Transformations
And
Color
2D Translation

- Component-wise addition of vectors

\[ v' = v + t \quad \text{where} \quad v = \begin{bmatrix} x \\ y \end{bmatrix}, \quad v' = \begin{bmatrix} x' \\ y' \end{bmatrix}, \quad t = \begin{bmatrix} dx \\ dy \end{bmatrix} \]

and

\[ x' = x + dx \]

\[ y' = y + dy \]

To move polygons: translate vertices (vectors) and redraw lines between them

- Preserves lengths (isometric)
- Preserves angles (conformal)
- Translation is thus "rigid-body"
Component-wise scalar multiplication of vectors:

\[ v' = S v \]

where \( v = \begin{bmatrix} x \\ y \end{bmatrix}, \quad v' = \begin{bmatrix} x' \\ y' \end{bmatrix} \)

and \( S = \begin{bmatrix} s_x & 0 \\ 0 & s_y \end{bmatrix} \)

\[ x' = s_x x \]
\[ y' = s_y y \]

- Does not preserve lengths
- Does not preserve angles (except when scaling is uniform)

Side effect: House shifts position relative to origin.
2D Rotation

\[ v' = R_\theta v \]

where \[ v = \begin{bmatrix} x \\ y \end{bmatrix}, \quad v' = \begin{bmatrix} x' \\ y' \end{bmatrix} \]

and \[ x' = x \cos \theta - y \sin \theta \]
\[ y' = x \sin \theta + y \cos \theta \]

**NB:** A rotation by 0 angle, i.e. no rotation at all, gives us the identity matrix

- Proof by sine and cosine summation formulas
- Preserves lengths in objects, and angles between parts of objects
- Rotation is rigid-body
2D Rotation and Scale are Relative to Origin

- Suppose object is not centered at origin and we want to scale and rotate it.
- Solution: move to the origin, scale and/or rotate in its local coordinate system, then move it back.

This sequence suggests the need to compose successive transformations...
Homogenous Coordinates

- Translation, scaling and rotation are expressed as:
  
  translation: \( \mathbf{v}' = \mathbf{v} + t \)

  scale: \( \mathbf{v}' = S\mathbf{v} \)

  rotation: \( \mathbf{v}' = R\mathbf{v} \)

- Composition is difficult to express
  
  - translation is not expressed as a matrix multiplication

- Homogeneous coordinates allows expression of all three transformations as 3x3 matrices for easy composition

\[
P_{2d}(x, y) \rightarrow P_h(wx, wy, w), \quad w \neq 0
\]

\[
P_h(x', y', w), \quad w \neq 0
\]

\[
P_{2d}(x, y) = P_{2d}\left(\frac{x'}{w}, \frac{y'}{w}\right)
\]

- \( w \) is 1 for affine transformations in graphics

- Note: \( \mathbf{p} = (x, y) \) becomes \( \mathbf{p} = (x, y, 1) \)

  This conversion does not transform \( \mathbf{p} \). It is only changing notation to show it can be viewed as a point on \( w = 1 \) hyperplane
What is \( \begin{bmatrix} x \\ y \\ w \end{bmatrix} \)?

- \( P_{2d} \) is intersection of line determined by \( P_h \) with the \( w = 1 \) plane.

Infinite number of points correspond to \((x, y, 1)\): they constitute the whole line \((tx, ty, tw)\).
2D Homogeneous Coordinate Transformations (1/2)

- For points written in homogeneous coordinates,

\[
\begin{bmatrix}
  x \\
  y \\
  1
\end{bmatrix}
\]

translation, scaling and rotation relative to the origin are expressed homogeneously as:

\[
T(d_x, d_y) = \begin{bmatrix}
  1 & 0 & d_x \\
  0 & 1 & d_y \\
  0 & 0 & 1
\end{bmatrix}
\]

\[
v' = T(d_x, d_y) v
\]

\[
S(s_x, s_y) = \begin{bmatrix}
  s_x & 0 & 0 \\
  0 & s_y & 0 \\
  0 & 0 & 1
\end{bmatrix}
\]

\[
v' = S(s_x, s_y) v
\]

\[
R(\phi) = \begin{bmatrix}
  \cos \phi & -\sin \phi & 0 \\
  \sin \phi & \cos \phi & 0 \\
  0 & 0 & 1
\end{bmatrix}
\]

\[
v' = R(\phi) v
\]
Examples

• Translate $[1,3]$ by $[7,9]$

\[
\begin{bmatrix}
1 & 0 & 7 \\
0 & 1 & 9 \\
0 & 0 & 1 \\
\end{bmatrix} \cdot \begin{bmatrix}
1 \\
3 \\
1 \\
\end{bmatrix} = \begin{bmatrix}
8 \\
12 \\
1 \\
\end{bmatrix}
\]

• Scale $[2,3]$ by 5 in the X direction and 10 in the Y direction

\[
\begin{bmatrix}
5 & 0 & 0 \\
0 & 10 & 0 \\
0 & 0 & 1 \\
\end{bmatrix} \cdot \begin{bmatrix}
2 \\
3 \\
1 \\
\end{bmatrix} = \begin{bmatrix}
10 \\
30 \\
1 \\
\end{bmatrix}
\]

• Rotate $[2,2]$ by $90^\circ (\pi/2)$

\[
\begin{bmatrix}
\cos(\pi/2) & -\sin(\pi/2) & 0 \\
\sin(\pi/2) & \cos(\pi/2) & 0 \\
0 & 0 & 1 \\
\end{bmatrix} \cdot \begin{bmatrix}
2 \\
2 \\
1 \\
\end{bmatrix} = \begin{bmatrix}
0 & -1 & 0 \\
1 & 0 & 0 \\
0 & 0 & 1 \\
\end{bmatrix} \cdot \begin{bmatrix}
2 \\
2 \\
1 \\
\end{bmatrix} = \begin{bmatrix}
-2 \\
2 \\
1 \\
\end{bmatrix}
\]
2D Homogeneous Coordinate Transformations (2/2)

- Consider the rotation matrix:

\[
R(\phi) = \begin{bmatrix}
\cos \phi & -\sin \phi & 0 \\
\sin \phi & \cos \phi & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

- The 2 x 2 submatrix columns are:
  - unit vectors (length=1)
  - perpendicular (dot product=0)
  - vectors into which X-axis and Y-axis rotate

- The 2 x 2 submatrix rows are:
  - unit vectors
  - perpendicular
  - vectors that rotate into X-axis and Y-axis

- Preserves lengths and angles of original geometry. Therefore, matrix is a “rigid body” transformation.
Matrix Compositions: Using Translation

• Avoiding unwanted translation when scaling or rotating an object not centered at origin:
  – translate object to origin, perform scale or rotate, translate back.

\[ \text{House}(H) \quad T(dx,dy)H \quad R(\theta)T(dx,dy)H \quad T(-dx,-dy)R(\theta)T(dx,dy)H \]

• How would you scale the house by 2 in “its” y and rotate it through 90°?

\[ \text{House}(H) \quad S(1,2)H \quad R(\pi / 2)S(1,2)H \]

• Remember: matrix multiplication is not commutative! Hence order matters! (refer to the Transformation Game at Demos->Scenegraphs)
Matrix Multiplication is NOT Commutative

Translate by
x=6, y=0 then
rotate by 45°

Rotate by 45°
then translate by
x=6, y=0
3D Basic Transformations (1/2)

(right-handed coordinate system)

- Translation

\[
\begin{bmatrix}
1 & 0 & 0 & dx \\
0 & 1 & 0 & dy \\
0 & 0 & 1 & dz \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

- Scaling

\[
\begin{bmatrix}
s_x & 0 & 0 & 0 \\
0 & s_y & 0 & 0 \\
0 & 0 & s_z & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]
3D Basic Transformations (2/2)

(right-handed coordinate system)

- Rotation about X-axis
  \[
  \begin{bmatrix}
  1 & 0 & 0 & 0 \\
  0 & \cos \theta & -\sin \theta & 0 \\
  0 & \sin \theta & \cos \theta & 0 \\
  0 & 0 & 0 & 1
  \end{bmatrix}
  \]

- Rotation about Y-axis
  \[
  \begin{bmatrix}
  \cos \theta & 0 & \sin \theta & 0 \\
  0 & 1 & 0 & 0 \\
  -\sin \theta & 0 & \cos \theta & 0 \\
  0 & 0 & 0 & 1
  \end{bmatrix}
  \]

- Rotation about Z-axis
  \[
  \begin{bmatrix}
  \cos \theta & -\sin \theta & 0 & 0 \\
  \sin \theta & \cos \theta & 0 & 0 \\
  0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 1
  \end{bmatrix}
  \]
Skew/Shear/Translate (1/2)

- “Skew” a scene to the side:

$$Skew_\theta = \begin{bmatrix} 1 & \frac{1}{\tan \theta} \\ 0 & 1 \end{bmatrix}$$ 

2D non-homogeneous

$$Skew_\theta = \begin{bmatrix} 1 & \frac{1}{\tan \theta} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

2D homogeneous

- Squares become parallelograms - x coordinates skew to right, y coordinates stay same
- $90^\circ$ between axes becomes $\theta$
- Like pushing top of deck of cards to the side – each card shifts relative to the one below
- Notice that the base of the house (at y=1) remains horizontal, but shifts to the right.

![Diagram](image)

$\theta = \frac{\pi}{4}$

NB: A skew of 0 angle, i.e. no skew at all, gives us the identity matrix, as it should
Transformations in Scene Graphs (1/3)

• 3D scenes are often stored in a directed acyclic graph (DAG) called a *scene graph*
  – WPF (implementation not accessible to the programmer)
  – Open Scene Graph (used in the Cave)
  – Sun’s Java3D™
  – X3D™ (VRML™ was a precursor to X3D)

• Typical scene graph format:
  – **objects** (cubes, sphere, cone, polyhedra etc.)
    – stored as nodes (default: unit size at origin)
  – **attributes** (color, texture map, etc.) and **transformations** are also nodes in scene graph
    (labeled edges on slide 2 are an abstraction)
Transformations in Scene Graphs \((2/3)\)

Closer look at Scenegraph from slide 2 ...

1. Leaves of tree are standard size object primitives
2. We transform them
3. To make sub-groups
4. Transform subgroups
5. To get final scene

Slides modified from Andries Van Dam’s Intro to Graphics at Brown U
Transformations in Scene Graphs (3/3)

- Transformations affect all child nodes
- Sub-trees can be reused, called group nodes
  - instances of a group can have different transformations applied to them (e.g. group3 is used twice—once under t1 and once under t4)
  - must be defined before use
Composing Transformations in a Scene Graph (1/2)

- Transformation nodes contain at least a matrix that handles the transformation;
  - may also contain individual transformation parameters

- To determine final composite transformation matrix (CTM) for object node:
  - compose all parent transformations during prefix graph traversal
  - exact detail of how this is done varies from package to package, so be careful
Composing Transformations in a Scene Graph (2/2)

- Example:

- for o1, CTM = m1
- for o2, CTM = m2 * m3
- for o3, CTM = m2 * m4 * m5

- for a vertex v in o3, position in the world (root) coordinate system is:

  CTM v = (m2 * m4 * m5)v
Short Linear Algebra
Digression: Vector and Matrix Notation, A non-Geometric Example (1/2)

Let’s Go Shopping

- Need 6 apples, 5 cans of soup, 1 box of tissues, and 2 bags of chips

- Stores A, B, and C (East Side Market, Whole Foods, and Store 24) have following unit prices respectively

<table>
<thead>
<tr>
<th></th>
<th>1 apple</th>
<th>1 can of soup</th>
<th>1 box of tissues</th>
<th>1 bag of chips</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Side</td>
<td>$0.20</td>
<td>$0.93</td>
<td>$0.64</td>
<td>$1.20</td>
</tr>
<tr>
<td>Whole Foods</td>
<td>$0.65</td>
<td>$0.95</td>
<td>$0.75</td>
<td>$1.40</td>
</tr>
<tr>
<td>Store 24</td>
<td>$0.95</td>
<td>$1.10</td>
<td>$0.90</td>
<td>$3.50</td>
</tr>
</tbody>
</table>
A Non-Geometric Example (2/2)

- Shorthand representation of the situation (assuming we can remember order of items and corresponding prices):

- Column vector for quantities, $q$:

$$
\begin{bmatrix}
6 \\
5 \\
1 \\
2
\end{bmatrix}
$$

- Row vector corresponding prices at stores ($P$):

<table>
<thead>
<tr>
<th>Store</th>
<th>Price vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>store A (East Side)</td>
<td>$[0.20 \ 0.93 \ 0.64 \ 1.20]$</td>
</tr>
<tr>
<td>store B (Whole Foods)</td>
<td>$[0.65 \ 0.95 \ 0.75 \ 1.40]$</td>
</tr>
<tr>
<td>store C (Store 24)</td>
<td>$[0.95 \ 1.10 \ 0.90 \ 3.50]$</td>
</tr>
</tbody>
</table>
What do I pay?

Let’s calculate for each of the three stores.

• **Store A:**

\[
\text{totalCost}_A = \sum_{i=1}^{4} P(A)_i q_i
\]

\[
= (0.20 \cdot 6) + (0.93 \cdot 5) + (0.64 \cdot 1) + (1.20 \cdot 2)
\]

\[
= (1.2 + 4.65 + 0.64 + 2.40)
\]

\[
= 8.89
\]

• **Store B:**

\[
\text{totalCost}_B = \sum_{i=1}^{4} P(B)_i q_i = 3.9 + 4.75 + 0.75 + 2.8
\]

\[
= 12.2
\]

• **Store C:**

\[
\text{totalCost}_C = \sum_{i=1}^{4} P(C)_i q_i = 5.7 + 5.5 + 0.9 + 7 = 19.1
\]
Using Matrix Notation

• Can express these sums more compactly:

\[
P(All) = \begin{bmatrix}
  \text{totalCost}_A \\
  \text{totalCost}_B \\
  \text{totalCost}_C
\end{bmatrix} = \begin{bmatrix}
  0.20 & 0.93 & 0.64 & 1.20 \\
  0.65 & 0.95 & 0.75 & 1.40 \\
  0.95 & 1.10 & 0.90 & 3.50
\end{bmatrix} \begin{bmatrix}
  6 \\
  5 \\
  1 \\
  2
\end{bmatrix}
\]

• Determine totalCost vector by row-column multiplication
  – dot product is the sum of the pairwise multiplications
    • Apply this operation to rows of prices and column of quantities

\[
\begin{bmatrix}
  a & b & c & d
\end{bmatrix} \begin{bmatrix}
  x \\
  y \\
  z \\
  w
\end{bmatrix} = ax + by + cz + dw
\]
Introduction to Color
Framing the Context

• Graphics used to concentrate on interaction, then “photorealism”, which was based on performance-centered hacks
• Now both are important, as is non-photorealistic rendering
• Photorealistic rendering increasingly physically-based and perception-based
• An understanding of the human visual and proprioceptive systems are essential to creating realistic user experiences
Why Study Color in Computer Graphics?

- Physics and measurement for realism
  - what does coding an RGB triple mean?
- Perception and aesthetics for selecting appropriate user interface colors
  - why a bright red and orange striped bedroom is a bad idea
  - how to put on matching pants and shirt in the morning
  - what are perceptual/physical forces driving one’s “taste” in color?
- Color models for providing users with easy color selection
  - systems for naming and describing colors
- Color models, measurement and color gamuts for converting colors between media
  - why colors on your screen may not be printable, and vice-versa
  - managing color in systems with computers, monitors, scanners, and printers
- We study it as useful background for rendering and because it provides a good introduction to signal processing
  - also used for image processing and physically-based rendering
- Graphics group has worked on color tools for Adobe

Slides modified from Andries Van Dam’s Intro to Graphics at Brown U
Why is Color Difficult?

- Color is an immensely complex subject, drawing on physics, physiology, psychology, art, and graphic design.
- Many theories, measurement techniques, and standards for colors, yet no one theory of human color perception is universally accepted.
- Color of object depends not only on object itself but also on light source illuminating it, on color of surrounding area, and on human visual system (the eye/brain mechanism).
- Some objects reflect light (wall, desk, paper), while others also transmit light (cellophane, glass).
  - Surface that reflects only pure blue light illuminated with pure red light appears black.
  - Pure green light viewed through glass that transmits only pure red also appears black.
**What is color?**

- Color is a property of objects that our minds create – an interpretation of the world around us
  - unique to humans and higher primates
- Color perception stems from two main components:
  1) Physical properties of the world around us
    - electromagnetic waves interact with materials in the world and eventually reach your eyes
    - visible light comprises the portion of the electromagnetic spectrum that our eyes can detect (380nm/violet – 740nm/red)
      - photoreceptors in the eye convert light (photons) into electro-chemical signals which are then processed by our brains – rods and cones
  2) Physiological interpretation of “raw data” coming into our eyes
    - less well-understood and incredibly complex higher level processing
    - very dependent on past experience and object associations
- Both are important to understanding our sensation of color
Our Visual System Constructs our Reality: The Ultimate VR System

- **Still incompletely understood**
  - Understanding our “wiring” is insufficient
  - Both retina and brain work together to result in “seeing,” having a retina alone is insufficient
  - New tools (e.g. fMRI) greatly increases our understanding but also introduces new questions

- **Some viewing capabilities hardwired, others learned**
  - We acquire a visual vocabulary
  - What looked real a few years ago, no longer does

- **Huge innate pattern recognition ability**

- **Visual faster than higher-level cognitive processing**
  - For example roads use symbols instead of words for signs (but “dual coding” is always better)

- **Invariances/perceptual constancies are crucial for sense-making**
  - Size, rotation and position constancy of objects despite varying projections on the eye
  - Color constancy despite changing wavelength distributions
  - Person recognition despite everything else changing

- **Optical illusions**
  - Completing incomplete feature
  - Seeing patterns
  - Seeing 3d (perspective, camera obscura, sidewalk art)
Achromatic Light (1/2)

- Achromatic light: intensity (quantity of light) only
  - called intensity or luminance or measure of light’s energy or brightness
    - the psychophysical sense of perceived intensity
  - gray levels (e.g., from 0.0 to 1.0)
    - we can distinguish approximately 128 gray levels
  - seen on black and white displays
  - note Mach banding/edge enhancement – stay tuned
Achromatic Light (2/2)

- Eye is much more sensitive to slight changes in luminance (intensity) of light than slight changes in color (hue)
  - "Colors are only symbols. Reality is to be found in luminance alone... When I run out of blue, I use red." (Pablo Picasso)

- Picasso's Poor People on the Seashore uses various shades of blue that differ from each other in luminance but hardly at all in color (hue). The melancholy blue color serves an emotional role, but does not affect our recognition of the scene.

- The biological basis for the fact that color and luminance can play distinct roles in our perception of art, or of real life, is that color and luminance are analyzed by different subdivisions of our visual system, and these two subdivisions are responsible for different aspects of visual perception. The parts of our brain that process information about color are located several inches away from the parts that analyze luminance -- as anatomically distinct as vision is from hearing.

Source:
- Includes in-depth explanations of many interesting natural phenomena relating to color (including several interactive applications)
- [http://www.webexhibits.org/causesofcolor/](http://www.webexhibits.org/causesofcolor/)
Chromatic Light

Example of an HSV color picker

Ingredients of a Rainbow

<table>
<thead>
<tr>
<th>Color</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>violet</td>
<td>360–450 nm</td>
</tr>
<tr>
<td>blue</td>
<td>450–495 nm</td>
</tr>
<tr>
<td>green</td>
<td>495–570 nm</td>
</tr>
<tr>
<td>yellow</td>
<td>570–590 nm</td>
</tr>
<tr>
<td>orange</td>
<td>590–620 nm</td>
</tr>
<tr>
<td>red</td>
<td>620–750 nm</td>
</tr>
</tbody>
</table>

- Factors of visual color sensations
  - Brightness / intensity
  - Chromaticity / color
  - Hue / position in spectrum (red, green, ...)
  - Saturation / vividness
Dynamic Range

- **Dynamic Range**: ratio of maximum to minimum discernible intensity; our range is $10^8$ to $10^{10}$ photons/sec
  - Dynamic range thus $10^{10}$
    - Extraordinary precision achieved via adaptation, where the eye acclimates to changes in light over time by adjusting its pupil size
    - At any one moment, human eye has much lower dynamic range of about 10,000:1

- Dynamic range of a display gives you an idea of how many distinct intensities can be depicted on that display

- **Note**: dynamic range (ratio of intensities) of a display is not the same as its gamut (number of displayable colors)
  - Term also applies to audio, printers, cameras, etc.

- **Display Examples**:

<table>
<thead>
<tr>
<th>Display Media</th>
<th>Dynamic Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple 30” HD Display</td>
<td>700 : 1</td>
</tr>
<tr>
<td>CRT</td>
<td>50-200 : 1</td>
</tr>
<tr>
<td>Photographic prints</td>
<td>100 : 1</td>
</tr>
<tr>
<td>Photographic slides</td>
<td>1000 : 1</td>
</tr>
<tr>
<td>Coated paper printed in B/W</td>
<td>100 : 1</td>
</tr>
<tr>
<td>Coated paper printed in color</td>
<td>50 : 1</td>
</tr>
<tr>
<td>Newsprint printed in B/W</td>
<td>10 : 1</td>
</tr>
</tbody>
</table>

- ink bleeding and random noise considerably decreases DR in practice

Slides modified from Andries Van Dam’s Intro to Graphics at Brown U
High Dynamic Range (2/3)

- **High Dynamic Range (HDR):** describes images and display media which compress the visible spectrum to allow for greater contrast between extreme intensities
  - Takes advantage of non-linearities inherent in perception and display devices to compress intensities in a smart fashion
  - Allows a display to artificially depict an exaggerated contrast between really dark darks and really bright brights

(images from Wikipedia)
High Dynamic Range (3/3)

- Can combine photos taken at different exposures into an aggregate HDR image with more overall contrast (higher dynamic range)
  - Generally 32-bit image format (e.g., OpenEXR or RGBE)
  - HDR and tone mapping are hot topics in rendering!

(Images from www.hdrsoft.com)
Color Terms

- *Hue* distinguishes among colors such as red, green, purple, and yellow
- *Saturation* refers to how pure the color is, how much white/gray is mixed with it
  - red saturated; pink unsaturated
  - royal blue saturated; sky blue unsaturated
  - pastels are less vivid, less intense
- *Lightness*: perceived achromatic intensity of reflecting object
- *Brightness*: perceived intensity of a self-luminous object, such as a light bulb, the sun, or a CRT
- Can distinguish ~7 million colors when samples placed side-by-side (JNDs – Just Noticeable Diffs.)
  - with differences only in hue, \( \lambda \) difference of JND colors are 2nm in central part of visible spectrum, 10 nm at extremes – non-uniformity!
  - about 128 fully saturated hues are distinct
  - eye less discriminating for less saturated light (from 16 to 23 saturation steps for fixed hue and lightness), and less sensitive for less bright light
- **Subtractive mixture** occurs with inks for print medium, paints that absorb light.
- In subtractive mixture, light passed by two filters (or reflected by two mixed pigments) is wavelengths passed by first **minus** that which is subtracted by second.
- First filter passes 420 - 520 nanometers (broad-band blue filter), while second passes 480 - 660 nanometers (broad-band yellow filter). Light that can pass through both is in 480 - 520 nanometers, which appears green.
• **Additive mixture** used to mix R, G, B guns of CRT.

• Light passed by two filters (or reflected by two pigments) impinges upon same region of retina.

• Pure blue and yellow filtered light on same portion of the screen, reflected upon same retinal region. Image is gray, not green (as in subtractive mixture).
Complementary hues: Any hue will yield gray if additively mixed (in correct proportion) with opposite hue on color circle. Such hue pairs are complementaries. Of particular importance are the pairs that contain four unique hues: red-green, blue-yellow.

- These complementary “unique” hues play a role in opponent color perception discussed later
- Note that only for perfect red and green do you get gray – CRT red and green both have yellow components and therefore sum to yellowish gray
Color Contrast

• Gray patches on blue and yellow backgrounds are physically identical, look different

• Difference in perceived brightness: patch on blue looks brighter than on yellow, result of brightness contrast.

• Also a difference in perceived hue. Patch on blue looks yellowish, while patch on yellow looks bluish. This is color contrast: hues tend to induce their complementary colors in neighboring areas.

For a good applet on this, check out: 
http://www.cs.brown.edu/courses/cs092/VA10/HTML/start.html
and click on any Albers Plate link
Negative Afterimage

- Stare at center of figure for about a minute or two, then look at a blank white screen or a white piece of paper
- Blink once or twice; negative afterimage will appear within a few seconds showing the rose in its “correct” colors (red petals and green leaves)
Specifying (Naming) Color

• How to refer to/name a particular color?
• Compare unknown and sample from a collection
  – colors must be viewed under a standard light source
  – depends on human judgment
• PANTONE® Matching System
  in printing industry

• Munsell color-order system
  – set of samples in 3D space
  – hue, value/lightness, chroma (saturation)
  – equal perceived distances between neighbors

• Artists specify color as tint, shade, tone
  using pure white and black pigments
• Ostwald system is sir
Psychophysics

• Tint, shade, and tone: subjective. Depend on observer’s judgment, lighting, sample size, context...

• Colorimetry: quantitative; measurement via spectroradiometer (measures reflected/radiated light), colorimeter (measures primary colors), etc.

<table>
<thead>
<tr>
<th>Perceptual term</th>
<th>Colorimetry term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hue</td>
<td>Dominant wavelength</td>
</tr>
<tr>
<td>Saturation</td>
<td>Excitation purity</td>
</tr>
<tr>
<td>Lightness (reflecting objects)</td>
<td>Luminance</td>
</tr>
<tr>
<td>Brightness (self-luminous objects)</td>
<td>Luminance</td>
</tr>
</tbody>
</table>

• Physiology of vision, theories of perception still active research areas

• **Note**: our auditory and visual processing are very different!
  - both are forms of signal processing
  - visual processing integrates/much more affected by context
  - more than half of our cortex devoted to vision
  - vision probably dominant sense, though it is apparently harder to be deaf than blind
Color Matching

- Need way to describe colors precisely for industry and science
- Tristimulus Theory makes us want to describe all visible colors in terms of three variables (to get 3D coordinate space) vs. infinite number of spectral wavelengths or special reference swatches...
- Choose three well-defined light colors to be the three variables/"primaries" (R, G, B)
- People sit in a dark room matching colors

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4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.
CIE Chromaticity Diagram


Inset: CIE 1931 chromaticity diagram

Slides modified from Andries Van Dam’s Intro to Graphics at Brown U
CIE Space: International Commission on Illumination

• Now we have a way (specifying a color’s CIE X, Y, and Z values) to precisely characterize any color using only three variables!

• Very convenient! Colorimeters, spectroradiometers measure X, Y, Z values.

• Used in many areas of industry and academia—from paint to lighting to physics and chemistry.

• International Telecommunication Union uses 1931 CIE color matching functions in their recommendations for worldwide unified colorimetry