

Physically Based Simulation

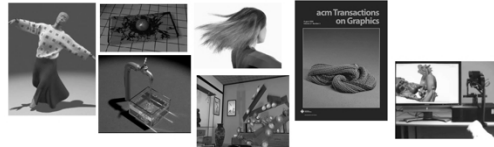
Examples
Particle Systems
Numerical Integration
Cloth Simulation
[Angel Ch. 11.2-11.6]

Jernej Barbic
University of Southern California

1

Physics in Computer Graphics

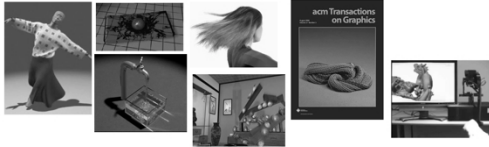
- Very common
- Computer Animation, Modeling (computational mechanics)
- Rendering (computational optics)



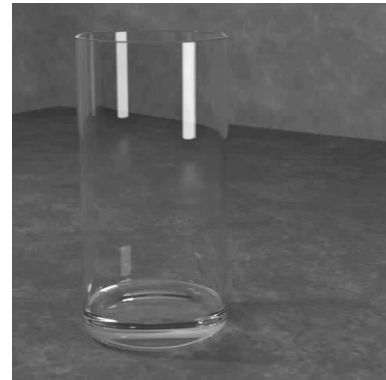
2

Physics in Computer Animation

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



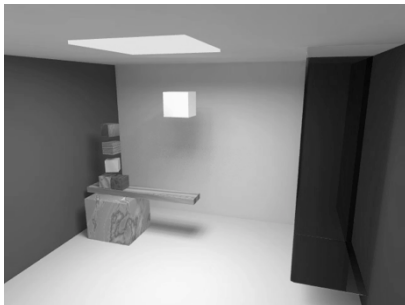
Fluids



Enright, Marschner,
Fedkiw,
SIGGRAPH 2002

Fluids and Rigid Bodies

[Carlson, Mucha, Turk,
SIGGRAPH 2004]



5

Fluids with Deformable Solid Coupling

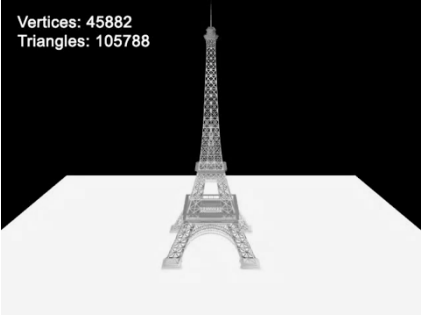
[Robinson-Mosher,
Shinar,
Gretarsson,
Su, Fedkiw,
SIGGRAPH 2008]

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

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

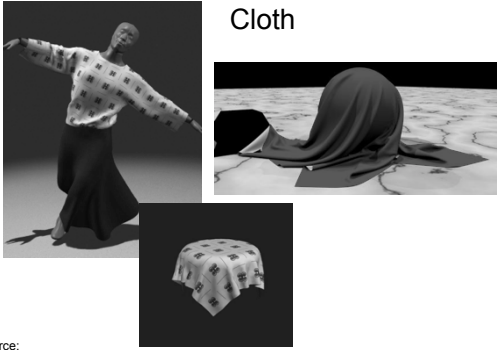
Deformations

Vertices: 45882
Triangles: 105788



[Barbic and James, SIGGRAPH 2005]

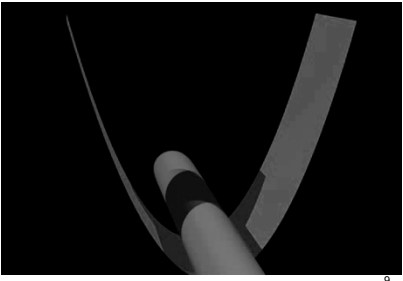
Cloth



Source:
ACM SIGGRAPH

8

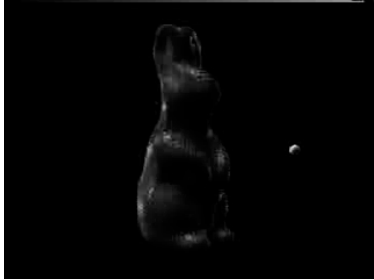
Cloth (Robustness)



[Bridson, Fedkiw, Anderson, ACM SIGGRAPH 2002]

9

Simulating Large Models

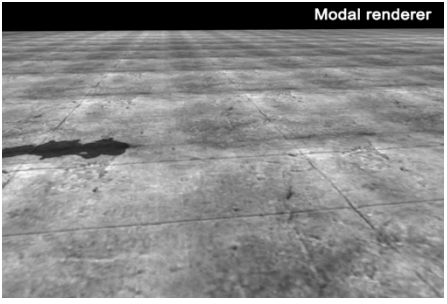


[Doug James, PhD Thesis, UBC, 2001]

10

Sound Simulation (Acoustics)

Modal renderer



[James, Barbic, Pai, SIGGRAPH 2006]

11

Multibody Dynamics

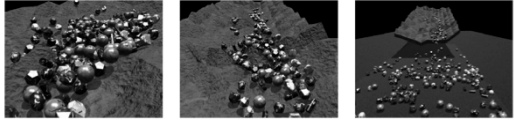


Figure 1: *Avalanche*: 300 rocks tumble down a mountainside.

12

Multibody Dynamics + Self-collision Detection



[Barbic and James, SIGGRAPH 2010]

13

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]

14

Haptic Interfaces

- hap-tic ('hap-tik)
adj.
Of or relating to the sense of touch; tactile.



15

Surgical Simulation



[James and Pai,
SIGGRAPH 2002]

16

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

17

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

18

Particle System

- Basic physical system in computer graphics
- We have N particles
- They interact with some forces
- Fire, Smoke, Cloth, ...
- Very popular for its simplicity



[William Reeves, SIGGRAPH 1983]

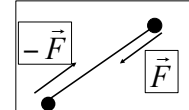
19

Newton's Laws

- Newton's 2nd law:

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

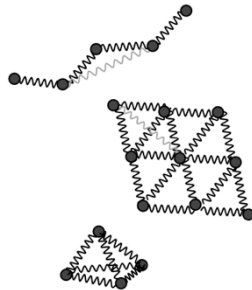
- Gives acceleration, given the force and mass
- Newton's 3rd law: If object A exerts a force F on object B, then object B is at the same time exerting force -F on A.



20

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

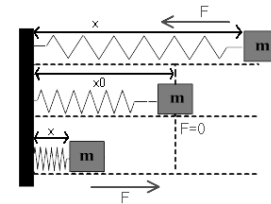
21

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



22

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:

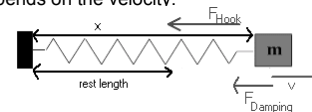
$$\vec{F} = -k_{Hook} (|\vec{L}| - R) \frac{\vec{L}}{|\vec{L}|}$$

23

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:

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



- k_d = damping coefficient
- k_d different than k_{Hook} !!

24

A network of springs

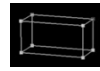
- Every mass point connected to some other points by springs
- Springs exert forces on mass points
 - Hook's force
 - Damping force
- Other forces
 - External force field
 - Gravity
 - Electrical or magnetic force field
 - Collision force



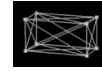
25

Network organization is critical

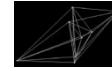
- For stability, must organize the network of springs in some clever way



Basic network



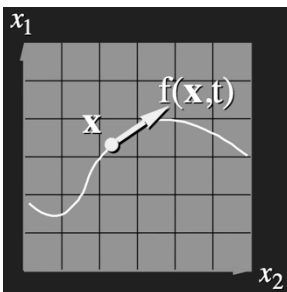
Stable network



Network out of control

26

Time Integration



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

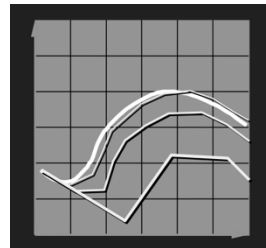
$x = x(t)$ is particle trajectory

Source: Andy Witkin, SIGGRAPH

27

Euler Integration

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



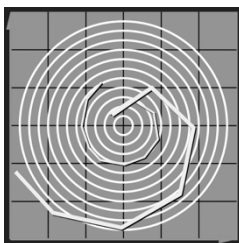
Simple,
but inaccurate.

Unstable with
large timesteps.

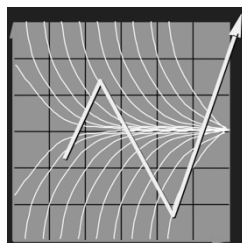
Source: Andy Witkin, SIGGRAPH

28

Inaccuracies with explicit Euler



Gain energy

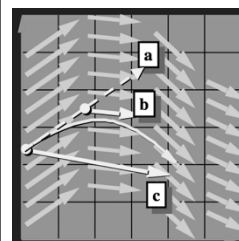


"Blow-up"

Source: Andy Witkin, SIGGRAPH

29

Midpoint Method



Source: Andy Witkin, SIGGRAPH

Improves stability

1. Compute Euler step
 $\Delta x = \Delta t f(x, t)$
2. Evaluate f at the midpoint
 $f_{\text{mid}} = f((x+\Delta x)/2, (t+\Delta t)/2)$
3. Take a step using the midpoint value
 $x(t + \Delta t) = x(t) + \Delta t f_{\text{mid}}$




30

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

31

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

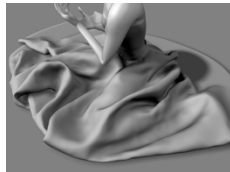


[Baraff and Witkin, SIGGRAPH 1998]

32

Challenges

- Complex Formulas
- Large Matrices
- Stability
- Collapsing triangles
- Self-collision detection



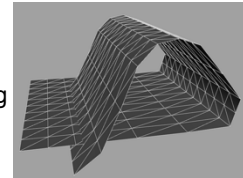
[Govindaraju et al. 2005]

33

Self-collisions: definition

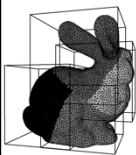
Deformable model is self-colliding iff

there exist non-neighboring intersecting triangles.



34

Bounding volume hierarchies



AABBs
Level 1

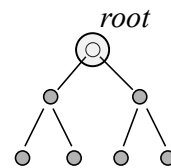


AABBs
Level 3

- [Hubbard 1995]
- [Gottschalk et al. 1996]
- [van den Bergen 1997]
- [Bridson et al. 2002]
- [Teschner et al. 2002]
- [Govindaraju et al. 2005]

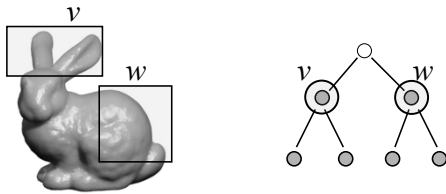
35

Bounding volume hierarchy



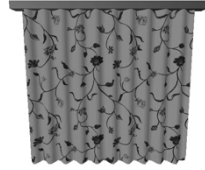
36

Bounding volume hierarchy



37

Real-time cloth simulation

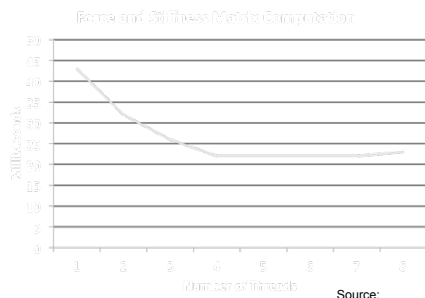


Source:
Andy Pierce

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

38

Multithreading implementation



Source:
Andy Pierce

39

Summary

- Examples of physically based simulation
- Particle Systems
- Numerical Integration
- Cloth Simulation

40