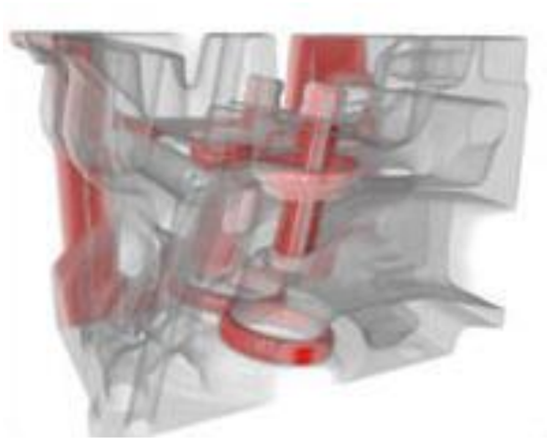
How Do We Add Color?

- We learned earlier in the term that color plays a vital role in visualization
- The skull in the right image was colored white, the skin a transparent orange color
- Where did these colors come from?
- The input is just a grayscale, 8-bit volume, after all
- Also, what happened to all the blood vessels, muscles, and other biological structures? They seem to have disappeared, but we know they were in the original data-set
- Evidently there was some sort of mapping of density to color and opacity
- Skull → white
- Skin → transparent orange
- Flesh → 100% transparent (0% opacity)

Classification

- So, in general, a voxel stores some density value
- This density can have many meanings, depending on the origin of the dataset:
  - stress, strain, temperature (finite element applications, numerical simulations)
  - X-ray absorption of a material (computed tomography (CT))
  - magnetic spin relaxation property of a material (MRI)
  - a material tag (voxelization)
- We would like to give certain aspects of the dataset meaningful visual attributes, such as colors
- For this purpose, the raw values have to be translated into colors and attenuation properties (opacity)
- These assignments are made based on the voxel's material
- This assignment process is formally called *classification*



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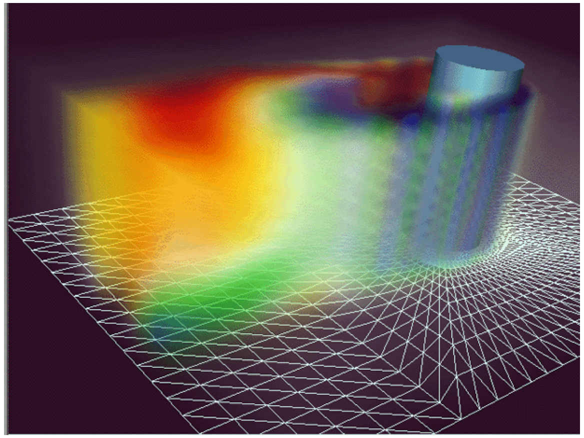
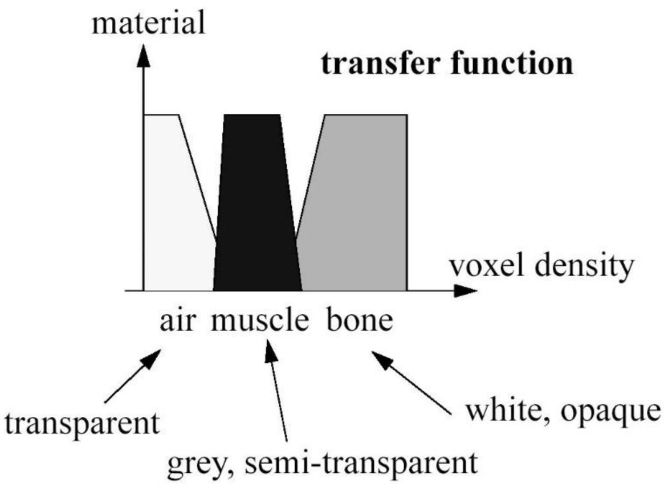
Classification

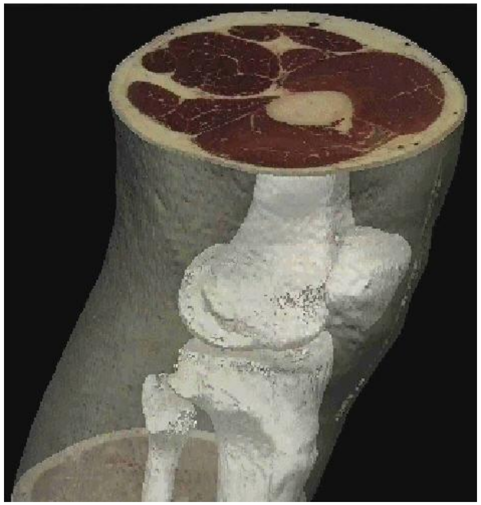


- *Classification* is the task of assigning an (R,G,B,A) tuple to an 8-bit density
- But how do we do this?
- We use a set of four *transfer functions* that map density to R, G, B and A
- In X-ray rendering, each interpolated sample along the ray was assigned the same weight; all we did was add them up
- Now we will let the user decide how much each density level will contribute to the final image
- Example: if we want to visualize high densities (e.g., bone), we would assign a high opacity to such densities, and assign lower opacities or even zero opacity (full translucency) to lower densities
- Let's see an example

Classification

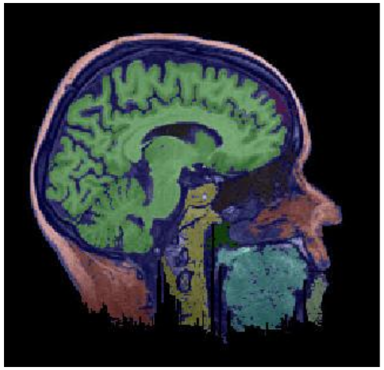
- In simple cases (such as CT), each material has a characteristic raw density range





- Some datasets (for example MRI) do not have unique density-material correspondences
- These require more sophisticated segmentation methods (seed growing, clustering)

segmentation



render

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Transfer Functions

- Think of the volume as a transparent gel that we are looking through
- With X-ray rendering, each sample along the rays are assigned the same importance, in some sense
- Low densities contribute to the final image as much as high densities
- Transfer functions allow us to change the relative contributions of densities
- So, if we wanted to make high densities contribute more (e.g., to see bone), we should assign higher importance to those densities
- In volume rendering, this importance is assigned by the opacity
- So, if we want to view bone, we assign high opacity to densities corresponding to bone
- As the viewing rays traverse the volume, the system will use those opacities (and colors) to modulate the pixel value accordingly
- So even though the bone was given high opacity, since the skin was assigned non-zero opacity and the color orange, the skull has an orange cast to it

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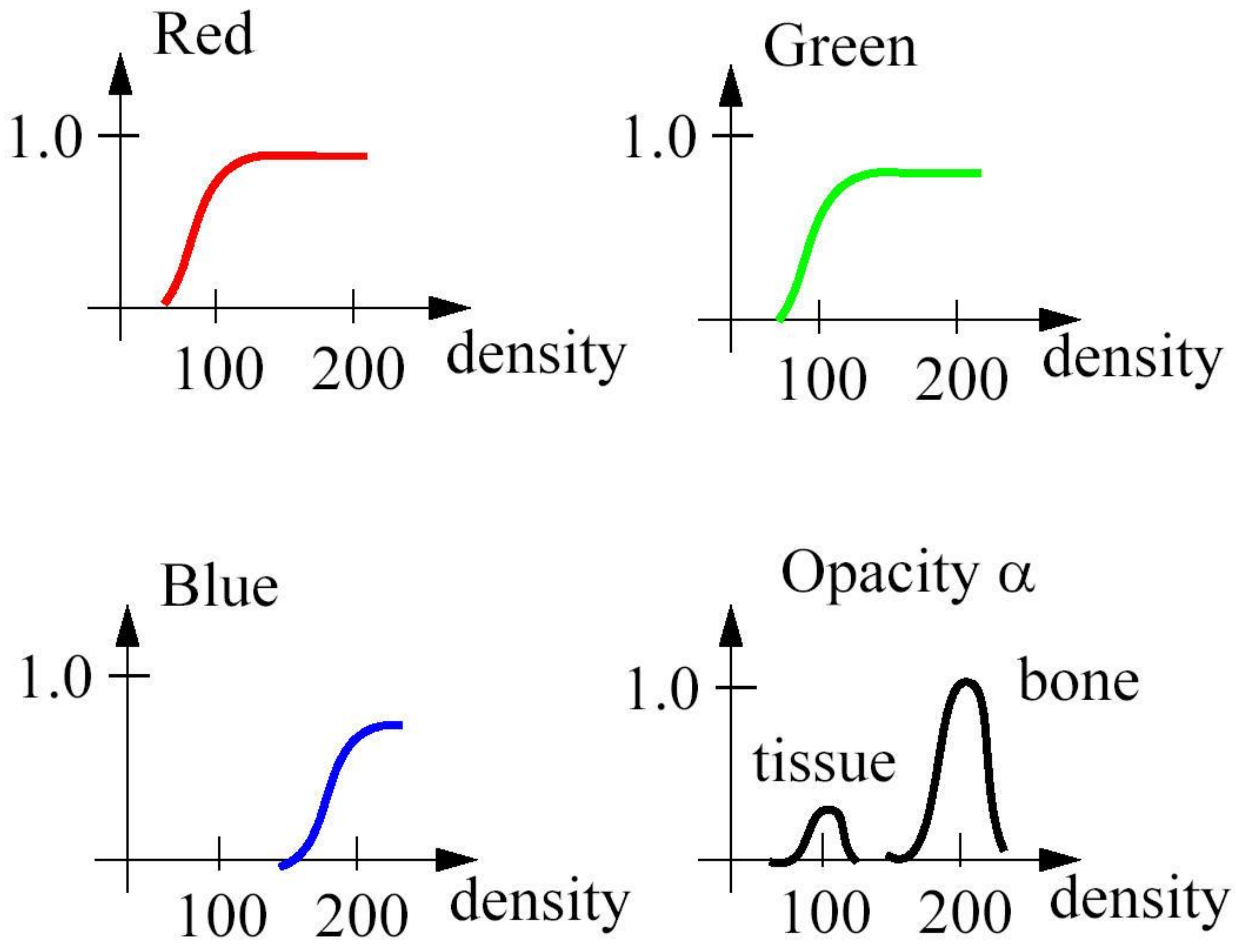
Transfer Functions



Transfer Functions

- Notice how transfer functions are similar to intensity transformations
- In both cases, the input is density (or intensity)
- For intensity transformations, the output is also intensity
- For transfer functions, the output is either color or opacity
- Unlike in X-ray rendering, can now assign arbitrary, non-negative weights to voxels and generate interesting effects
- Interpolate density then assign color
- So what happens when our viewing ray accumulates full opacity (1.0)?
- In other words, it could happen that half-way through traversing the volume, a ray hits full opacity
- What this means is every other sample we encounter along the ray will be occluded by the opaque structures in front that we have already processed
- This is why we can't see the back side of the skull
- Early ray termination optimization

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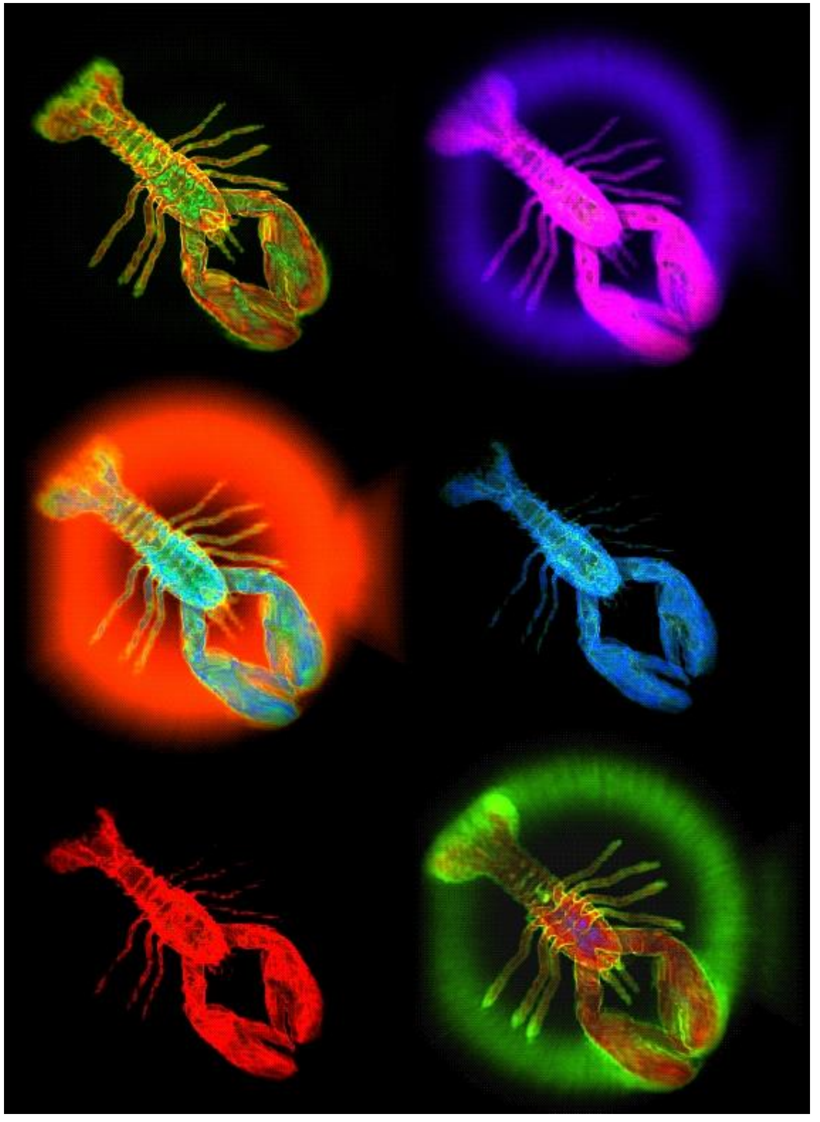
Transfer Function Design Galleries

- Transfer functions are somewhat unintuitive to use at times
- Remember our motivation for histogram equalization?
- That gave us an automatic process
- Unfortunately, there is no such automatic process for transfer function generation because of the wide variety of volumetric data-sets and the wide range of features people wish to visualize from data-sets
- But, there is one way in which a computer can help us: so-called *transfer function design galleries*
- A set of randomly-generated transfer functions that the system mutates (based on user input) to generate a new gallery



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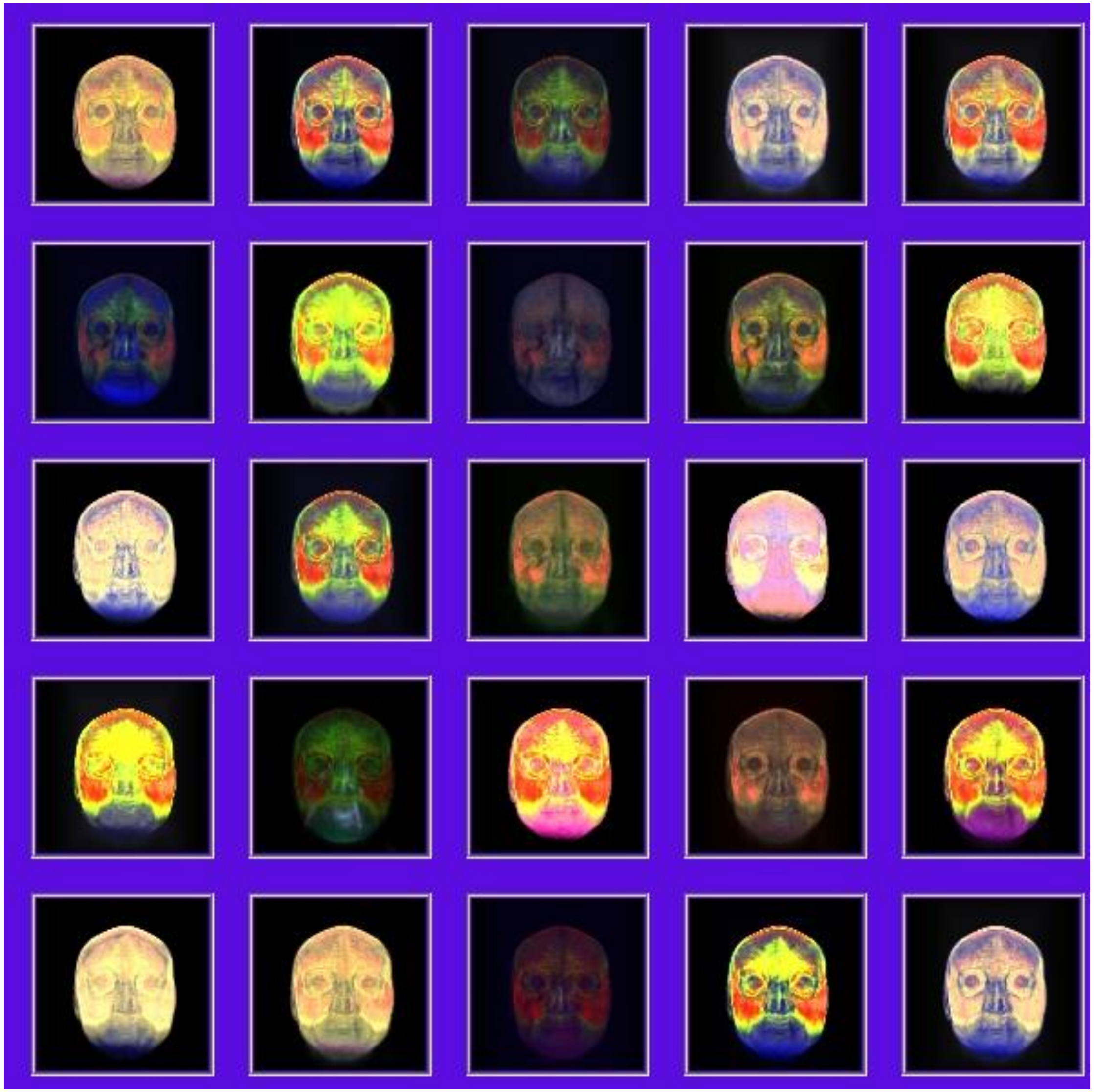
Transfer Function Design Galleries



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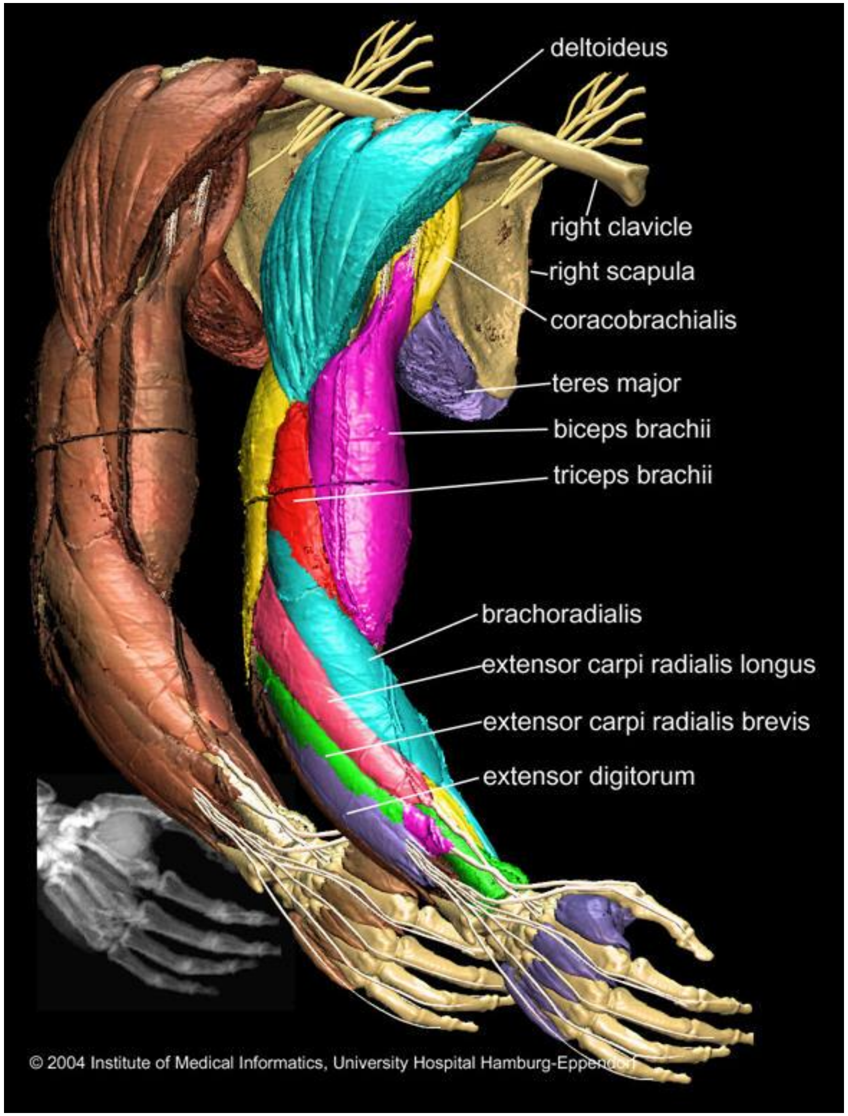
Visible Male Visualization

- Let's see a movie of transfer functions being used at real time to visualize the visible male data-set (6)
- Watch the bottom of the two graphs, which shows the α transfer function

Segmentation

- Related to the task of classification is *segmentation*, the process of extracting features from a data-set
- Basically, segmentation assigns a material label to each voxel in a data-set
- e.g., a voxel value of 100 might indicate that a particular voxel is muscle, but which muscle? Does a density of 200 indicate a tooth or the jaw in which the tooth is located?
- Classification can't answer these questions
- Segmentation – done manually or with some algorithm – partitions a data-set into logical pieces



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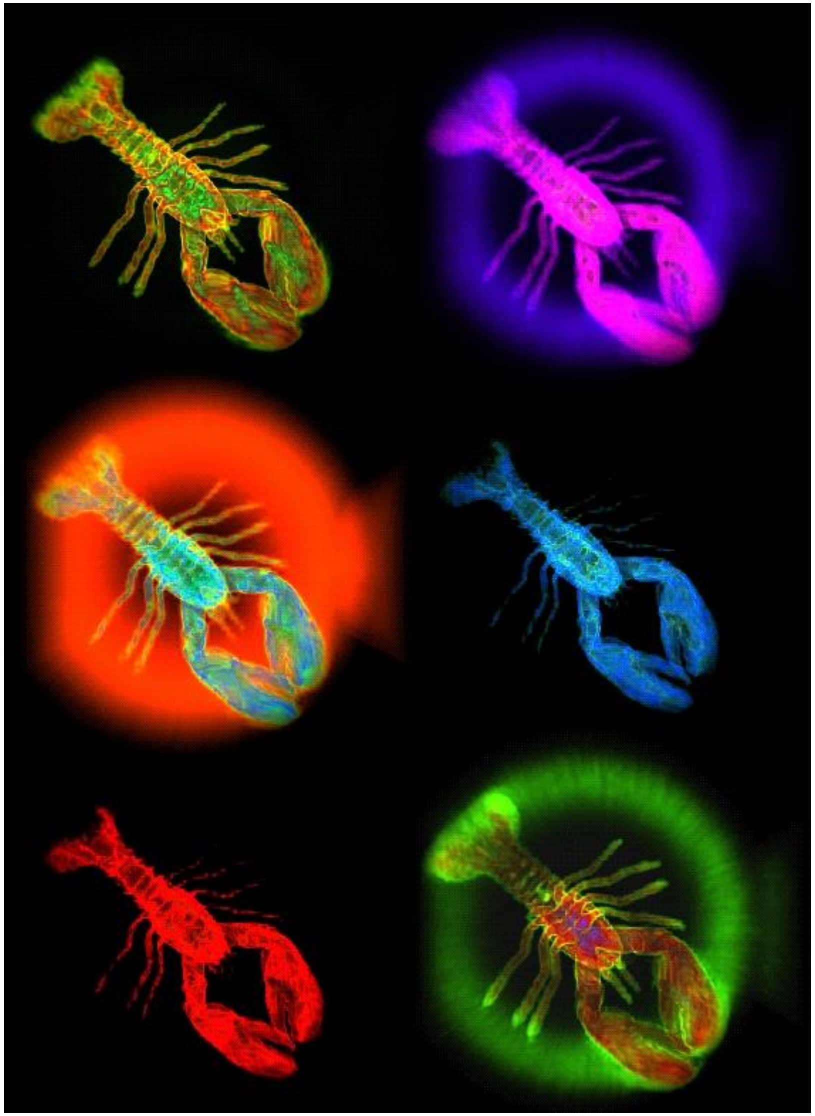
Segmentation

- Segmentation is, in general, an extremely difficult and potentially time-consuming process
- There is no single segmentation algorithm that can solve all or even most segmentation problems
- Almost without exception, a certain level of human intervention is needed at some point during execution
- Numerous algorithms for each particular application
- Can you think of some reasons why there is no single, really good way of segmenting data? After all, classification, despite its faults, is actually a pretty solution to the problem it addresses (assigning color to voxels)
- Consider the many domains in which volume rendering is used
- Many sources of data
- Many, many differences in the underlying structures of data
- Just look at the human body, especially the abdomen and all the organs and complex structures (branching lungs/blood vessels, tubular gastrointestinal tract, etc.)
- Movie of brain tumor segmentation (4)

How About Shading

- We haven't seen yet how to employ shading with volume rendering to make objects look 3D
- In fact, we aren't required to shade our volumetric objects, but it sure helps in revealing structure
- The lobsters on the right are not shaded
- Note that we can distinguish different materials, but it's hard to discern 3D shape
- So, we can use transfer functions in volume rendering and omit shading, but let's take a look at how we *can* incorporate shading into volume rendering
- Let's look at some traditional computer graphics shading techniques and extend them to volumetric ray-casting



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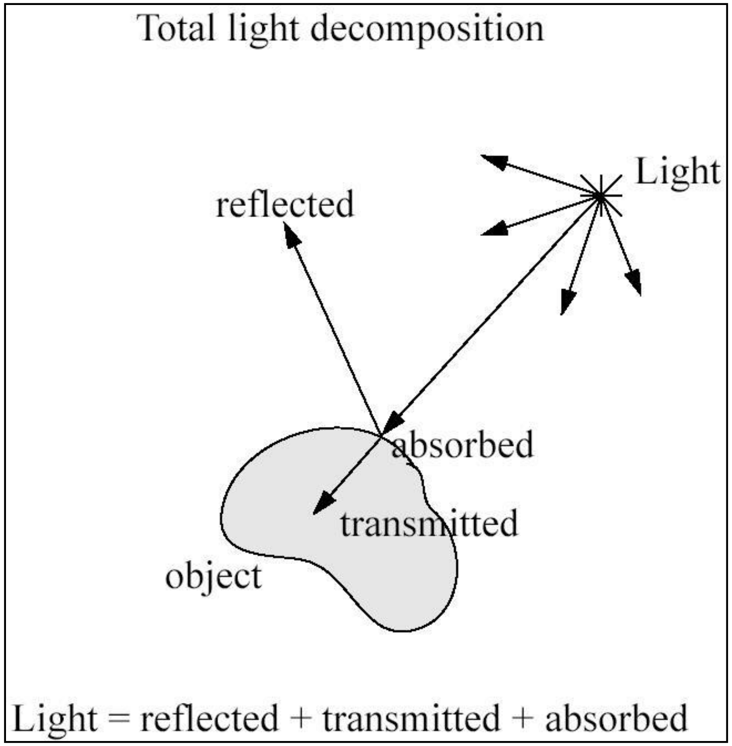
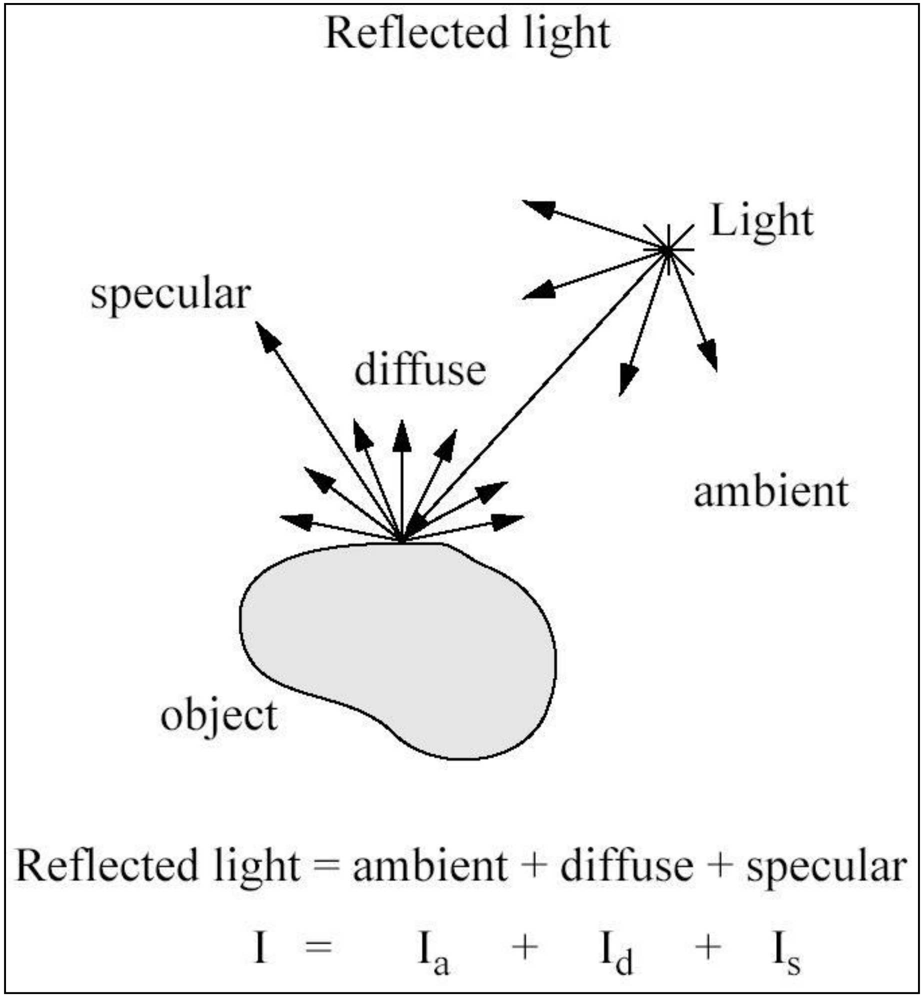
Illumination and Shading

- Now we'll look at how to shade **surfaces** to make them look 3D
- We'll see different *shading models*, or frameworks that determine a surface's color at a particular point
- These shading models can be easily modified to incorporate illumination and shading into the volume rendering pipeline
- A shading model checks what the lighting conditions are and then figures out what the surface should look like based on the lighting conditions and the surface parameters:
- Amount of light reflected (and which color(s))
- Amount of light absorbed
- Amount of light transmitted (passed through)
- Thus, we can characterize a surface's shading parameters by how much incoming light that strikes a surface is reflected to the eye, absorbed by the object, and transmitted



Reflected Light

- Typically in computer graphics, unless we are trying to create effects like refraction, diffraction and translucency, we are mostly concerned with the reflected light – that light which bounces off the object and enters the eye (camera, really)
- We'll use equations to make it easy to compare one shading model to another



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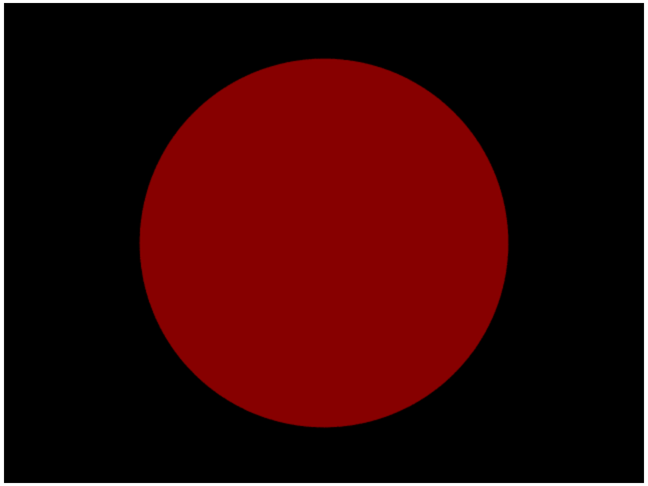
Ambient Reflection

- *Ambient reflection* refers to reflected light that originally came from the "background" and has no clear source
- Models general level of brightness in the scene
- Accounts for light effects that are difficult to compute (secondary diffuse reflections, etc)
- Constant for all surfaces of a particular object and the directions it is viewed from
- Directionless light
- One of many hacks or kludges used in computer graphics since every ray of light or photon has to come from somewhere!

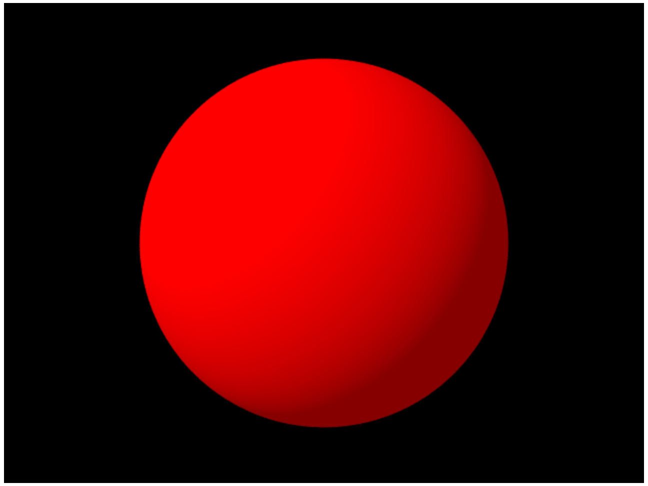


Ambient-lit sphere

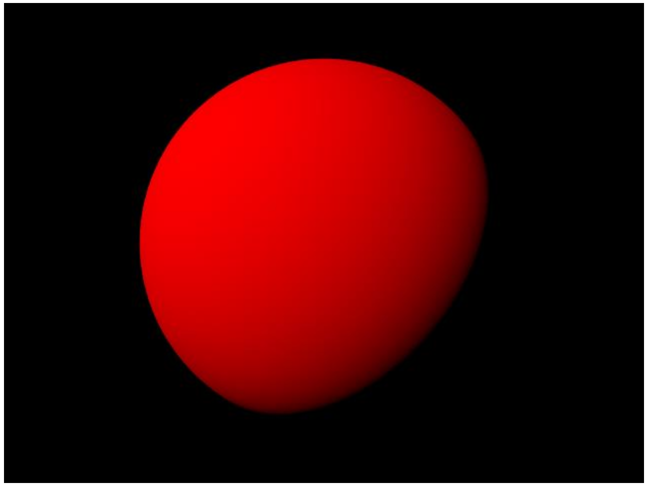
- Imagine yourself standing in a room with the curtains drawn and the lights off
- Some sunlight will still get through, but it will have bounced off many objects before entering the room
- When an object reflect this kind of light, we call it *ambient reflection*
- $I_a = k_a \cdot I_A$ I_A = ambient light k_a = material's ambient reflection coefficient

Diffuse Reflection

- Models dullness, roughness of a surface
- Equal light scattering in all directions
- For example, chalk is a diffuse reflector
- Unlike ambient reflection, diffuse reflection is dependent on the location of the light relative to the object
- So, if we were to move the light from the front of the sphere to the back, there would be little or no diffuse reflection visible on the near side of the sphere
- Compare with ambient light, which has no direction
- With ambient, it doesn’t matter where we position the camera since the light source has no true position
- Computer graphics purists don’t use ambient lights and instead rely on diffuse light sources to give some minimal light to a scene



Ambient & diffuse



Diffuse only

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Diffuse Reflection

- Diffuse reflection is also called *Lambertian reflection*
- Lambertian cosine law:

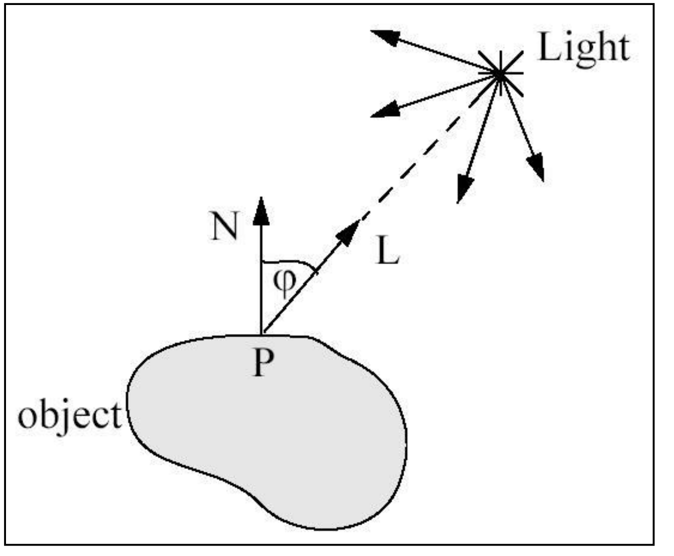
$$I_d = k_d I_L \cos\varphi = k_d I_L N \cdot L$$

dot product: $(N_x \cdot L_x + N_y \cdot L_y + N_z \cdot L_z)$

- I_L: intensity of light source
- N: surface normal vector
- L: light vector (unit length)

$$L = \frac{Light - P}{|Light - P|} = \left(\frac{Light_x - P_x}{|L'|}, \frac{Light_y - P_y}{|L'|}, \frac{Light_z - P_z}{|L'|} \right)$$

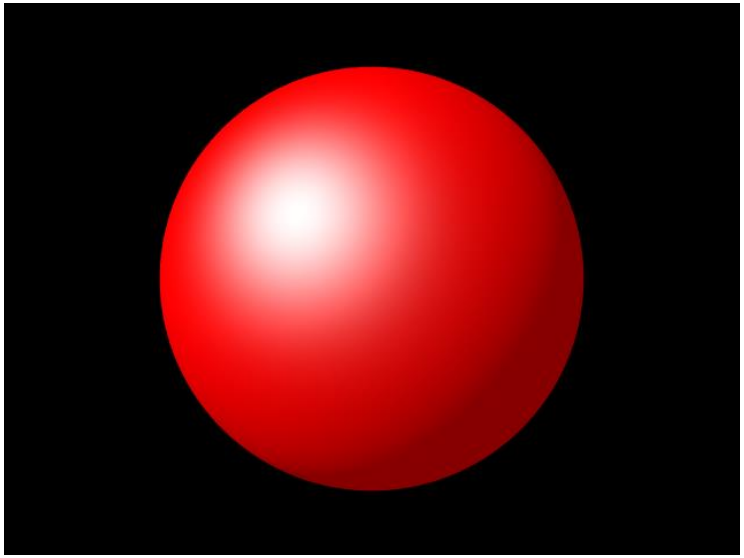
$$|L'| = \sqrt{(Light_x - P_x)^2 + (Light_y - P_y)^2 + (Light_z - P_z)^2}$$



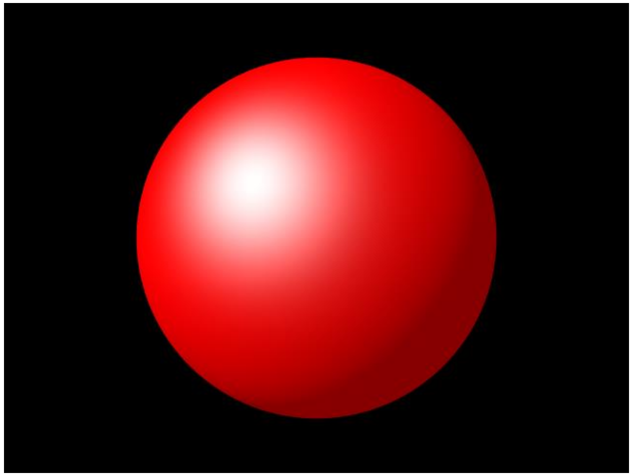
- φ: angle of light incidence
- k_d: diffuse reflection coefficient (material constant)
- Note: $I_d = 0$ for $N \cdot L < 0$
- What does this inequality mean intuitively?

Specular Reflection

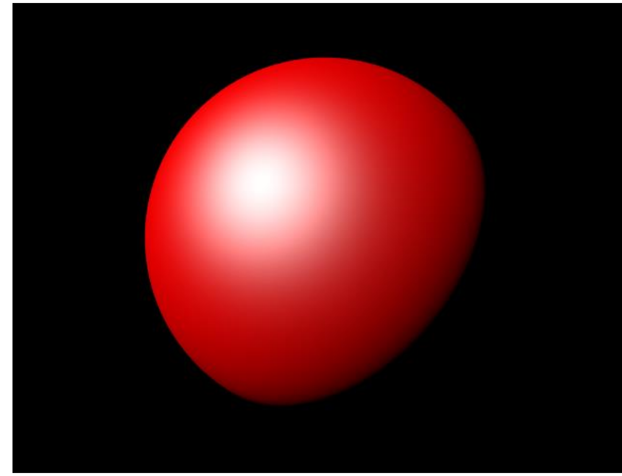
- Models reflections on shiny surfaces (polished metal, chrome, plastics, etc.)
- Specular reflection is *view-dependent* – the specular *highlight* will change as the camera's position changes
- This implies we need to take into account not only the angle the light source makes with the surface, but the angle the viewing ray makes with the surface
- Example: the image you perceive in a mirror changes as you move around
- Example: the chrome on your car shines in different ways depending on where you stand to look at it



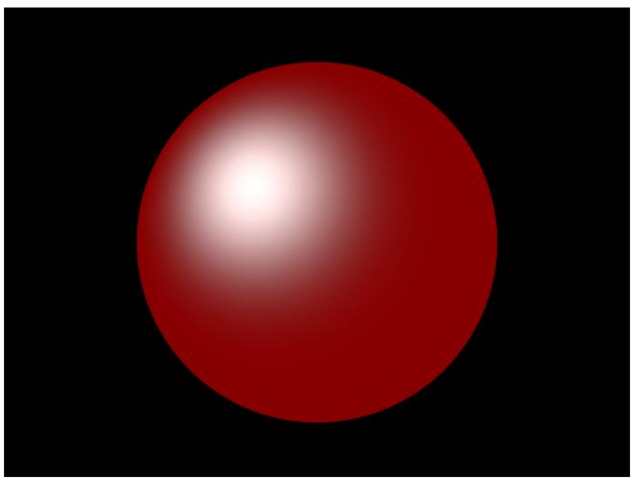
Specular Reflection



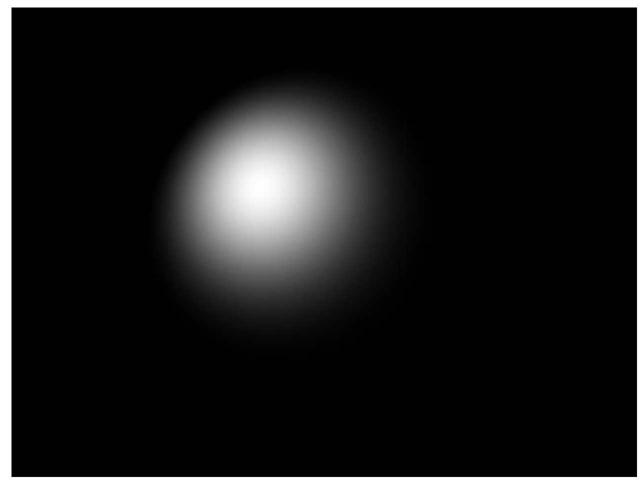
Specular & diffuse & ambient



Specular & diffuse



Specular & ambient

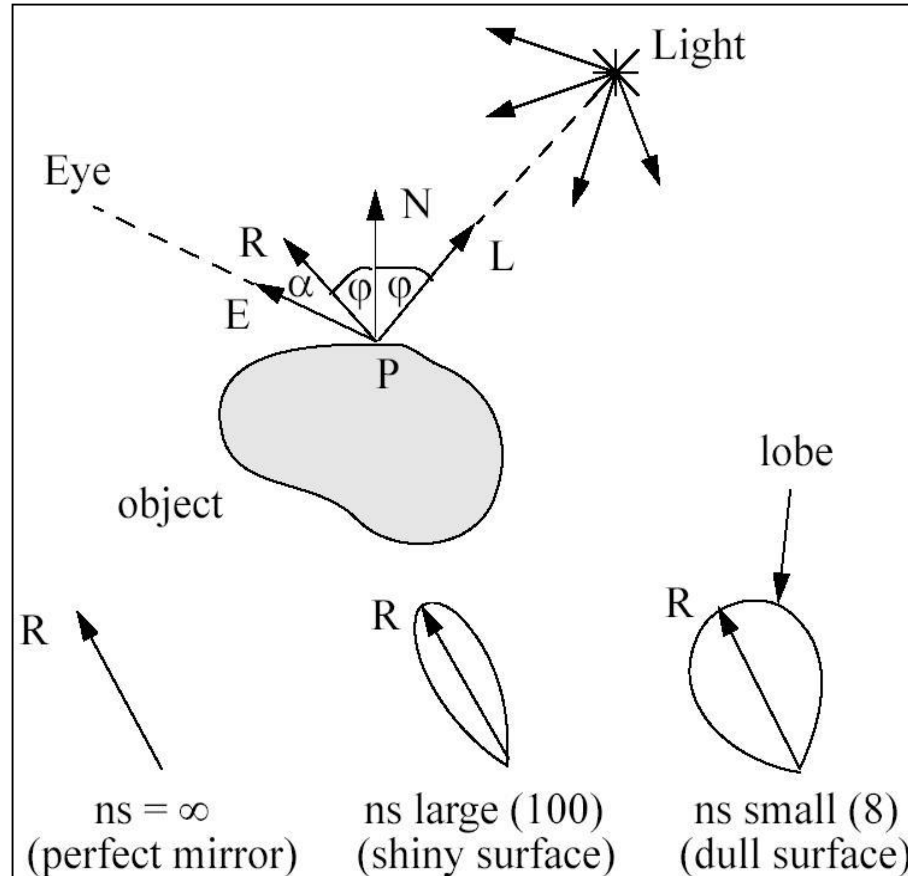


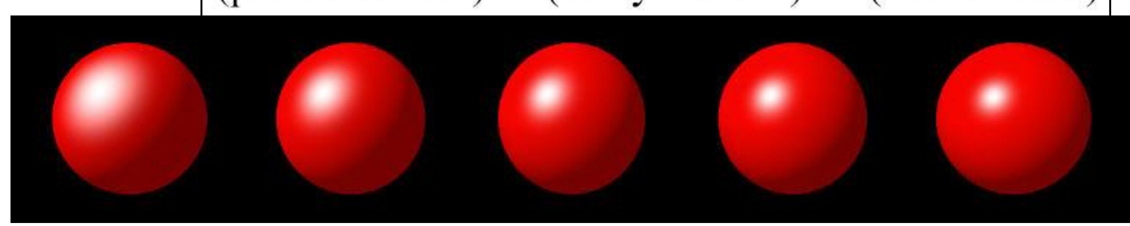
Specular only

- Ideal specular reflector (perfect mirror) reflects light only along reflection vector R
- Non-ideal reflectors reflect light in a lobe centered about R
- Phong specular reflection model:

$$I_s = k_s\, I_L\, (\cos \alpha)^{ns} = k_s\, I_L\, (E \cdot R)^{ns}$$

- cos(α) models this lobe effect
- The width of the lobe is modeled by Phong exponent ns, it scales cos(α)
- I_L: intensity of light source
- L: light vector
- R: reflection vector = 2 N (N·L) - L
- E: eye vector = (Eye-P) / |Eye-P|
- α: angle between E and R
- ns: Phong exponent
- k_s: specular reflection coefficient





increasing *ns* value →

Total Reflected Light

- Total reflected light (for a white object):

$$I = k_a I_A + k_d I_L N \cdot L + k_s I_L (E \cdot R)^{ns}$$

- Multiple light sources:

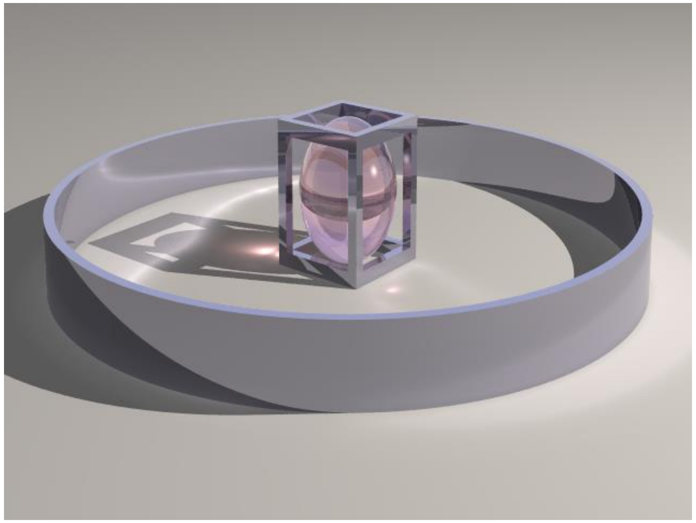
$$I = k_a I_A + \sum_i (k_d I_i N \cdot L_i + k_s I_i (E \cdot R_i)^{ns})$$

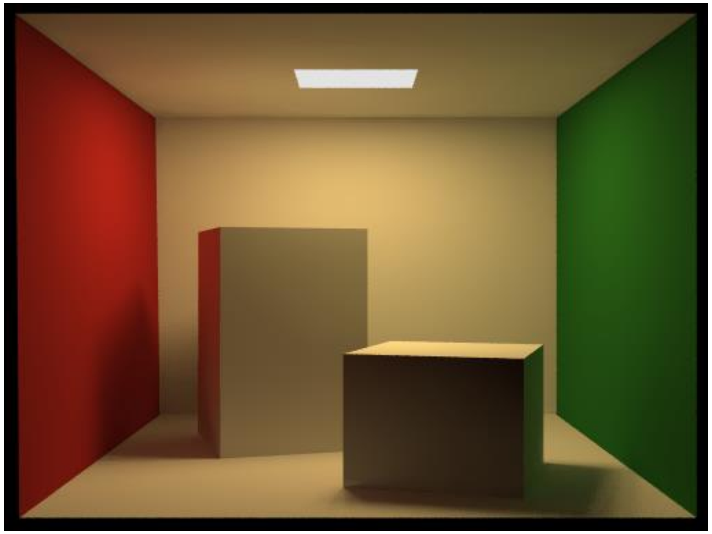
- Usually, I is a color vector of RGB
- Object has color $C_{obj} = (R_{obj}, G_{obj}, B_{obj})$
- Object reflects I, modulated by C_{obj}
- Color C reflected by object:

$$C = C_{obj}(k_a I_A + \sum_i (k_d I_i N \cdot L_i)) + \sum_i (k_s I_i (E \cdot R_i)^{ns})$$

- In many applications, the specular color is not modulated by object color
  - specular highlight has the color of the light source
- k_s, k_d, k_a in [0.0, 1.0]
- R,G,B in [0.0, 1.0]. Remapped to [0, 255] for display
- See Foley chapter 16 for the various formulae and computations

Other Shading and Illumination Concepts/Effects

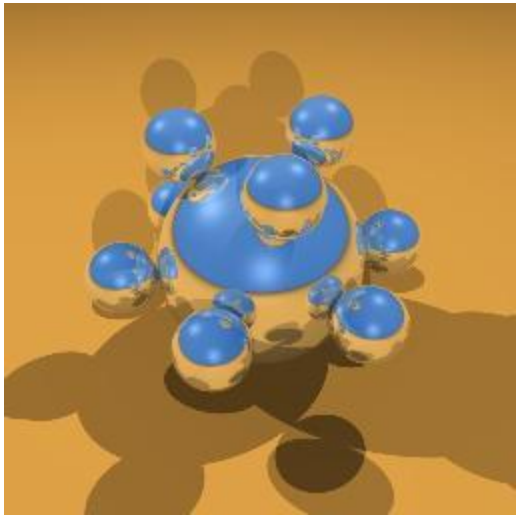


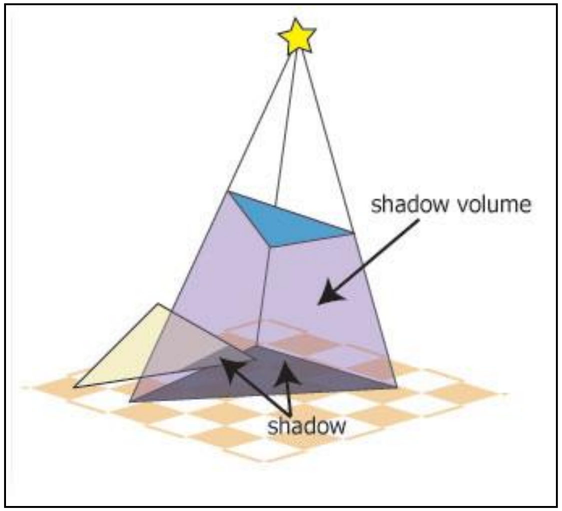


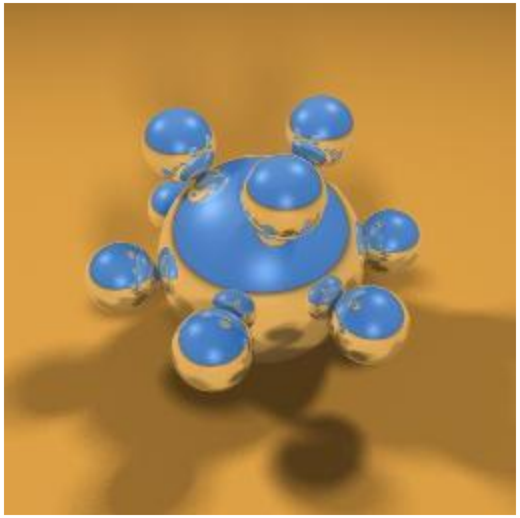
- Area lights
- Shadows
- Refraction
- Reflection
- Caustics
- Color bleeding
- Radiosity
- Camera effects
- …and many, many more!
- Most fall under the general area of *global illumination*, which is capable of generating all those *photorealistic* images you see in movies and special effects
- Most require the use of *ray-tracing*, rather than *ray-casting*, and radiosity
- Want to try it yourself? Go to www.povray.org and try out the free POV-Ray ***surface*** ray-tracing program
- Later in the term we may have time to see how these sophisticated effects can be generalized and used in volume visualization

Shadows

- Hard shadows and soft shadows
- Hard shadows: caused by very distance light sources, like the sun
- Soft shadows: caused by close light sources, usually area light sources, like light bulbs
- Different techniques for generating shadows
- Depend on whether we are using traditional graphics rendering techniques or ray-tracing
- Ray-tracing techniques often employ *shadow volumes*
- Cast rays from *light source* to the object: occluded objects lie in a volumetric region of space that is in shadow







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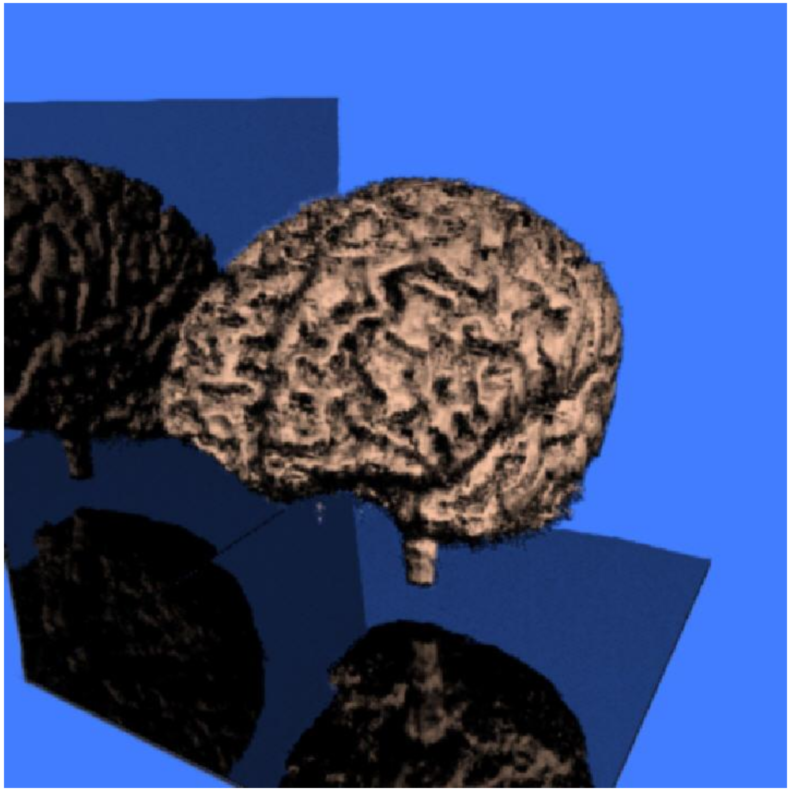
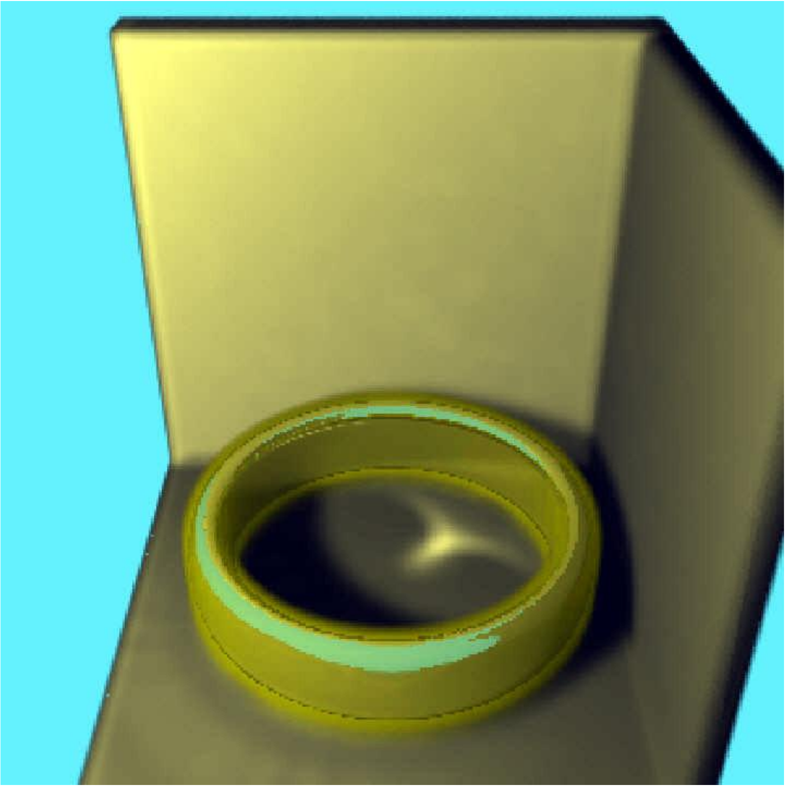
Global Illumination for Volume Visualization



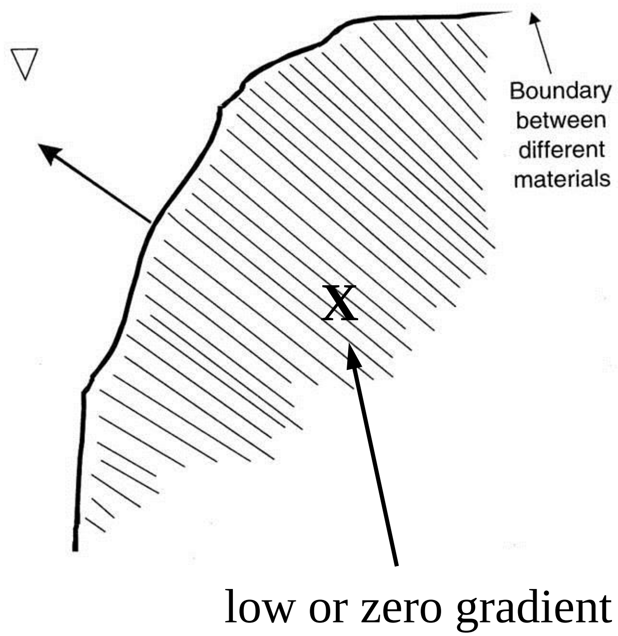


Integrating Shading Model with Volume Visualization

- All of these shading models can be adapted to generate very effective volume renderings
- In polygon rendering, we compute the shading information for each vertex or pixel
- In volume rendering, we perform the shading calculations for each voxel
- But what about the normal vectors?
- We can assign a direction at each voxel using the voxel's *gradient*, which is the indication of greatest change of the dataset
- Let's look at what the gradient is and how to compute it

What is the Gradient

- Gradient is a vector that measures how quickly voxel intensities in a data set change
- Evaluated at some 3D point in space
- Useful for revealing certain characteristics about the data set
- Consider the engine with the two different types of metal of differing densities
- The gradient will be high at those voxels at the boundary where the two metals meet
- In regions where the material is constant, the gradient is zero because there is no change
- Hence, gradient is the vector of first derivatives in the *x*, *y* and *z* directions



Gradient Definition

- Let's define a function $f\,(x,y,z)$ that returns the value of the data-set at the given position
- If (x,y,z) lies on the grid, then we just return its value
- Otherwise, interpolate the value
- The gradient is therefore:

$$\nabla f(x,y,z) = \begin{bmatrix} \frac{df}{dx} \\ \frac{df}{dy} \\ \frac{df}{dz} \end{bmatrix}$$

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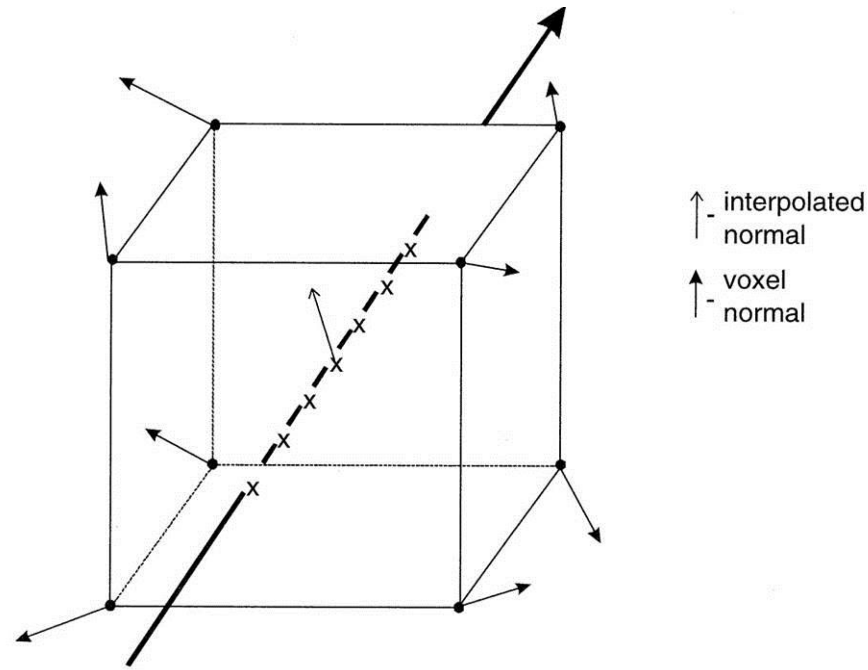
Gradient Interpolation

- As we march along the ray, we interpolate the densities in order to assign colors to samples
- We can also interpolate the gradients
- At the start of the algorithm, we compute the gradient at each voxel
- During ray traversal, we employ trilinear interpolation to estimate the gradient at the sample position
- Note that gradient is invariant of the illumination model, light positions, etc.
- Like the densities, the gradients are intrinsic attributes of the models
- In contrast, colors and opacities can be changed at run-time since they are actually not part of the data



- Later we will look at *compositing* more closely to see exactly how we mathematically accumulate colors and opacities, and how shading is incorporated

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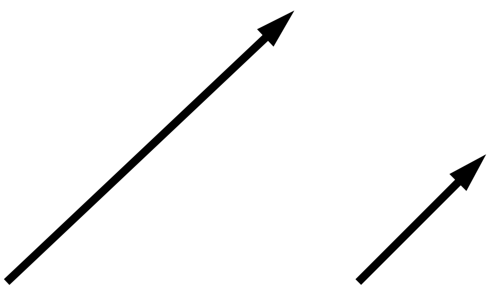
Gradient Magnitude

- The gradient gives both the direction and magnitude of the rate of change in the intensities
- Sometimes we need only the magnitude, sometimes just the direction, sometimes we need both
- It depends on the volume rendering algorithm we are using and which stage of the algorithm we are currently executing
- Gradient magnitude:

$$\left|\nabla f(x,y,z)\right| = \sqrt{\left(\frac{df}{dx}\right)^2 + \left(\frac{df}{dy}\right)^2 + \left(\frac{df}{dz}\right)^2}$$



Same direction, different magnitude

Same magnitude, different direction

Gradient Computation

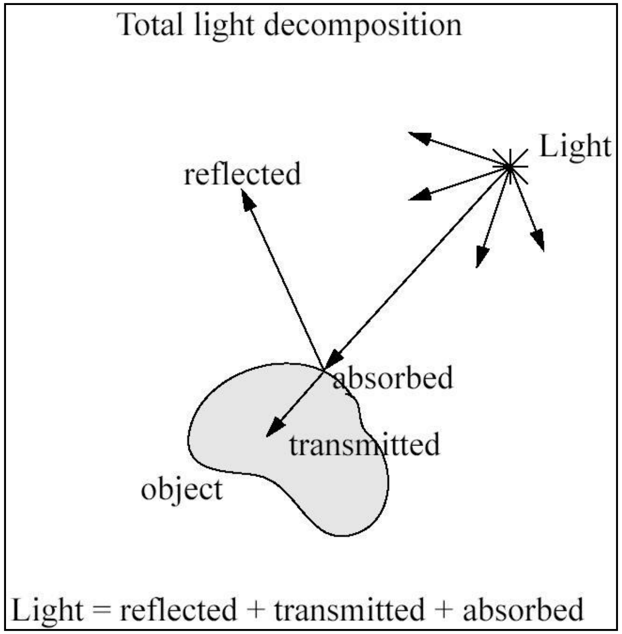
- In calculus, often we can calculate the gradient analytically because we are given a continuous function
- 99% of the time in volume visualization we are dealing with discrete data, so we need to estimate the gradient somehow
- The most popular technique is called *central differences*
- The central difference gradient operator at point (x,y,z) is defined as

$$D_x = f(x-1, y, z) - f(x+1, y, z)$$
$$D_y = f(x, y-1, z) - f(x, y+1, z)$$
$$D_z = f(x, y, z-1) - f(x, y, z+1)$$

- The gradient at (x,y,z) is therefore: $D(x,y,z) = [D_x\ D_y\ D_z]^T$
- Note that sometimes we normalize the gradient by dividing it by its length to generate a unit vector: $D/|D|$
- Our decision to normalize the gradient depends on our reason for computing the gradient in the first place
- Throughout future discussion it will be clear when we are using the normalized or un-normalized gradient

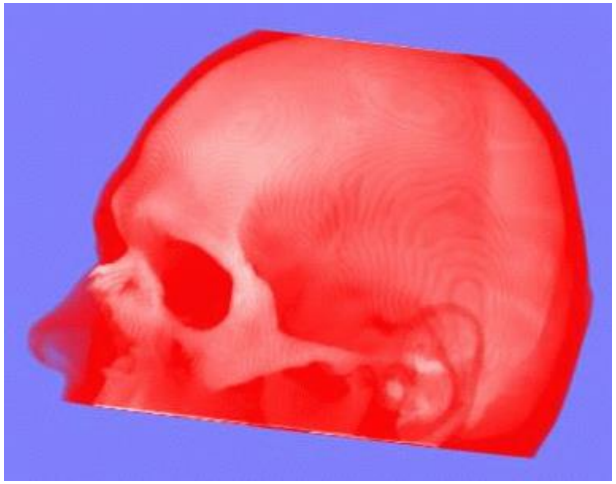
Why Volumetric Shading (What's the Point)?

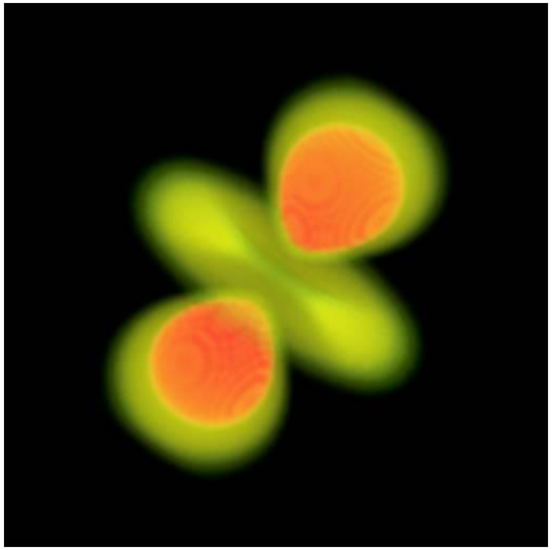
- The gradient allows us to assign a direction vector to each voxel
- This (normalized) vector is used just like the normal vector in surface graphics
- It will modulate the color we assign to samples and thereby allow us to create 3D effects
- Look at the skull on the right
- It looks 3D because we have incorporated diffuse reflection into the illumination model
- The light source is in front of the volume, which causes the top and sides of the skull to look rounded, which they are!
- Voxels whose gradient vectors make a large angle with the light ray appear darker

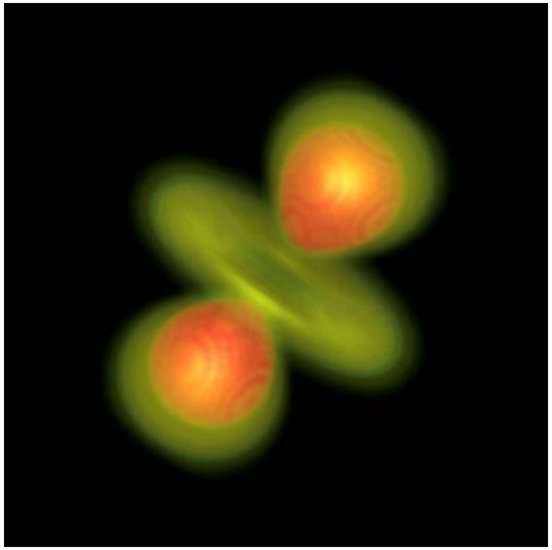


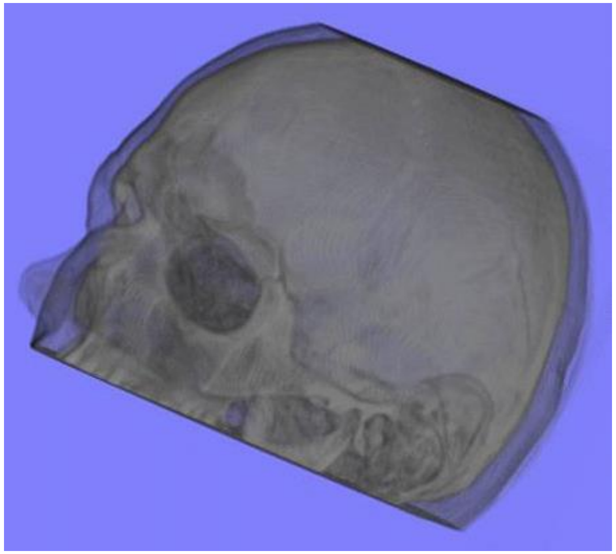
Volumetric Shading

- Volumetric shading is useful not only for viewing surfaces implied by the data (e.g., skull/skin boundary), but also for semitransparent renderings, especially when combined with good R, G, B, A transfer functions
- Compare:



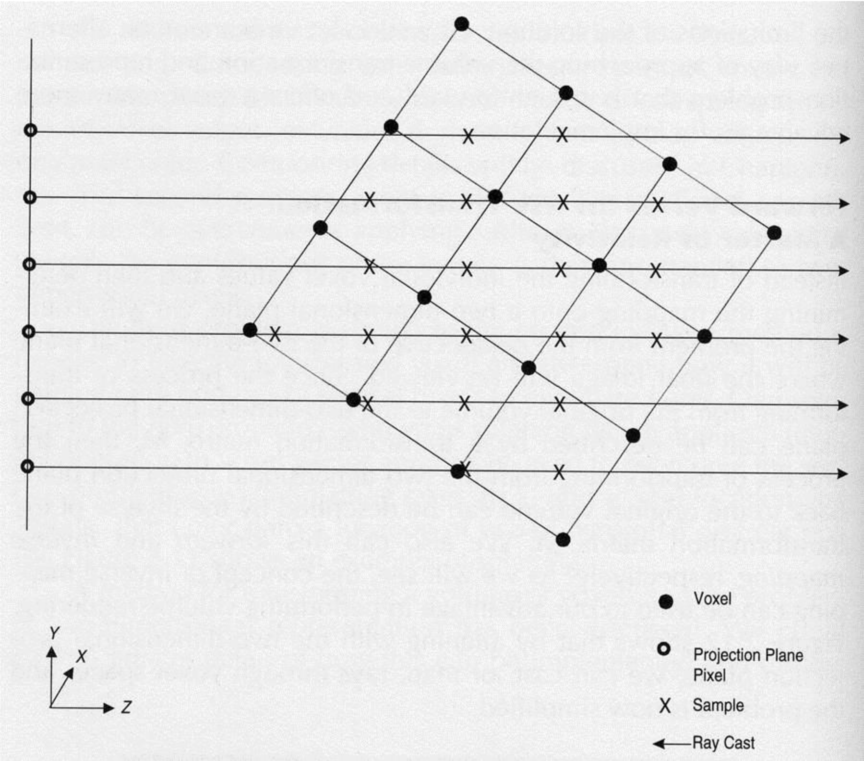






Volumetric Shading

- When we looked at X-ray and maximum intensity projection, we learned about compositing, which is the process for accumulating data along the viewing rays
- But how do we incorporate color, opacity and shading information?
- First we interpolate the density at a given sample position
- Then we assign a color and opacity to each the sample, and shade using the interpolated gradient
- When we shoot the rays through the volume, we have to blend all these samples together, …



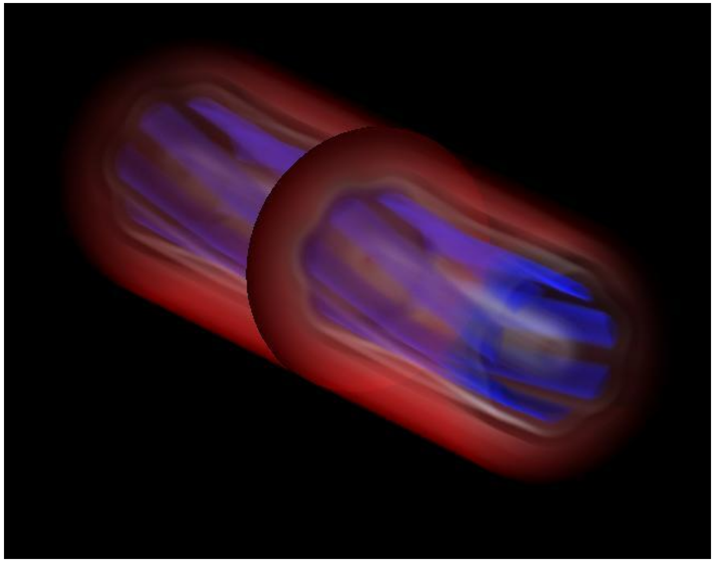
- We'll see how this is done in the near future

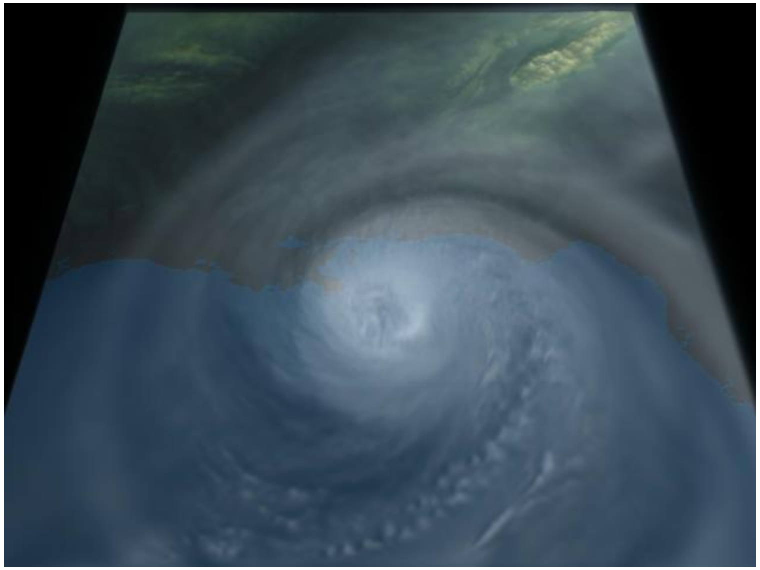
Handling Ambient and Diffuse Shading

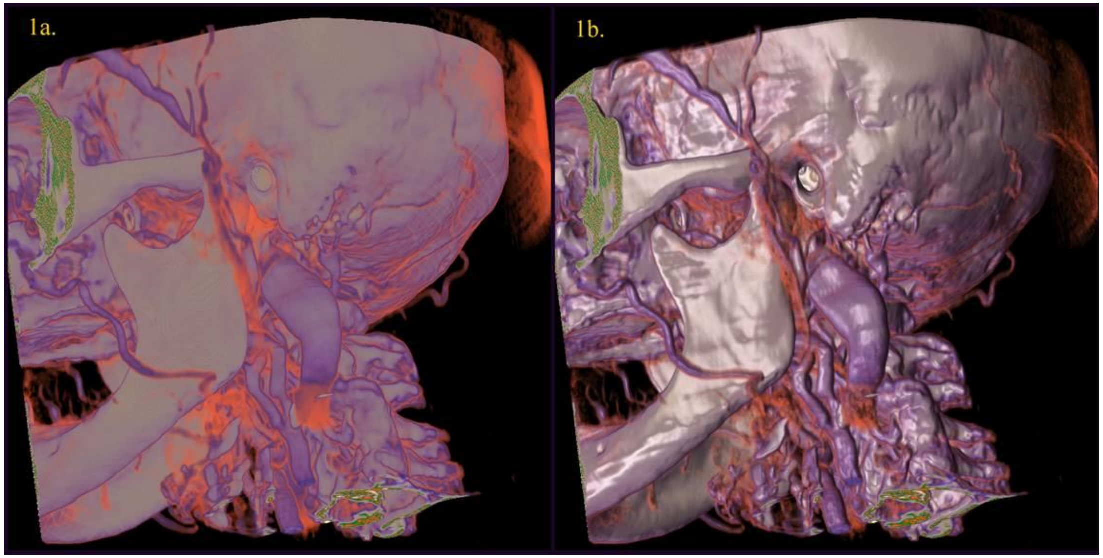
$$C = C_{obj}(k_a I_A + k_d I_L N \cdot L)$$

- You should be capable of implementing ambient and diffuse shading for a single light source
- Extra credit to implement Phong shading terms
- The normal vector N is replaced by the estimated gradient D
- Make sure you remember to normalize the gradients for the shading computations or else the volumes will come out either much darker or much brighter than you expect
- The dot product ($N \cdot L$) should be between [-1, +1]
- What if it's 0? What does that mean?
- How about if it's negative? What should you do in this situation?

More Volume Shading Examples







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Summary So Far

- Density and gradient interpolation
- Color specification via transfer functions
- Shading and illumination models

- Q: How do we put this all together?
- A: Compositing.
- Compositing is what will enable us to shoot the viewing rays through the volume, accumulating color and opacity as we go, in order to generate the final rendered image

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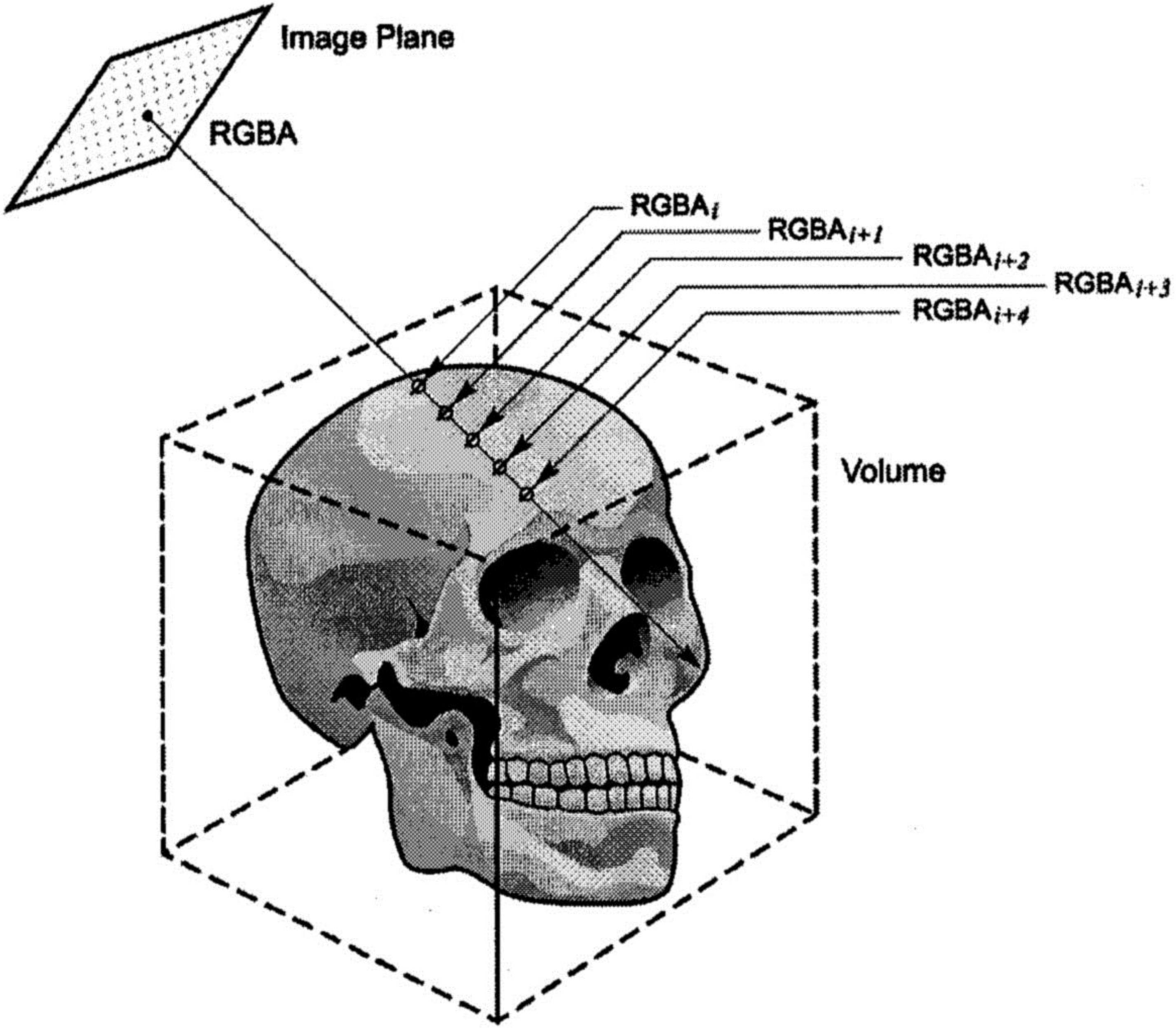
Compositing Overview



Compositing

- Recall the continuous and discretized forms of the X-ray integral:

$$I_{i,j} = \int_0^L f(P_{i,j} + t \cdot r_{i,j})dt$$

$$I_{i,j} = \sum_{k=0}^{L/\Delta t} f(P_{i,j} + k \cdot \Delta t \cdot r_{i,j}) \cdot \Delta t$$

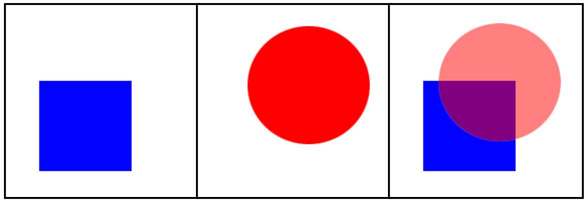
- Compositing (i.e., accumulation of densities) was simply the addition of interpolated densities along the ray
- In essence, each sample was assigned the same opacity
- We know now that in general volume rendering, we can use transfer functions to assign opacities and colors as desired
- Compositing in general is a more sophisticated process, which we need to investigate carefully
- Without a proper formulation for accumulating colors and opacities, our rendered images won’t turn out as we expect

Compositing

- More specifically, compositing is the accumulation of colors weighted by opacities; we weight by opacity in order to support semitransparent rendering
- Suppose we had two images we wanted to composite (blend) together
- Colors and opacities of back pixels are attenuated by opacities of front pixels:

$$rgb_{new} = RGB_{back} \cdot \alpha_{back} (1 - \alpha_{front}) + RGB_{front} \cdot \alpha_{back}$$

$$\alpha_{new} = \alpha_{back} \cdot (1 - \alpha_{front}) + \alpha_{front}$$



- By combining terms for efficiency we get:

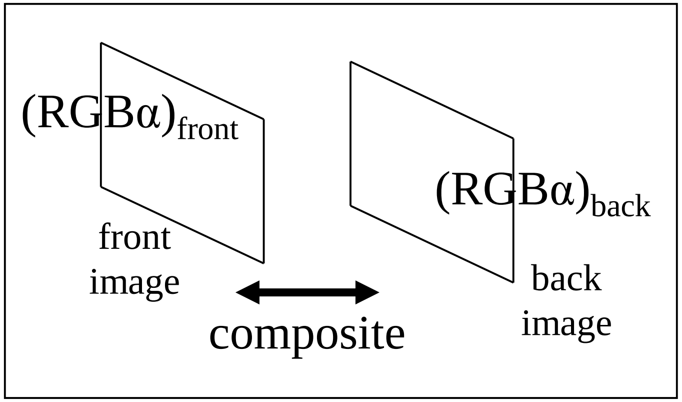
$$rgb_{back} = RGB_{back} \cdot \alpha_{back}$$

$$rgb_{front} = RGB_{front} \cdot \alpha_{front}$$

two recursive equations that can be used to composite any number of objects front-to-back:

$$rgb_{new\_front} = rgb_{back} \cdot (1 - \alpha_{front}) + rgb_{front}$$

$$\alpha_{new\_front} = \alpha_{back} \cdot (1 - \alpha_{front}) + \alpha_{front}$$



- Volume rendering uses this recursive expression to combine (=composite) the samples taken along the ray
- You can see why opacity plays such an important role in this process

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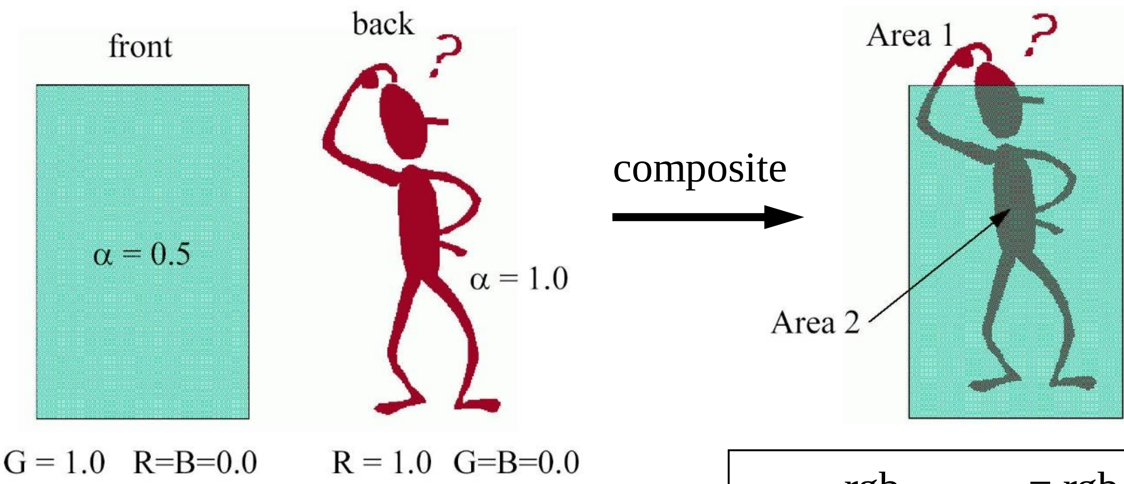
Compositing Example



$$rgb_{new\_front} = rgb_{back}\,(1 - \alpha_{front}) + rgb_{front}$$
$$\alpha_{new\_front} = \alpha_{back}\,(1 - \alpha_{front}) + \alpha_{front}$$

Area 1:

$\{r, g, b\}_{front} = \{0.0, 0.0, 0.0\}$

$\{r, g, b\}_{back} = \{1.0, 0.0, 0.0\}$

$\{r, g, b\}_{new\_front} =$

$\{1.0\,(1 - 0.0) + 0.0,$
$0.0\,(1 - 0.0) + 1.0,$
$0.0\,(1 - 0.0) + 0.0\}$
$= \{1.0, 0.0, 0.0\}$

$\alpha_{new\_front} = 1.0\,(1 - 0.0) + 0.0 = 1.0 = \alpha_{back}$

Area 2:

$\{r, g, b\}_{front} = \{0.0, 0.5, 0.0\}$

$\{r, g, b\}_{back} = \{1.0, 0.0, 0.0\}$

$\{r, g, b\}_{new\_front} =$

$\{1.0\,(1 - 0.5) + 0.0,$
$0.0\,(1 - 0.5) + 1.0,$
$0.0\,(1 - 0.5) + 0.0\}$
$= \{0.5, 0.5, 0.0\}$

$\alpha_{new\_front} = 1.0\,(1 - 0.5) + 0.5 = 1.0$

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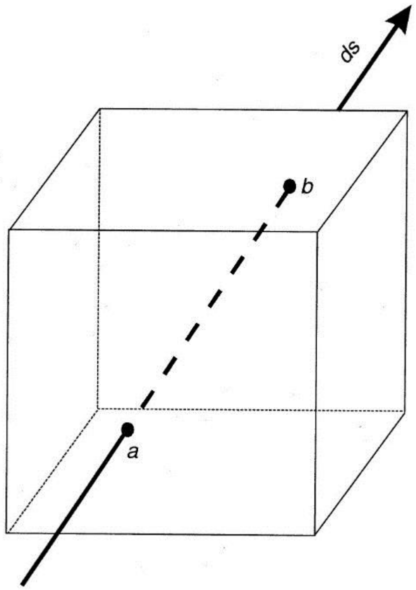
Ray Casting Integral

- We've looked at particular ray casting integrals: for X-ray rendering, and MIP rendering
- These are special cases of the general ray casting integral, which incorporates user-defined color, opacity and shading information
- The general ray casting integral is:

$$I(a,b) = \int_a^b g(s) e^{-\int_a^s \tau(s)\,dx} ds$$



- *I(a,b)* is the intensity (not exactly color) of one pixel
- *ds* is the direction of the ray
- The ray runs from *a* to *b*
- *g(s)* is the source term (describes the illumination model)
- *τ(x)* is the extinction coefficient that describes the rate that light is occluded per unit length due to scattering or extinction of light (i.e., voxel transparency)
- *g(s)* incorporates the color transfer functions, *τ(x)* incorporates the opacity transfer function

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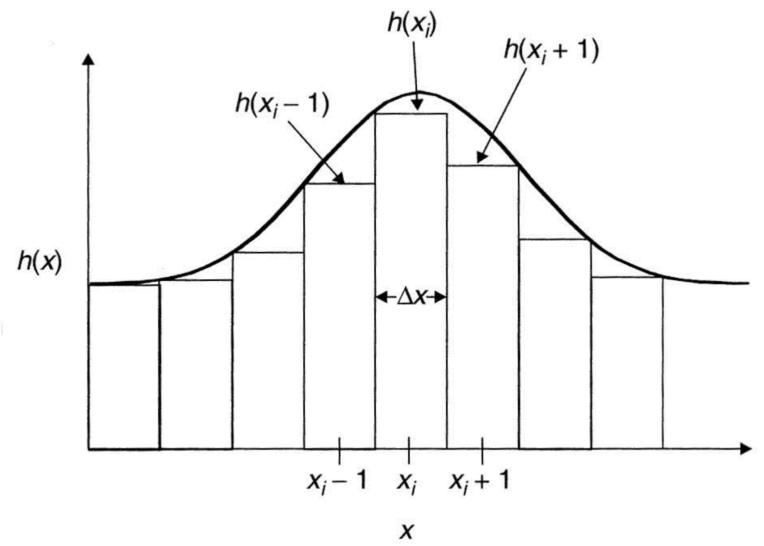
Integral Discretization

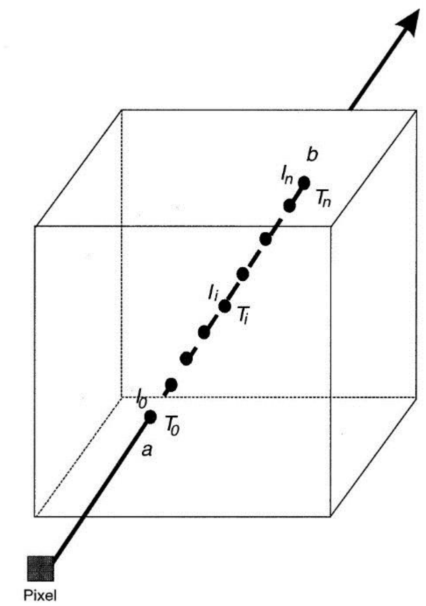
- In order to evaluate any definite integral in a computer, we need to discretize it
- One popular technique is to use a *Riemann sum*.

$$\int_0^d h(x)dx \approx \sum_{i=0}^{n} h(x_i)\Delta x$$



- Step size is Δx, and we assume the value inside an interval is constant
- Suppose we have computed the color and opacity on one ray at discrete sample points
- The discrete ray integral becomes:

$$I(a,b) = \sum_{i=0}^{n} I_j \prod_{j=0}^{i-1} T_j$$

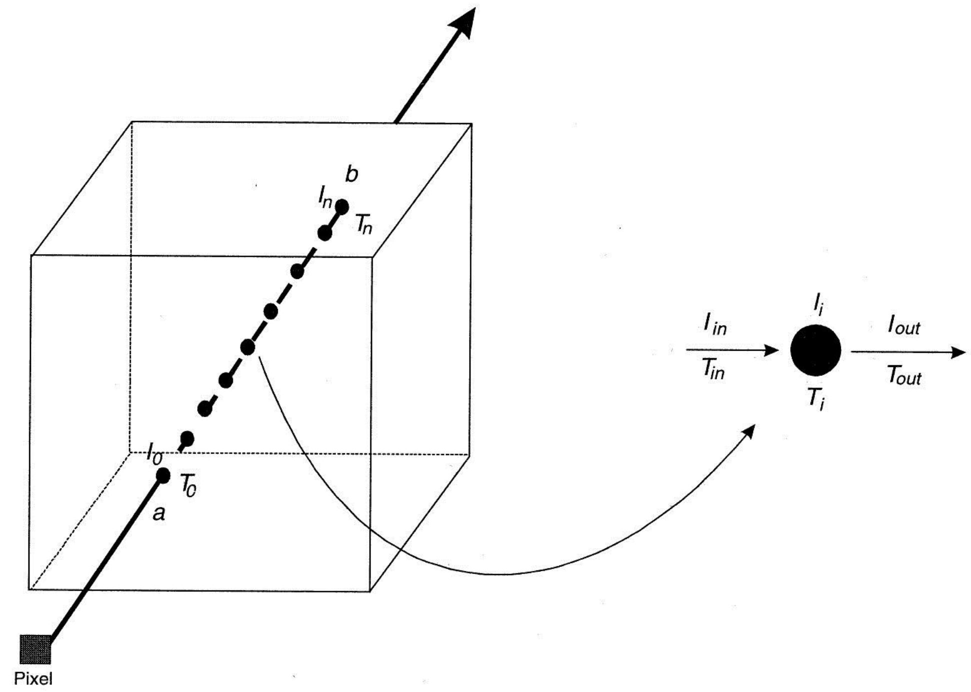


- I_i is the total light emitted (intensity) of a point at position *i* on the ray
- T_j is the transparency (1 – opacity or 1 – α)

Compositing

$$I(a,b) = \sum_{i=0}^{n} I_j \prod_{j=0}^{i-1} T_j$$

- Intuitively, the equation tells us that the total intensity I accumulated on one ray at the current sample point is the intensity I_i multiplied with all the transparencies $(1 - \alpha_j)$ encountered so far on the ray
- Thus, I_i is weighted by all preceding sample points
- The intensity is not the color, but rather the color times opacity at the sample point: $I_i = C_i \bullet \alpha_i$
- This is not the only way to define intensity, but it is the most common
- The colors are determined using the transfer functions and modulated using the illumination model, if any
- So we composite samples that have been both classified and shaded



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Compositing Implementation

$$I(a,b) = \sum_{i=0}^{n} I_j \prod_{j=0}^{i-1} T_j$$

```
Trans = 1.0;
Inten = I[0];  // I[0..n] stores the intensities of the sample points

for (i = 1; i <= n; i++)
{
        Trans = Trans * T[i-1];  // T[0..n] stores sample point transparencies
        Inten = Inten + Trans * I[i];
}
```

- We should break the loop when *Trans* equals zero or gets very close. This is the same as saying we should stop when opacity hits almost 1.0
- This optimization is called *early ray termination*
- Remember that intensity is color times opacity

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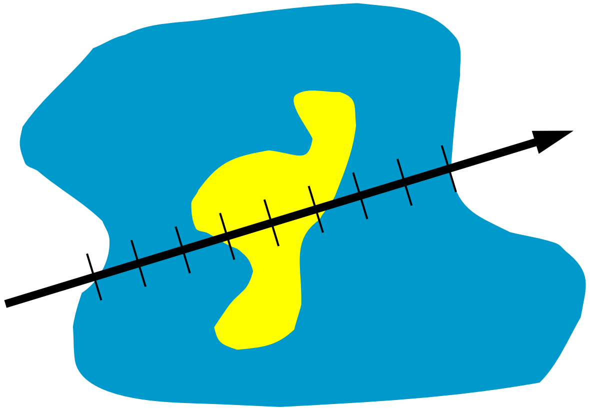
Full Volume Rendering

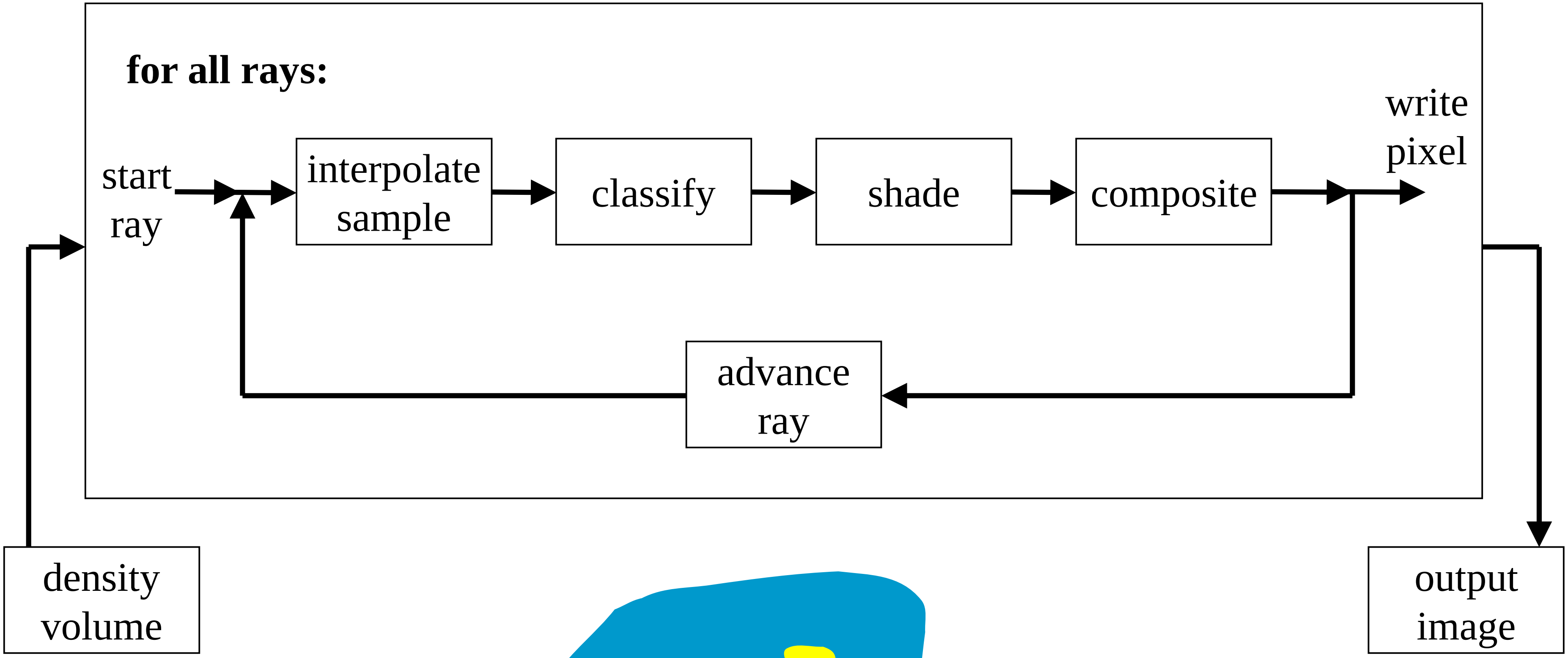


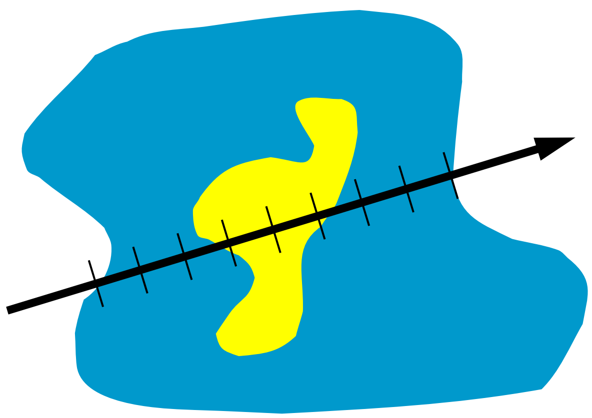
- We have looked a number of tasks:
- Interpolation
- Classification
- Shading
- Compositing
- In volume rendering, we will use them in the following algorithm:
- Along each viewing ray:

1. Interpolate density at current ray position
2. Classify interpolated density to assign color and opacity
3. Shade interpolated density to modulate color, depending on the shading and illumination parameters/model
4. Composite the classified and shaded sample
5. Advance ray to the next interpolated position and go to step 1

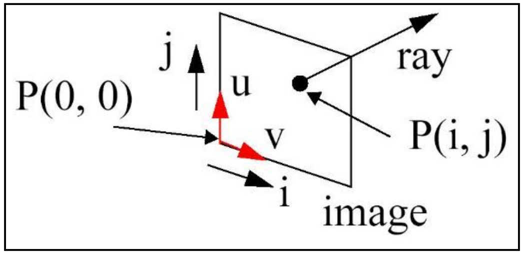
- We stop when the accumulated opacity reaches 1.0 on the ray

Full Volume Rendering





Full Volume Rendering: Algorithm for Orthographic Viewing



FullVolRenOrtho(Volume V, int stepSize, Image I)

```
ray = u x v / | u x v| // vector perpendicular to camera plane
for each image pixel i, j
    P(i, j) = P(0, 0) + i · v + j · u; // the location of image pixel (i, j) in world (volume) space
    {r, g, b} = 0, α = 0; // initialize red, green, blue color and opacity α to 0
    for (t = t_front; t <= t_back; t += stepSize) // traverse the volume front to back
        sampleLoc = P(i, j) + t · stepSize · ray; // step along the ray
        intVal = Interpolate(V, sampleLoc);
        if (AlphaTransFunc(intVal) > 0.05) // only do work for non-transparent samples
            gradVec = ComputeGradientVector(V, sampleLoc);
            {R,G,B}=Shade(gradVec, lightSource, eye, sampleLoc, {R,G,B}TransFunc(intVal));
            {r, g, b}=AlphaTransFunc(intVal) · {R,G,B} · (1 - α) + {r, g, b}; // composite color
            α = AlphaTransFunc(intVal) · (1 - α) + α; // composite opacity
            if (α > 0.95) // everything further is hidden and can't be seen, so stop the ray
                I(i, j) = {r, g, b}; break; // write color to image pixel and go to next pixel
```

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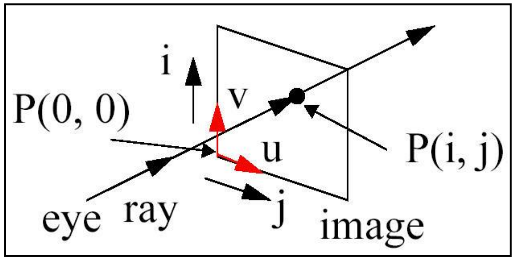
Full Volume Rendering: Algorithm for Perspective Viewing

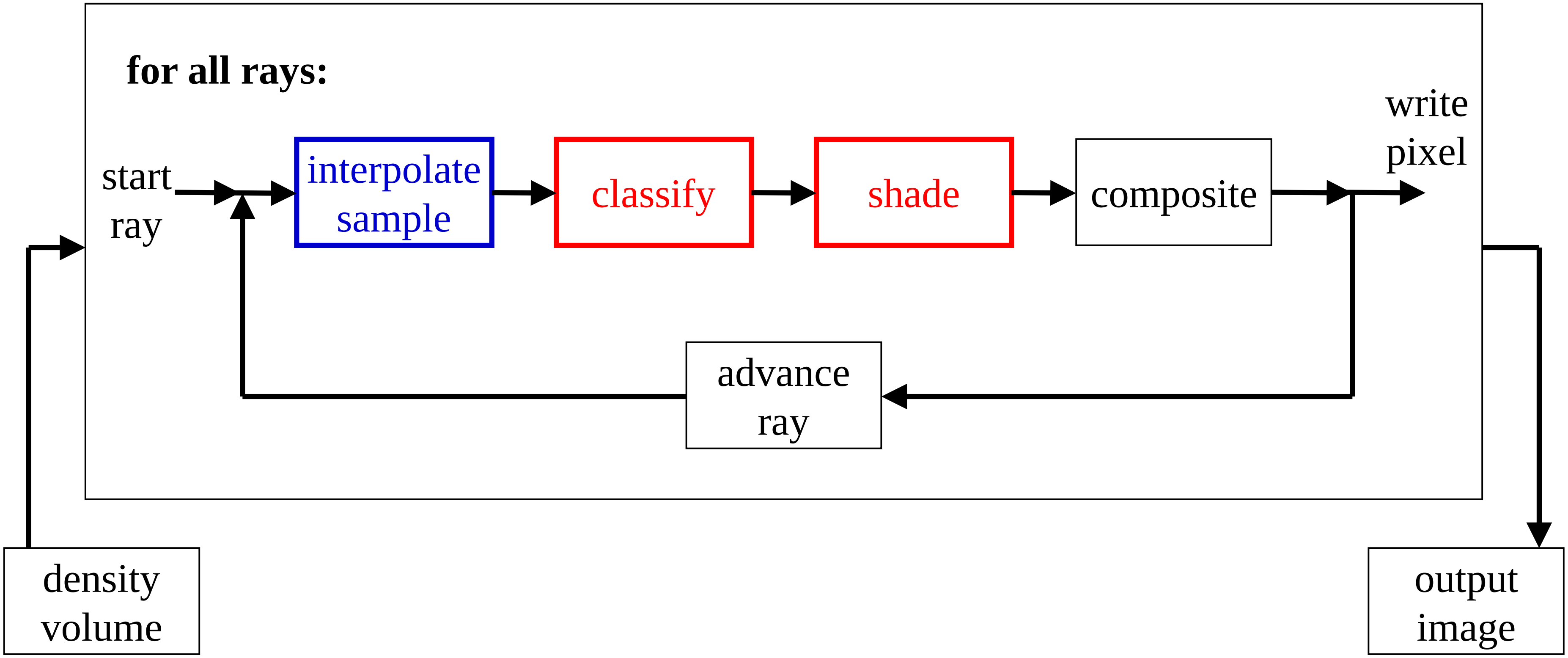


FullVolRenPersp(Volume V, int stepSize, Image I)

```
for each image pixel i, j
    ray = (P(i, j) - eye) / | (P(i, j) - eye) | // the ray direction vector, normalized
    P(i, j) = P(0, 0) + i · v + j · u; // the location of image pixel (i, j) in world (volume) space
    {r, g, b} = 0, α = 0; // initialize red, green, blue color and opacity α to 0
    for (t = t_front; t <= t_back; t += stepSize) // traverse the volume front to back
        sampleLoc = P(i, j) + t · stepSize · ray; // step along the ray
        intVal = Interpolate(V, sampleLoc);
        if (AlphaTransFunc(intVal) > 0.05) // only do work for non-transparent samples
            gradVec = ComputeGradientVector(V, sampleLoc)
            {R,G,B}=Shade(gradVec, lightSource, eye, sampleLoc, {R,G,B}TransFunc(intVal));
            {r, g, b}=AlphaTransFunc(intVal) · {R,G,B} · (1 - α) + {r, g, b}; // composite color
            α = AlphaTransFunc(intVal) · (1 - α) + α; // composite opacity
            if (α > 0.95) // everything further is hidden and can't be seen, so stop the ray
                I(i, j) = {r, g, b}; break; // write color to image pixel and go to next pixel
```

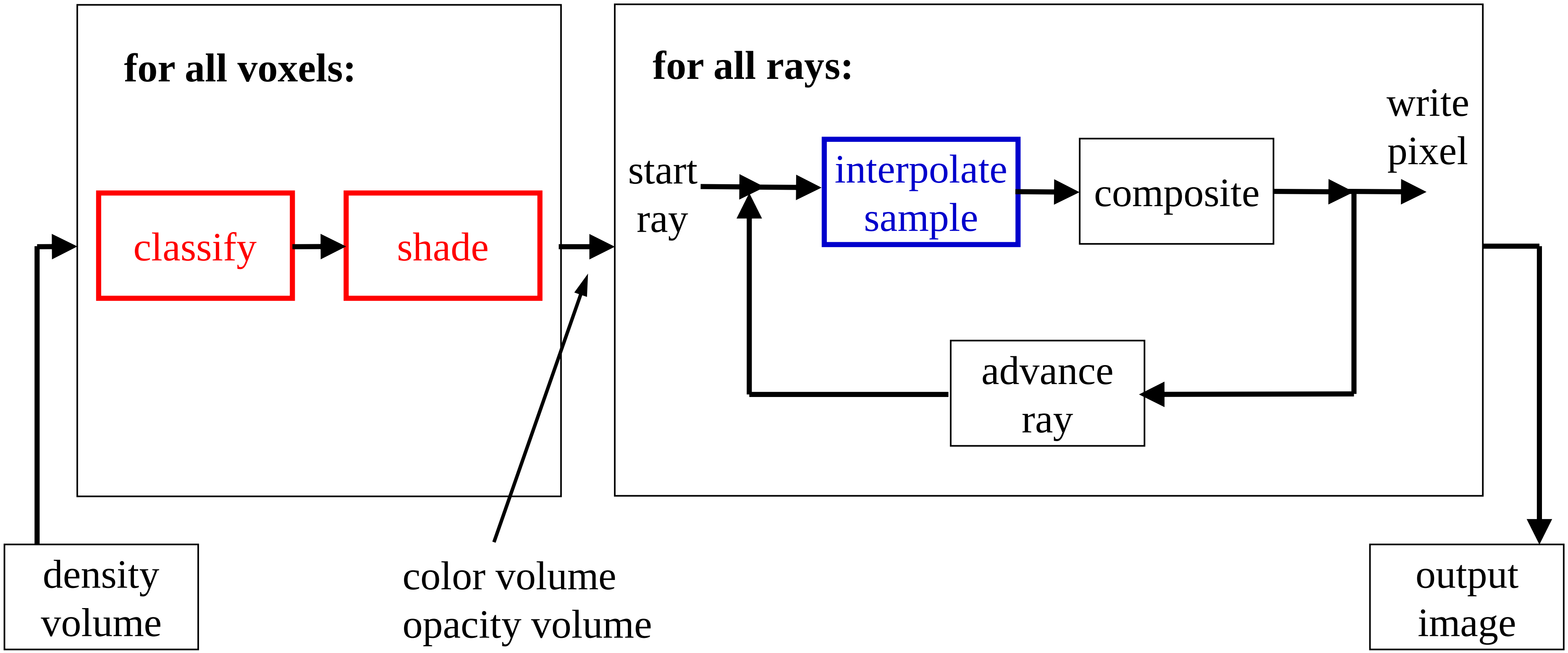
Full Volume Rendering

- This volume rendering framework is known as the *post-shaded pipeline*
- Classification and shading are performed after interpolation and sampling



Pre-shaded Pipeline

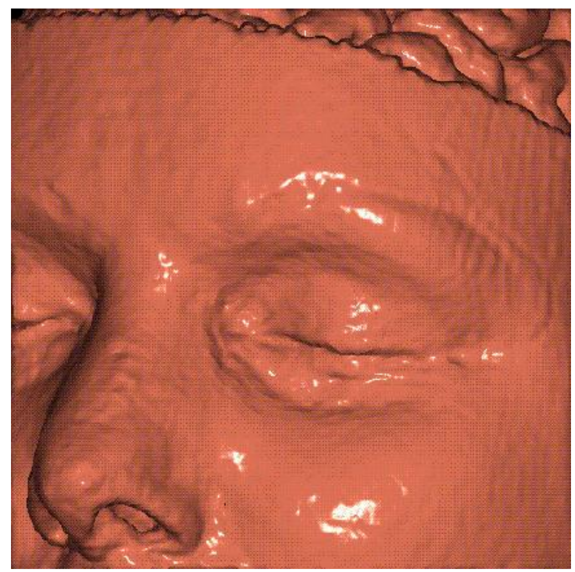
- The other possibility is to perform interpolation after classification and shading
- This is known as the *pre-shaded pipeline*



Which one is Better: Pre vs Post-Shading?

- Pre-shading is potentially faster because we can classify and shade all voxels before ray casting starts and then just interpolate the colors along the rays at sample positions
- With post-shading, we perform the classification during ray-traversal, which is more expensive
- However, pre-shading introduces blurring artifacts

pre-shaded



post-shaded

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What Causes the Blurring?