

**Mike Bailey**  
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### Seminar Goals

- Provide a background for everything else you will see at SIGGRAPH 2012
- Create a common understanding of computer graphics vocabulary
- Help appreciate the images you will see
- Get more from the Exhibition
- Provide pointers for further study

## Mike Bailey

- Professor of Computer Science, Oregon State University
- Has worked at Sandia Labs, Purdue University, Megatek, San Diego Supercomputer Center (UC San Diego), and OSU
- Has taught over 4,600 students in his classes
- [mjb@cs.oregonstate.edu](mailto:mjb@cs.oregonstate.edu)



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## Specific Topics

- The Graphics Process
- How to Attend SIGGRAPH
- Graphics Hardware
- Modeling
- Rendering
- Animation
- Finding More Information



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## Schedule

- 9:00 Welcome and Overview
- 9:10 How to Attend SIGGRAPH
- 9:20 The Graphics Process
- 9:40 Graphics Hardware
- 10:00 Modeling
- 10:30 Break
- 10:45 Maybe our vision isn't as good as we think it is ☺
- 10:50 Rendering
- 11:15 Animation
- 11:50 Finding Additional Information
- 12:00 Finish



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# You can't see it all, so ...

Think Strategically -- Make a Plan, Make a Schedule, Set Priorities !  
Your time is valuable.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Tuesday, August 4													
2														
3	5:00 AM													
4	5:30 AM													
5	6:00 AM													
6	6:30 AM													
7	7:00 AM													
8	7:30 AM													
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34	8:30 PM													
35	9:00 PM													
36	9:30 PM													
37	10:00 PM													
38	10:30 PM													
39	11:00 PM													

In general, rank your top 3 things you want to see for each timeslot. Then, if one session is boring or not as useful as you'd thought, quickly move to your next priority.

Remember to give priority points to the things you can't "re-live" after it has happened !

# OMG – Where do I Start in the Exhibition?



## Exhibition Strategy

- Look at the list of vendors in the Program and Buyers Guide
- Make a list of the ones you *really* must see and **sort the list by booth number**
- Booth numbers are XXYY, where XX is the Aisle # and YY is  $(\frac{1}{3}) \times$  the number of feet from the front
- For example, AMD = booth 709, which is Aisle 7;  $5 \times 09 = 45$  feet from the front
- Start at one end of the floor and work your way across



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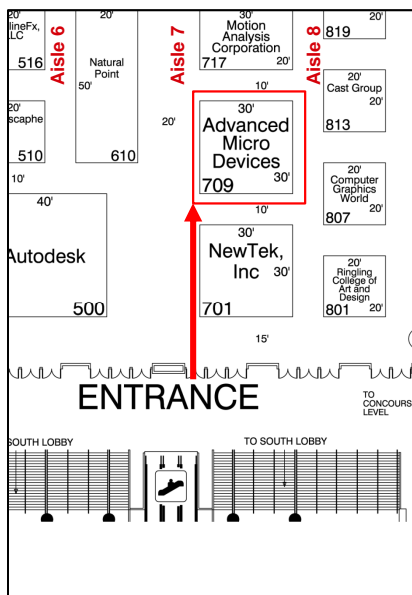
	D	E	F
Animation Magazine		2000	
NVIDIA		2001	
Dimension 3D Printing		2010	
PNY		2017	
3D MD		2018	
Fusion IO		2022	
Caustic Graphics		2026	
T-Splines		2028	
Web3D Consortium		2029	
Lightspeed		2034	
Wolfram Research		2085	
Pixar		2111	
Interplayware		2125	
Raven3D		2128	
Vis Trails		2129	
AutoDesk		2201	
Spheren VR		2228	
Naswest Design		2404	
<b>AMD / ATI</b>		<b>2417</b>	
Laika		2501	
Wacom		2509	
AK Peters		2527	
Springer		2601	
Xerox		2605	
Addison Wesley		2609	
Journey Ed		2626	
Future Publishing		2627	
Intelligraphics		2631	
Interactive Data Visualization		2700	
Google		2719	
Wiley		2725	
Digital Domain		2800	
LA Immersive Technologies Enterpri		2900	
Rhythm and Hues		3111	
Objet		3125	
RapidMind		3131	
3D Consortium		3200	
Side Effects		3206	
Point Grey		3211	
Fraunhofer		3311	
Purdue		3319	
Weiss		3331	
Baton Rouge Digital Industries		3405	
Immersion Games		3411	
NVIDIA Sketch Match		3424	
Computational Geometry Algorithms		3429	
EON Reality		3430	
JVC		3501	
Turbosquid		3600	
Digipen		3605	
Renderosity		3606	



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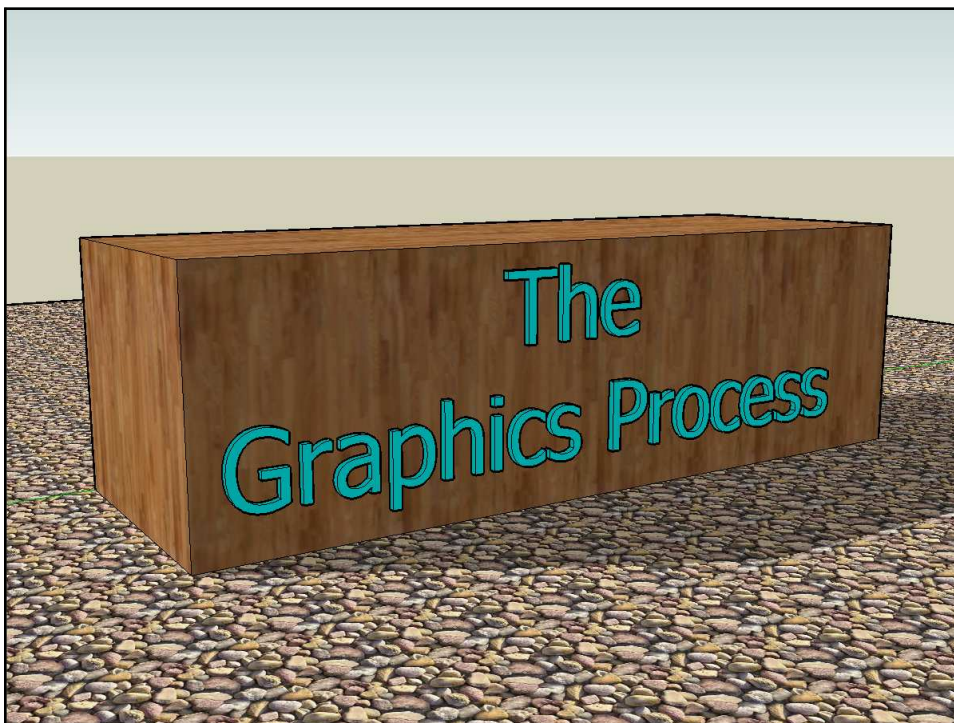
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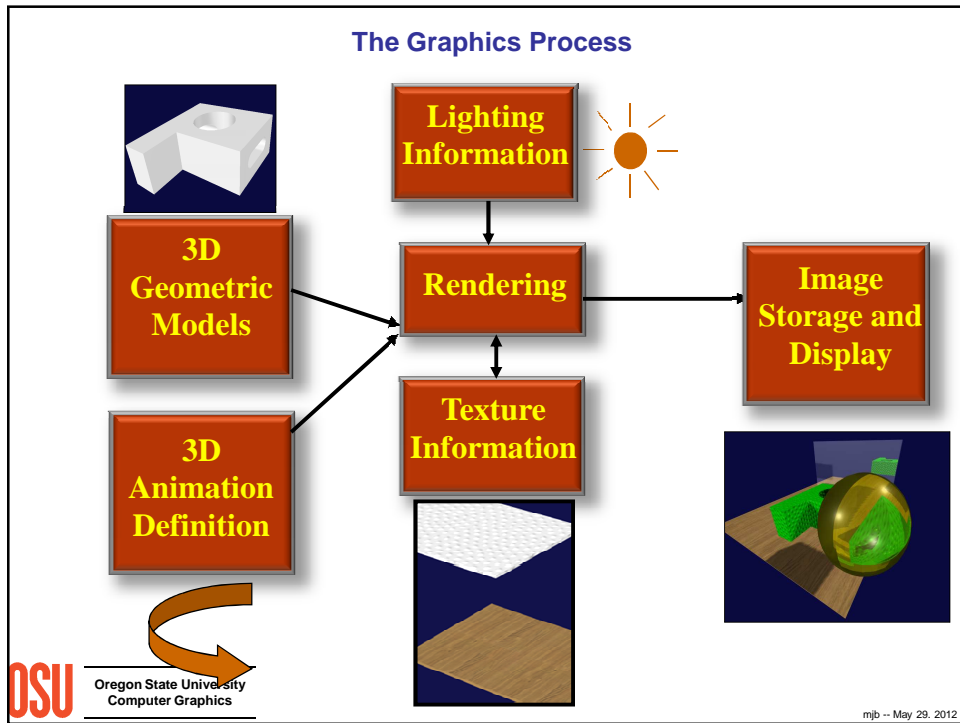
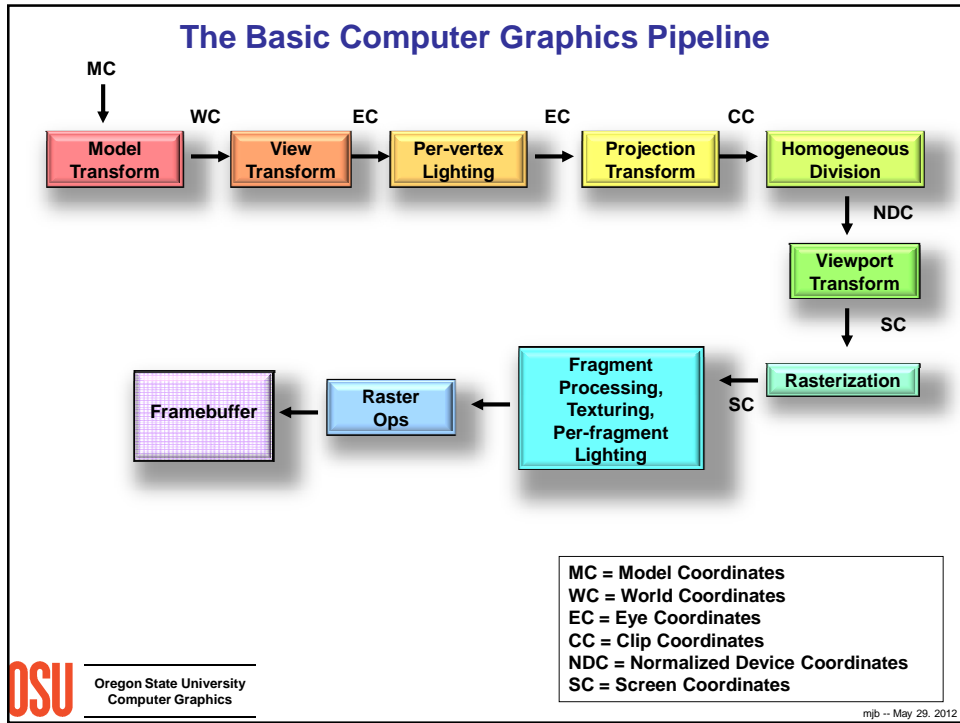
## Exhibition Strategy

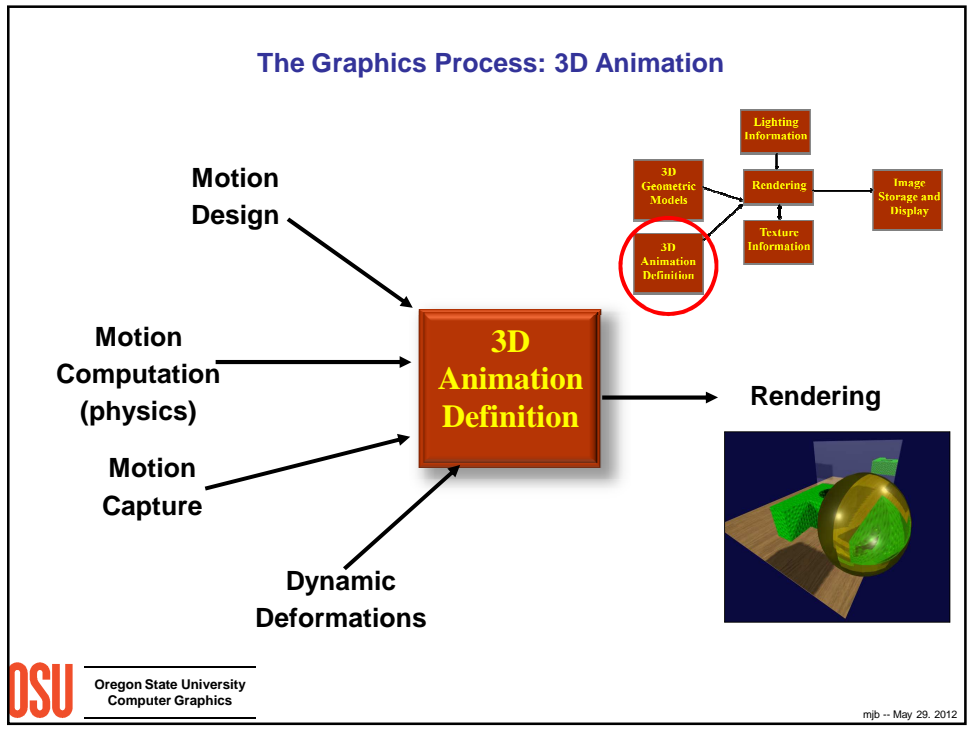
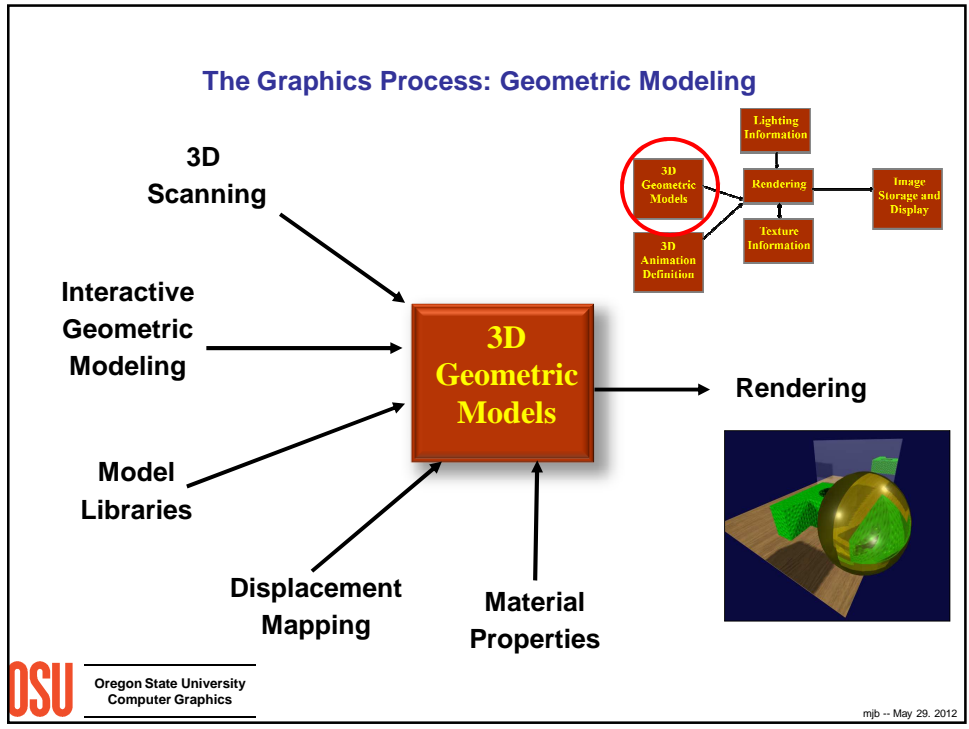


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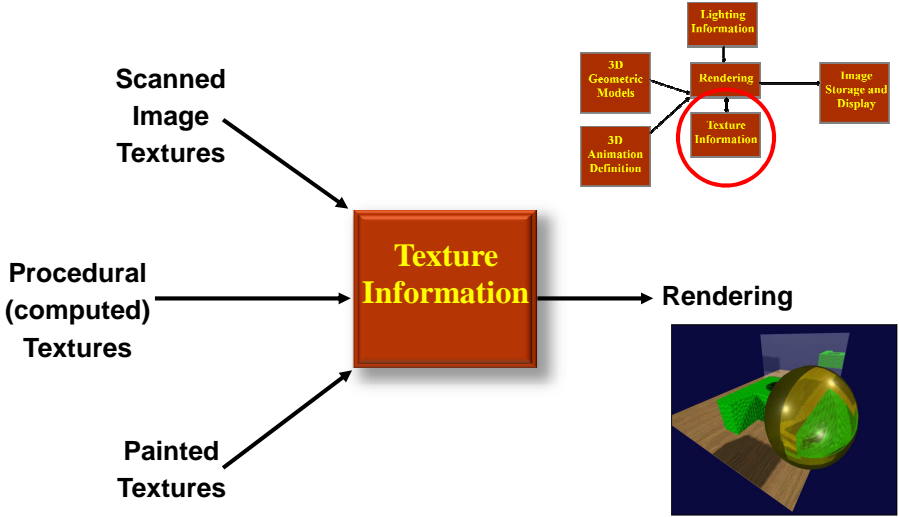




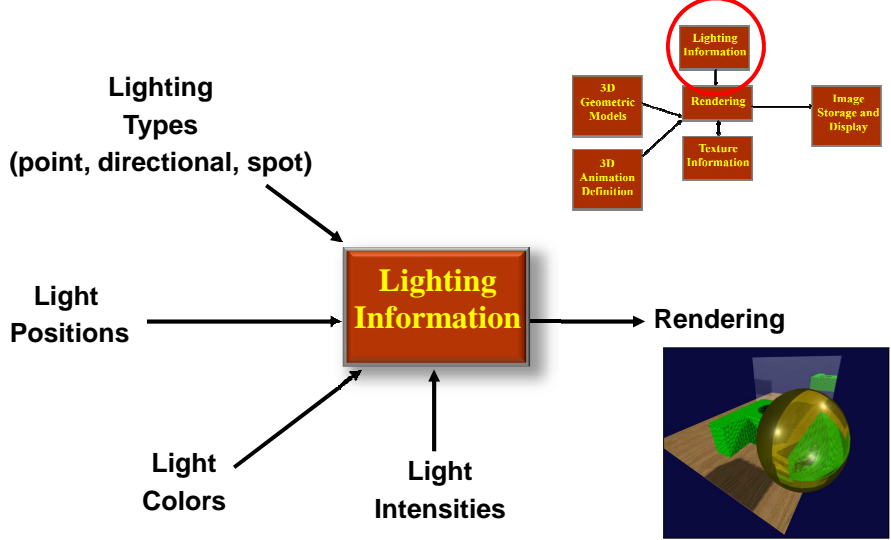


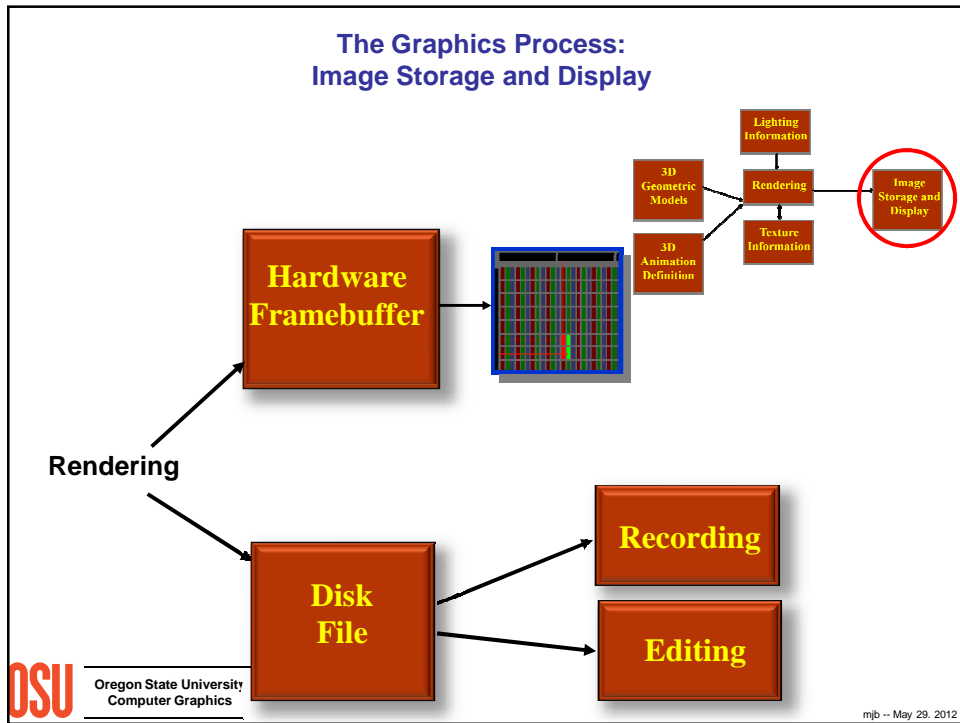
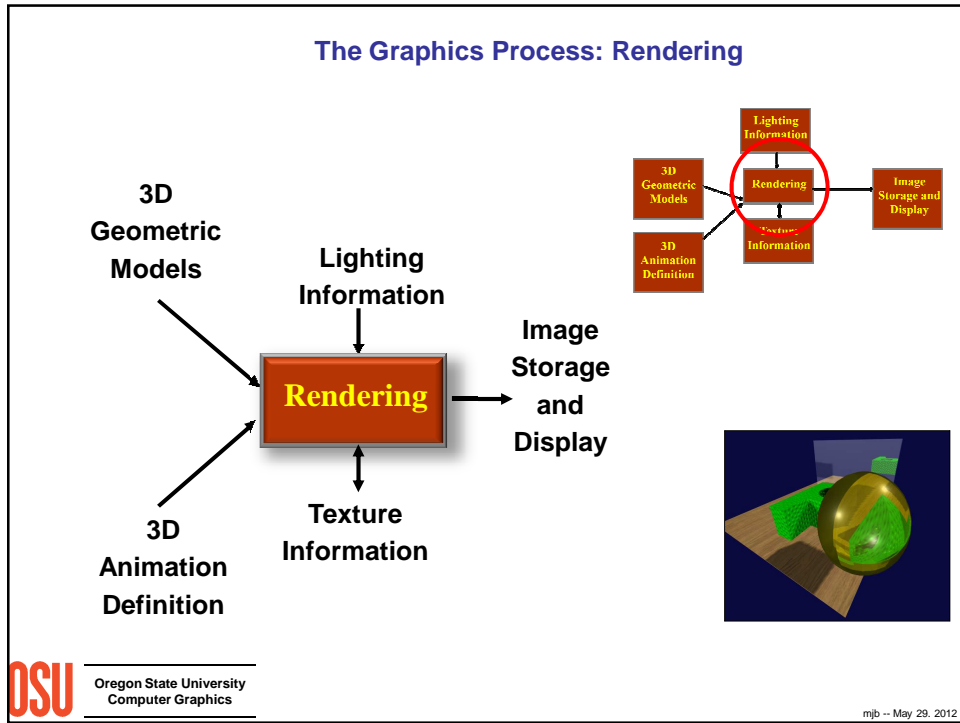


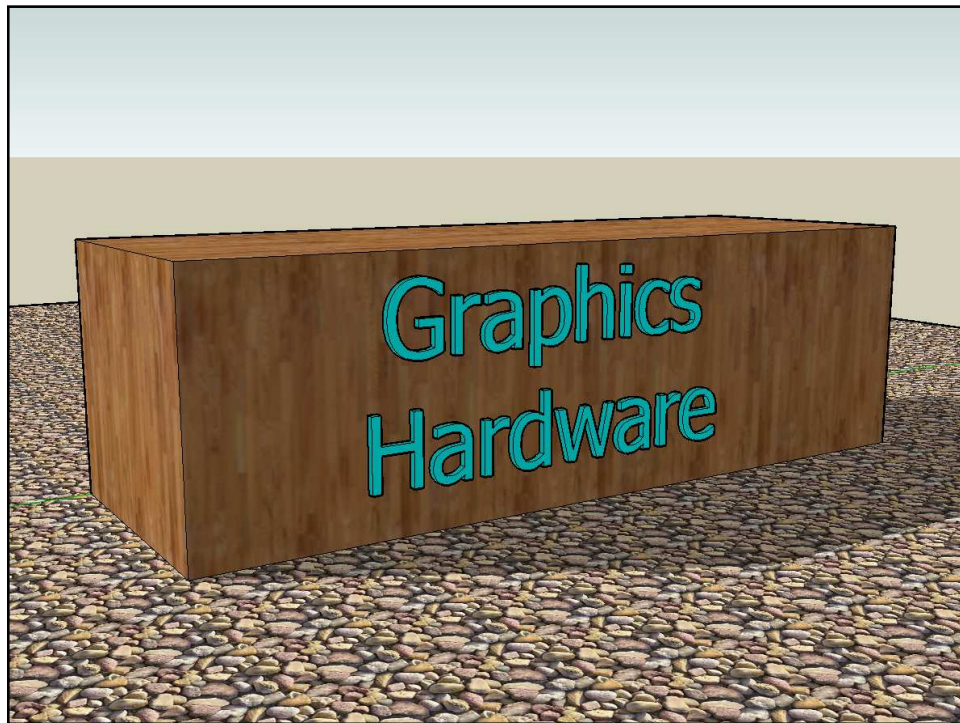
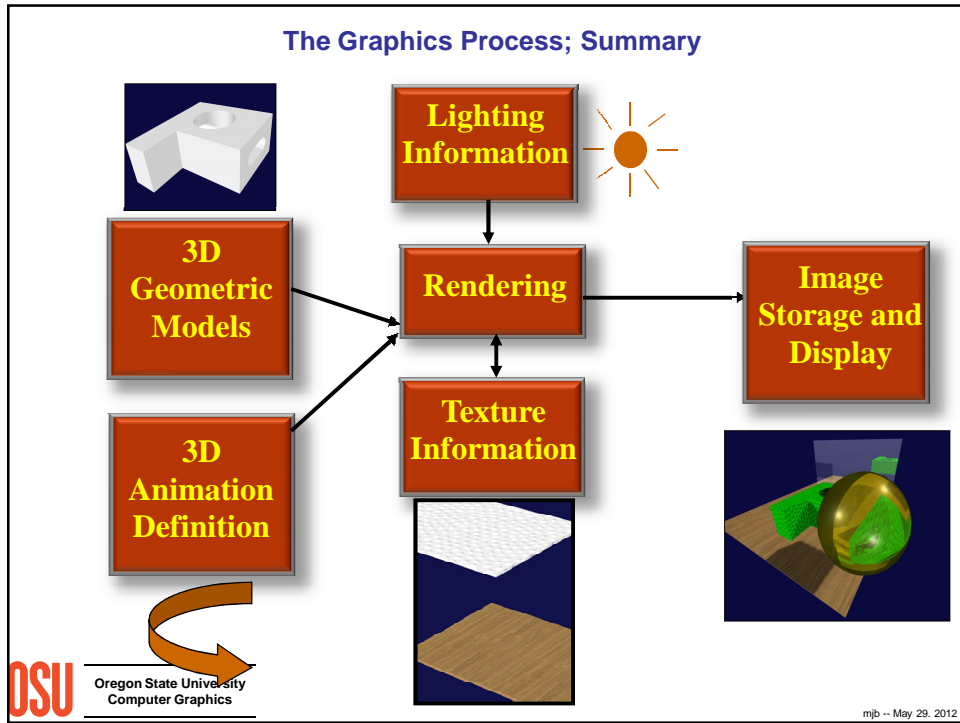
### The Graphics Process: Texturing

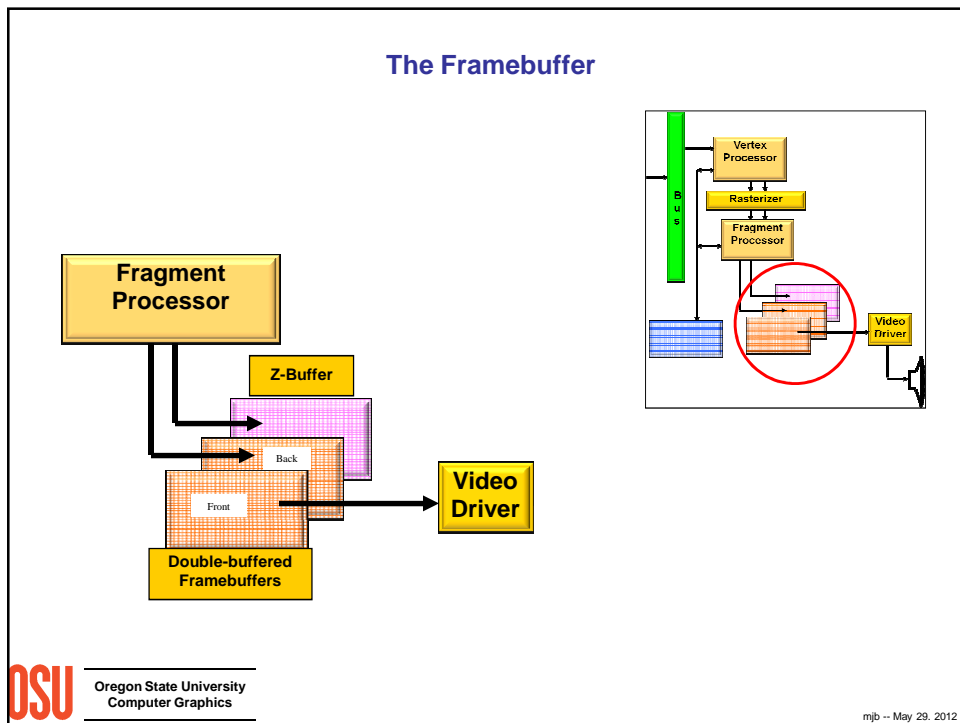
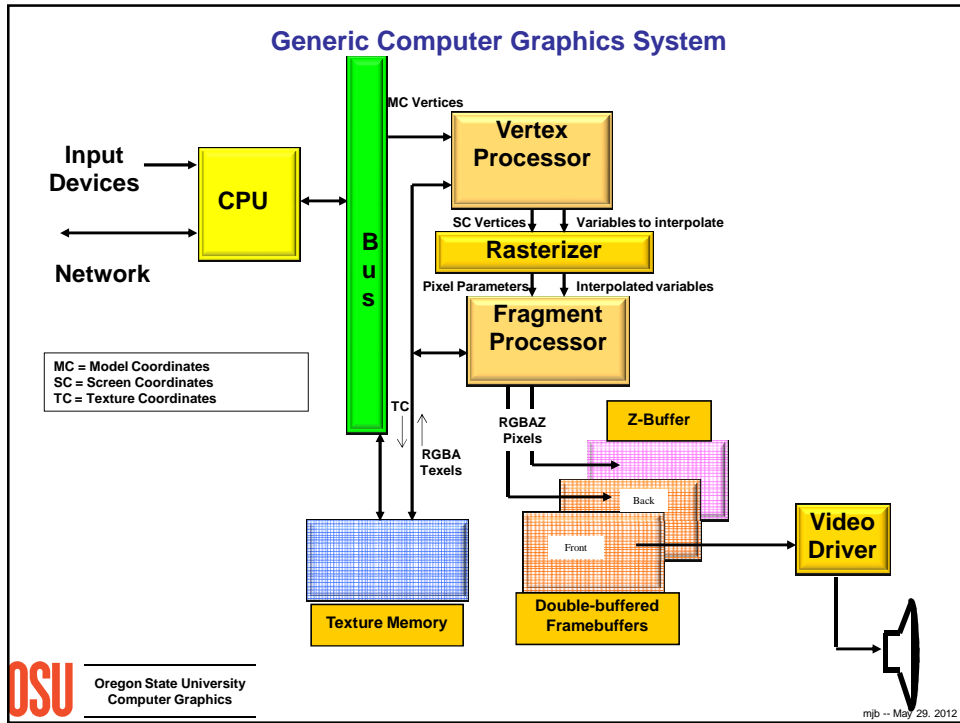


### The Graphics Process: Lighting



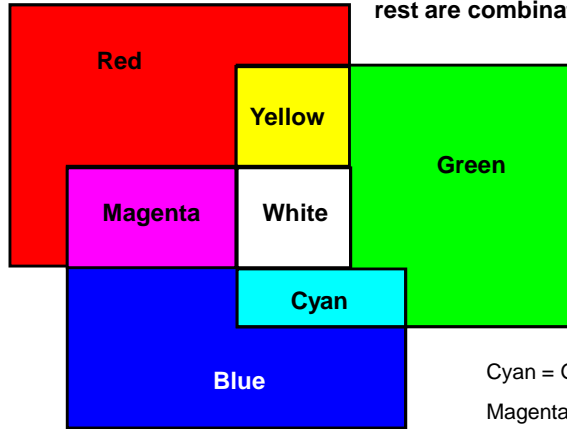






## The Framebuffer Uses Additive Colors (RGB)

Red, Green, and Blue are provided. The rest are combinations of those three.



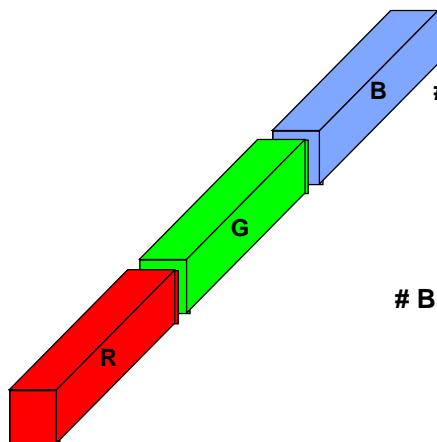
Cyan = Green + Blue

Magenta = Red + Blue

Yellow = Red + Green

White = Red + Green + Blue

## The Framebuffer: Integer Color Storage



# Bits/color

# Intensities per color

8

$2^8 = 256$

10

$2^{10} = 1024$

12

$2^{12} = 4096$

# Bits/pixel

Total colors:

24

$2^{24} = 16.7 \text{ M}$

30

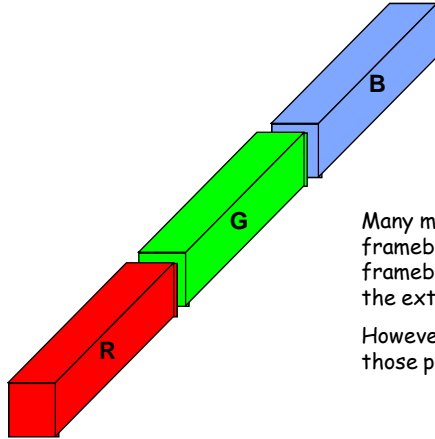
$2^{30} = 1 \text{ B}$

36

$2^{36} = 69 \text{ B}$

## The Framebuffer: Floating Point Color Storage

- 16- or 32-bit floating point for each color component



### Why so much?

Many modern algorithms do arithmetic on the framebuffer color components, or treat the framebuffer color components as data. They need the extra precision during the arithmetic.

However, the display system cannot display all of those possible colors.

## The Framebuffer

- *Alpha* values
  - Transparency per pixel
    - $\alpha = 0$ . is invisible
    - $\alpha = 1$ . is opaque
  - Represented in 8-32 bits (integer or floating point)
  - Alpha blending equation:

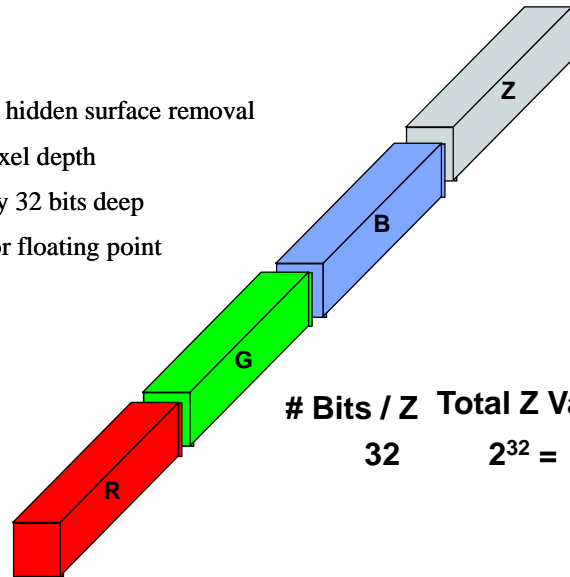
$$Color = \alpha C_1 + (1 - \alpha) C_2$$



## The Framebuffer

- **Z-buffer**

- Used for hidden surface removal
- Holds pixel depth
- Typically 32 bits deep
- Integer or floating point



# Bits / Z Total Z Values:  
32  $2^{32} = 4 \text{ B}$

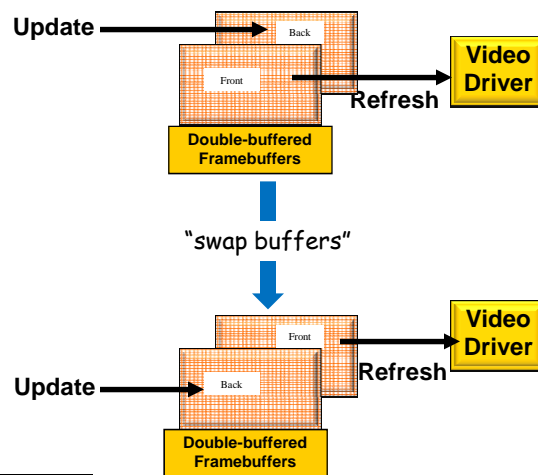


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## The Framebuffer

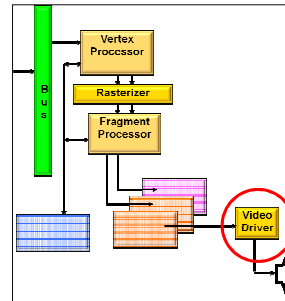
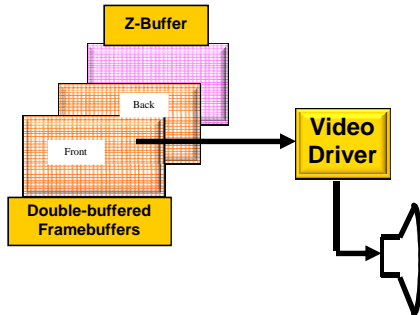
**Double-buffering:** Don't let the viewer see *any* of the scene until the entire scene is drawn



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## The Video Driver

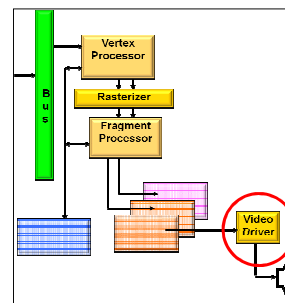


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## The Video Driver

- $N$  **refreshes/second** ( $N$  is usually between 50 and 100)
- Framebuffer contains the R,G,B that define the color at each pixel
- Cursor
  - Appearance is stored near the video driver in a "mini-framebuffer"
  - $x,y$  is given by the CPU
- Video input

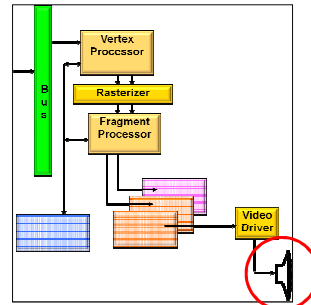
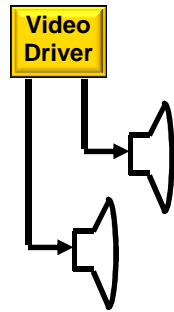


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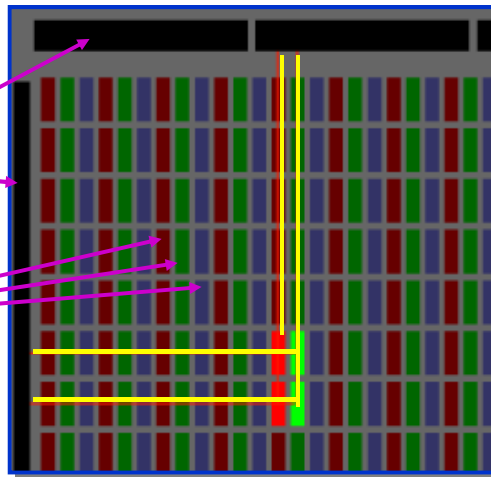


## The Computer Graphics Monitor(s)



## Displaying Color on a Computer Graphics LCD Monitor

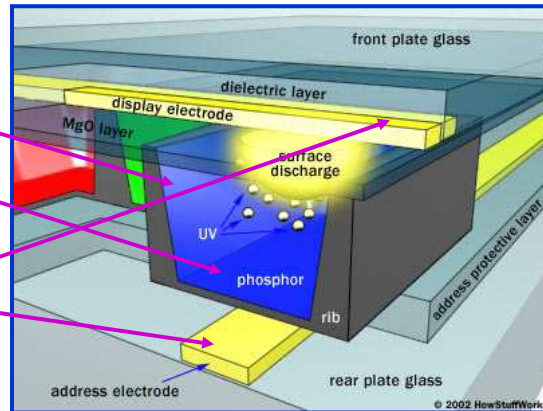
- Grid of electrodes
- Color filters



Source: <http://electronics.howstuffworks.com>

## Displaying Color on a Plasma Monitor

- Gas cell
- Phosphor
- Grid of electrodes



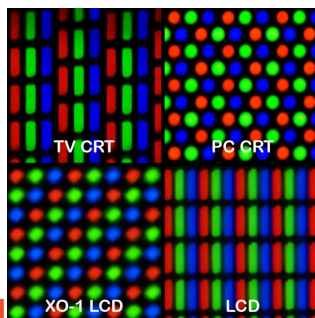
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<http://electronics.howstuffworks.com>

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## Display Resolution

- **Pixel** resolutions (1280x1024, 1600x1200, 1920x1152 are common on the desktop)
- Screen size (13", 16", 19", 21" are common)
- Human acuity: 1 arc-minute is achieved by viewing a 19" monitor with 1280x1024 resolution from a distance of ~40 inches



Mobile devices have set this back.

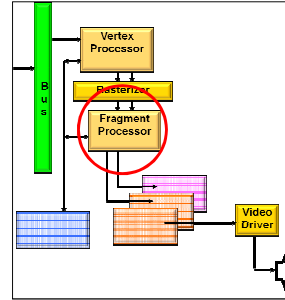
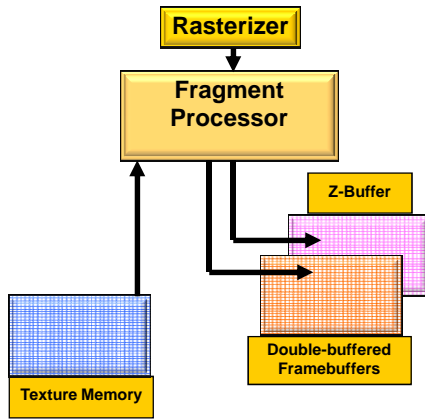


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[http://en.wikipedia.org/wiki/File:Pixel\\_geometry\\_01\\_Pengo.jpg](http://en.wikipedia.org/wiki/File:Pixel_geometry_01_Pengo.jpg)

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## The Fragment Processor

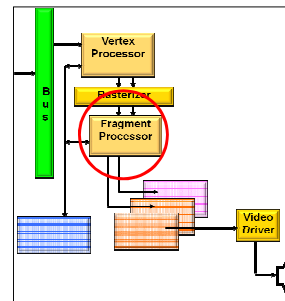


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## The Fragment Processor

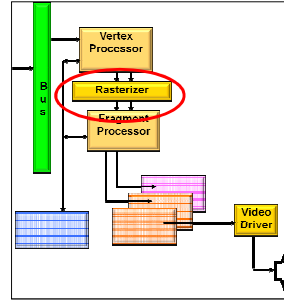
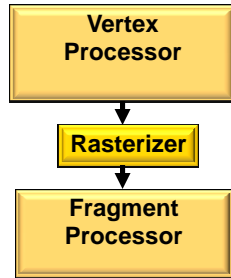
- Takes in all information that describes this pixel
- Produces the RGBA for that pixel's location in the framebuffer



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## The Rasterizer

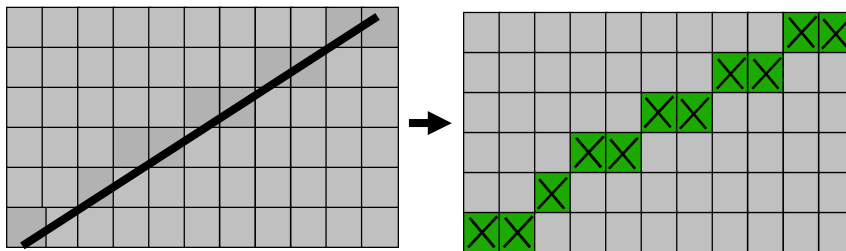


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## Rasterization

- Turn screen space vertex coordinates into pixels that make up lines and polygons
- A great place for custom electronics
- Anti-aliasing is often built-in



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Anti-aliasing is Implemented by Oversampling within Each Pixel



No AA

4x

16x

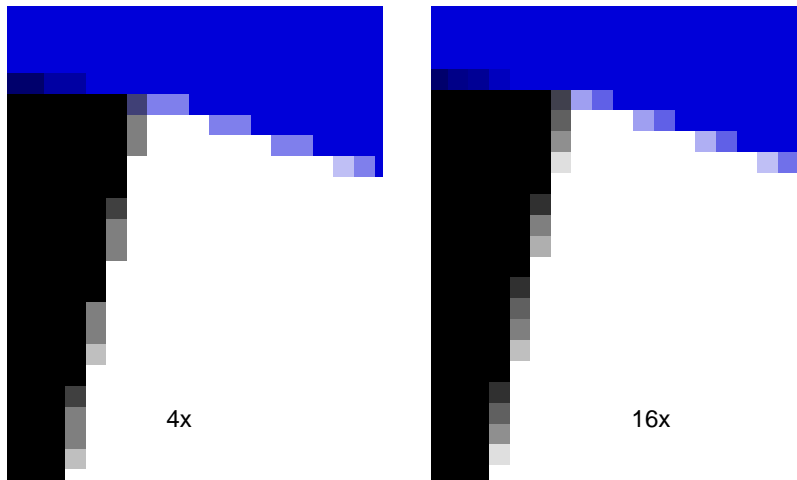
NVIDIA



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Anti-aliasing is Implemented by Oversampling within Each Pixel



4x

16x

NVIDIA

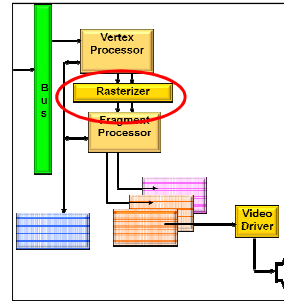


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## Rasterizers Can Interpolate:

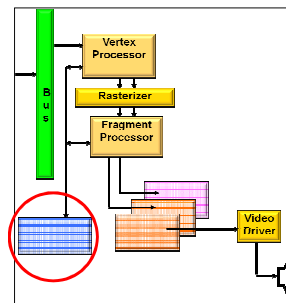
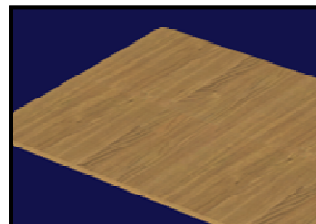
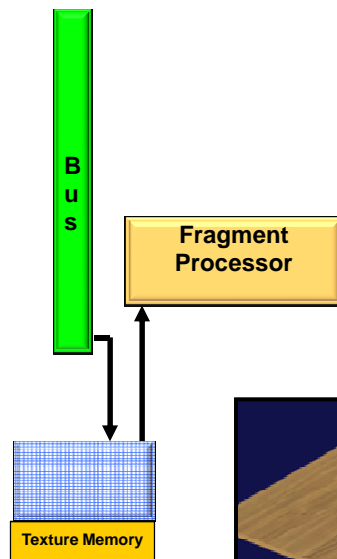
- X and Y
- Red-green-blue values
- Alpha values
- Z values
- Intensities
- Surface normals
- Texture coordinates
- Custom values given by the shaders



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## Texture Mapping

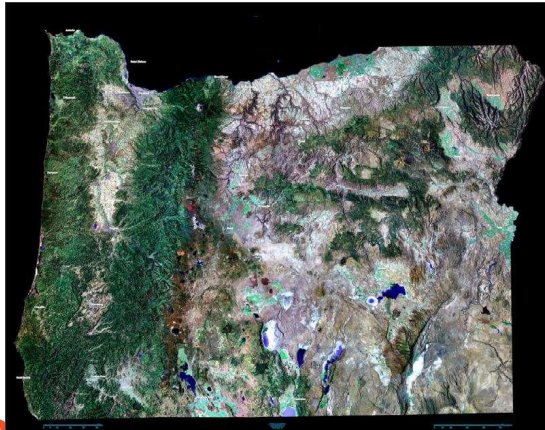


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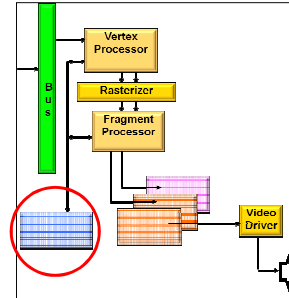
## Texture Mapping

- “Stretch” an image onto a piece of geometry
- Image can be generated by a program or scanned in
- Useful for realistic scene generation



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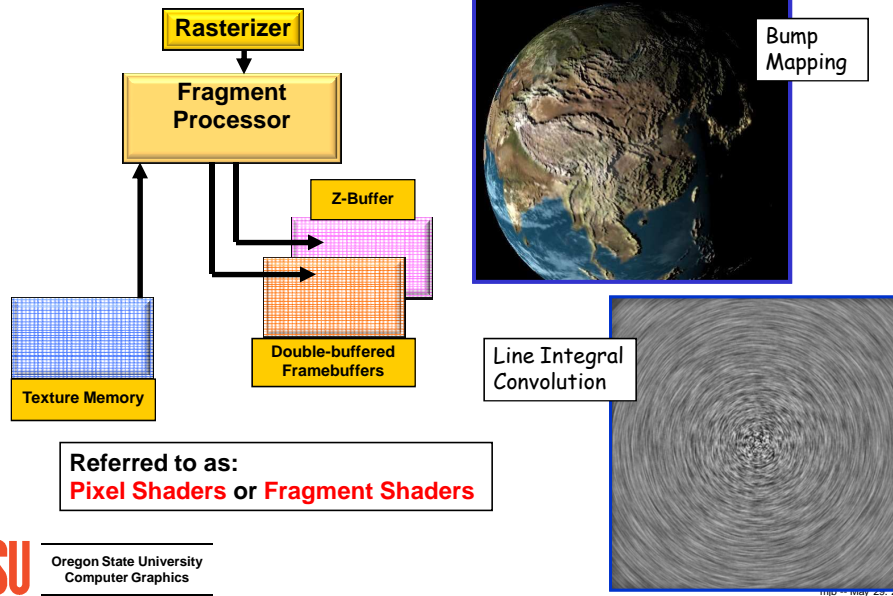
<http://2ols.com>



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## Something Cool:

### Write-Your-Own Fragment-Processor Code

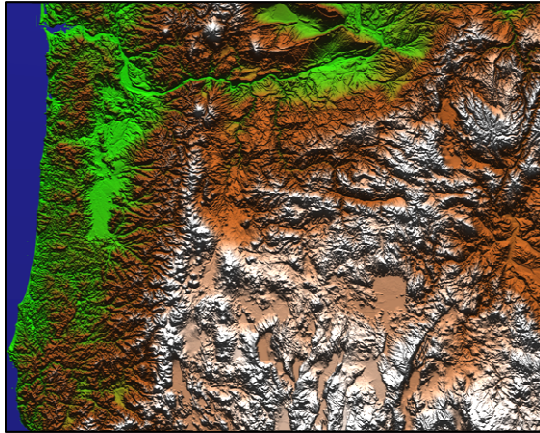


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## Procedural Texture Mapping

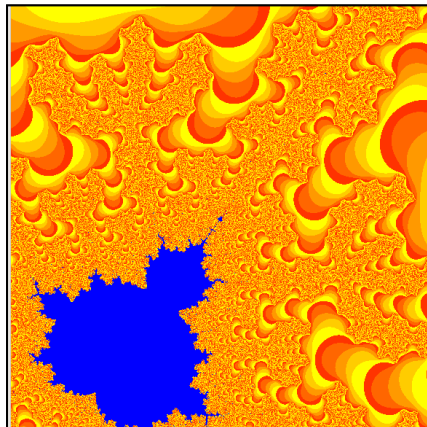
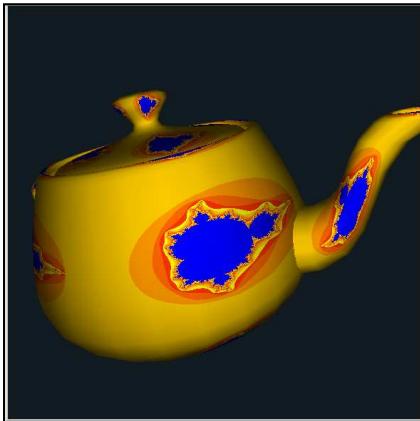
Create a texture from an equation. In this case, the equation takes a grid of heights and produces surface normals for lighting



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## Procedural Textures

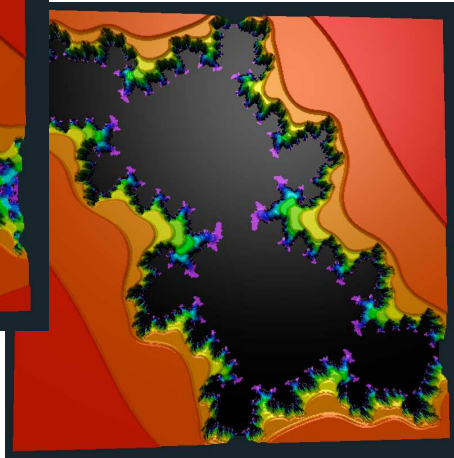
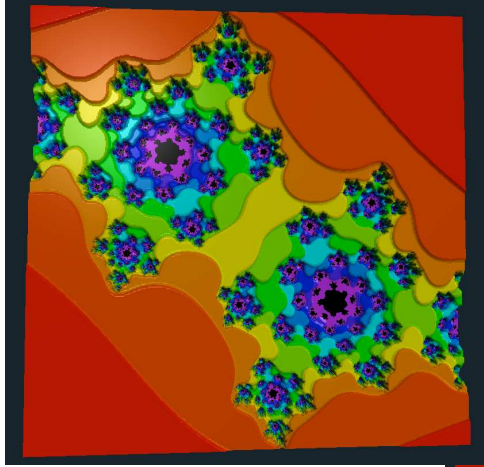


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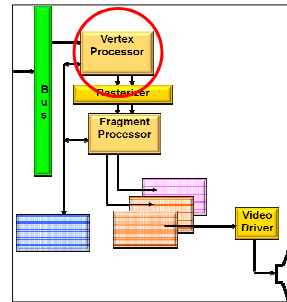
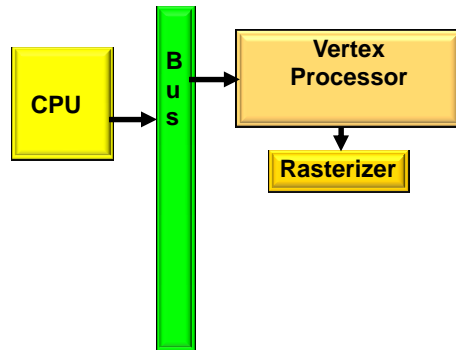


## Procedural Textures



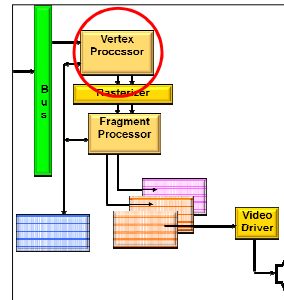
Josie Hunter

## The Vertex Processor



## Vertex Processor

- Coordinates enter in model units
- Coordinates leave in screen (pixel) units
- Another great place for custom electronics



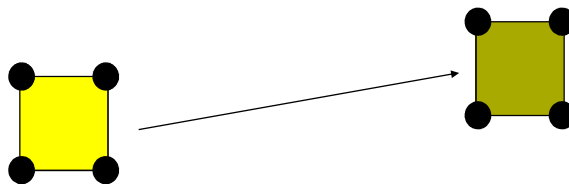
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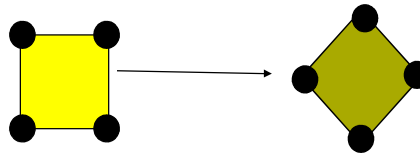
## Vertex Processor: Transformations

- Used to correctly place objects in the scene

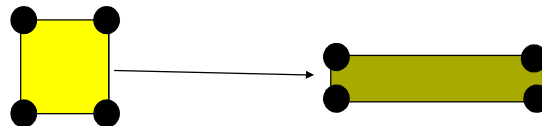
- Translation



- Rotation



- Scaling



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## Vertex Processor: Windowing and Clipping

- Declare which portion of the 3D universe you are interested in viewing
- This is called the *view volume*
- Clip away everything that is outside the viewing volume



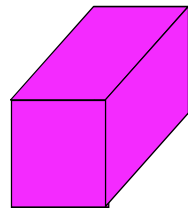
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## Vertex Processor: Projection

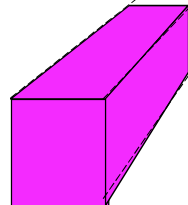
- Turn 3D coordinates into 2D

– *Parallel projection*



Parallel lines  
remain parallel

– *Perspective projection*



Some parallel lines  
appear to converge



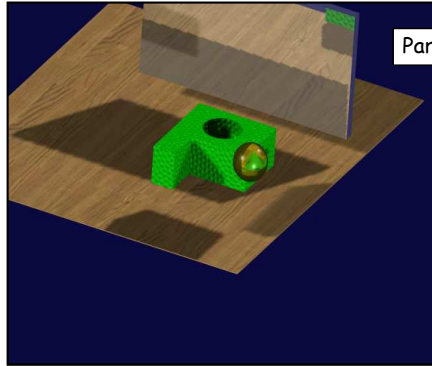
"vanishing point"



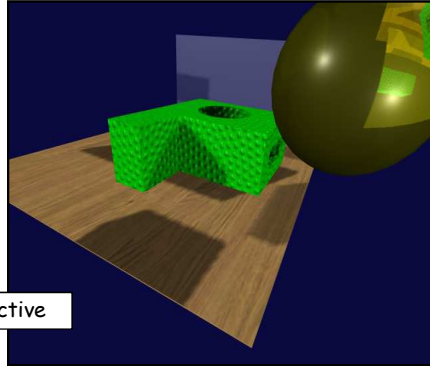
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## Vertex Processor: Projection



Parallel



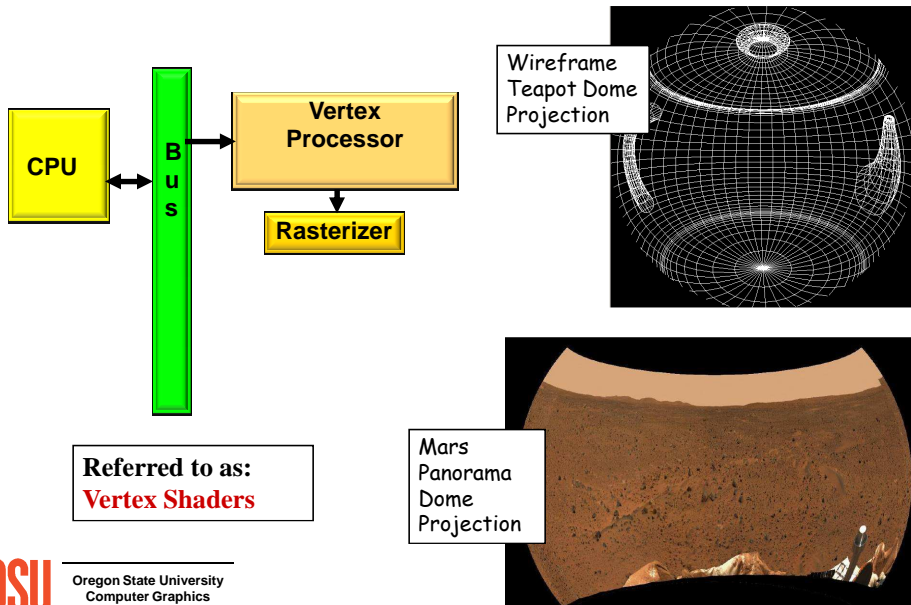
Perspective



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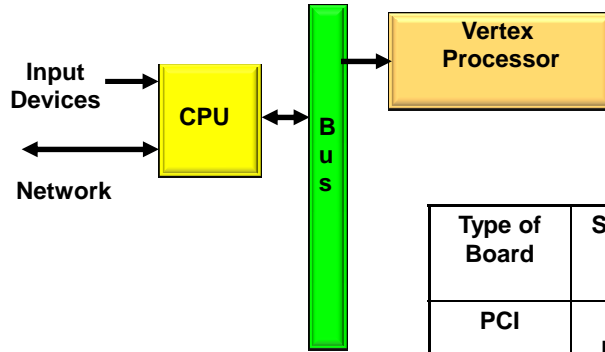
## Something Cool: Write-Your-Own Vertex Code



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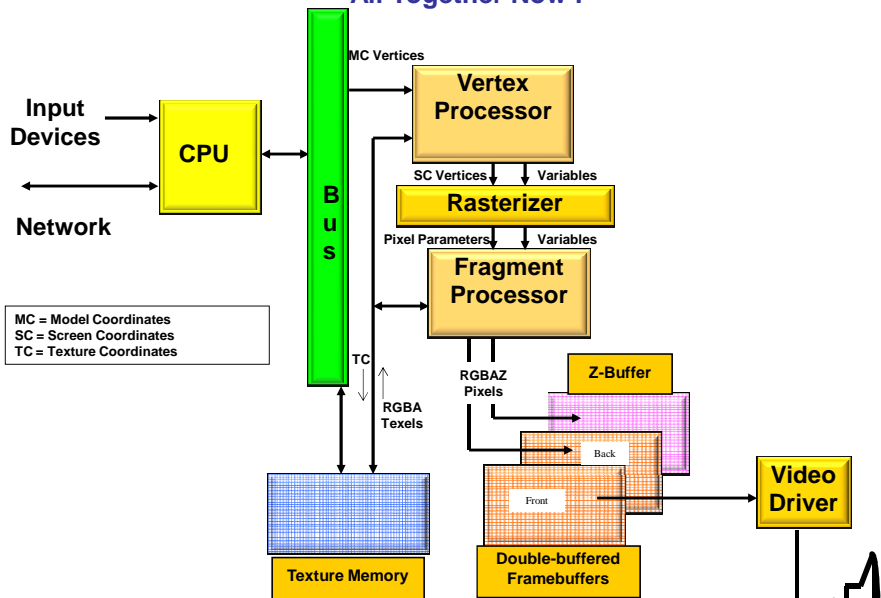
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### The CPU and Bus

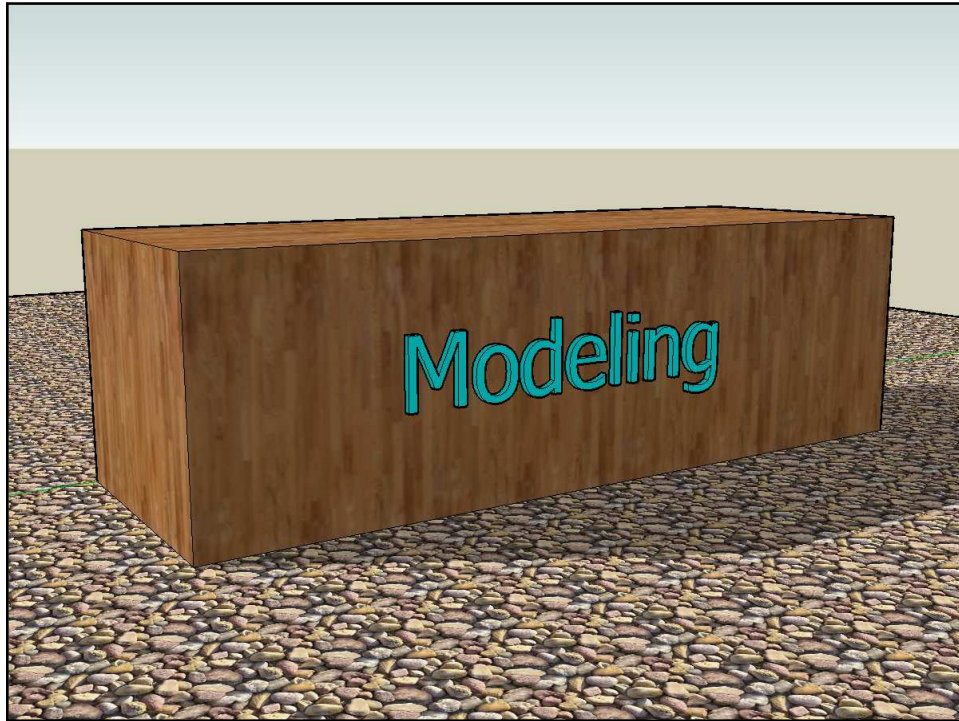


Type of Board	Speed to Board	Speed from Board
PCI	132 Mb/sec	132 Mb/sec
AGP 8X	2 Gb/sec	264 Mb/sec
PCI Express	4 Gb/sec	4 Gb/sec

### All Together Now !



MC = Model Coordinates  
SC = Screen Coordinates  
TC = Texture Coordinates



### What is a Model?

A is a model of B if A can be used to ask questions about B.

In computer graphics applications, what do we want to ask about B?

- What does B look like?
- How do I want to interact with (shape) B?
- Does B need to be a legal solid?
- How does B interact with its environment?
- What is B's surface area and volume?

These questions, and answers, control what type of geometric modeling you need to do

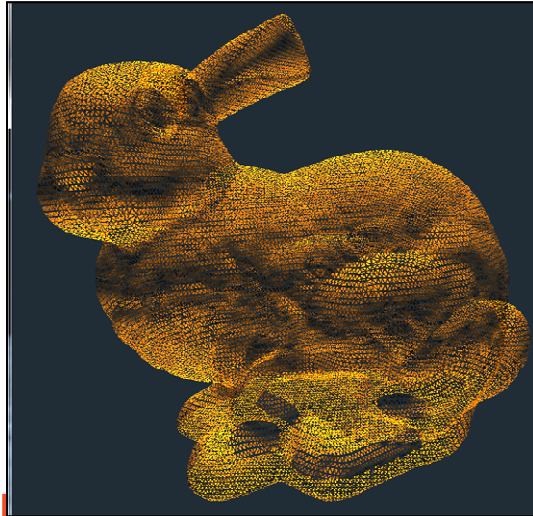


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## Explicitly Listing Geometry and Topology

Models can consist of thousands of vertices and faces – we need some way to list them efficiently



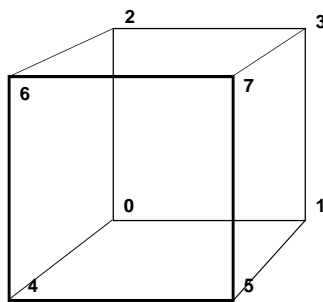
<http://graphics.stanford.edu/data/3Dscanrep>

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## Explicitly Listing Geometry and Topology



```
static GLfloat CubeColors[ ][3] =  
{  
    { 0., 0., 0. },  
    { 1., 0., 0. },  
    { 0., 1., 0. },  
    { 1., 1., 0. },  
    { 0., 0., 1. },  
    { 1., 0., 1. },  
    { 0., 1., 1. },  
    { 1., 1., 1. },  
};
```

```
static GLfloat CubeVertices[ ][3] =  
{  
    { -1., -1., -1. },  
    { 1., -1., -1. },  
    { -1., 1., -1. },  
    { 1., 1., -1. },  
    { -1., -1., 1. },  
    { 1., -1., 1. },  
    { -1., 1., 1. },  
    { 1., 1., 1. },  
};
```

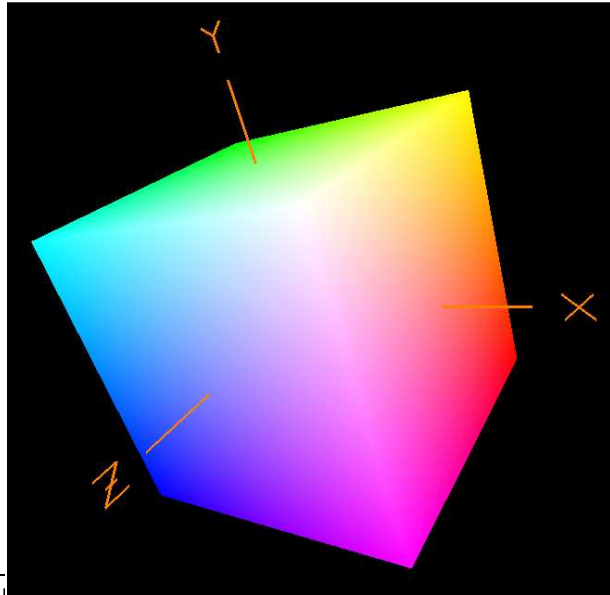
```
static GLuint CubeIndices[ ][4] =  
{  
    { 0, 2, 3, 1 },  
    { 4, 5, 7, 6 },  
    { 1, 3, 7, 5 },  
    { 0, 4, 6, 2 },  
    { 2, 6, 7, 3 },  
    { 0, 1, 5, 4 },  
};
```

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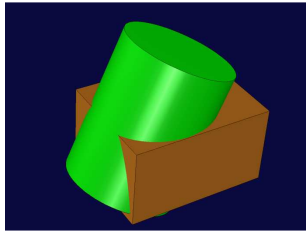
### Cube Example



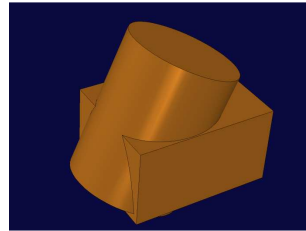
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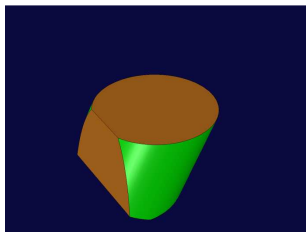
### Solid Modeling Using Boolean Operators



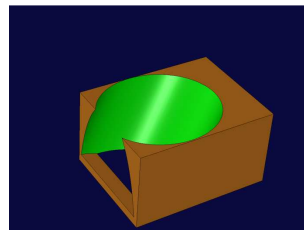
Two Overlapping Solids



Union



Intersection



Difference

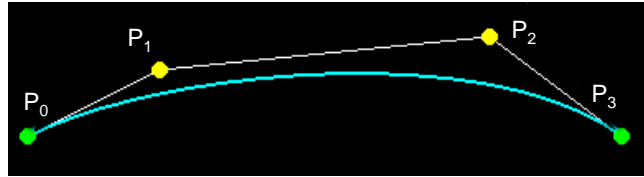


Or  
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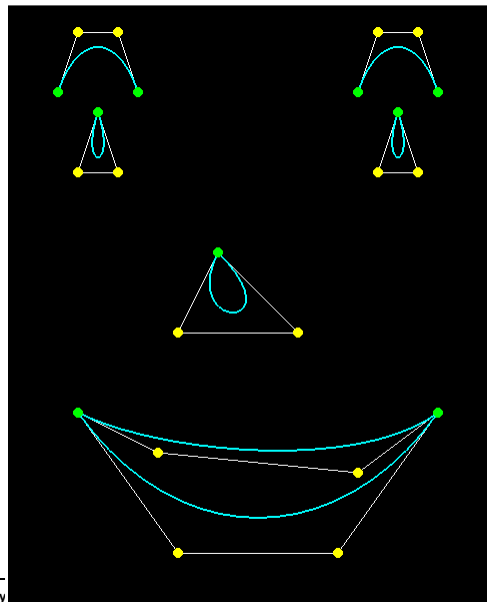


### Curve Sculpting – Bezier Curve Sculpting

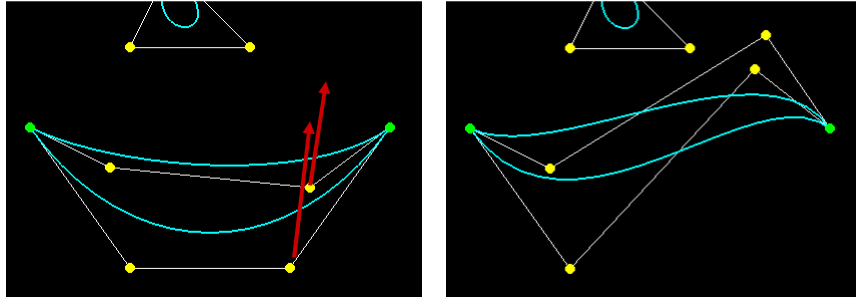


$$P(t) = (1-t)^3 P_0 + 3t(1-t)^2 P_1 + 3t^2(1-t)P_2 + t^3 P_3$$
$$0. \leq t \leq 1.$$

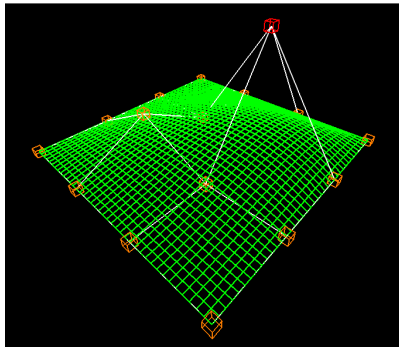
### Curve Sculpting – Bezier Curve Sculpting Example



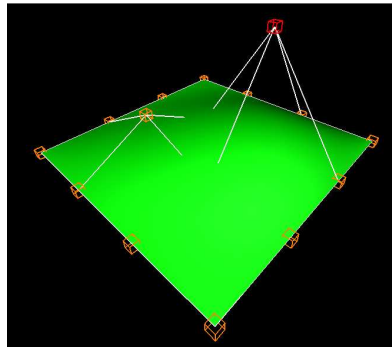
### Curve Sculpting – Bezier Curve Sculpting Example



### Surface Sculpting

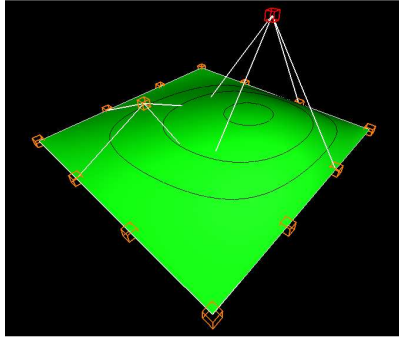


Wireframe

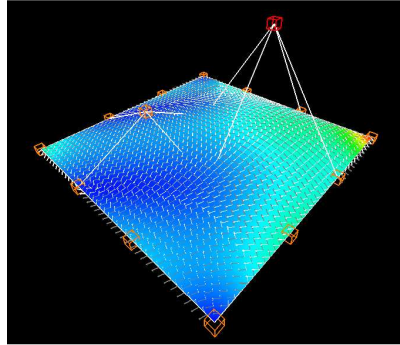


Surface

## Surface Equations can also be used for Analysis



With Contour Lines



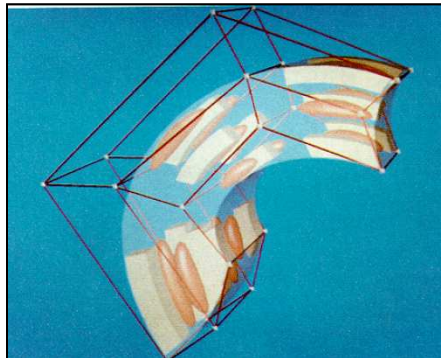
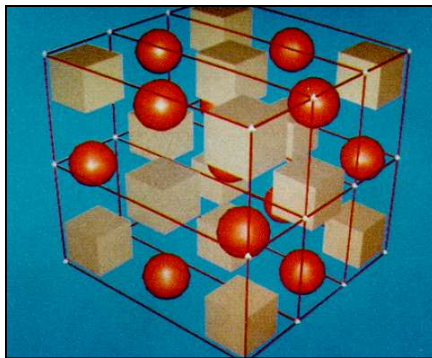
Showing Curvature



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## Volume Sculpting



Sederberg and Parry



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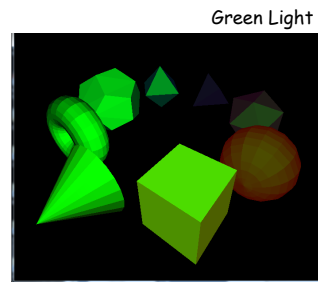
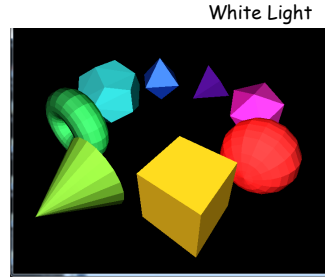
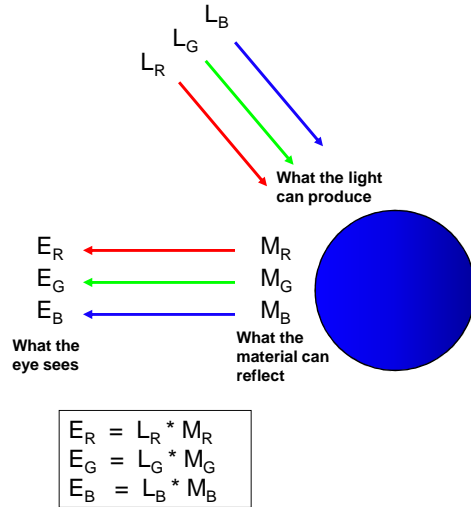
## Rendering

Rendering is the process of creating an image of a geometric model. Again, there are questions you need to ask:

- How realistic do I want this image to be?
- How much compute time do I have to create this image?
- Do I need to take into account lighting?
- Does the illumination need to be global or will local do?
- Do I need to take into account shadows?
- Do I need to take into account reflection and refraction?



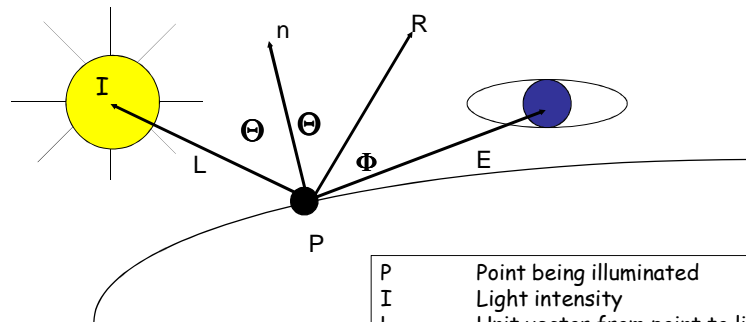
## Fundamentals of Computer Graphics Lighting



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## The Computer Graphics Lighting Environment



- |   |                                 |
|---|---------------------------------|
| P | Point being illuminated         |
| I | Light intensity                 |
| L | Unit vector from point to light |
| n | Unit vector surface normal      |
| R | Perfect reflection unit vector  |
| E | Unit vector to eye position     |



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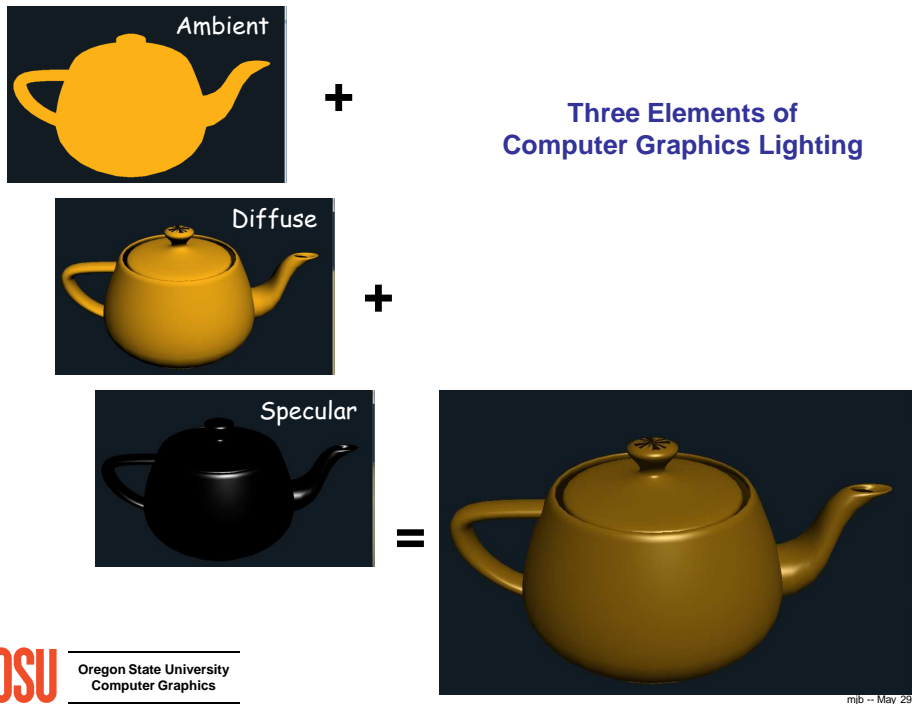
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### Three Elements of Computer Graphics Lighting

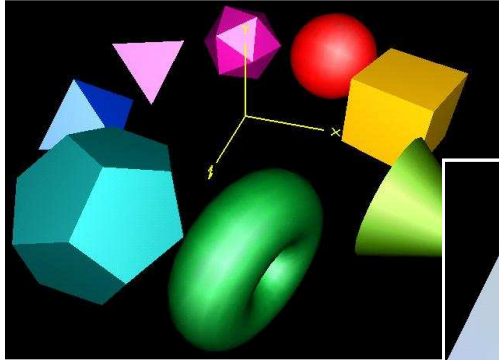
- 1. Ambient = a constant      Accounts for light bouncing "everywhere"
- 2. Diffuse =  $I \cdot \cos\Theta$       Accounts for the angle between the incoming light and the surface normal
- 3. Specular =  $I \cdot \cos^S\phi$       Accounts for the angle between the "perfect reflector" and the eye; also the exponent,  $S$ , accounts for surface shininess

Note that  $\cos\Theta$  is just the dot product between unit vectors  $L$  and  $n$

Note that  $\cos\phi$  is just the dot product between unit vectors  $R$  and  $E$

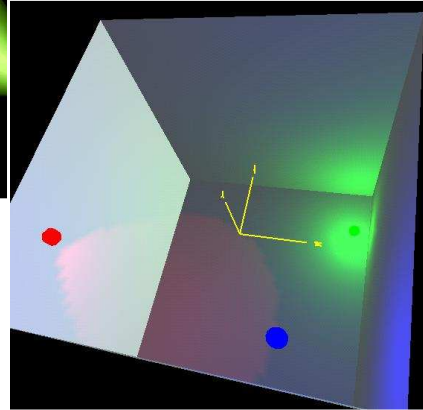


## Lighting Examples



Omnidirectional Point Light

Spot Lights



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## Two Types of Rendering

1. Starts at the object
2. Starts at the eye

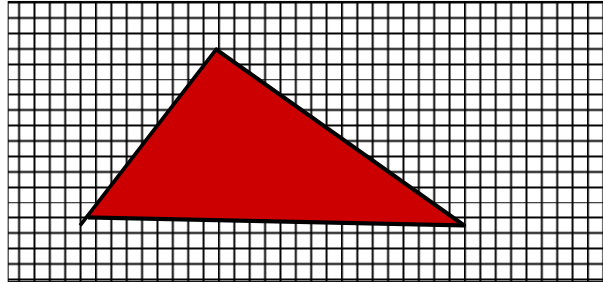


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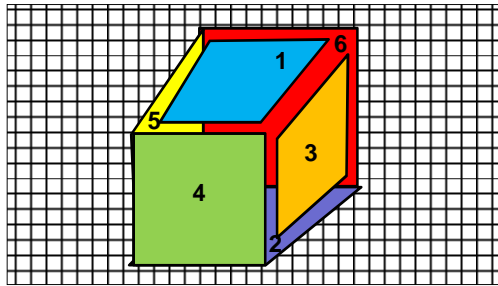
## Starts at the Object

This is the typical kind of rendering you get on a graphics card. Start with the geometry and project it onto the pixels.

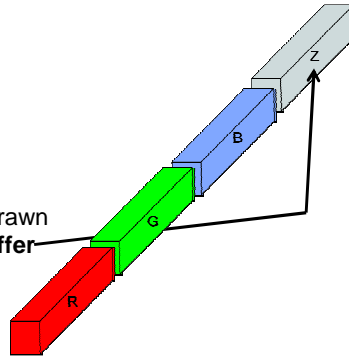


## How do things in front look like they are *really* in front?

Your application might draw the polygons in 1-2-3-4-5-6 order, but 1, 3, and 4 still need to look like they were drawn last:



Either the polygons need to be re-arranged to be drawn in a back-to-front order, or we need to have a **Z-buffer**





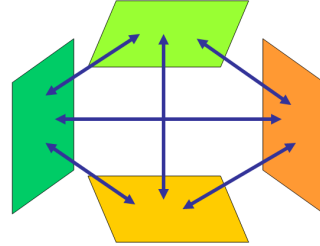
## Another From-the-Object Method -- Radiosity

Based on the idea that all surfaces gather light intensity from all other surfaces

The fundamental radiosity equation is an energy balance that says:

“The light energy leaving surface  $i$  equals the amount of light energy generated by surface  $i$  plus surface  $i$ 's reflectivity times the amount of light energy arriving from all other surfaces”

$$B_i A_i = E_i A_i + \rho_i \sum_j B_j A_j F_{j \rightarrow i}$$



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## The Radiosity Equation

$$B_i A_i = E_i A_i + \rho_i \sum_j B_j A_j F_{j \rightarrow i}$$

$B_i$  is the light energy intensity shining from surface element  $i$

$A_i$  is the area of surface element  $i$

$E_i$  is the internally-generated light energy intensity for surface element  $i$

$\rho_i$  is surface element  $i$ 's reflectivity

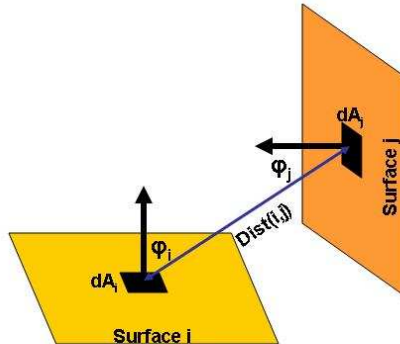
$F_{j \rightarrow i}$  is referred to as the Form Factor, or Shape Factor, and describes what percent of the energy leaving surface element  $j$  that arrives at surface element  $i$



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### The Radiosity Shape Factor



$$F_{j \rightarrow i} = \int_{A_i} \int_{A_j} \text{visibility}(di, dj) \frac{\cos \Theta_i \cos \Theta_j}{\pi \text{Dist}(di, dj)^2} dA_j dA_i$$



### The Radiosity Matrix Equation

Expand  $B_i A_i = E_i A_i + \rho_i \sum_j B_j A_j F_{j \rightarrow i}$

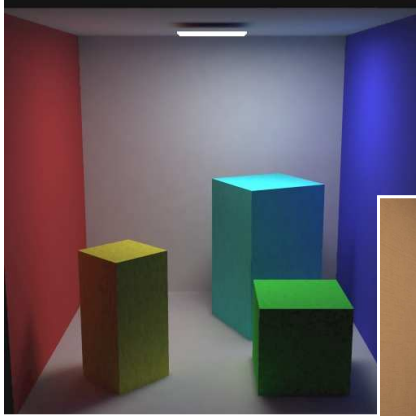
For each surface element, and re-arrange to solve for the surface intensities, the  $B$ 's:

$$\begin{bmatrix} 1 - \rho_1 F_{1 \rightarrow 1} & -\rho_1 F_{1 \rightarrow 2} & \dots & -\rho_1 F_{1 \rightarrow N} \\ -\rho_2 F_{2 \rightarrow 1} & 1 - \rho_2 F_{2 \rightarrow 2} & \dots & -\rho_2 F_{2 \rightarrow N} \\ \dots & \dots & \dots & \dots \\ -\rho_N F_{N \rightarrow 1} & -\rho_N F_{N \rightarrow 2} & \dots & 1 - \rho_N F_{N \rightarrow N} \end{bmatrix} \begin{Bmatrix} B_1 \\ B_2 \\ \dots \\ B_N \end{Bmatrix} = \begin{Bmatrix} E_1 \\ E_2 \\ \dots \\ E_N \end{Bmatrix}$$

This is a lot of equations!



## Radiosity Examples



AR Toolkit



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Autodesk

11/10/2012

## Radiosity Examples



Cornell University



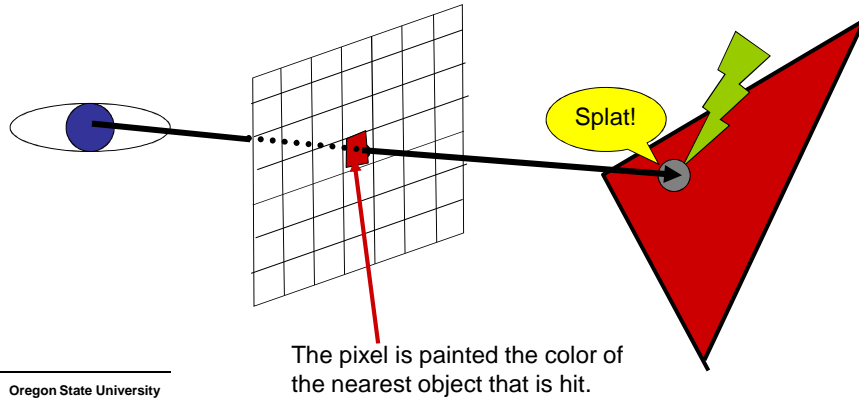
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Cornell University

11/10/2012

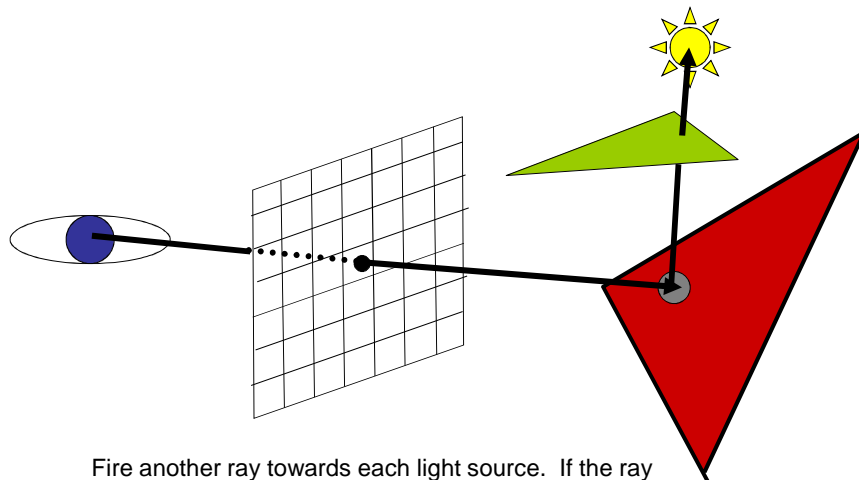
### Starts at the Eye

The most common approach in this category is ray-tracing:



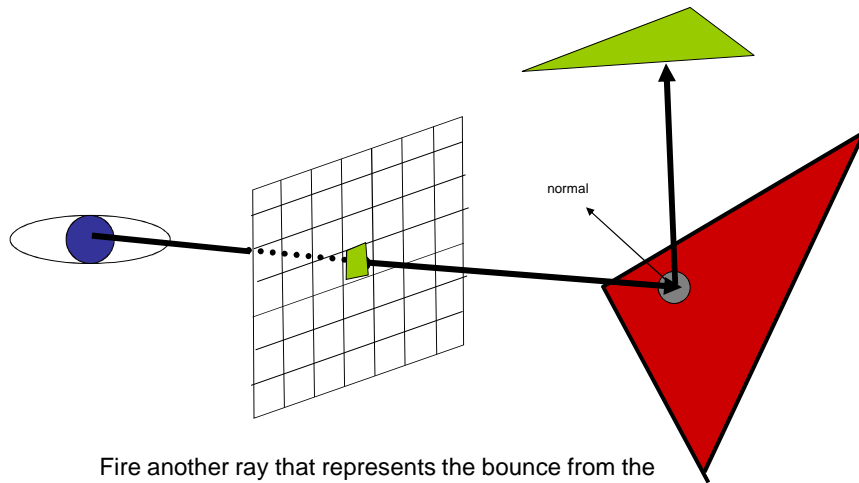
### Starts at the Eye

It's also easy to see if this point lies in a shadow:



### Starts at the Eye

It's also easy to handle reflection



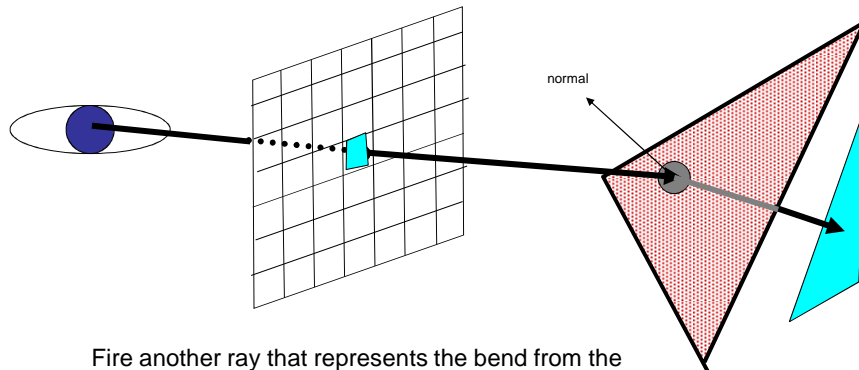
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Fire another ray that represents the bounce from the reflection. Paint the pixel the color that this ray sees.

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### Starts at the Eye

It's also easy to handle refraction

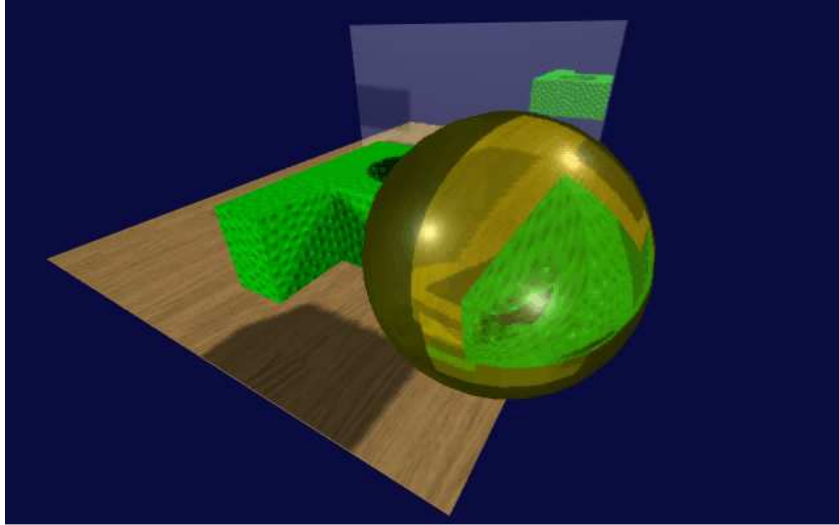


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Fire another ray that represents the bend from the refraction. Paint the pixel the color that this ray sees.

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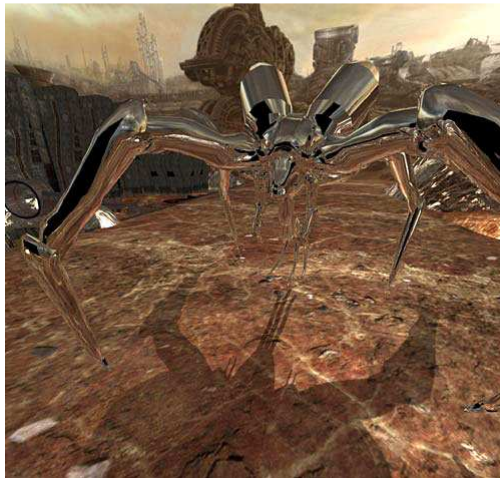
## Ray Tracing Examples



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## Ray Tracing Examples



Quake 4 Ray-Tracing Project



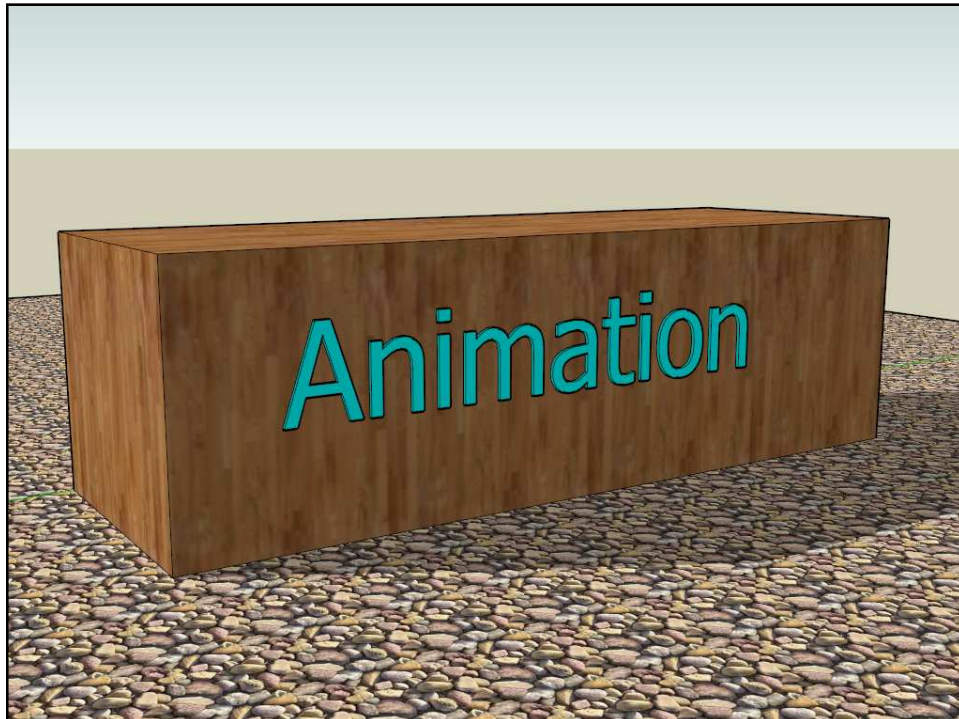
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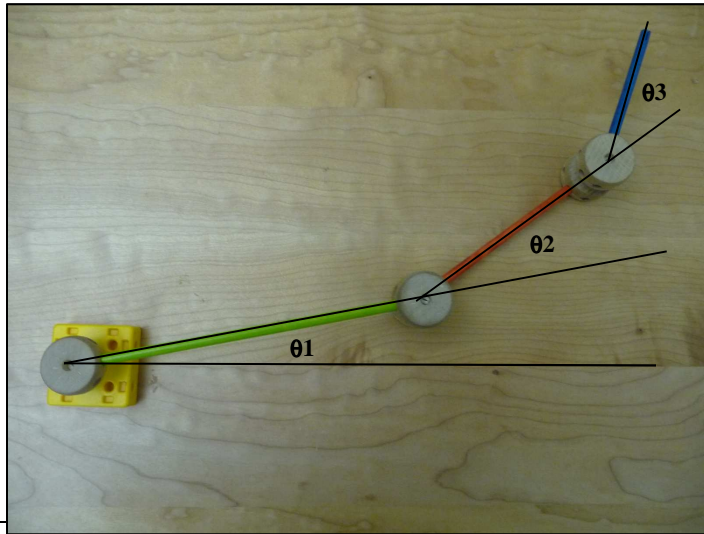
## Ray Tracing Examples



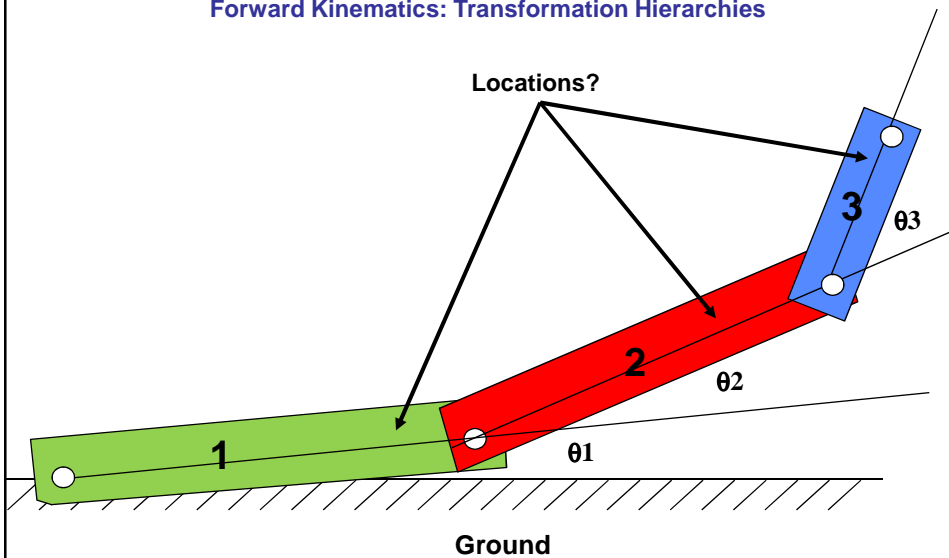
IBM's Cell Interactive Ray-tracer



Forward Kinematics:  
Change Parameters – Things Move  
(All Children Understand This)

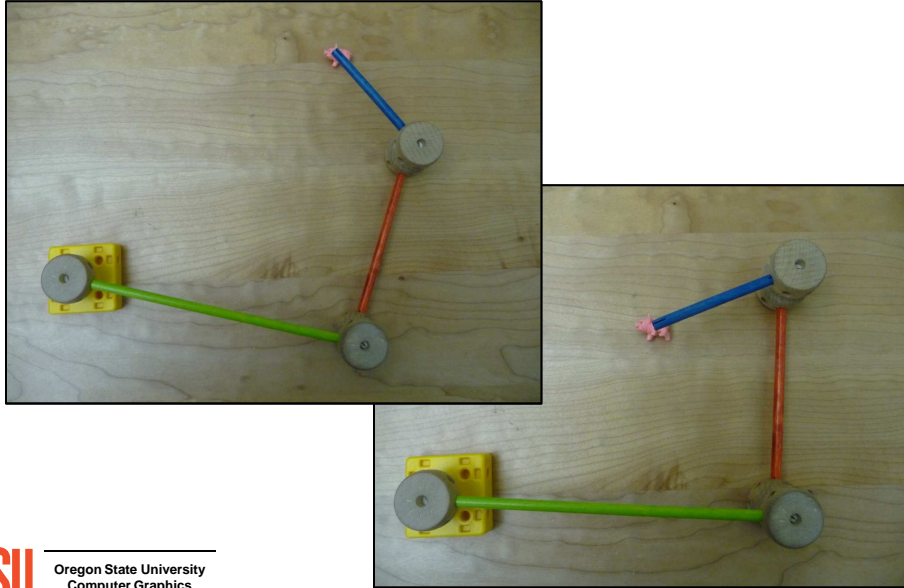


Forward Kinematics: Transformation Hierarchies



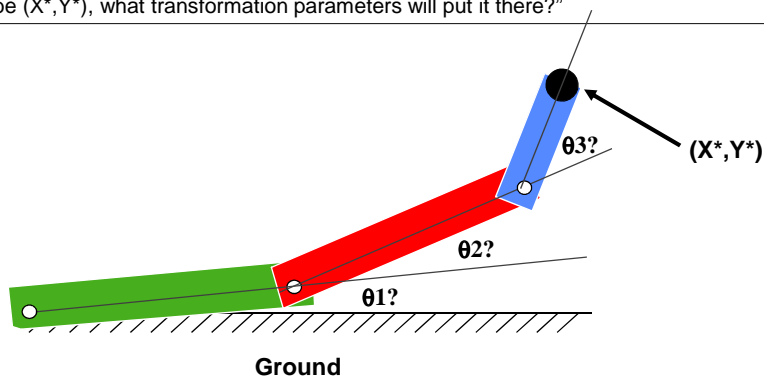


**Inverse Kinematics (IK):**  
Things Need to Move – What Parameters Will Make Them Do That?

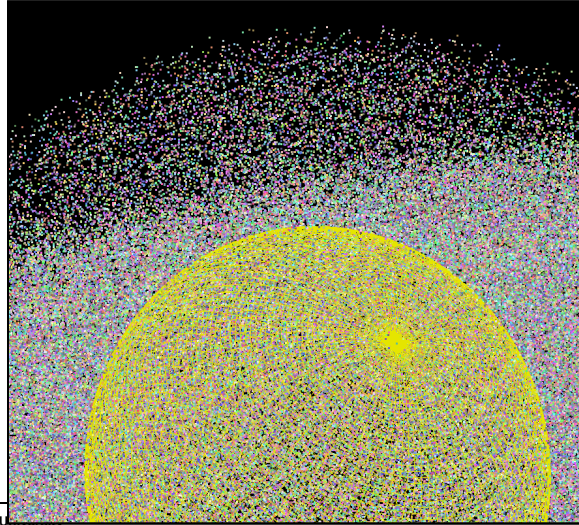


**Inverse Kinematics**

**Forward Kinematics** solves the problem "if I know the link transformation parameters, where are the links?".  
**Inverse Kinematics (IK)** solves the problem "if I know where I want the end of the chain to be  $(X^*, Y^*)$ , what transformation parameters will put it there?"



## Particle Systems: A Cross Between Modeling and Animation?

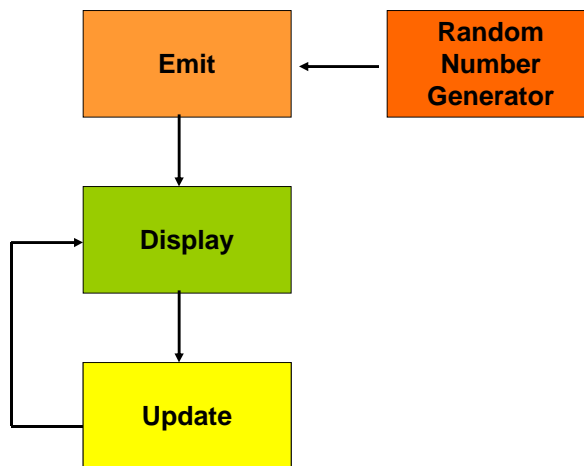


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## Particle Systems: A Cross Between Modeling and Animation?

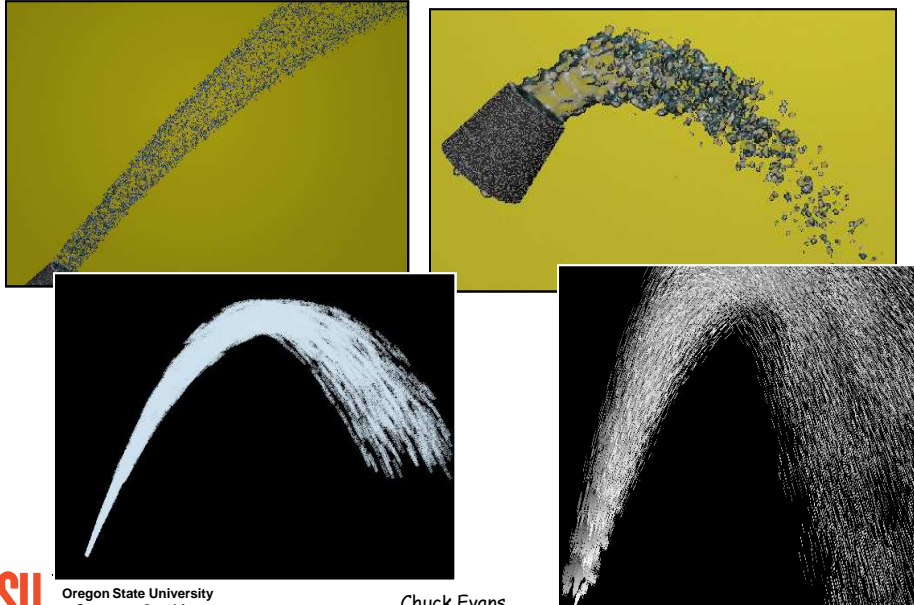
The basic process is:



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### Particle Systems Examples

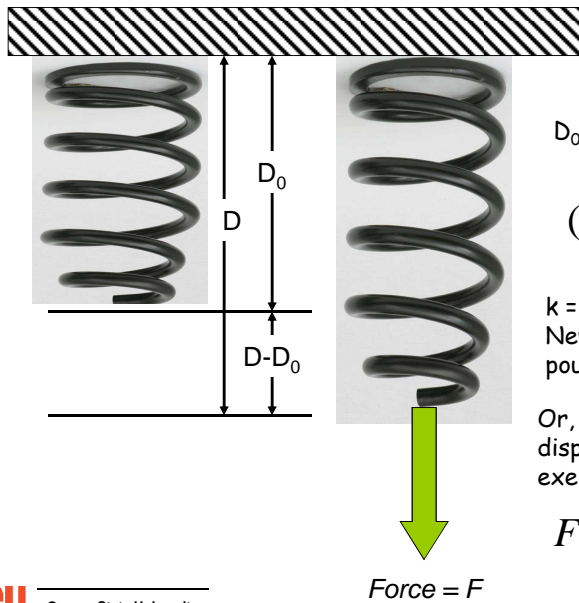


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Chuck Evans

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### Animating using Physics



$D_0$  = unloaded spring length

$$(D - D_0) = \frac{F}{k}$$

$k$  = *spring stiffness* in  
Newtons/meter or  
pounds/inch

Or, if you know the  
displacement, the force  
exerted by the spring is:

$$F = k(D - D_0)$$

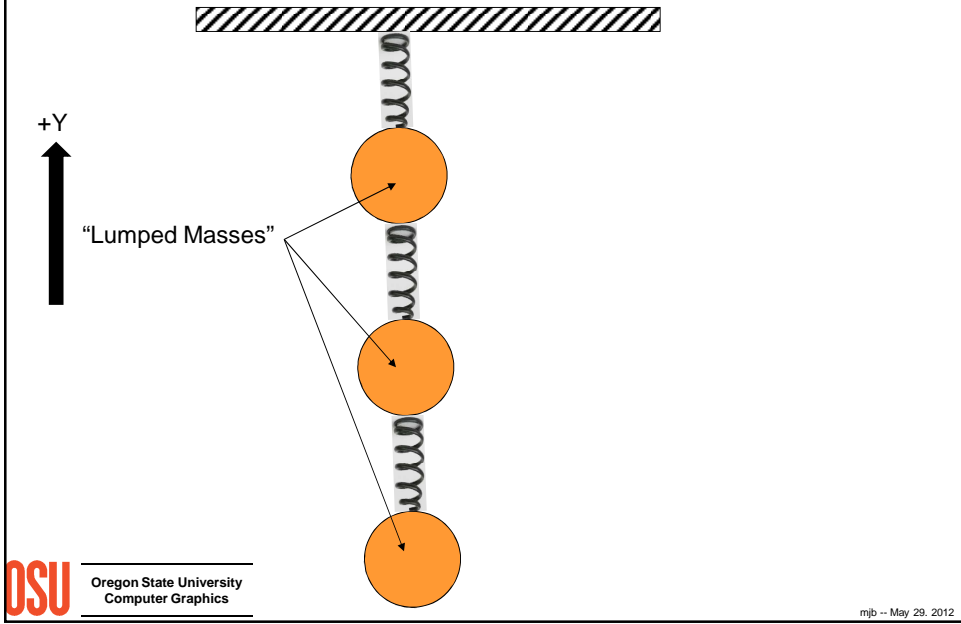
Force =  $F$

This is known as Hooke's law

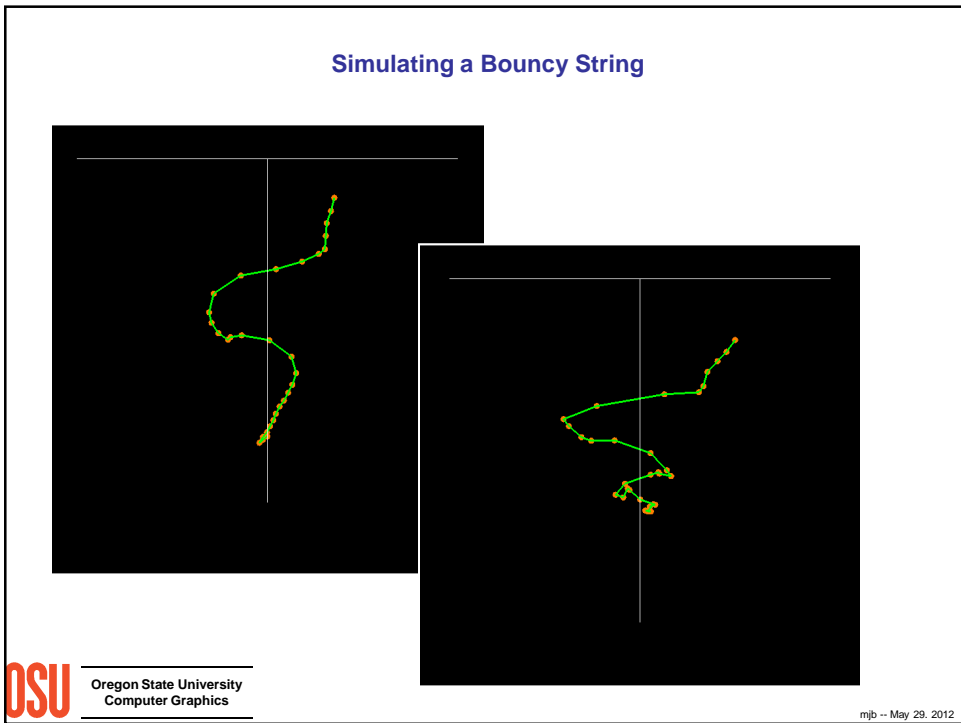
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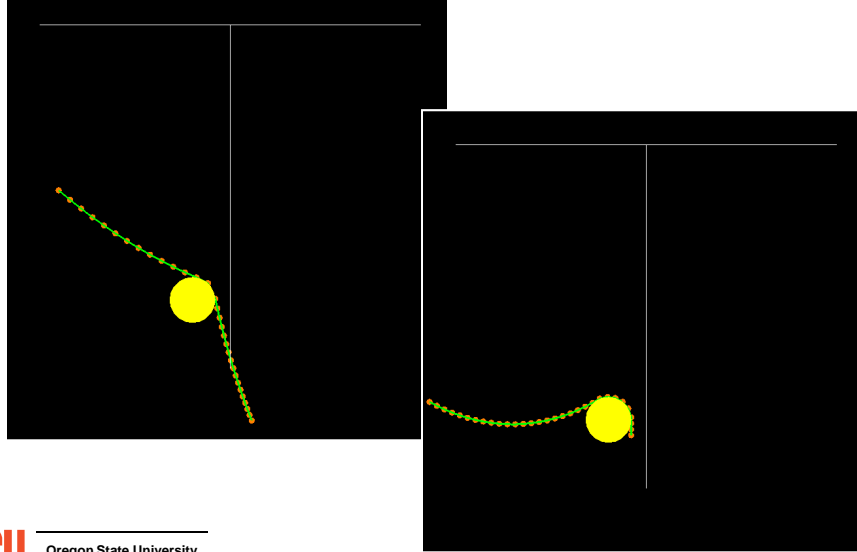
### Animating using the Physics of a Mesh of Springs



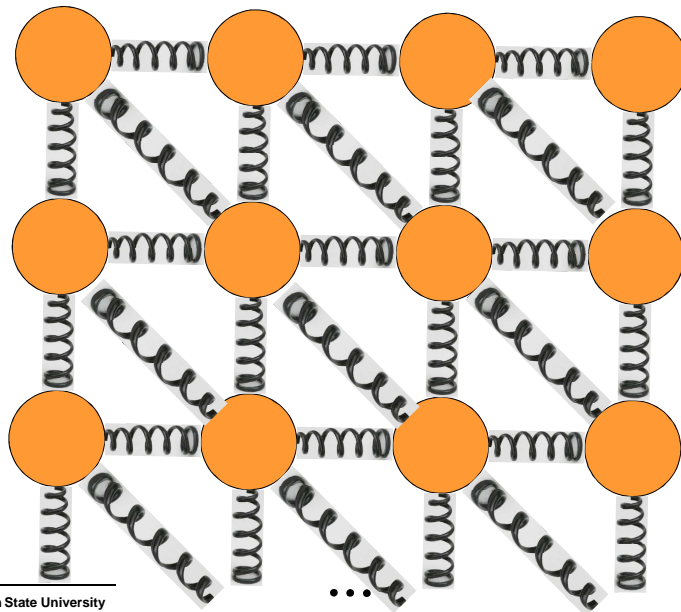
### Simulating a Bouncy String



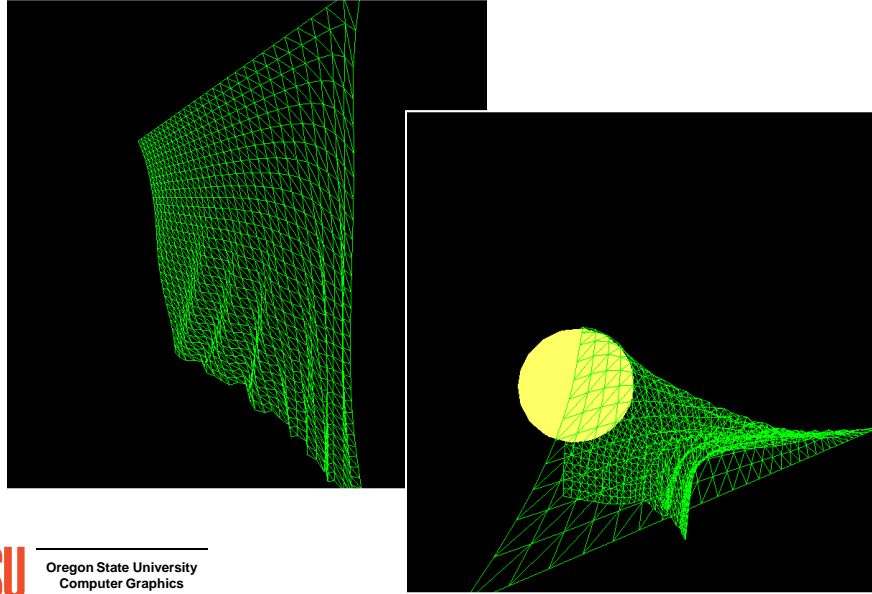
### Placing a Physical Barrier in the Scene



### Animating Cloth



### Cloth Examples



### Cloth Examples



David Breen, Donald House, Michael Wozny: *Predicting the Drape of Woven Cloth Using Interacting Particles*

### Cloth Examples



MiraLab, University of Geneva



### Motion Capture

NaturalPoint



Polhemus

Polhemus



MocapLab





# Where to Find More Information about Computer Graphics and Related Topics

Mike Bailey  
Oregon State University

## 1. References

### 1.1 General Computer Graphics

SIGGRAPH Online Bibliography Database:

<http://www.siggraph.org/publications/bibliography>

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*Journal of Graphics, GPU, and Game Tools*: published by A.K. Peters  
(<http://www.akpeters.com>, 617-235-2210)

*Game Developer*: published by CMP Media  
(<http://www.gdmag.com>, 415-905-2200)  
(Once a year publishes the *Game Career Guide*.)

*Computer Graphics Quarterly*: published by ACM SIGGRAPH  
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*Computers & Graphics*, published by Elsevier  
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*Transactions on Visualization and Computer Graphics*: published by IEEE  
(<http://www.computer.org>, 714-821-8380)

*Transactions on Graphics*: published by ACM  
(<http://www.acm.org>, 212-869-7440)

*Cinefex*  
(<http://www.cinefex.com>, 951-781-1917)

### 3. Professional organizations

ACM .....Association for Computing Machinery  
<http://www.acm.org>  
212-869-7440

SIGGRAPH .....ACM Special Interest Group on Computer Graphics  
<http://www.siggraph.org>  
212-869-7440

SIGCHI .....ACM Special Interest Group on Computer-Human Interfaces  
<http://www.acm.org/sigchi>  
212-869-7440

SIGHPC .....ACM Special Interest Group on High-Performance Computing  
<http://sighpc.org>  
212-869-7440

EuroGraphics ...European Association for Computer Graphics  
<http://www.eg.org>  
Fax: +41-22-757-0318

IEEE.....Institute of Electrical and Electronic Engineers



<http://www.computer.org>  
202-371-0101

IGDA .....International Game Developers Association  
<http://www.igda.org>  
856-423-2990

NAB .....National Association of Broadcasters  
<http://www.nab.org>  
800-521-8624

ASME .....American Society of Mechanical Engineers  
<http://www.asme.org>  
800-THE-ASME

#### 4. Upcoming Conferences

##### ACM SIGGRAPH:

2012: Los Angeles, CA – August 5-9  
2013: Anaheim, CA – July 21-25  
2014: Vancouver, BC – August 10-14  
<http://www.siggraph.org/s2012>  
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##### ACM SIGGRAPH Asia:

2012: Singapore – November 28-December 1  
<http://www.siggraph.org/asia2012>

##### ACM SIGCHI:

2013: Paris, France – April 27 - May 2  
<http://www.sigchi.org>

##### SC: International Conference for High Performance Computing, Networking, Storage, and Analysis:

2012: Salt Lake City, UT -- November 10-16  
<http://www.supercomputing.org>

##### IEEE Visualization:

2012: Seattle, WA – October 14-19  
<http://visweek.org>

##### Eurographics

2013: Girona, Spain – May 6-10  
<http://eg2013.udg.edu/>

##### Game Developers Conference:

2013: San Francisco, CA – March 25 - 29  
<http://www.gdconf.com>

##### E3Expo

2012: Los Angeles, CA – June 7-9

<http://www.e3expo.com>

PAX (Penny Arcade Expo)

2012: Seattle, WA – August 31 – September 2

<http://www.paxsite.com>

ASME International Design Engineering Technical Conferences (includes the Computers and Information in Engineering conference):

2012: Chicago, IL – August 12-15

<http://www.asmeconferences.org/idetc2012>

National Association of Broadcasters (NAB):

2013: Las Vegas, NV – April 6-11

<http://www.nab.org>

## **5. Graphics Performance Characterization**

The GPC web site tabulates graphics display speeds for a variety of vendors' workstation products. To get the information, visit:

<http://www.spec.org/benchmarks.html#gwpg>