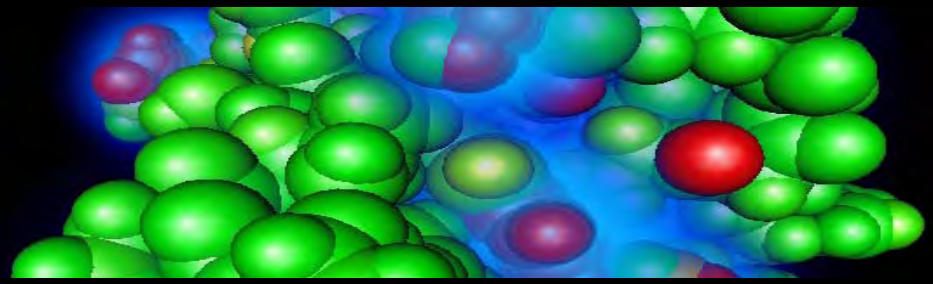


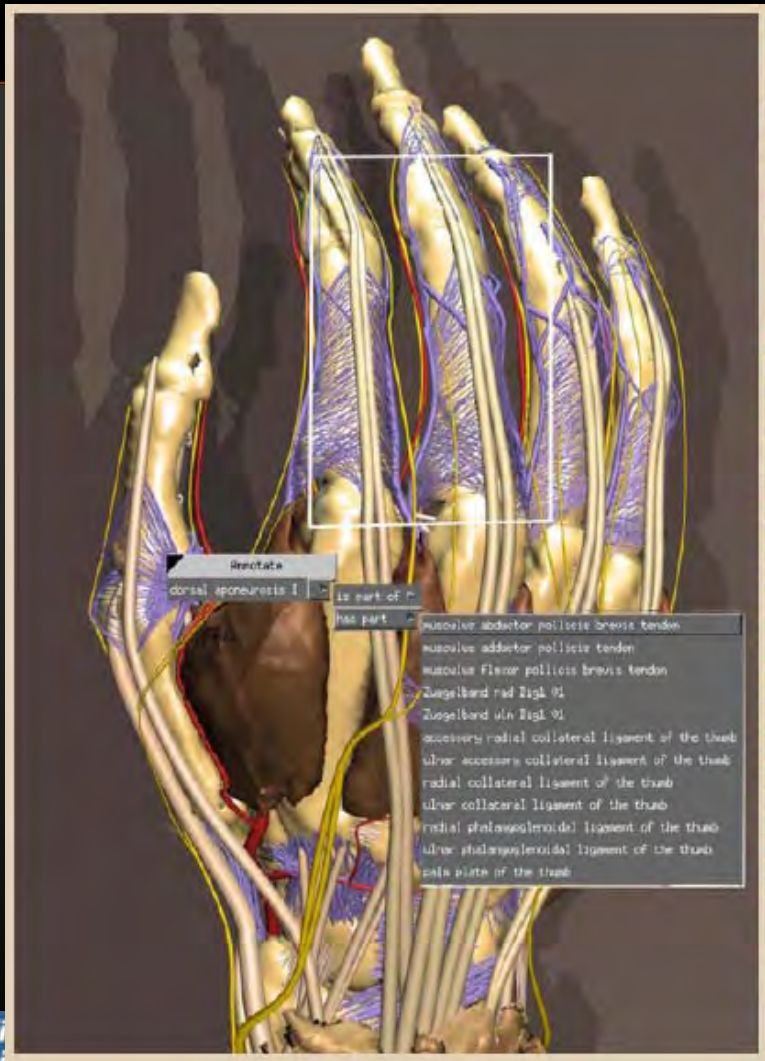
Scientific Visualization: The Modern Oscilloscope for "Seeing the Unseeable"

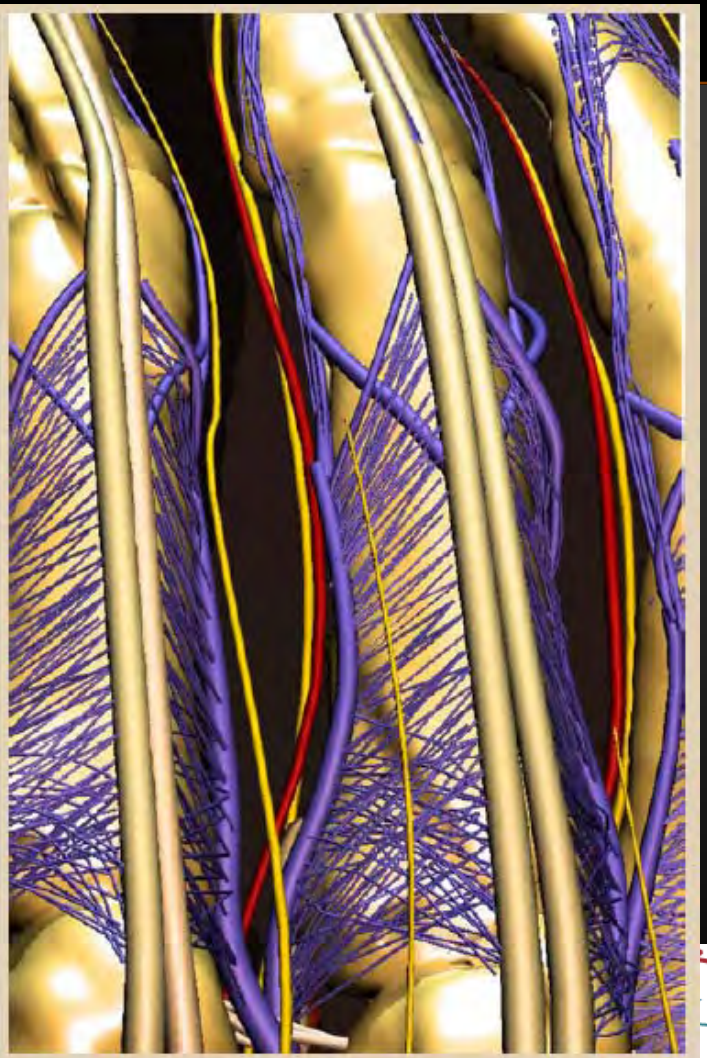
E. Wes Bethel

Lawrence Berkeley National Laboratory

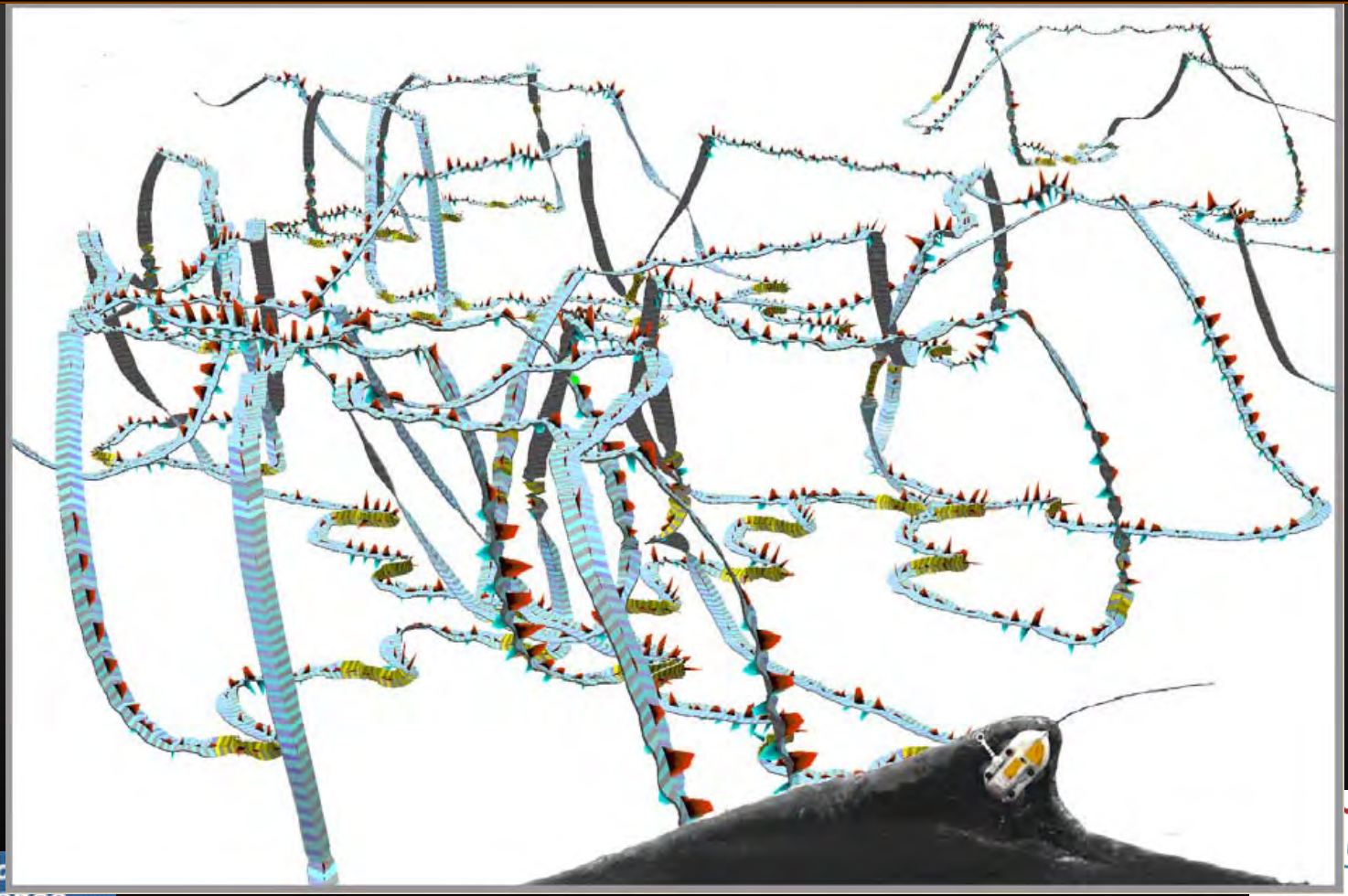
24 June 2008

Seeing the Unseeable - Anatomy

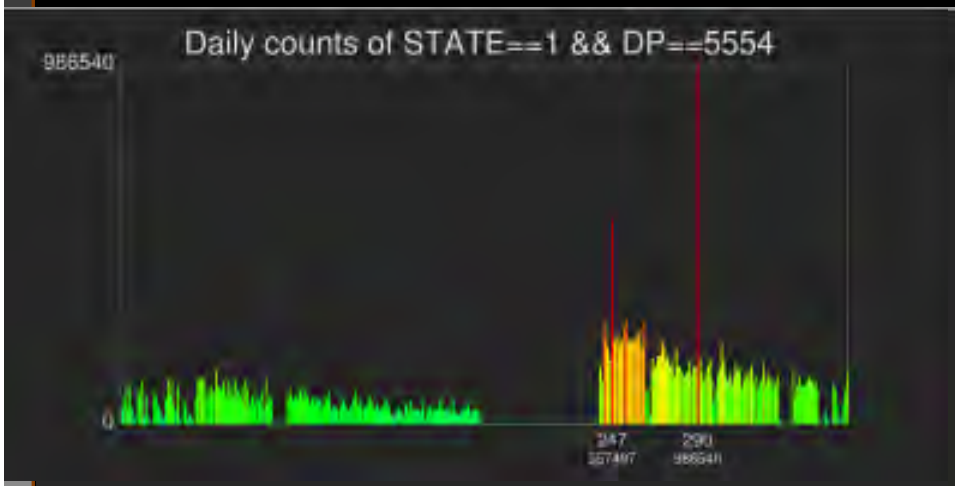


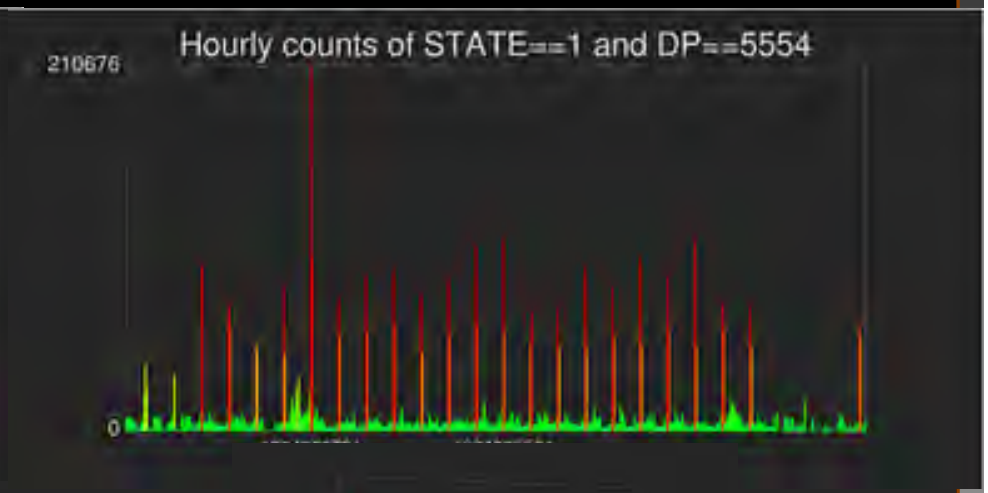


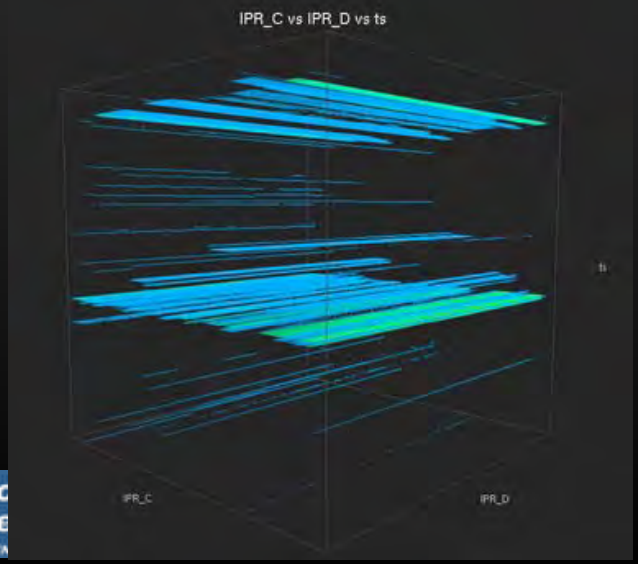
Seeing the Unseeable – Whale Swim Path

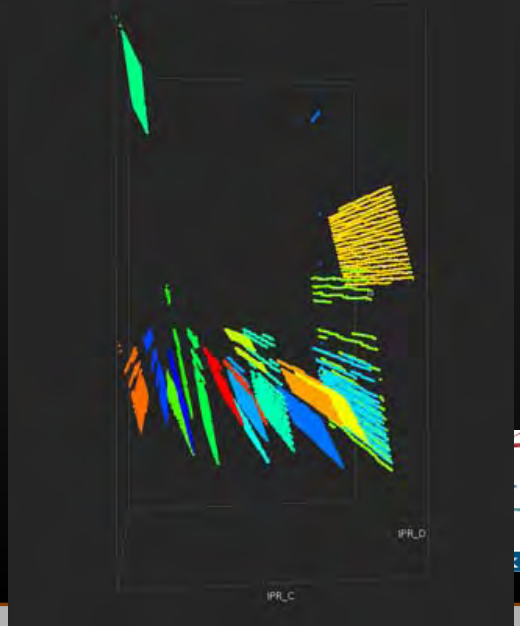


Seeing the Unseeable – Cyberattack

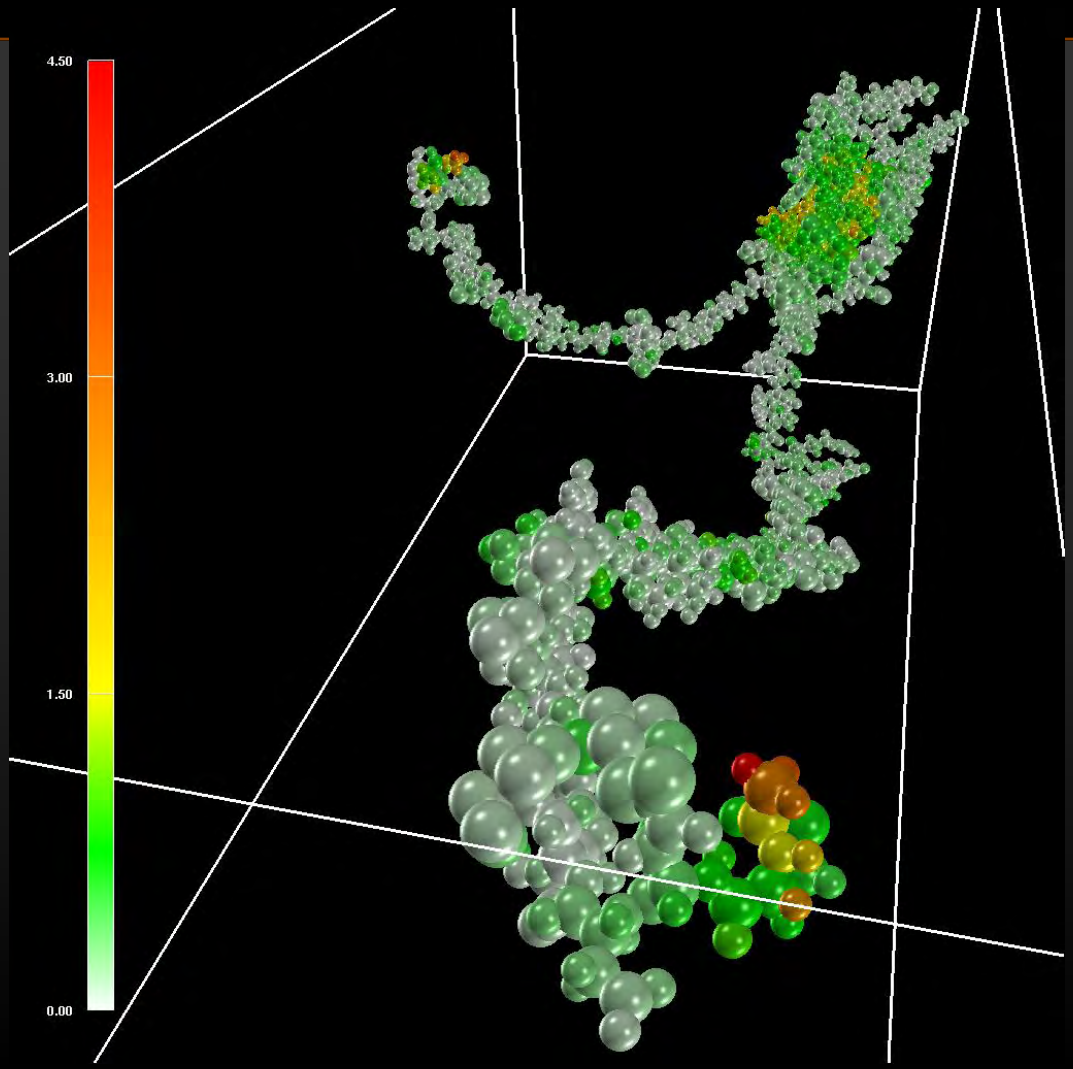








Seeing the Unseeable – Protein Folding



Today's Discussion Topics

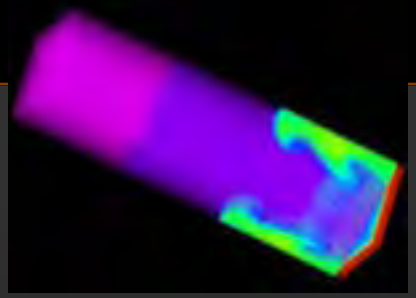
- **Objective: familiarize you with an interesting, problem-rich science domain.**
- **How?**
  - Intro to CG and Visualization
  - Ray Tracing and the Shading Equation.
  - Graphics APIs and the Graphics Pipeline.
  - Visualization: Examples, Challenges, Future.

Office of Science
U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

Introduction to CG and Visualization

What is Computer Graphics and Visualization?



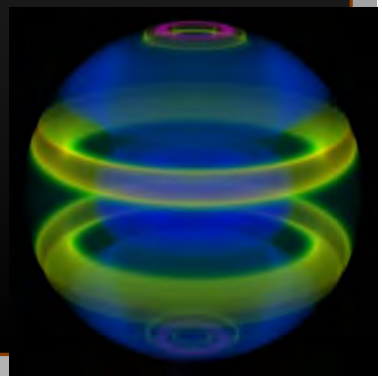
- **Graphics:**
  - Transformation of data into images.
  - Pen plotters (60's, 70's), storage tubes (70's), electrostatic plotters and raster displays (80's and beyond).
- **Visualization:**
  - Transformation of data into images.
- **Computer Graphics and Visualization are an alloy comprised of:**
  - Computer science, cognitive science, mathematics, industrial engineering, etc.

Office of Science
U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

What are Computer Graphics and Visualization?

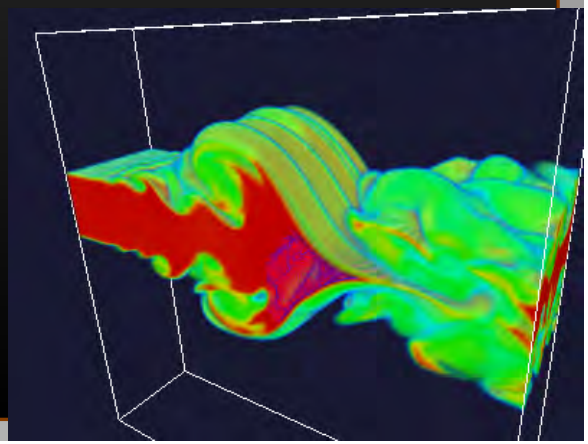
- **If both graphics and visualization are "transformation of data into images," what is the difference?**
  - Graphics tends to focus on the process of rendering
    - Transformation of primitives into pixels
    - Shading, photorealism, etc.
  - Visualization tends to focus on the mapping of abstract data (e.g., velocity) into constructs that can be rendered (e.g., triangles).
  - The distinction occasionally becomes blurry.



Office of Science
U.S. DEPARTMENT OF ENERGY

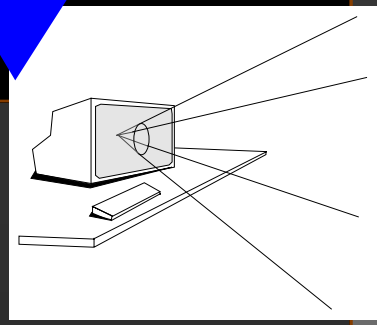
Why Computer Graphics and Visualization?

- The visual cortex and associated machinery occupy more than half our brains – ***we are innately visual creatures.***
- Vision is our principal means for understanding and interacting with the world.
- The best connection between humans and computers is through the high-bandwidth connection of our highly evolved visual system.

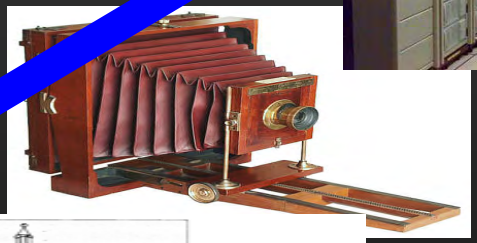


Office of Science
U.S. DEPARTMENT OF ENERGY

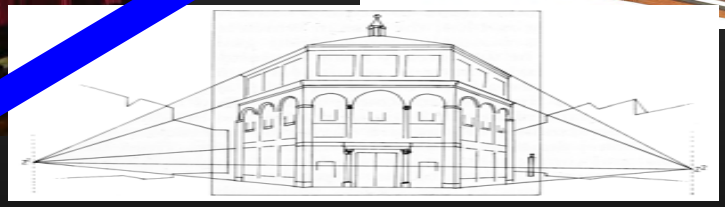
The Path Towards Graphics and Visualization



Computers



Photography



Geometry,
Perspective and models

Art and painting

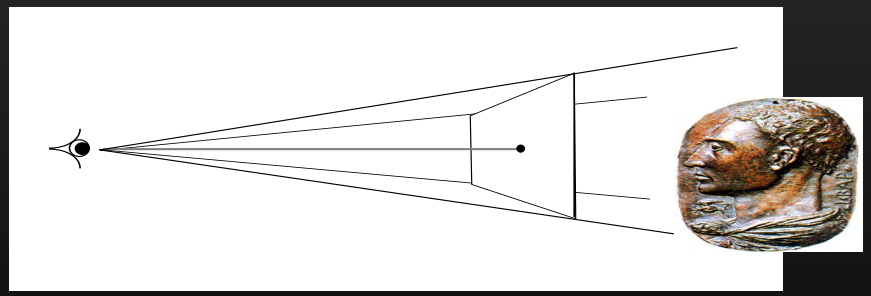
The Invention of Drawing

- **Painting based on mythical tale as told by Pliny the Elder: Corinthian man traces shadow of departing lover. Detail from** The Invention of Drawing**, 1830: Karl Friedrich Schinkle (Mitchell p.1)**

Understanding Perspective

Incorrect perspective, Giotto, c.1295-1300

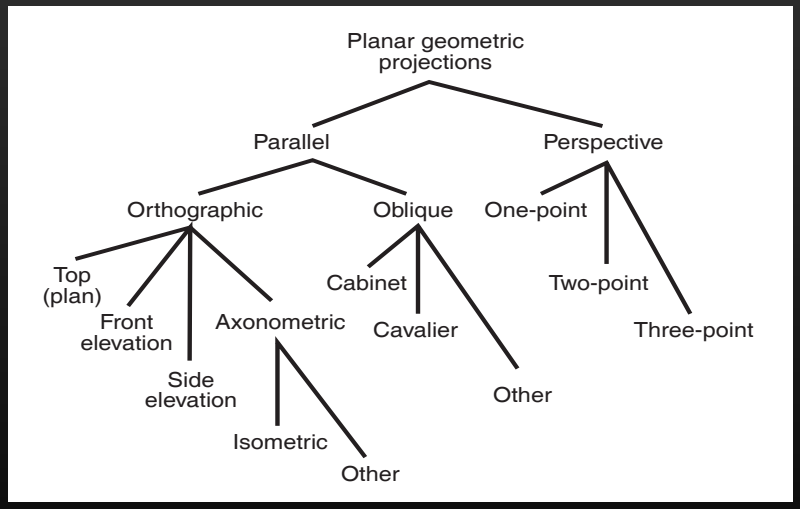
Correct perspective,
Last Supper, Da Vinci, 1495

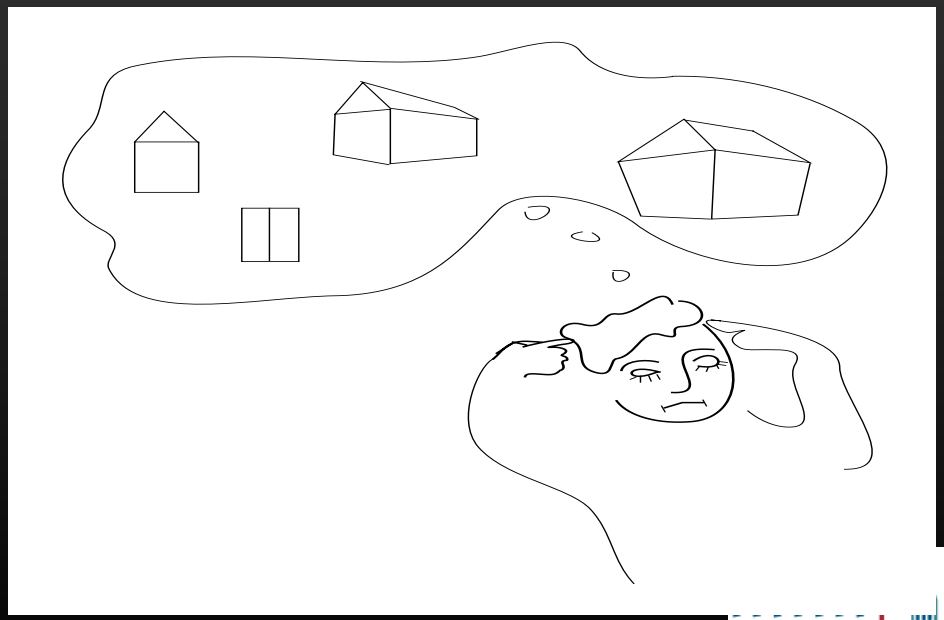


Alberti's 1435 treatise, *Della Pittura*, explained perspective for the first time

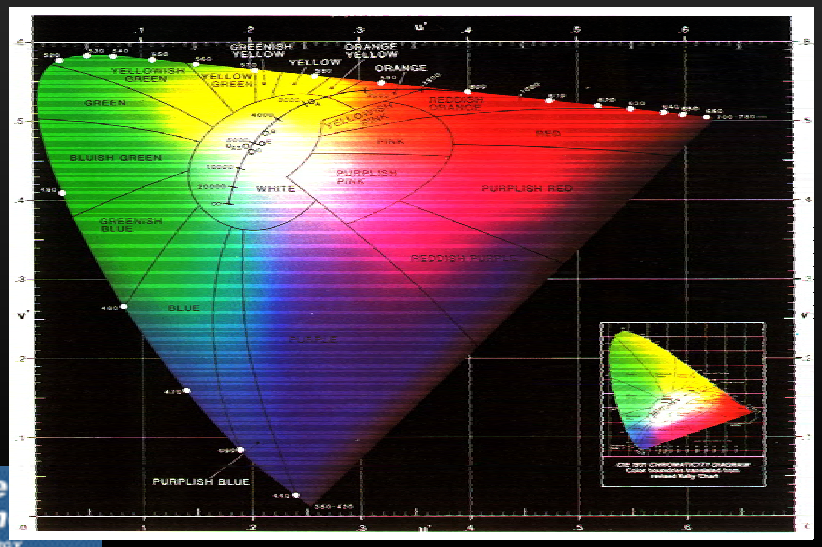
Projections

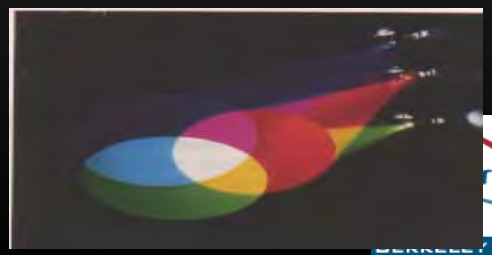
Ender, c. 1855
(detail of clockwork)





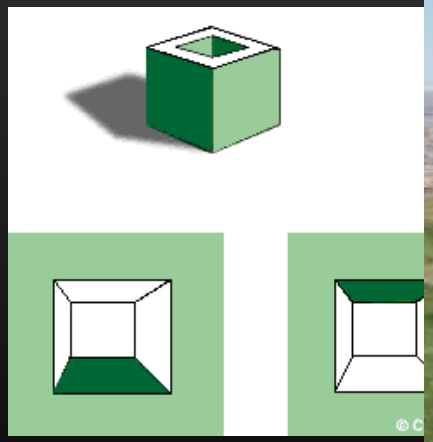
Color and Perception

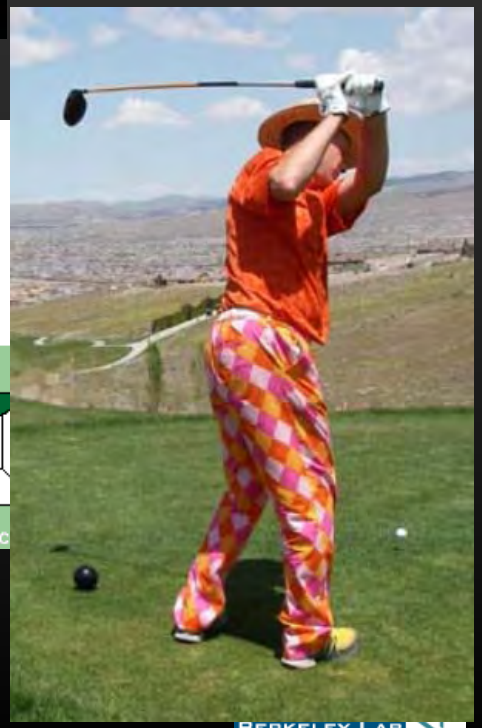




Uses of Color

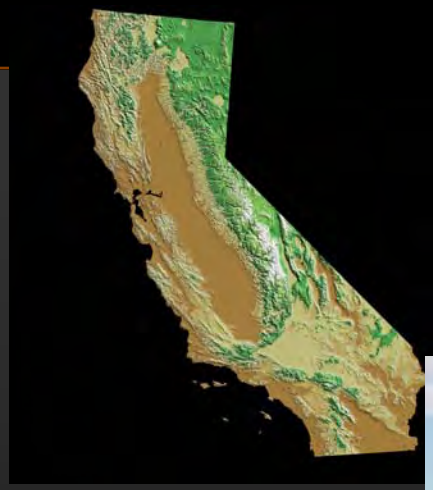
- To label, to indicate set membership.
- To indicate a value or magnitude.
- To represent reality.
- To decorate.

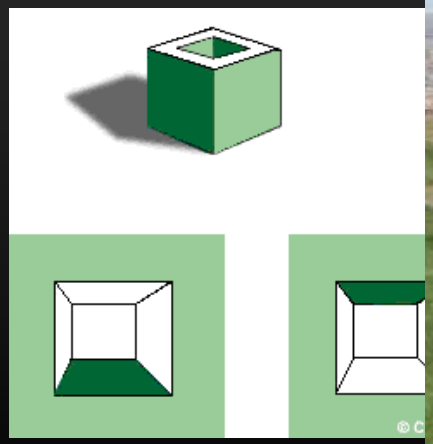


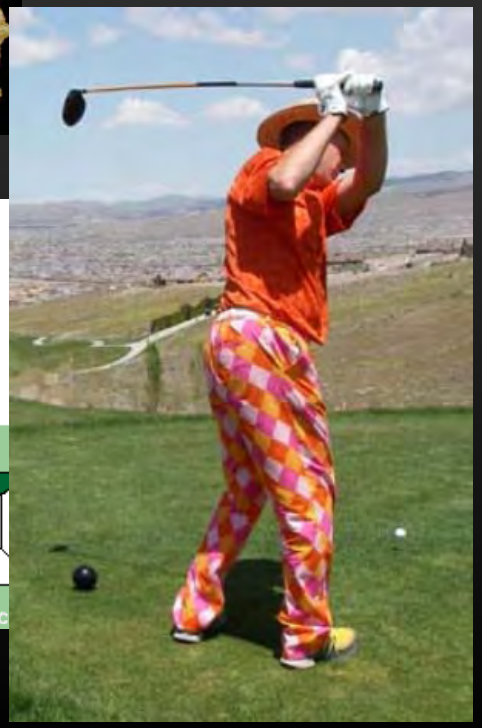


Graphics vs. Visualization

- Top row: information encoded/presented using color (vis).
- Bottom row: color used decoratively or to represent reality.



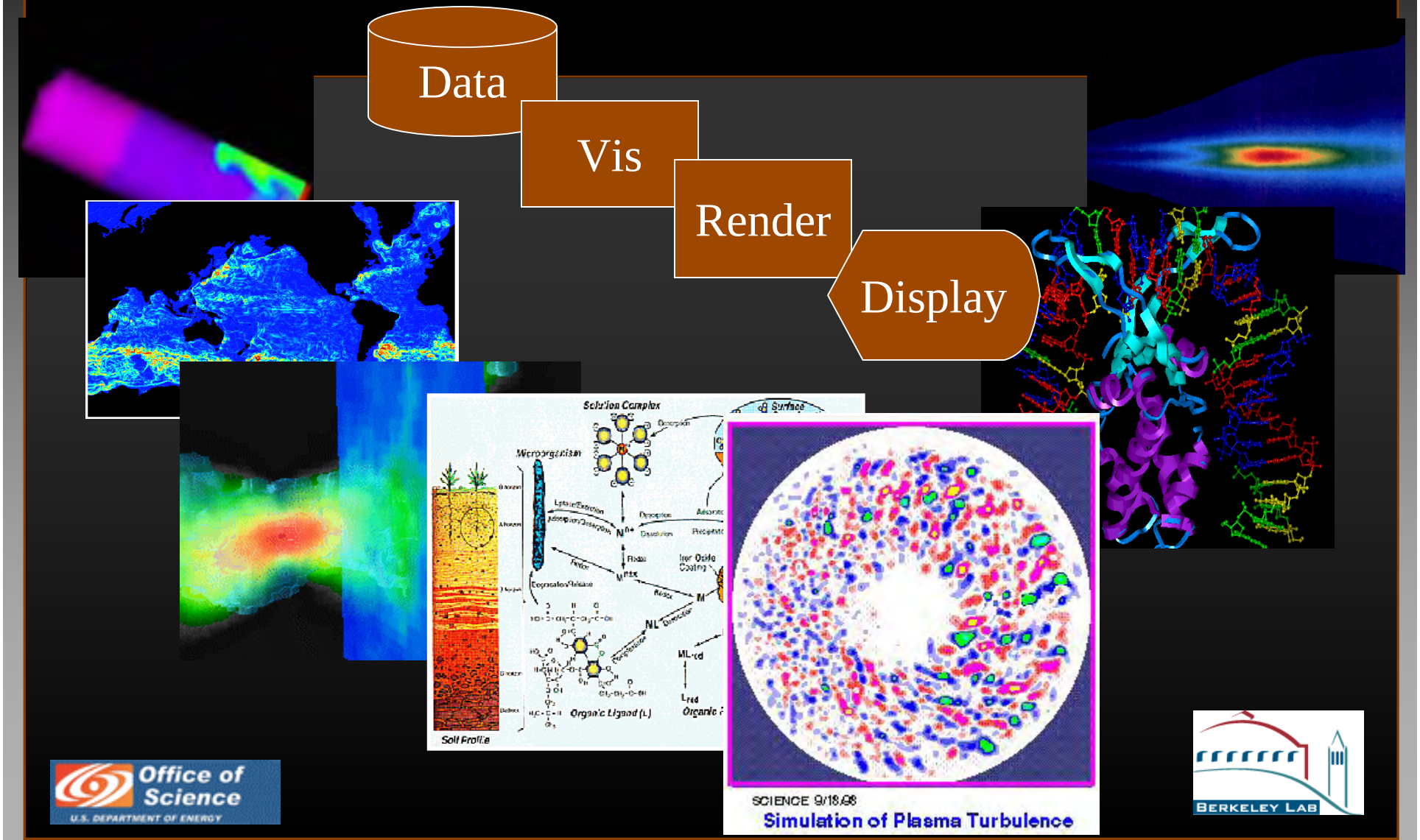




Office of Science
U.S. DEPARTMENT OF ENERGY

The Quest for Photorealism

Visualization – Enable Insight

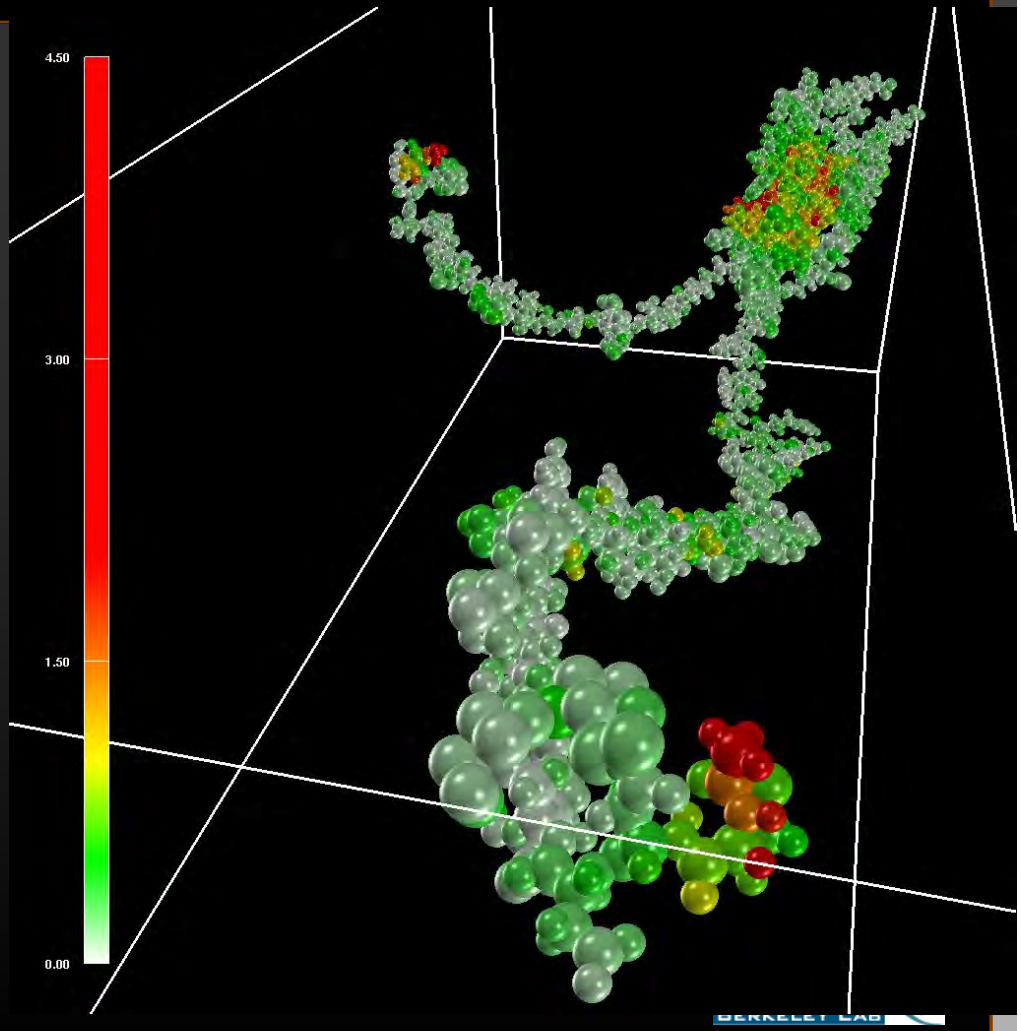


Office of Science
U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

Visualization – Good Use of Color

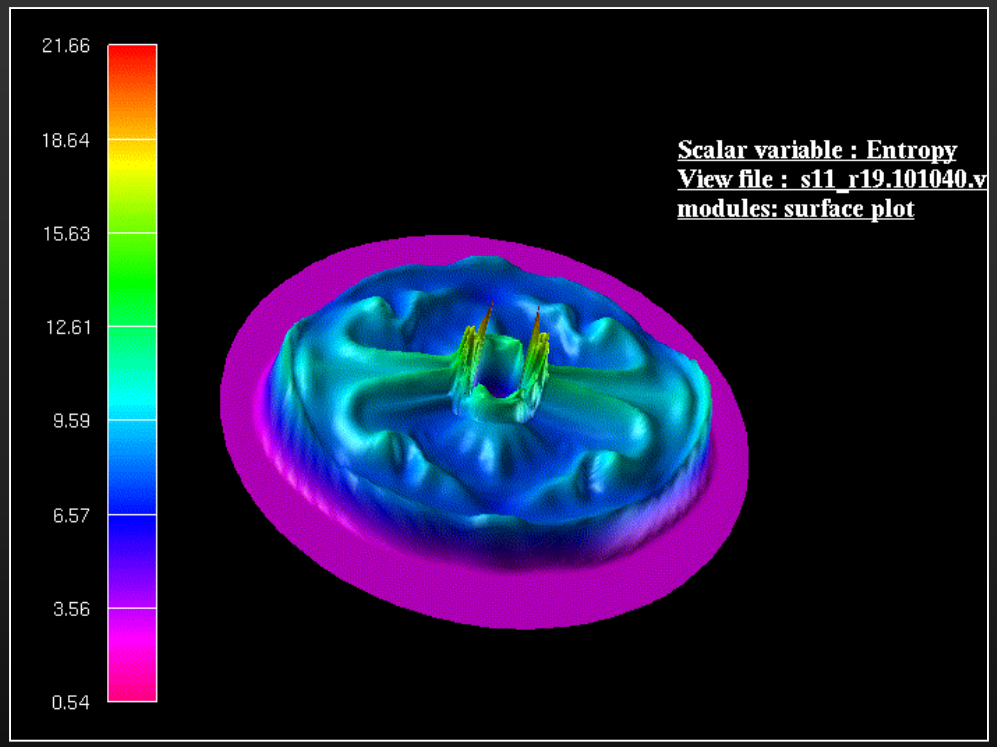
- Use “background colors from nature” for background elements.
- Use colors that produce a strong, innate biological response for features of interest.



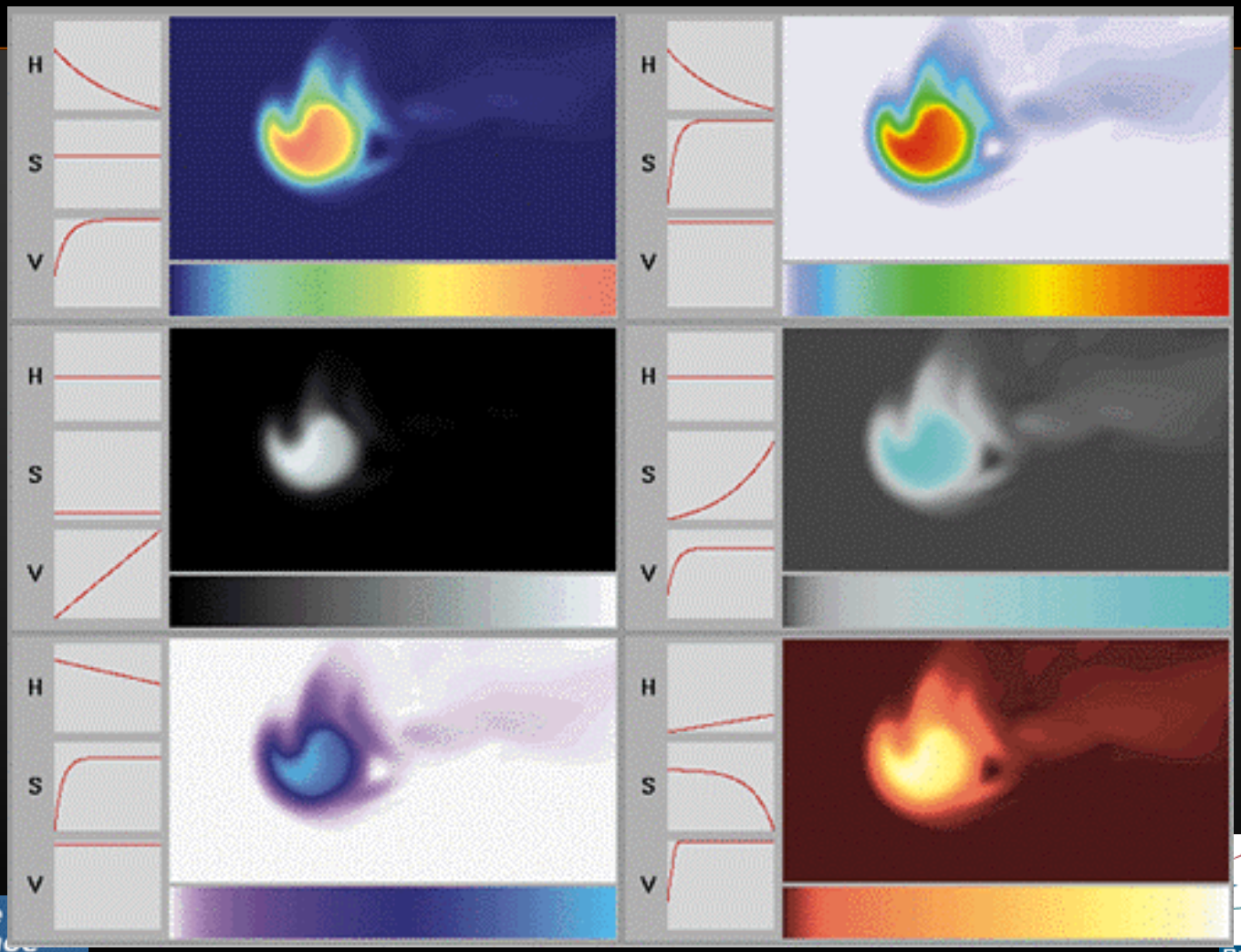
Office of Science
U.S. DEPARTMENT OF ENERGY

Visualization – Bad Use of Color

- The “hue ramp” color table
- Induces 1+1=3 effect: eyes perceive a contour that doesn’t really exist
- What are “important” aspects of a given visualization?



Visualization – Use of Color



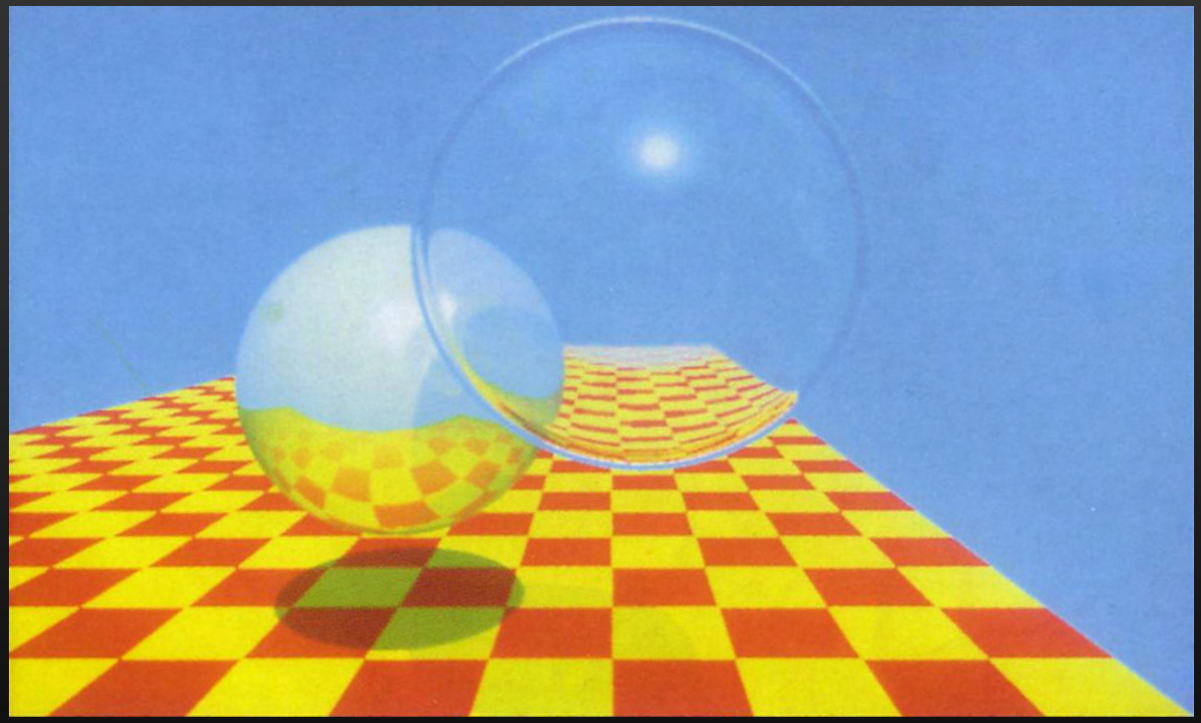
Central Problem in Computer Graphics: The Shading Equation

- **Given a collection of objects and scene parameters, compute the color of each pixel on the screen.**
- **Two broad approaches:**
  - Object order: for each triangle (object), compute which screen pixels each one covers, compute color for all covered pixels.
  - Image order: for each image pixel, compute which objects contribute to the pixel color.

Office of Science
U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

Ray Tracing and the Rendering Equation – Image-Order CG



Ray Tracing

- An Improved Illumination Model for Shaded Display, Whitted, SIGGRAPH 1980.
- The role of the illumination model is to determine how much light is reflected to the viewer from a visible point on a surface as a function of light source direction and strength, viewer position, surface orientation, and surface properties.

Phong's Illumination Equation (Not Ray Tracing – Yet)

$$I = I_a + k_d \sum_{j=1}^{j=ls} (\bar{N} \cdot \bar{L}_j) + k_s \sum_{j=1}^{j=ls} (\bar{N} \cdot \bar{L}'_j)^n, \qquad (1)$$

where

I = the reflected intensity,
I_a = reflection due to ambient light,
k_d = diffuse reflection constant,
$\bar{N}$ = unit surface normal,
$\bar{L}_j$ = the vector in the direction of the jth light source,
k_s = the specular reflection coefficient,
$\bar{L}'_j$ = the vector in the direction halfway between the viewer and the jth light source,
n = an exponent that depends on the glossiness of the surface.

Whitted's Improvement (Ray Tracing)

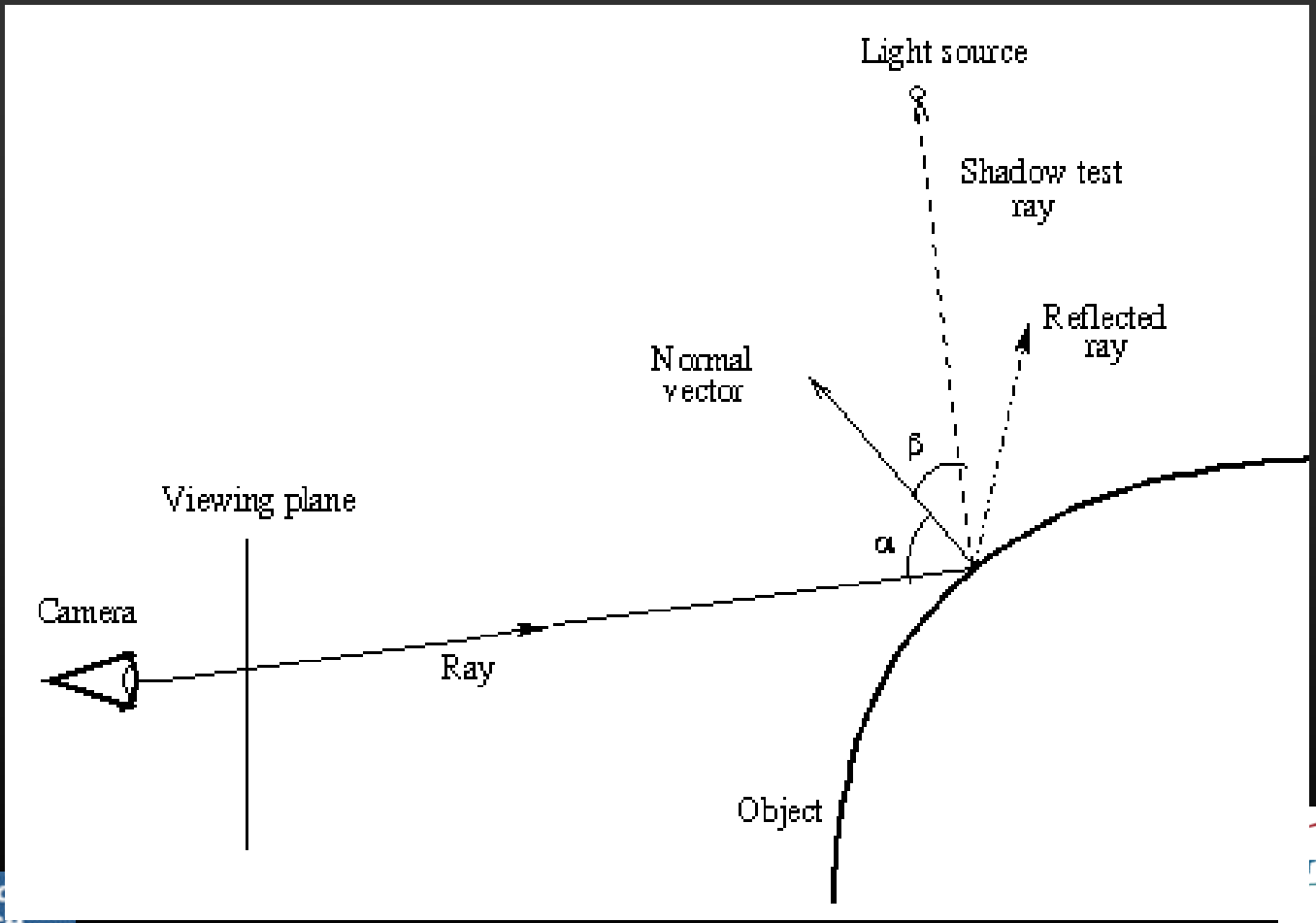
- Retain diffuse term (computationally overwhelming to account for scene objects as light sources) from Phong Model.
- "Refine" specular term, add transmissive term.

$$I = I_a + k_d \sum_{j=1}^{j=ls} (\bar{N} \cdot \bar{L}_j) + k_s S + k_t T, \qquad (2)$$

where

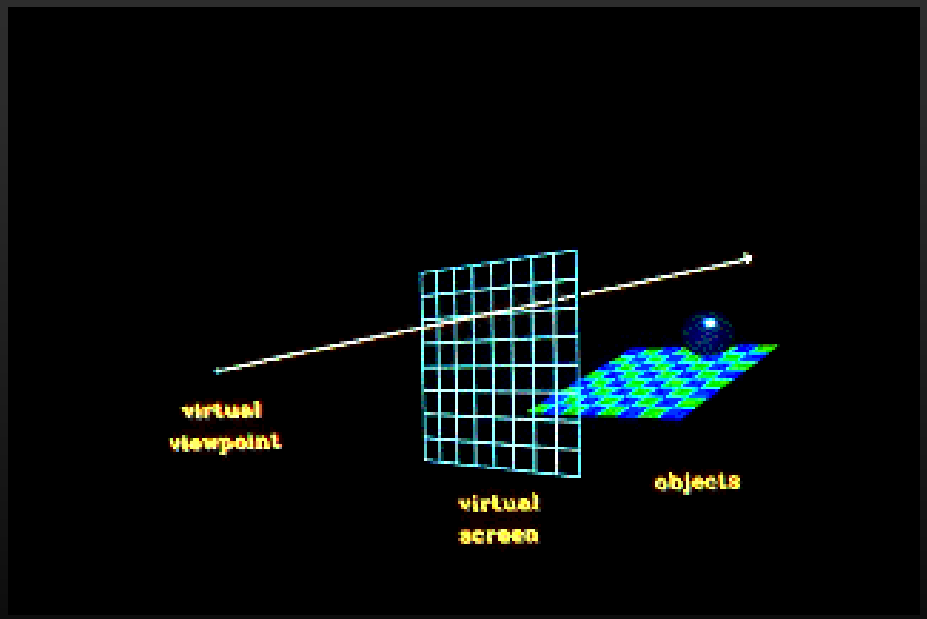
S = the intensity of light incident from the $\bar{R}$ direction,
k_t = the transmission coefficient,
T = the intensity of light from the $\bar{P}$ direction.

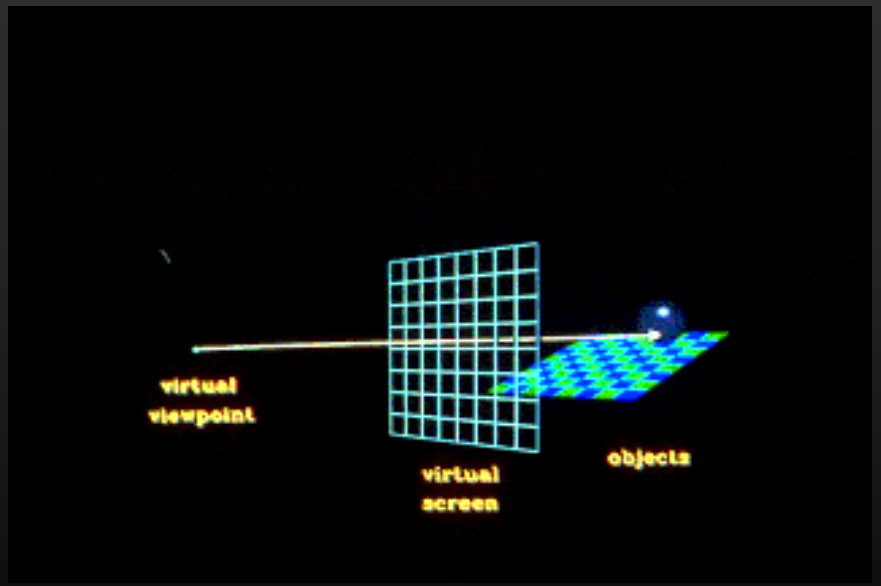
Whitted's Improvement, ctd.



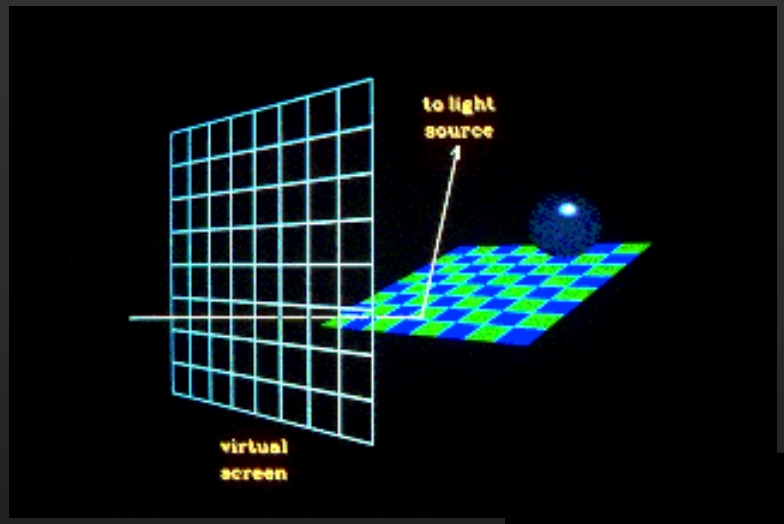
Example Rays – Simple Intersections

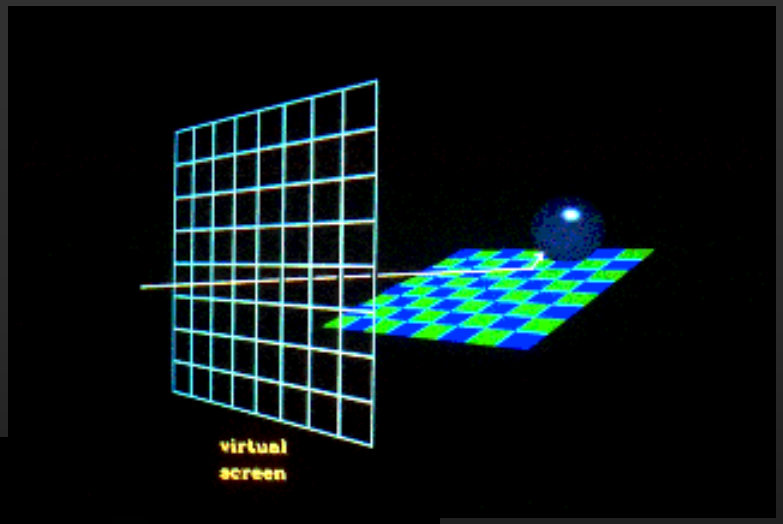
- (See http://www.siggraph.org/education/materials/HyperGraph/raytrace/rtrace1.htm)

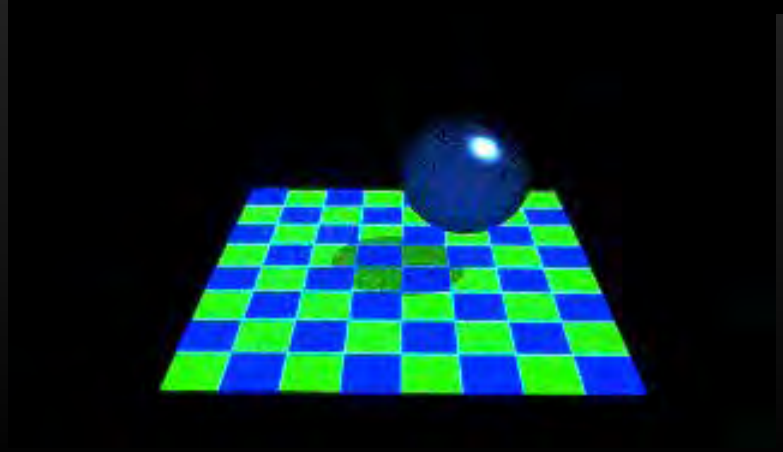




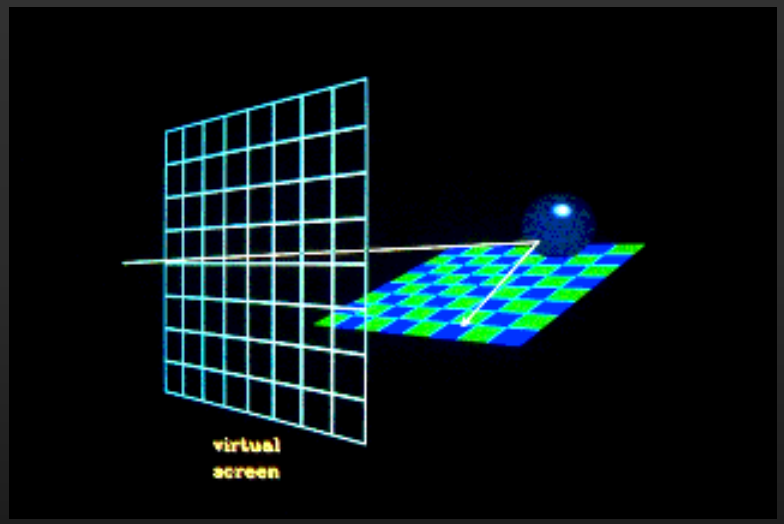
Shadow Rays

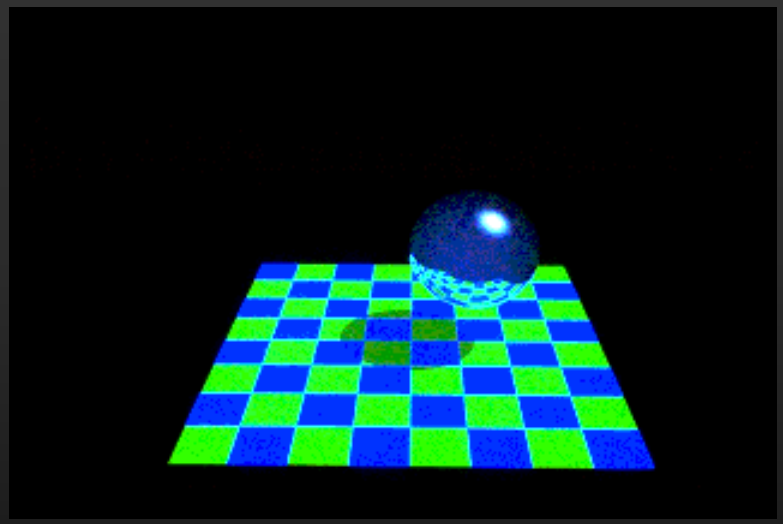






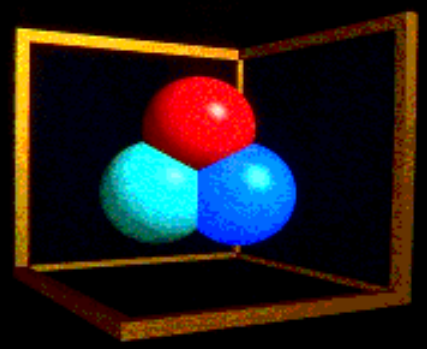
Reflected Rays



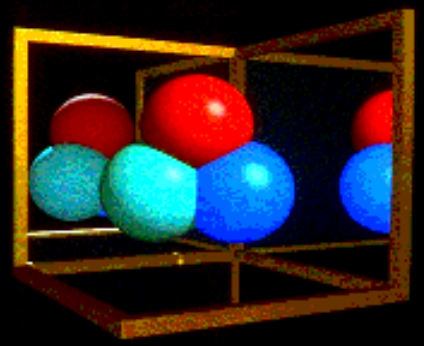


More Reflected Rays

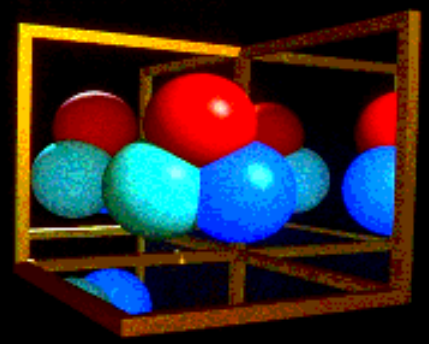
Zero bounces



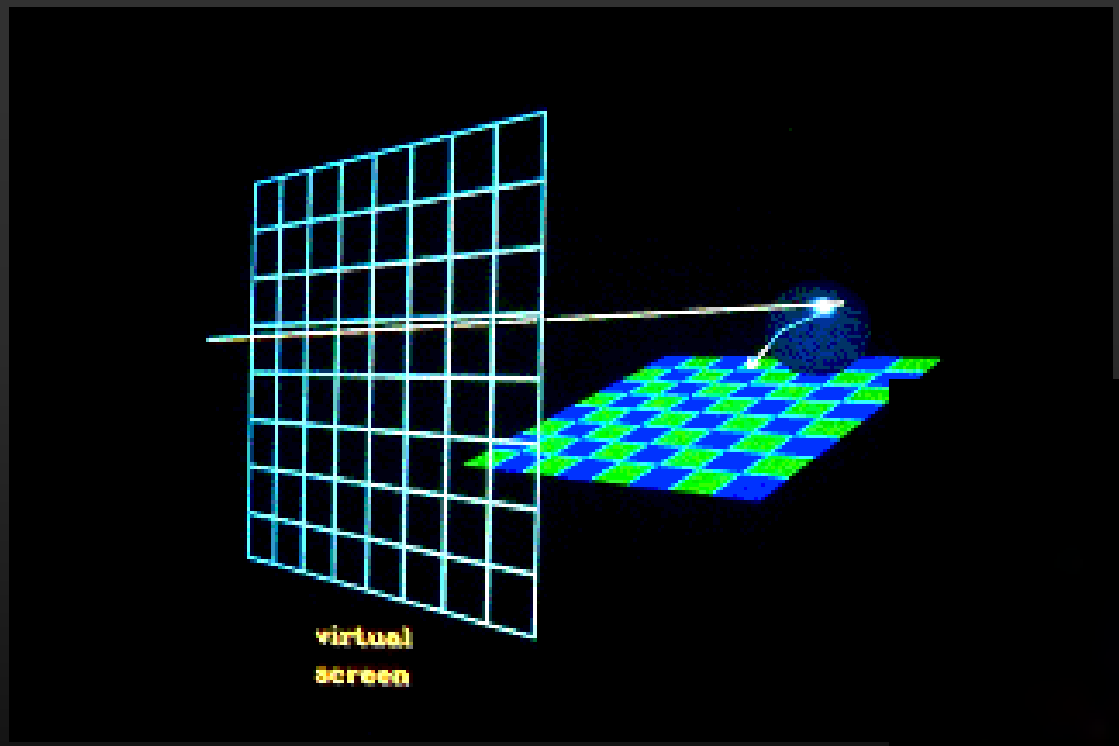
One bounce

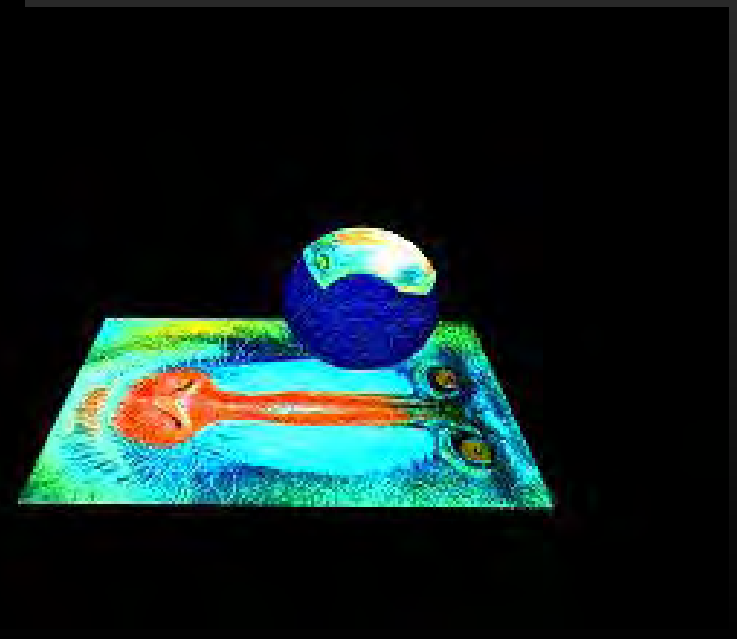


Two bounces



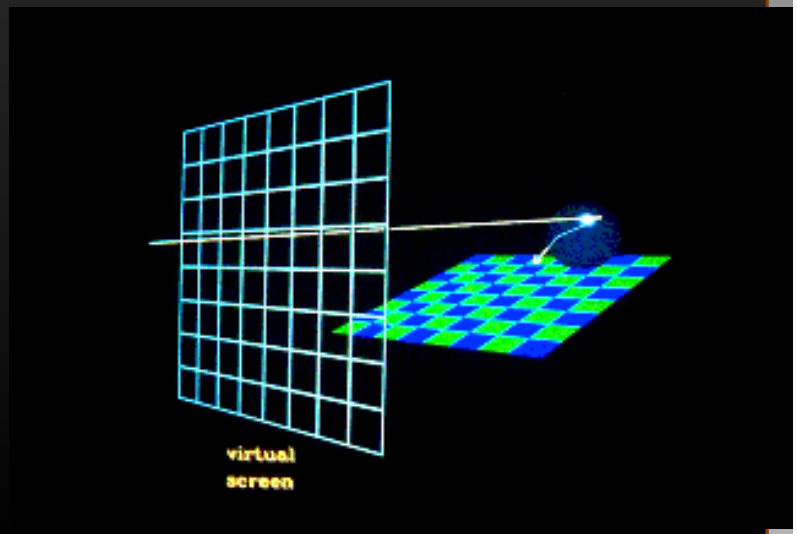
Refracted Rays





Parallelizing Ray Tracing

- **Computation of color at each pixel is relatively independent.**
  - Image-order parallelization (data parallelism).
  - Requires (potential) duplication of the scene on each node.
- **Challenges**
  - Load balancing.
  - Data distribution.



Office of Science
U.S. DEPARTMENT OF ENERGY

Graphics APIs and the Graphics Pipeline – Object-Order CG

(Images from Doom3)

What is a Graphics API?

- **Declarative: what, not how.**
  - Scene description: viewer here, trees there, lights just so.
  - Can use a variety of rendering systems: Renderman, POVRay, Performer, OpenRM Scene Graph, etc.
- **Imperative: how, not what.**
  - A series of draw commands.
  - OpenGL, DirectX, D3D, Xlib, etc.

OpenGL

- **Industry-standard graphics API.**
  - Supported on all major platforms.
  - Relationship between OpenGL and window system.
- **Basic primitives: lines, triangles, points.**
  - Higher level primitives (NURBS, quadrics) built using fundamental geometry.
- **Phong lighting model, but Gouroud shading.**

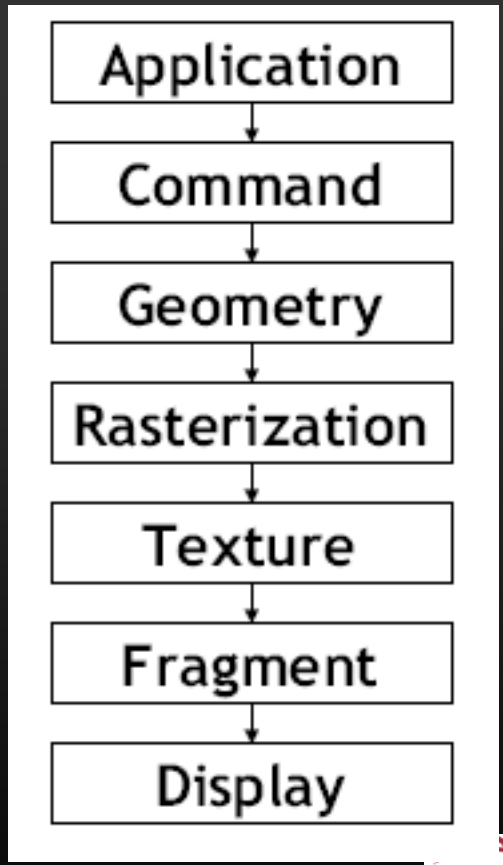
Example OpenGL Code

```
glBegin(GL_POLYGON);
  glColor(RED);
  glVertex3i(0,0,0);
  glVertex3i(1,0,0);
  glVertex3i(0,1,0);
glEnd()
```

```
glBegin(GL_POLYGON);
  glColor(RED);
  glVertex3i(0,0,0);
  glColor(BLUE);
  glVertex3i(1,0,0);
  glColor(BLUE);
  glVertex3i(0,1,0);
glEnd()
```

General: Graphics Pipeline

- Application issues “draw” commands.
- Each command dispatches objects (e.g., geometry).
- Each object is scan-converted into pixel fragments.
- Each fragment is textured, etc.
- And finally displayed.

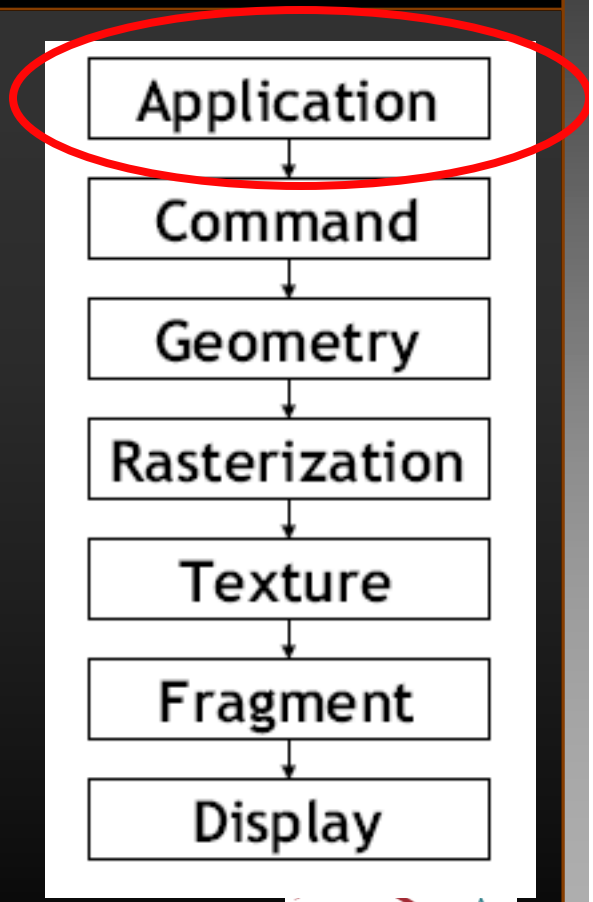


Office of Science
U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

The Graphics Application

- **Application**
  - Simulation
  - Visualization
  - Database Traversal
  - User interaction (games!)

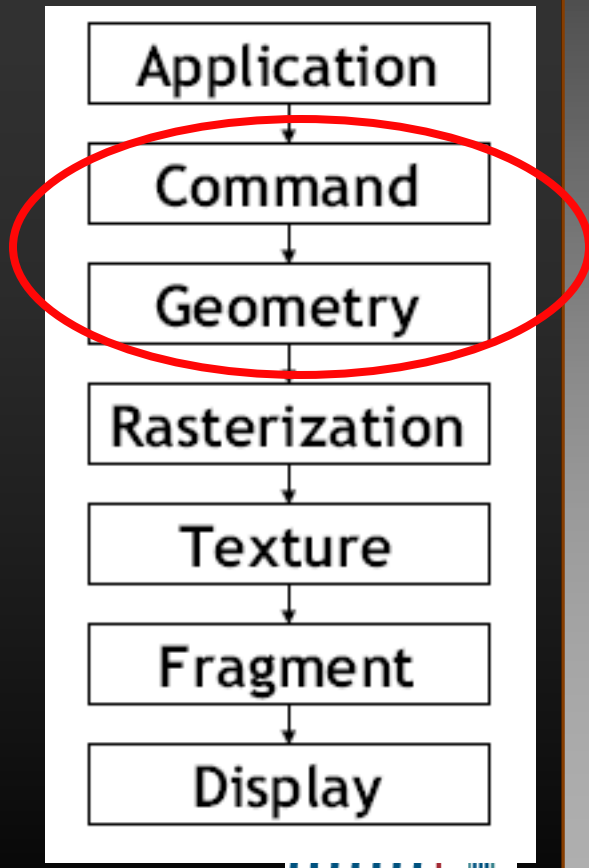


Office of Science
U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

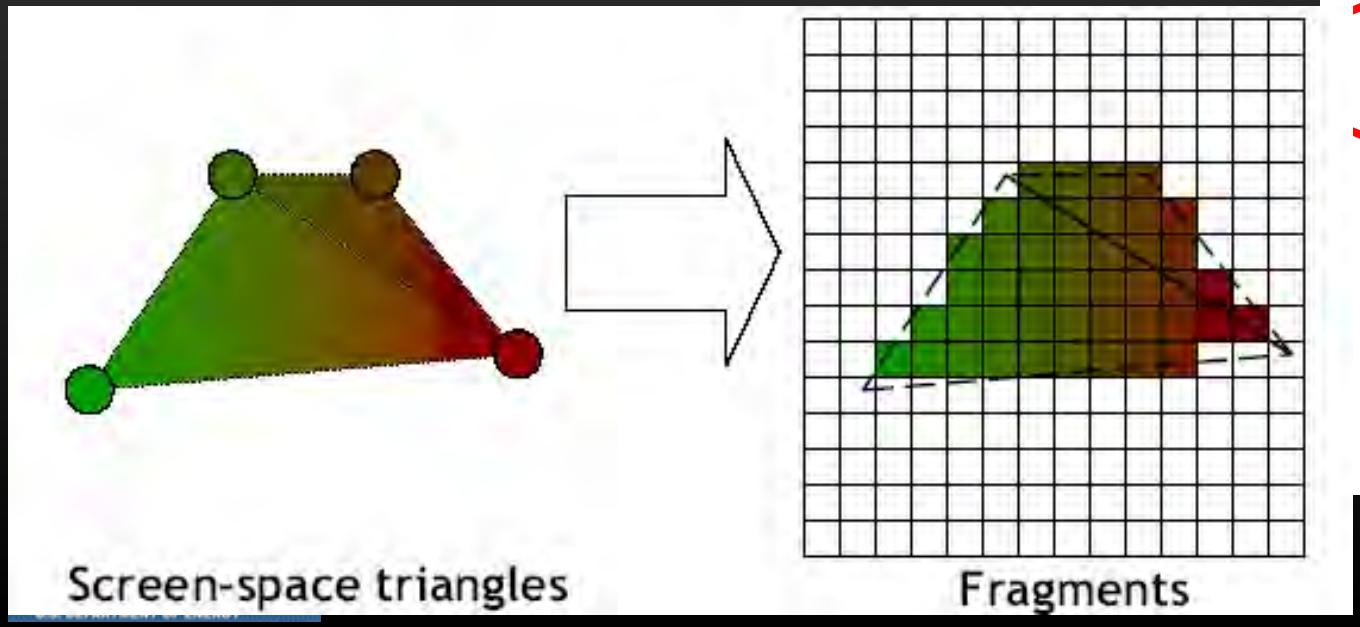
Commands and Geometry

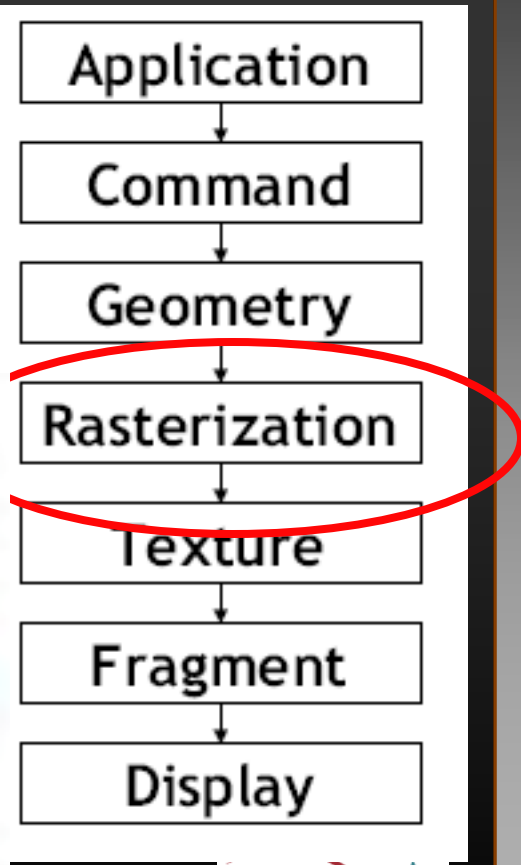
- **Command**
  - (What kinds of commands?)
  - Buffering, parsing.
- **Geometry**
  - Transform, light.
  - Automatic operations.
  - Culling, clipping.



Rasterization

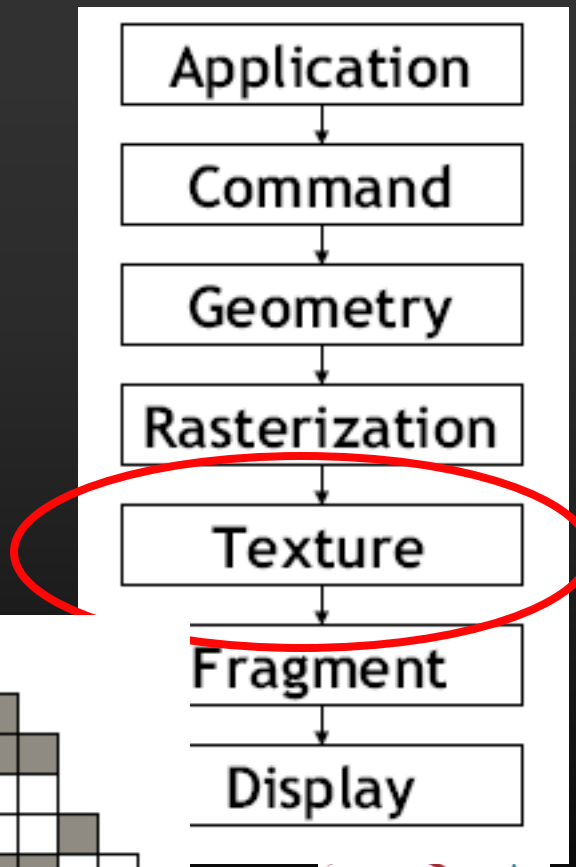
- Setup, sampling (produces "fragments", interpolation (color, depth).

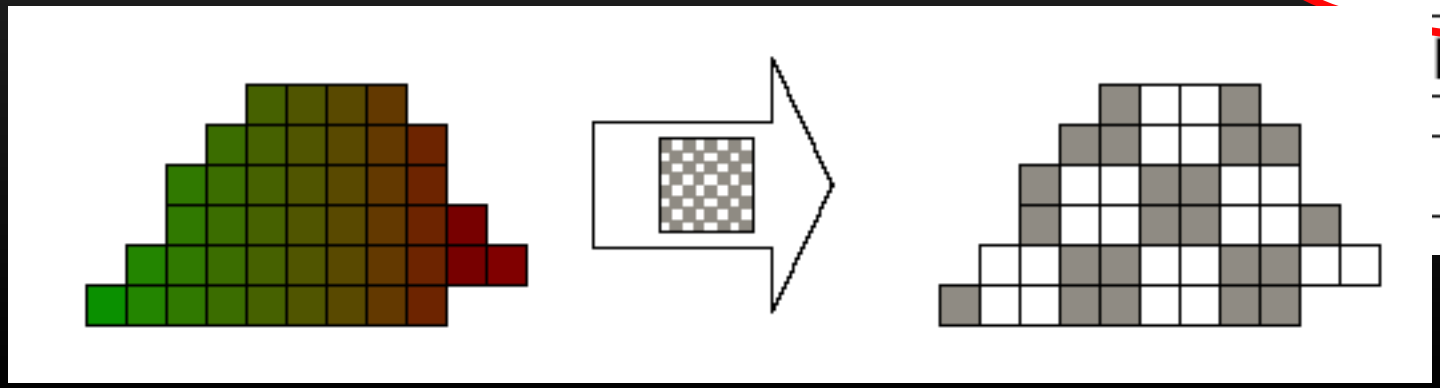




Texturing

- Texture transformation and projection.
- Texture address calculation.
- Texture filtering.





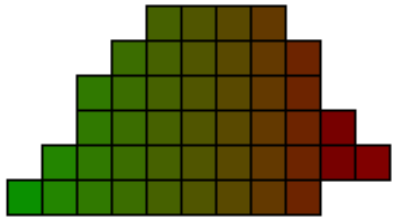
Fragment Operations

Texture combiners and fog

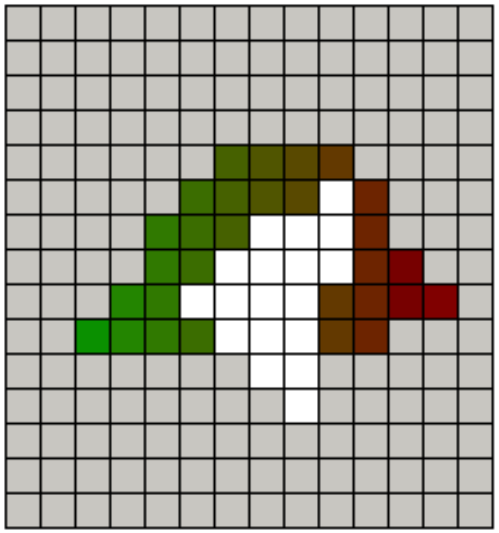
Owner, scissor, depth, alpha and stencil tests

Blending or compositing

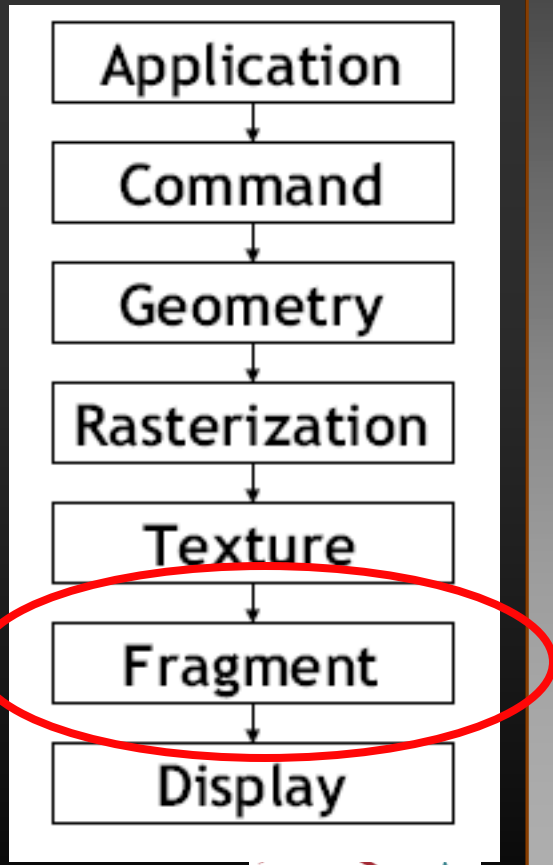
Dithering and logical operations



Textured Fragments



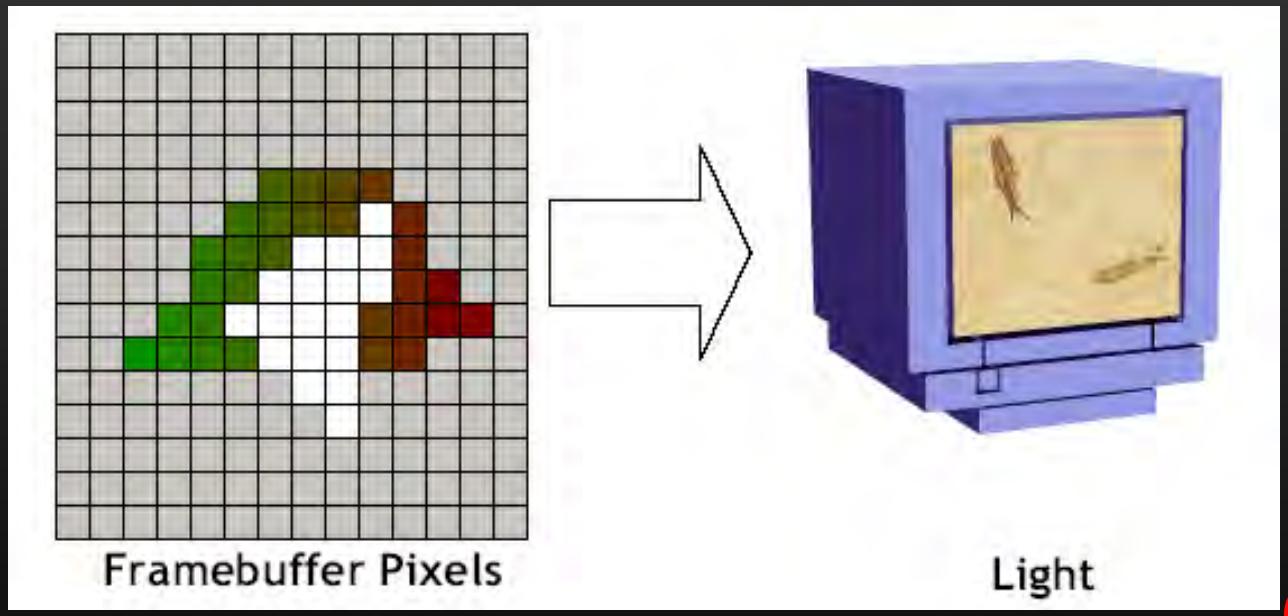
Framebuffer Pixels

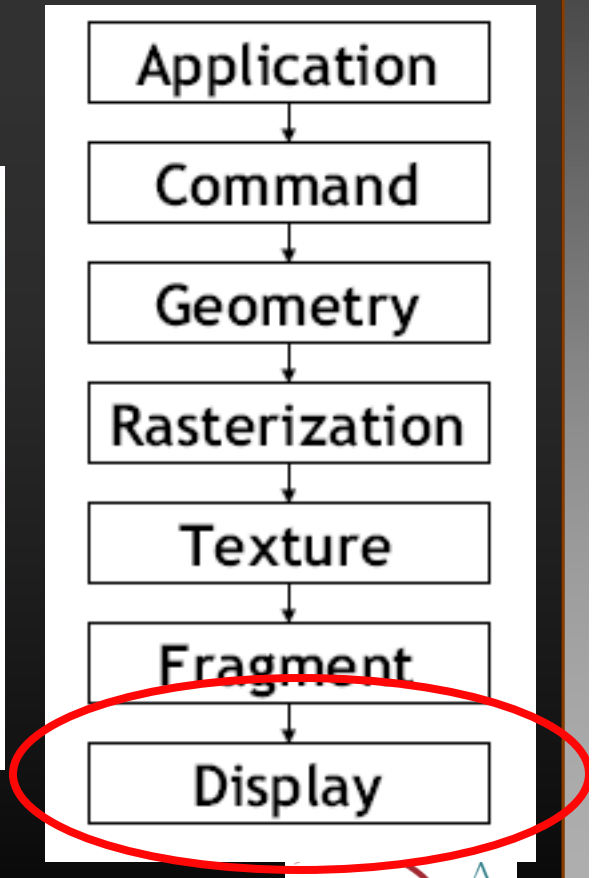


Office of Science
U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

Display

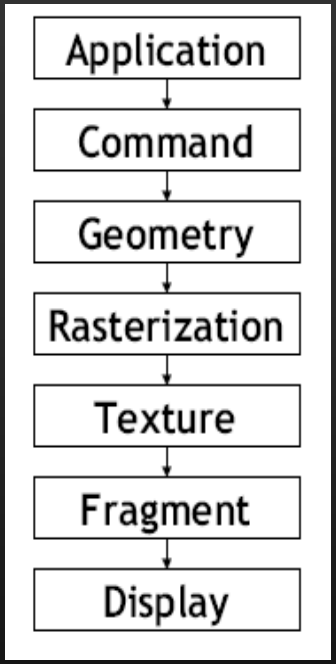

Framebuffer Pixels
Light


Application
Command
Geometry
Rasterization
Texture
Fragment
Display

Parallelism in Graphics

Sources of Parallelism

- **Task parallelism**
  - Graphics Pipeline
    - Parallelizing operations within a single pipe.
    - Pipelining operations within a single pipe.
- **Data Parallelism**
  - Frame & image parallel (image order).
  - Object/geometry parallel (object order).



Office of Science
U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

Parallelism and GPUs

- **NVIDIA 8800 GTX Ultra**
  - 16 processors, 768 threads each.
  - 12K simultaneous threads!
- **These threads are simultaneously working on:**
  - Transform and light (vertex operations)
  - Rasterization
  - Texturing/fogging/alpha blending/stencil (fragment ops)

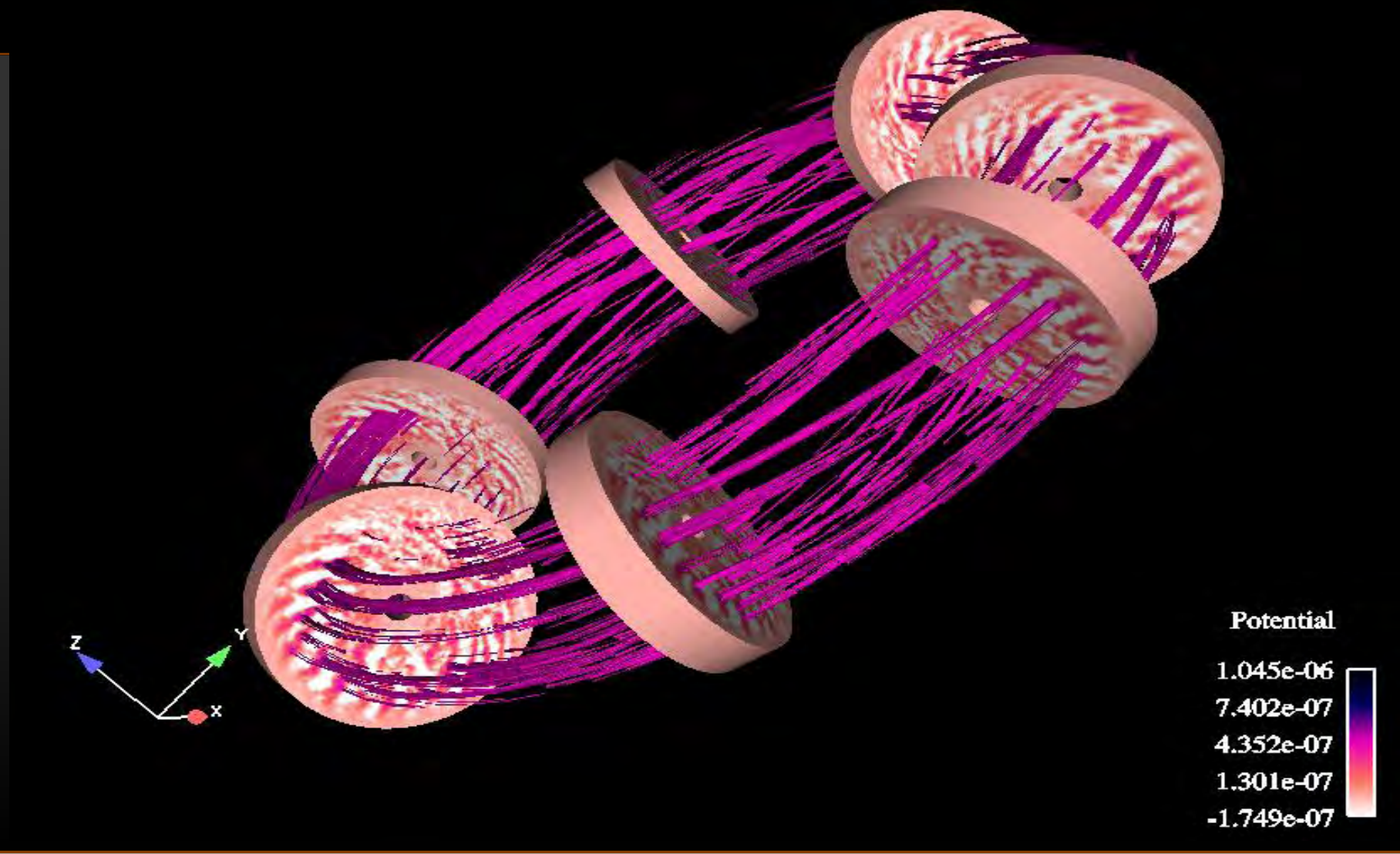
Programming GPUs

- **"Old Way"**
  - Vertex and fragment programs.
  - "Assembly language" programming
- **New Way: Compute Unified Device Architecture – CUDA**
  - C language with extensions for multithreading
  - Lots of promise/interest for high performance computing.
  - Teraflop GPUs vs. Gigaflop CPUs

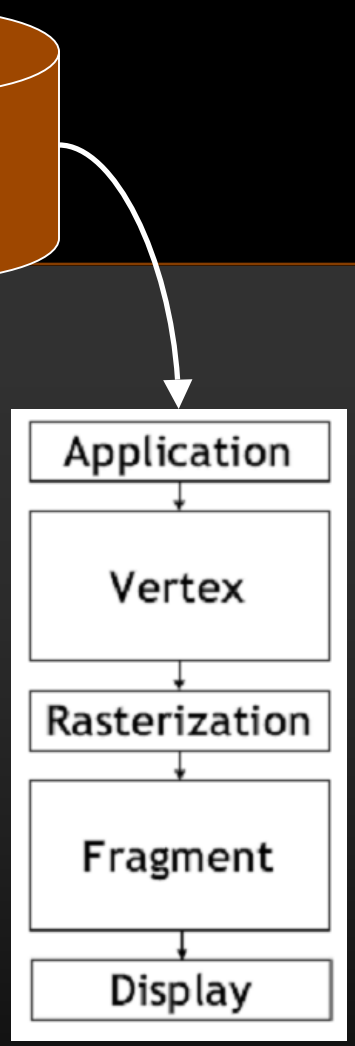
Office of Science
U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

Visualization



Visualization



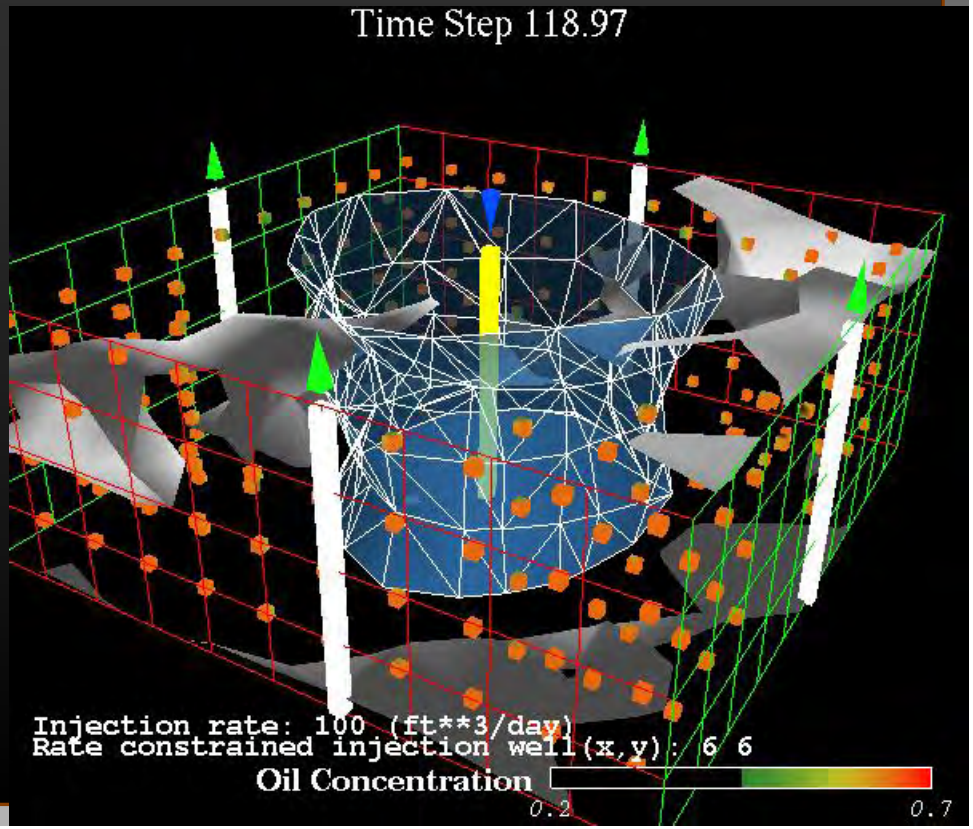
- **Visualization is the art/science of transforming abstract data into images.**
- **Visualization algorithms:**
  - Produce data that can be then processed by a traditional graphics pipeline, or
  - Are rendering algorithms that produce images.
  - Are highly data intensive (opportunity for performance gain through parallelism!!)

Visualization Research Examples

- Petroleum Reservoir Modeling
- Protein structure prediction
- Quantitative analysis/comparison of Rayleigh-Taylor instability

Petroleum Reservoir Modeling

- **Problem:**
  - Find optimal location of injection and production wells.
  - No direct solution
- **Approach**
  - Leverage human intuition
  - Couple simulation and visualization



Office of Science
U.S. DEPARTMENT OF ENERGY

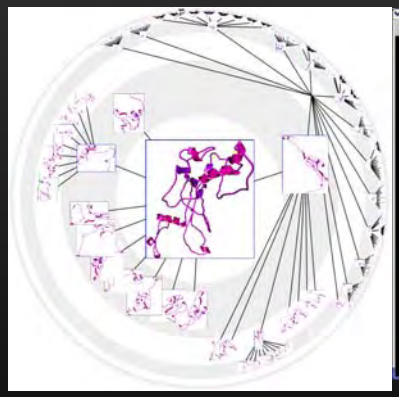
Protein Structure Prediction

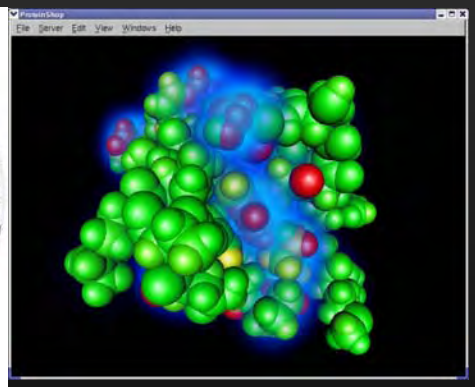
```
Conf: 99999999999999999999999999999999999999
Pred: HHHHHHHCCCEEEEEEECCCEEEEEEECCCCCCC
AA:   FKQYANDNGVDGVWTYDDATKTFTVTEMVTEVPVA
```

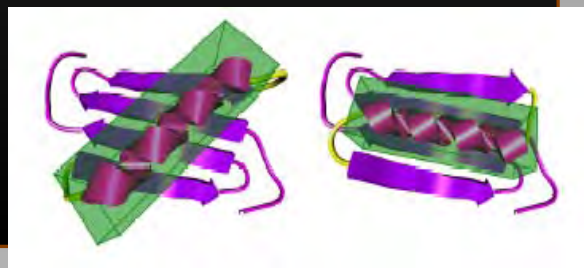
Problem: what is the minimal-energy structure of a sequence of amino acids?

Solution: Nature knows, but computing an answer is NP-hard (not solvable).

Approach: Human-guided setup, computer-aided energy optimization and minimization.



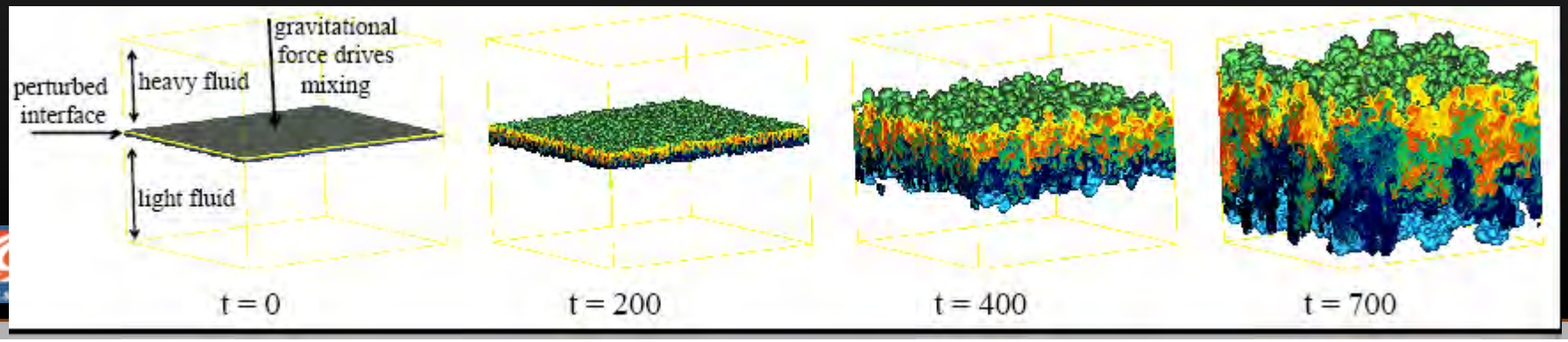




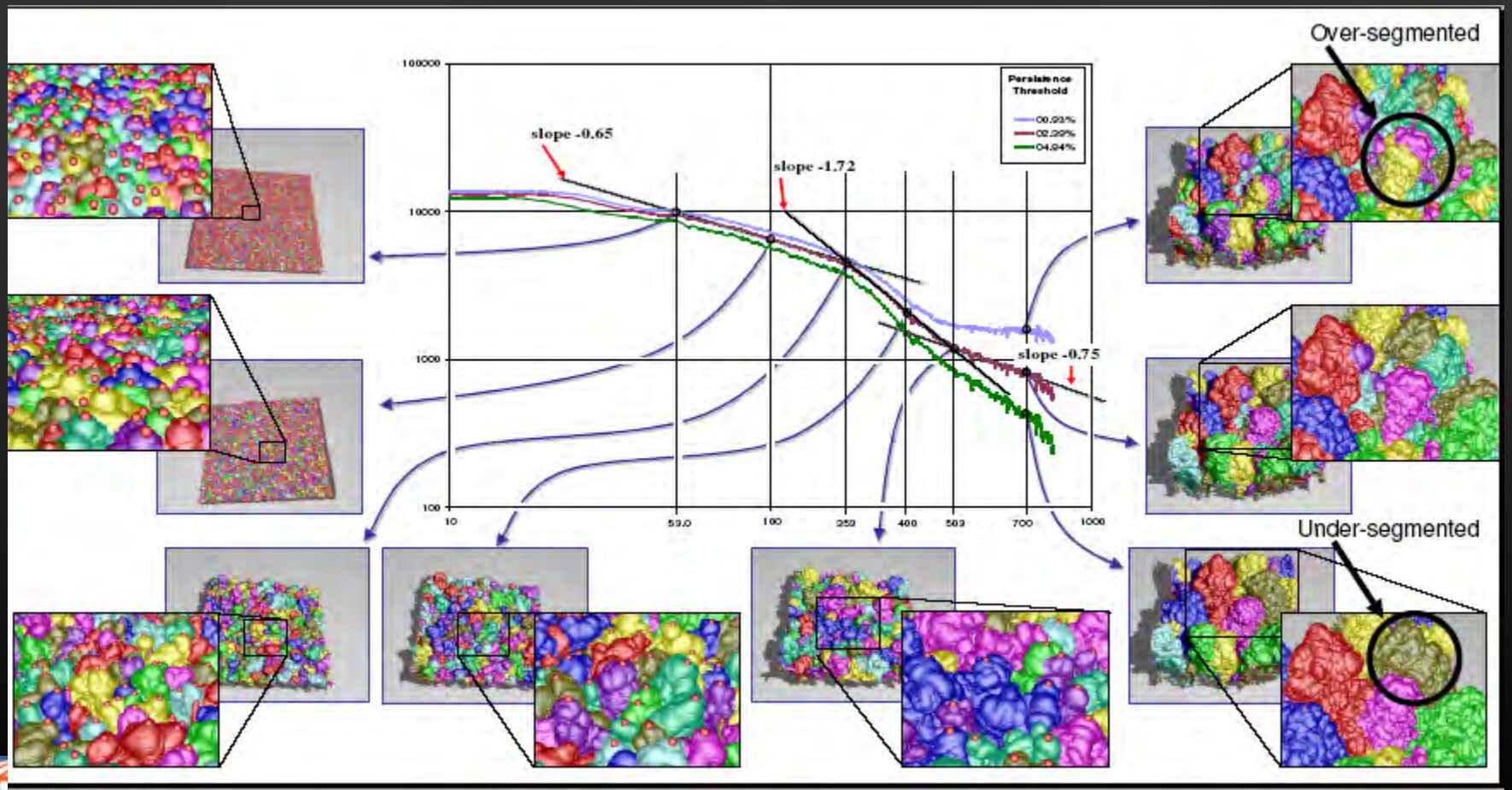
Office of Science
U.S. DEPARTMENT OF ENERGY

Rayleigh-Taylor Instability

- **Problem: understand impact of various parameters on mixing.**
  - Want to compare results of different simulations.
- **Solution: topological analysis to identify, count, and track mixing regions.**

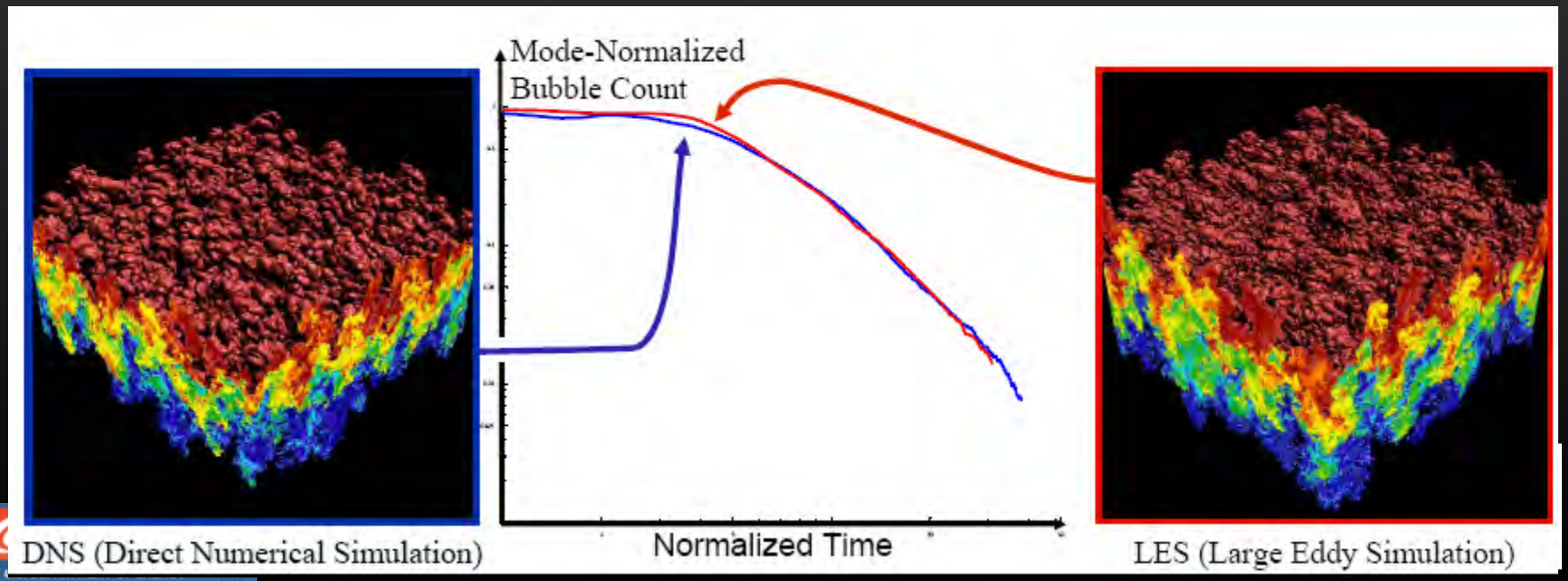


Rayleigh-Taylor Instability, ctd.

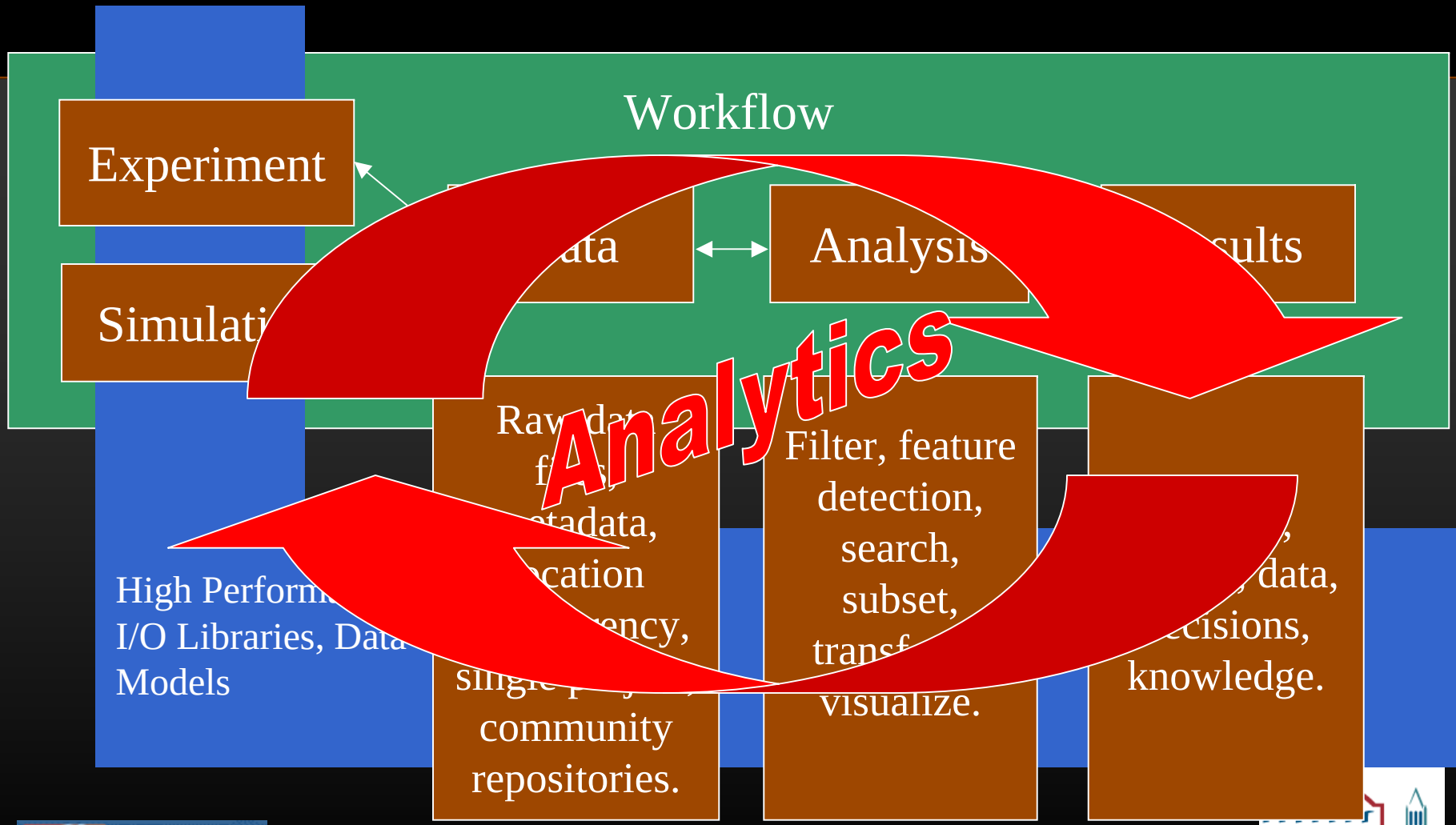


Rayleigh-Taylor Instability, ctd.

- Bubble count: quantitative basis for comparison (sim-sim, in this case)



Map of the Problem Space

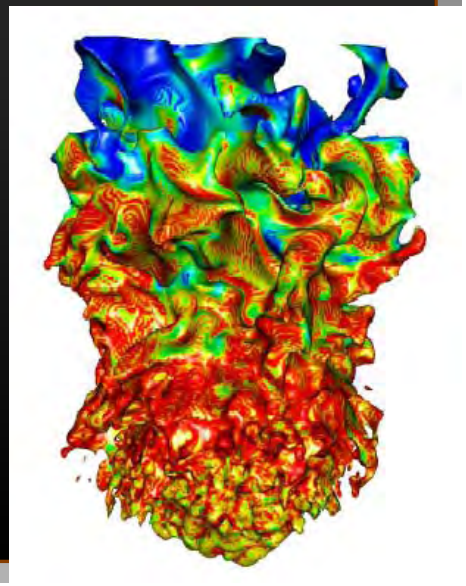


Office of Science
U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

Challenges in Visualization/Graphics

- **Primary problems**
  - Computing platforms machines becoming more powerful and complex: increased parallelism, heterogeneous architectures.
  - Data becoming larger and more complex: increased spatial resolution, more variables, more timesteps.
- **Secondary problems**
  - Comparing datasets: sim-sim, experiment-sim.
  - Analysis to find/confirm correlations.
- **Really big problem**
  - Too much information!

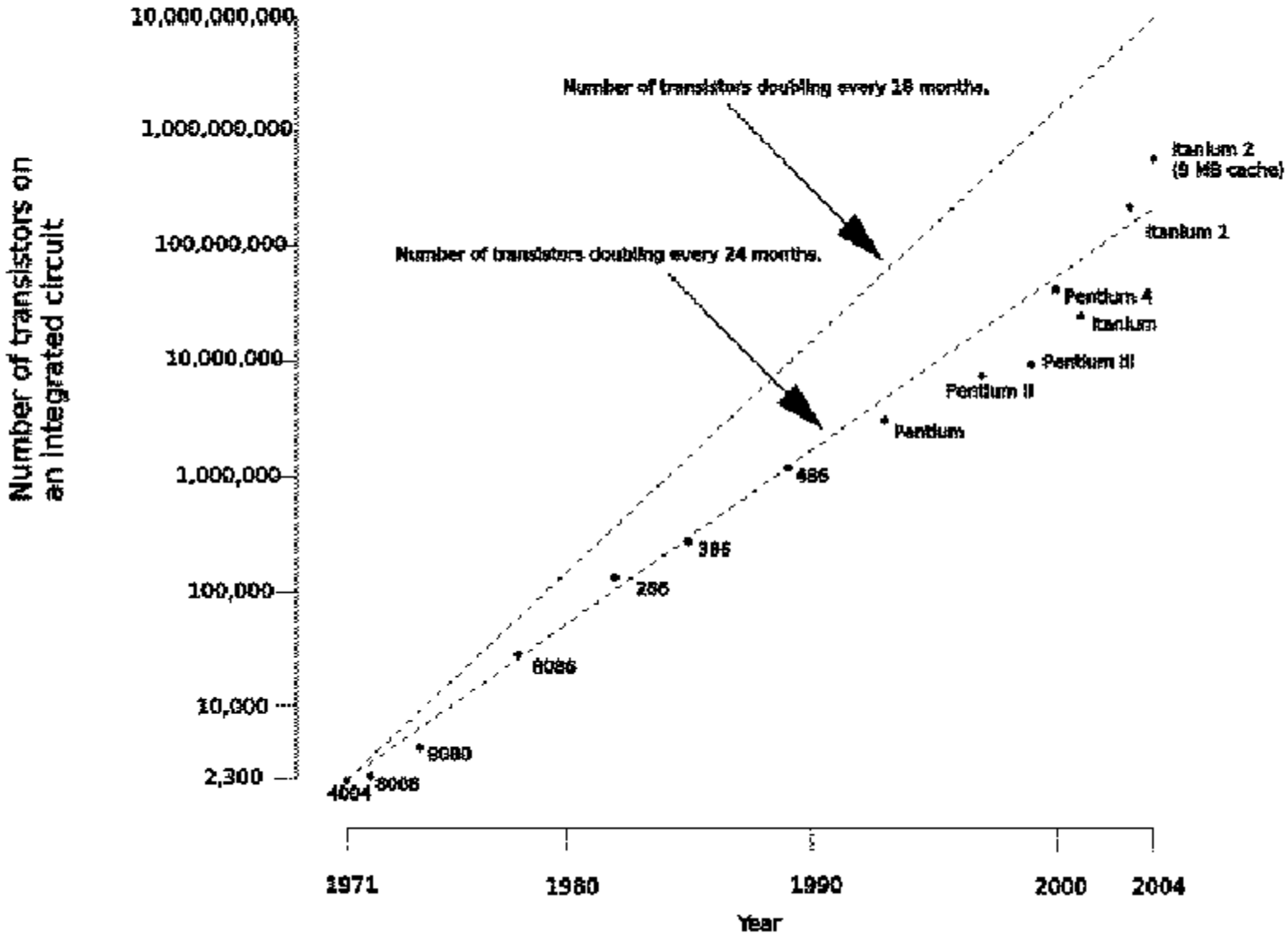


Office of Science
U.S. DEPARTMENT OF ENERGY

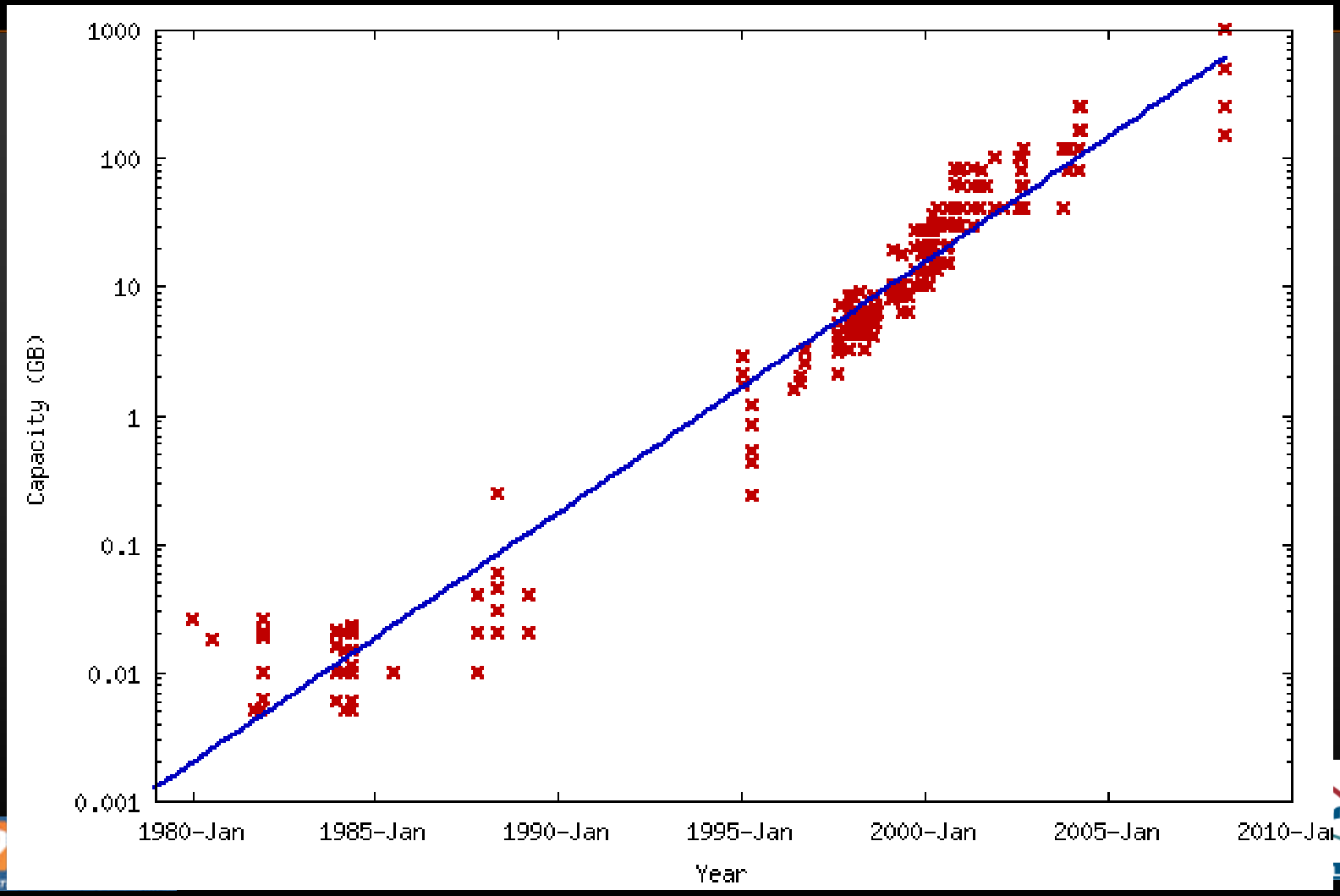
Big Problem – Information Overload

- **Our ability to create and store information exceeds our capacity to understand it.**
- **Information requires attention to process:**
  - "A wealth of information creates a poverty of attention." – Hebert Simon, Nobel Prize, 1971.
- **Major challenge: gain insight from data.**

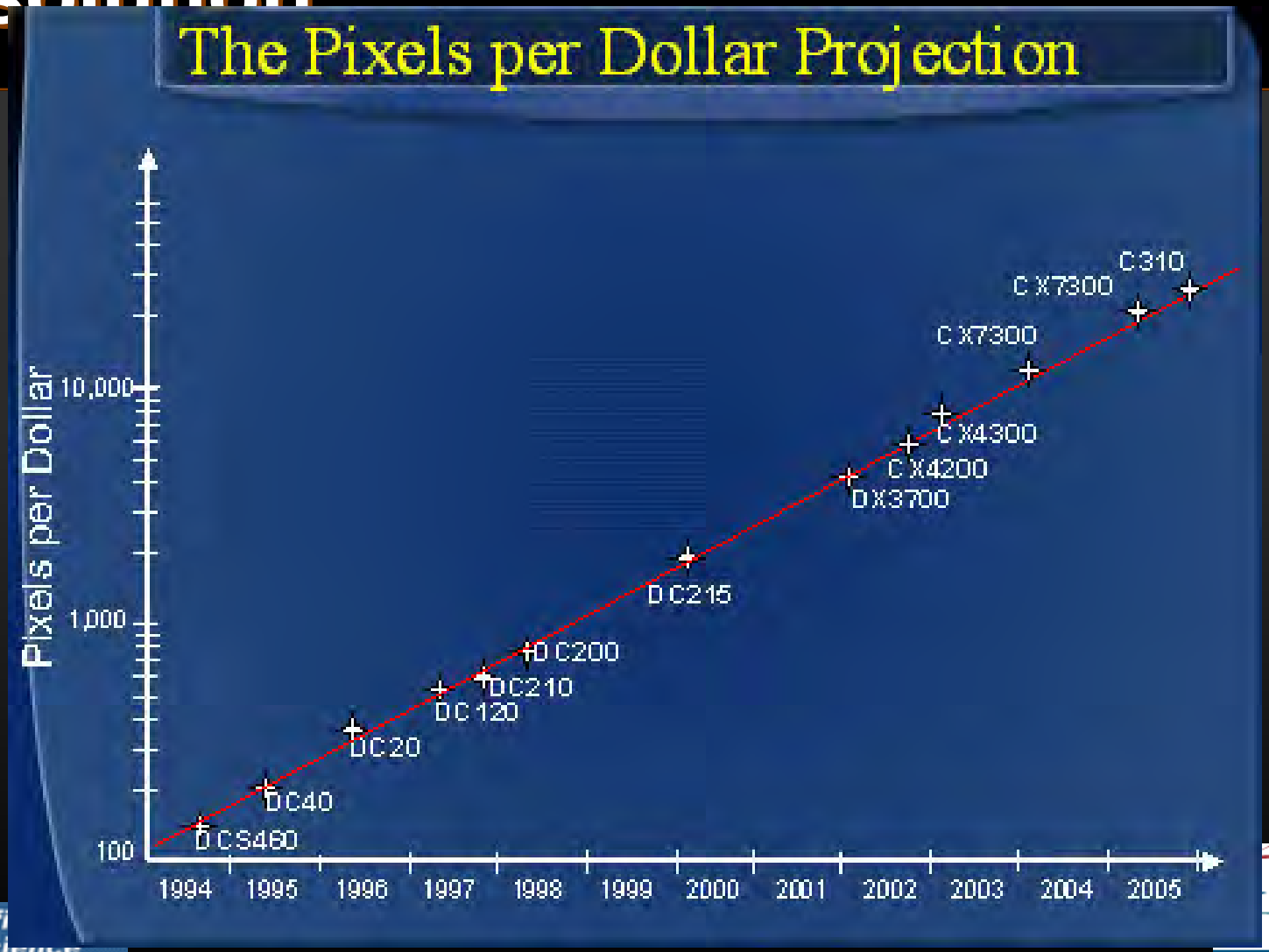
Moore's Law


Number of transistors doubling every 18 months.
Number of transistors doubling every 24 months.
Itanium 2
(9 MB cache)
Itanium 2
Pentium 4
Itanium
Pentium III
Pentium II
Pentium
486
386
286
8086
8080
8008
4004
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
2,300
Number of transistors on an integrated circuit
1971
1980
1990
2000
2004
Year

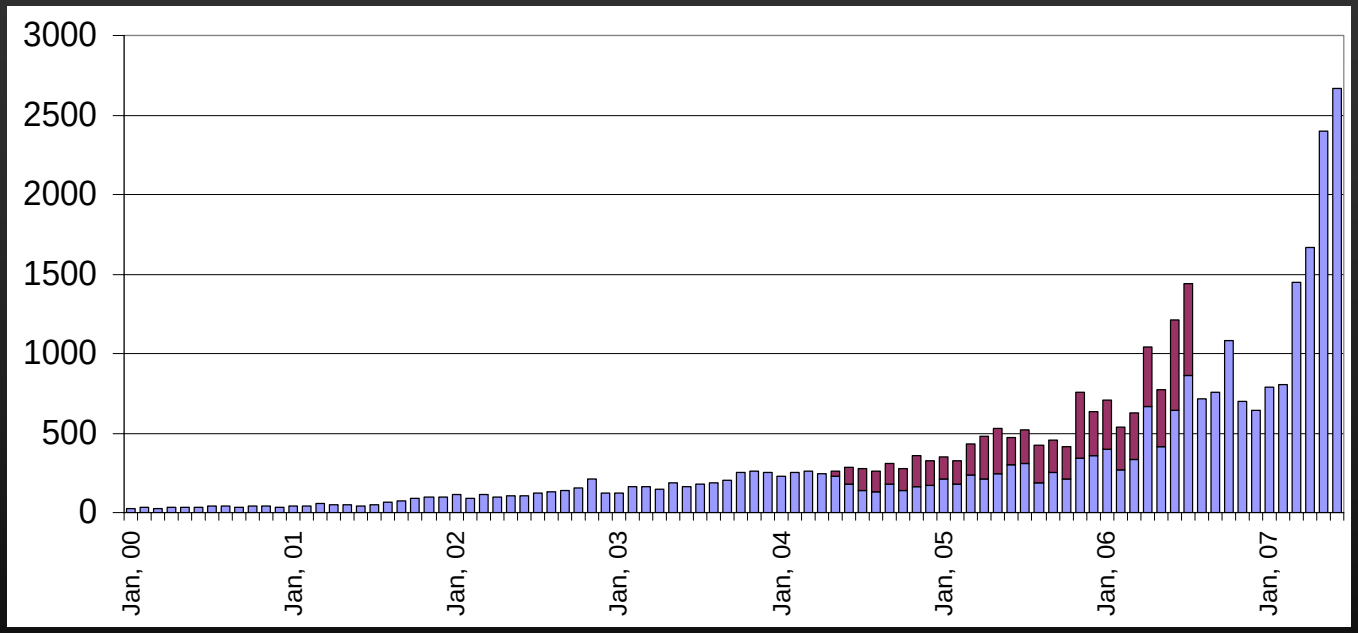
Moore's Law – PC Hard Drive Capacity



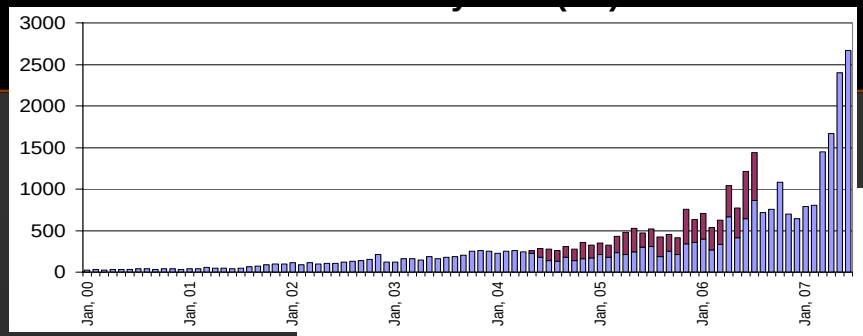
Moore's Law – Digital Camera Resolution

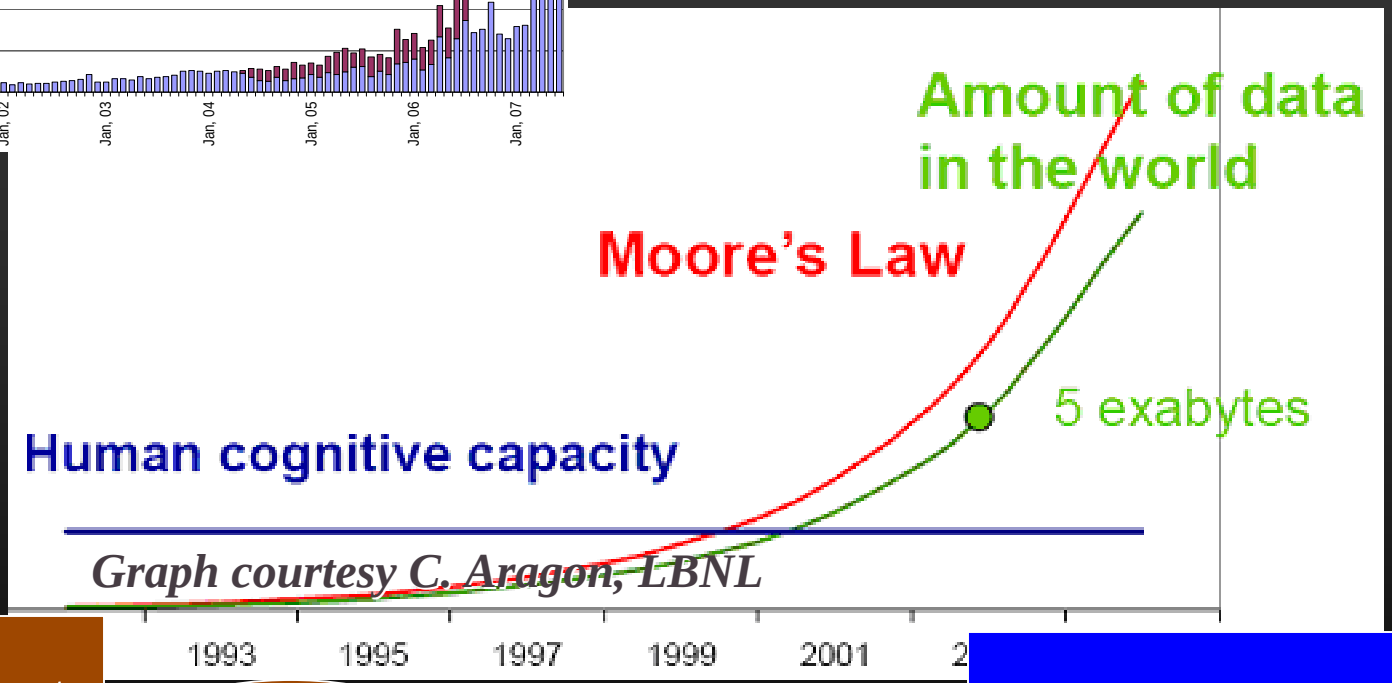


ESnet: Shatters PB barrier

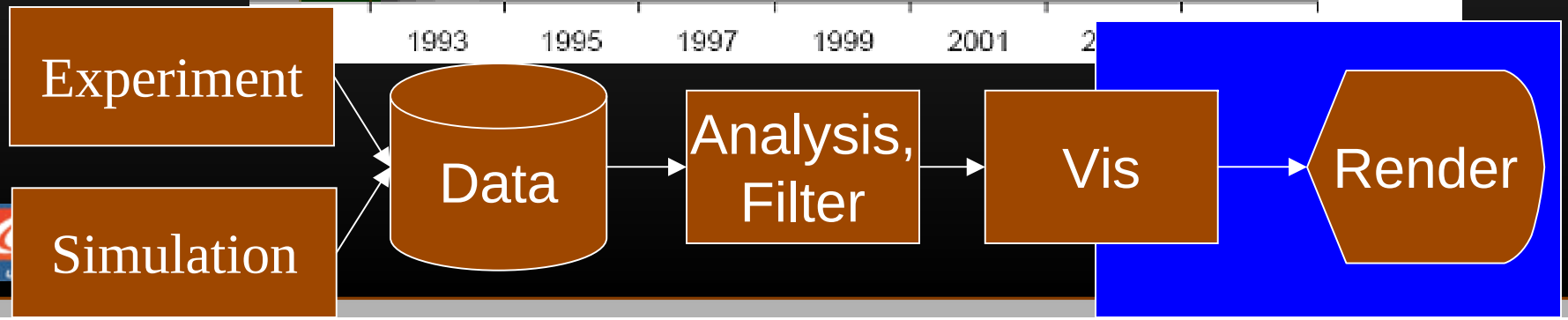


Human Cognitive Limit



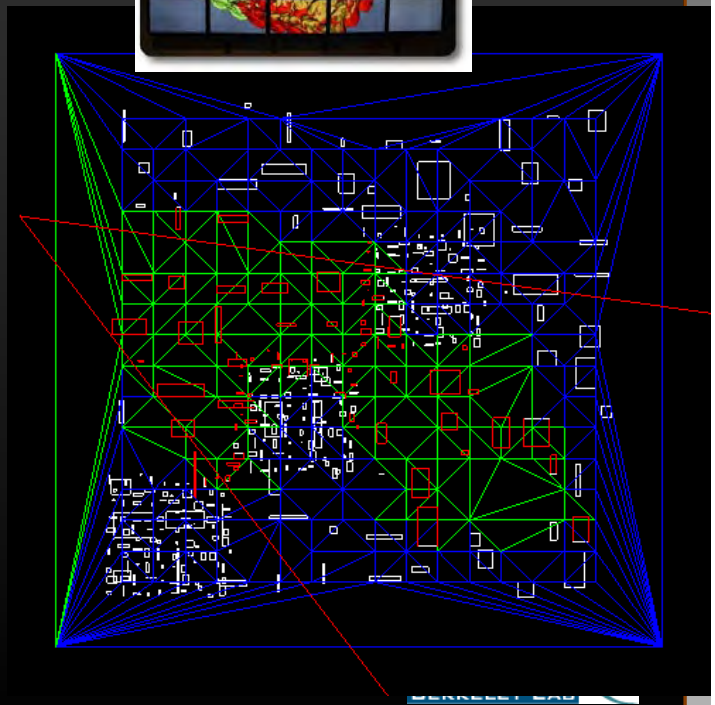


Graph courtesy C. Aragon, LBNL



How is Cognitive Bandwidth Abused?

- **The "meat grinder" syndrome**
  - Can't "see" a TB, much less a PB
    - Depth complexity
      - 1k^3 grid → O(2-20)
        - » Can't see it
      - 4k^3 grid → O(20-200)
        - » Can't store it
    - Spatial complexity
      - Mesh cells map to sub-pixels



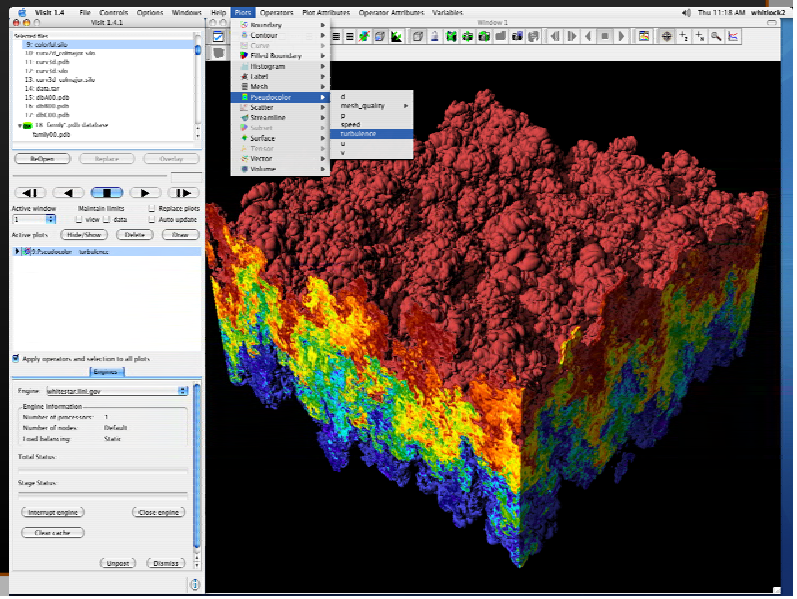
Office of Science
U.S. DEPARTMENT OF ENERGY

LBNL Visualization Program

- DOE's SciDAC Visualization and Analytics Center for Enabling Technologies (VACET).
- NERSC Analytics.
- High performance visualization research.

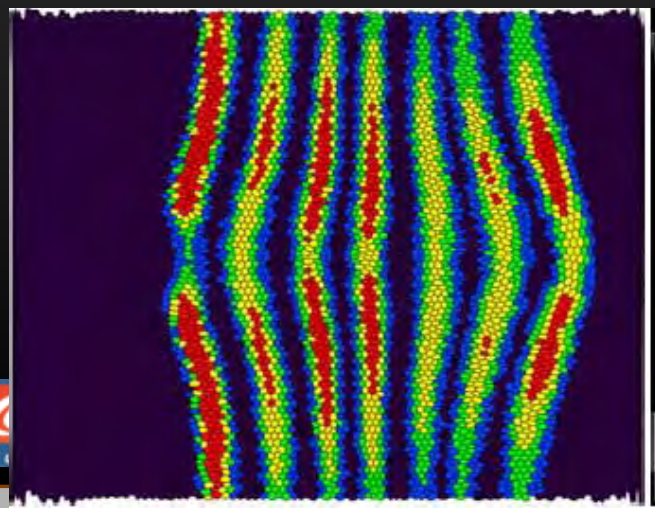
The Road Ahead (< 5-10 years)

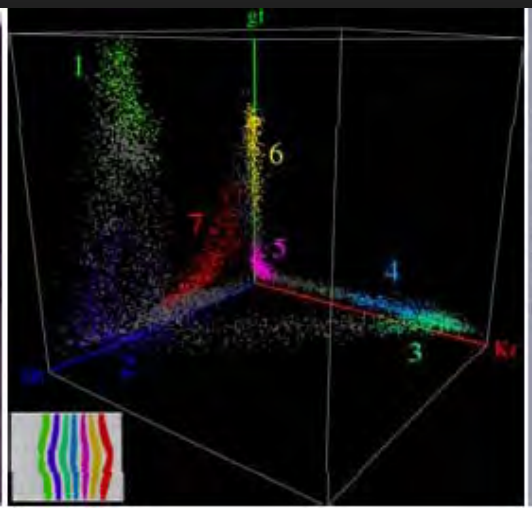
- **Effectively leverage emerging computational platforms for visual data analysis.**
  - MPP systems, hybrid/hierarchical parallelism.
  - “Exotic systems”:
    - CellBE, GPU, etc.

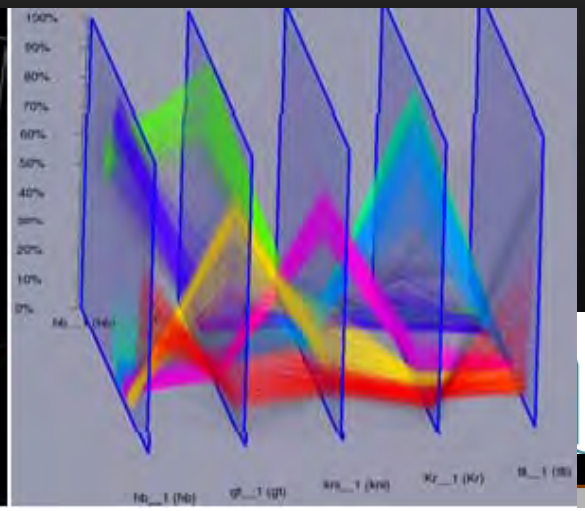


The Road Ahead (< 5-10 years)

- **Increasing efficiency of data understanding techniques and methodologies.**
  - Combining visualization and traditional data analysis.







The Road Ahead (< 5-10 years)

- **Usability engineering.**
  - Objective: simplify ease-of-use of complex machinery.
  - Factors: parallel machines, distributed teams, large and complex data, diverse software, …
- **A very difficult set of problems!**
  - Data formats “Tower of Babel” problem.
  - Interface standards non-existent:
    - Programming interfaces
    - Data and “execution” interfaces
    - User interfaces

Office of Science
U.S. DEPARTMENT OF ENERGY

The End