Color serves different purposes in art and in information visualization:

- In *art*, color is used for creative and expressive purposes
- In *information visualization*, color is used to help the viewer perceive information as readily as possible
Extensive perceptual studies have been conducted to determine what kinds of patterns humans are best at distinguishing.

In brief, there are several *popout channels*: hue, value (lightness), size, elongation, orientation, motion, and spatial grouping.

Note that *hue* and *value* are popout channels, but saturation is not.

Click *here* for a fascinating website devoted to perception in visualization.
How we see color
Humans have better color vision than most large animals

Grass-eaters, such as cows and zebras, have only two dimensions of color vision

Tigers (and more generally cats) have only two dimensions of color vision, but they don’t respond to it readily; motion sensitivity is more critical for them

Color very useful to fruit-eaters though!
There are two types of light receptors at the back of the retina: rods and cones

*Rods* are:

- More numerous
- Specialized for very low light levels
- Not so useful for modern humans, who usually work in good light

*Cones* are:

- The basis for normal daytime vision
- Divided into three subtypes: *short-*, *middle-*, and *long-wavelength sensitive*
- We’ll refer to these by the colors they most closely correspond to: *blue* for short, *green* for middle, and *red* for long

This gives us in essence a 3-dimensional system of vision (and is the reason that televisions and monitors have 3 different types of liquid crystal filters)
Sensitivity functions for the three classes of cone receptors. Cone receptors are sensitive to light having wavelengths between 400 and 700 nanometers (1 nm = 10^{-9} meters).

Note that the sensitivity distributions of long (L) and medium (M) wavelength-sensitive cones overlap considerably. The brain takes the difference between the two signals to get useful hue information.

It is impossible to reproduce pure spectral colors with printing inks so the color bands below should only be taken as rough approximations to the actual hues.
Note the clumpiness of red and green sensitive cones

Black and white images need only be on two different cones (any two), so we can see detail well with black and white

With purely chromatic differences, detail is harder because they need to fall on different types
One implication of having few and weak blue-sensitive cones: blue text on a black background doesn’t work well

Showing small blue text on a black background is a bad idea

Yellow, however, excites both green and red cones, so it works poorly on white and well on black

Showing small yellow text on a white background is a bad idea

Showing small yellow text on a white background is a bad idea
*Opponent process theory* was proposed by Ewald Hering in Vienna in 1878

The theory asserts that we have three *color-opponent channels*:

- red-green
- yellow-blue
- black-white (or luminance)

Note how this implies that red, green, yellow, blue, black, and white are singled out (strong + or - signals in only one channel)

This is in keeping with the 1969 Berlin-Kay study in which they found these color terms to be most commonly used in a large collection of languages

We now have physiological verification of this theory

Color signals from receptors are transformed early in the processing of visual information
The red-green channel represents the *difference* between the signals of the green and red cones.

The luminance channel *sums* the outputs of the green and red cones.

The yellow-blue channel represents the *difference* between the green and blue cones (which is also the *difference* between the luminance channel and the blue cones).

For those who have had some linear algebra, this is a *change of basis*.
These channels have important implications for information design, so we now look at some of their properties

*Contrast:* we can detect *differences within any individual channel* quite well

Here is an example within the black-white channel

Click *here* for another black-white example
In the red-green and yellow-blue channels, the effects of contrasts are harder to predict.
The luminance channel also carries a greater capacity to convey spatial detail than the other two channels.

It is also better for motion information, and it is the main channel for processing stereoscopic depth information.
The luminance channel is what we use to understand the shape of 3-dimensional surfaces from shading as well.
Saturation corresponds to a strong signal on one or both of the chromatic (red-green and yellow-blue) channels

Maximum saturation varies with luminance

Luminance is nonlinear: we are more sensitive to dark gray differences than to light differences (although this effect depends on the background)

Sharpening is the effect that with a light background, we are more sensitive to differences near white (and the opposite for a dark gray background)
Color segmentation is that property that we have a strong tendency to segment smoothly changing colors into regions consisting of unique hues.

Notice how the eye tends to divide the smoothly varying colors in the square on the left into regions of red, green, yellow and blue. To a lesser extent, purple and orange can be seen. It is almost impossible to see the neutral gray in the center. In the segmented version (on the right), more colors are clearly evident even though there are actually fewer present.
About 8% of males are color blind, meaning that they are missing the red-green channel.

Color-blind individuals will have difficulty distinguishing the patch of green colors from the surrounding red colors.

They will have no difficulty distinguishing a patch of yellow colors from the surrounding blue colors.
A word of caution: although color space is 3-dimensional, *perceived* color space is more complicated, as it depends heavily on things such as:

- Surrounding colors
- Orientation with respect to the light source
- Whether or not it appears to be in light or in shadow
- The texture of the surface on which it lies

Click *here* for an interesting demonstration of this
Implications for information visualization
If you only take one piece of information home from this talk, it should be:

**To show detailed information, use luminance contrast.**

This holds especially for small text.

The International Standards Organization (ISO) recommends at least a 3:1 ratio between the luminance of the text and the luminance of the background.

This really means black (or very dark) text on white (or light pastel hues), or the reverse.
This rule is less essential for larger text

APRIL is the cruellest month, breeding
Lilacs out of the dead land, mixing
Memory and desire, stirring
Dull roots with spring rain.
Winter kept us warm, covering
Earth in forgetful snow, feeding
A little life with dried rubers.

T.S. Eliot

When text is small it is essential that there be luminance contrast with the background color. Notice how the text is hardest to read when the luminance contrast is lowest. When text is big, anything goes.

In the larger version of this pattern, the colors are the most salient features. In the much smaller versions, to the right, the luminance values dominate so that a circular O pattern becomes the most distinct feature.
To color-code information, consider:

- Visual distinctness
- Learnability

To help with learnability, start with the standard hues (red, green, yellow, and blue) and then move to others with relatively consistent names (pink, brown, orange, grey, purple, etc.)

People have studied exactly how many colors are readily learnable; answer seem to vary from about 6 to 12.

One problem with more is that colors are perceived relative to background or nearby colors.
Note that for visual searches, the colors of the background and other symbols are as important as the symbol being searched for.
To contrast large and small areas, small areas should be strongly colored and have luminance contrast with larger background areas.

Large areas should have more subdued colors; they will contrast with other larger areas anyway.

GOOD. This example uses high saturation (strong colors) to code small areas such as symbols and lines. Larger background areas are all light and low saturation.

A black contrasting border is used to separate the yellow circle from its background because both have similar luminance.

BAD. This example shows what happens when the colors used for small areas and large areas are switched. The color codes used for the symbols and lines are difficult to discriminate because of contrast effects.

Besides being completely ineffective, the second example would generally be regarded as unattractive.
For *emphasis and highlighting*, a strong signal on any opponent channel will attract attention better than a weak signal.

Strength here is relative to the background.

An important PowerPoint lesson: do not highlight text with a color that reduces the luminance contrast.
Liberty consists in the freedom to do everything which injures no one else; hence the exercise of the natural rights of each man has no limits except those which assure to the other members of the society the enjoyment of the same rights. These limits can only be determined by law.

Law can only prohibit such actions as are hurtful to society. Nothing may be prevented which is not forbidden by law, and no one may be forced to do anything not provided for by law.

Declaration of the Rights of Man
National Assembly of France 1989
In maps (of all types — geographical, of the stock market, of temperatures, etc.), color can be used to:

- Help people perceive patterns in the data
- Allow people to read quantitative values from the map

Luminance is a good channel to use for these.

Sometimes choosing a zero value can be important.

For this, try a neutral value on the red-green or yellow-blue channels and then increase saturation in either direction to show positives and negatives.
A black-white (top left) sequence reveals the features of the map much better than a red-green sequence (top right). Even better is a sequence of colors that consistently increases in lightness while cycling through a range of hues (bottom left). A stepped sequence allows for more precision, especially when reading from a key, although less detail is revealed (bottom right).
This kind of color sequence is preferable to stepping through the spectrum.

If you ask people to order purple, blue, cyan, green, yellow, red, you will get answers that are all over the board.

Increase the number of colors, and many people will arrive at a circular ordering similar to the spectrum because parts of the spectrum have a perceptual ordering, although the whole spectrum does not.

If you ask people to order grays of various shades, you’ll generally get either a black-white or a white-black ordering as an answer.
For color on shaded surfaces, recall that shape from shading information comes from the luminance channel.

A colored pattern that interferes with luminance channel information prevents us from seeing the shape.
The psychological and symbolic aspects of color should also be considered.
All in all, choosing color for information visualization is a complex problem that involves trade-offs.

Every piece of information cannot be maximally distinct!

Consideration of consistency of design may also need to be taken into account.

In general, think about what sort of visual queries your audience will be performing and give those priority.
Almost all of the material in this talk came from the chapter on color in Colin Ware’s book *Visual Thinking for Design* (2008)

The websites used in this talk are:

*Perception in Visualization* by Christopher Healey of NCSU.
http://www.csc.ncsu.edu/faculty/healey/PP/index.html

*Illusions and Demos* by Edward Adelson of MIT.
http://web.mit.edu/persci/people/adelson/illusions_demos.html

*Illusions of Light* by Beau Lotto of Lottolab Studio.
http://www.lottolab.org/articles/illusionsoflight.asp

Two other websites of interest are:
88 *Visual Phenomena & Optical Illusions* by Michael Bach of the University of Freiburg.
http://www.michaelbach.de/ot/

*Illusions Gallery* by David T. Landrigan of the University of Massachusetts Lowell.
http://dragon.uml.edu/psych/illusion.html