CSCI 480 Computer Graphics
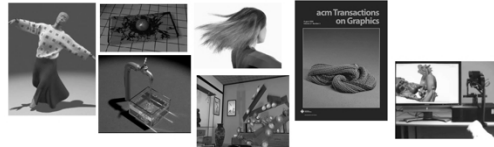Lecture 21

Physically Based Simulation

Examples
Particle Systems
Numerical Integration
Cloth Simulation
[Angel Ch. 11.2-11.6]

Apr 15, 2013
Jernej Barbic
University of Southern California
http://www-bcf.usc.edu/~jbarbic/cs480-s13/

1

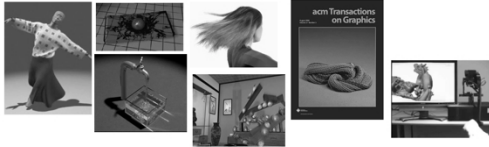## Physics in Computer Graphics

- Very common
- Computer Animation, Modeling (computational mechanics)
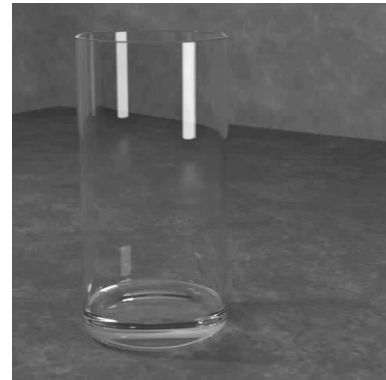- Rendering (computational optics)

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Physics in Computer Animation

- Fluids
- Smoke
- Deformable strands (rods)
- Cloth
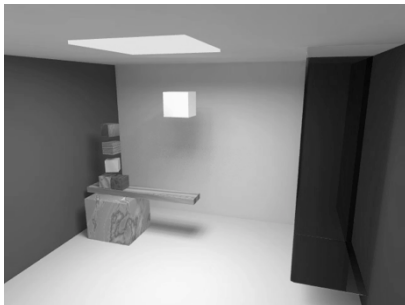- Solid 3D deformable objects .... and many more!

Fluids

Enright, Marschner,
Fedkiw,
SIGGRAPH 2002

Fluids and Rigid Bodies   [Carlson, Mucha, Turk, SIGGRAPH 2004]
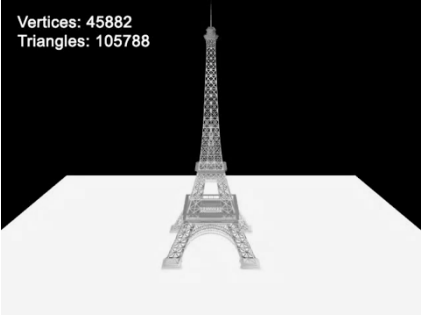

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Fluids with Deformable Solid Coupling

[Robinson-Mosher,
Shinar,
Gretarsson,
Su, Fedkiw,
SIGGRAPH 2008]

Two-way Coupling of Fluids to Rigid
and Deformable Solids and Shells

Avi Robinson-Mosher
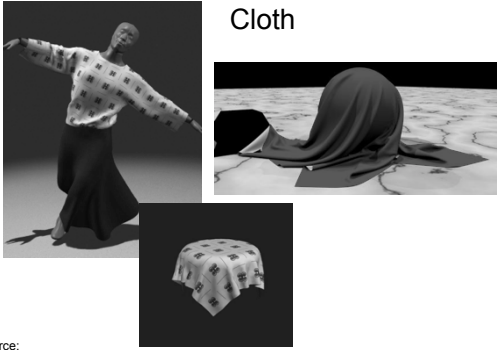Tamar Shinar
Jon Gretarsson
Jonathan Su
Ronald Fedkiw

Deformations

Vertices: 45882
Triangles: 105788
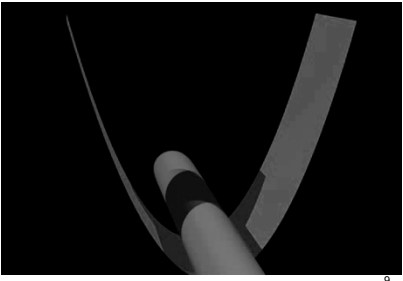
[Barbic and James, SIGGRAPH 2005]

Cloth

Source:
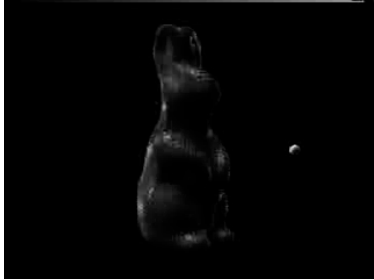ACM SIGGRAPH

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Cloth (Robustness)

[Bridson, Fedkiw, Anderson, ACM SIGGRAPH 2002

9

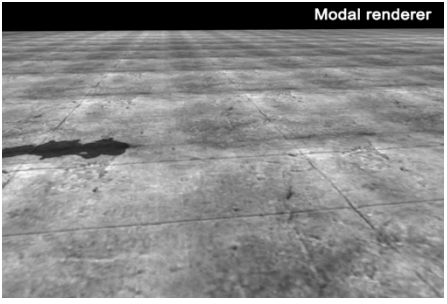### Simulating Large Models

[Doug James, PhD Thesis, UBC, 2001]

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Sound Simulation (Acoustics)

Modal renderer

[James, Barbic, Pai, SIGGRAPH 2006]
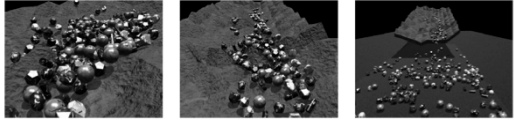
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Multibody Dynamics

Figure 1: *Avalanche:* 300 rocks tumble down a mountainside.

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Multibody Dynamics + Self-collision Detection

[Barbic and James, SIGGRAPH 2010]

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Physics in Games

Real-Time Deformation and Fracture
in a Game Environment

Eric Parker
Pixelux Entertainment

James O'Brien
U.C. Berkeley

Video Edited by Sebastian Burke

From the proceedings of SCA 2009, New Orleans

[Parker and James,
Symposium on Computer Animation 2009]

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Haptic Interfaces

• hap·tic ('hap-tik)
  a*dj*.
  Of or relating to the sense of touch; tactile.

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Surgical Simulation

[James and Pai,
SIGGRAPH 2002]

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Offline Physics

• Special effects (film, commercials)

• Large models:
  millions of particles / tetrahedra / triangles

• Use computationally expensive rendering
  (global illumination)

• Impressive results

• Many seconds of computation time per frame

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Real-time Physics

• Interactive systems:
  computer games
  virtual medicine (surgical simulation)

• Must be fast (30 fps, preferably 60 fps for games)
  Only a small fraction of CPU time devoted to
  physics!

• Has to be stable, regardless of user input

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Particle System

- Basic physical system in computer graphics

- We have N particles

- They interact with some forces

- Fire, Smoke, Cloth, ...

[William Reeves, SIGGRAPH 1983]
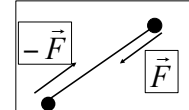
- Very popular for its simplicity

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Newton's Laws
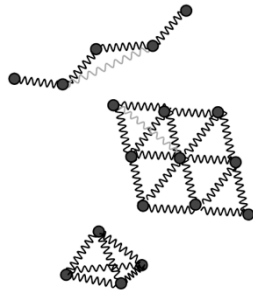
- Newton's 2nd law:

$$\vec{F} = m\vec{a}$$

- Gives acceleration, given the force and mass

- Newton's 3rd law: If object A exerts a force F on object B, then object B is at the same time exerting force -F on A.

$-\vec{F}$ $\vec{F}$

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Case Study: Mass-spring Systems

- Mass particles connected by elastic springs

- One dimensional: rope, chain

- Two dimensional: cloth, shells

- Three dimensional: soft bodies
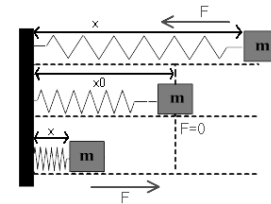
Source:Matthias Mueller, SIGGRAPH

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Single spring

- Obeys the *Hook's law*:

    F = k (x - x$_0$)

- x$_0$ = rest length
- k = spring elasticity (*stiffness*)
- For x<x$_0$, spring wants to extend
- For x>x$_0$, spring wants to contract

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Hook's law in 3D

- Assume A and B two mass points connected with a spring.
- Let L be the vector pointing from B to A
- Let R be the spring rest length
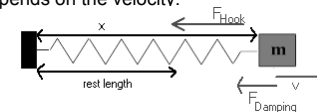- Then, the elastic force exerted on A is:

$$\vec{F} = -k_{Hook}(|\vec{L}| - R)\frac{\vec{L}}{|\vec{L}|}$$

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Damping

- Springs are not completely elastic
- They absorb some of the energy and tend to decrease the velocity of the mass points attached to them
- Damping force depends on the velocity:

$$\vec{F} = -k_d\vec{v}$$

F$_{Hook}$

rest length   F$_{Damping}$

- k$_d$ = damping coefficient
- k$_d$ different than k$_{Hook}$!!

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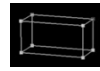## A network of springs

- Every mass point connected to some other points by springs

- Springs exert forces on mass points
  - Hook's force
  - Damping force

- Other forces
  - External force field
    - Gravity
    - Electrical or magnetic force field
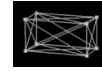 - Collision force
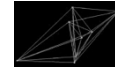
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Network organization is critical

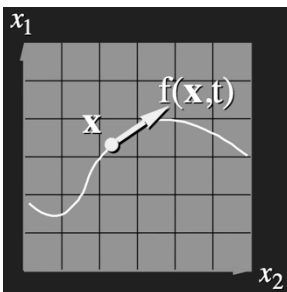- For stability, must organize the network of springs in some clever way

Basic network   Stable network   Network out of control
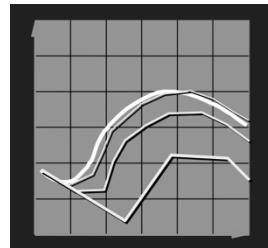
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Time Integration

x_1

$f(\mathbf{x}, t)$

$\mathbf{x}$

x_2

Source:Andy Witkin, SIGGRAPH

Physics equation:
$x' = f(x, t)$

$x = x(t)$ is particle trajectory

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Euler Integration

$x(t + \Delta t) = x(t) + \Delta t\, f(x(t))$
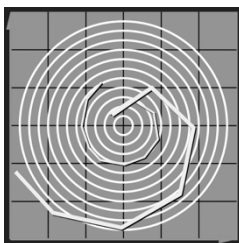

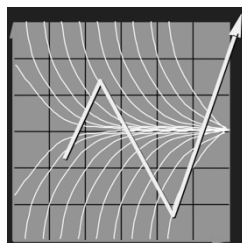Simple, but inaccurate.

Unstable with large timesteps.

Source:Andy Witkin, SIGGRAPH

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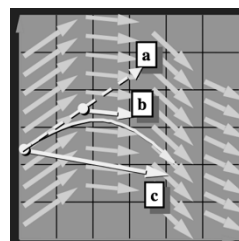## Inaccuracies with explicit Euler

Gain energy   "Blow-up"

Source:Andy Witkin, SIGGRAPH

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Midpoint Method

a

b

c

Source:Andy Witkin, SIGGRAPH

Improves stability

1. Compute Euler step
   $\Delta x = \Delta t\, f(x, t)$

2. Evaluate f at the midpoint
   $f_{mid} = f((x + \Delta x)/2, (t + \Delta t)/2)$

3. Take a step using the midpoint value
   $x(t + \Delta t) = x(t) + \Delta t\, f_{mid}$

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Many more methods

- Runge-Kutta (4th order and higher orders)

- Implicit methods
  - sometimes unconditionally stable
  - very popular (e.g., cloth simulations)
  - a lot of damping with large timesteps

- Symplectic methods
  - exactly preserve energy, angular momentum and/or other physical quantities
  - Symplectic Euler

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Cloth Simulation

- Cloth Forces
  - Stretch
  - Shear
  - Bend
- Many methods are a more advanced version of a mass-spring system
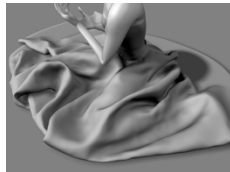- Derivatives of Forces
  - necessary for stability

[Baraff and Witkin, SIGGRAPH 1998]

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Challenges

- Complex Formulas

- Large Matrices

- Stability

- Collapsing triangles

[Govindaraju et al. 2005]

- Self-collision detection
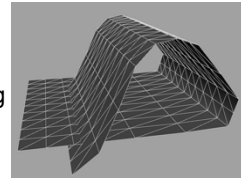
33

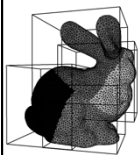## Self-collisions: definition

Deformable model is self-colliding iff

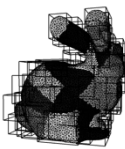there exist non-neighboring intersecting triangles.
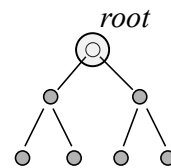
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Bounding volume hierarchies

AABBs Level 1   AABBs Level 3

[Hubbard 1995]

[Gottschalk et al. 1996]

[van den Bergen 1997]

[Bridson et al. 2002]
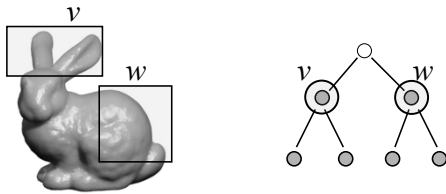
[Teschner et al. 2002]

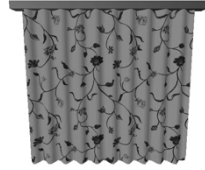[Govindaraju et al. 2005]

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Bounding volume hierarchy

root   *root*

36

Bounding volume hierarchy

v

w

v w

37

Real-time cloth simulation

Source:
Andy Pierce

Model	Triangles	FPS	% Forces + Stiffness Matrix	% Solver
Curtain	2400	25	67	33

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Multithreading implementation
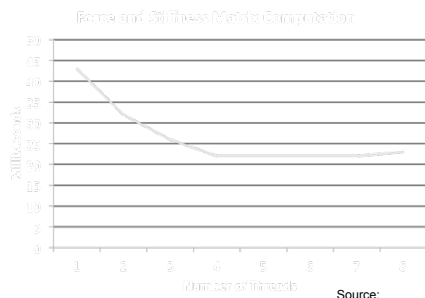
Source:
Andy Pierce

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Summary

- Examples of physically based simulation

- Particle Systems

- Numerical Integration

- Cloth Simulation

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