulation
  1. Model the cloth



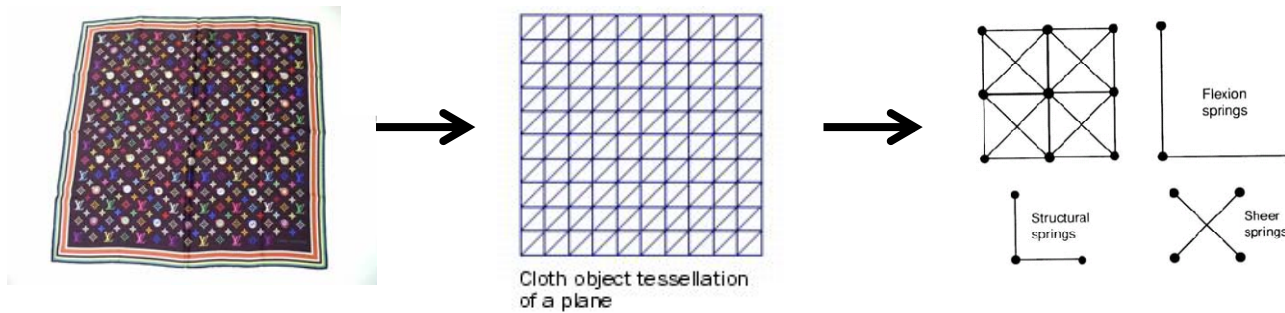
# Introduction

- Steps of Cloth Simulation
  2. Choose the cloth model system



# Introduction

- Steps of Cloth Simulation
  3. Derive and solve an equation



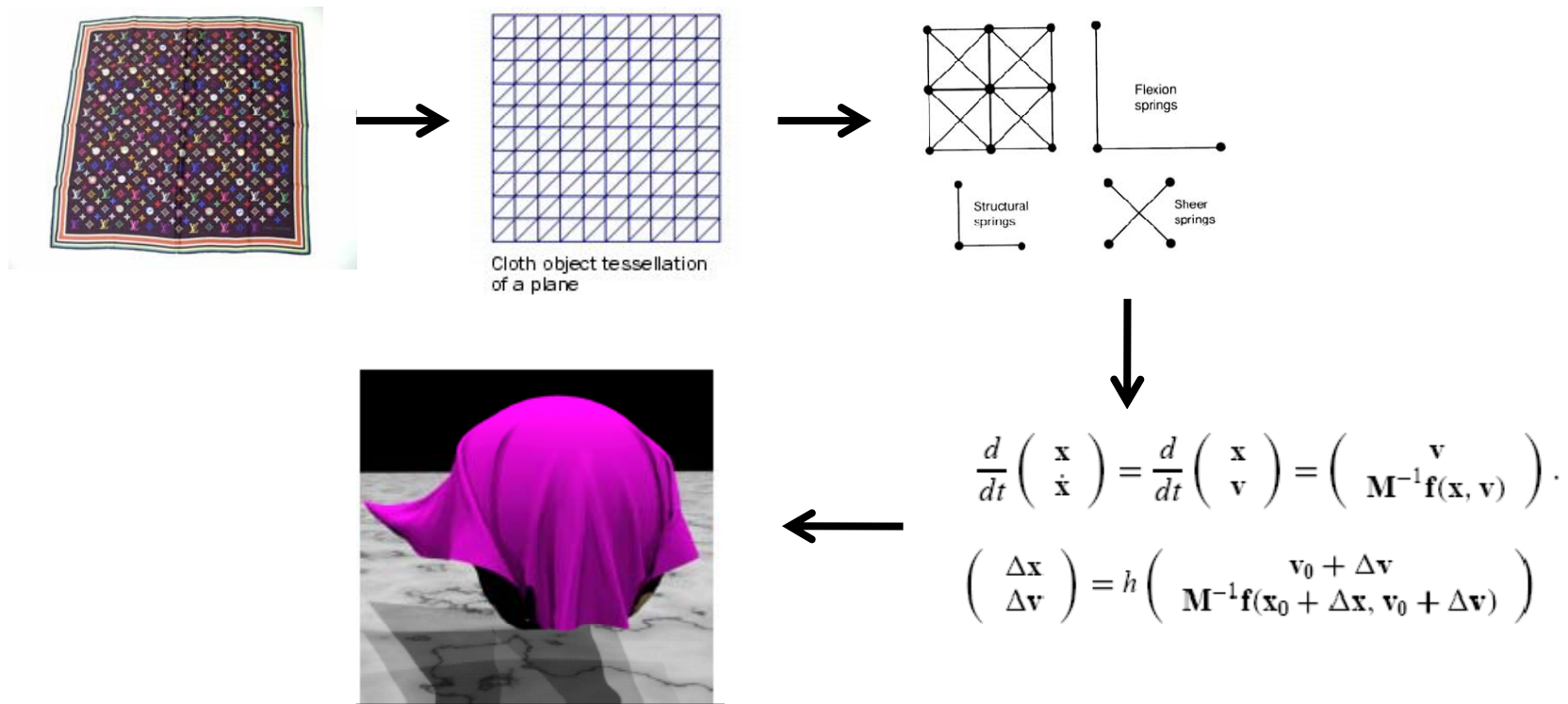
$$\frac{d}{dt} \begin{pmatrix} \mathbf{x} \\ \dot{\mathbf{x}} \end{pmatrix} = \frac{d}{dt} \begin{pmatrix} \mathbf{x} \\ \mathbf{v} \end{pmatrix} = \begin{pmatrix} \mathbf{v} \\ \mathbf{M}^{-1} \mathbf{f}(\mathbf{x}, \mathbf{v}) \end{pmatrix}.$$

$$\begin{pmatrix} \Delta \mathbf{x} \\ \Delta \mathbf{v} \end{pmatrix} = h \begin{pmatrix} \mathbf{v}_0 + \Delta \mathbf{v} \\ \mathbf{M}^{-1} \mathbf{f}(\mathbf{x}_0 + \Delta \mathbf{x}, \mathbf{v}_0 + \Delta \mathbf{v}) \end{pmatrix}$$



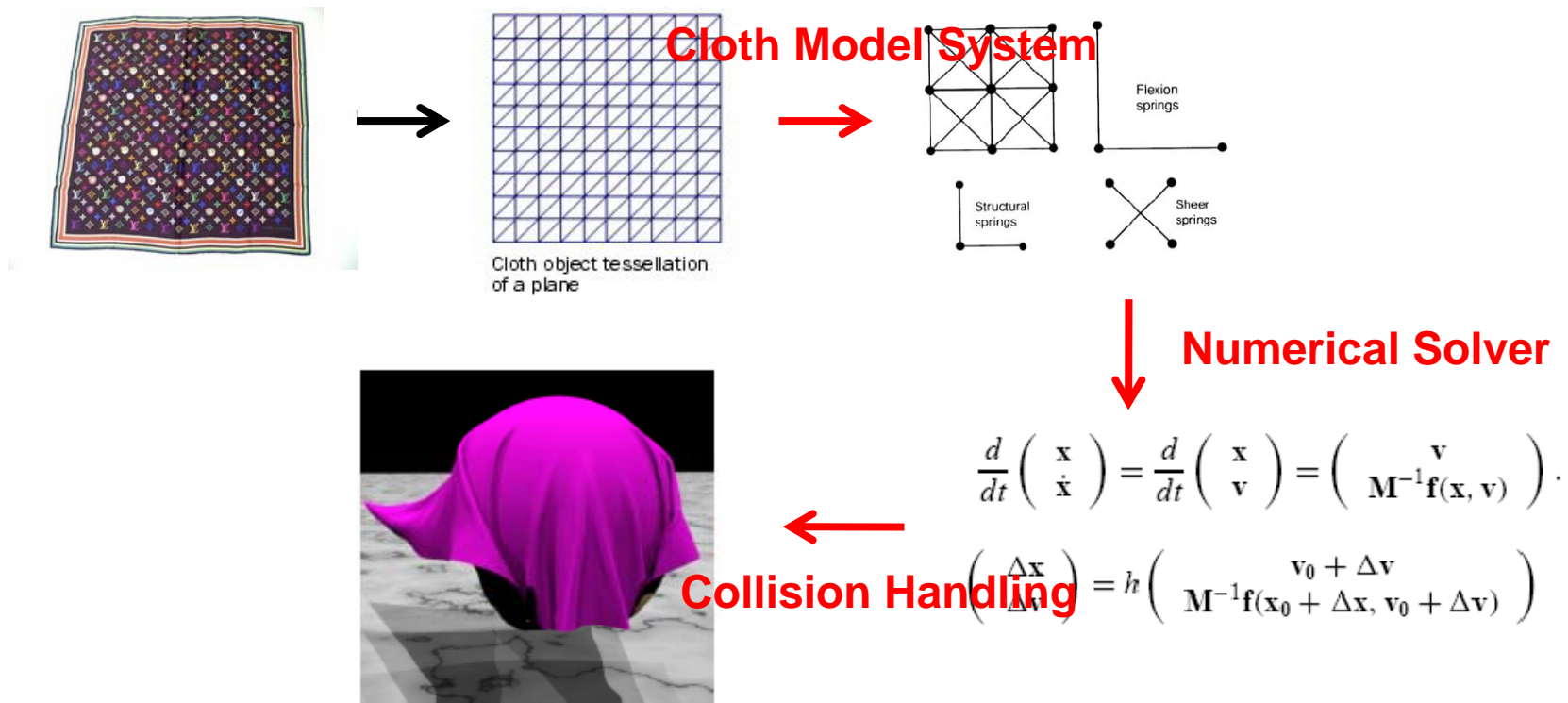
# Introduction

- Steps of Cloth Simulation
  - Collision handling (Collision detection + response)



# Introduction

- Steps of Cloth Simulation
  - Collision handling (Collision detection + response)

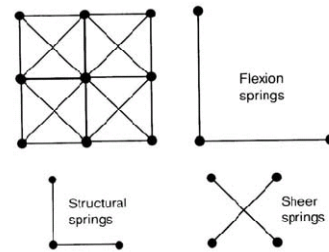


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# Three Parts of Cloth Simulation

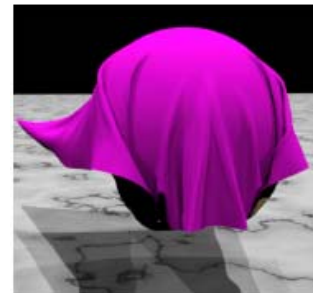
1. Cloth Model System



2. Numerical Solver

$$\frac{d}{dt} \begin{pmatrix} \mathbf{x} \\ \dot{\mathbf{x}} \end{pmatrix} = \frac{d}{dt} \begin{pmatrix} \mathbf{x} \\ \mathbf{v} \end{pmatrix} = \begin{pmatrix} \mathbf{v} \\ \mathbf{M}^{-1}\mathbf{f}(\mathbf{x}, \mathbf{v}) \end{pmatrix}.$$
$$\begin{pmatrix} \Delta\mathbf{x} \\ \Delta\mathbf{v} \end{pmatrix} = h \begin{pmatrix} \mathbf{v}_0 + \Delta\mathbf{v} \\ \mathbf{M}^{-1}\mathbf{f}(\mathbf{x}_0 + \Delta\mathbf{x}, \mathbf{v}_0 + \Delta\mathbf{v}) \end{pmatrix}$$

3. Collision Handling

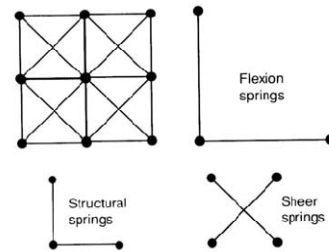


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# Three Parts of Cloth Simulation

## 1. Cloth Model System



## 2. Numerical Solver

$$\frac{d}{dt} \begin{pmatrix} \mathbf{x} \\ \dot{\mathbf{x}} \end{pmatrix} = \frac{d}{dt} \begin{pmatrix} \mathbf{x} \\ \mathbf{v} \end{pmatrix} = \begin{pmatrix} \mathbf{v} \\ \mathbf{M}^{-1} \mathbf{f}(\mathbf{x}, \mathbf{v}) \end{pmatrix}.$$
$$\begin{pmatrix} \Delta \mathbf{x} \\ \Delta \mathbf{v} \end{pmatrix} = h \begin{pmatrix} \mathbf{v}_0 + \Delta \mathbf{v} \\ \mathbf{M}^{-1} \mathbf{f}(\mathbf{x}_0 + \Delta \mathbf{x}, \mathbf{v}_0 + \Delta \mathbf{v}) \end{pmatrix}$$

## 3. Collision Handling

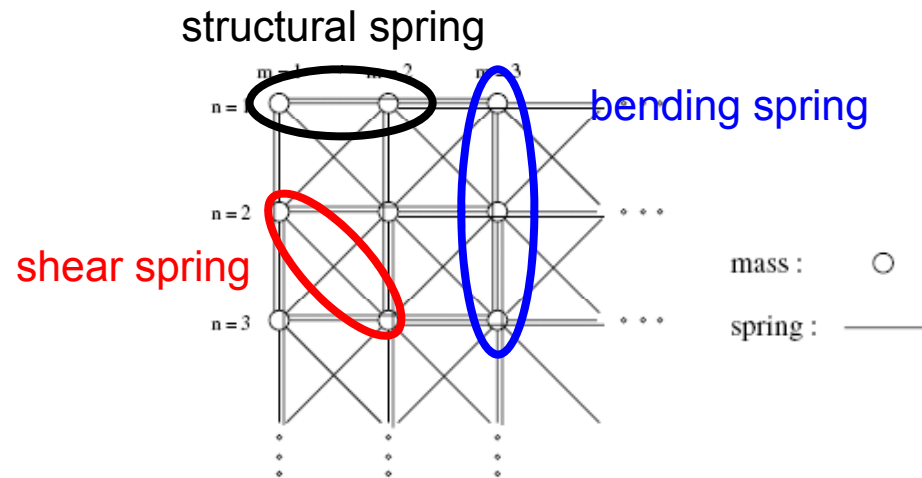


# Three Parts of Cloth Simulation

## 1. Cloth Model System

- Deformation Constraints in a Mass- Spring Model to Describe Rigid Cloth Behavior

Xavier Provot, Graphics Interface, 1995.

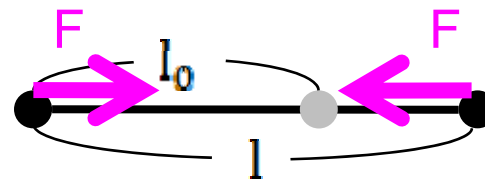
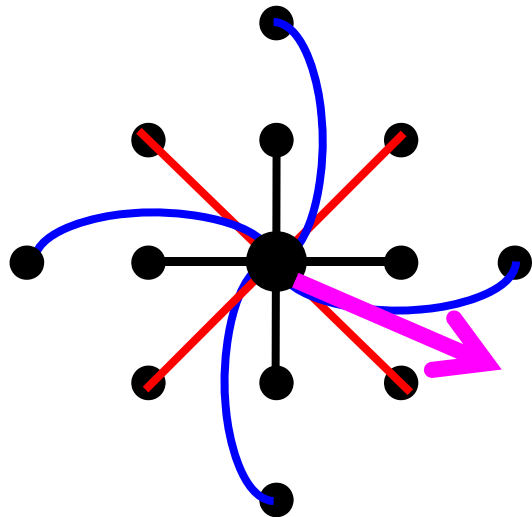


# Three Parts of Cloth Simulation

## 1. Cloth Model System

- Deformation Constraints in a Mass-Spring Model to Describe Rigid Cloth Behavior

Xavier Provot, Graphics Interface, 1995.



$$\mathbf{F} = -K \times (l - l_0)$$

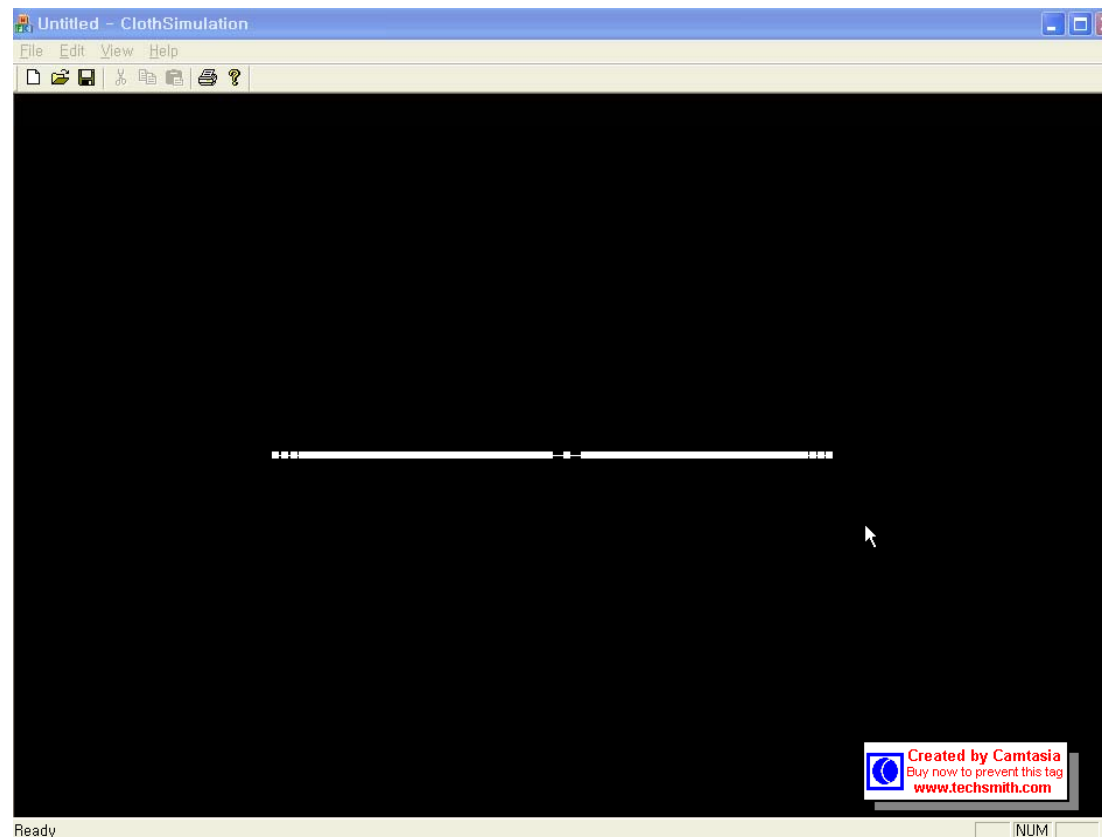
$$\begin{cases} \mathbf{a}_{i,j}(t + \Delta t) = \frac{1}{\mu} \mathbf{F}_{i,j}(t) \\ \mathbf{v}_{i,j}(t + \Delta t) = \mathbf{v}_{i,j}(t) + \Delta t \mathbf{a}_{i,j}(t + \Delta t) \\ P_{i,j}(t + \Delta t) = P_{i,j}(t) + \Delta t \mathbf{v}_{i,j}(t + \Delta t) \end{cases}$$

# Three Parts of Cloth Simulation

## 1. Cloth Model System

- Deformation Constraints in a Mass- Spring Model to Describe Rigid Cloth Behavior

Xavier Provot, Graphics Interface, 1995.

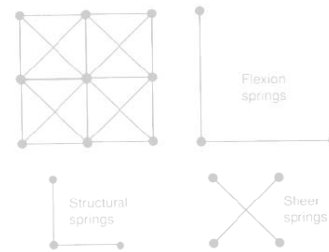


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# Three Parts of Cloth Simulation

1. Cloth Model System



2. Numerical Solver

$$\frac{d}{dt} \begin{pmatrix} \mathbf{x} \\ \dot{\mathbf{x}} \end{pmatrix} = \frac{d}{dt} \begin{pmatrix} \mathbf{x} \\ \mathbf{v} \end{pmatrix} = \begin{pmatrix} \mathbf{v} \\ \mathbf{M}^{-1} \mathbf{f}(\mathbf{x}, \mathbf{v}) \end{pmatrix}.$$
$$\begin{pmatrix} \Delta \mathbf{x} \\ \Delta \mathbf{v} \end{pmatrix} = h \begin{pmatrix} \mathbf{v}_0 + \Delta \mathbf{v} \\ \mathbf{M}^{-1} \mathbf{f}(\mathbf{x}_0 + \Delta \mathbf{x}, \mathbf{v}_0 + \Delta \mathbf{v}) \end{pmatrix}$$

3. Collision Handling





# Three Parts of Cloth Simulation

## 2. Numerical Solver

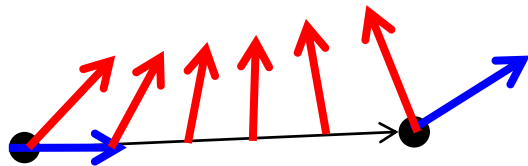
- Large Steps in Cloth Simulation

David Baraff, et al., SIGGRAPH, 1998.

$$\ddot{\mathbf{x}} = \mathbf{M}^{-1}\mathbf{f}(\mathbf{x}, \dot{\mathbf{x}}).$$

Newton's law

$$\frac{d}{dt} \begin{pmatrix} \mathbf{x} \\ \dot{\mathbf{x}} \end{pmatrix} = \frac{d}{dt} \begin{pmatrix} \mathbf{x} \\ \mathbf{v} \end{pmatrix} = \begin{pmatrix} \mathbf{v} \\ \mathbf{M}^{-1}\mathbf{f}(\mathbf{x}, \mathbf{v}) \end{pmatrix}$$



$$\mathbf{f}(\mathbf{x}, \mathbf{v}) = ?$$

# Three Parts of Cloth Simulation

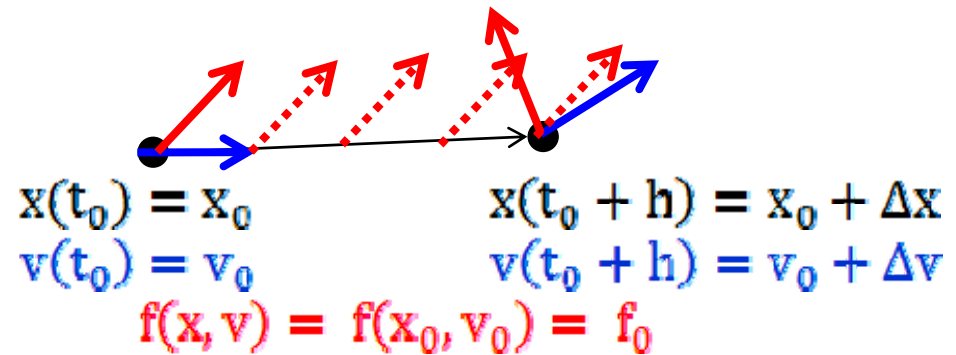
## 2. Numerical Solver

- Large Steps in Cloth Simulation

David Baraff, et al., SIGGRAPH, 1998.

### 1. Explicit Method

$$\begin{pmatrix} \Delta \mathbf{x} \\ \Delta \mathbf{v} \end{pmatrix} = h \begin{pmatrix} \mathbf{v}_0 \\ \mathbf{M}^{-1} \mathbf{f}_0 \end{pmatrix}$$



calculation cost is very low

time step(h) must be small to ensure stability

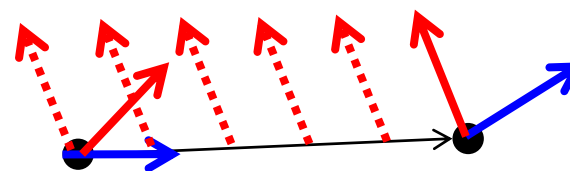
# Three Parts of Cloth Simulation

## 2. Numerical Solver

- Large Steps in Cloth Simulation

David Baraff, et al., SIGGRAPH, 1998.

### 2. Implicit Method



$$\begin{pmatrix} \Delta \mathbf{x} \\ \Delta \mathbf{v} \end{pmatrix} = h \begin{pmatrix} \mathbf{v}_0 + \Delta \mathbf{v} \\ \mathbf{M}^{-1} \mathbf{f}(\mathbf{x}_0 + \Delta \mathbf{x}, \mathbf{v}_0 + \Delta \mathbf{v}) \end{pmatrix}$$

$$\begin{aligned} \mathbf{x}(t_0) &= \mathbf{x}_0 & \mathbf{x}(t_0 + h) &= \mathbf{x}_0 + \Delta \mathbf{x} \\ \mathbf{v}(t_0) &= \mathbf{v}_0 & \mathbf{v}(t_0 + h) &= \mathbf{v}_0 + \Delta \mathbf{v} \end{aligned}$$

$$\mathbf{f}(\mathbf{x}, \mathbf{v}) = \mathbf{f}(\mathbf{x}_0 + \Delta \mathbf{x}, \mathbf{v}_0 + \Delta \mathbf{v})$$

$$\mathbf{f}(\mathbf{x}_0 + \Delta \mathbf{x}, \mathbf{v}_0 + \Delta \mathbf{v}) = \mathbf{f}_0 + \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \Delta \mathbf{x} + \frac{\partial \mathbf{f}}{\partial \mathbf{v}} \Delta \mathbf{v}$$

$$\left( \mathbf{I} - h \mathbf{M}^{-1} \frac{\partial \mathbf{f}}{\partial \mathbf{v}} - h^2 \mathbf{M}^{-1} \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \right) \Delta \mathbf{v} = h \mathbf{M}^{-1} \left( \mathbf{f}_0 + h \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \mathbf{v}_0 \right)$$

calculation cost is expensive

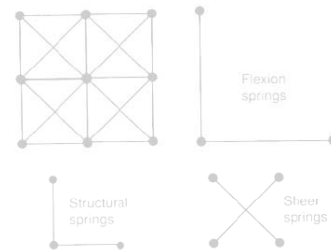
time step(h) can be large

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# Three Parts of Cloth Simulation

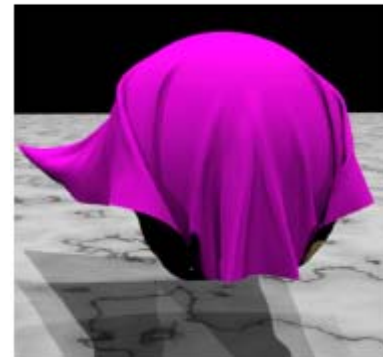
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3. Collision Handling



# Three Parts of Cloth Simulation

## 3. Collision Handling

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- Collision Handling

# Three Parts of Cloth Simulation

## 3. Collision Handling

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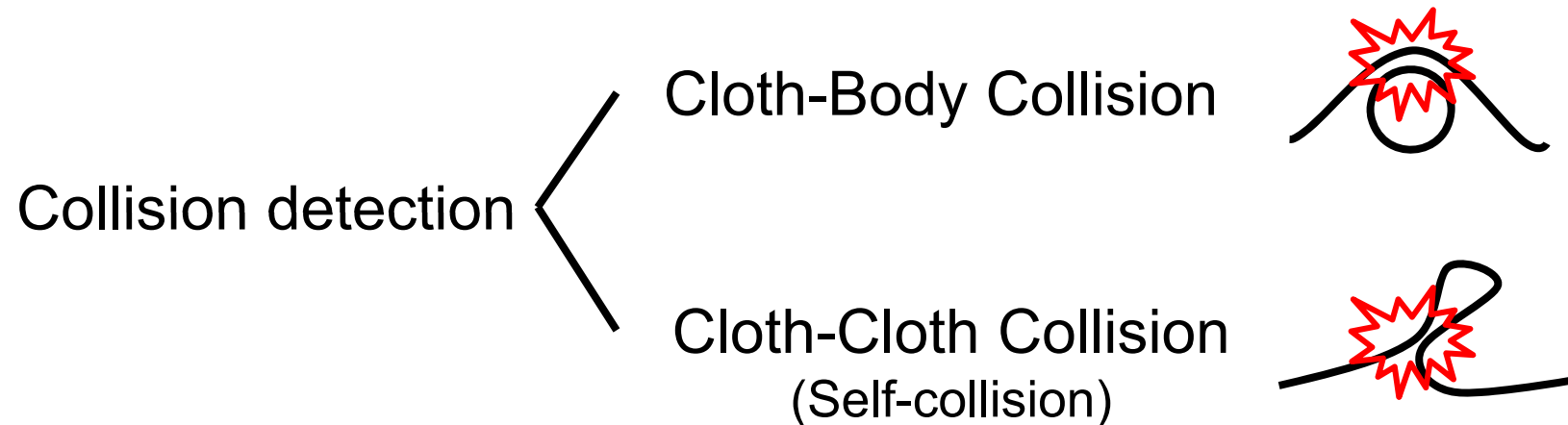
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- Collision Handling  
= Collision Detection + Collision Response

# Three Parts of Cloth Simulation

## 3. Collision Handling

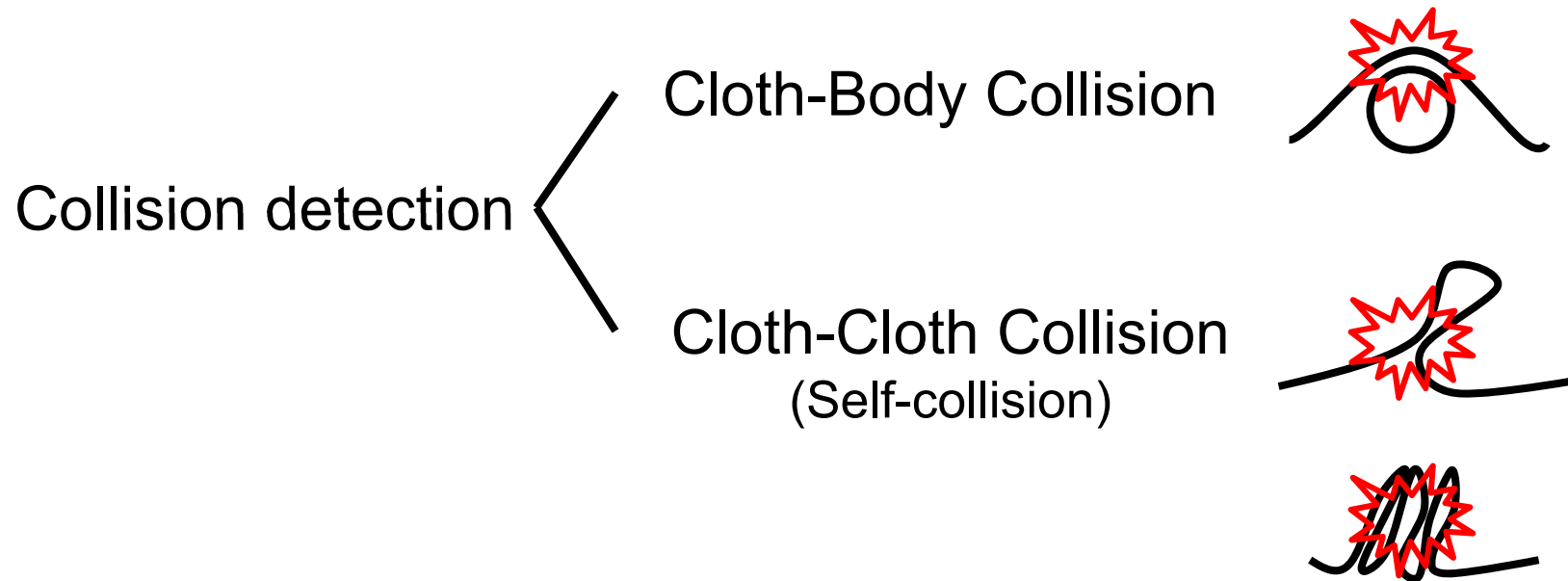
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# Three Parts of Cloth Simulation

## 3. Collision Handling

- Collision Handling  
= Collision Detection + Collision Response

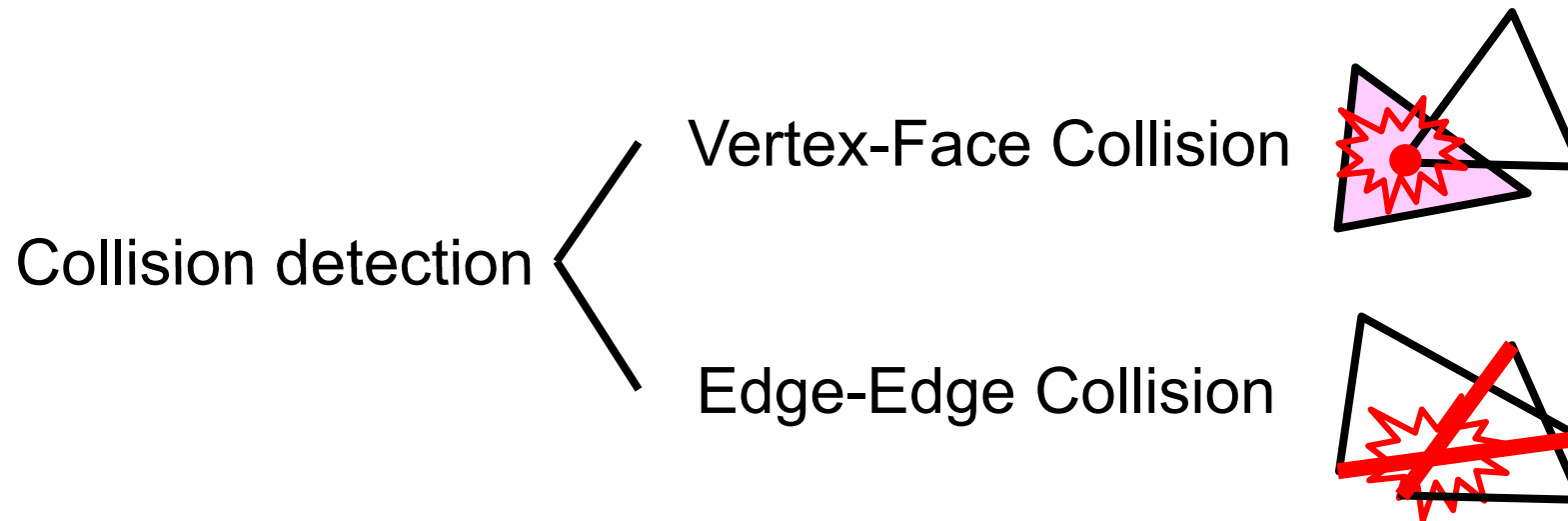




# Three Parts of Cloth Simulation

## 3. Collision Handling

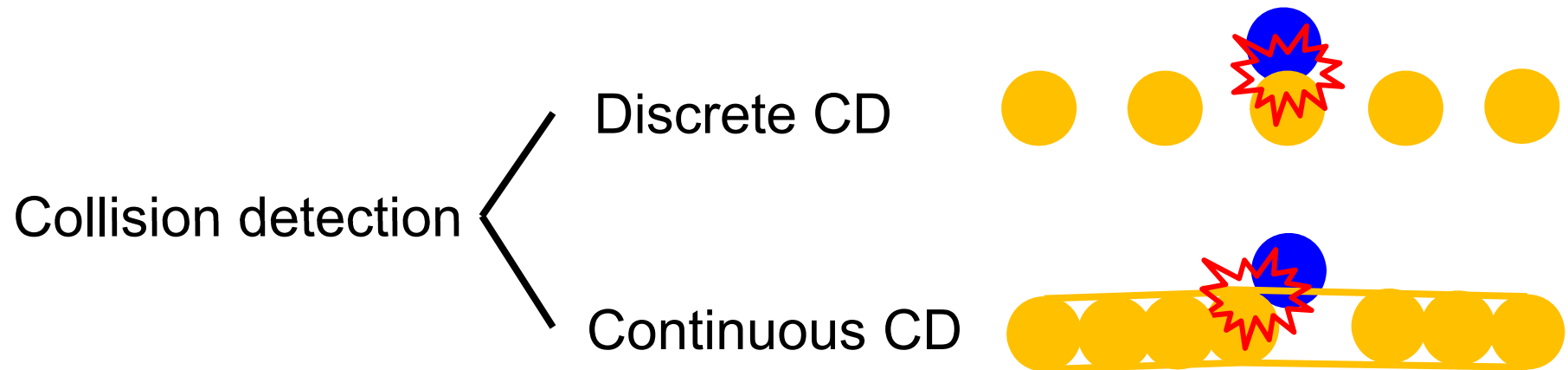
- Collision Handling  
= Collision Detection + Collision Response



# Three Parts of Cloth Simulation

## 3. Collision Handling

- Collision Handling  
= Collision Detection + Collision Response

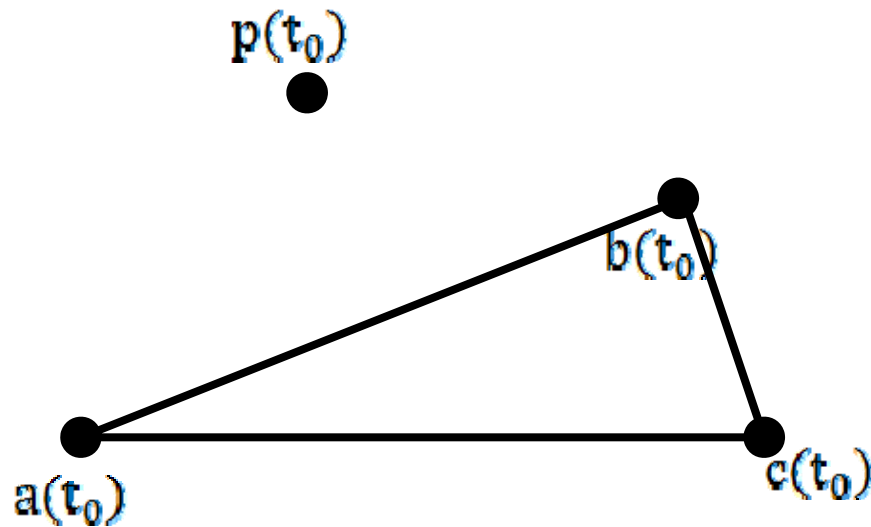


# Three Parts of Cloth Simulation

## 3. Collision Handling

- Collision and self-collision handling in cloth model dedicated to design garments

Xavier Provot, Graphics Interface, 1997.

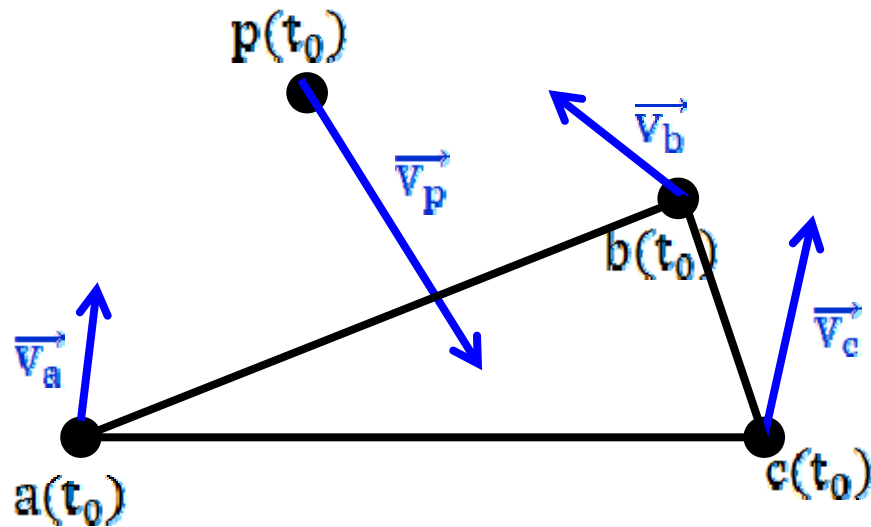


# Three Parts of Cloth Simulation

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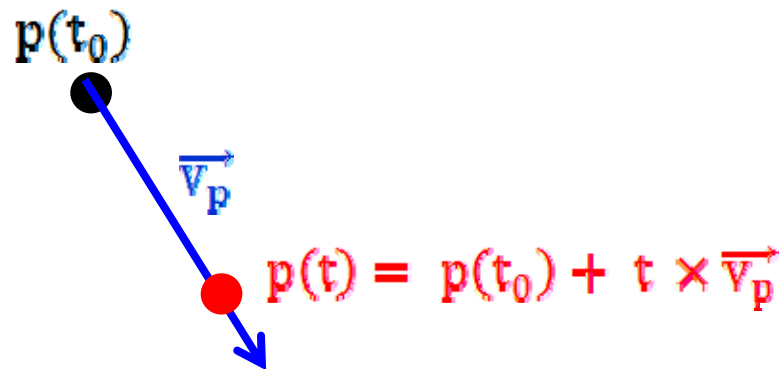


# Three Parts of Cloth Simulation

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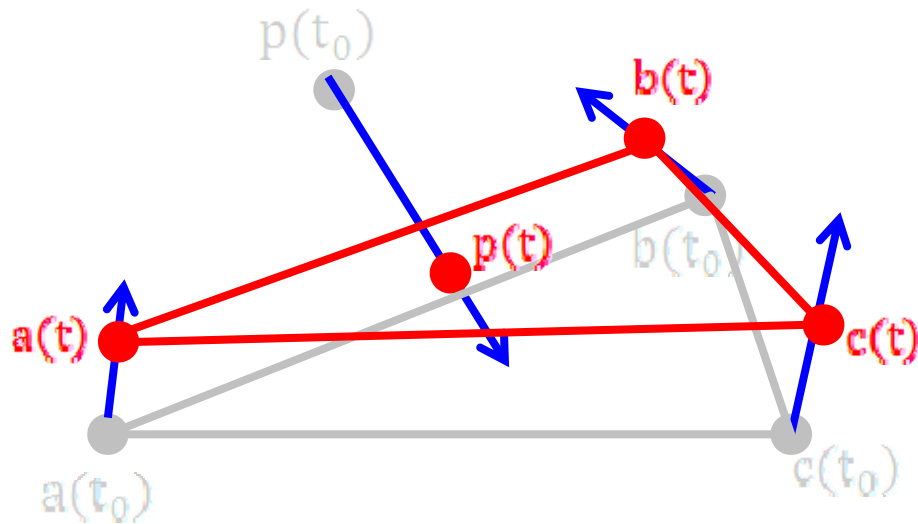


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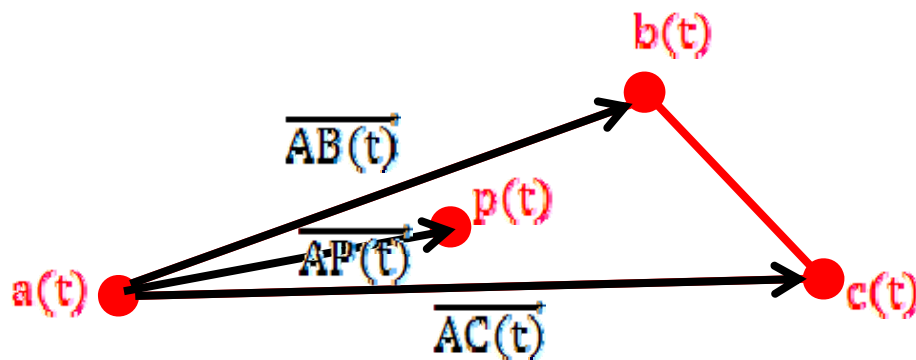
# Three Parts of Cloth Simulation

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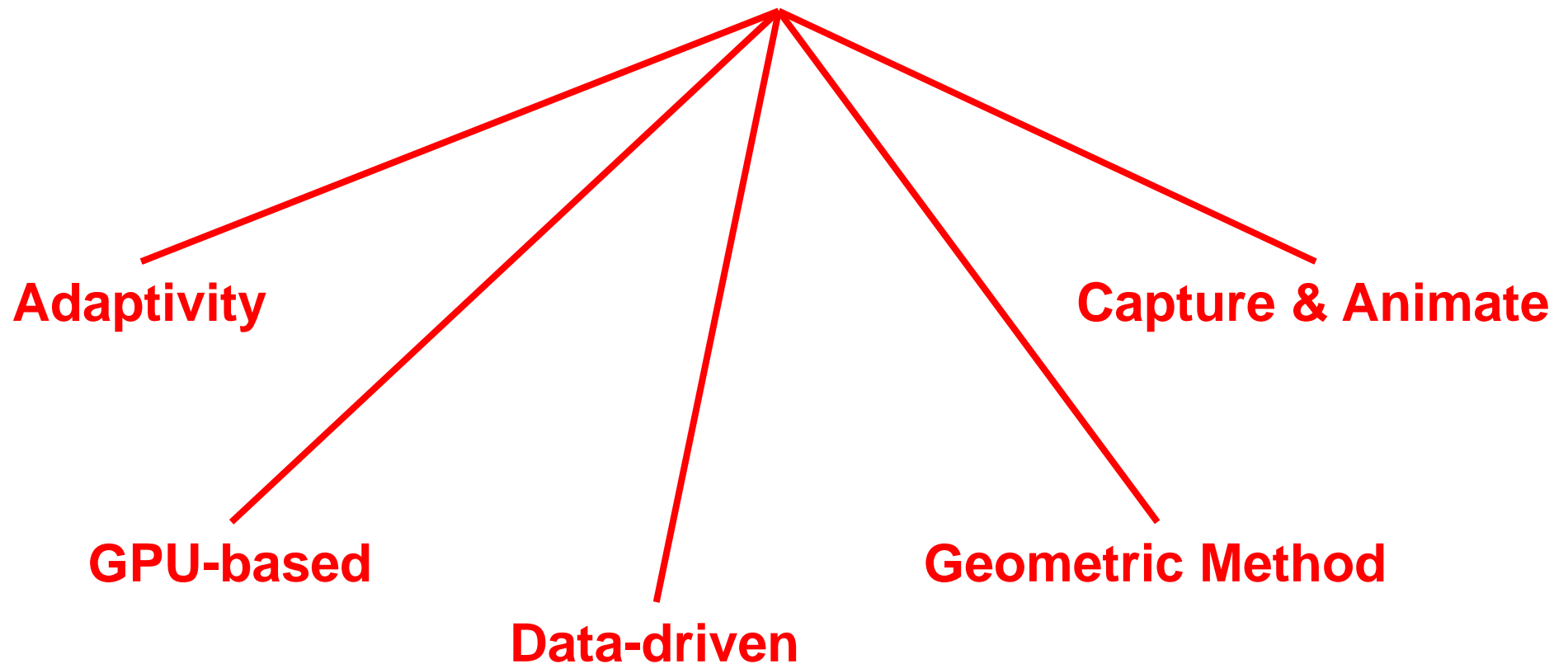
$$\exists t \in [t_0, t_0 + \Delta t] \text{ such that}$$
$$\exists u, v \in [0, 1], u + v \leq 1, \overrightarrow{AP}(t) = u\overrightarrow{AB}(t) + v\overrightarrow{AC}(t)$$



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# Sketch of recently developed methods

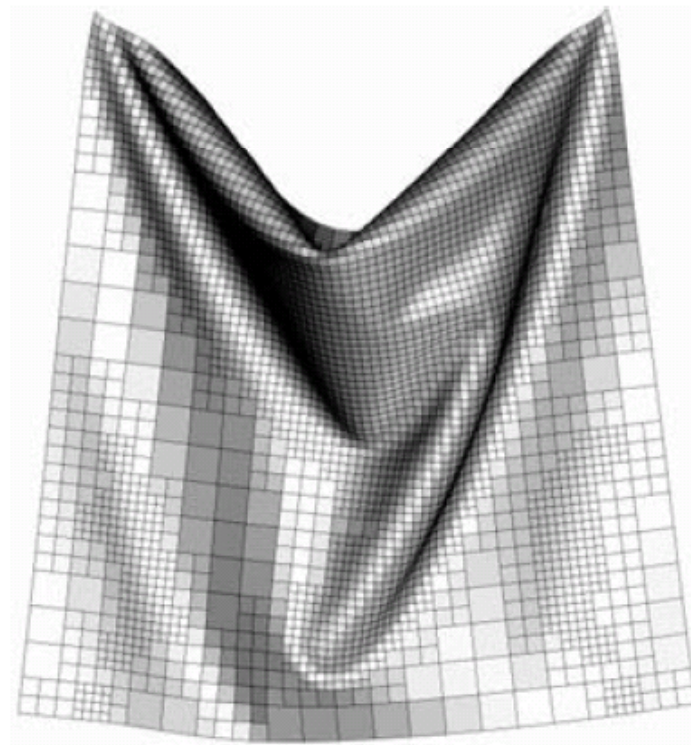
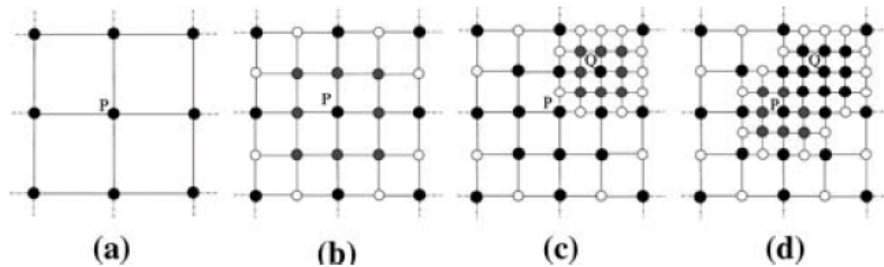




# Sketch of Recently Developed Methods

- Adaptive meshing for cloth animation

J. Villard, et al., Engineering with Computers, 2005.



**“Adaptivity”**

# Sketch of Recently Developed Methods

- GPU Based cloth simulation with Moving Humanoids

J. Rodriguez- Navarro, et al., 2005.



	fixed iter(20/40)	quasi-feedback
64 × 64	105/86	88-124
128 × 128	63/43	44-90
256 × 256	22/14	14-42

Table 1: Frame rate results for different cloth dimensions considering all body parts.

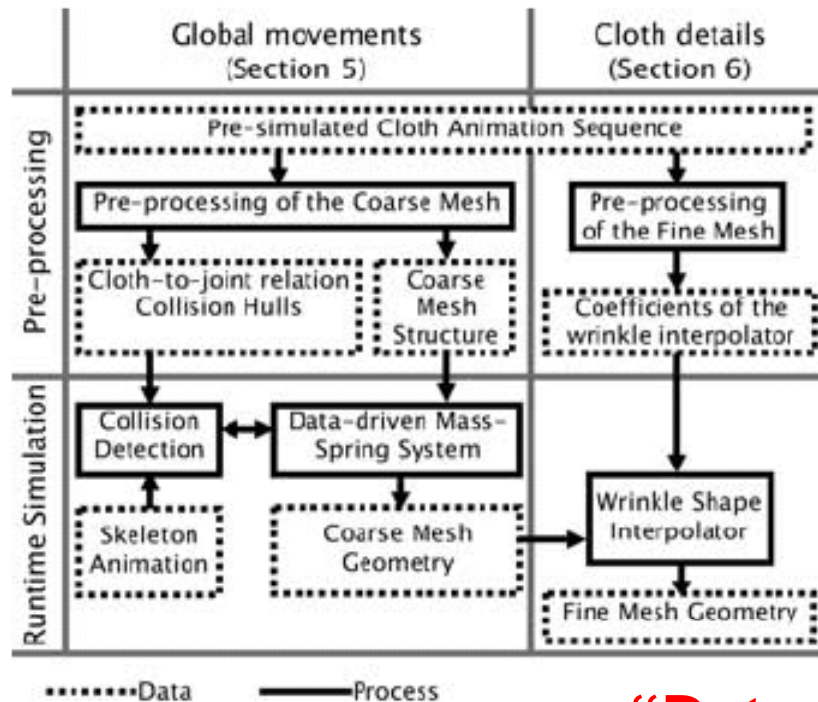
	fixed iter(20/40)	quasi-feedback
64 × 64	90-144/77-108	107-200
128 × 128	54-77/41-50	40-133
256 × 256	20-24/14-15	14-55

Table 2: Frame rate results for different cloth dimensions considering only body parts which can collide.

# Sketch of Recently Developed Methods

- A Data-Driven Approach for Real-Time Clothes Simulation

Frederic Cordier, et al., Pacific Graphics, 2005.

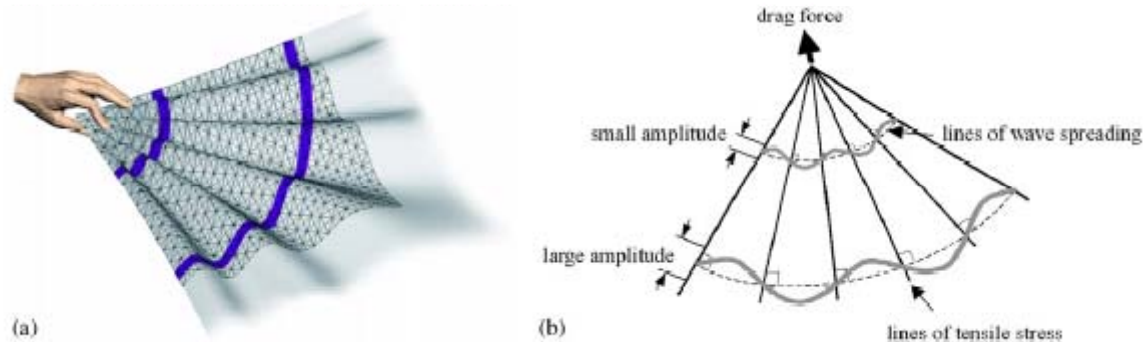


**“Data-Driven”**

# Sketch of Recently Developed Methods

- A real-time cloth draping simulation algorithm using conjugate harmonic functions

M. K. Kang, et al., Computers & Graphics, 2007.



**“Hybridization of geometric and physically based method”**

# Sketch of Recently Developed Methods

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- Capturing and Animating Occluded Cloth

Ryan White, et al., SIGGRAPH, 2007.



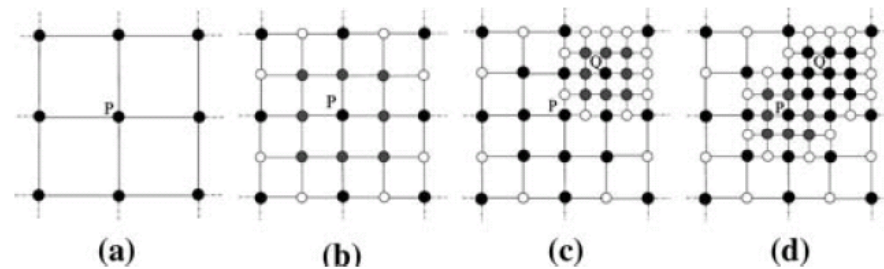
**“Capture & Animate”**

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# Challenging Problem

My works on adaptive simulation

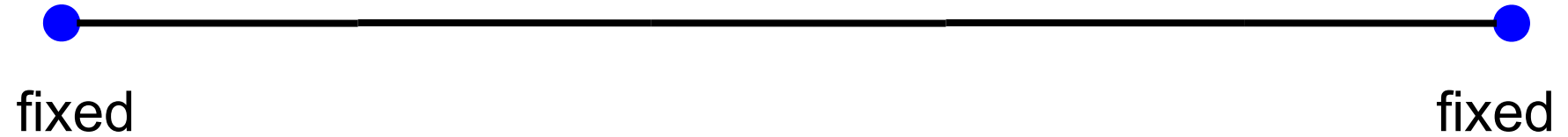


# Challenging Problem

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- Adaptive Cloth Simulation



# Challenging Problem

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- Adaptive Cloth Simulation





# Challenging Problem

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- Adaptive Cloth Simulation



# Challenging Problem

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- Adaptive Cloth Simulation



# Challenging Problem

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- Adaptive Cloth Simulation

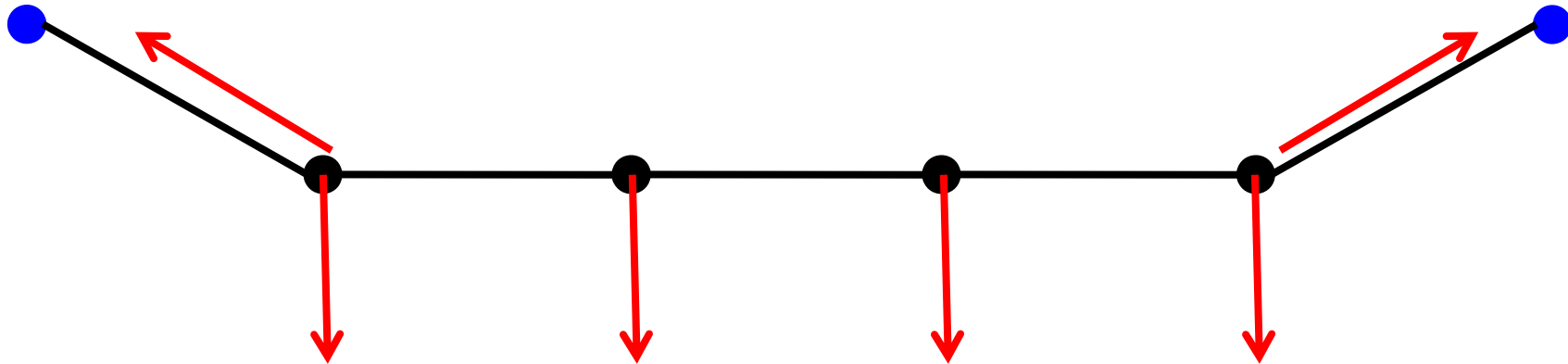


# Challenging Problem

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- Adaptive Cloth Simulation

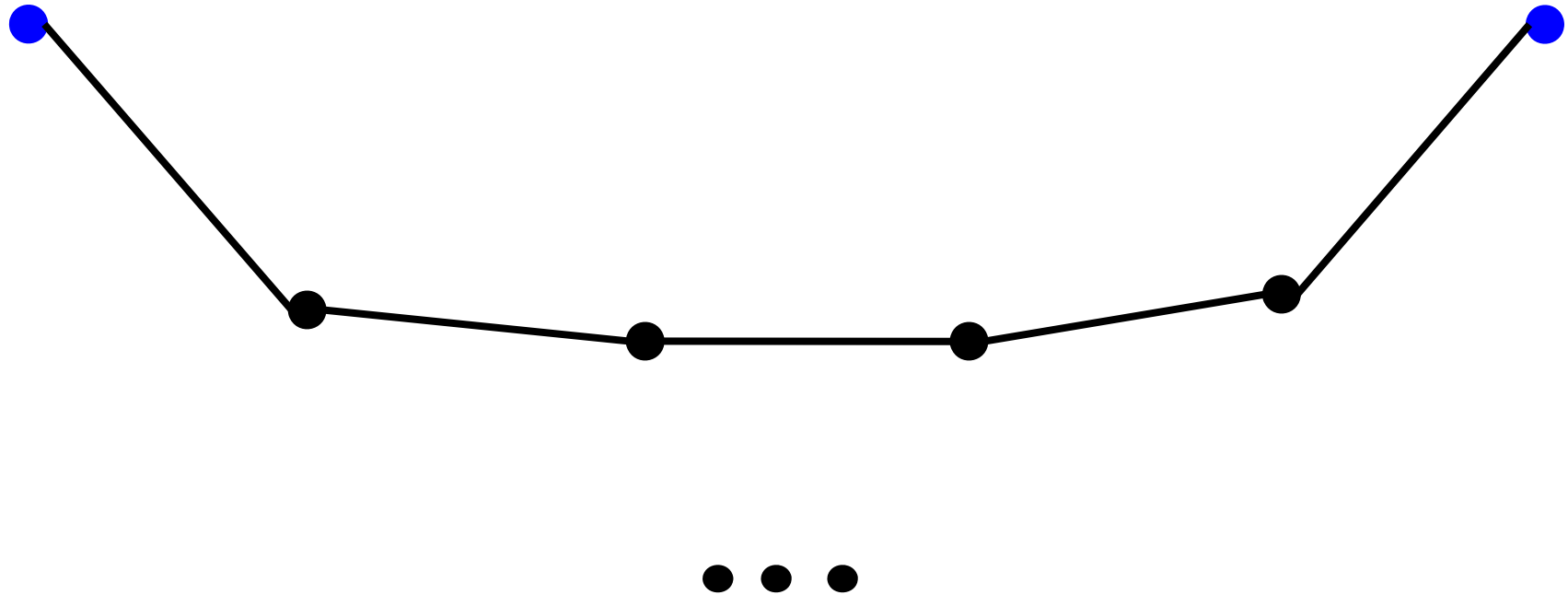


# Challenging Problem

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- Adaptive Cloth Simulation

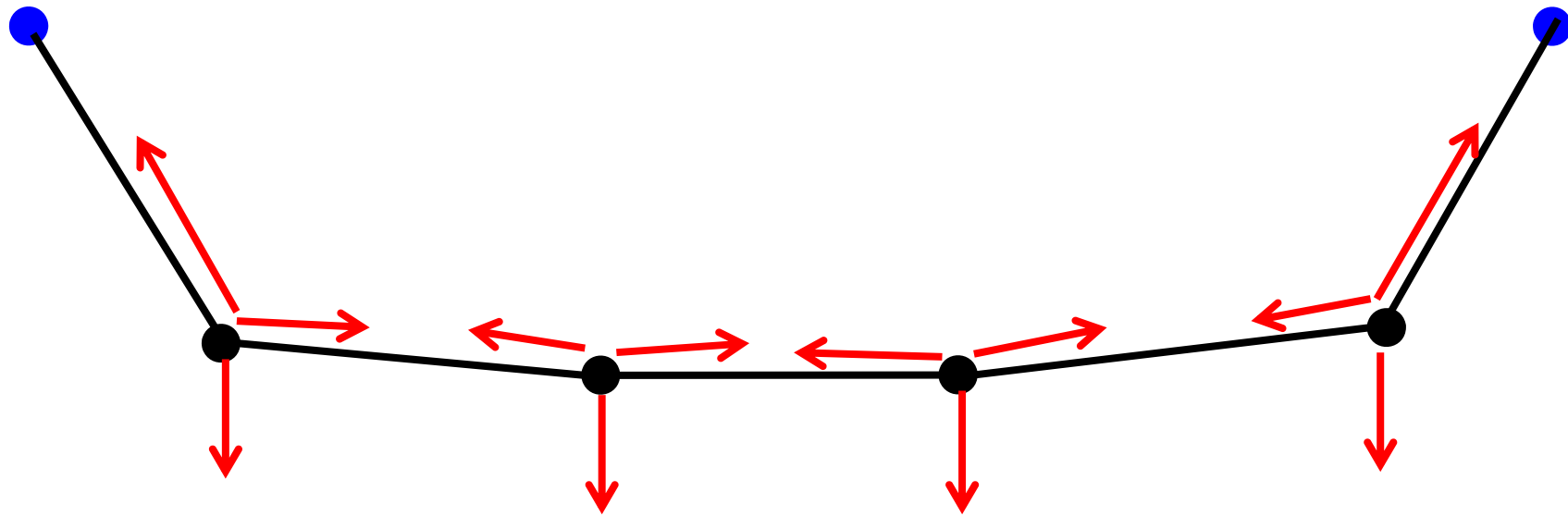


# Challenging Problem

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- Adaptive Cloth Simulation



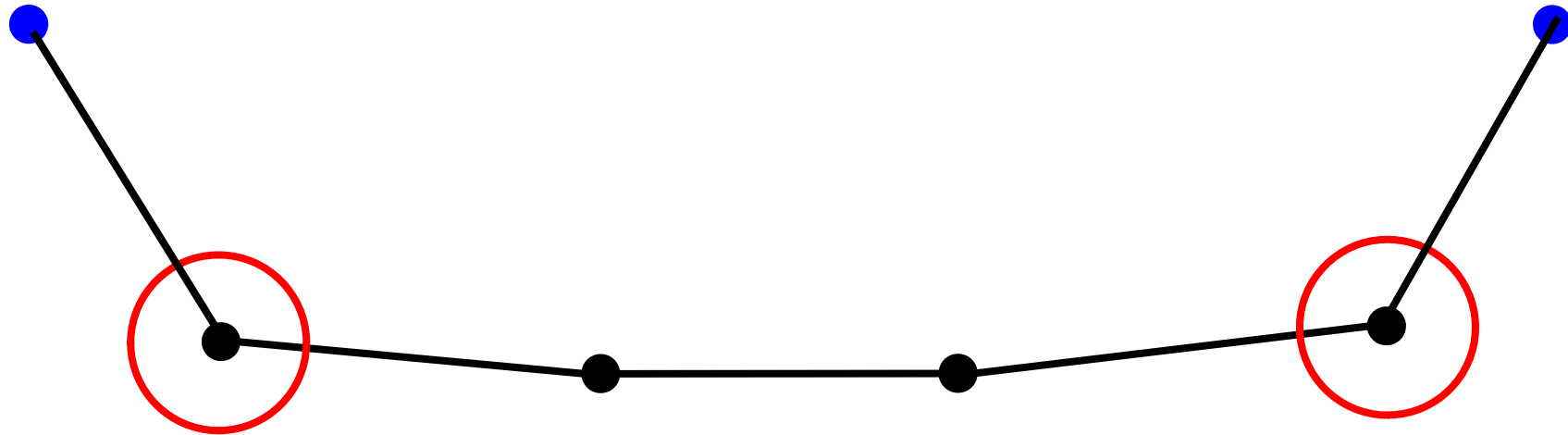
**“equilibrium status”**

# Challenging Problem

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- Adaptive Cloth Simulation



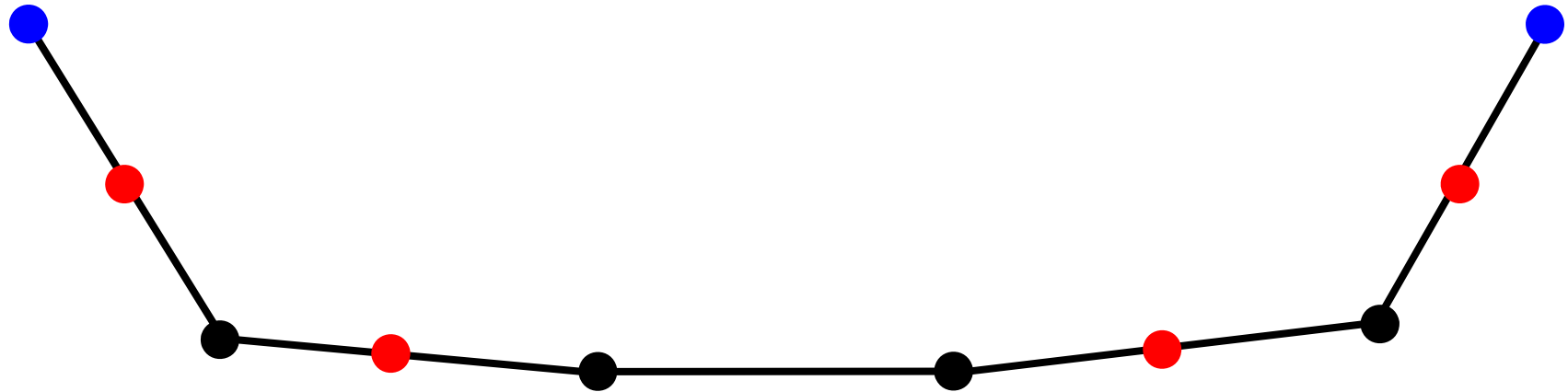
**“Refine”**

# Research

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- Adaptive Cloth Simulation



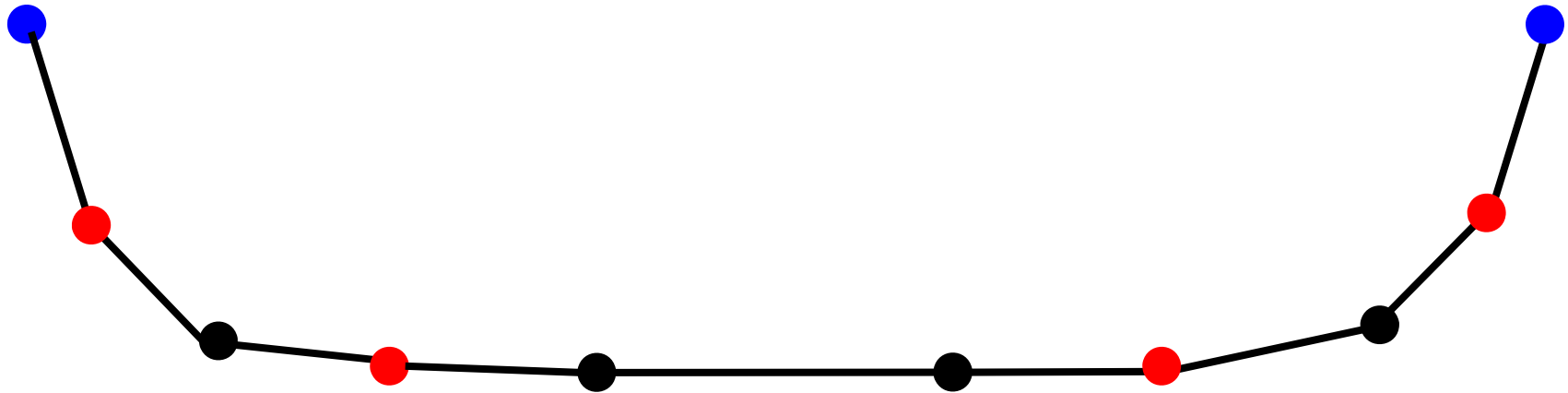


# Challenging Problem

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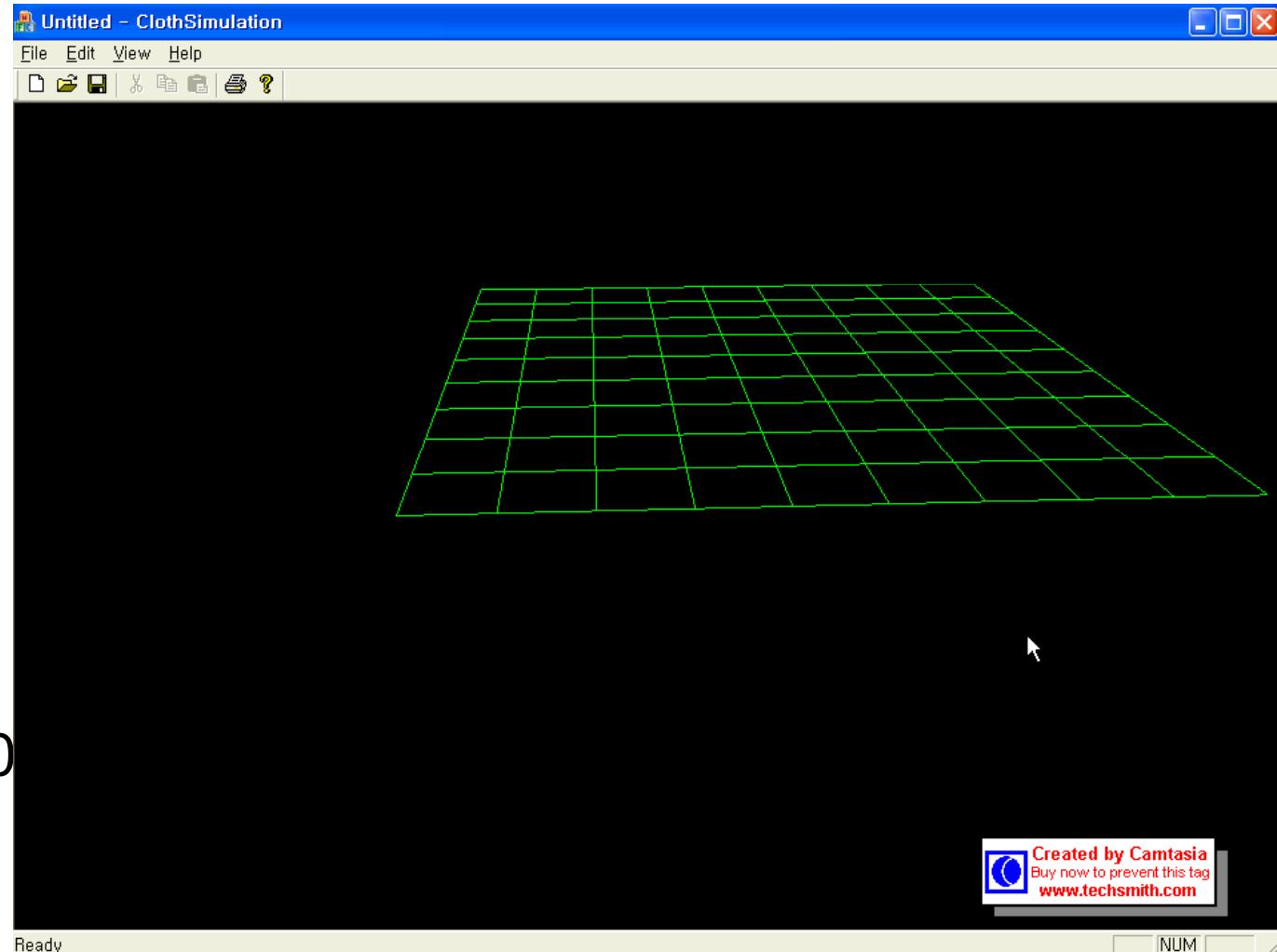
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- Adaptive Cloth Simulation



# Challenging Problem

- Adaptive Cloth Simulation
  - Demo



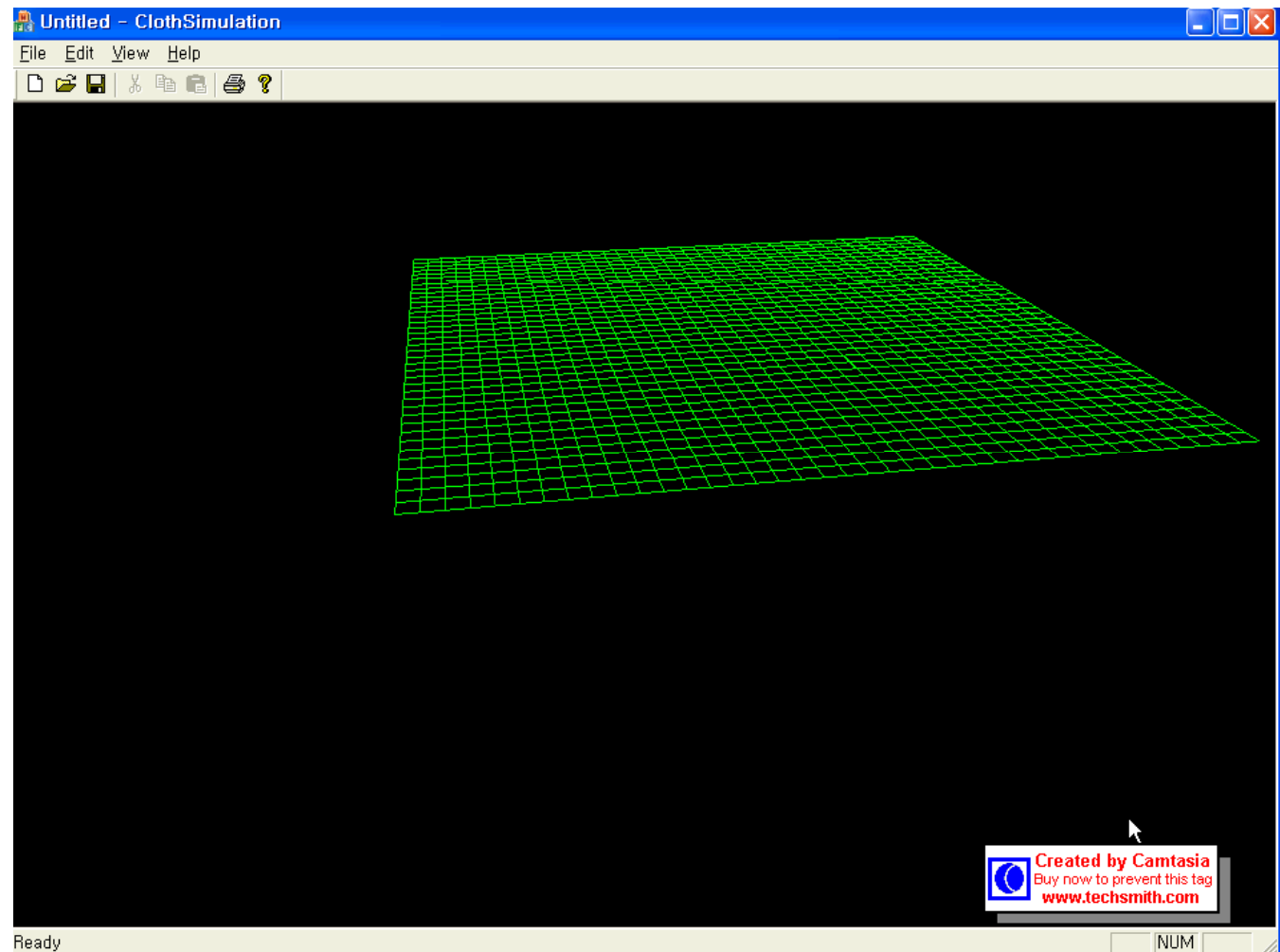
Grid size = 2

# of grid = 10 x 10

NO refine

# Challenging Problem

- Adaptive Cloth Simulation
  - Demo



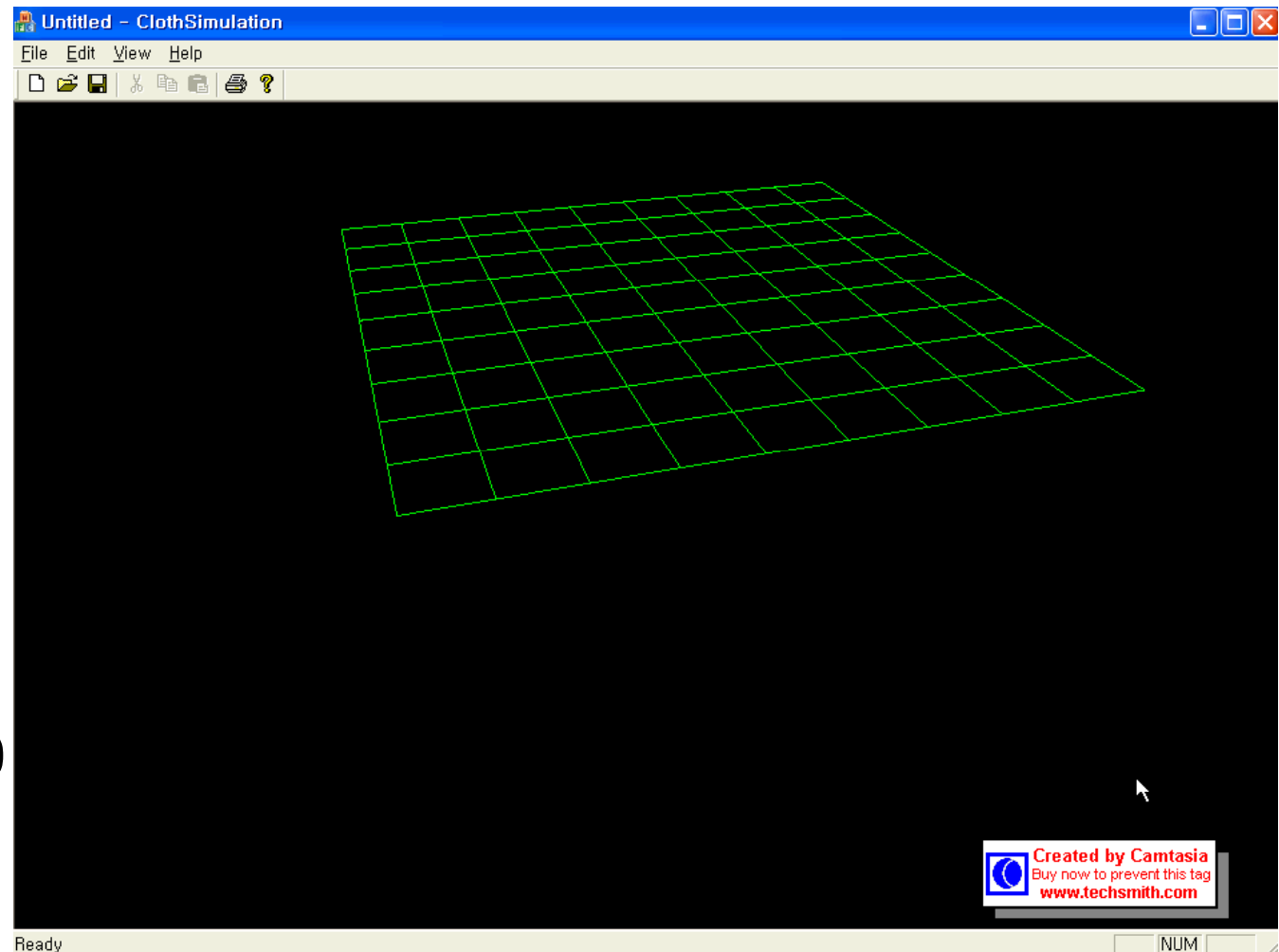
Grid size = 0.5

# of grid = 40 x 40

NO refine

# Challenging Problem

- Adaptive Cloth Simulation
  - Demo



Grid size = 2

# of grid = 10 x 10

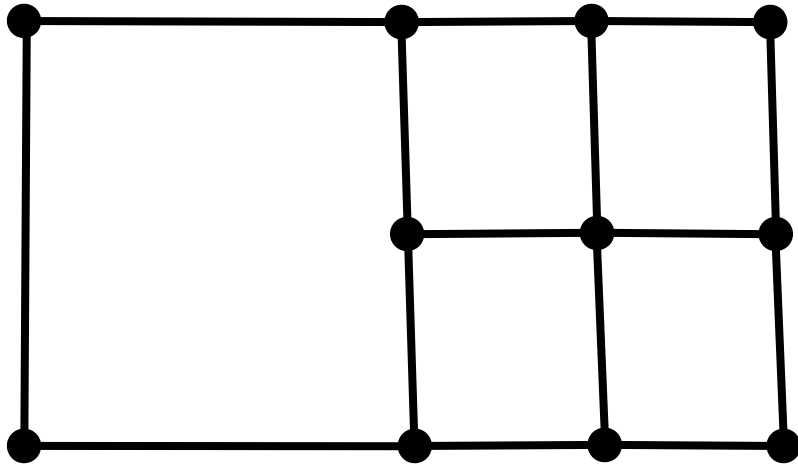
refine level : 2

# Challenging Problem

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- Adaptive Cloth Simulation
  - Problem
    1. T-junction Problem

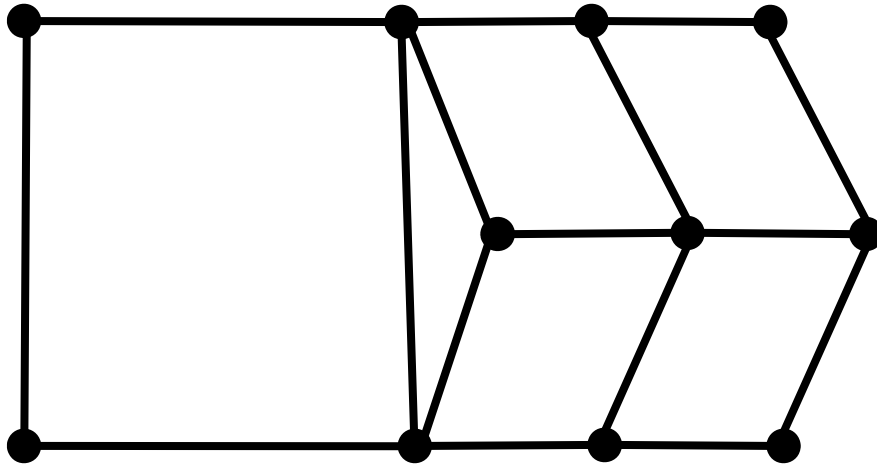


# Challenging Problem

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- Adaptive Cloth Simulation
  - Problem
    1. T-junction Problem

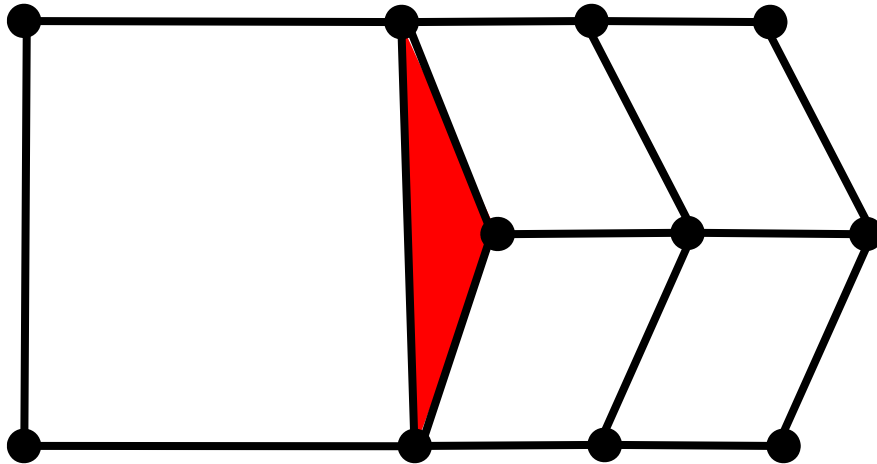


# Challenging Problem

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- Adaptive Cloth Simulation
  - Problem
    1. T- junction Problem



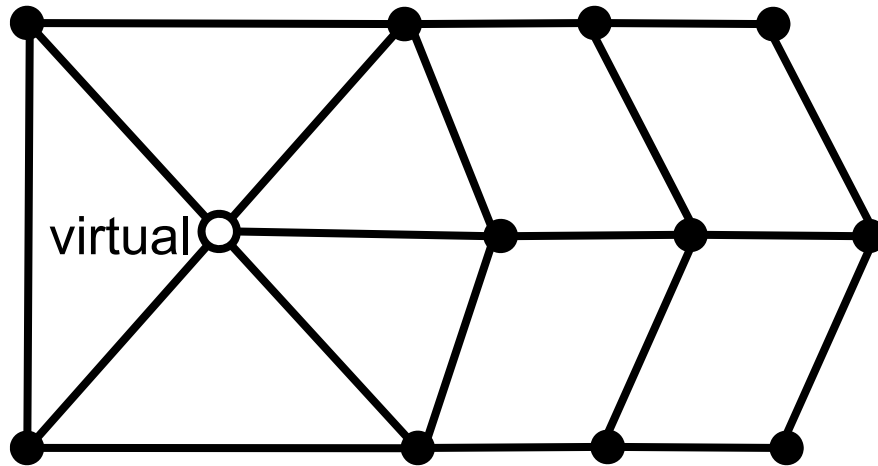
**“T-junction”**

# Challenging Problem

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- Adaptive Cloth Simulation
  - Problem
    1. T-junction Problem



**“4-8 subdivision rule”**

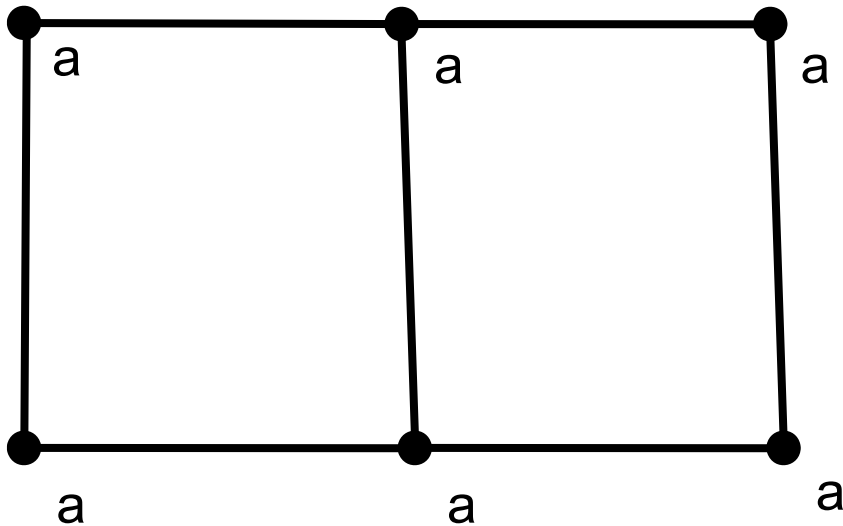


# Challenging Problem

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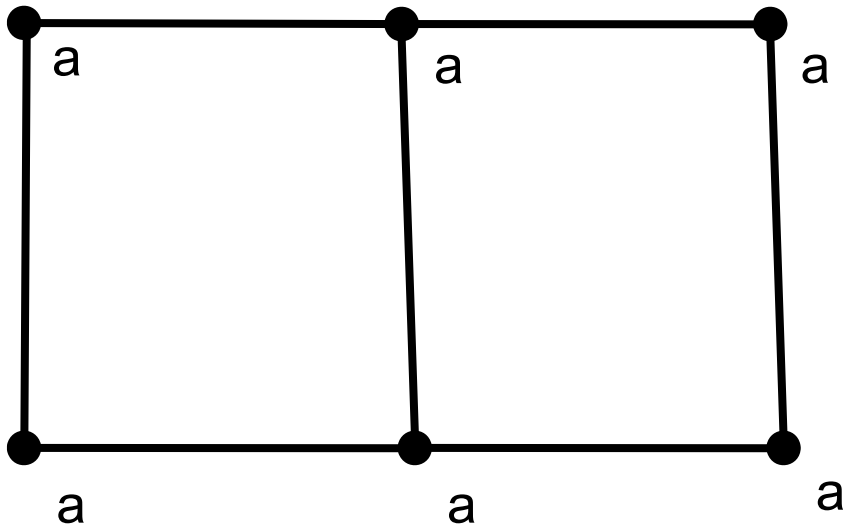
- Adaptive Cloth Simulation
  - Problem
    - 2. Mass distribution



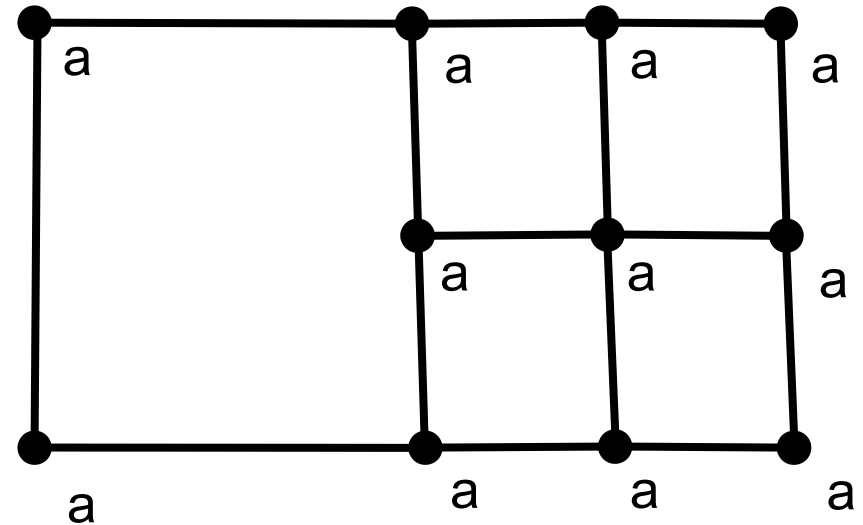
total mass =  $6a$

# Challenging Problem

- Adaptive Cloth Simulation
  - Problem
    - 2. Mass distribution



total mass =  $6a$



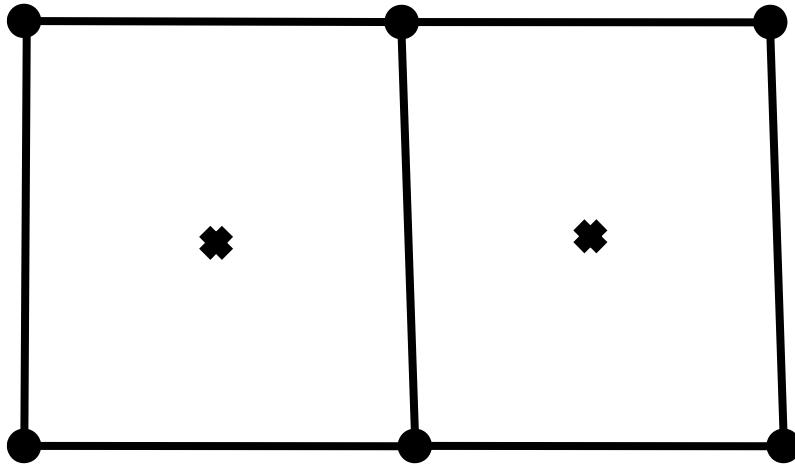
total mass =  $11a$

# Challenging Problem

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- Adaptive Cloth Simulation
  - Problem
    - 2. Mass distribution



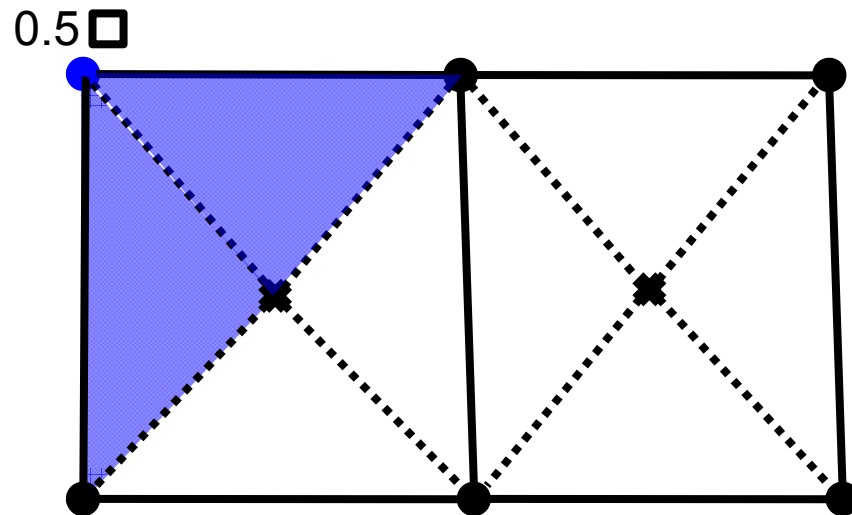


# Challenging Problem

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- Adaptive Cloth Simulation
  - Problem
    2. Mass distribution

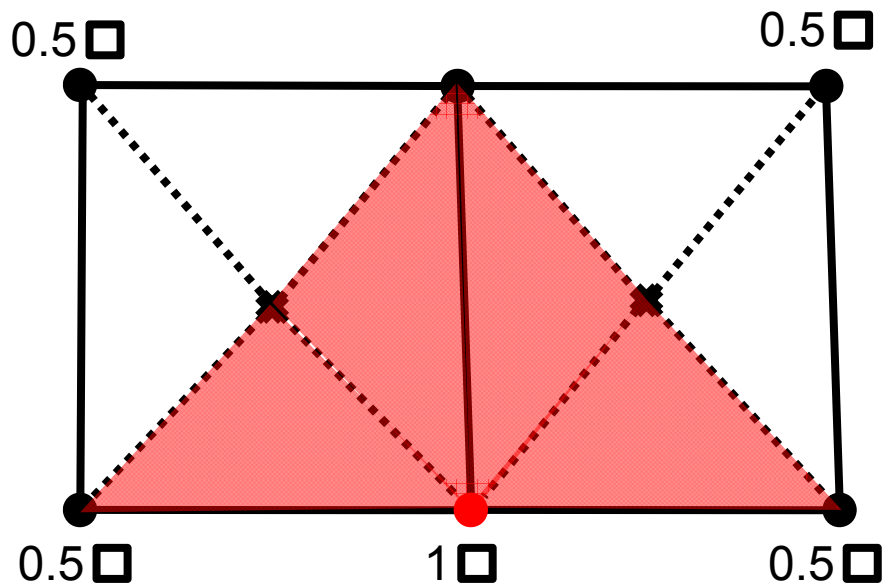


# Challenging Problem

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- Adaptive Cloth Simulation
  - Problem
    2. Mass distribution

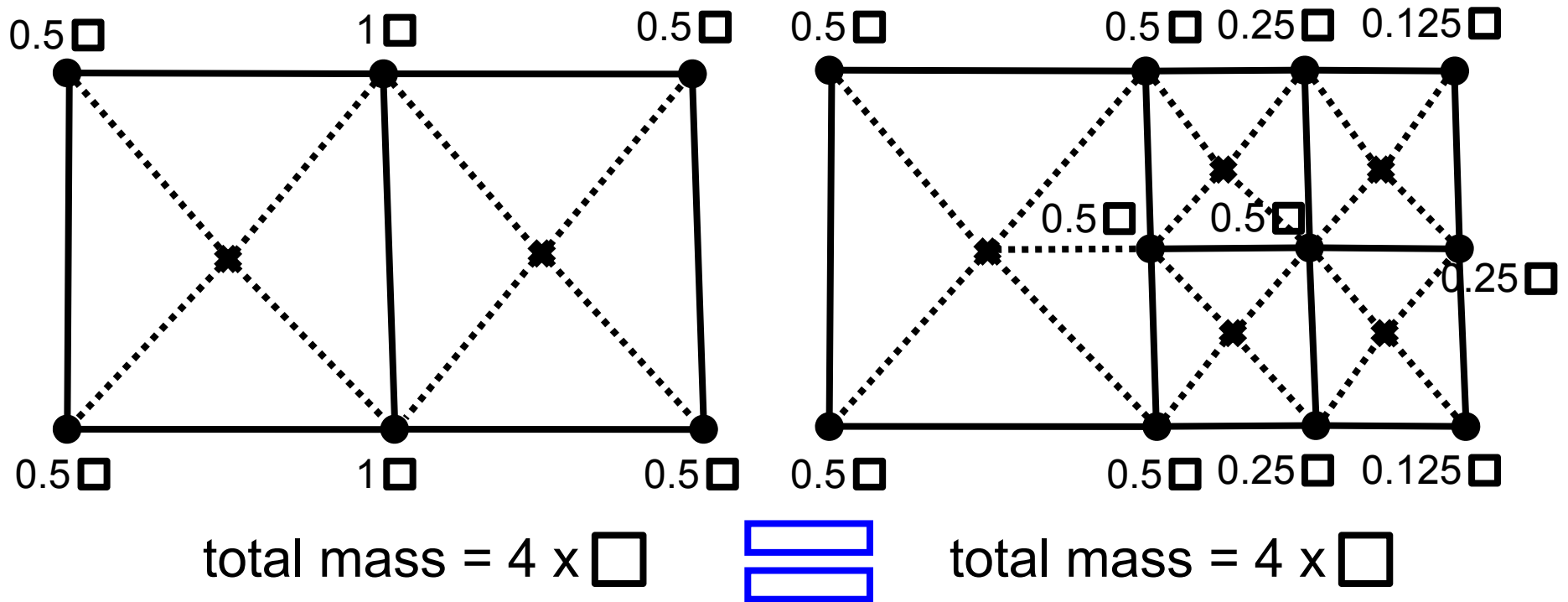


# Challenging Problem

- Adaptive Cloth Simulation

- Problem

2. Mass distribution



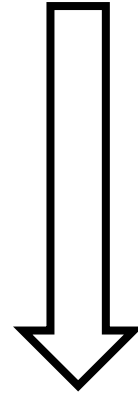
# Challenging Problem

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- Adaptive Cloth Simulation
  - Goal

Fast Cloth Simulation + Adaptive Cloth Simulation



View-dependent Multi-resolution

Adaptive Meshing

**Crowd Cloth Simulation**



# Conclusion

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- Cloth Simulation is popular since 1980s.
- Three Parts of Cloth Simulation is..
  - Cloth- Model System
  - Numerical Solver
  - Collision Handling
- But, still there is some challenging problem
- Crowd Cloth Simulation!