Computer Animation & Physical Simulation

Lecture 1: Introduction

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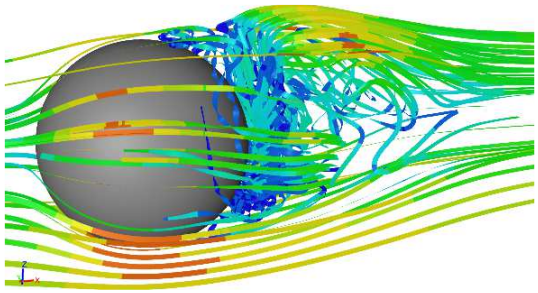
Why computer animation?

- **In short summary**
  - Application in any domain with time-varying phenomena
  - Generated by computers
  - Computer graphics for
    - Rendering animation results
    - Visualizing animation results



Computer Animation Is

- **Fun**
  - A lot of interesting dynamic contents
- **Important**
  - Provide tools for different domains

- **BUT difficult!**
  - Involve a lot of mathematics and physics
  - Require a lot of computing resources

Course Organization

- **More emphasis on physically-based simulation for computer animation**
  - Emphasis on technical discussions
  - Computer graphics & non-physically-based animation
  - Rigid-body dynamics
  - Soft-body dynamics
    - Hair, cloth, deformable solids
  - Fluid dynamics
    - Air and water
  - Dynamic coupling

Instructor and TA

- **Instructor:**
  - Prof. Xiaopei Liu
  - E-mail: liuxp@shanghaitech.edu.cn
  - Address: Room 202.J, SIST Building #2
  - Office hour: Tue/Thu 17:00 to 18:00
- **Teaching assistant**

Mr. Xiao Xiaoyu
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Mr. Fu Xinyi
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Office hour: Tuesday 16:50-17:50

Reference materials

- **No fixed textbook**
  - Too old to cover the advanced topics
  - Mainly based on course materials

- **Research papers**
  - More focused on research paper discussions
  - A course like a special-topic seminar, with group discussions

Webpage

- **We have a course webpage for your reference**
  - http://faculty.sist.shanghaitech.edu.cn/faculty/liuxp/course/cs275/

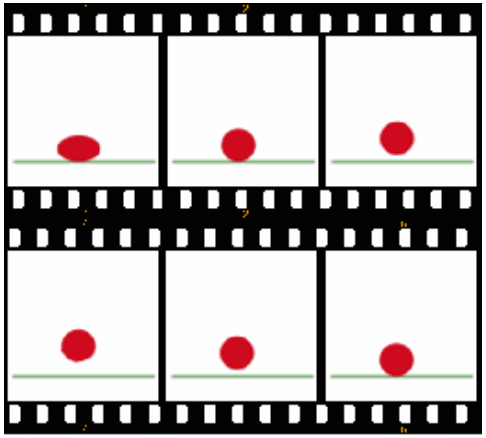
- **Online discussion**
  - Piazza page: https://piazza.com/shanghaitech.edu.cn/spring2024/cs275

Evaluation

- **Assignments (x 3, 45%) (probably no skeleton code)**
  - Basic animation projects
    - 3D skeleton-based animation (x1) and 3D physically-based animations (x2) on cloth and fluid dynamics
- **Presentation and discussion (5% x 5)**
  - Present and discuss the related research papers in the literature
- **Final project (30%)**
  - Project program (20%)
  - Presentation (10%)
  - Technical report (5%)

What is an animation?

- **The process of making illusion of time-varying process**
  - In terms of images
  - Rapid display of a sequence of images
  - Smooth enough in-between images

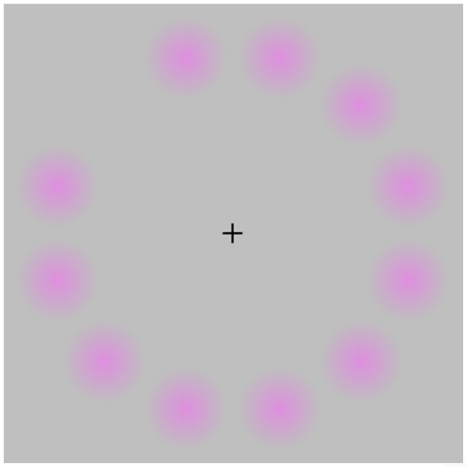


Time-Varying Process

- **The output characteristics depend explicitly on time**
  - System's behavior changes w.r.t time
  - Respond differently to the same input at different times
- **Common time-varying phenomena**
  - Change of location/orientation/shape
  - Change of lighting condition
  - Change of surface details
  - Change of physical environments
  - etc.

Phi Phenomena

- **The optical illusion of perceiving a series of still images**
  - Defined by Max Wertheimer in 1912
  - Persistence of vision
    - Black spaces that come between each "real" movie frame are not perceived
  - Foundation of theory of film
  - Part of motion perception



Computer Animation

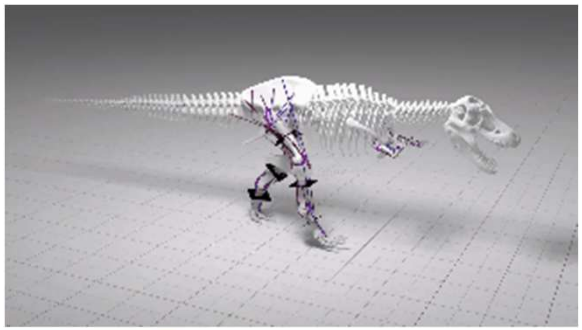
- **The process for generating animated images using computer**
  - Essentially a digital successor to the stop motion techniques used in traditional animation
  - Modern computer animation usually uses 3D computer graphics

Recording - Digital Video

- **An electronic representation of moving visual images**
  - In the form of encoded digital data
  - A series of digital images displayed in rapid succession
  - Compressed digital video formats
    - H.264
    - MPEG-4
  - Usually recorded by a recording device
  - Not a major concern by the course

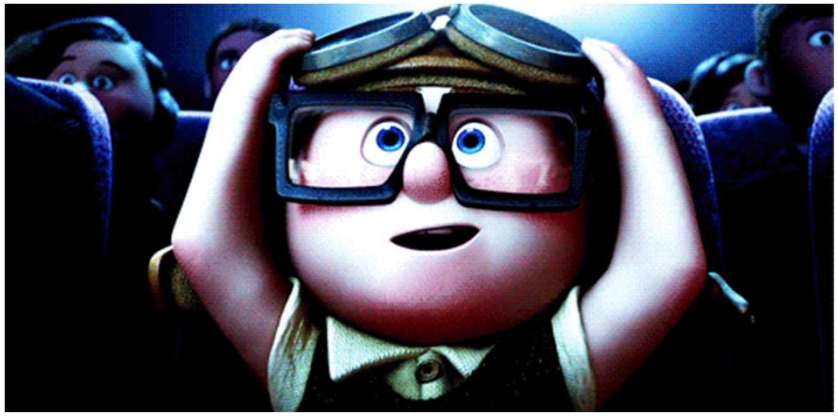
Synthesis – Computer Generated Image Sequence

- **Different from digital video, all images are generated by computer algorithms**
  - Closely related to computer graphics and image processing
  - How to store the animation?
    - Digital video format



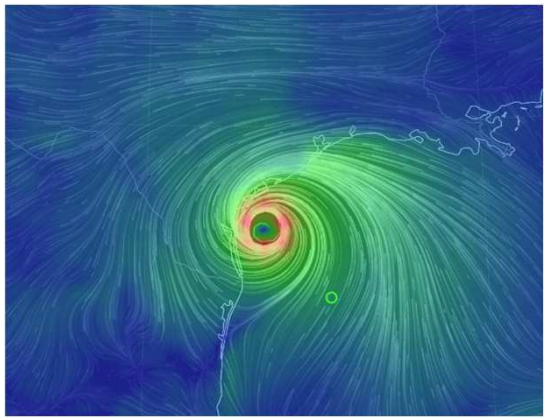
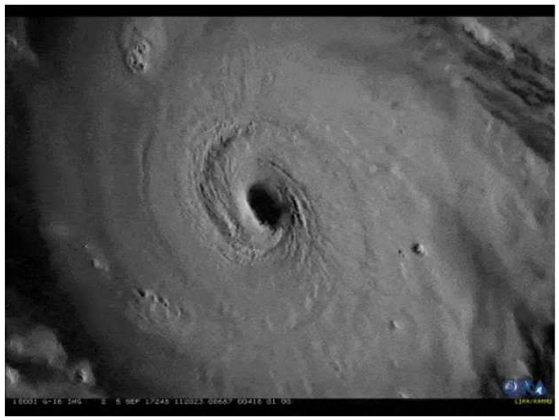
Why computer animation?

- **Entertainment industry**
  - Movies, games, advertisements
  - An important component for virtual reality
    - Real-time animation



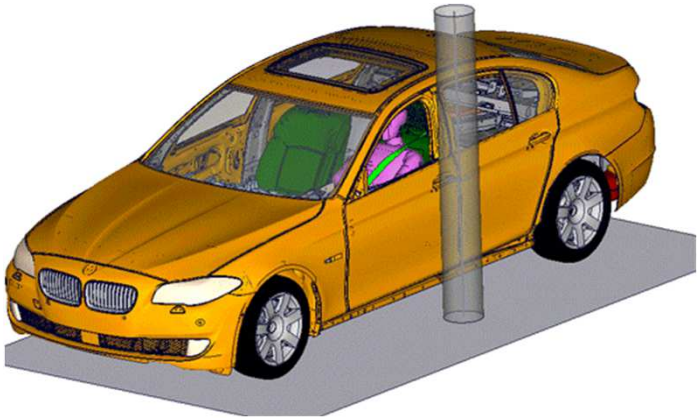
Why computer animation?

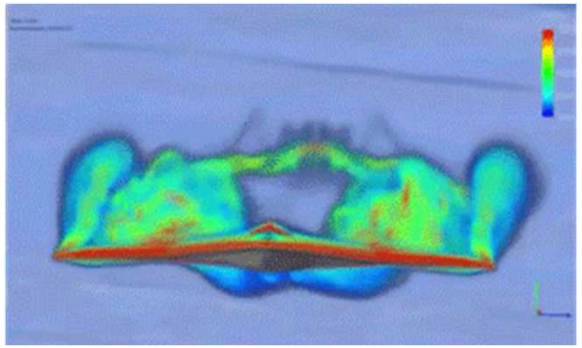
- **Scientific visualization**
  - Illustrate the dynamic process
  - Help intuitive understanding

Why computer animation?

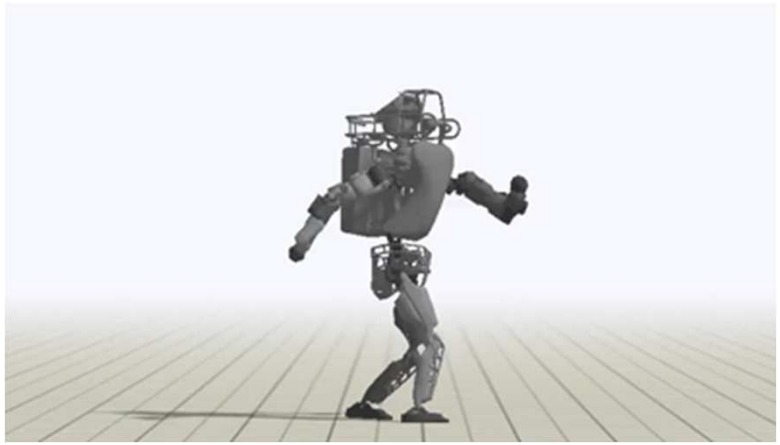
- **Industrial product design**
  - A dynamic process for design verification
  - More intuitive on design

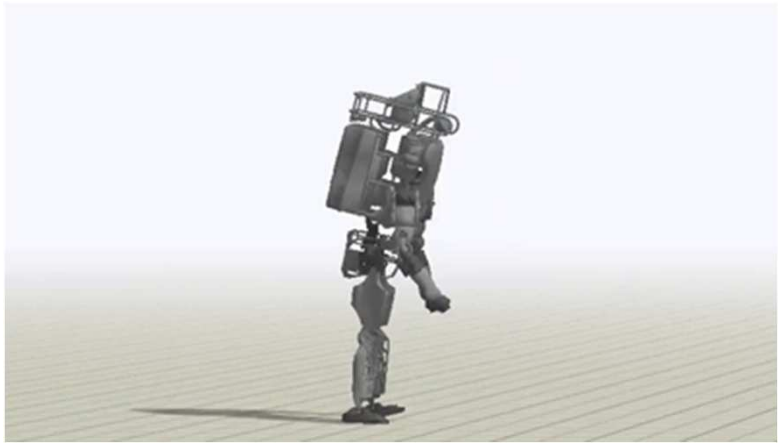




Why computer animation?

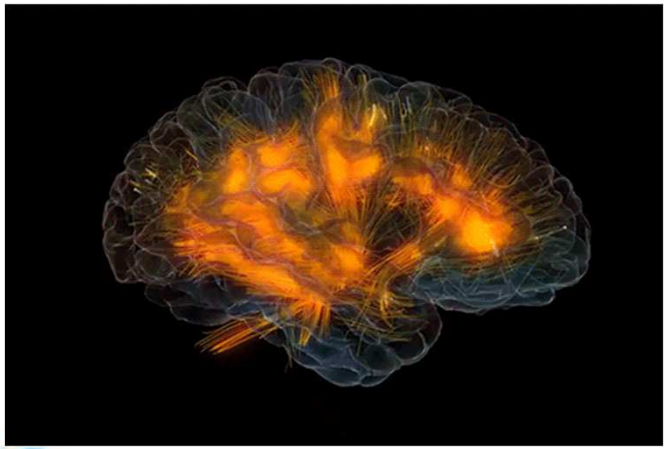
- **Robotic training**
  - A virtual environment for training intelligence of robots
  - Simulating the real physical environment and its response





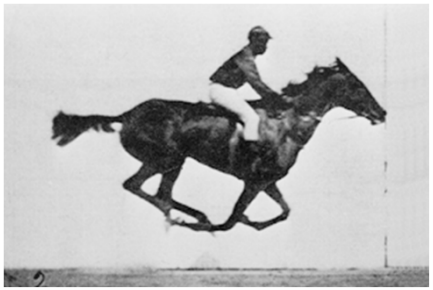
Why computer animation?

- **Medical diagnosis**
  - Dynamic physical process inside the human body
  - MRI image sequence or simulation



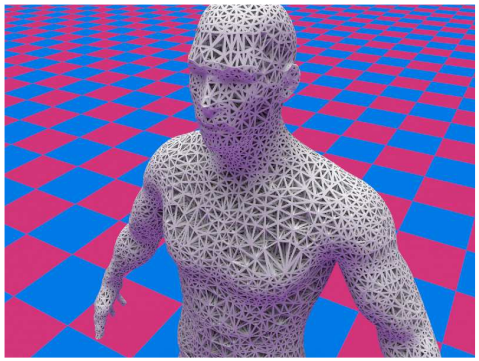
Early Stage of Animation

- **Traditional animation**
  - Also called cel animation or hand-drawn animation
  - Used for most animated films of the 20th century
  - The individual frames of a traditionally animated film are photographs of drawings
    - Each drawing differs slightly from the one before it



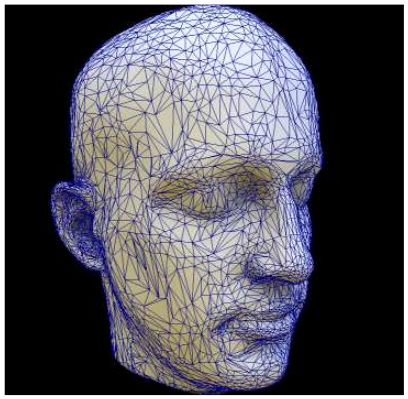
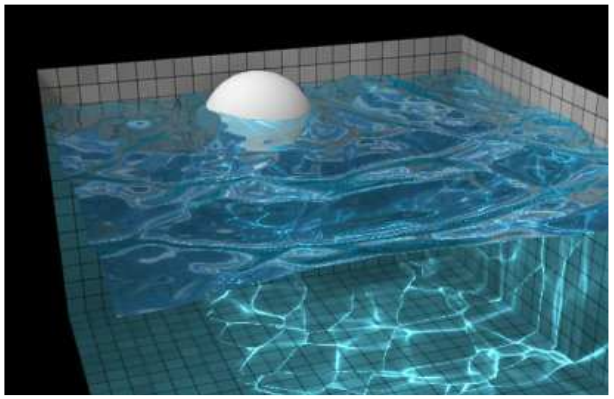
Animation in Computer Age

- **Computer graphics as a foundation**
  - Generate image sequence using computer
  - Both realistic and non-realistic
  - Based on geometry and physics (optics)



Role of Computer Graphics

- **Synthesize digital images purely by computer**
  - Camera modeling (projection)
  - Geometric modeling
  - Rendering

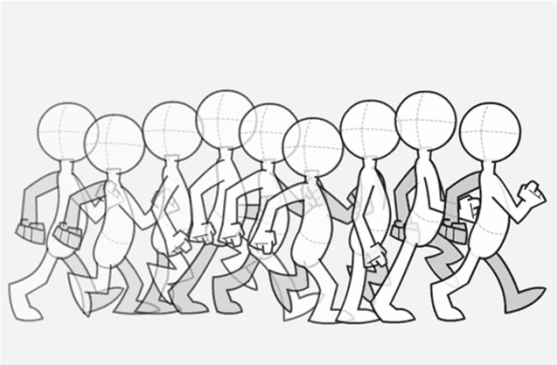
Important Concepts in Computer Animation

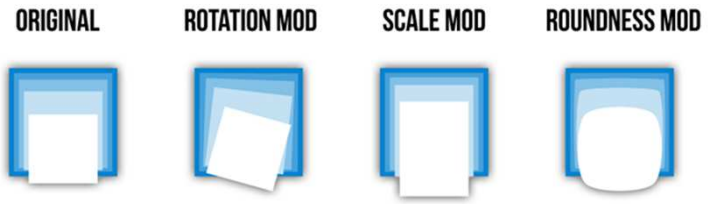
- **Frame**
  - One of the many single photographic images in a motion picture
- **Frame rate**
  - The frequency (rate) at which consecutive images (frames) appear on a display
- **Real-time v.s. offline computer animation**
  - Real-time performance: frame rate larger than a specific value (15 FPS or 24 FPS or even higher, application dependent)
    - Application: Computer games, virtual reality
  - Offline computer animation: special effects in movies/advertisement, industrial/scientific applications

I. Keyframe-based Computer Animation

Keyframing

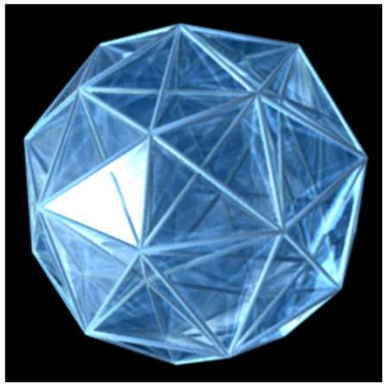
- **Smooth transition**
  - Define the starting and ending points
  - A sequence of key frames defines the movement

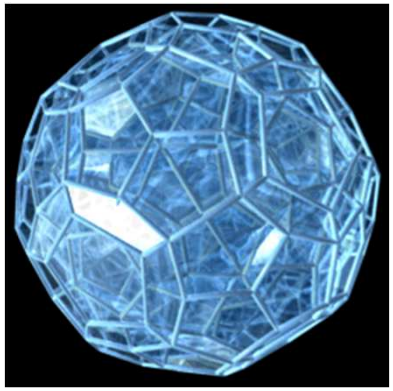


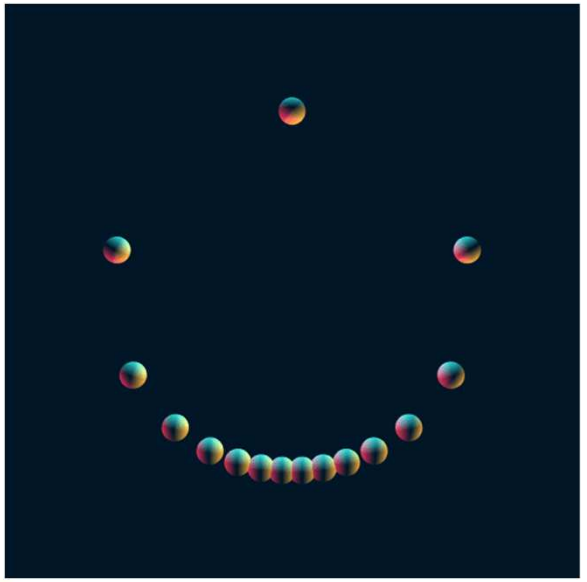


Geometric Transformation

- **Continuous rigid transformation for frame interpolation**
  - Translation, rotation sequences over time
  - The simplest method to create animation
  - Required in keyframe-based animation







Geometric Transformation

- **Warping**
  - Distort the shape of objects
  - Usually no topology changes

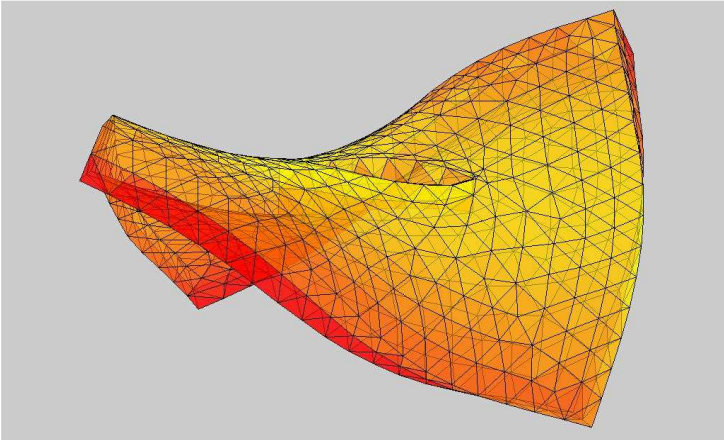
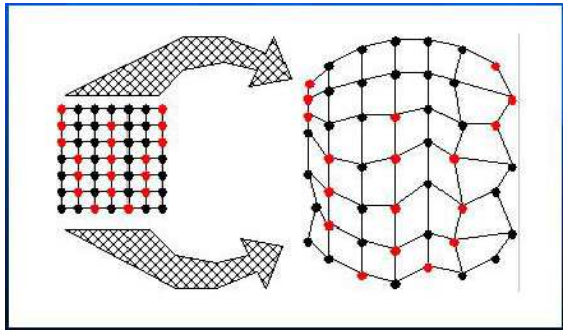
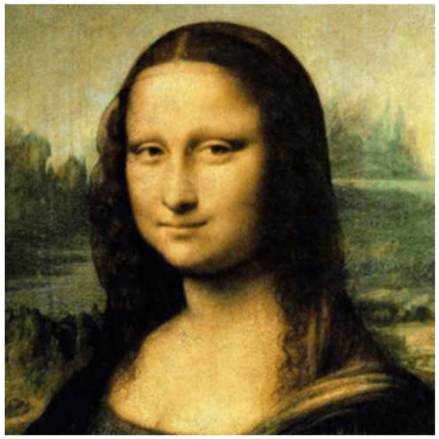


Image Warping

- **The process of digitally manipulating an image**
  - Any shapes portrayed in the image have been significantly distorted
  - Used for correcting image distortion as well as for creative purposes





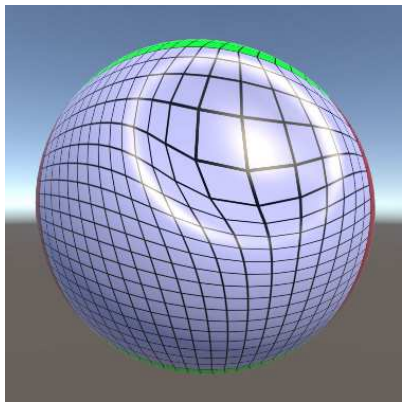
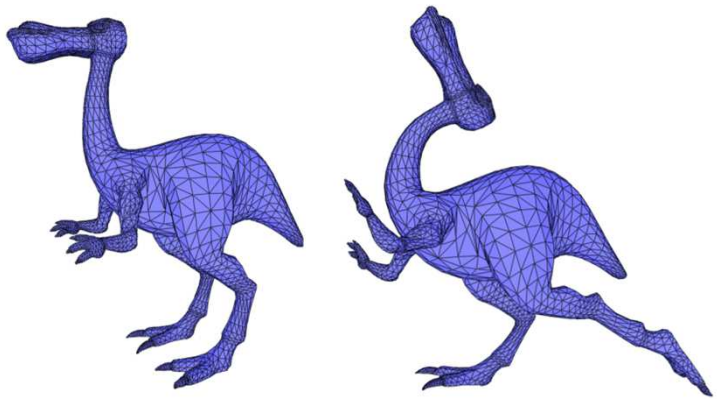
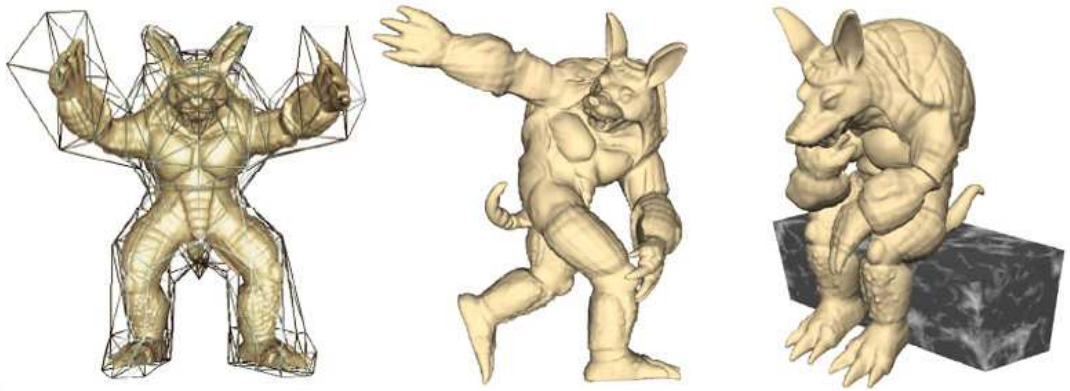
Morphing

- **A special effect in motion pictures**
  - Most often used to depict one person turning into another object
  - Feature matching with image warping/blending

II. Mesh Deformation/Reconstruction for Computer Animation

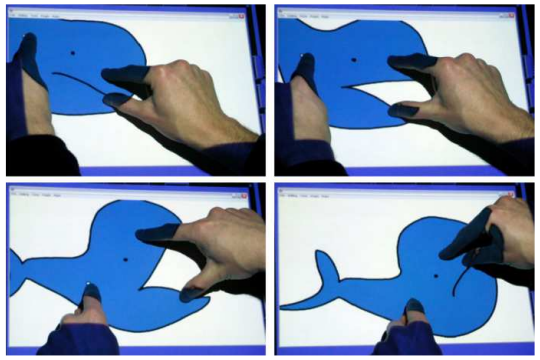
Mesh Deformation

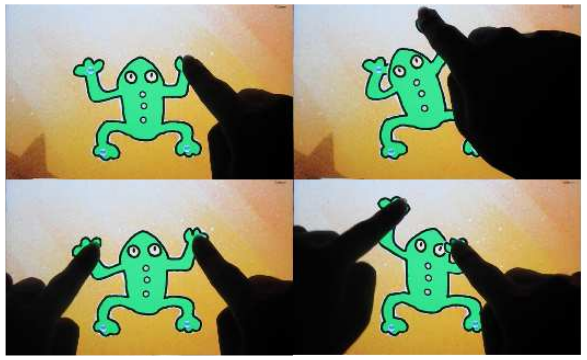
- **Change the shape of the mesh**
  - Change the position of vertices
  - May or may not change the topology

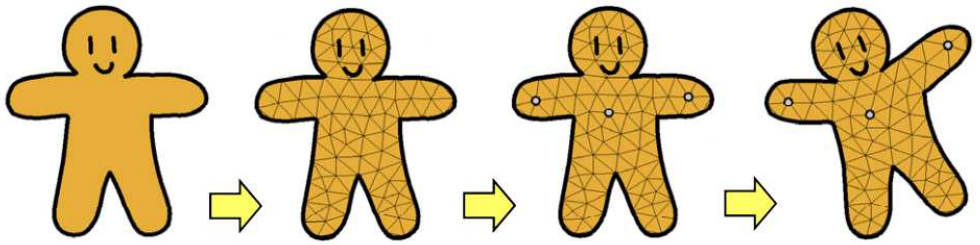




As-Rigid-As-Possible Shape Manipulation

- **The shape is represented by a triangle mesh**
  - Users move several vertices of the mesh as constrained handles
  - The vertex positions are computed by minimizing the distortion of each triangle

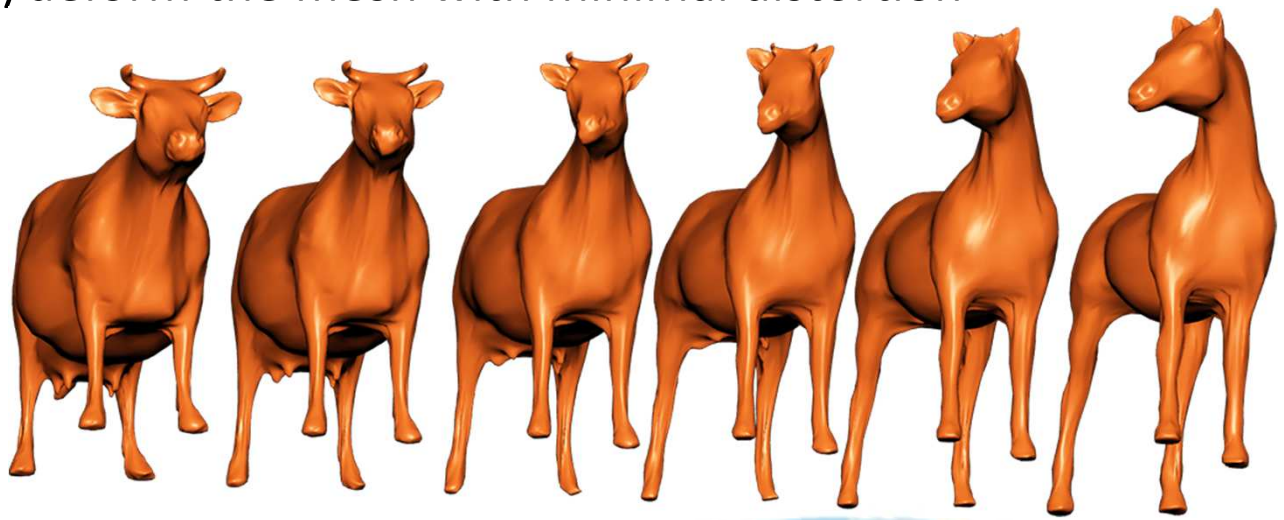






3D Morphing

- **Change smoothly from one shape to another**
  - Find shape correspondence
  - Warp/deform the mesh with minimal distortion

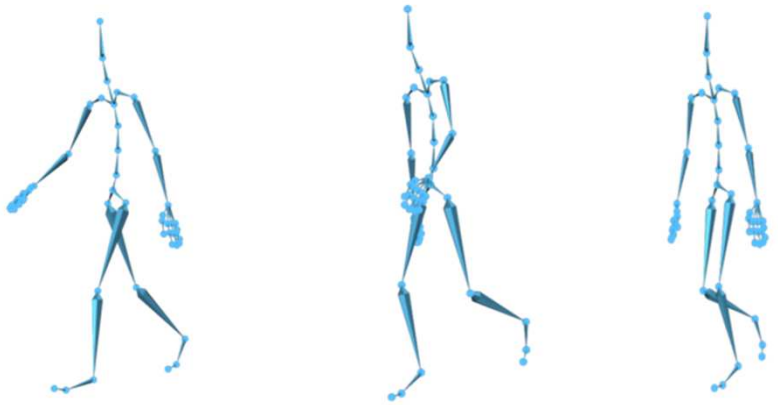


Character Animation

- **A specialized area of animation**
  - Bringing animated (virtual) characters to life
  - Creating the illusion of thought, emotion and personality

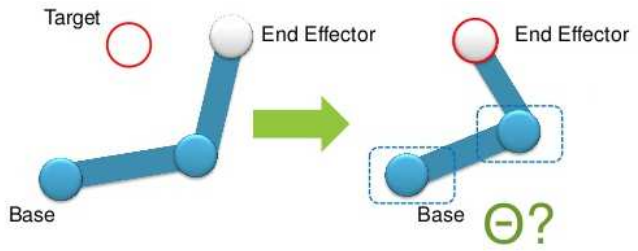
Skeleton Animation

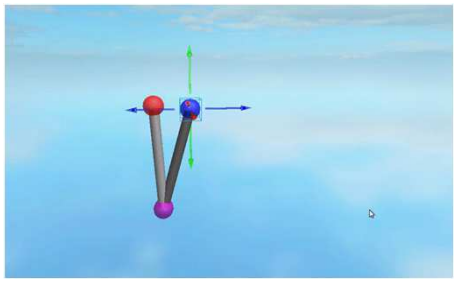
- **Abstract representation of a character**
  - By bones (skeletons)
  - Without surface (flesh) details

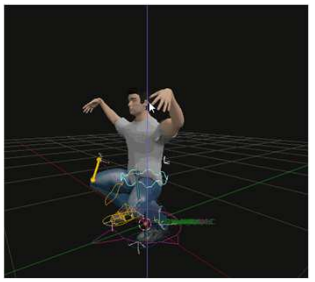


Inverse Kinematics

- **The use of the kinematics equations of a character skeleton**
  - To determine the joint parameters that provide a desired end position
  - Inverse kinematics transforms the motion plan into joint actuator trajectories for the character

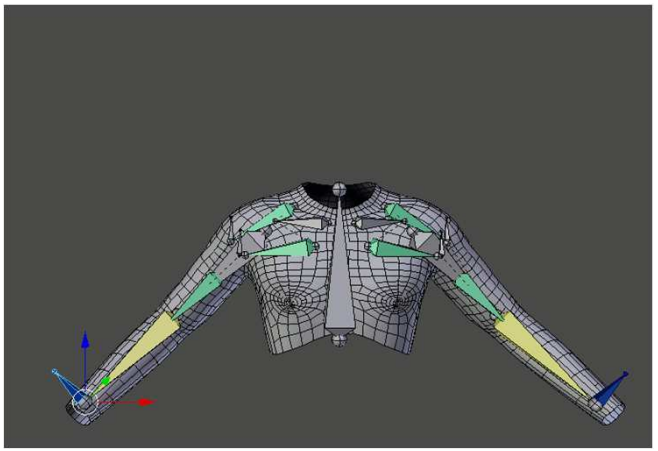






Skinning

- **The process of generating the surface detail of a skeleton**
  - Usually represented with a surface mesh
  - Can also be represented by a volumetric mesh (very few)

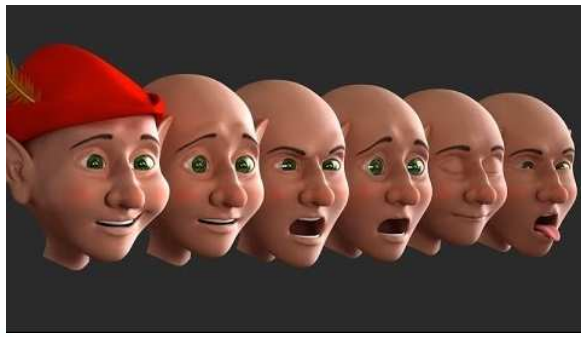


Motion Capture

- **The process of recording the movement of objects or people**
  - Based on feature points
  - Based on mesh reconstruction/deformation

Face Animation

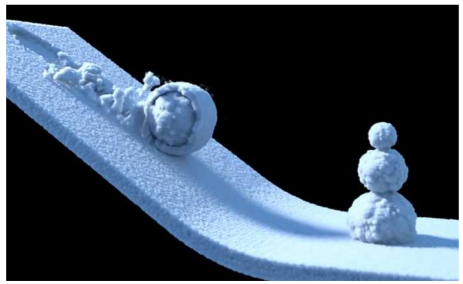
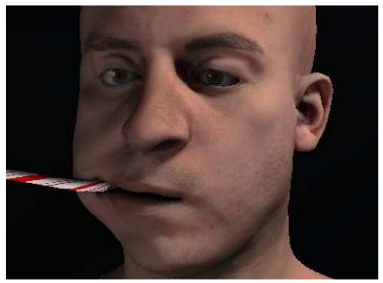
- **For generating and animating images or models of a character face**
  - 3D mesh deformation
  - Marker/markerless motion capture
  - Image-based 3D mesh reconstruction

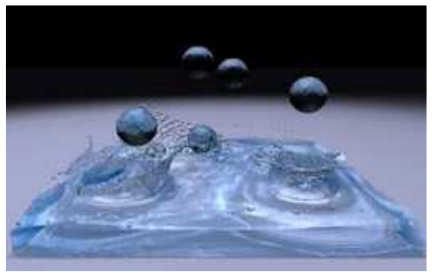


III. Physically-Based Computer Animation

Physically-based Computer Animation

- **An imitation of physical systems**
  - Usually involve physical laws
  - Solve physical dynamics equations numerically



III.a Particle System Simulation

Particle System

- **A large number of very small particles (usually sprites) to simulate certain kinds of physical phenomena**
  - Parameter update/simulation stage
  - Rendering stage

- **The dynamic equation**

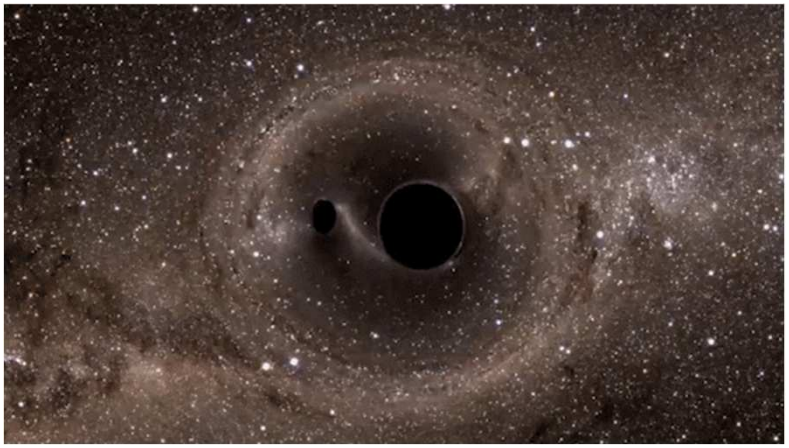
$$\mathbf{F} = \sum_{i=1}^{N} m_i \mathbf{A}_i$$

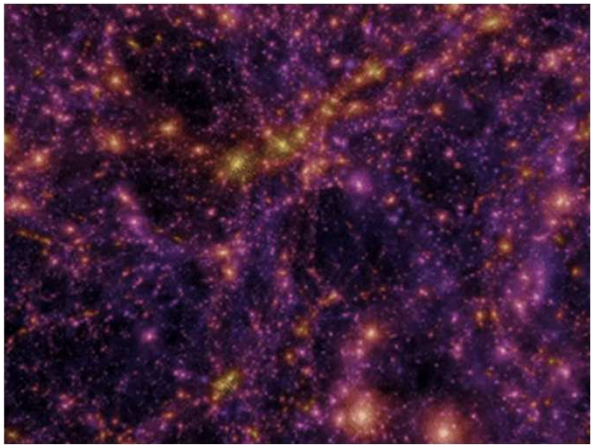
N-Body Simulation

- **A simulation of a dynamical system of particles**
  - Under the influence of physical (body & inter-particle) forces

Astronomical Animation

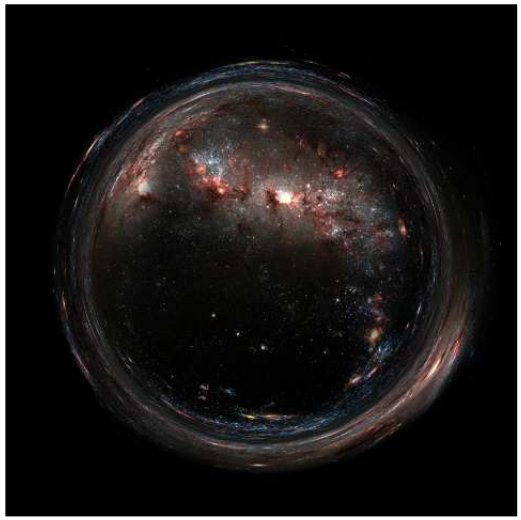
- **Simulation and animation for astrophysical phenomena**
  - For scientific study
  - For movie entertainment





Astronomical Animation

- **Astronomical animation in “interstellar”**
  - Rendering and animation of a wormhole



Science behind the animation

- **Theoretical physicist Kip Thorne**
  - Nobel Laurent 2017 for gravitational wave
  - Scientific consultant to ensure the accuracy of wormholes and relativity
  - Visual effect provided insights
    - Effects of gravitational lensing, etc.
    - Led to the publication of three scientific papers
  - Publish a book
    - The Science of Interstellar

III.b Rigid-Body Dynamics

Rigid-Body Dynamics

- **Rigid body dynamics**
  - Studies the movement of a single or a system of interconnected bodies under the action of external forces
  - Translation and rotation of reference frames attached to each body

- **Dynamic equations**

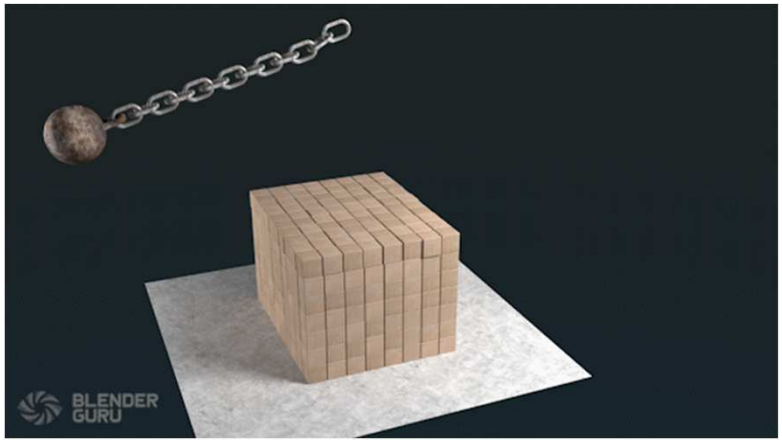
$$\mathbf{F} = \sum_{i=1}^{N} m_i \mathbf{A}_i, \quad \mathbf{T} = \sum_{i=1}^{N} (\mathbf{r}_i - \mathbf{R}) \times (m_i \mathbf{A}_i)$$

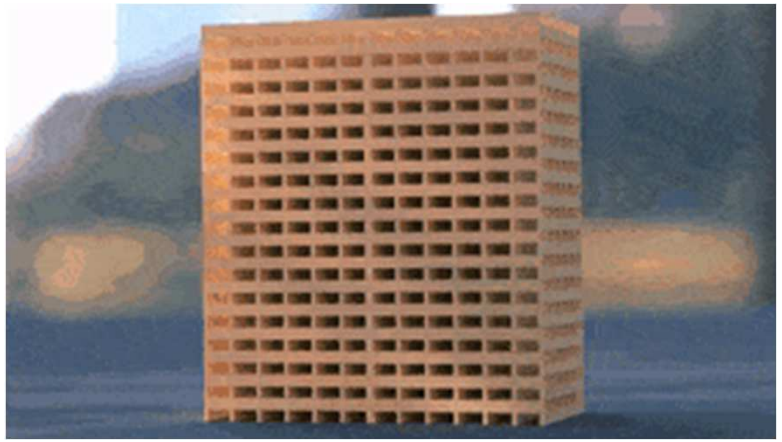
Multiple Rigid-Body Dynamics

- **The study of the dynamic behavior of interconnected rigid bodies**
  - Regular rigid body dynamics for each body
  - Constrained condition
    - Joints
    - Contacts
  - Largely occur in engineering design simulation
  - For animation:
    - Reproduce the dynamic process of real solid objects

Rigid Body Dynamics

- **Examples with contact constraints**





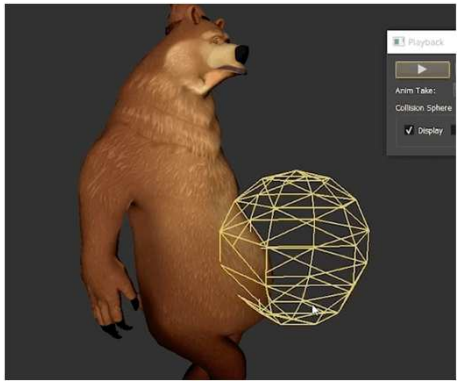
Fracture Dynamics

- **The study of the propagation of cracks in materials**
  - After the crack, the motion is governed by the rigid-body simulation

III.d Soft-Body Dynamics

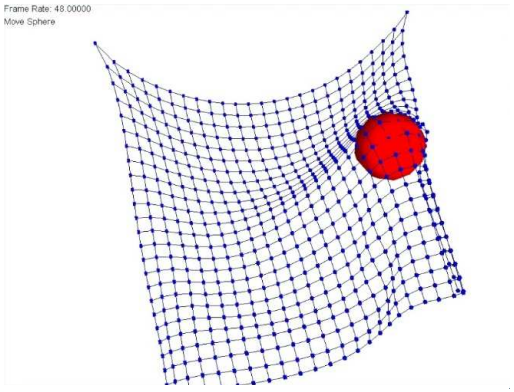
Soft Body Dynamics

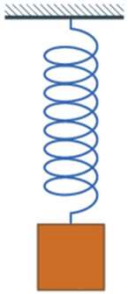
- **Visually realistic motion simulation of deformable objects**
  - 1D soft body (deformable curve): e.g. hair
  - 2D soft body (deformable surface): e.g. cloth
  - 3D soft body (deformable solid): e.g. rubber

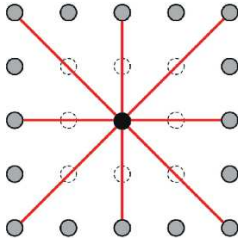


Mass-Spring Model

- **The body is modeled**
  - As a set of point masses (nodes)
  - Connected by ideal weightless elastic springs
  - Obey some variant of Hook's law



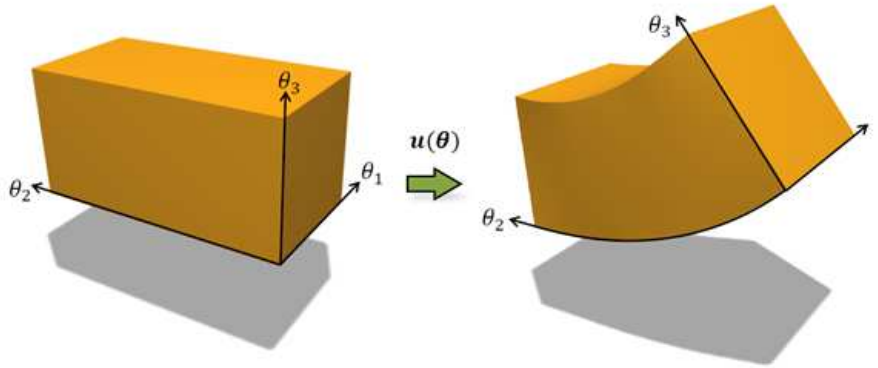




Solve system dynamics based on Newton's second law of motion

Continuum Model

- **Represent the whole domain continuously**
  - Based on a certain basis function interpolation
- **Measure deformation**
  - Strain tensor
- **Calculate internal energy or stress**
  - Constitutive relation
  - Linear v.s. nonlinear elasticity

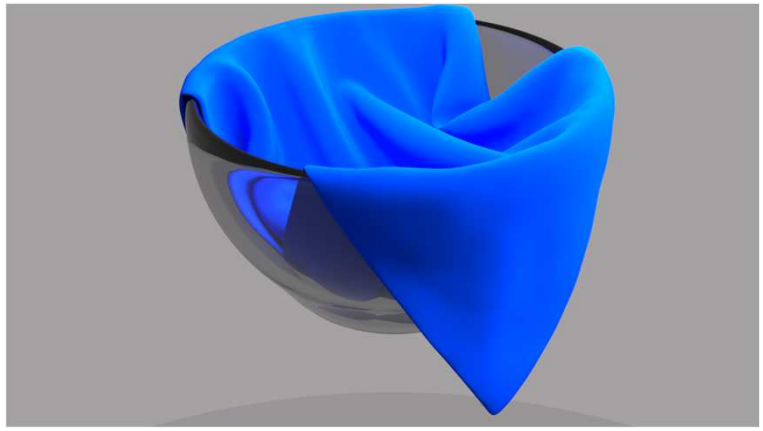


Hair Simulation

- **The study of deformable curves**
  - Mass/spring model applied to curves
  - Elastic rod model

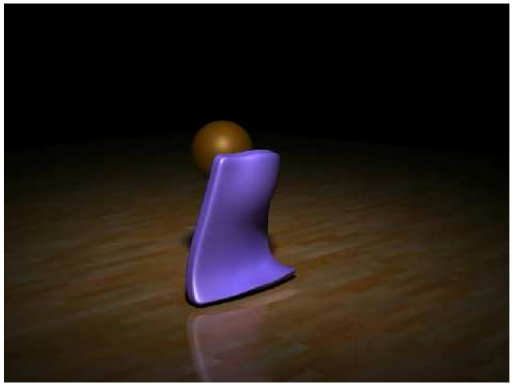
Cloth Simulation

- **The study of deformable surfaces (soft thin-shell)**
  - Mass/spring model applied to surfaces
  - Elastic thin-shell model



Deformable Solid Simulation

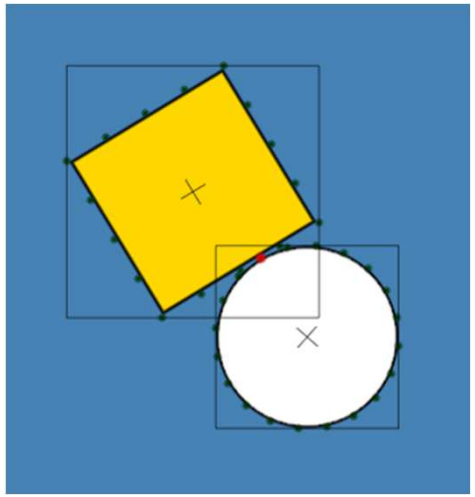
- **The study of deformable solid (volumetric)**
  - Mass/spring model applied to volume
  - Elastic solid model

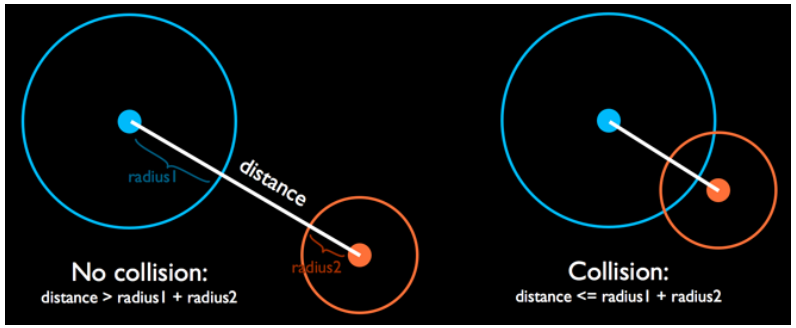


III.e Collision Detection

Collision Detection

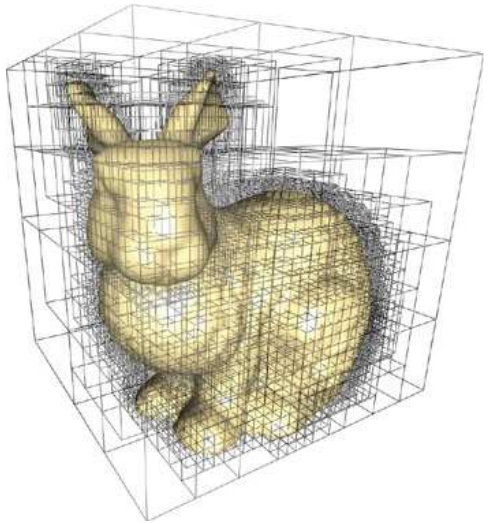
- **The computational problem of**
  - Detecting the intersection of two or more objects
  - Bounding-box or bounding-sphere

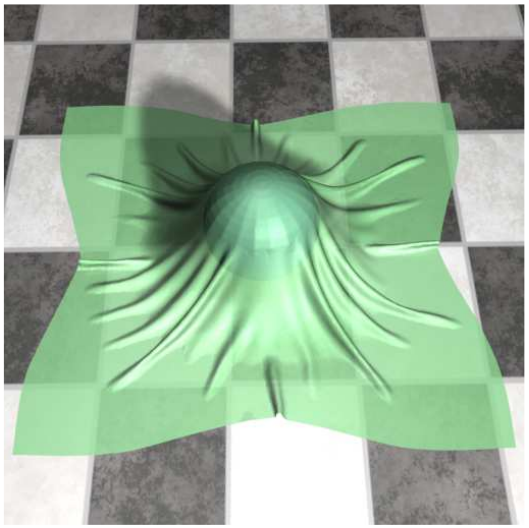




Collision Detection

- **Collision detection in 3D**
  - A hierarchical tree structure for detection tests

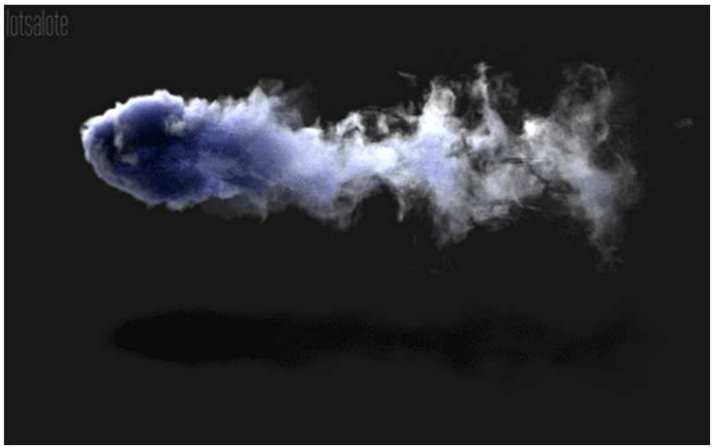




III.f Fluid Dynamics

Motion of Fluids

- **The matter that continually deforms under an applied stress**



Fluid Dynamics

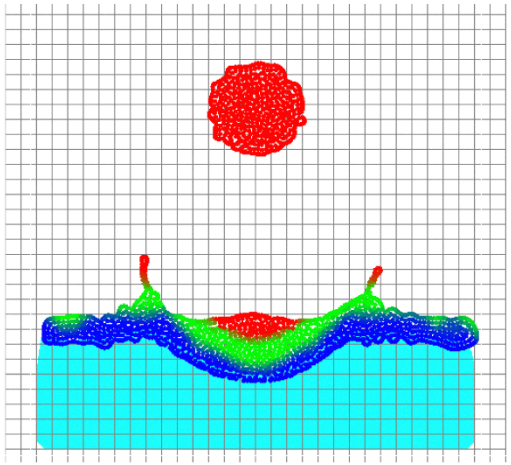
- **Conservation laws**
  - Conservation of mass
  - Conservation of momentum
  - Conservation of energy (optionally)

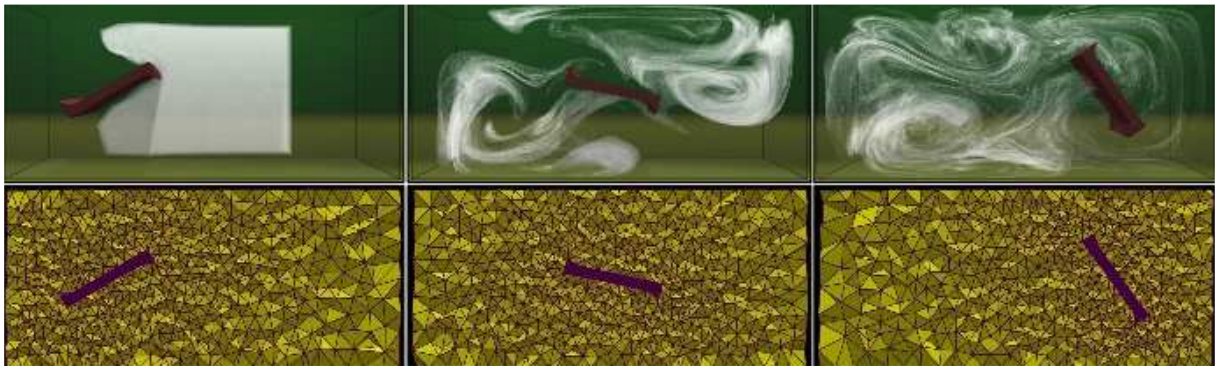
$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \frac{1}{\rho} \nabla \cdot \boldsymbol{\tau}_{shear} + \mathbf{g}$$

Eulerian Approach

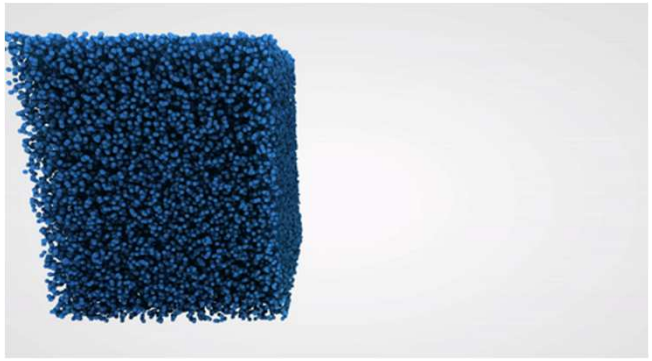
- **Numerical solution based on static grid/mesh**
  - Finite-difference/finite-volume methods
  - “Stable fluids” as typical pioneering work in graphics

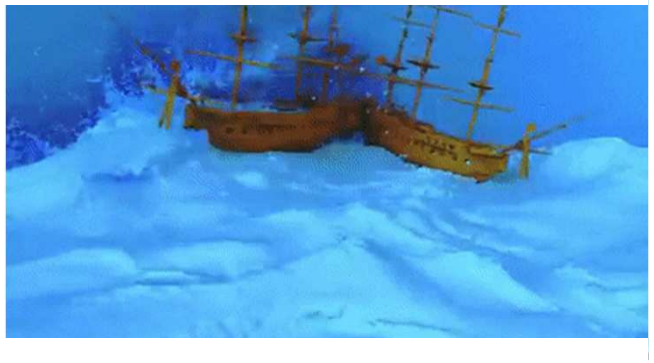




Lagrangian Approach

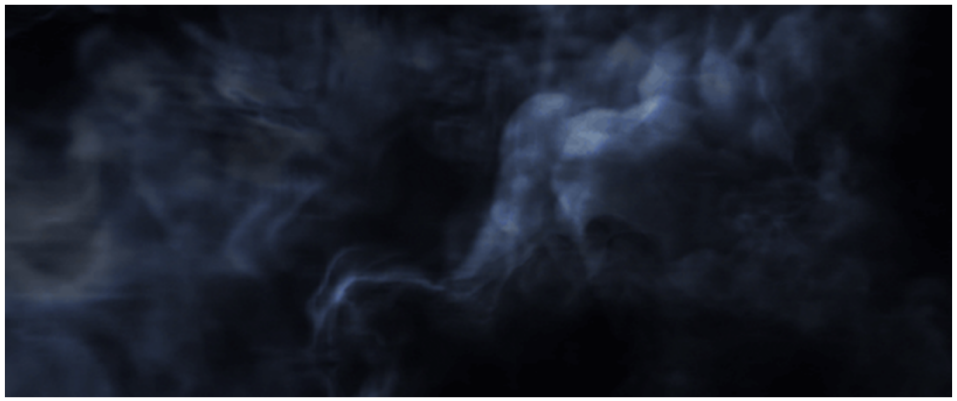
- **Numerical solution with particles moving with fluids**
  - SPH-based method
  - Typical work
    - Predictive-corrective incompressible SPH
    - Enforce incompressibility





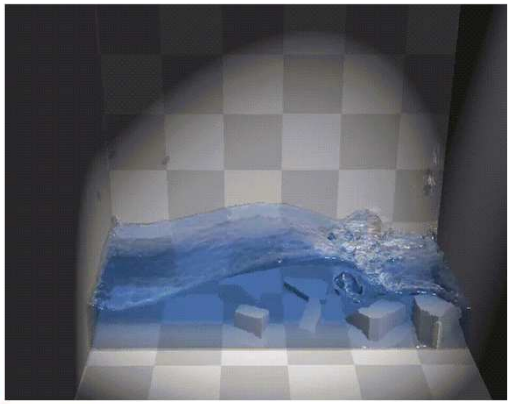
Smoke and Fire

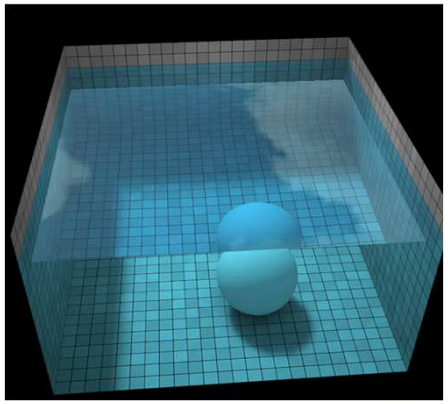
- **Evolution of particle density and temperature**
  - Solve both density and temperature equations
  - Volumetric rendering of smoke and fire



Water and Ocean

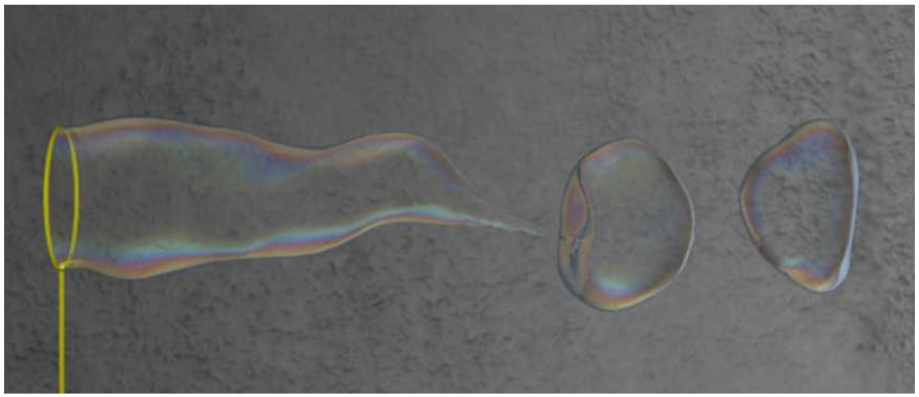
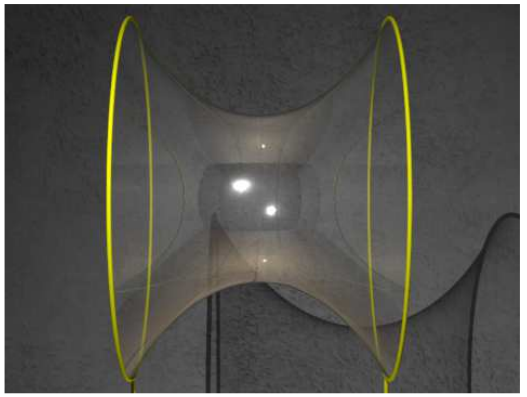
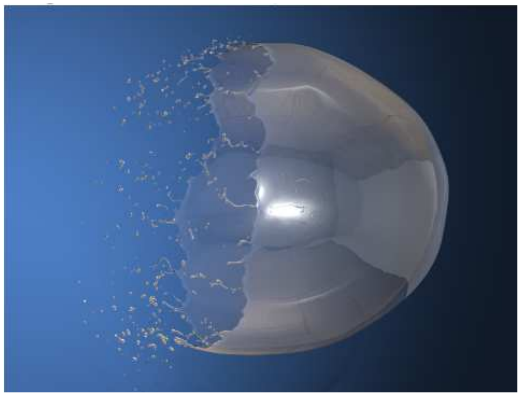
- **Interface tracking**
  - Water-air interface geometry
  - Evolve by flow equations, implicit surface evolution
  - Ray-tracing surface rendering with refraction





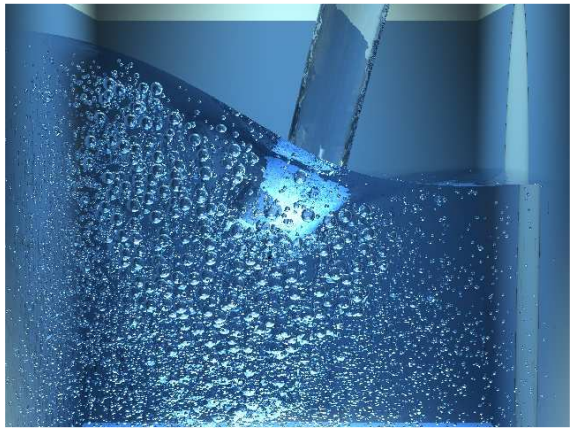
Surface Tension Flow

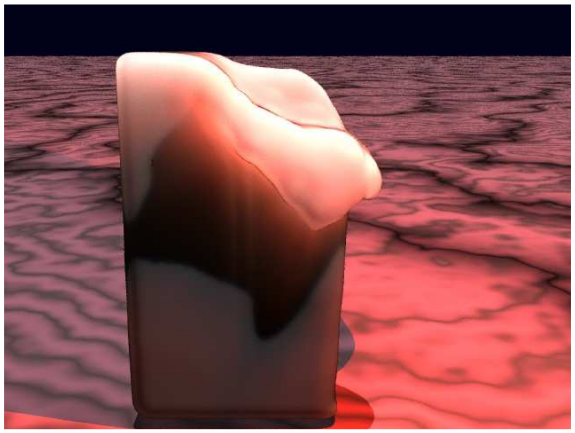
- **Thin-shell flow**
  - Dominated by surface tension

Multi-Phase Flow

- **Flow with different phases**
  - Interaction with different phases (bubbles)
  - Transition among different phases



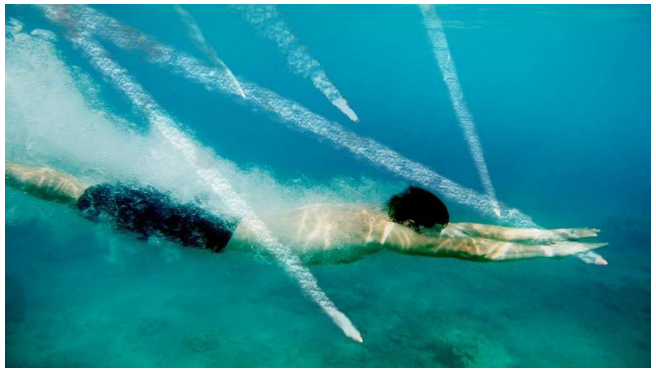


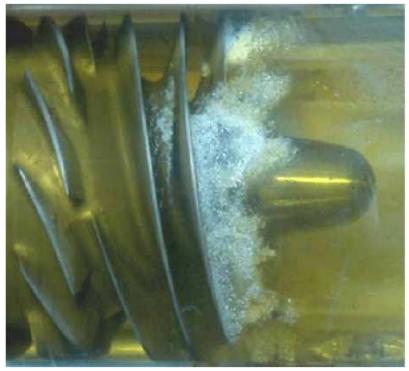
Multi-Phase Flow

- **Contact with solids**
  - Different wetting on solid surfaces

Multi-Phase Flow

- **Cavitation**
  - The formation of vapor cavities (bubbles) in a liquid
  - Due to phase change from large pressure difference

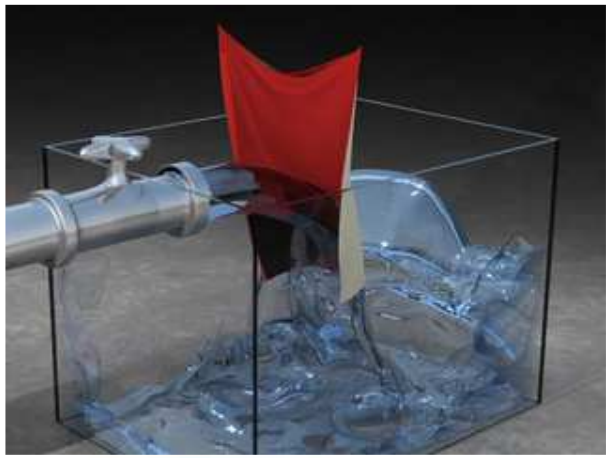




III.g Dynamic coupling problem

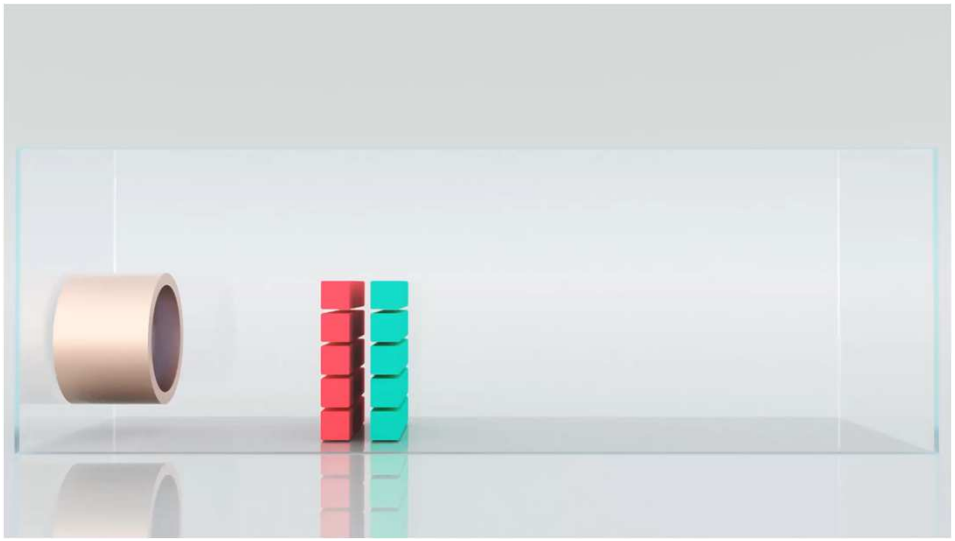
Fluid-Solid Coupling

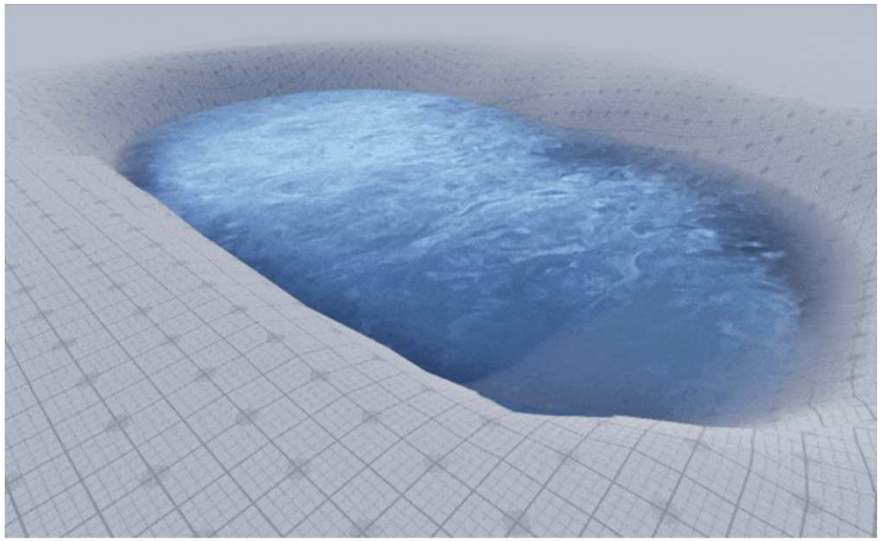
- **When there are solid objects as boundary**
  - Static v.s. moving
  - Fluid dynamics coupled with rigid/elastic dynamics



Fluid-Solid Coupling

- **Fluid simulation coupled with rigid body simulation**





Fluid-Solid Coupling

- **Fluid simulation coupled with soft-body**

Next Lecture: Computer Graphics