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Stable but Responsive Cloth

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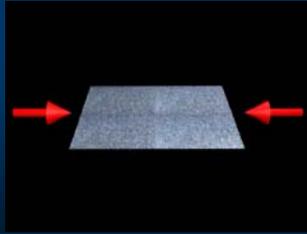
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Stable but Responsive Cloth?



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- Unstable Cloth



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- Stable but Non-Responsive Cloth



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Stability & Responsiveness do not GET ALONG!

- Damping can **Help** Stability
- Damping **Kills** Responsiveness

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- Damping can **Help** Stability
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What is the physical model behind cloth material?



Related Work

Physical Model

Terzopoulos and Fleischer, 1987
Carignan et al., 1992
Breen et al., 1994
Volino et al., 1995
Eberhardt et al., 1996
Eischen et al., 1996

Collision Resolution

Provot, 1997
Volino et al., 1995, 2000
Etmuss et al., 2000
Zhang and Yuen, 2000
Huh et al., 2001
Bridson and Fedkiw, 2002

Implicit Integration

Baraff and Witkin, 1998
Volino and Thalmann, 2000
Hauth and Etmuss, 2001

Interactive Simulation

Provot, 1995
Desbrun, 1999
Meyer et al., 1999
Kang et al., 2000, 2002

Physical Model of Cloth Material

- Weak resistance to bending
- Strong resistance to tension
- What about to **compression**?
 - Compression stiffness \approx Tension stiffness
 - Hookean model (Linear elastic model)

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$$\sigma = E\varepsilon, f = k(x-l)$$

Why Cloth Simulation is Unstable when Wrinkles are Formed?

An Experiment



- **Two Step Process**

- Resist + Buckle

- **How was the Buckling?**

- Explosive/Unstable

- Why?

strong resistance
to compression



weak resistance
to bending

It is a Physical Instability!

It's not a Numerical Instability

Interesting Findings

Will Cloth Behave Same Way?

- **Previous physical model is**

→ suited for paper

→ suited for aluminum sheet

→ **but not suited for cloth**

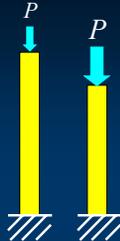
→ buckling of cloth is different

“Buckling”

Force : P



Compressed Length

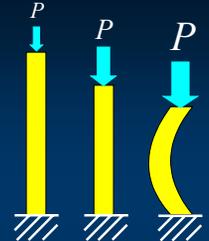


“Buckling”

Force : P



Compressed Length



Effect on Implicit Method

$$\left(\frac{\mathbf{I}}{\Delta t^2} + \mathbf{K} \right) \Delta \mathbf{x}_n = \mathbf{f}_{n-1}$$

- **Ill-conditioned or indefinite system matrix → Divergence!**

Stability can be Improved

$$\left(\frac{\mathbf{I}}{\Delta t^2} + \mathbf{K} \right) \Delta \mathbf{x}_n = \mathbf{f}_{n-1}$$

- **Reducing time step**

Stability can be Improved

$$\left(\frac{\mathbf{I}}{\Delta t^2} + \mathbf{K}\right)\Delta\mathbf{x}_n = \mathbf{f}_{n-1}$$

- Reducing time step \rightarrow Longer comp time

Stability can be Improved

$$\left(\frac{\mathbf{I}}{\Delta t^2} + \alpha\mathbf{K}\right)\Delta\mathbf{x}_n = \mathbf{f}_{n-1}$$

$(0 < \alpha < 1)$

- Reducing time step \rightarrow Longer comp time
- Reducing stiffness

Stability can be Improved

$$\left(\frac{\mathbf{I}}{\Delta t^2} + \alpha\mathbf{K}\right)\Delta\mathbf{x}_n = \mathbf{f}_{n-1}$$

$(0 < \alpha < 1)$

- Reducing time step \rightarrow Longer comp time
- Reducing stiffness \rightarrow Stretchy material

Stability can be Improved

$$\left(\frac{\mathbf{I}}{\Delta t^2} + \frac{\mathbf{D}}{\Delta t} + \alpha\mathbf{K}\right)\Delta\mathbf{x}_n = \mathbf{f}_{n-1}$$

- Reducing time step \rightarrow Longer comp time
- Reducing stiffness \rightarrow Stretchy material
- Adding damping

Stability can be Improved

$$\left(\frac{\mathbf{I}}{\Delta t^2} + \frac{\mathbf{D}}{\Delta t} + \alpha\mathbf{K}\right)\Delta\mathbf{x}_n = \mathbf{f}_{n-1}$$

- Reducing time step \rightarrow Longer comp time
- Reducing stiffness \rightarrow Stretchy material
- Adding damping \rightarrow Non-responsive cloth!

What We Propose:

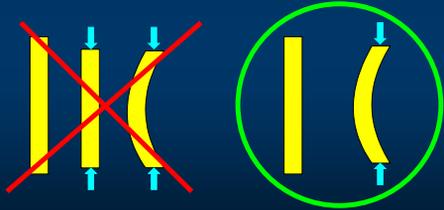
- Find a Physical Model that just makes \mathbf{K} always positive definite!

~~$$\left(\frac{\mathbf{I}}{\Delta t^2} + \frac{\mathbf{D}}{\Delta t} + \alpha\mathbf{K}\right)\Delta\mathbf{x}_n = \mathbf{f}_{n-1}$$~~

$$\left(\frac{\mathbf{I}}{\Delta t^2} + \mathbf{K}\right)\Delta\mathbf{x}_n = \mathbf{f}_{n-1}$$

How Can We Do That?

- Compression causes bending rather than shortening

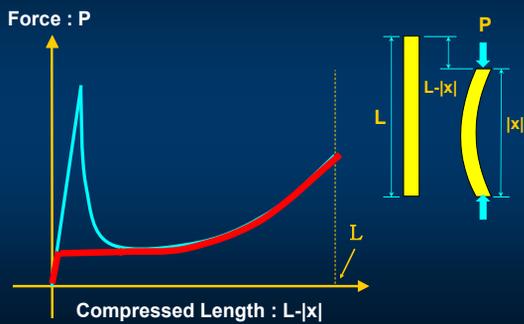


Immediate Buckling Assumption

Our Observation



New Force-Displacement Curve



The Stuff We Get

- A model that does not have buckling instability
→ Large time steps / Coarse meshes
- No Fictitious Damping is Needed
→ Realistic Cloth

Results



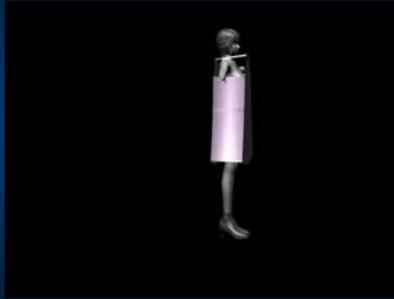
of particles = 3456, $\Delta t=0.011s$, CPU=0.25s

Leaping



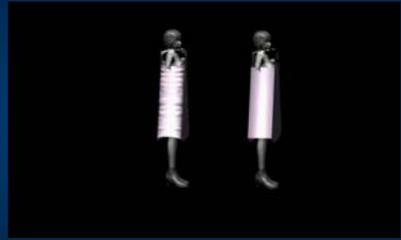
of particles = 5579, $\Delta t=0.011s$, CPU=0.47s

Walking



of particles = 5608, $\Delta t=0.011s$, CPU=0.51s

Comparison



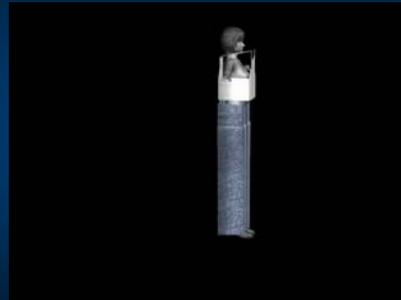
Fictitious damping
Adaptive time step size
Calculation time : 4 hours

No fictitious damping
Fixed time step size
Calculation time : 19 min

Contribution

- Found an Answer to: “Why Wrinkling is Unstable?”
- Proposed a “Realistic & Stable & Fast” Method

Jeans



of particles = 6624, $\Delta t=0.011s$, CPU=0.58s

Thank You

Limitations & Future Work

- Not suited for cloths that highly resist buckling
 - e.g. hemp cloth
- Uniform quadrilateral mesh limits the design freedom
 - Extend to irregular triangle mesh

Continuity Issue

- Sequential connection of elements



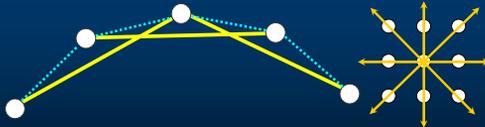
Continuity Issue

- Sequential connection of elements
 - Global bending is not handled



Continuity Issue

- Sequential connection of elements
 - Global bending is not handled
- Solution : Interlaced connection



Comparison 2

