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CS-184: Computer Graphics

Lecture #20: Spring and Mass systems

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Today

- Spring and Mass systems
  - Distance springs
  - Spring dampers
  - Edge springs

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Hanging Cloth

Huamin Wang, Ravi Ramamoorthi, and James F. O'Brien. "**Data-Driven Elastic Models for Cloth: Modeling and Measurement**". *ACM Transactions on Graphics*, 30(4):71:1–11, July 2011. Proceedings of ACM SIGGRAPH 2011, Vancouver, BC Canada.

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Walking Mannequin

Huamin Wang, Ravi Ramamoorthi, and James F. O'Brien. "**Data-Driven Elastic Models for Cloth: Modeling and Measurement**". *ACM Transactions on Graphics*, 30(4):71:1–11, July 2011. Proceedings of ACM SIGGRAPH 2011, Vancouver, BC Canada.

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A Simple Spring

- Ideal ***zero***-length spring

$$\boldsymbol{f}_{a\to b} = k_S(\boldsymbol{b} - \boldsymbol{a})$$

$$\boldsymbol{f}_{b\to a} = -\boldsymbol{f}_{a\to b}$$

- Force pulls points together
- Strength proportional to distance

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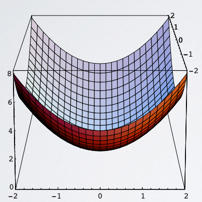
A Simple Spring

- Energy potential



$$E = 1/2\; k_S(\boldsymbol{b} - \boldsymbol{a}) \cdot (\boldsymbol{b} - \boldsymbol{a})$$

$$\boldsymbol{f}_{a\to b} = k_S(\boldsymbol{b} - \boldsymbol{a})$$

$$\boldsymbol{f}_{b\to a} = -\boldsymbol{f}_{a\to b}$$

$$\boldsymbol{f}_a = -\nabla_a E = -\left[\frac{\partial E}{\partial a_x}, \frac{\partial E}{\partial a_y}, \frac{\partial E}{\partial a_z}\right]$$

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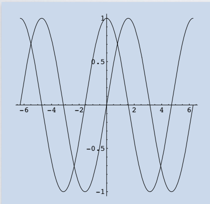
A Simple Spring

- Energy potential: kinetic *vs* elastic



$$E = 1/2\ k_S(\boldsymbol{b} - \boldsymbol{a}) \cdot (\boldsymbol{b} - \boldsymbol{a})$$

$$E = 1/2\ m(\dot{\boldsymbol{b}} - \dot{\boldsymbol{a}}) \cdot (\dot{\boldsymbol{b}} - \dot{\boldsymbol{a}})$$

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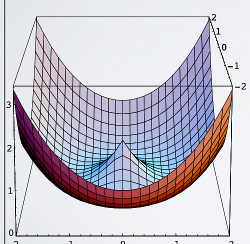
Non-Zero Length Springs

$$\boldsymbol{f}_{a \to b} = k_S \frac{\boldsymbol{b} - \boldsymbol{a}}{||\boldsymbol{b} - \boldsymbol{a}||} (||\boldsymbol{b} - \boldsymbol{a}|| - l)$$

Rest length



$$E = k_S\,(||\boldsymbol{b} - \boldsymbol{a}|| - l)^2$$

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Comments on Springs

- Springs with zero rest length are linear
- Springs with non-zero rest length are nonliner
  - Force ***magnitude*** linear w/ discplacement (from rest length)
  - Force direction is non-linear
  - Singularity at

$$||\boldsymbol{b} - \boldsymbol{a}|| = 0$$

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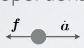
Damping

- "Mass proportional" damping



$$\boldsymbol{f} = -k_d \dot{\boldsymbol{a}}$$

  - Behaves like viscous drag on all motion
  - Consider a pair of masses connected by a spring
    - How to model rusty ***vs*** oiled spring
    - Should internal damping slow group motion of the pair?
  - Can help stability... up to a point

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Damping

- "Stiffness proportional" damping

$$\boldsymbol{f}_a = -k_d \frac{\boldsymbol{b}-\boldsymbol{a}}{||\boldsymbol{b}-\boldsymbol{a}||^2}(\boldsymbol{b}-\boldsymbol{a})\cdot(\dot{\boldsymbol{b}}-\dot{\boldsymbol{a}})$$

- Behaves viscous drag on change in spring length
- Consider a pair of masses connected by a spring
  - How to model rusty *vs* oiled spring
  - Should internal damping slow group motion of the pair?

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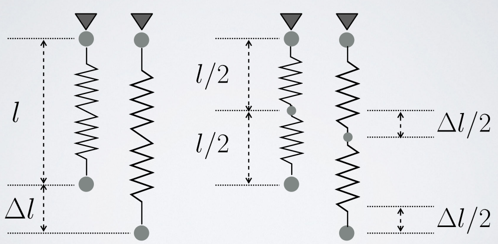
Spring Constants

- Two ways to model a single spring



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Spring Constants

- Constant k_S gives inconsistent results with different discretizations
- Change in length is not what we want to measure
- Strain: change in length as fraction of original length

$$\epsilon = \frac{\Delta l}{l_0}$$

Nice and simple for 1D...

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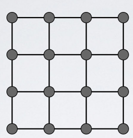
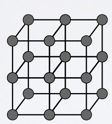
Structures from Springs

- Sheets



- Blocks



- Others

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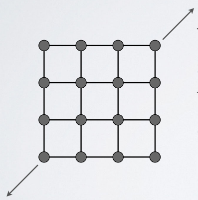
Structures from Springs

- They behave like what they are (obviously!)



This structure will not resist shearing

This structure will not resist out-of-plane bending either...

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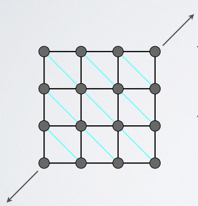
Structures from Springs

- They behave like what they are (obviously!)



This structure will resist shearing but has anisotopic bias

This structure still will not resist out-of-plane bending

Structures from Springs

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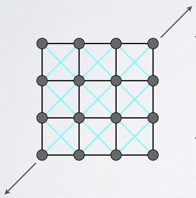
- They behave like what they are (obviously!)



This structure will resist shearing
Less bias
Interference between spring sets

This structure still will not resist out-of-plane bending

Structures from Springs

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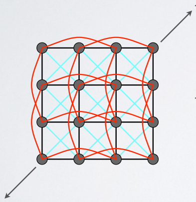
- They behave like what they are (obviously!)



This structure will resist shearing
Less bias
Interference between spring sets

This structure will resist out-of-plane bending
Interference between spring sets
Odd behavior

How do we set spring constants?

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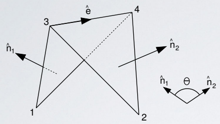
Edge Springs



$$u_1 = |E| \frac{N_1}{|N_1|^2} \qquad u_2 = |E| \frac{N_2}{|N_2|^2}$$

$$u_3 = \frac{(x_1 - x_4) \cdot E}{|E|} \frac{N_1}{|N_1|^2} + \frac{(x_2 - x_4) \cdot E}{|E|} \frac{N_2}{|N_2|^2}$$

$$u_4 = -\frac{(x_1 - x_3) \cdot E}{|E|} \frac{N_1}{|N_1|^2} - \frac{(x_2 - x_3) \cdot E}{|E|} \frac{N_2}{|N_2|^2}$$

$$F_i^e = k^e \frac{|E|^2}{|N_1| + |N_2|} \sin(\theta/2)\, u_i$$

From Bridson ***et al.***, 2003, also see Grinspun ***et al.***, 2003

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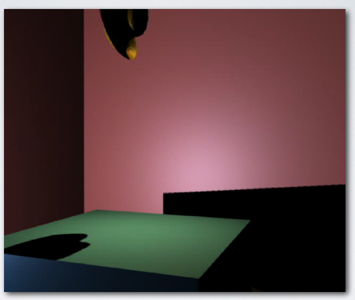
Example: Thin Material



Discrete Shells
SCA 2003
Eitan Grinspun, Anil Hirani, Mathieu Desbrun and Peter Schröder

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Strain Limiting

Bunny
Hollow Triangle Mesh
59K Elements

Huamin Wang, James F. O'Brien, and Ravi Ramamoorthi. "**Multi-Resolution Isotropic Strain Limiting**". In *Proceedings of ACM SIGGRAPH Asia 2010*, pages 160:1–10, December 2010.

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Adaptive Simulation

Suggested Reading

- Physically Based Modeling: Principles and Practice
  - Andy Witkin and David Baraff
  - http://www-2.cs.cmu.edu/~baraff/sigcourse/index.html
- Grinspun, Hirani, Desbrun, and Peter Schroder, "Discrete Shells," SCA 2003
- Bridson, Marino, and Fedkiw, "Simulation of Clothing with Folds and Wrinkles," SCA 2003
- O'Brien and Hodgins, "Graphical Modeling and Animation of Brittle Fracture," SIGGRAPH 99