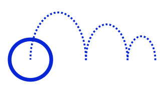
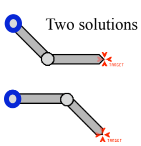
Rigid Body Dynamics, Fracture, & Deformation

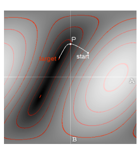
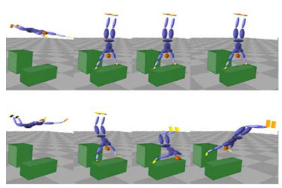
Announcements: Quiz

- On Friday (3/4), in class
- One 8.5x11 sheet of notes allowed
- Sample quiz (from last year) is posted online
- Focus on “reading comprehension” and material for Homeworks 0, 1, & 2

Last Time?

- Keyframing
- Procedural Animation
- Physically-Based Animation
- Forward and Inverse Kinematics
- Motion Capture

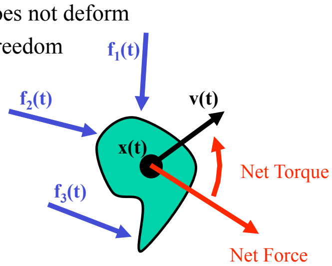



Today

- Rigid Body Dynamics
- Finite Element Method
- Deformation
- Fracture

Rigid Body Dynamics

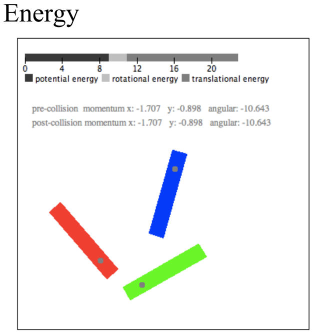
- Could use particles for all points on the object
  - But rigid body does not deform
  - Few degrees of freedom
- Use only one particle at the center of mass
- Compute Net Force & Net Torque



Nice Reference Material: **http://www.pixar.com/companyinfo/research/pbm2001/**
http://www.myphysicslab.com/collision.html

Energy & Rigid Body Collisions

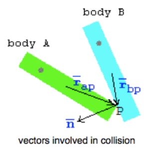
- Total Energy = Kinetic Energy + Potential Energy + Rotational Energy
- Total Energy stays constant if there is no damping and no friction



http://www.myphysicslab.com/collision.html

Collision Between Two Objects

- Suppose a vertex on body A is colliding into an edge of body B at point P. Define the following variables:

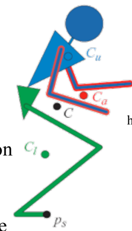


m_a, m_b = mass of bodies A, B
$\bar{r}_{ap}$ = distance vector from center of mass of body A to point P
$\bar{r}_{bp}$ = distance vector from center of mass of body B to point P
ω_{a1}, ω_{b1} = initial pre-collision angular velocity of bodies A, B
ω_{a2}, ω_{b2} = final post-collision angular velocity of bodies A, B
$\bar{v}_{a1}, \bar{v}_{b1}$ = initial pre-collision velocities of center of mass bodies A, B
$\bar{v}_{a2}, \bar{v}_{b2}$ = final post-collision velocities of center of mass bodies A, B
$\bar{v}_{ap1}$ = initial pre-collision velocity of impact point on body A
$\bar{v}_{bp1}$ = initial pre-collision velocity of impact point on body B
$\bar{n}$ = normal (perpendicular) vector to edge of body B
e = elasticity (0 = inelastic, 1 = perfectly elastic)

http://www.myphysicslab.com/collision.html

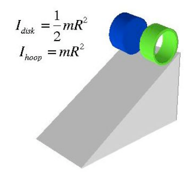
Center of Mass & Moment of Inertia

- Center of Mass: mean location of all mass in the system
- Moment of Inertia: a measure of an object's resistance to changes to its rotation
- If a solid cylinder & a hollow tube have the same radius & the same mass, which will reach the bottom of the ramp first?



Liu & Popović

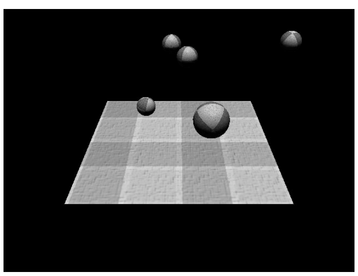
http://en.wikipedia.org/wiki/Fosbury_Flop



http://solomon.physics.sc.edu/~tedeschi/demo/demo12.html

Rigid Body Dynamics

- Physics
  - Velocity
  - Acceleration
  - Angular Momentum
- Collisions
- Friction

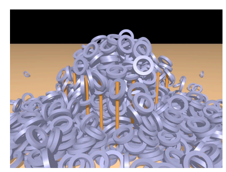


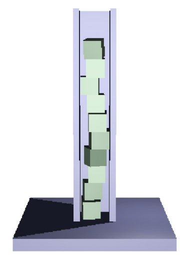
from: Darren Lewis
http://www-cs-students.stanford.edu/~dalewis/cs448a/rigidbody.html

Collisions

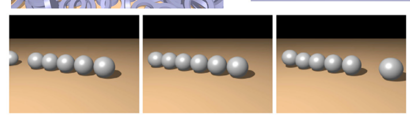
Victor J. Milenkovic & Harald Schmidl
Optimization-Based Animation
SIGGRAPH 2001

- We know how to simulate bouncing really well
- But resting collisions are harder to manage





Guendelman, Bridson & Fedkiw
Nonconvex Rigid Bodies with Stacking
SIGGRAPH 2003



Today

- Rigid Body Dynamics
- Finite Element Method
- Deformation
- Fracture

Simulation of Non-Rigid Objects

- We modeled string & cloth using mass-spring systems. Can we do the same?
- Yes…
- But a more physically accurate model uses *volumetric elements:*

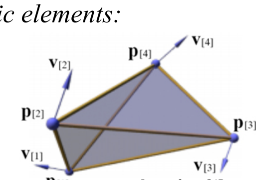


Image from O'Brien et al. 1999

Finite Element Method

- To solve the continuous problem (deformation of all points of the object)
  - Discretize the problem
  - Express the interrelationship
  - Solve a big linear system
- More principled than Mass-Spring

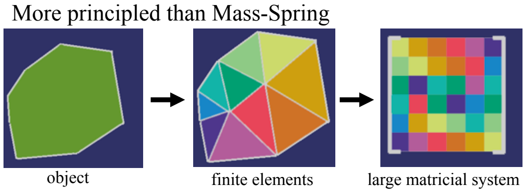
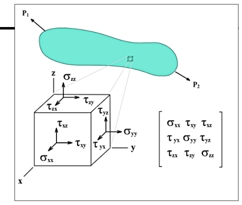


Diagram from Debunne et al. 2001

Strain & Stress

- Stress
  - the internal distribution of forces within a body that balance and react to the loads applied to it
  - *normal stress* & *shear stress*



http://en.wikipedia.org/wiki/Image:Stress_tensor.png

- Strain
  - material deformation caused by stress.
  - measured by the change in length of a line or by the change in angle between two lines

$$\varepsilon = \frac{\Delta_l}{l_0}$$

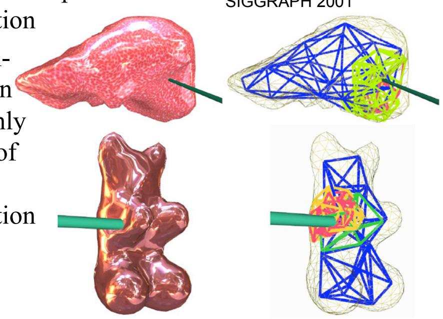
Today

- Rigid Body Dynamics
- Finite Element Method
- Deformation
- Fracture

Level of Detail

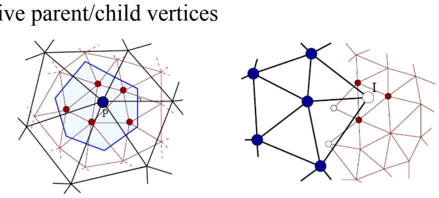
Gilles Debunne , Mathieu Desbrun, Marie-Paule Cani, & Alan H. Barr
Dynamic Real-Time Deformations using Space & Time Adaptive Sampling
SIGGRAPH 2001

- Interactive shape deformation
- Use high-resolution model only in areas of extreme deformation



Multi-Resolution Deformation

- Use Voronoi diagrams to match parent & child vertices.
- Interpolate values for inactive interface vertices from active parent/child vertices

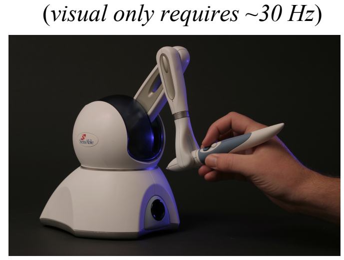


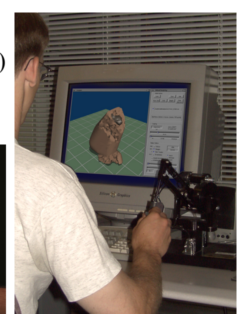
- *Need to avoid interference of vibrations between simulations at different resolutions*

Debunne et al. "Dynamic Real-Time Deformations using Space & Time Adaptive Sampling", 2001

Haptic Device

- "3D mouse" + force feedback
- 6 DOF (position & orientation)
- *requires 1000 Hz refresh* (*visual only requires ~30 Hz*)

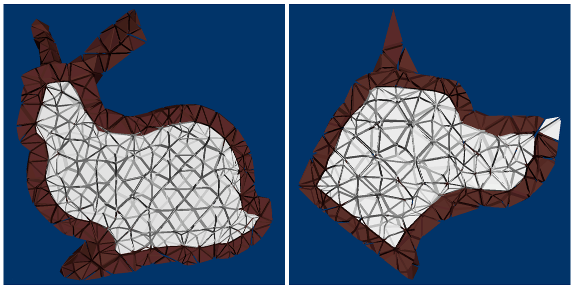




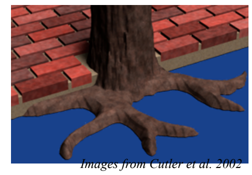
Sensable's Phantom
http://www.sensable.com/

Multiple Materials

Mueller, Dorsey, McMillan, Jagnow, & Cutler
Stable Real-Time Deformations
Symposium on Computer Animation 2002



Tree Stump



Images from Cutler et al. 2002

Image from Cutler et al. 2002

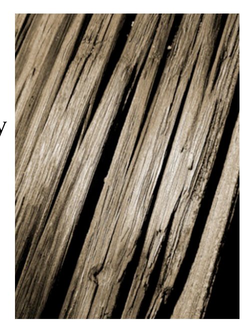
Image from Cutler et al. 2002

Today

- Rigid Body Dynamics
- Finite Element Method
- Deformation
- Fracture

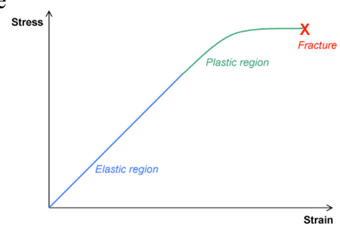
Some Definitions

- *Isotropic*: is a property which does not depend on the direction.
- *Anisotropic*: is a property which is directionally dependent.



Some Definitions

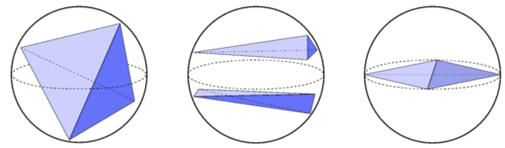
- *Elastic Deformation*: Once the forces are no longer applied, the object returns to its original shape.
- *Plastic Deformation*: An object in the plastic deformation range will first have undergone elastic deformation, which is reversible, so the object will return part way to its original shape.



http://en.wikipedia.org/wiki/Image:Stress-strain1.png

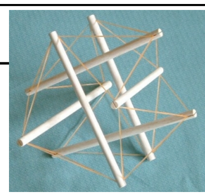
Some Definitions

- *Degenerate/Ill-conditioned Element*: a.k.a. how "equilateral" are the elements?
  - Ratio of volume^2 to surface area^3
  - Smallest *solid* angle
  - Ratio of volume to volume of smallest circumscribed sphere



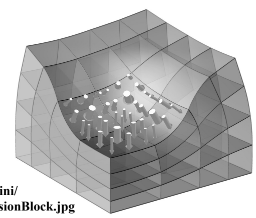
Some Definitions

- *Tension*: The direction of the force of tension is parallel to the string, away from the object exerting the stretching force.



http://fig.cox.miami.edu/~cmallery/255/255chem/tensegrity.sticks.jpg

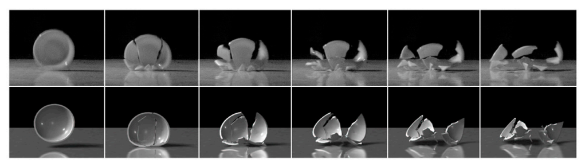
- *Compression*: resulting in reduction of volume



http://www.aero.polimi.it/~merlini/SolidMechanics-FiniteElasticity/CompressionBlock.jpg

Reading for Today:

- James O'Brien & Jessica Hodgins *"Graphical Modeling and Animation of Brittle Fracture"* SIGGRAPH 1999.



- Fracture threshhold
- Remeshing
  - need connectivity info!
- Material properties
- Parameter tuning

Fracture Opening Modes

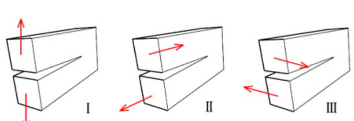
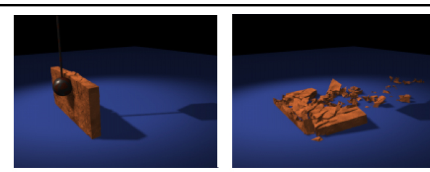
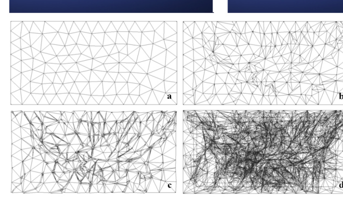


Image from O'Brien et al. 1999

Figure 6: Three loading modes that can be experienced by a crack. Mode I: Opening, Mode II: In-Plane Shear, and Mode III: Out-of-Plane Shear. Adapted from Anderson [1].

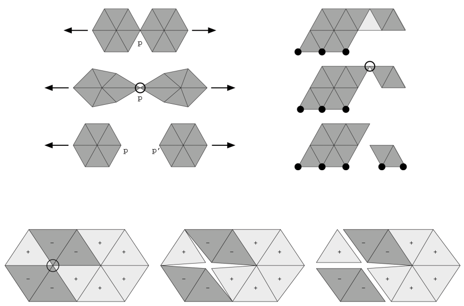
Local Mesh Refinement





Images from O'Brien et al. 1999

Managing Fracture Adjacency



Images from Cutler 2003

Fracture Propagation Difficulties

- Need to track direction of fracture propagation?

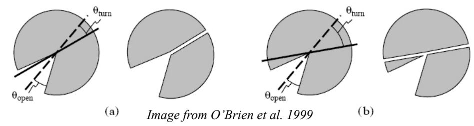


Image from O'Brien et al. 1999

- Need to track crack tip?

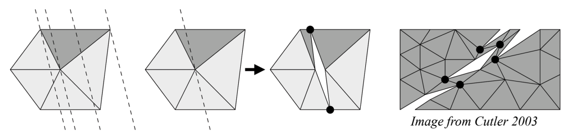
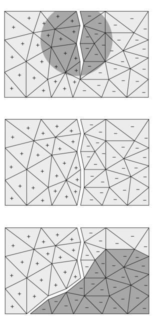
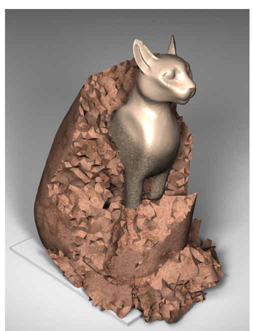


Image from Cutler 2003

Controlling Speed of Propagation



(*no remeshing*)



Images from Cutler 2003

Questions?

Readings for Tuesday 3/1: *(read both)*

- "An improved illumination model for shaded display" Turner Whitted, 1980.
- "Distributed Ray Tracing", Cook, Porter, & Carpenter, SIGGRAPH 1984.