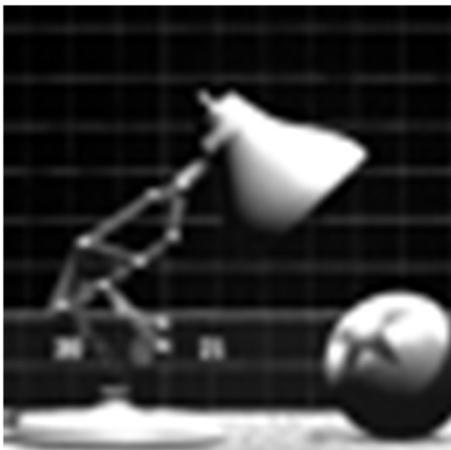


Computer Graphics/Fondamenti di COMPUTER GRAPHICS



Pixar Animation Studios,
1986 John Lasseter

A.A.2024/2025

Serena Morigi

serena.morigi@unibo.it

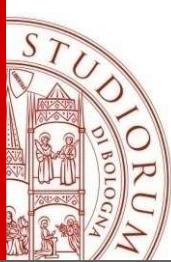
Dipartimento di Matematica

Università di Bologna

course website:

[Virtuale website Graphics \(unibo.it\)](#)

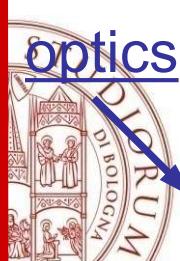
Virtual Learning Environment (VLE)



Computer Graphics is...

**Computer Graphics =
pretty pictures**

**of possibly moving, possibly
interactive, solid or fluid,
artificial or living things for
people to see on displays**



optics

light

colour

kinematics

usability

mechanics

optimization

geometry

aesthetics

photography

animation

pretty pictures of possibly moving, possibly interactive, solid or fluid, artificial or living things for people to see on displays

fluid dynamics

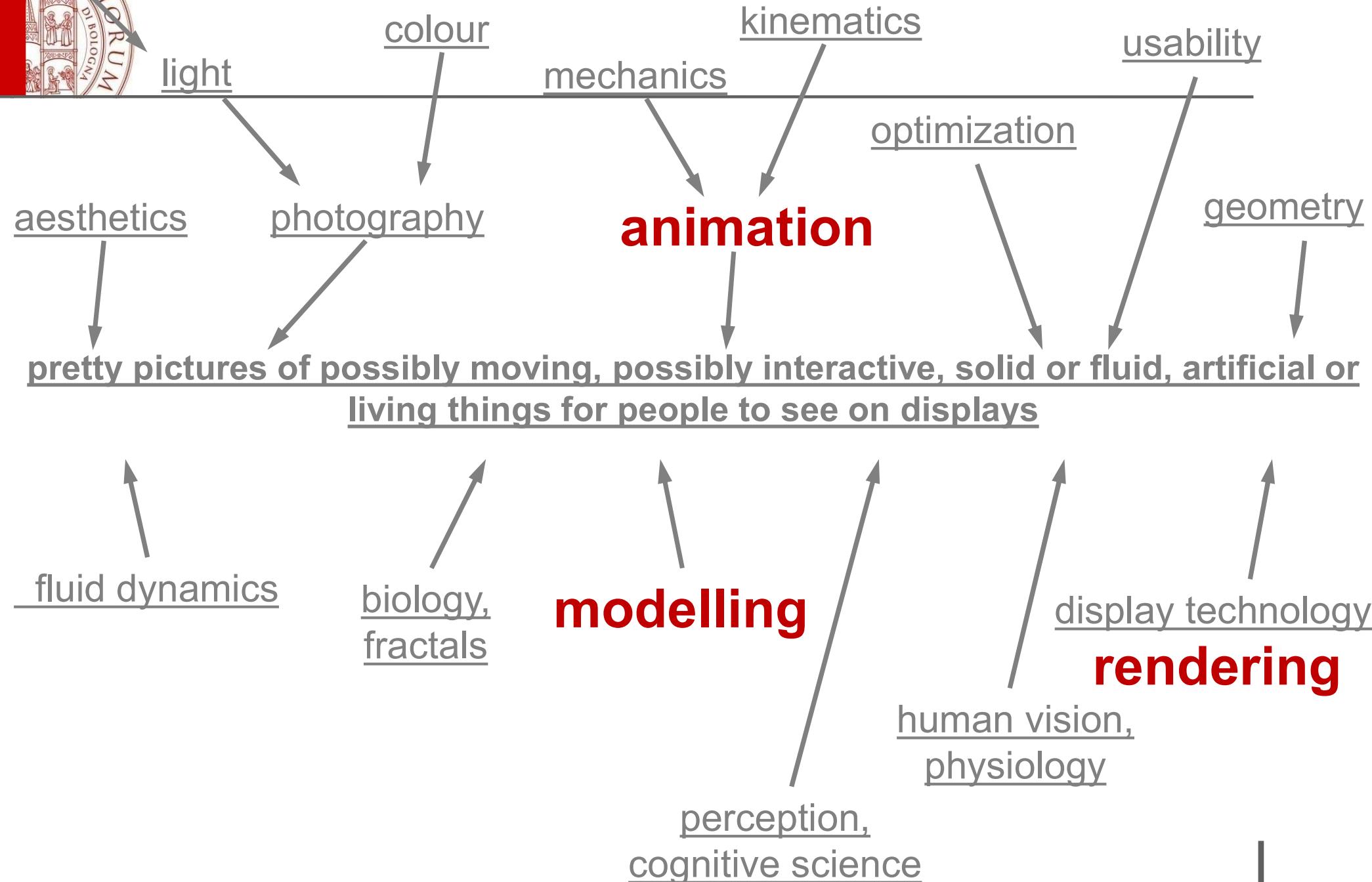
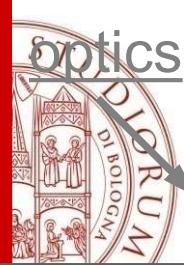
biology,
fractals

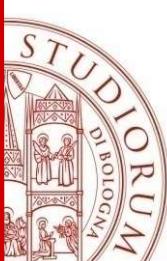
modelling

display technology,
rendering

human vision,
physiology

perception,
cognitive science

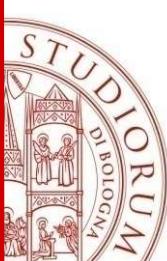




What you will learn

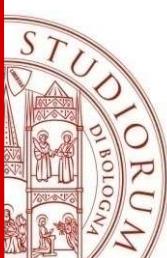
- Fundamentals of computer graphics algorithms
 - Modelling, Rendering, Animation
- We will concentrate on 3D, not 2D image processing
- Theoretical background (math) for the technical aspects of drawing pictures
- Basics of real-time rendering and graphics hardware
- Modern OpenGL / Basic GLSL / Blender

It's not supposed to be a programming course or math course, except that programming and math are necessary enabling technologies



How much math?

- **Mathematical concepts for graphics**
- Lots of simple linear algebra/calculus
 - Vectors, matrices, basis, solving systems of equations
 - Basic computational geometry
 - Get it right, it will help you a lot!
- Always in a concrete and visual context
- Many of the mathematical and algorithmic tools are useful in other engineering and scientific context



Grading Policy

- Assignments: 45%

6CFU:

4 over 6 programming assignments (individually)
alternatively:

– individual project or seminar presentation

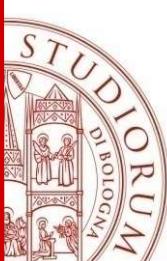
8CFU:

6 programming assignments (individually)

4 can be replaced by :

– individual project or seminar presentation

- Final Exam: 50% – oral
- Participation: 5%



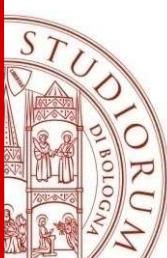
Assignments

0: **Warm up 2D and 3D**

- 1: trajectories in 2D
- 2: gaming/animation 2D
- 3: interaction and 3D scene (mesh display)
- 4: modelling in Blender

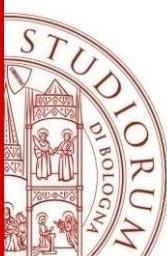
3D scanning/VR/3D printing

- 5: rendering and Ray Tracing contest in Blender
- 6: 3D scene texturing and special effects



Who needs Computer Graphics?

- Computer-Aided Design/Manufacturing
- Medical Imaging
- Simulation
- Architecture
- Electronic publishing
- Computer Animation / Film Production
- Art
- Games
- ...



Industrial Design

The final product is 3D

- Aeroplane
- Cars
- Boat
- Toys
- Tools
-

Spend more time doing
what you do best: design.





Boeing Home

Commercial Home

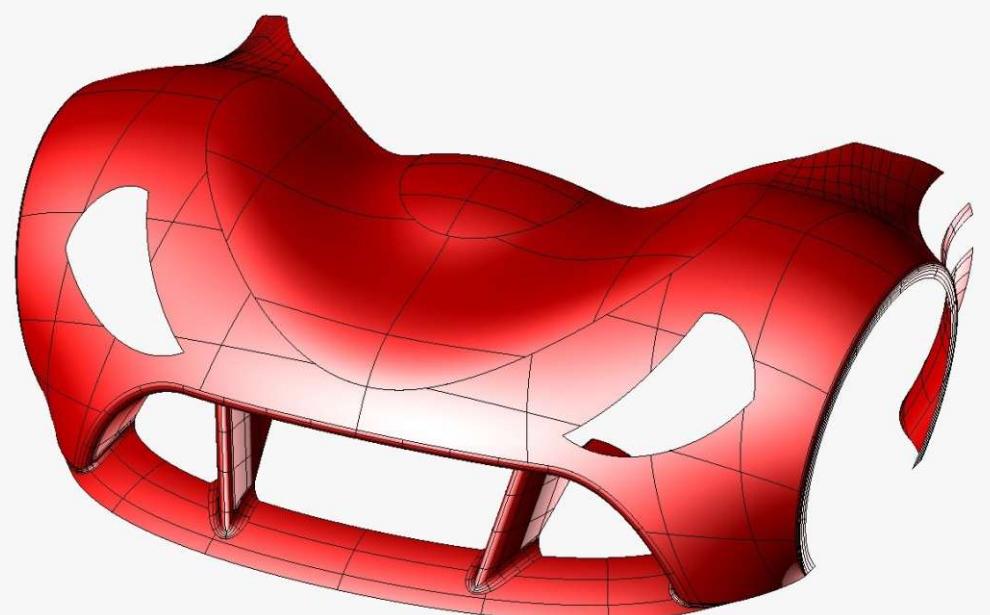
777 Home



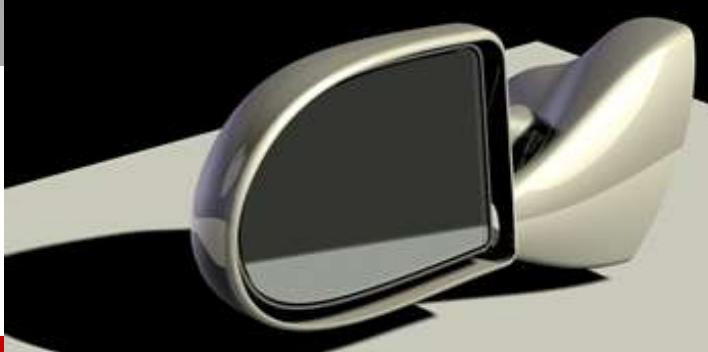
CAD Systems



William Fetter coined term “computer graphics” in 1960 to describe new design methods he was pursuing at Boeing



think³



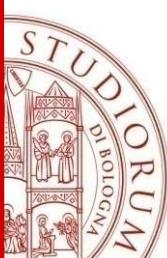


ALESSI





AL



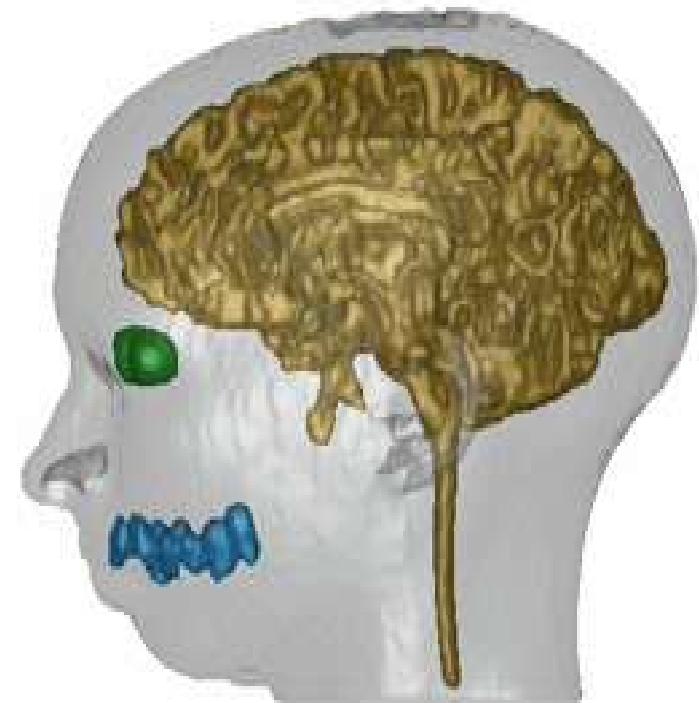
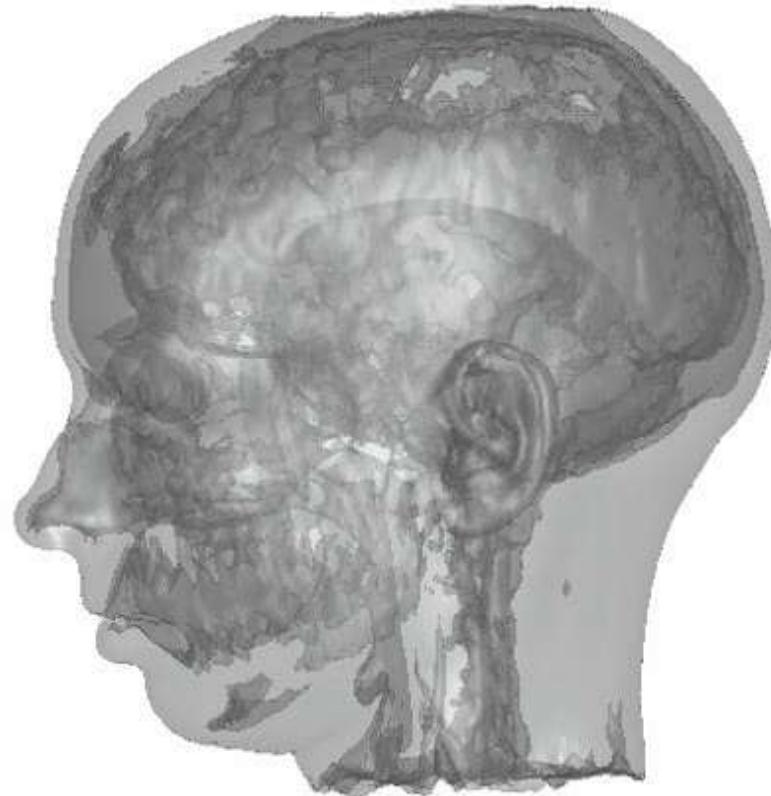
Medical Imaging

How to represent volume data?

-volume rendering

Magnetic resonance MRI (3D volume 257^3)

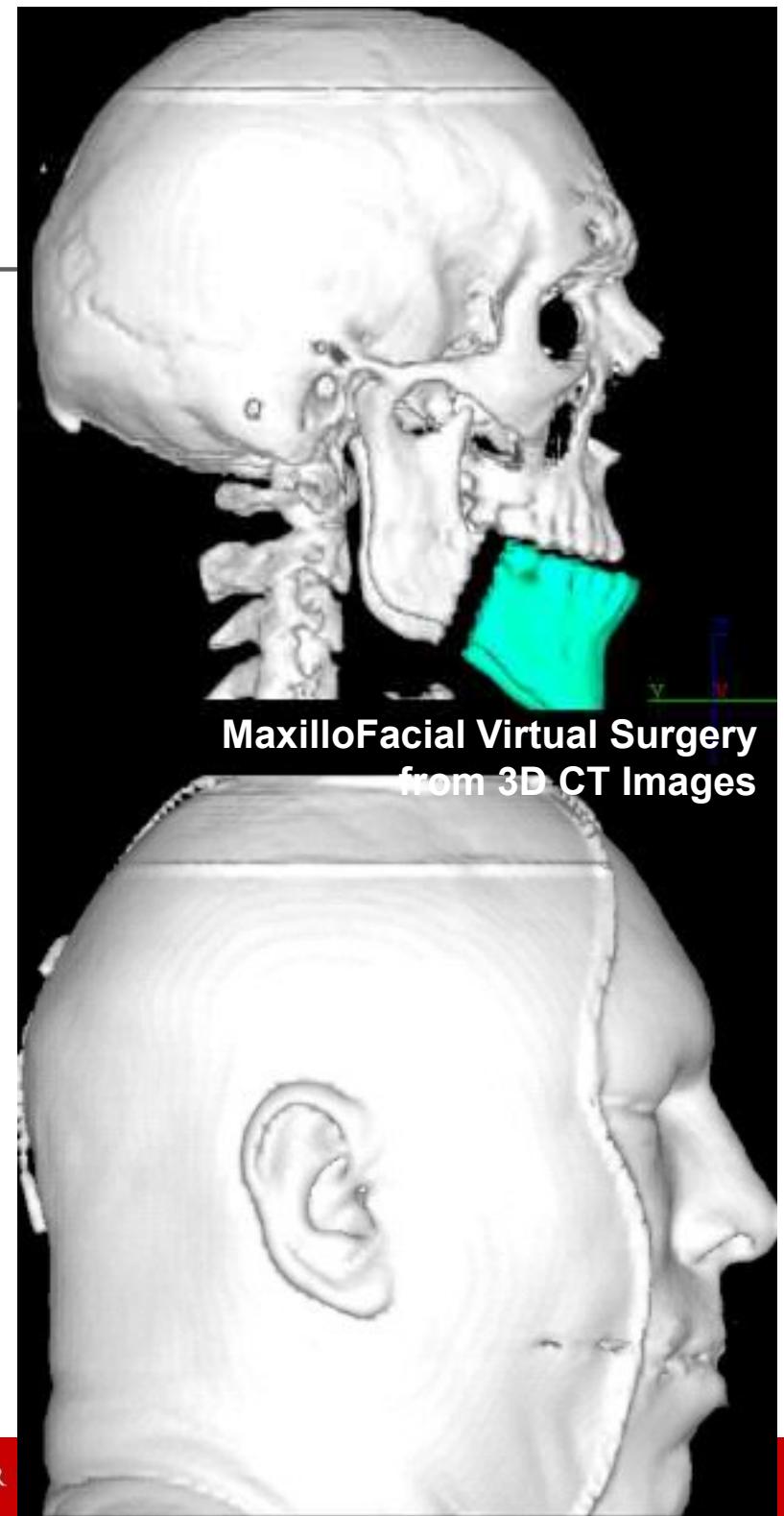
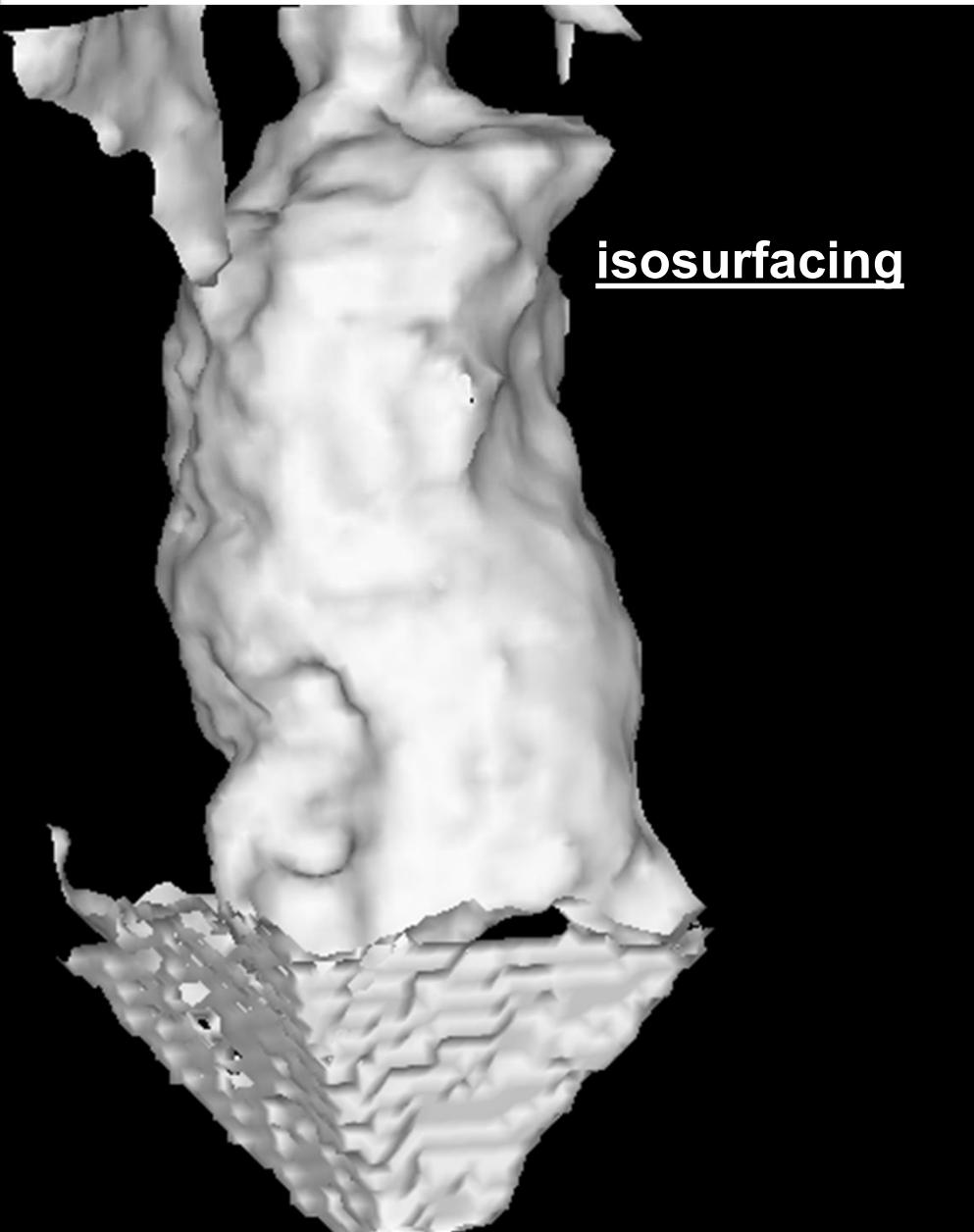
-isosurfacing



segmentation

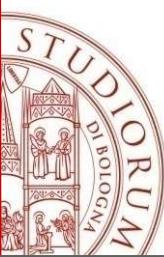


Medical Imaging



Collaboration –ESAOTE

ALMA MATER

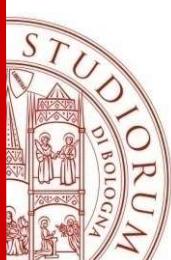


Scientific Visualization

“The merging of data with the display of geometric objects through computer graphics”

DATA + GEOMETRY:

- Understanding of data
- Insight into information
- Presentation and sharing of insights.



Scientific Visualization

The Piedmont Flood of November 1994:
Numerical Simulations at FISBAT



Chemistry

Bioengineering

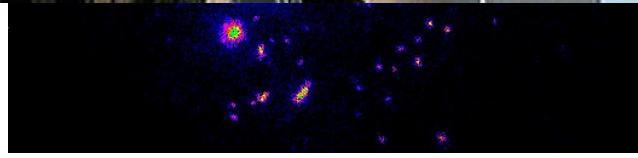
Engineering

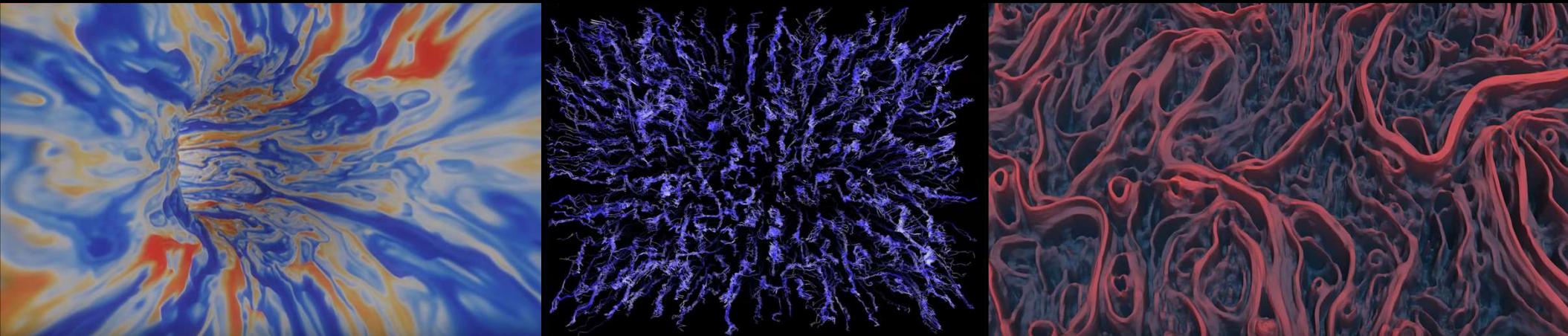
Human

Astrophysics

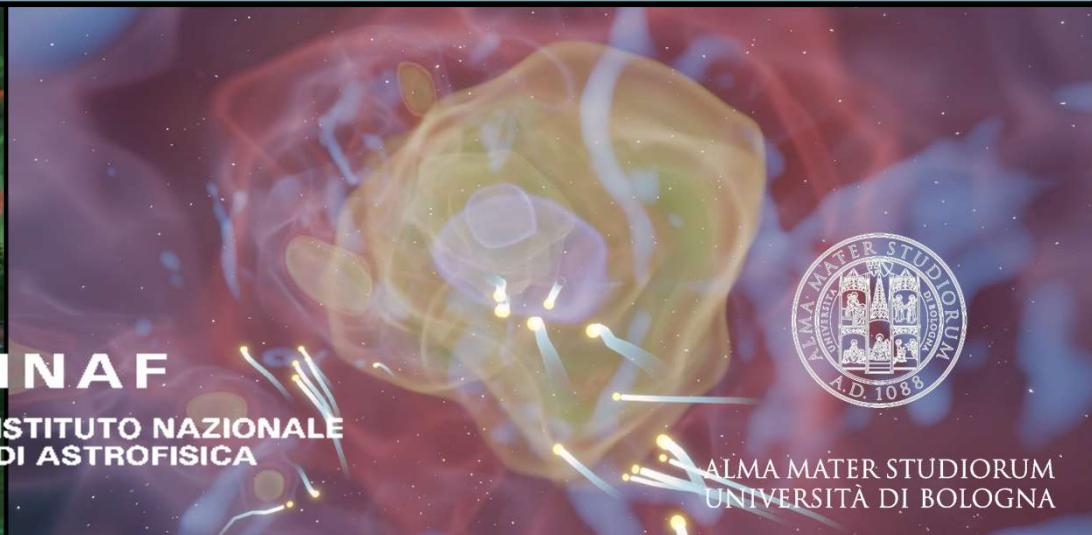
PURDUE CRASH SIMULATION TEAM
Simulation design by S. Kilic

[Link full video](#)





Into The (Un)Known



Relics of a cutting out boarding project



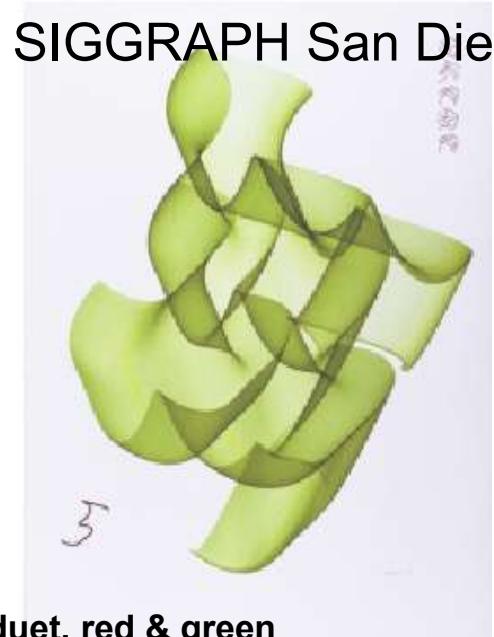


Art

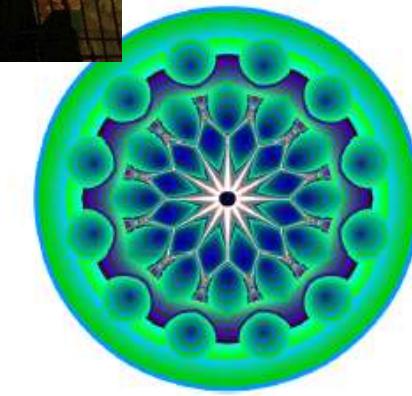
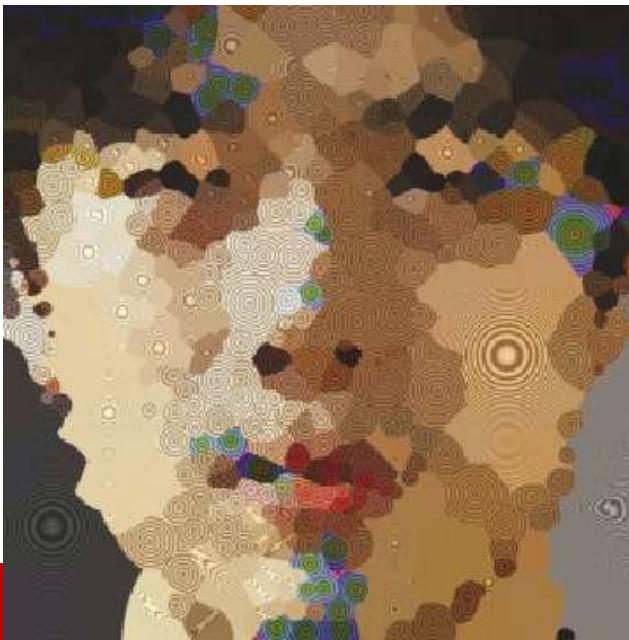
Video Mapping 3D



ART GALLERY 2005, SIGGRAPH San Diego

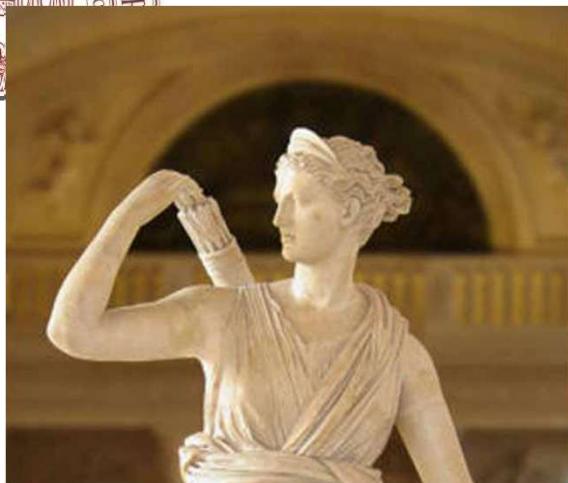


Cyberflower duet, red & green

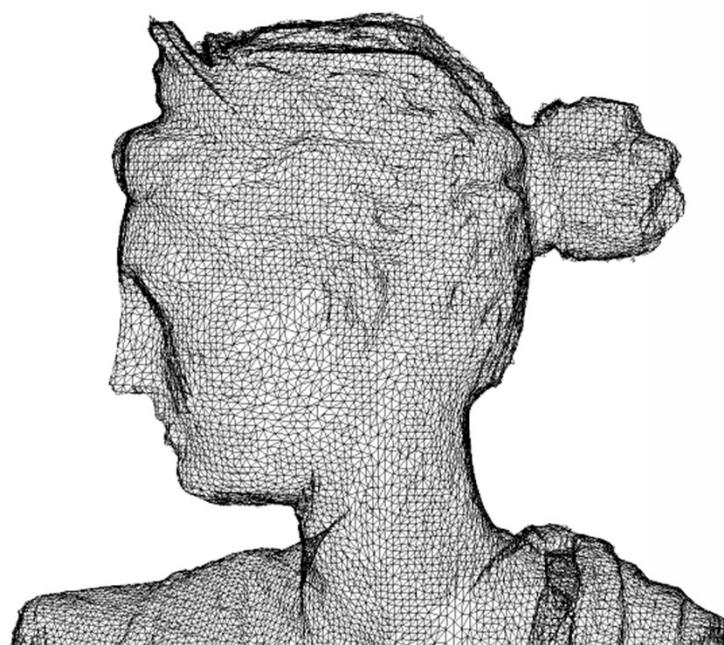


Polynomiography:
visualizzazione
di approssimazioni di zeri
di polinomi. Fig: degree 36

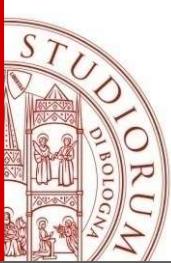




Art



Surface fairing

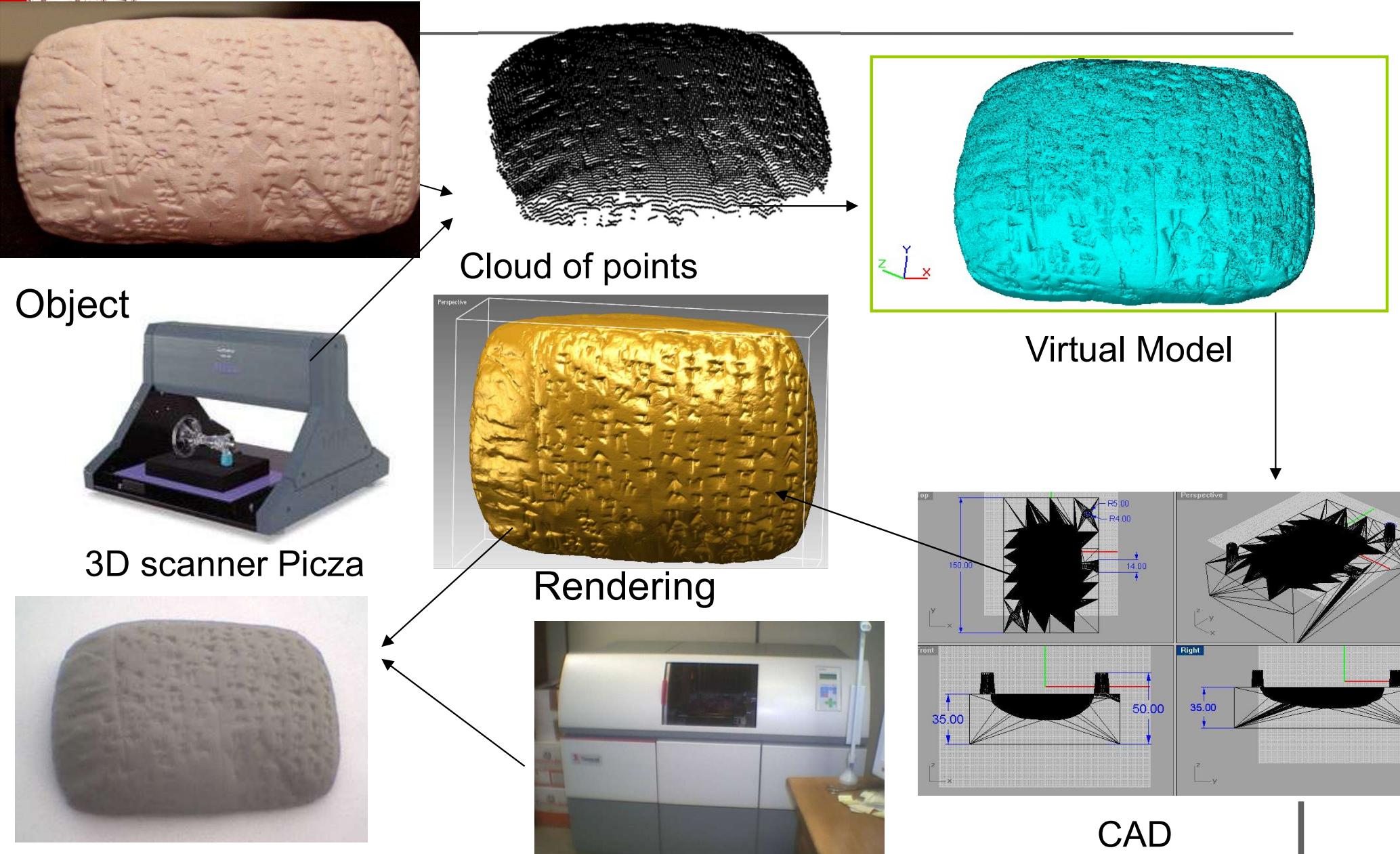


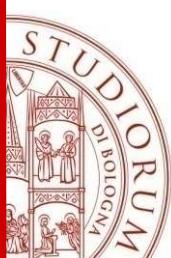
Reverse Engineering andRapid Prototyping



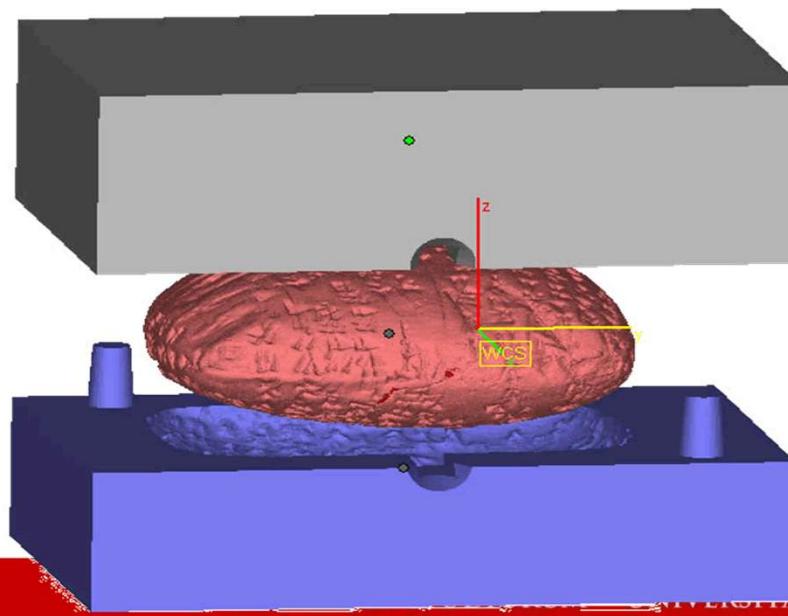
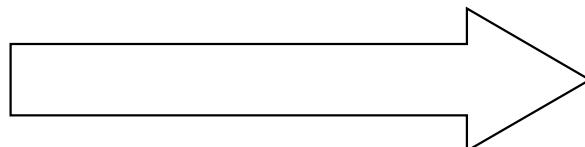
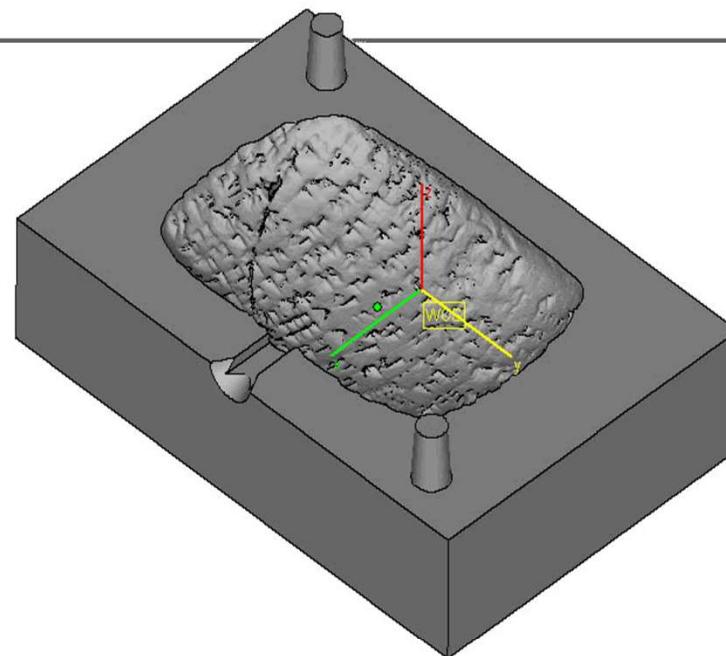
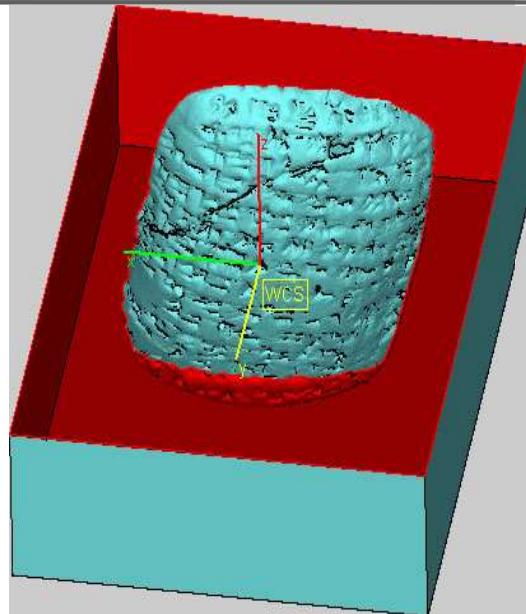
La Tavoletta Cuneiforme

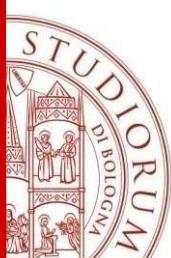
(tesi di S. Trerè - ENEA -Bologna)





CAD PostProcessing





Architectural Walkthroughs

Virtual paths: Apa alla scoperta di Bologna



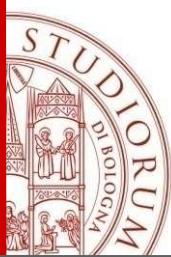
Making of del cartoon 3D visibile nella saletta immersiva del Museo della Storia di Bologna. Apa, il protagonista del cartoon, è doppiato da Lucio Dalla



Cineca, Bologna

2012 Al centro del Museo della Storia di Bologna, in una sala immersiva, è possibile vedere il cartoon 3D che il Cineca ha realizzato per Genus Bononiae: un cartone animato stereoscopico sulla storia di Bologna che combina un grande rigore filologico e le più innovative tecnologie con l'intento di informare divertendo.

Computer applications of virtual reality are a valuable tool to provide new means of access to the history of a city.



Digital Twin

A digital twin is a virtual copy, a digital representation of a physical product, process, or system.

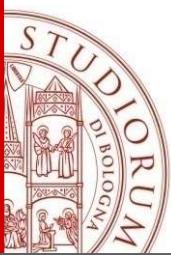


The object being studied — for example, a wind turbine — is outfitted with various sensors related to vital areas of functionality. These sensors produce data about different aspects of the physical object's performance, such as energy output, temperature, weather conditions and more. This data is then relayed to a processing system and applied to the digital copy.

Once informed with such data, the virtual model can be used to run simulations, study performance issues and generate possible improvements, all with the goal of generating valuable insights — which can then be applied back to the original physical object.

Bologna Digital Twin





E-business -- E-commerce



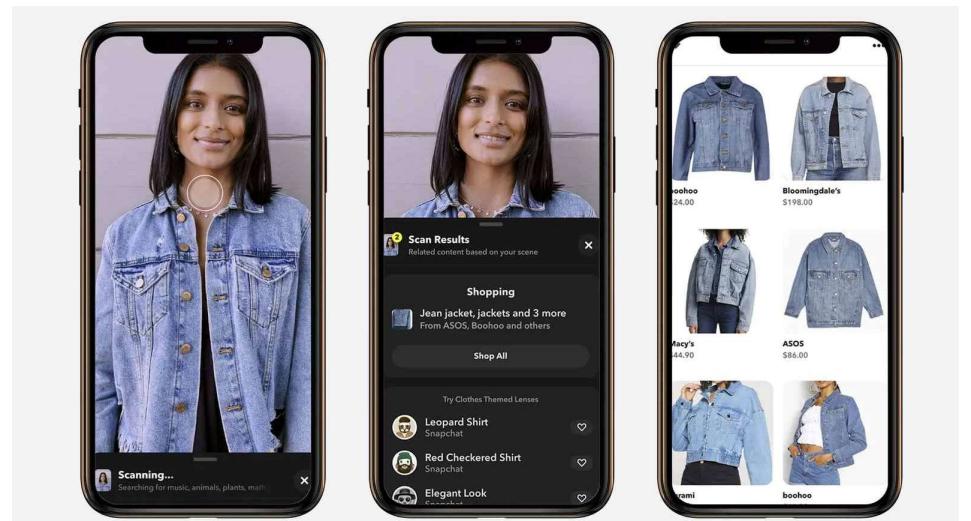
“Graphics is a practical representation of your ideas.”



Amazon, eBay, Etsy, and Shopify....



AR-powered virtual try ons in the fashion industry





Entertainment

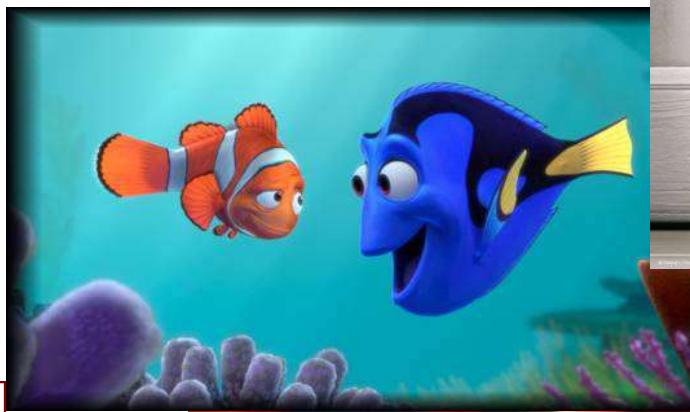
- Video Games
- Animated Film
- Visual Effects

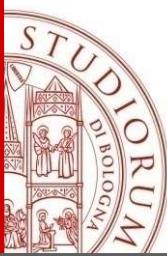
PIXAR Animation Studios

Luxo Junior (1986)
Red's Dream (1987)
Toy Story (1995)
A Bug's Life (1998)
Toy Story 2 (1999)
Monster, Inc. (2001)
Finding Nemo (2003)
The Incredibles (2004)
Cars (2006)
Ratatouille (2007).....

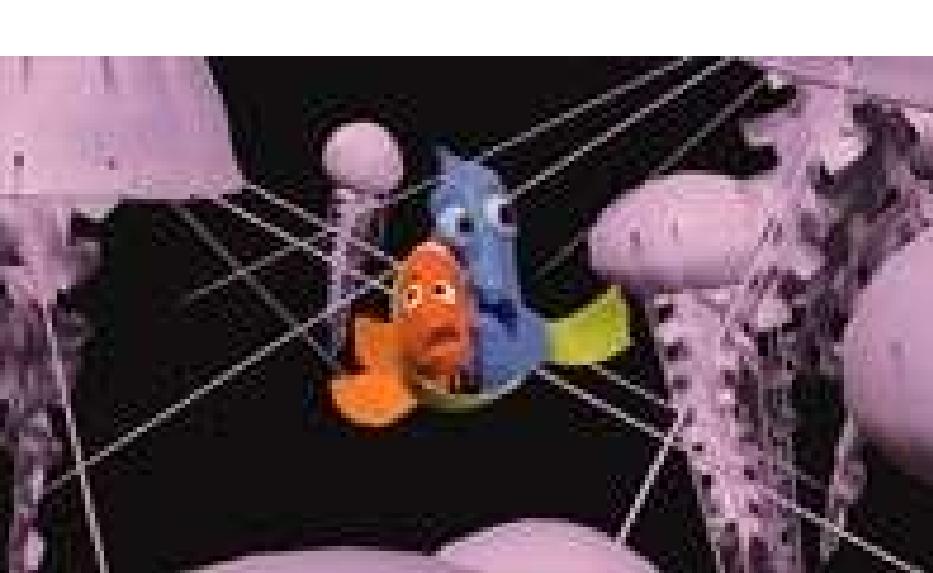
DREAMWORKS

Shrek/Shrek 2,3
(2003/2005/2007)
Madagascar (2005)

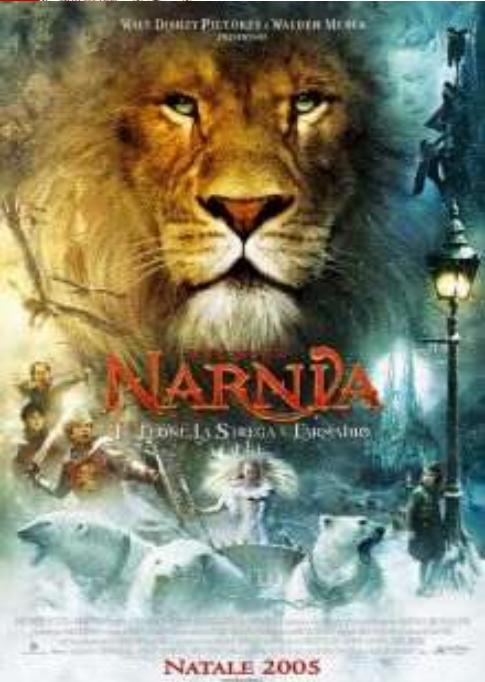




PIXAR Animation Studios



Film, Visual Effects



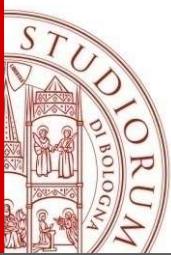
CG creature skin and muscles, skin rendering, motion capture, rigid and deformable dynamics, image-based modeling, digital doubles, fluid and smoke simulation, 3D compositing, cloth simulation, and new animation techniques.

(Industrial Light & Magic (ILM), Sony Pictures Imageworks, Inc.)



(ESC Entertainment)

Facial capture in Avatar
(2009)



Visual effects



The day after tomorrow

Liquids,
gases,
Solids



Star Wars Episode III

Destruction:
fracture, explosions, etc.



Videogames



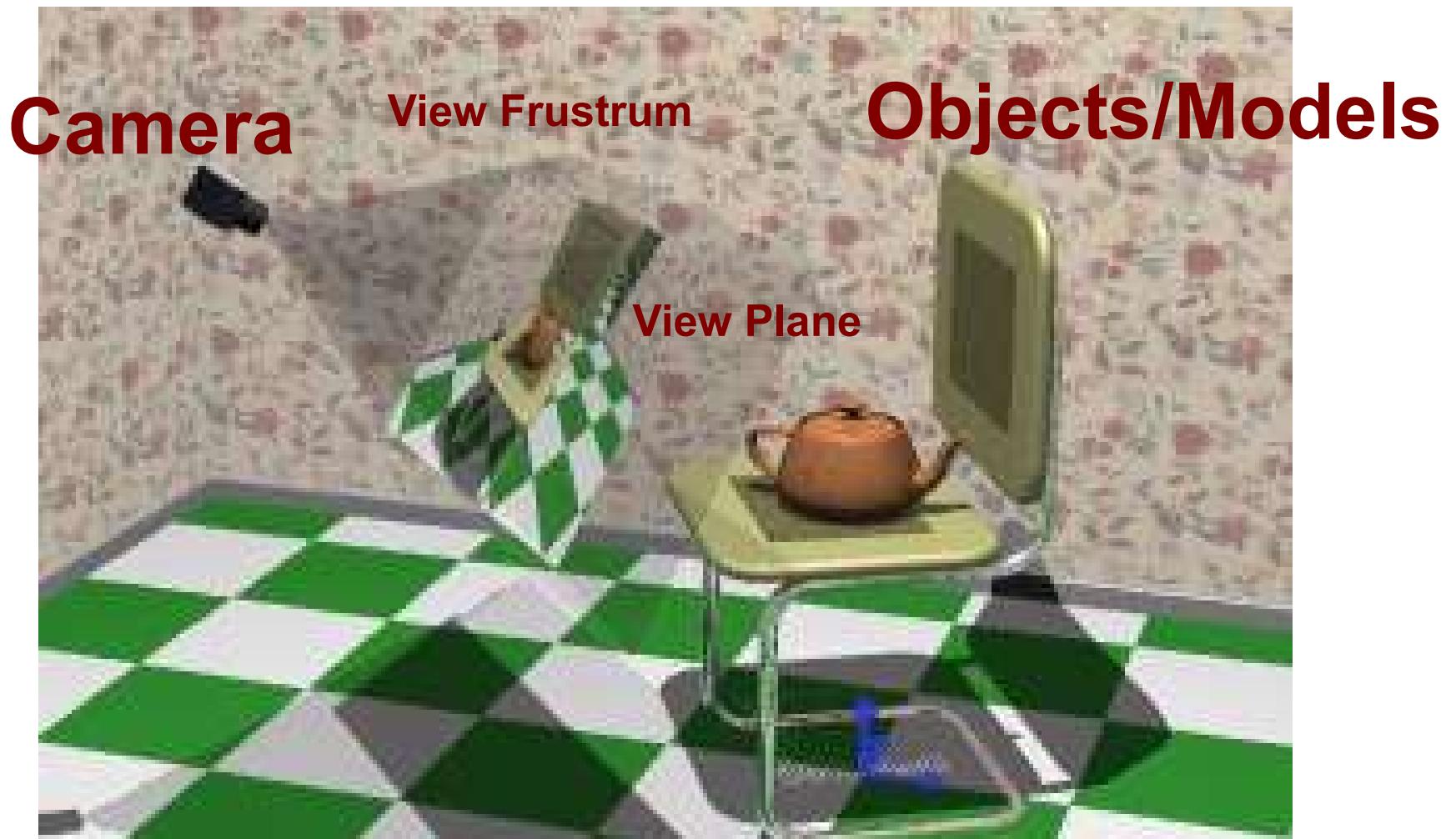
XBOX ONE X





CG basics:

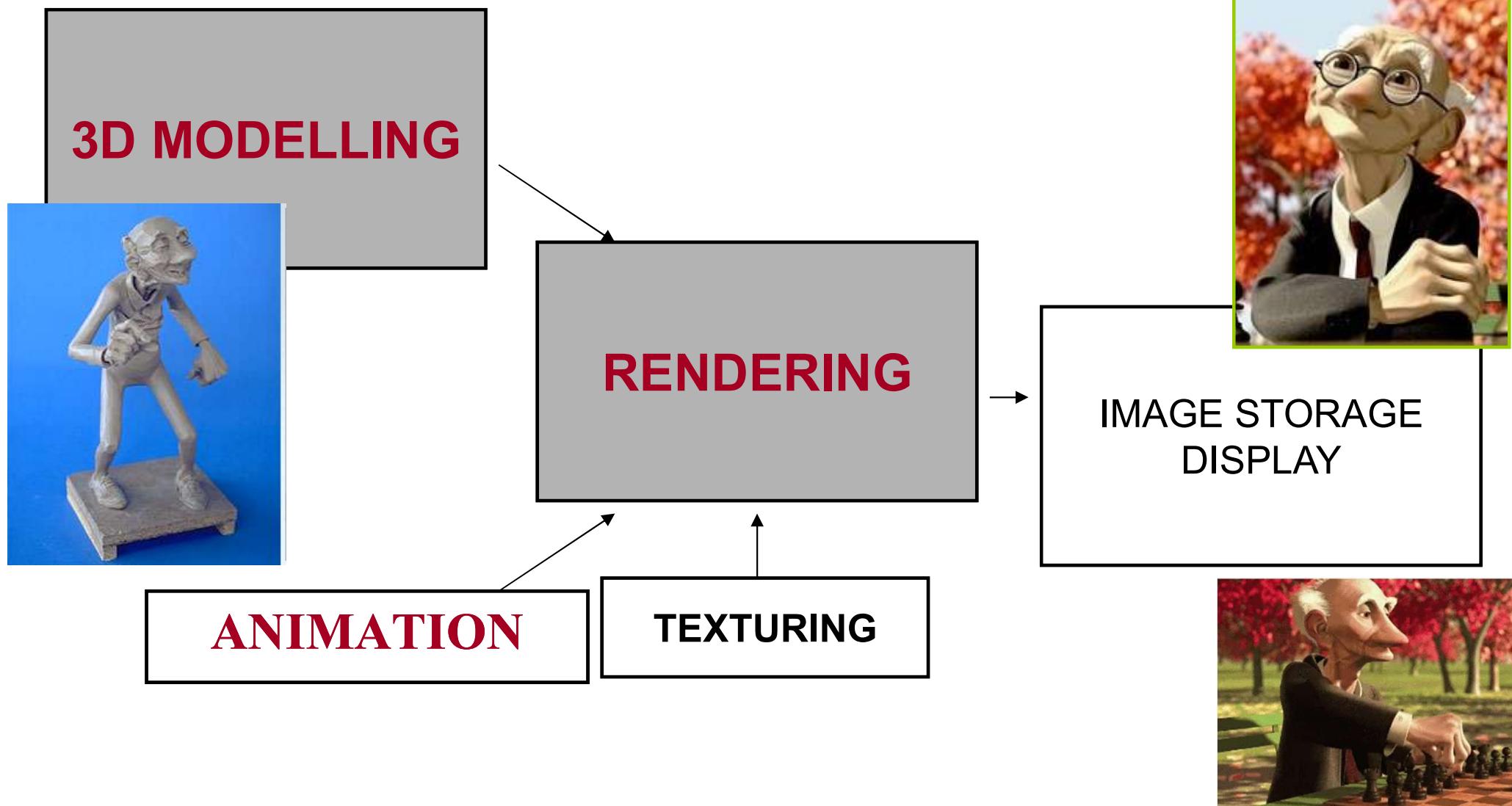
Virtual objects, scene, Viewer (camera)

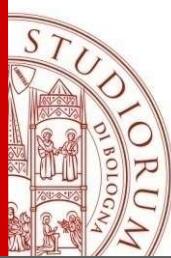




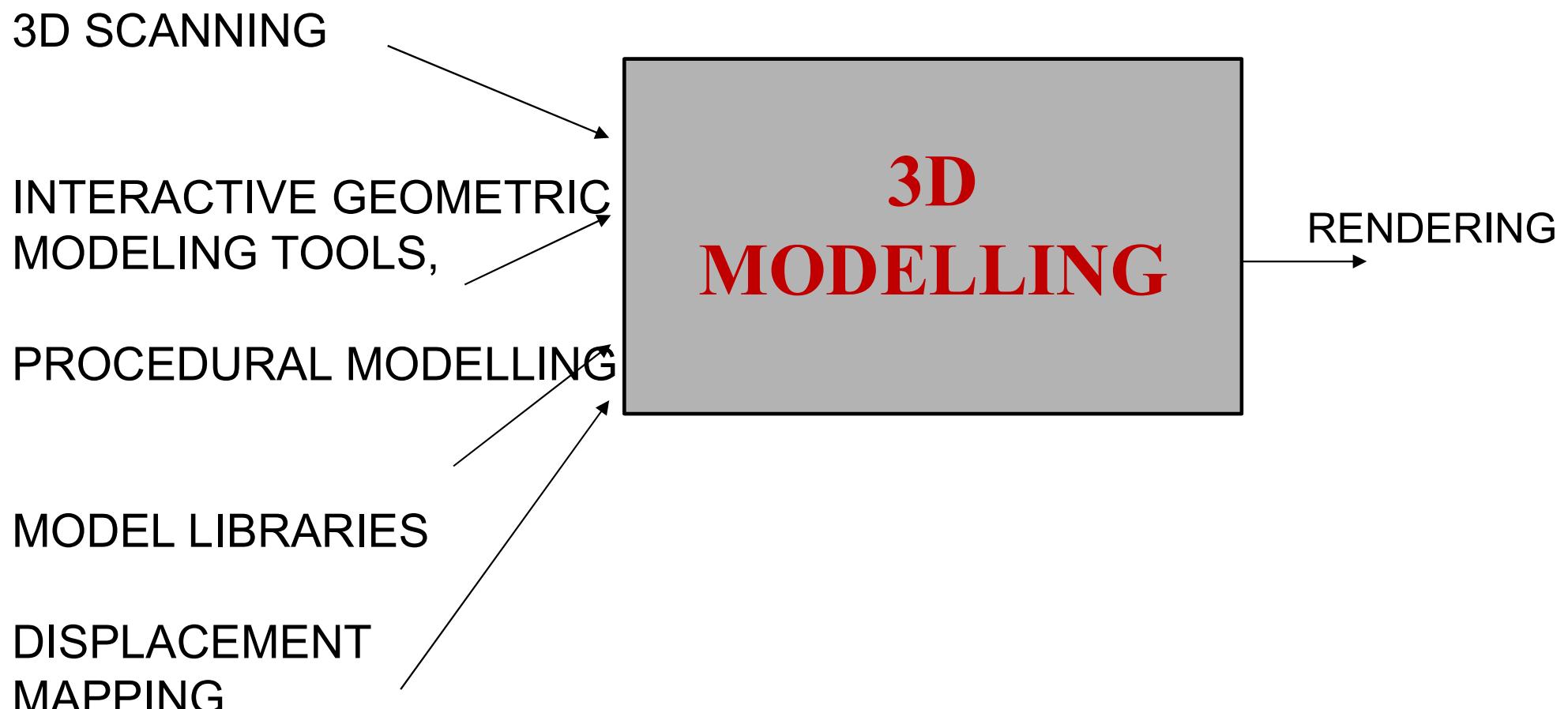
The graphics process

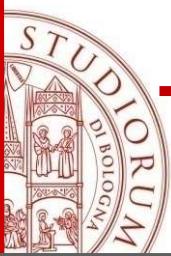
Pixar, 'Geri's game'



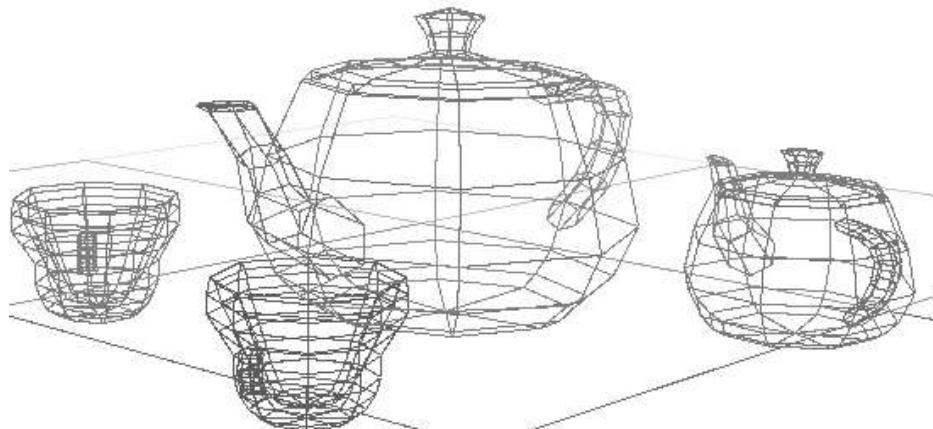
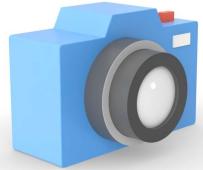


The graphics process: Geometric Modeling

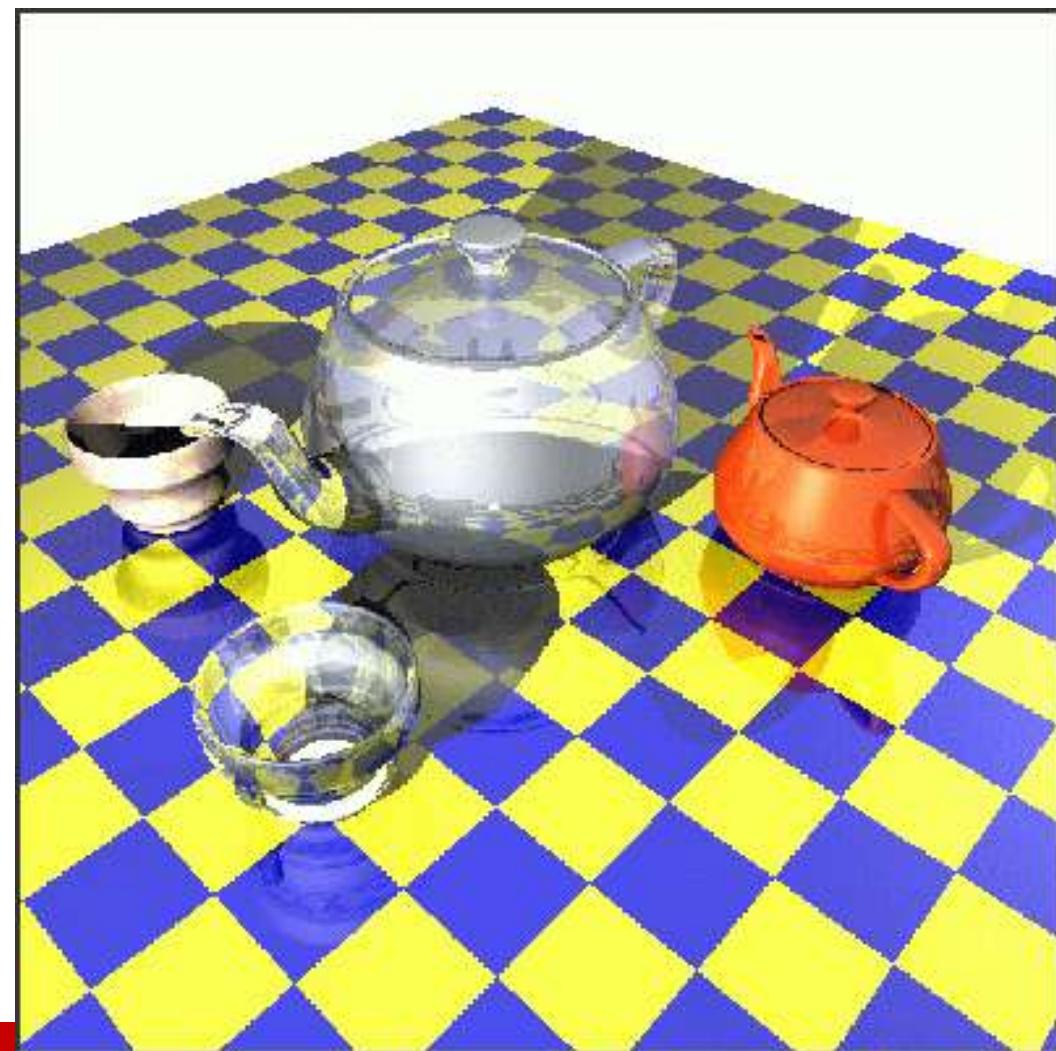


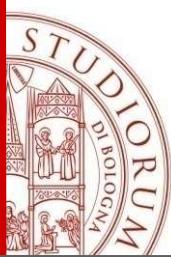


The graphics process: Rendering

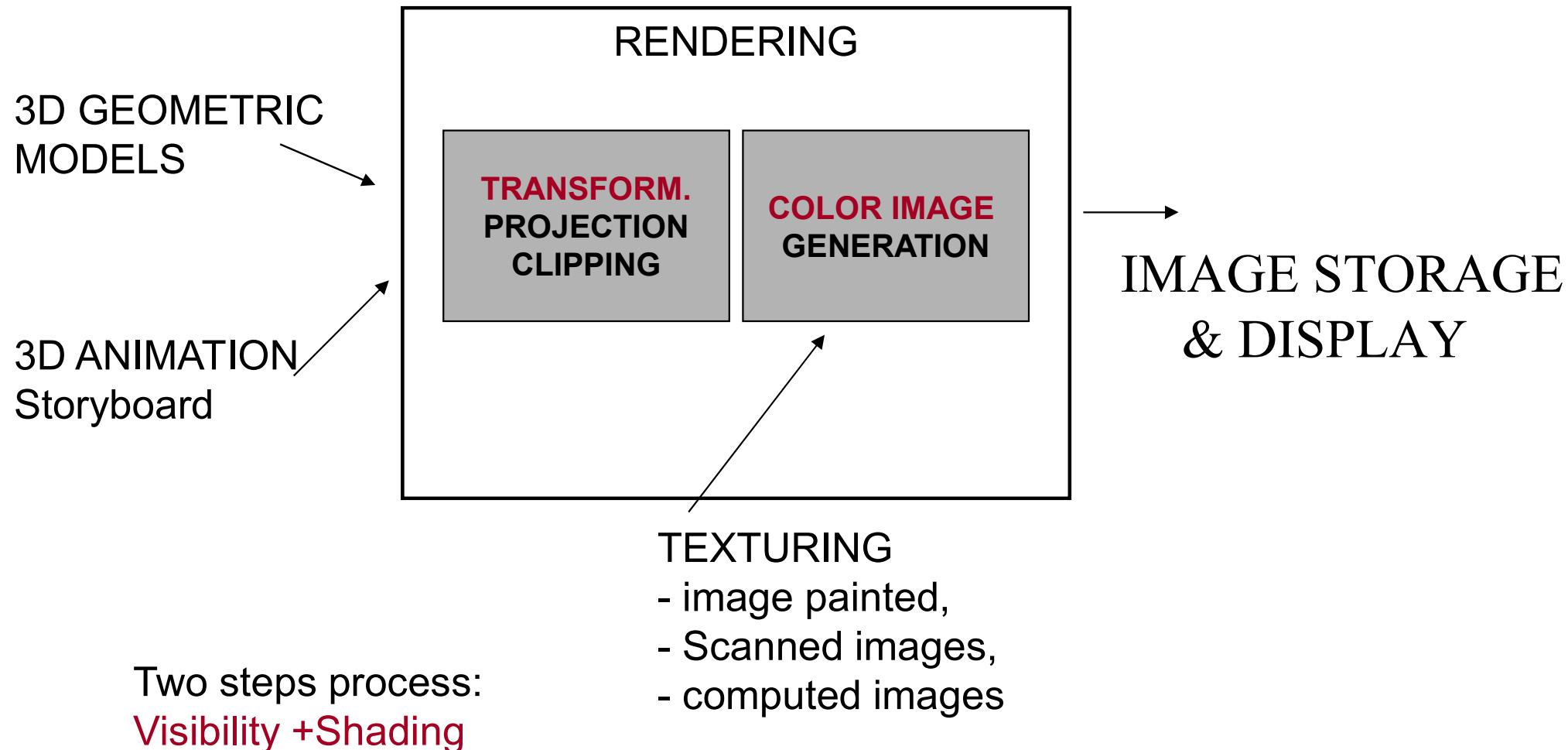


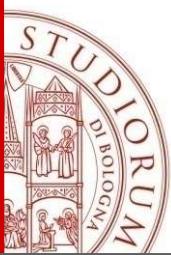
**Produce bidimensional
images from a
3D scene and a camera**





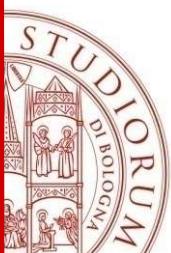
The graphics process: RENDERING





3D MODELLING

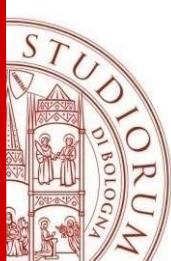
Design the shape of 3D objects



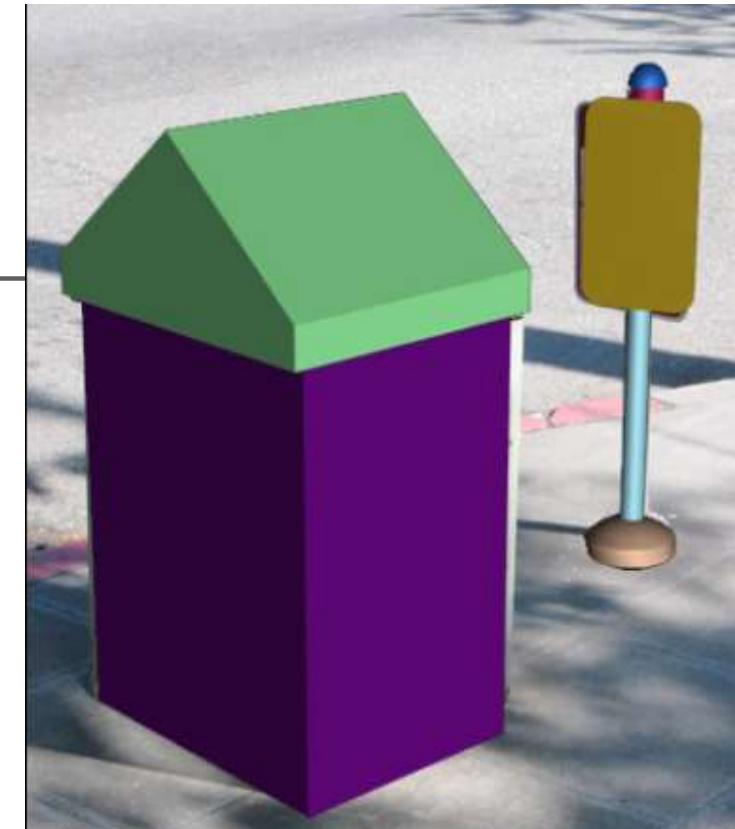
Seeing in 3D

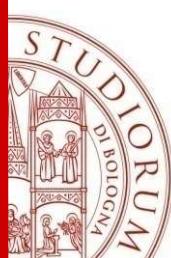
- The world in basic shapes
- Shapes are instances of primitives (e.g., spheres, cubes, etc.)





Reduction to primitives
(e.g., spheres, cubes,
etc.)





Simple but not too simple

- Real shapes are complex
- More detail = more realism
 - takes longer to model, longer to render, and occupies more disk space

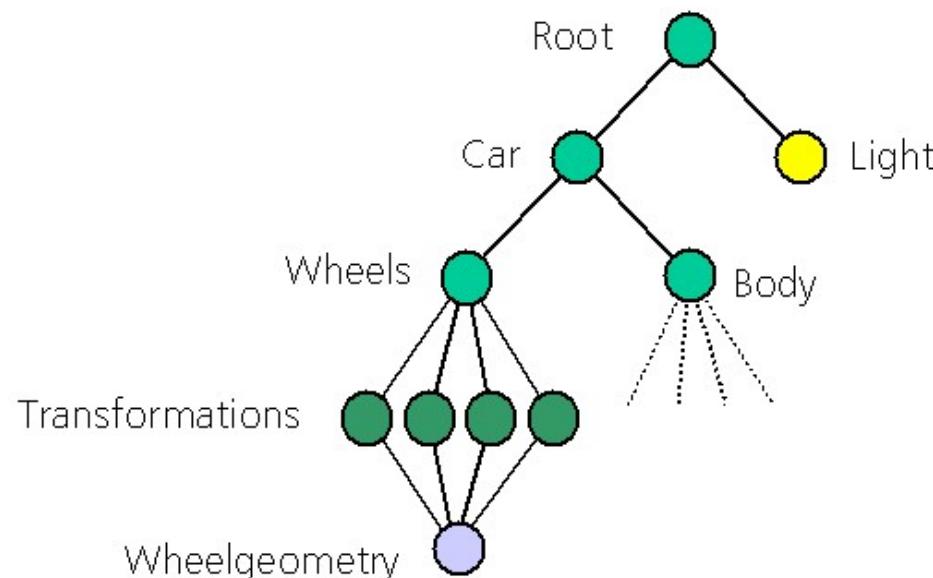


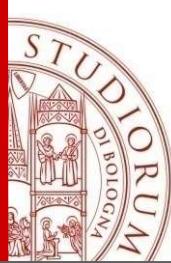


Primitives and instances

Object to be modeled is (visually) analyzed, and then decomposed into collections of primitive shapes.

Tree diagram provides visual method of expressing “composed of” relationships of model





Different detail when required



models from **coarse to fine**



Level-of-Detail(LOD):

As object gets farther away from viewer, replace it with a lower-polygon version or lower quality texture map.

Discontinuous jumps in model detail



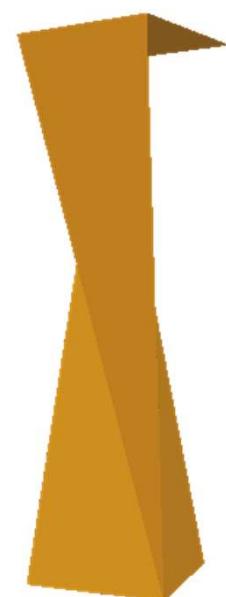
10,108 polys



1,383 polys

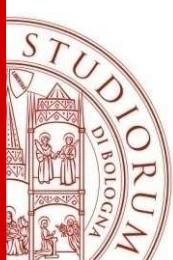


474 polys



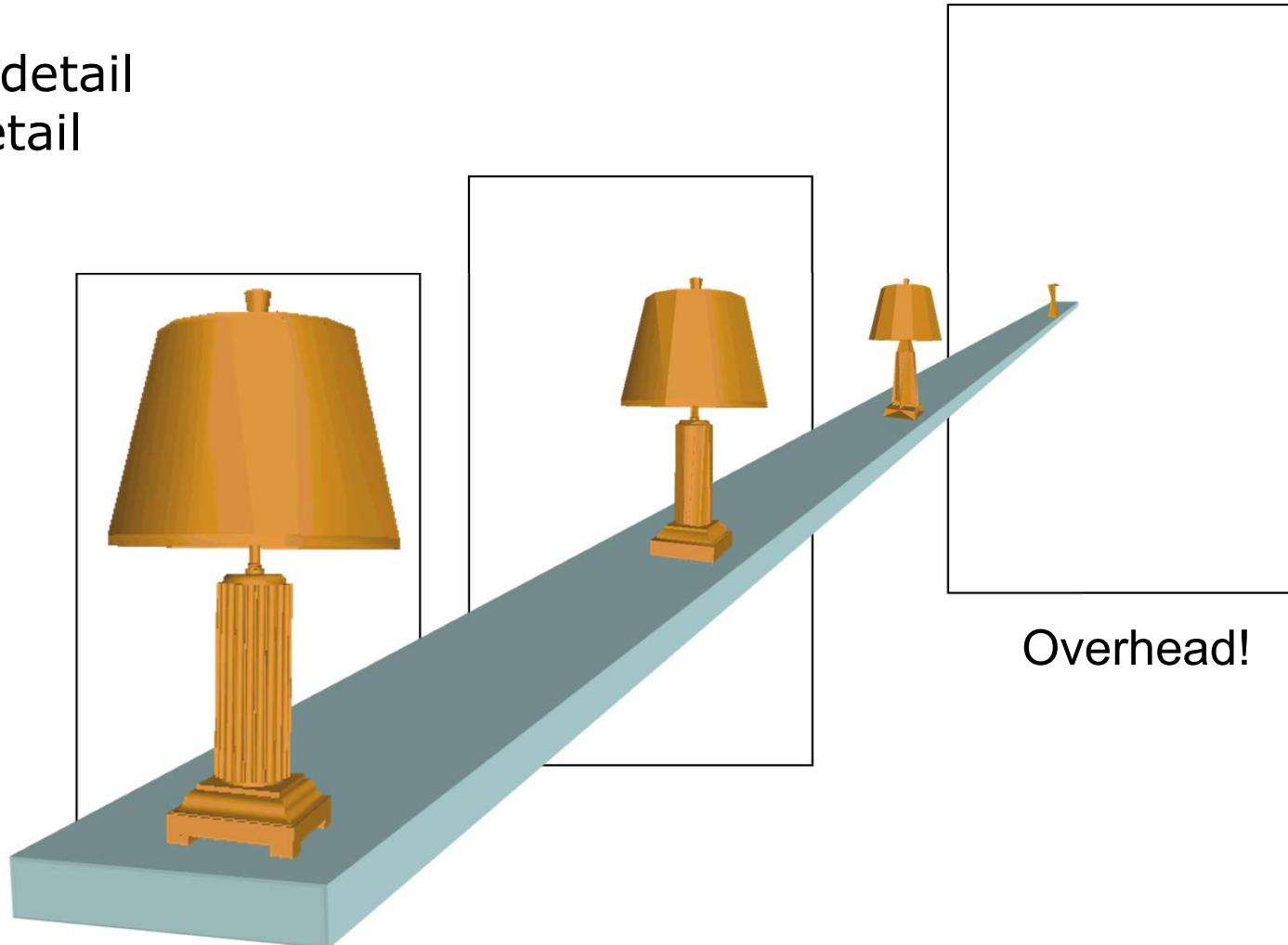
46 polys

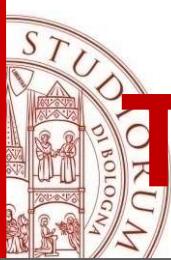
Courtesy IBM



LOD:

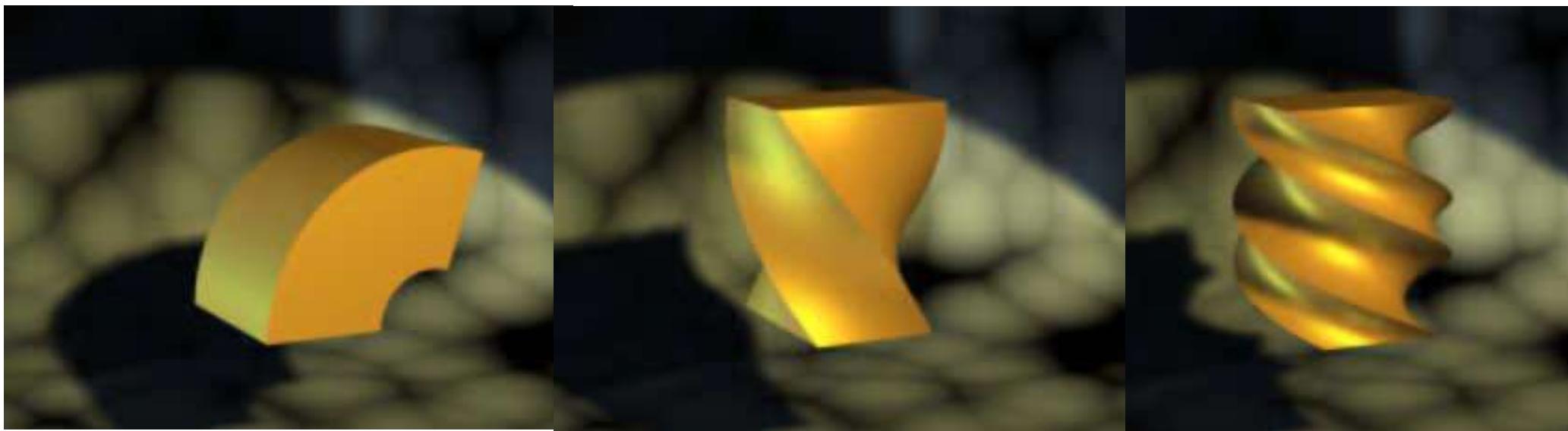
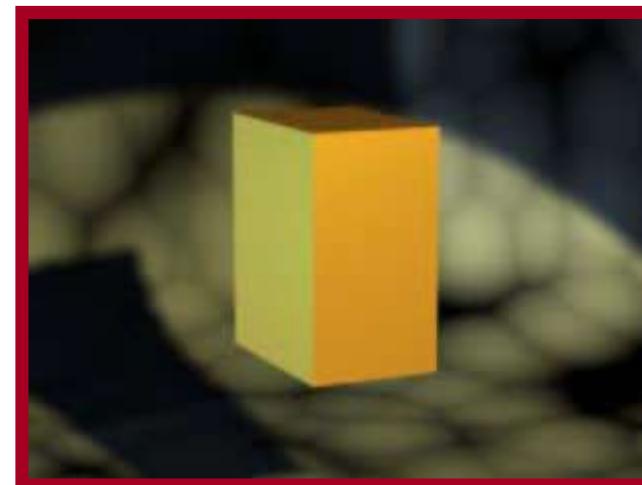
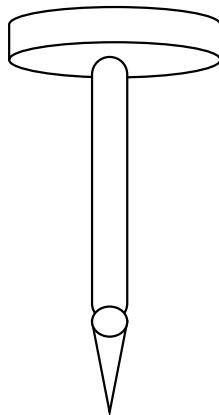
- Use only enough detail
- Switch level of detail

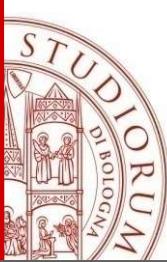




Types of Geometric Modelers

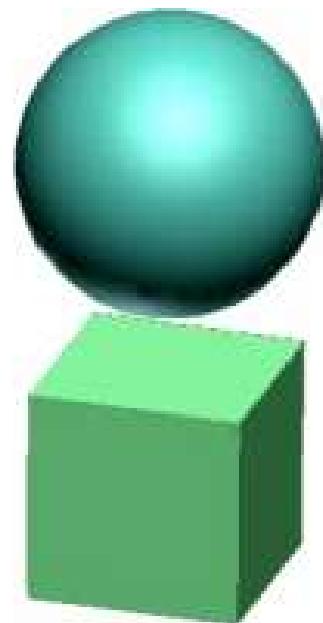
1) Box Modifiers





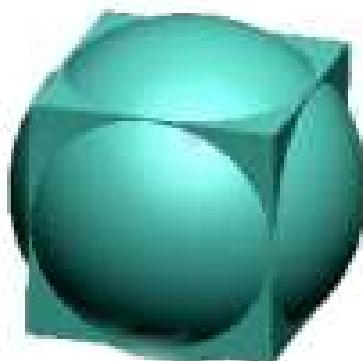
2) Constructive Solid Geometry (CSG)

- Combination of Solid Primitives by boolean operators
- Each rule combines two solids



**primitive
solide**

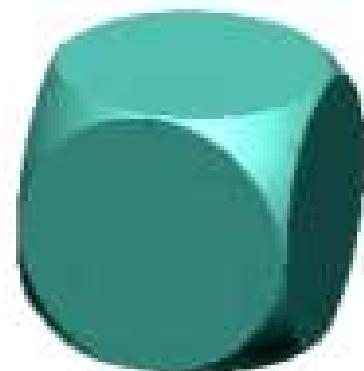
unione



sottrazione



intersezione





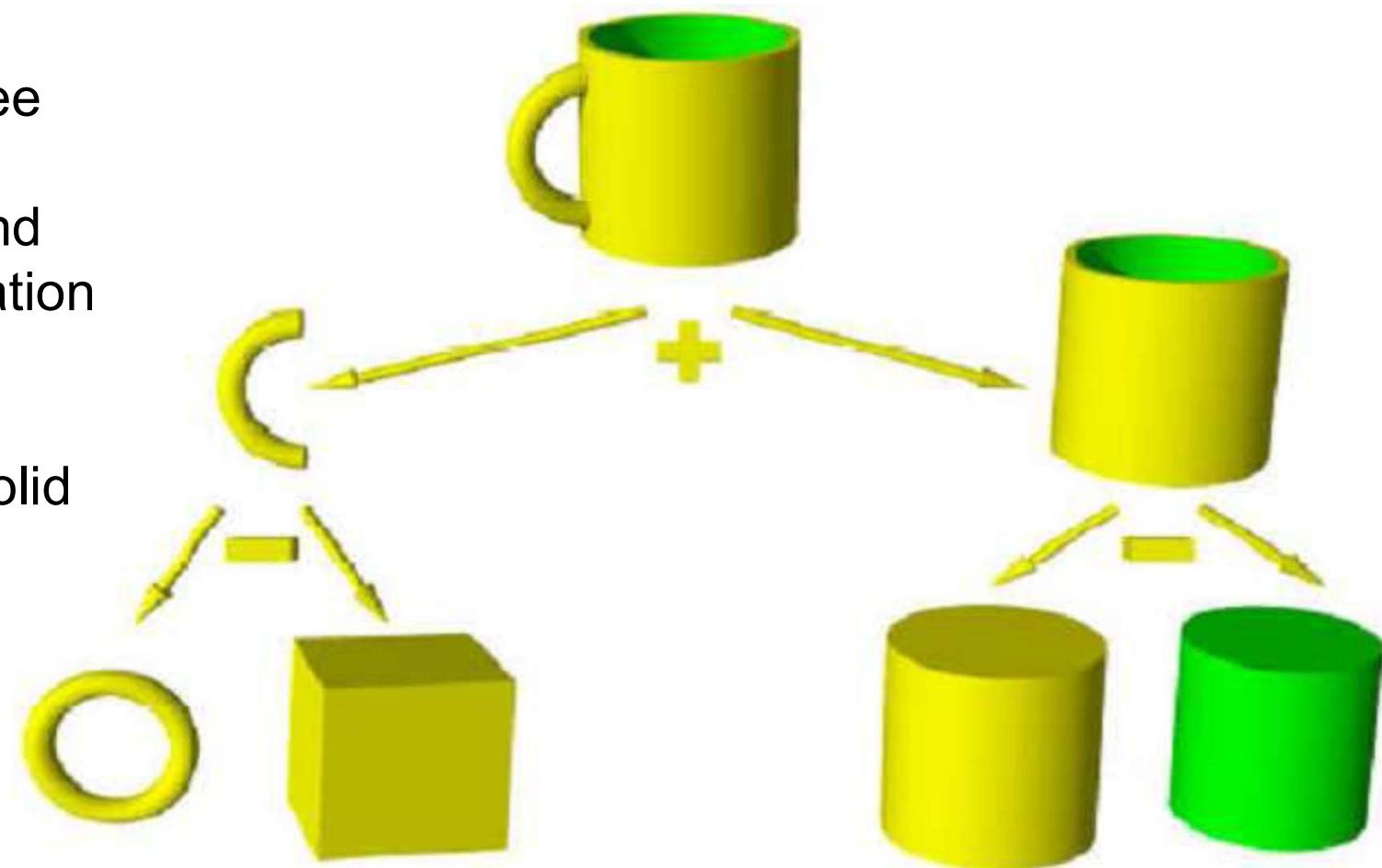
Constructive Solid Geometry

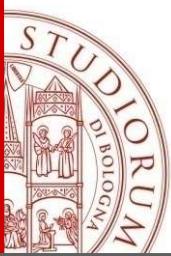
CSG TREE

A solid object is represented by a tree structure :
Boolean operation and geometric transformation at each level

Leafs: Solid issues

Root: the resulting solid



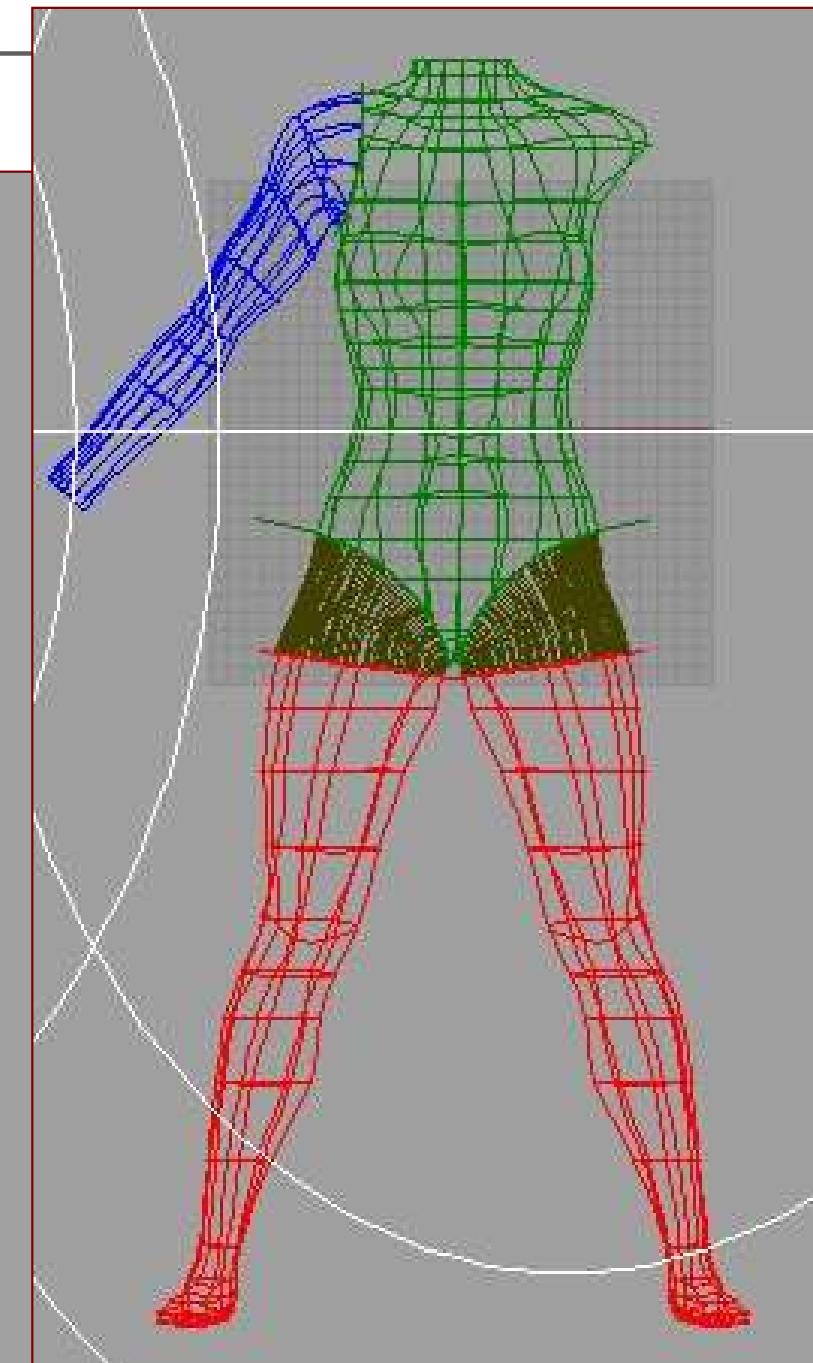


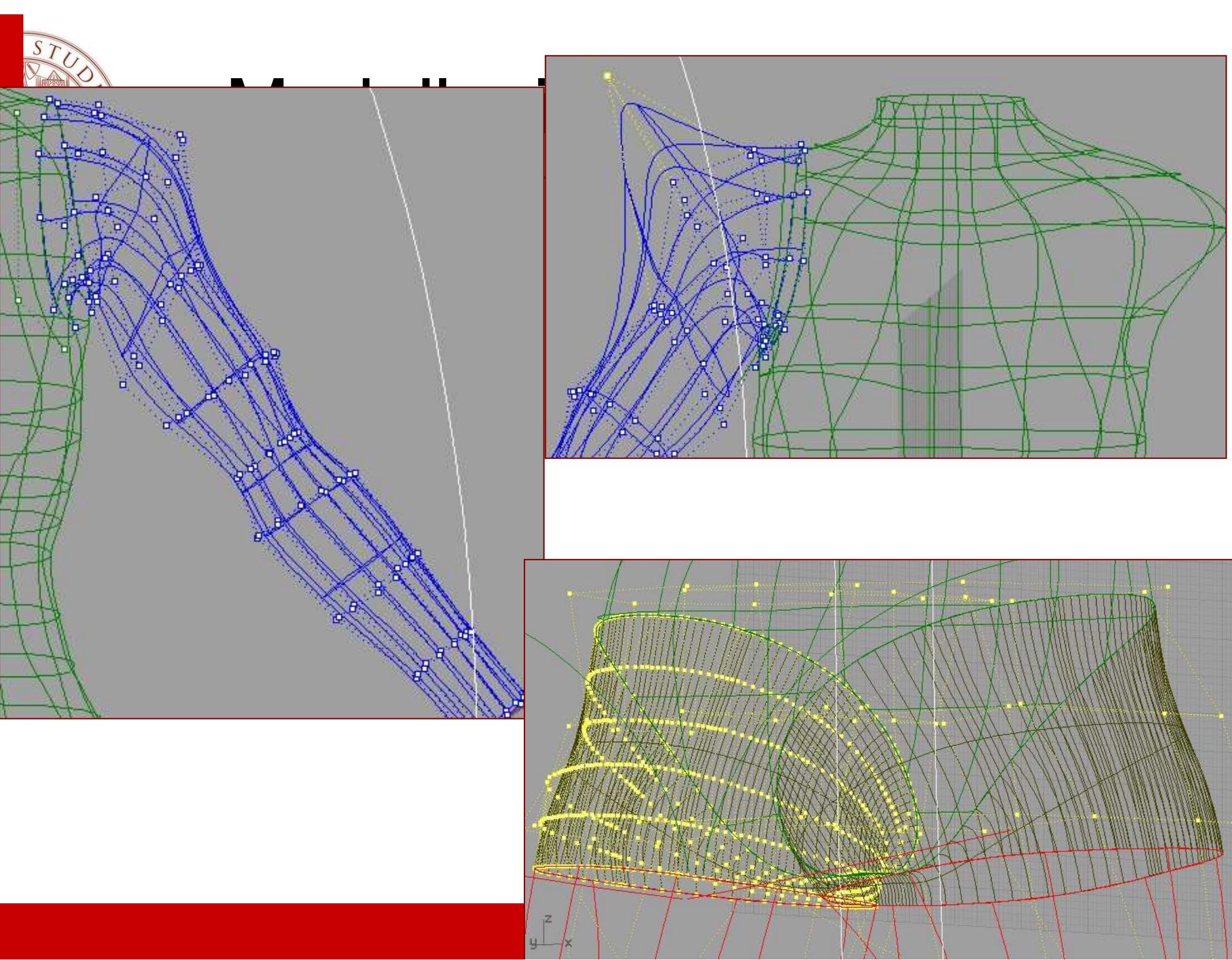
3) Interactive modeling: spline

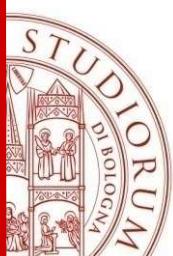
Patch: curved surfaces



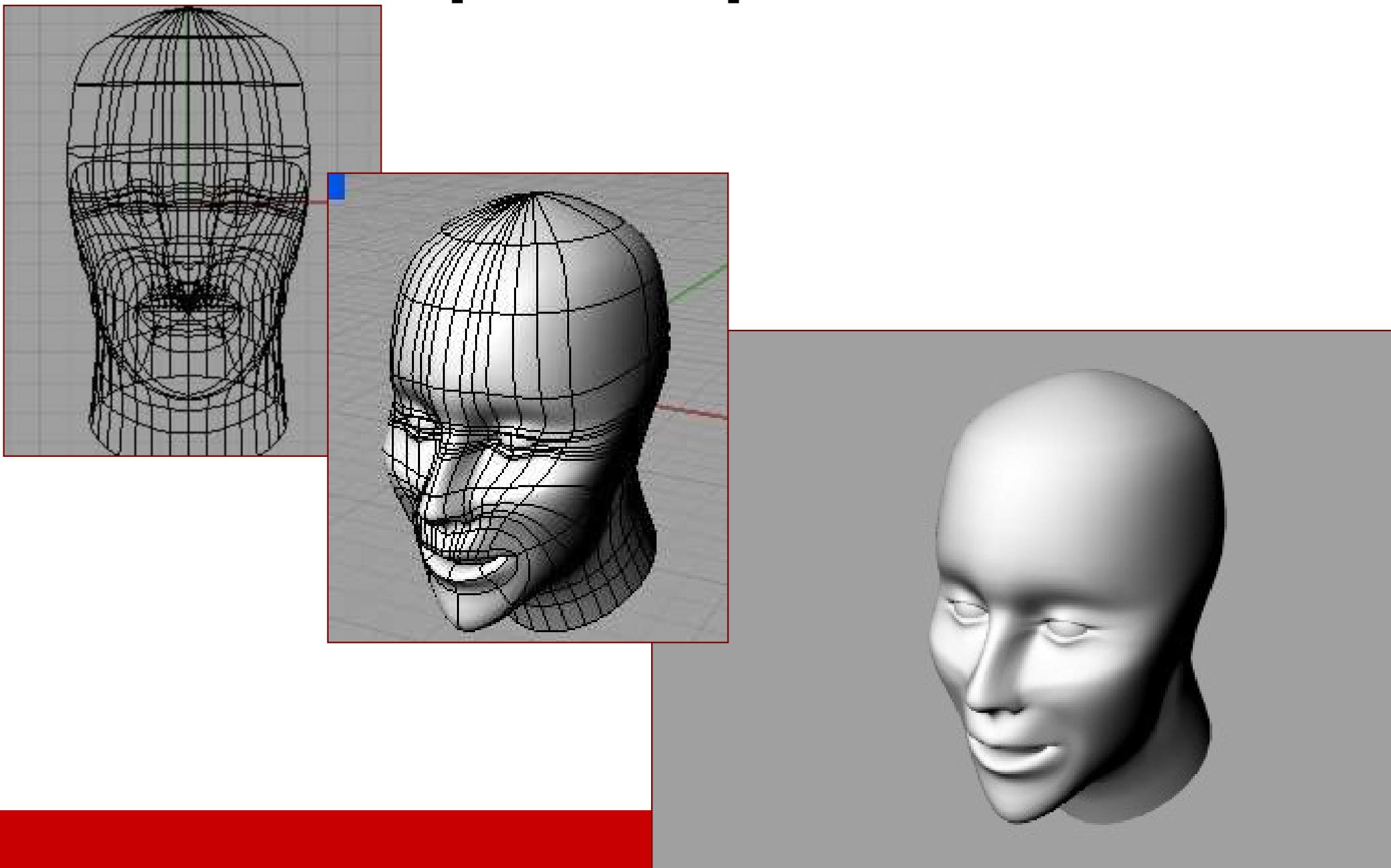
Continuous
mathematical
surface
representations

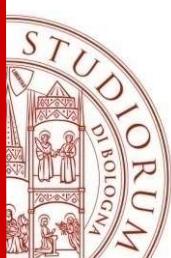




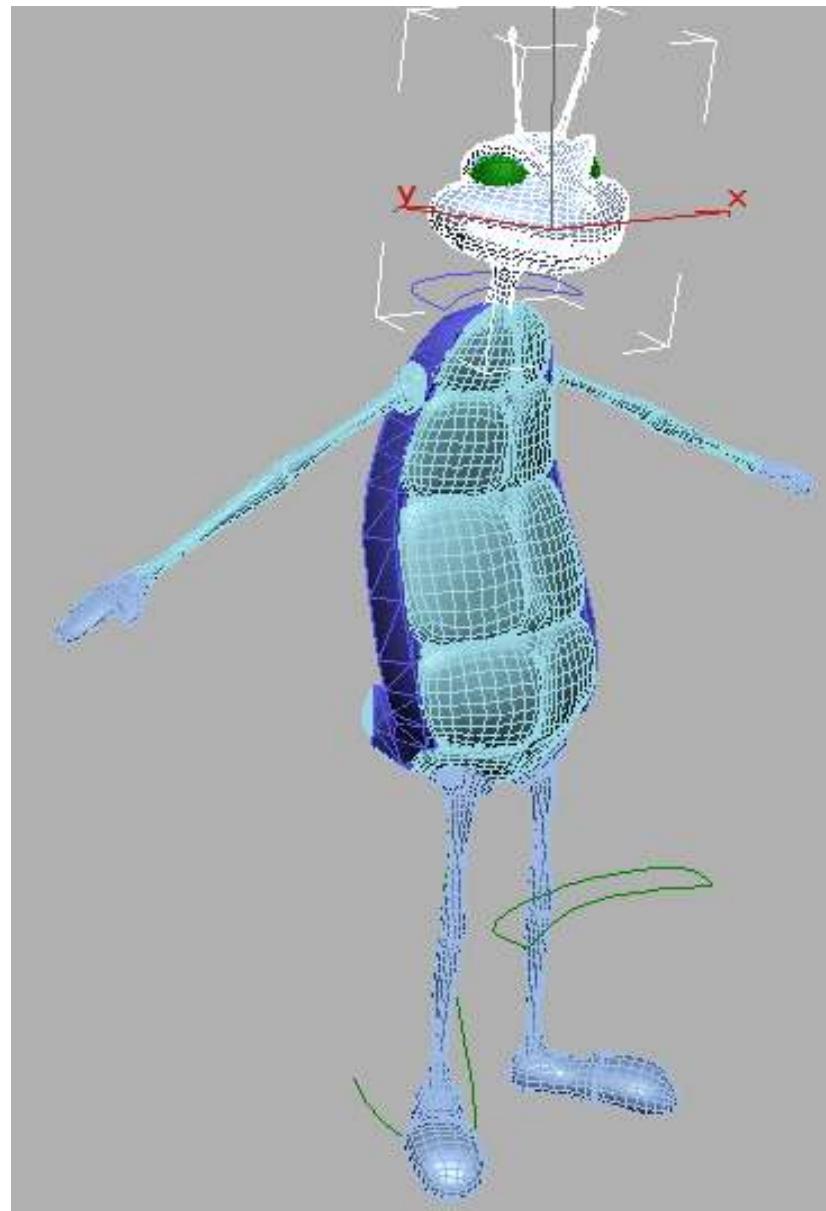


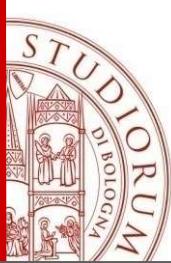
Interactive modeling: patch spline



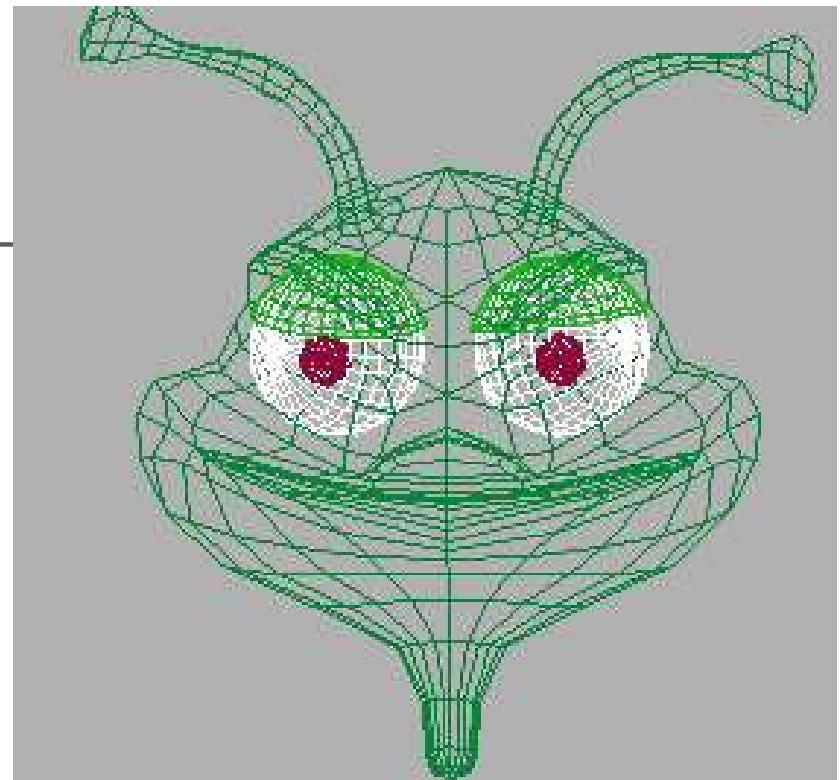
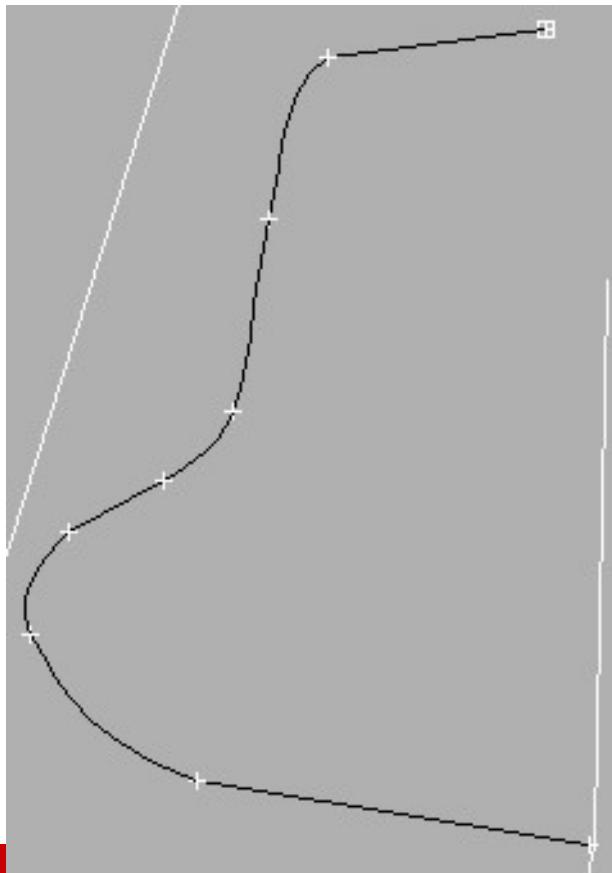


Surfaces from curves



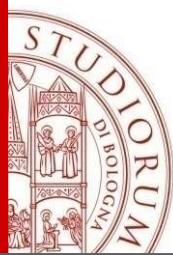


Rotation

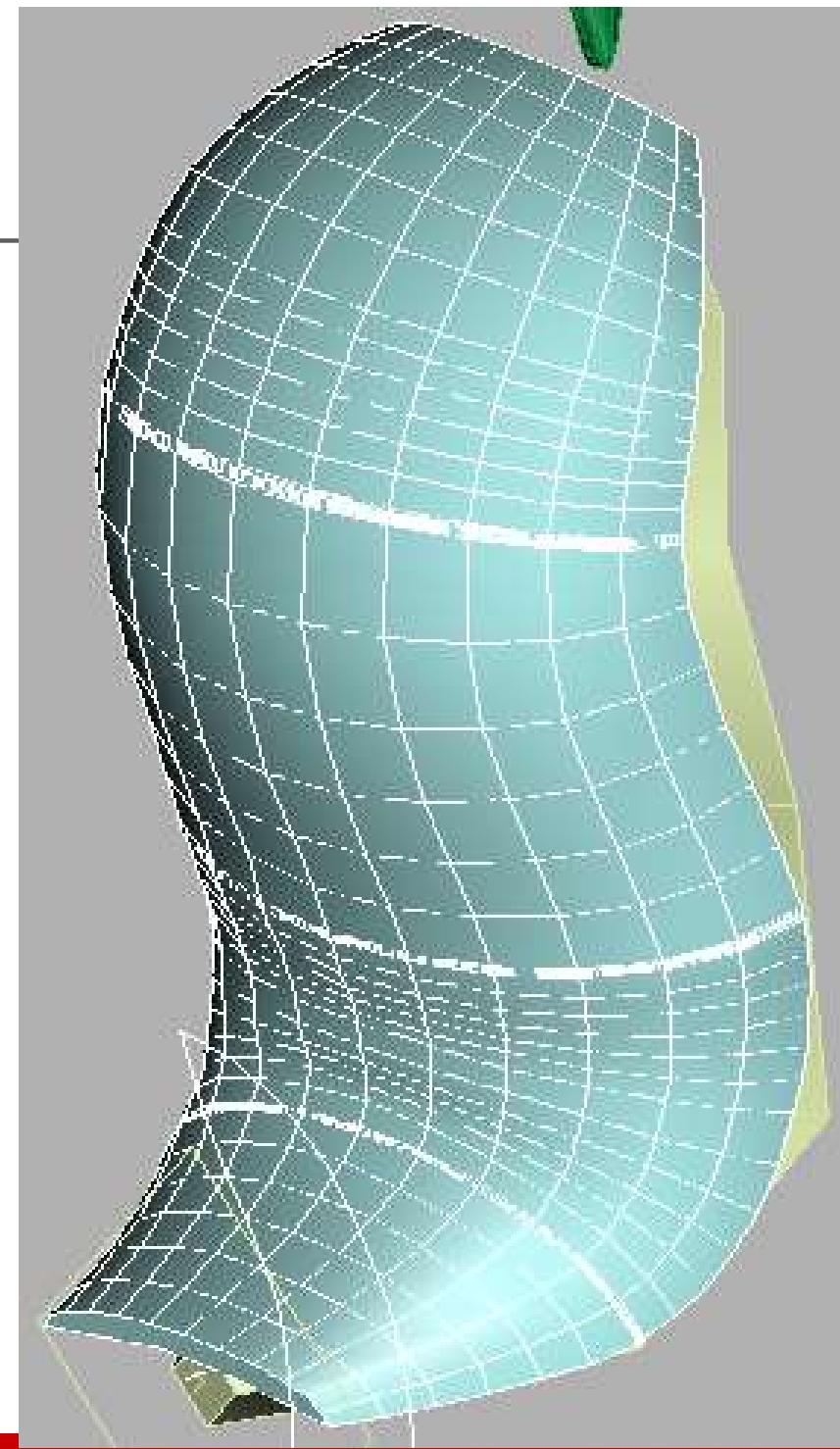
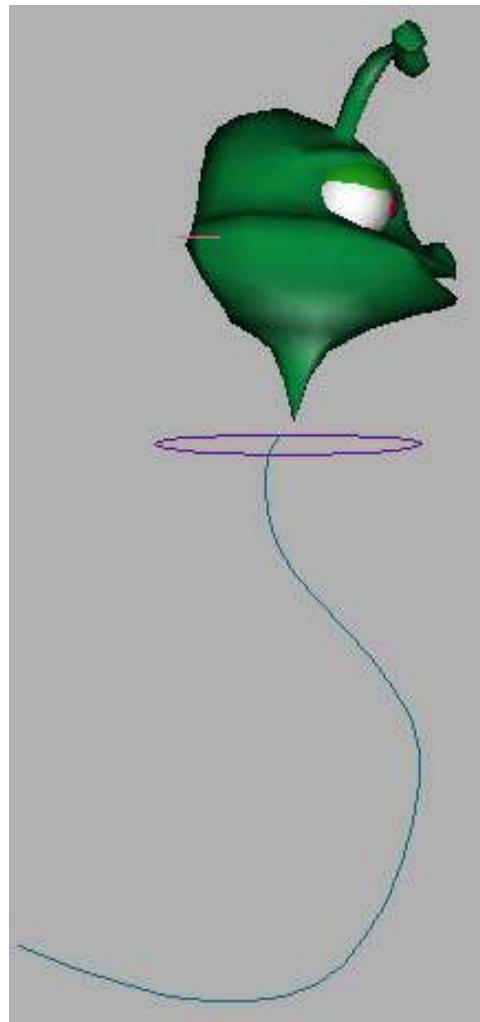


iva

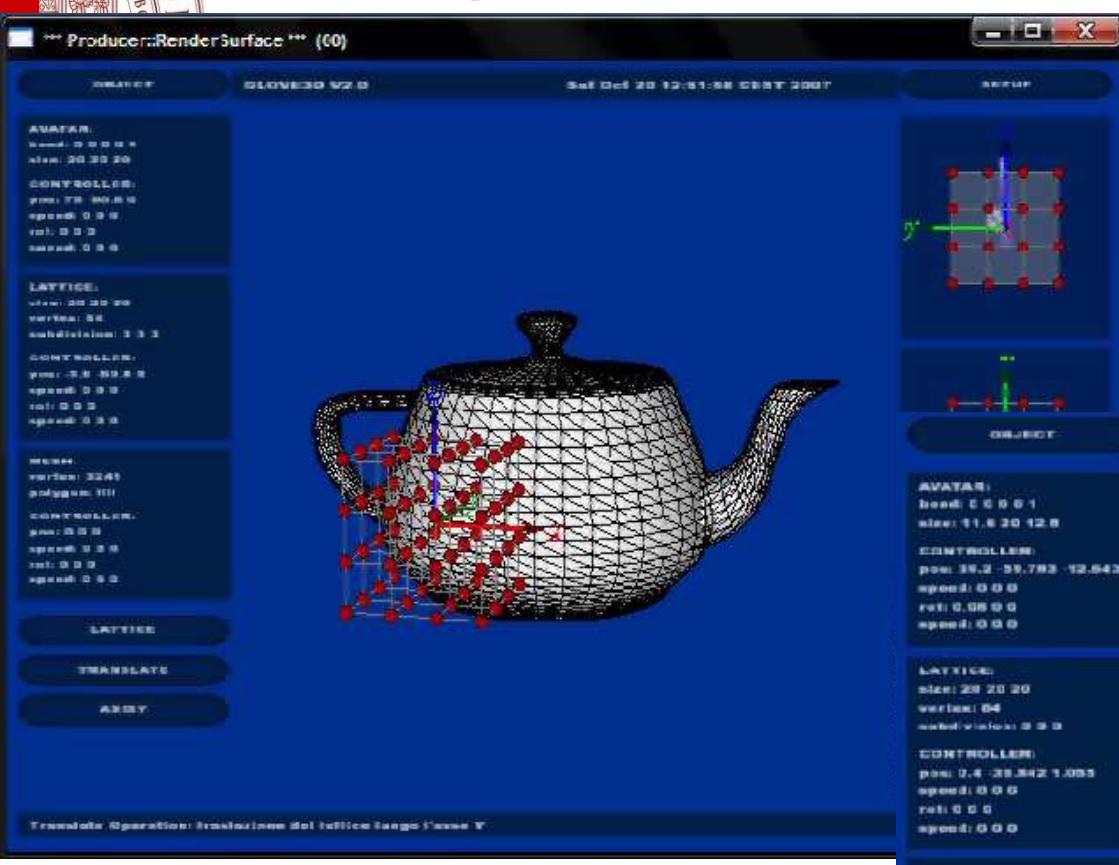




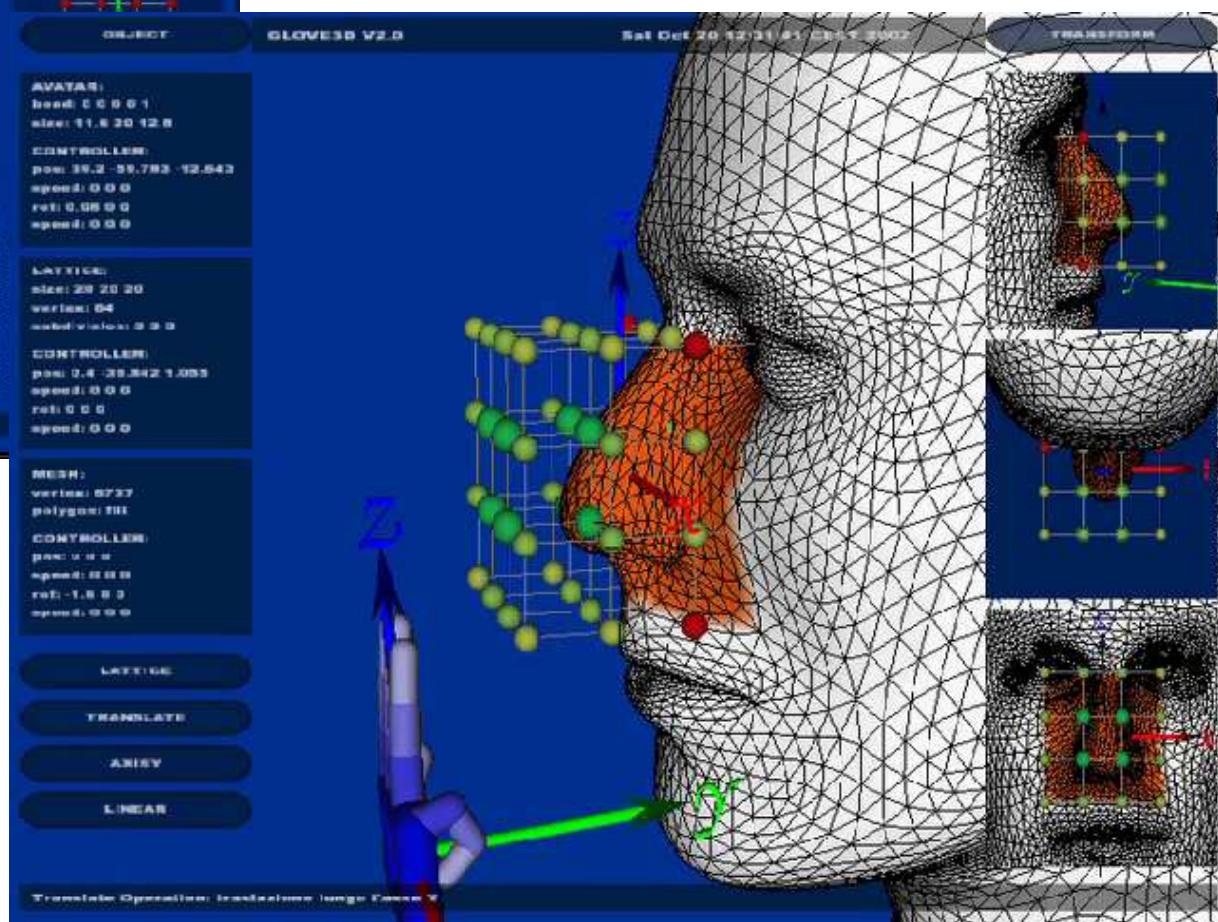
Swinging



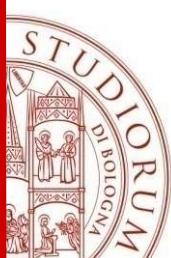
4) Free-form deformation



Change the space,
not the object



Great for animation



5) Captured Modeling:

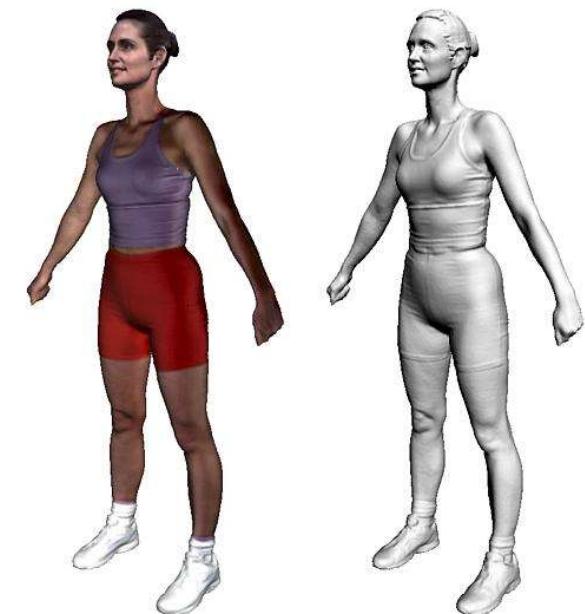
Polygonal models (mesh)
by 3D scanners

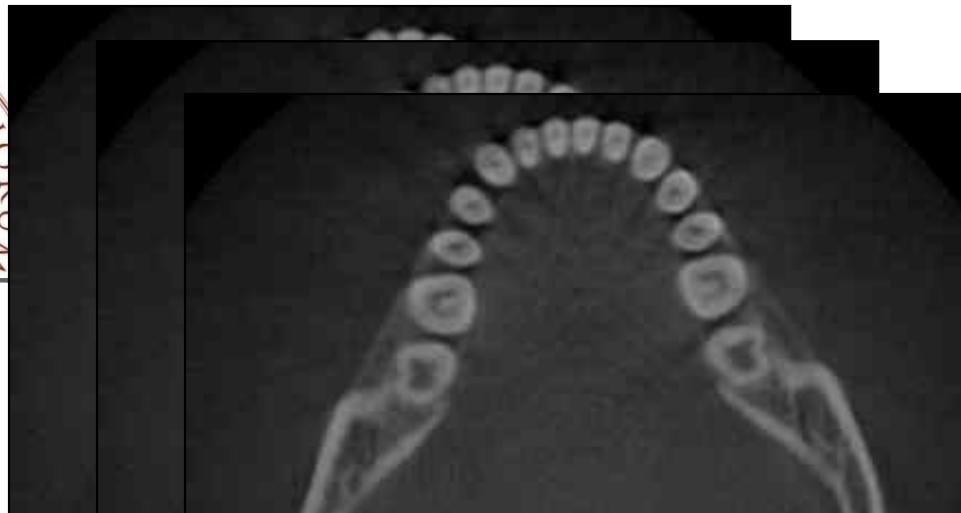
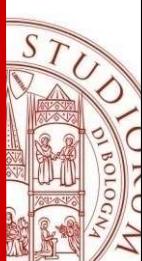


Microscribe
touch 3D scanner

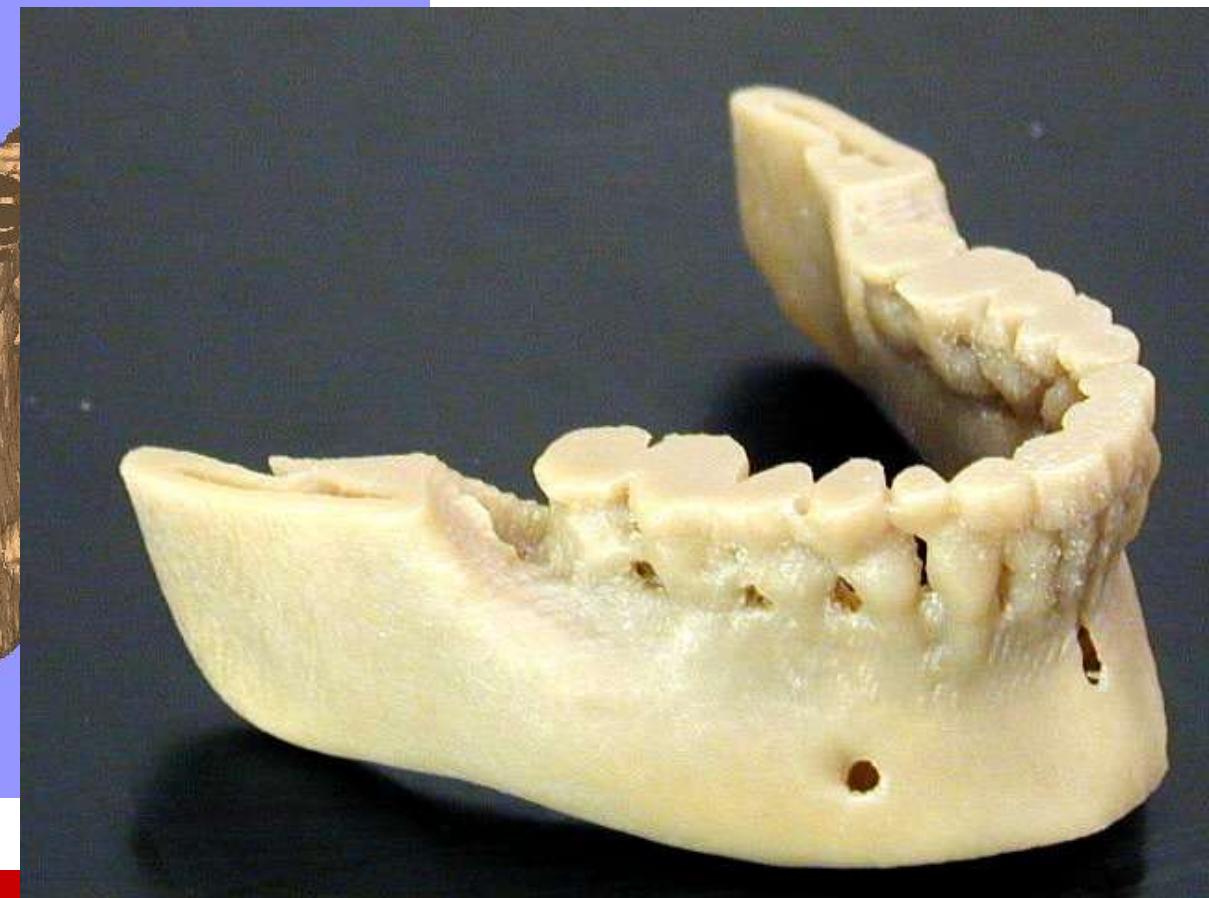
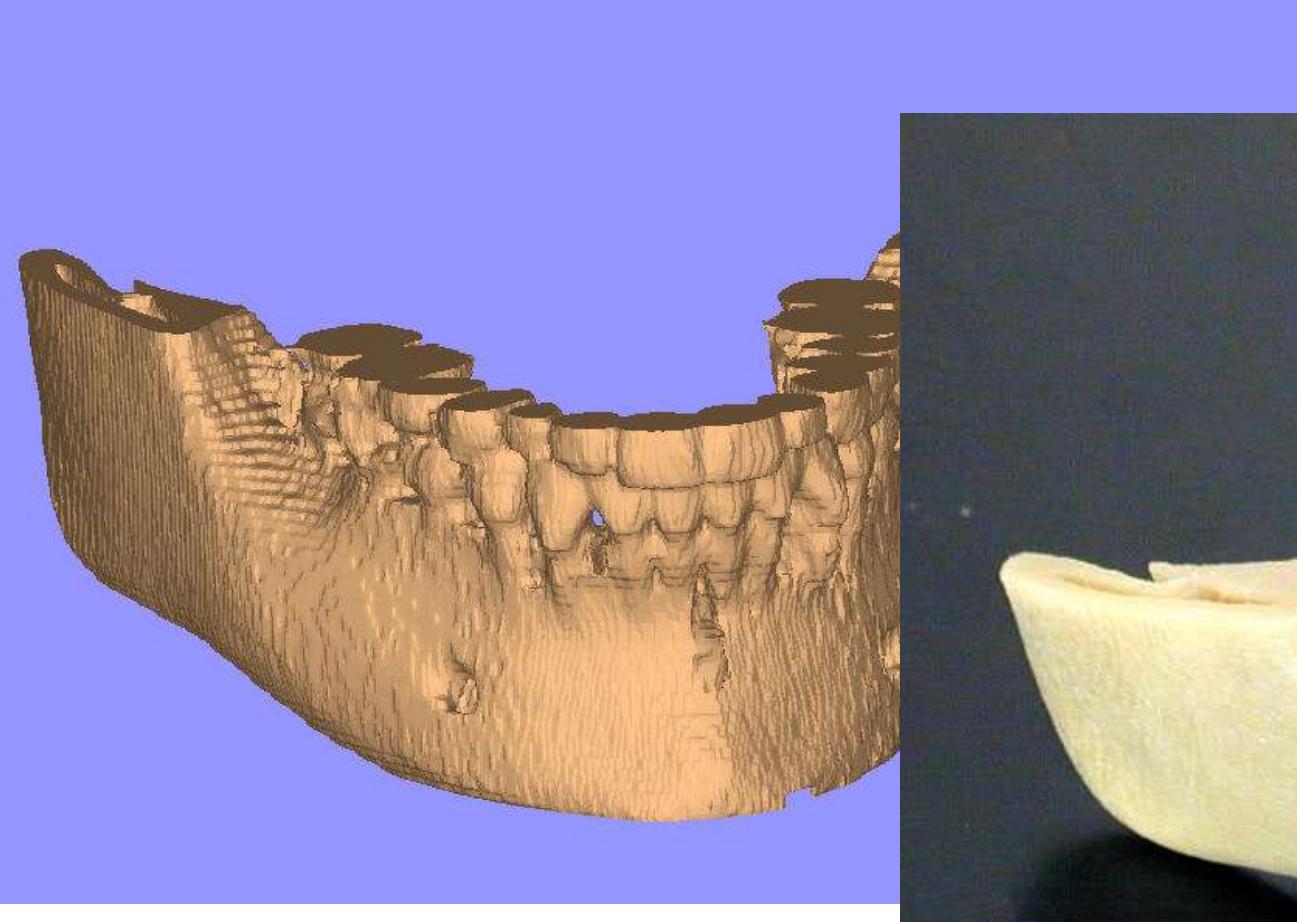


3D laser scanner
WholeBody WP4 CyberWare





CT, cone-beam
Shape reconstruction



Courtesy of ENEA, Bologna



EUREKA
Doing business
through technology



EXEL
ADVANCED TECHNOLOGY

SmartPen: an interactive device for a fast reverse engineering system



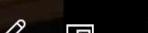
original

wireframe (restored)

rendering (restored)

freehand handle

00:06:22

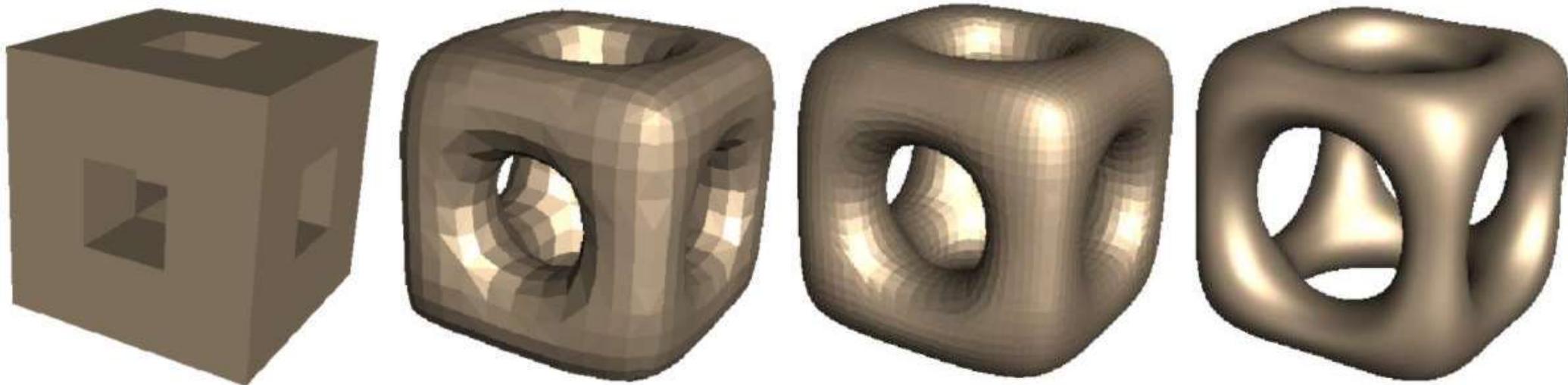




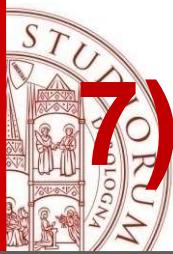
6) Subdivision Modelling

REFINEMENT:

The smoothed object is obtained iterating a refinement procedure



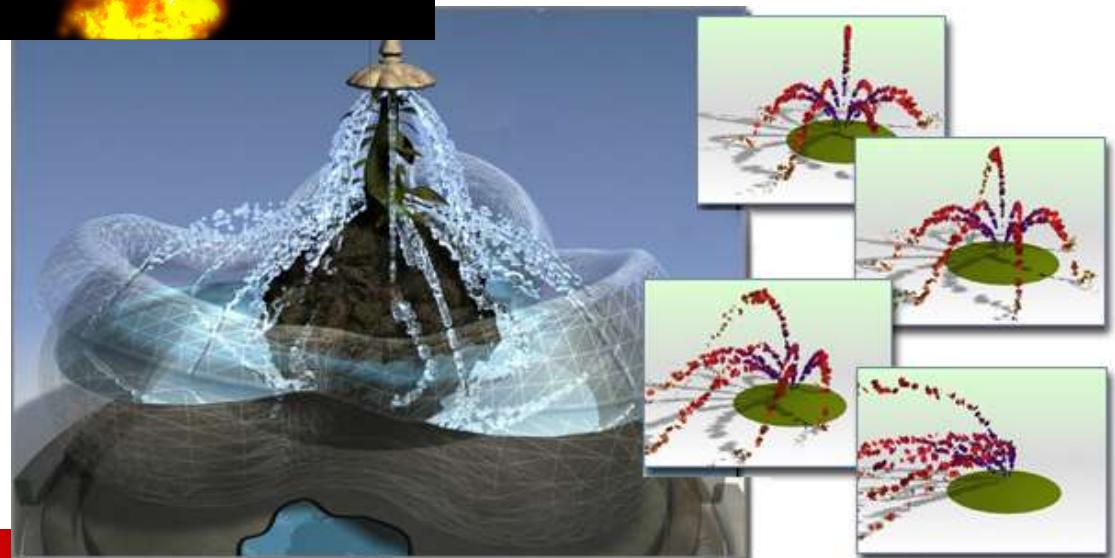
subdivide triangles into more triangles, moving to
a continuous limit surface



7) Procedural/generative Modeling

Procedural geometry is **geometry modelled in code**.

Instead of building 3D meshes by hand using software such as Maya, 3DS Max or Blender, the mesh is built using programmed instructions.





7) Procedural/generative Modeling

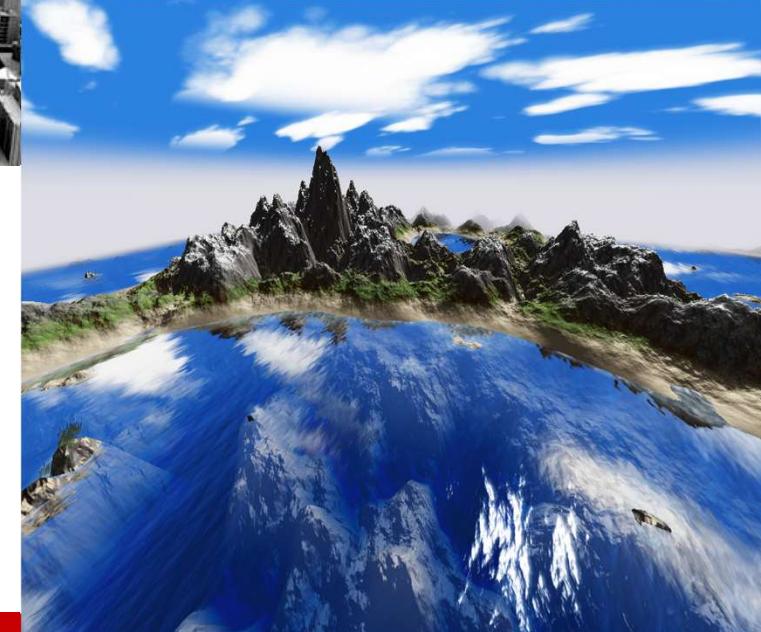


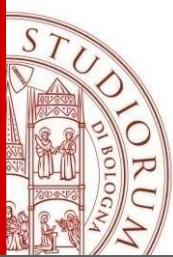
This modeling paradigm describes a shape by a sequence of processing steps.

Simple shapes will be defined and combined to create the geometry.



Each shape is controlled by parameters. Filters are applied to the shapes to transform (scale, translate, rotate) the geometry, or flip the normal vector orientation. Boolean operations are used to combine the shapes





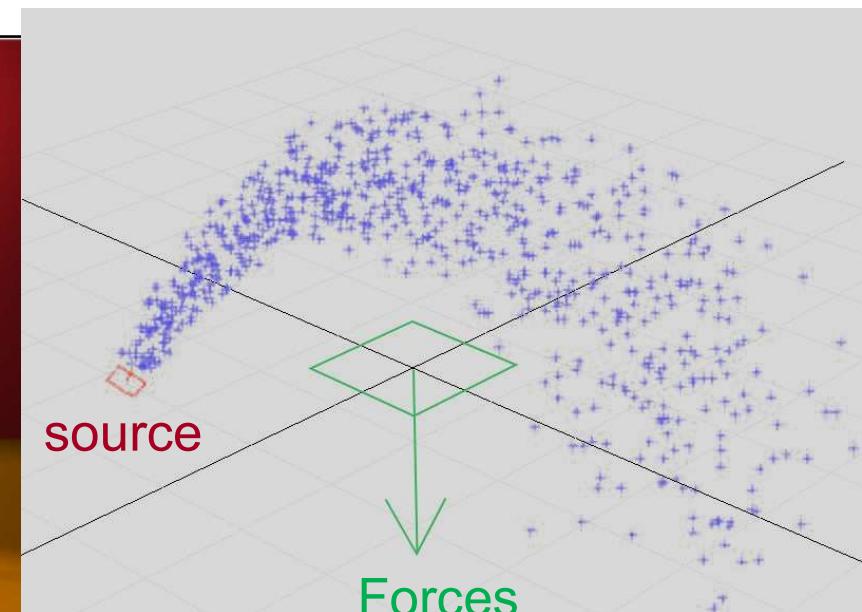
7) Procedural/generative Modeling Particle Systems

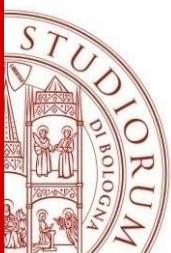
- Collection of simple objects rendered as point sources
- Large groups can produce interesting effects
- Simple motion - e.g., local rules, simple physics
- Supplement basic ballistic rules

Collisions
Interactions
Force fields
Springs
Others...



Karl Sims, SIGGRAPH 1990

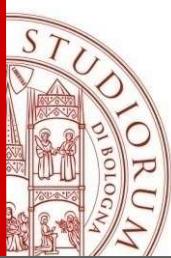




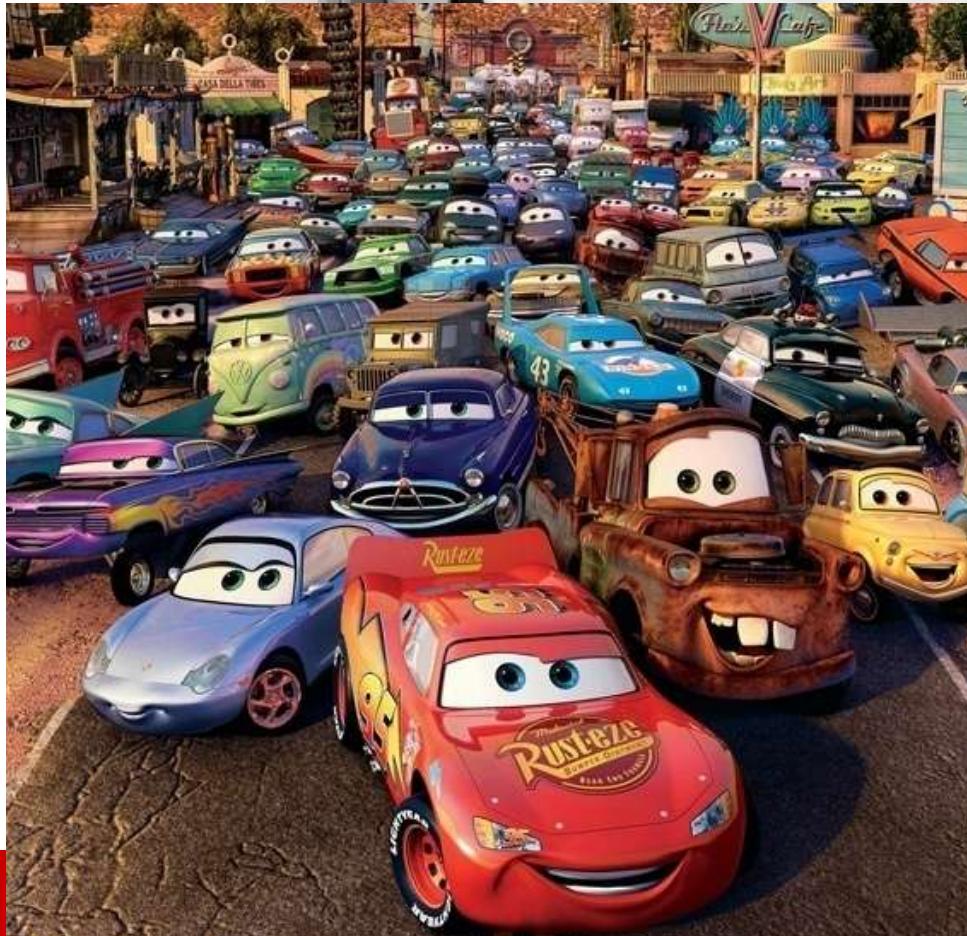
3D MODELLING

Many primitives...many tools
Choose what you need and...

**THINK BEFORE
MODELLING!**



From
Shad



RENDERING:



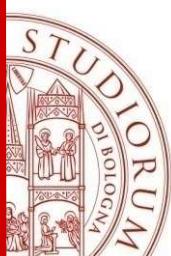
'Cars', Pixar Animation Studios



The Rendering Equation

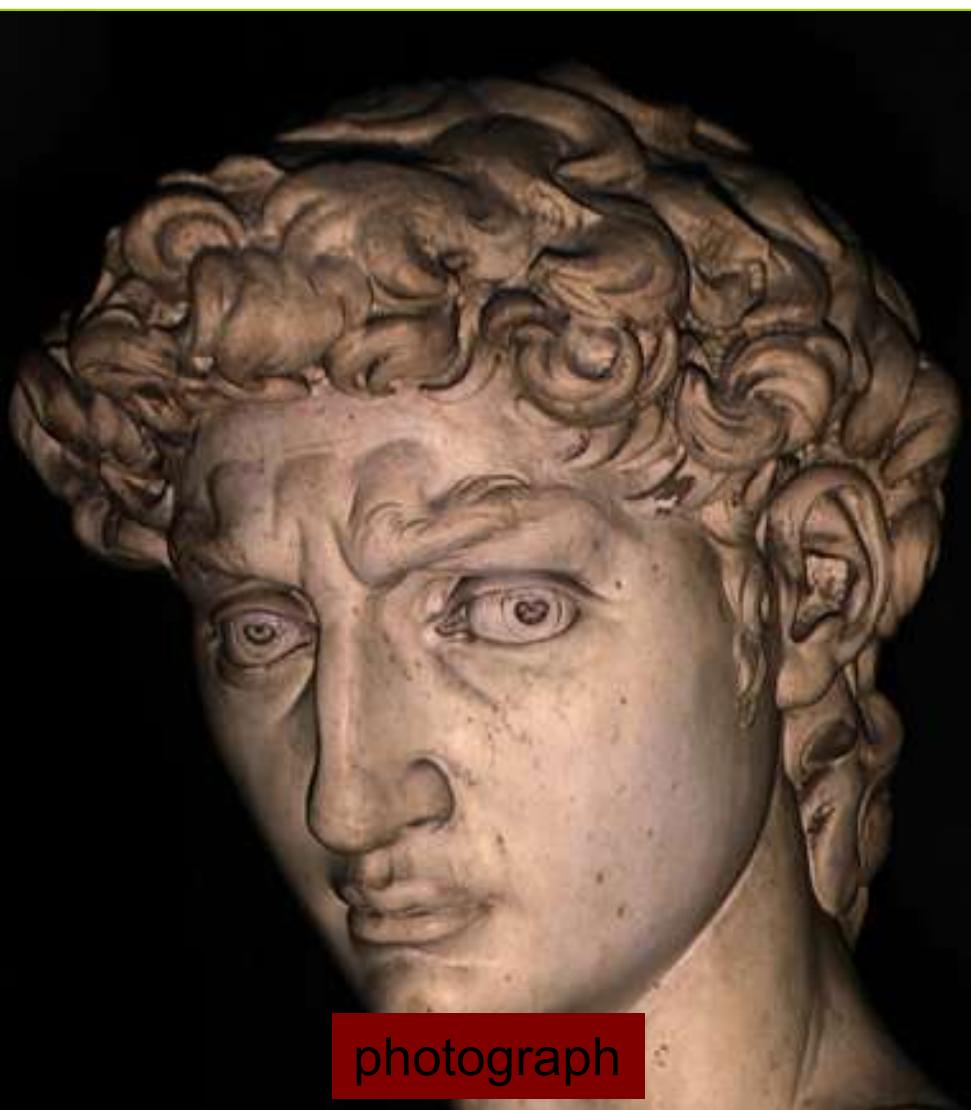
- Unifies all algorithms
- Based on nuclear physics
- Trivial and self-evident

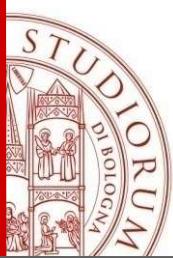
$$\begin{aligned} L(\mathbf{r}, \vec{\omega}, \lambda, \mathbf{e}, t) = & \mu(\mathbf{r}, \mathbf{s}) \left[L^e(\mathbf{s}, \vec{\omega}, t, \lambda) \right. \\ & + m_p(\vec{\omega}) \int_{-\infty}^t d(t - \tau) P_p(\mathbf{s}, \lambda) \int_{\Theta_i^i} L(s, \vec{\omega}', \lambda, \mathbf{e}, \tau) \cos \theta' d\vec{\omega}' d\tau \\ & + \int_{\Theta_i^i} f(\mathbf{s}, \lambda, \vec{\omega}' \rightarrow \vec{\omega}) \int_{\mathcal{R}_V} P_f(\mathbf{s}, \lambda' \rightarrow \lambda) L(\mathbf{s}, \vec{\omega}', \lambda', \mathbf{e}, t) d\lambda' \cos \theta' d\vec{\omega}' \Big] \\ & + \int_0^{h(\mathbf{r}, \vec{\omega})} \mu(\mathbf{r}, \mathbf{a}) \left[L^e(\mathbf{a}, \vec{\omega}, t, \lambda) \right. \\ & + m_p(\vec{\omega}) \int_{-\infty}^t d(t - \tau) P_p(\mathbf{a}, \lambda) \int_{\Theta_i^i} L(s, \vec{\omega}', \lambda, \mathbf{e}, \tau) \cos \theta' d\vec{\omega}' d\tau \\ & \left. + \int_{\Theta_i^i} f(\mathbf{a}, \lambda, \vec{\omega}' \rightarrow \vec{\omega}) \int_{\mathcal{R}_V} P_f(\mathbf{a}, \lambda' \rightarrow \lambda) L(\mathbf{a}, \vec{\omega}', \lambda', \mathbf{e}, t) d\lambda' \cos \theta' d\vec{\omega}' \right] d\alpha \end{aligned}$$



Photorealistic Rendering

..refers to rendering a 3D scene in a realistic way

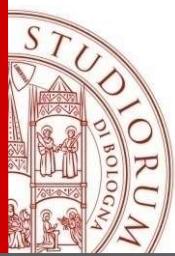




Photorealistic Rendering

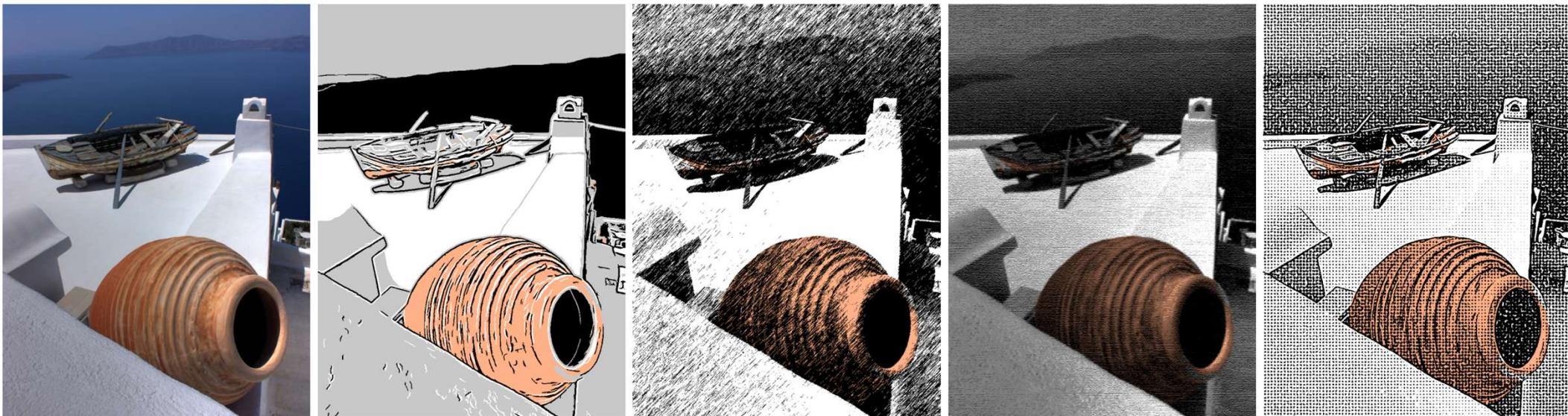
Modern photoreal rendering algorithms are essentially a physically based simulation of light propagation and scattering throughout a 3D environment.



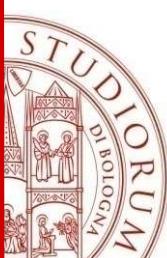


Non-photorealistic rendering

Artistic rendering—trying to evoke hand-drawn or hand-painted styles, such as charcoal sketching, pen and ink illustration, or oil painting (Cartoon rendering style)

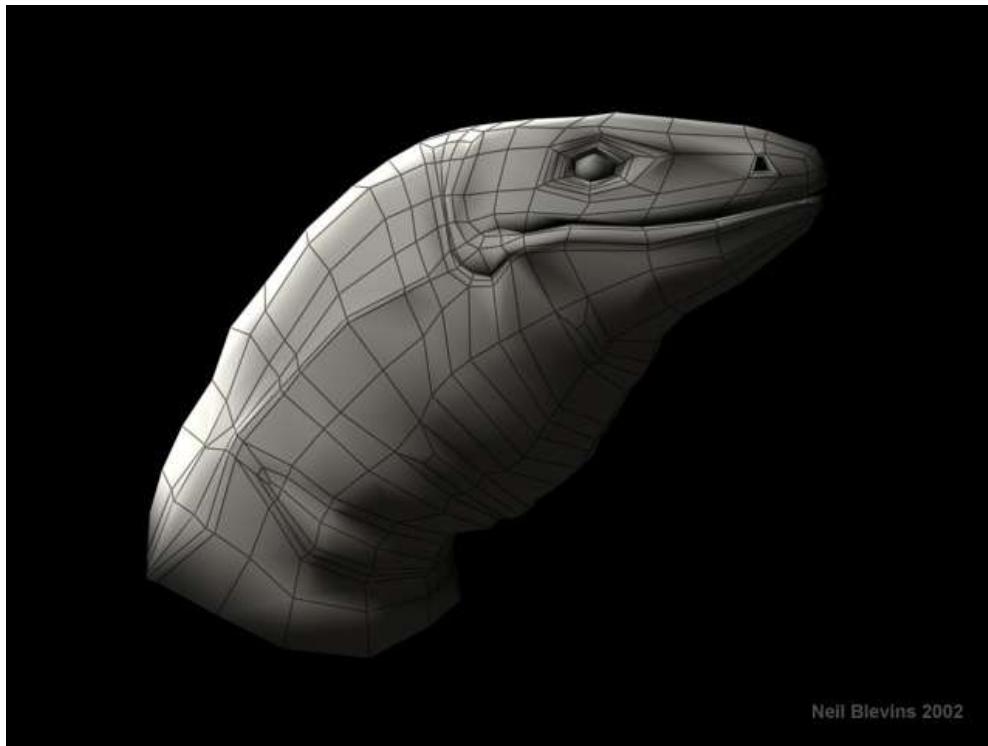


Original image



Rendering:

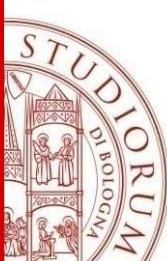
interaction between light and material



A 3D scene is:

Geometry (triangles, lines, points, and more)

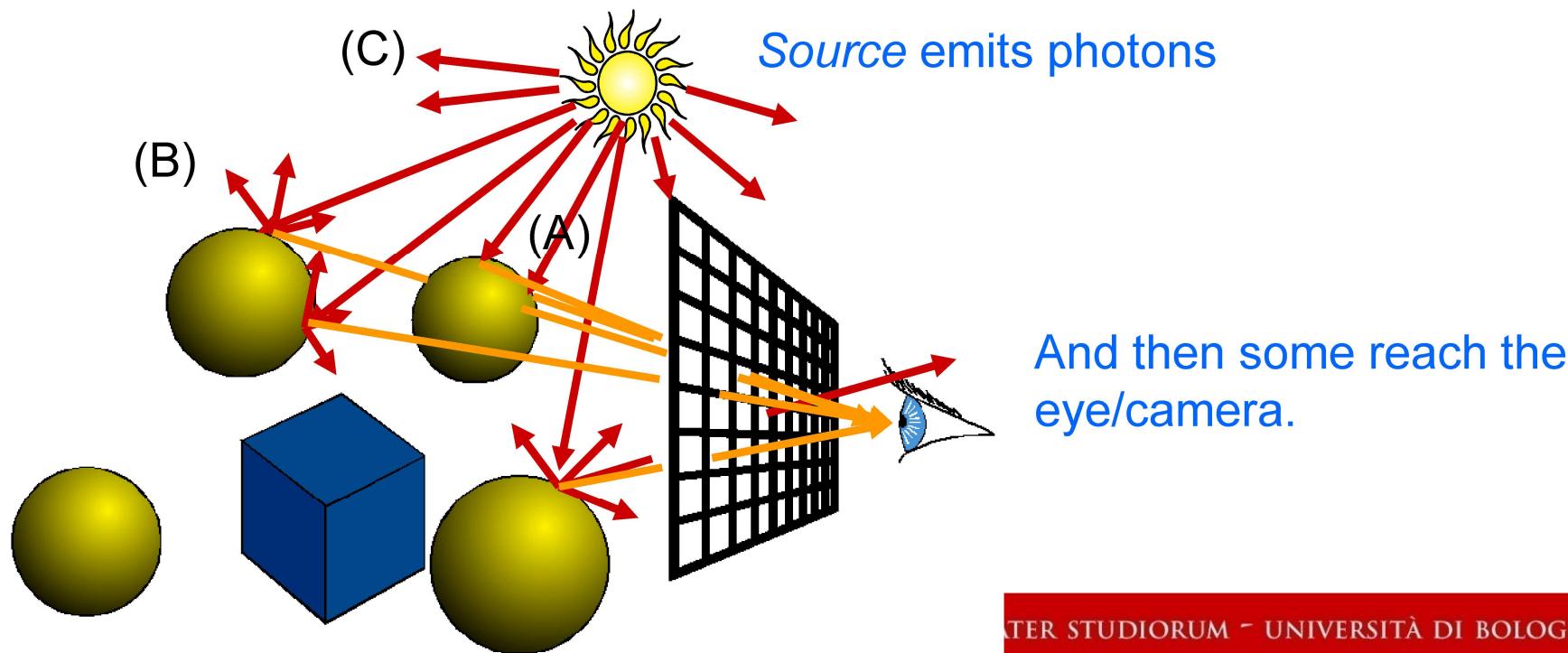
Light sources, Material properties, Textures (images onto the geometry)

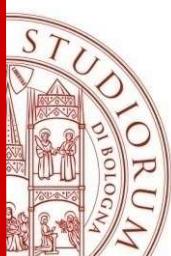


Lighting

When the rays hit an object they:

- (A) reflect to the viewer
- (B) bounce off in a new direction
- (C) out of room or are absorbed

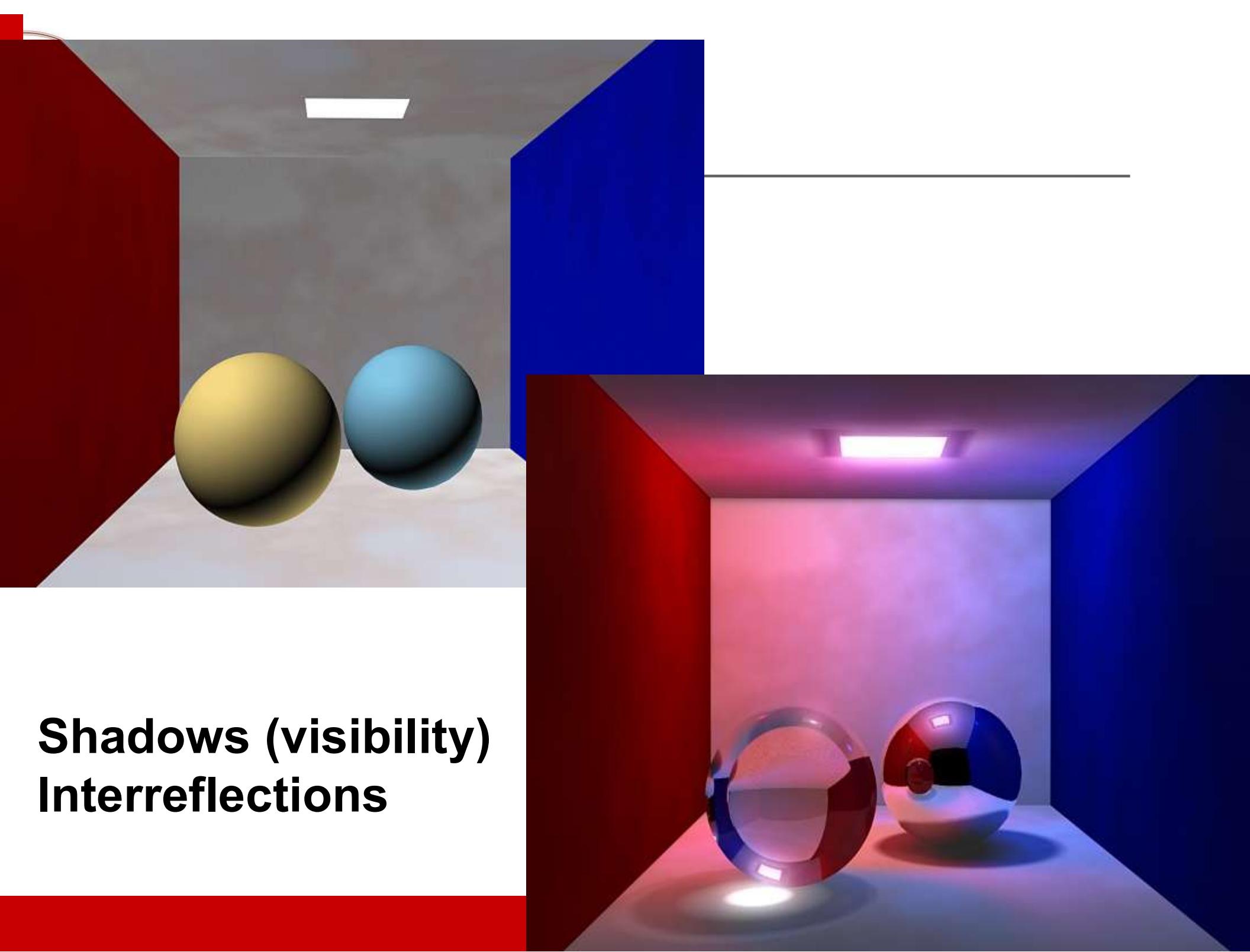




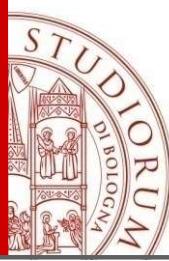
Material Properties

- Modeling Lighting
- Transparency
- Reflectance
- Shadows (visibility)
- Interreflections





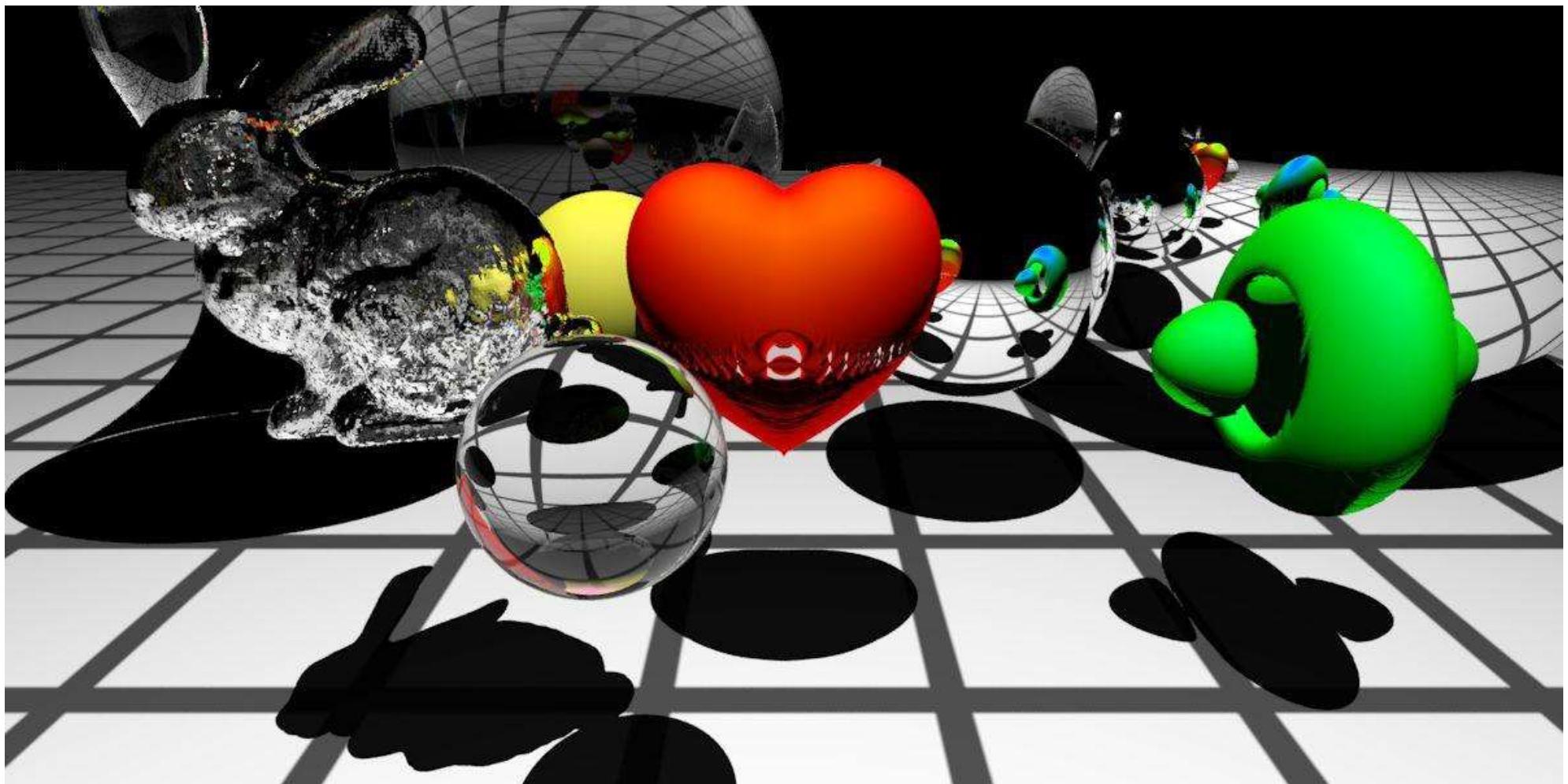
Shadows (visibility) Interreflections

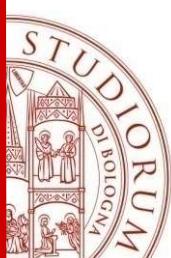


Lighting (Global Models)

Ray tracing

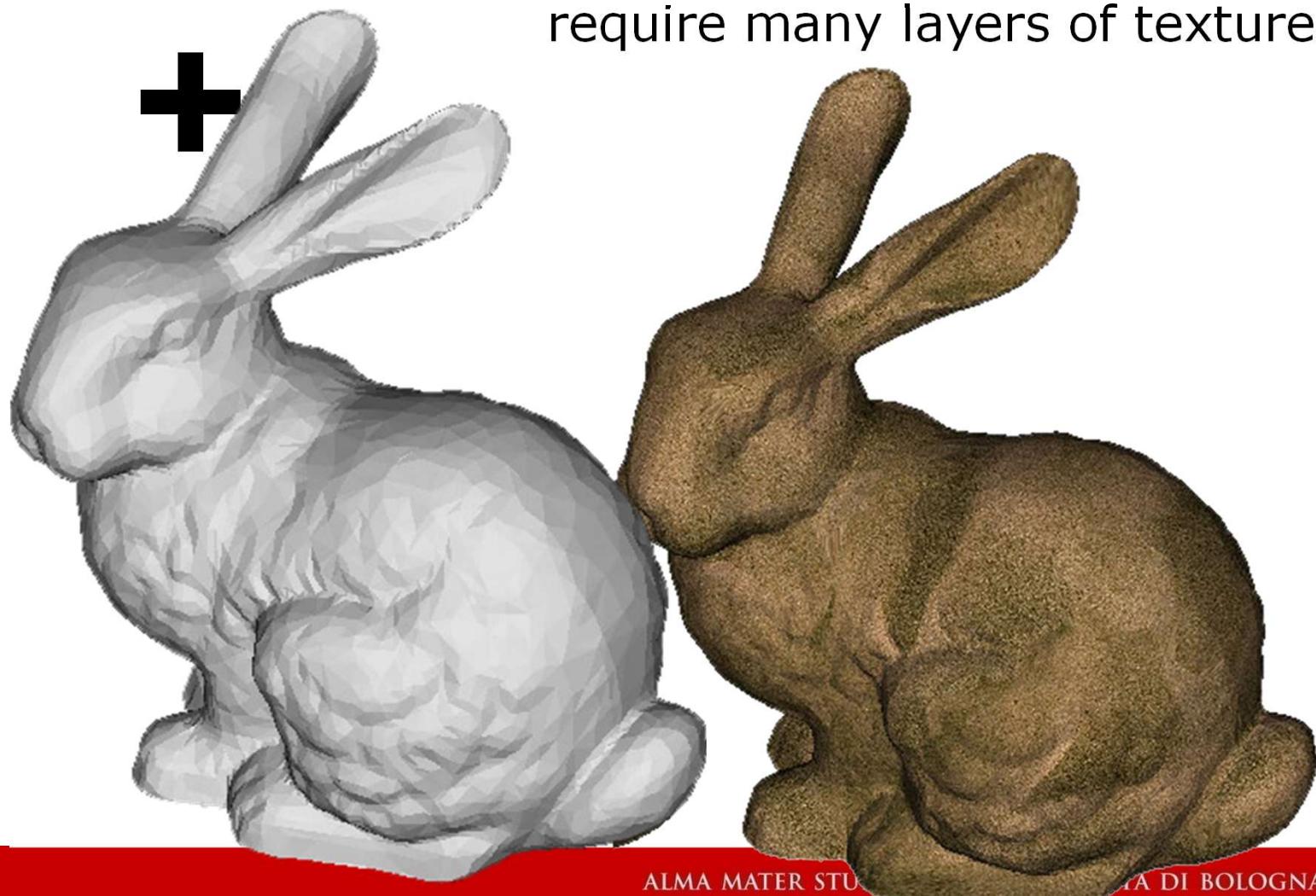
- Ray: **shadows, lighting, reflection, transparency**

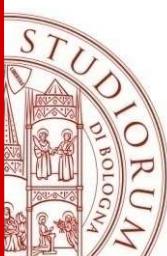




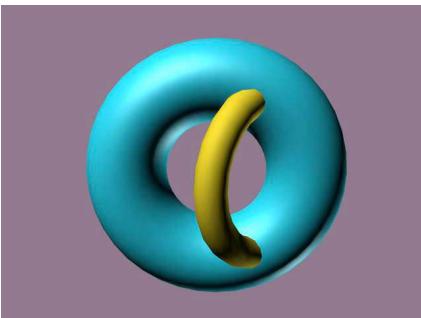
Texture Mapping

map an image onto surface geometry to create appearance of fine surface details. A high level of realism may require many layers of textures.



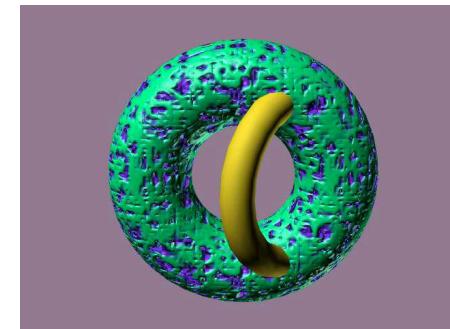


Bump Mapping



fake surface normals by applying height field (intensities in the map indicate height above surface).

From height field calculate gradient across surface and use this to perturb the surface normal.





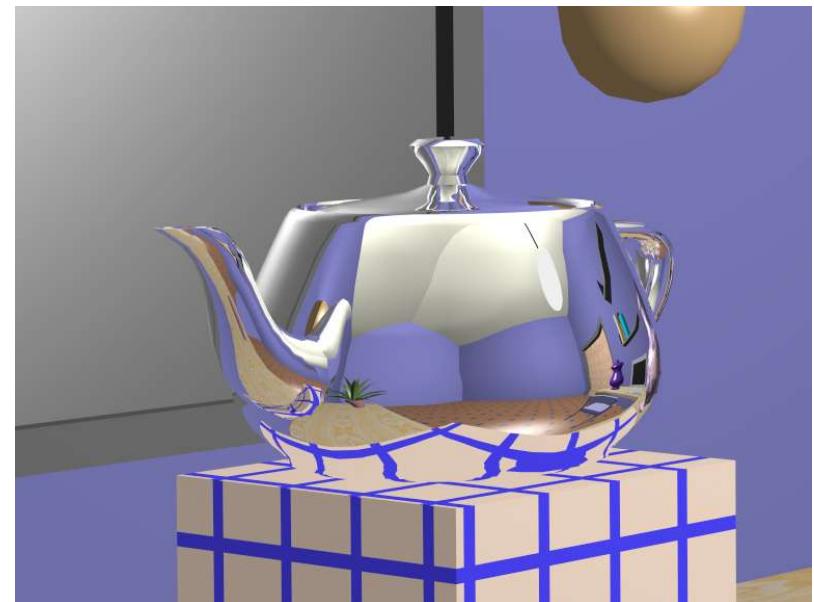
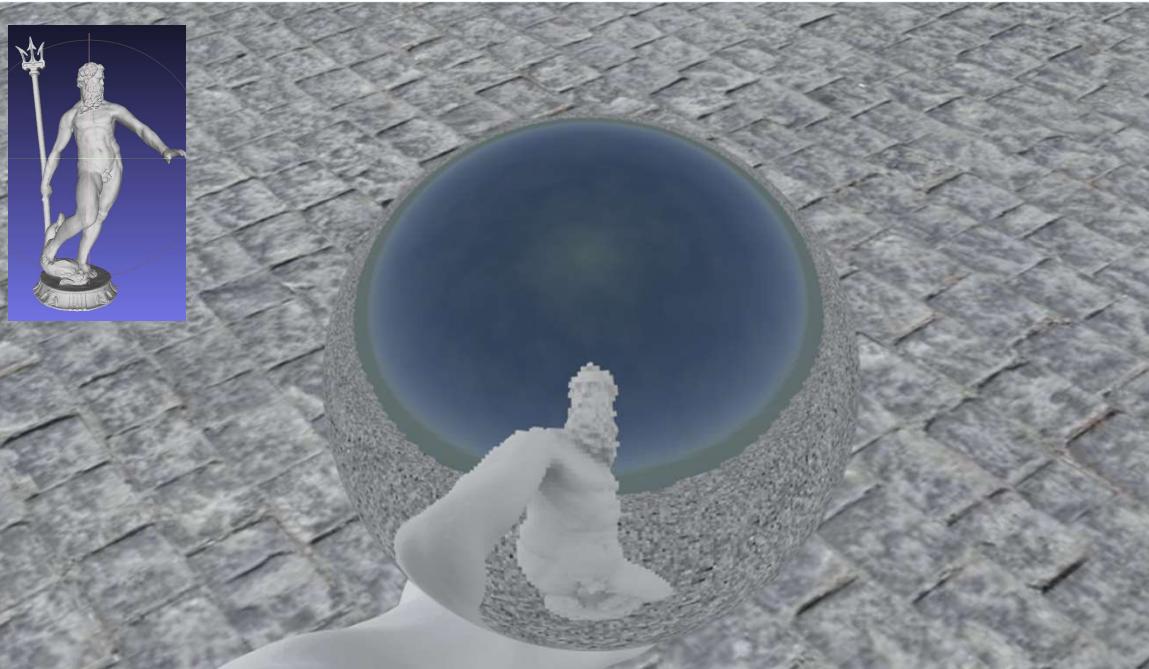
Displacement vs. Bump mapping





Environmental Mapping

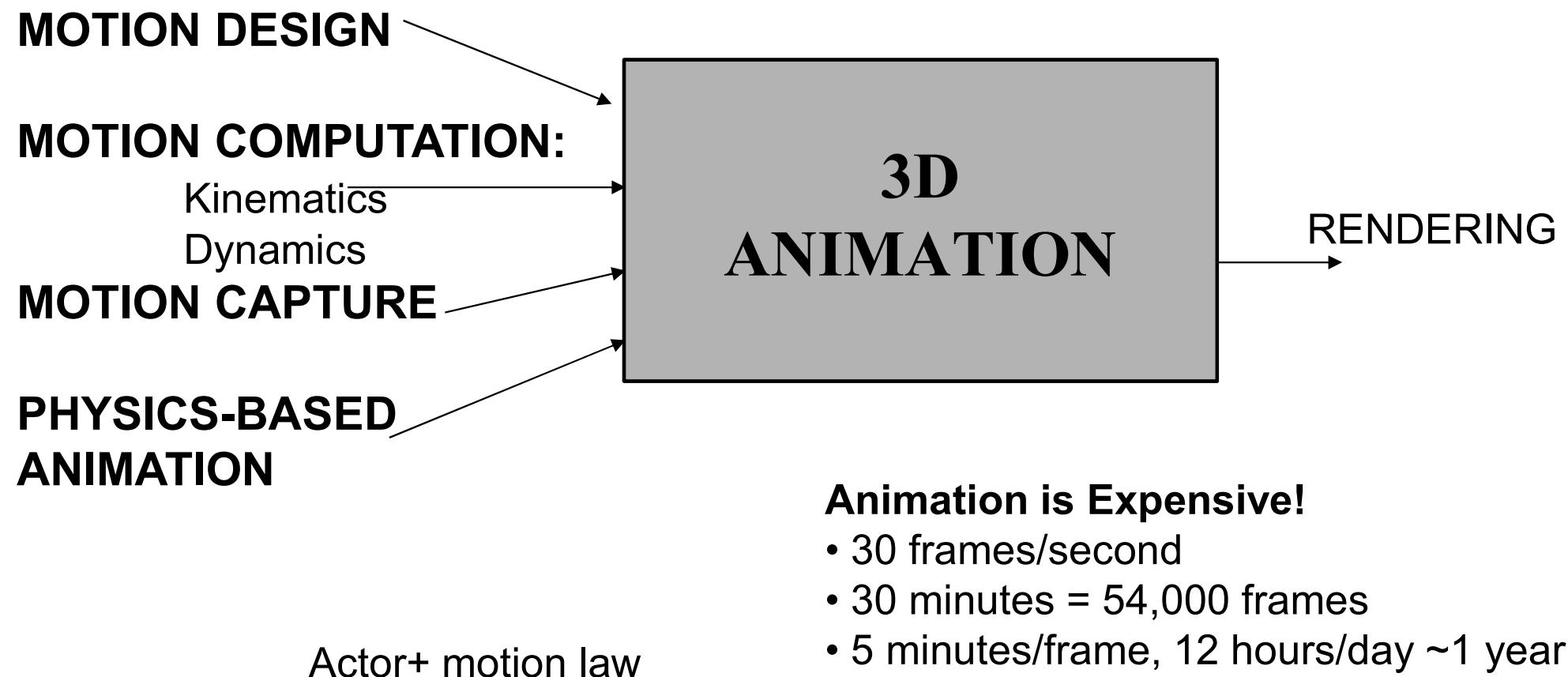
multiple images (textures) which record global reflection and lighting on object. These images are resampled during rendering to extract view-specific information which is then applied as texture to object.





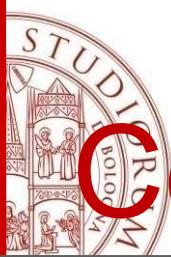
Computer Animation

Making things alive/Making them move



Animation is Expensive!

- 30 frames/second
- 30 minutes = 54,000 frames
- 5 minutes/frame, 12 hours/day ~1 year



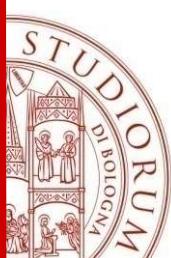
Computer Animation

- **What is Animation?**
 - Make objects change over time according to scripted actions



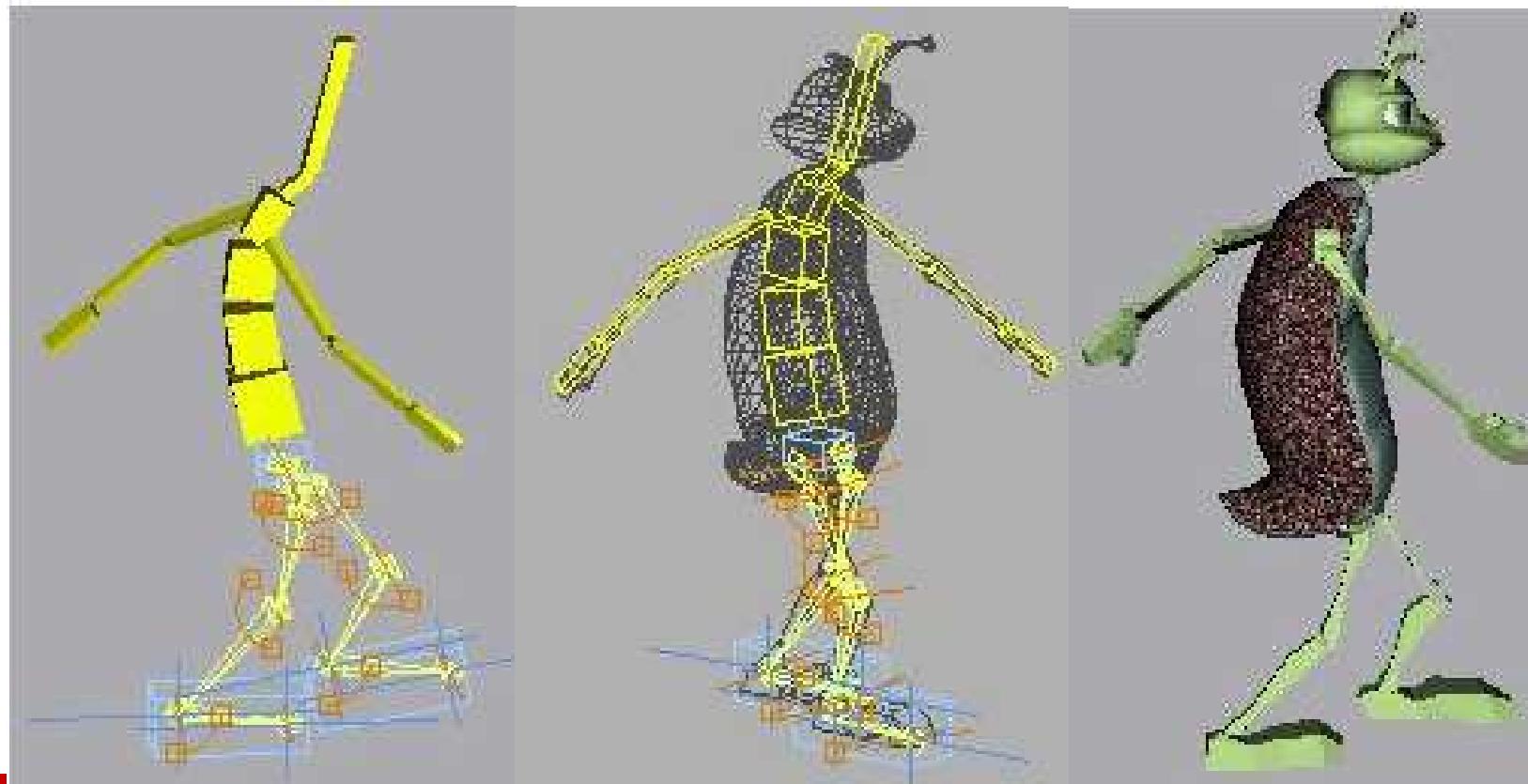
- **What is Simulation?**
 - Predict how objects change over time according to physical laws

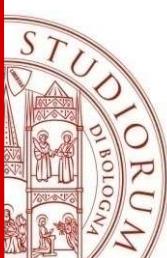




Link, joint, skinned mesh

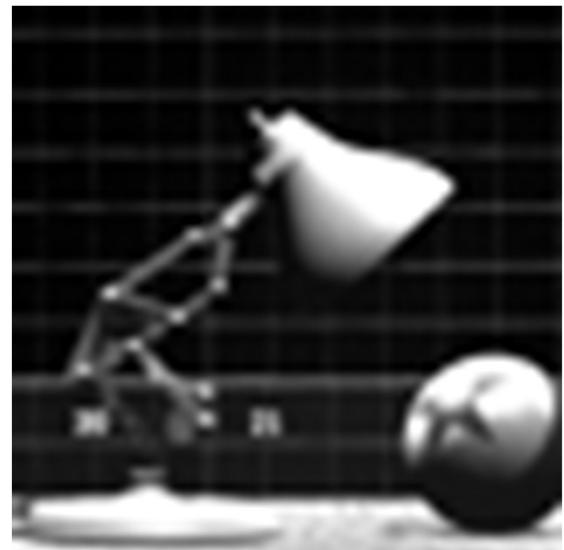
- **Skeleton Animation (or rigging):** technique which animates an articulated object represented by a mesh and a skeleton (a hierarchical set of interconnected parts called joints or bones)
- **Skinning:** Mesh Deformation via Smooth/Rigid Binding of Bones and Skeletons

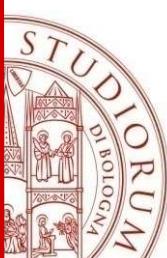




Animating actors

- Keyframe
- Physics-based animation
- Motion Capture

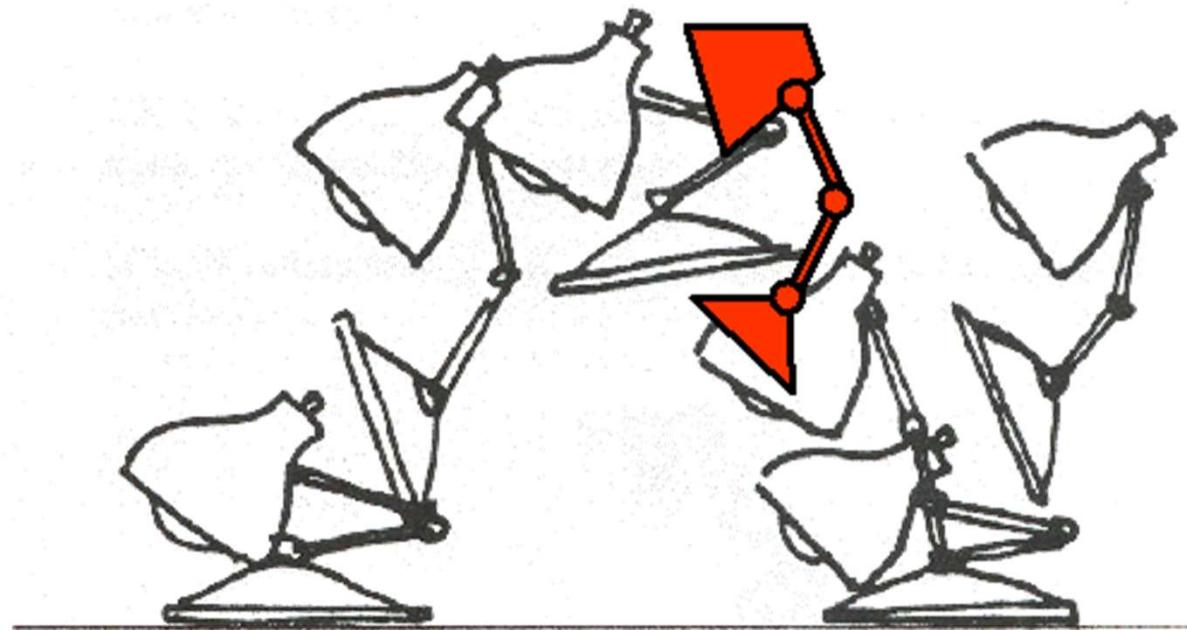




Keyframe

- **Keyframe:**

Define Character Poses at Specific Time Steps Called “Keyframes”



- **Key and inbetween:**

- Define **pose vector**
- Define the **keyframes**,
- Compute **inbetween** for a smooth animation(spline).



Computer Animation by keyframe



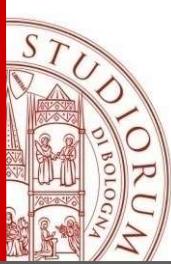
**Realizzazione dell'animazione
"Owen the Sweeper"**

(Tesi di Marchesini Stefano, 2004)

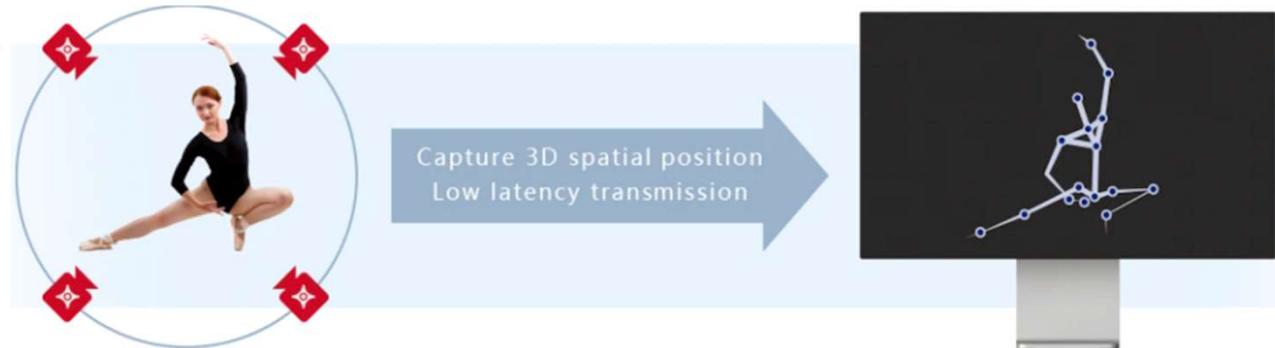
ALMA MATER STUDIORUM - UNIVERSITÀ DI BOLOGNA



**Realizzazione dell'animazione “Owen the Sweeper”
(Tesi di Marchesini Stefano, 2004)**



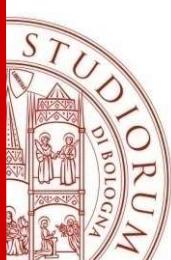
Motion Capture



- Capture of motion of (human) actor:
 - Whole body
 - Upper body
 - face
- Using a physical device to control animation



Andy Serkis in “Gollum”
“The lord of the rings”



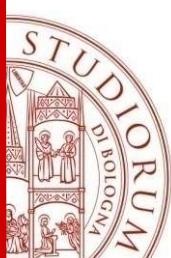
MoCap: Facial Motion Capture



Geometry

Dynamics
(Motion, Deformation, etc.)

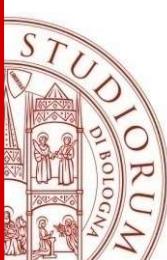
Rendering
(Illumination Model)



MoCap: Body Motion Capture

OptiTrack - Optical Motion Capture Systems and Tracking Software





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UNIVERSITÀ DI BOLOGNA

Thanks
for your attention!

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Dipartimento di Matematica
serena.morigi@unibo.it
<http://www.dm.unibo.it/~morigi>

