CSSS 569 · Visualizing Data

COGNITIVE ISSUES IN DATA VISUALIZATION

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The Cognitive Science of Visual Displays of Information

Suppose we design the most beautiful, data rich display we can

But we use elements that humans can't perceive: Ultraviolet light.

The limits of human vision render our display useless

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Now suppose we design the most beautiful, data rich display we can

We use elements humans *can* perceive, but get systematically wrong

No better? Even worse?

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Unfortunately, cognitive errors are everywhere

But few designers of scientific visuals pay close attention to them

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Ideally, we would have an algorthm to accomplish the following:

```
cognitivelyAdjustedGraphic <- correctForErrors(InitialGraphic)
```

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Ideally, we would have an algorthm to accomplish the following:

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cognitivelyAdjustedGraphic <- correctForErrors(InitialGraphic)
```

Alas, this does not exist

The cognitive study of graphics is difficult

Hard to systematically understanding how graphical elements combine & interact

Instead, many specific errors known from experiments

These experiments provide warnings about dangerous techniques

To minimize error, we can try to use more reliable graphical elements

The Cognitive Hierarchy of Graphical Elements

Graphical elements used to encode data:

More accurate	Position on a plane
	Line length
	Angle & slope
↑	Area
	Volume
Less accurate	Color

Source:
Cleveland & McGill, JRSS, 1987

Graphical elements are *not* all equal in clarity

People are much better at judging line length than angle or grayscale

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To show and correlate multivariate data, we'd like to use multiple or multifunctional elememts

Color and size and shape, for example

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Will they all be processed equally...

accurately?
quickly?
with similar intensity?
separately?
at highest available level of measurement?

Unfortunately, NO.

The Cognitive Hierarchy of Graphical Elements

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More accurate	Position on a plane
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Cleveland & McGill, JRSS, 1987

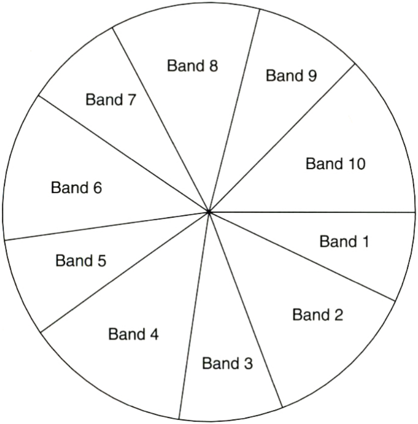
Simple advice:

Reserve elements at the top of the list for important variables

Try to avoid using the elements at the bottom of the list to encode *quantitative* data (but redundant usage is fine)

Exception: color *can* effectively encode qualitative data

Cognitive Failures and Solutions 1



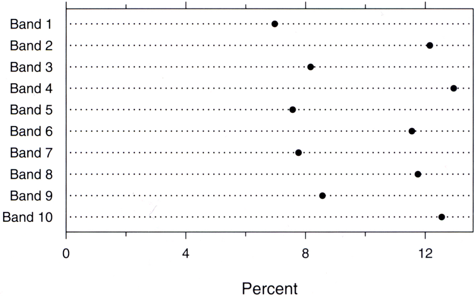
Cognitive failures:
Angular data encoding

Can you describe these data?

The exact sizes of the pies?

Source:
Cleveland, *The Elements of Graphing Data*

Cognitive Failures and Solutions 1

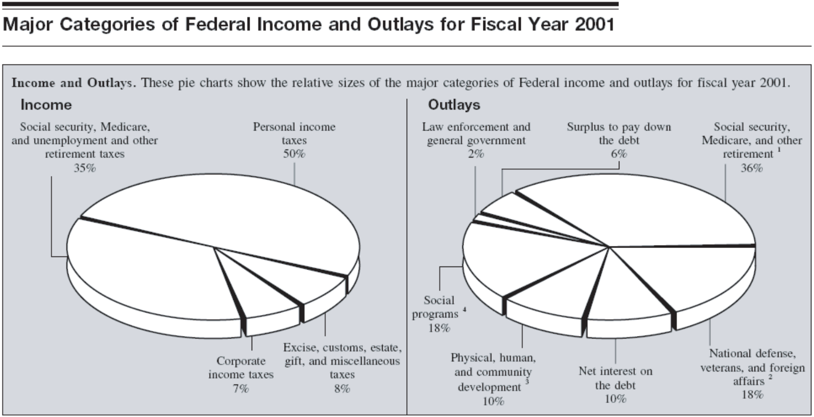


Cognitive solution:
Location *data encoding*

Did you notice that half of the slices are exactly 50% larger than the others?

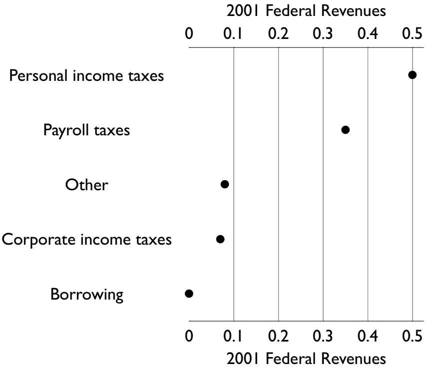
Did you guess the exact sizes correctly?

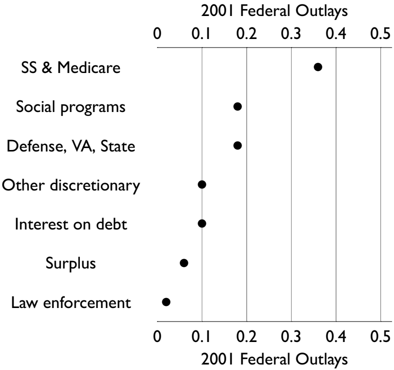
Source:
Cleveland, *The Elements of Graphing Data*



My favorite pie chart. Budget data printed on the back of the US tax forms.
Would a dot chart be as good? Better?

Cognitive Failures and Solutions 2

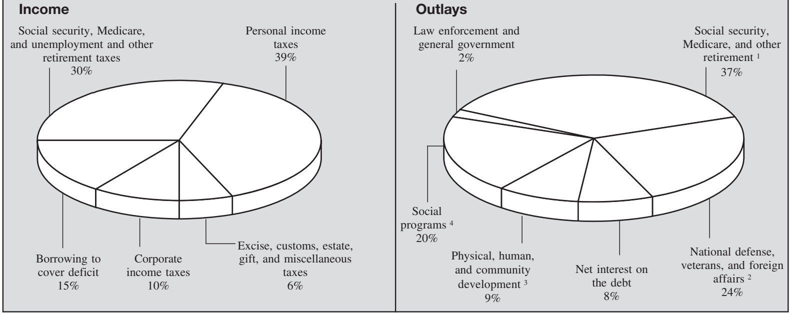




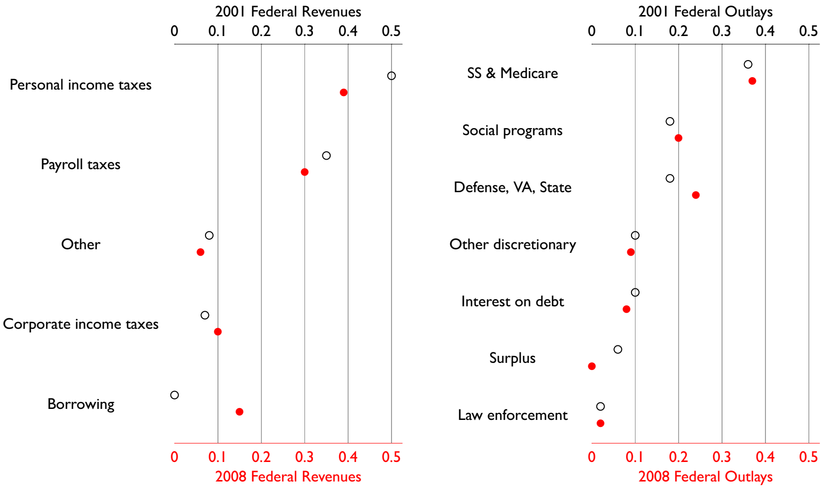
I think this is at least as good as the pie.
Unlike the pie, could be expanded to, say, 10 categories without much fuss.
Note that I have **diagonalized** the dot plot by sorting.
This is always helpful for reading and comparing data correctly.

Major Categories of Federal Income and Outlays for Fiscal Year 2008

Income and Outlays. These pie charts show the relative sizes of the major categories of federal income and outlays for fiscal year 2008.



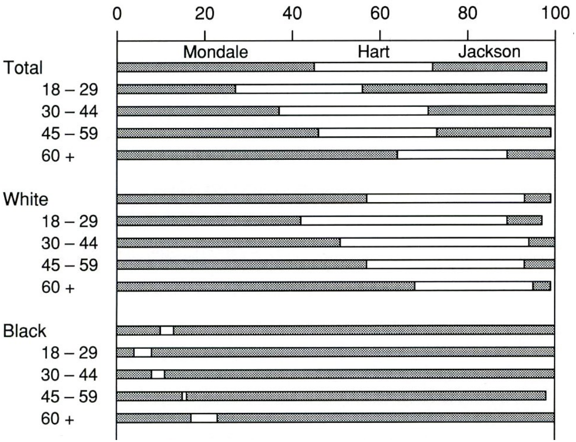
Budget pies went missing for most of the decade
They returned in 2009 – right after a presidential election



Another advantage of dotplots: easy comparison across plots through integration

This is also why dotplots are more useful than barplots

Cognitive Failures and Solutions 3



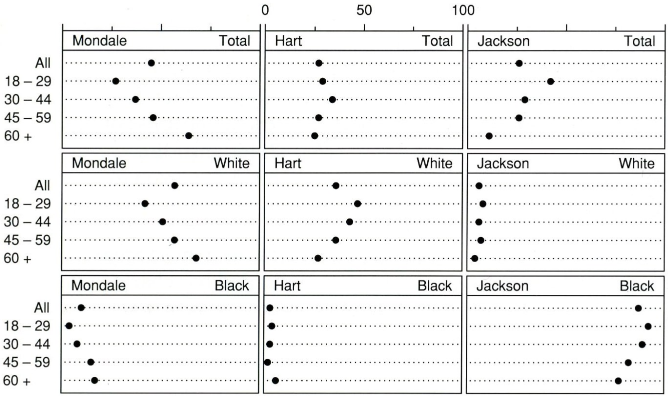
Source:
Cleveland, *The Elements of Graphing Data*

Another reason to prefer dotplots to barplots

Consider this stacked bar plot

How do Hart and Mondale's support depend on age of voter?

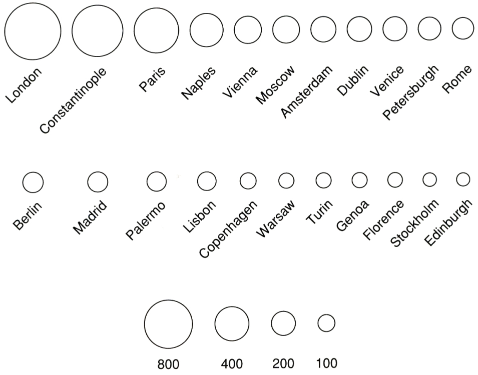
How do these patterns vary by race of voter?



Now consider an array of dotplots of the same data

How do Hart and Mondale's support depend on age of voter?

How do these patterns vary by race of voter? By race × age?



Cognitive failures:
Area data encoding

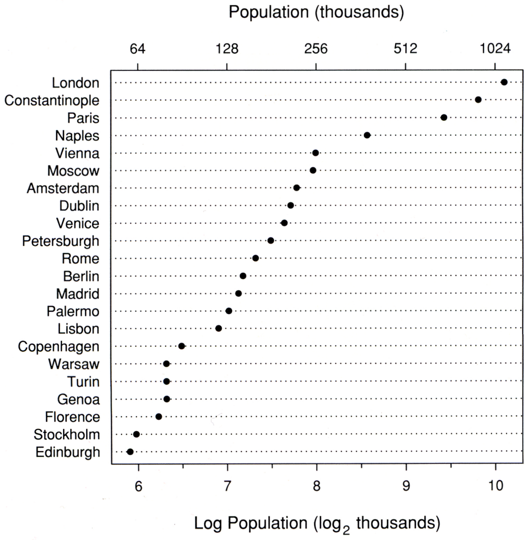
Is there a smooth increase in city size across these data?

How much bigger was Lisbon than Copenhagen?

Can we even be sure the areas represent population? What if the diameter is what matters?

Source:
Cleveland, *The Elements of Graphing Data*

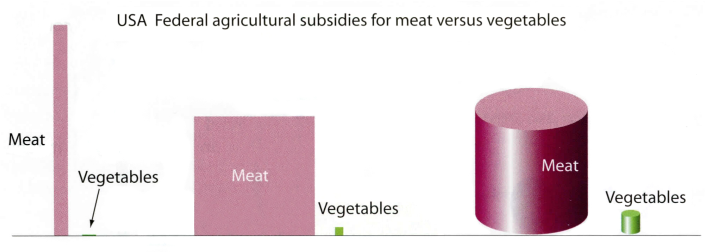
Cognitive Failures and Solutions 4



Cognitive solution:
Location *data encoding*

Lisbon was about fifty percent bigger than Copenhagen

The progression is far from smooth, even on a log scale



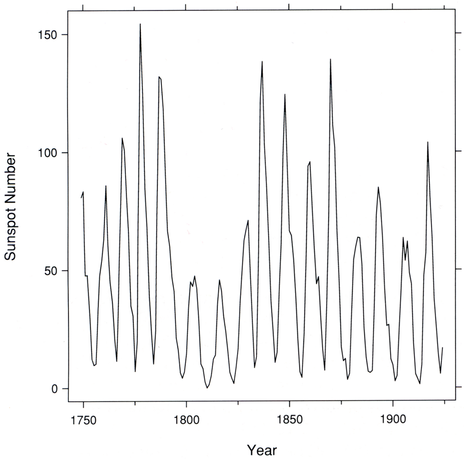
Source: Ware, *Information Visualization*

Perception of volume is even worse than area!

Many viewers read the volumes as if they were areas:
never use volume to represent quantities

Use measures based on length or location, rather than area or volume

Cognitive Failures and Solutions 5



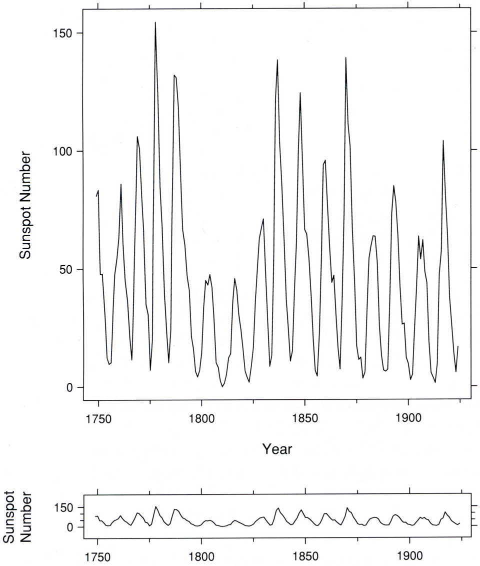
Cognitive failures:
Hard-to-read lineplots

Poor angular perception can make some lineplots hard to read

Are these spikes symmetrical?

Source:
Cleveland, *The Elements of Graphing Data*

Cognitive Failures and Solutions 5



Cognitive solution:
better aspect ratio

Choosing a better aspect ratio can make lineplots easier to read

The goal is to make slopes close to 1.0 or −1.0

Cleveland calls this "banking to 45 degrees," because angles near 45 are easier for humans to distinguish

Ah-ha! vs Hmm...

Sometimes differences take conscious effort to distinguish. Find the 3′s:

8568972698468976268976435892265986598655489768926989‌8

0246299687402655762798678904567923276928546098677209‌8

9083457980279075904709827908579084772908759082790875‌4

9870985674906897578625984569024379047219079070981145‌0

8568972698468976268976445892265986598655489768926989‌8

Ah-ha! vs Hmm...

Sometimes differences take conscious effort to distinguish. Find the 3's:

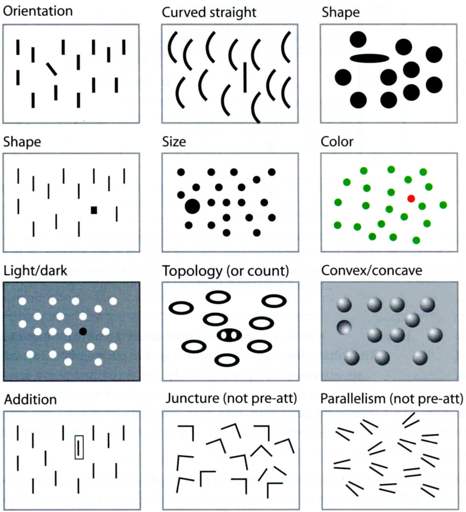
8568972698468976268976435892265986598655489768926989 8
0246299687402655762798678904567923276928546098677209 8
9083457980279075904709827908579084772908759082790875 4
9870985674906897578625984569024379047219079070981145 0
8568972698468976268976445892265986598655489768926989 8

Sometimes encoded data pop right out. Find the 3's:

8568972698468976268976435892265986598655489768926989 8
0246299687402655762798678904567923276928546098677209 8
9083457980279075904709827908579084772908759082790875 4
9870985674906897578625984569024379047219079070981145 0
8568972698468976268976445892265986598655489768926989 8

Same information in both examples.
But our brains process color differences "pre-attentively" – fast & effortlessly

Source: Ware, *Information Visualization*



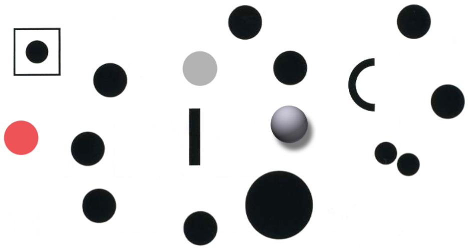
Where possible, **pre-attentive differences** should be exploited

The essence of graphics that "hit you between the eyes"

Tables of numbers seldom if ever achieve this

Source:
Ware, *Information Visualization*

Ah-ha! vs Hmm...



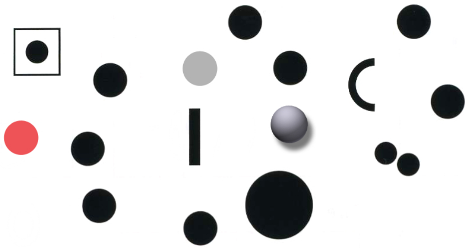
But there's only so much pre-attention to go around

As you add pre-attentive differences, the effect of each diminishes

(though not necessarily equally: some are stronger than others)

Source:
Ware, *Information Visualization*

Glyphs and Data Display

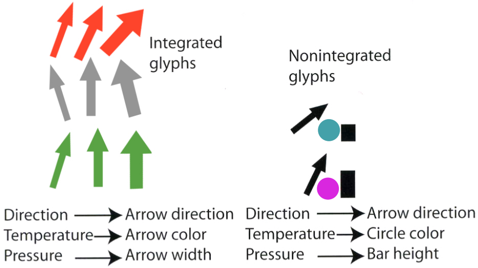


The symbols plotted at the left are *glyphs*

Each might represent a single case in a dataset

Source:
Ware, *Information Visualization*

Glyphs and Data Display



Source:
Ware, *Information Visualization*

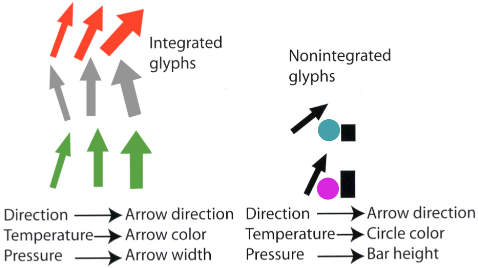
The symbols plotted at the left are *glyphs*

Each might represent a single case in a dataset

But each glyph can carry multiple dimensions

The is best achieved using an *integrated* set of glyph characteristics, one per dimension

Glyphs and Data Display

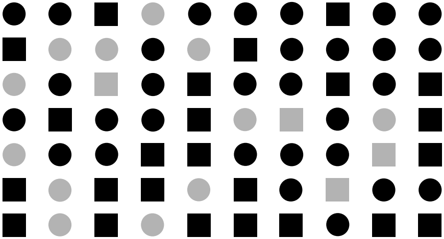


Source:
Ware, *Information Visualization*

Number Dimensions of a glyph
$\geq$
Number of variables encoded

The more variables you encode to dimensions of glyphs, the harder it is to pre-attentively separate the dimensions

Glyphs and Data Display



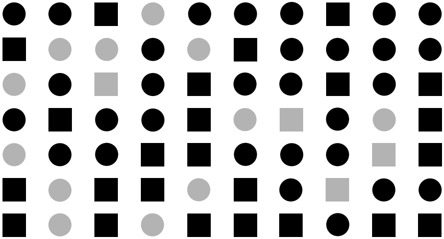
Source: *Ware, Information Visualization*

Number Dimensions of a glyph
$\geq$
Number of variables encoded

The more variables you encode to dimensions of glyphs, the harder it is to pre-attentively separate the dimensions

Quick! Pick out the **gray squares**

Glyphs and Data Display



Number Dimensions of a glyph

$\geq$

Number of variables encoded

The more variables you encode to dimensions of glyphs, the harder it is to pre-attentively separate the dimensions

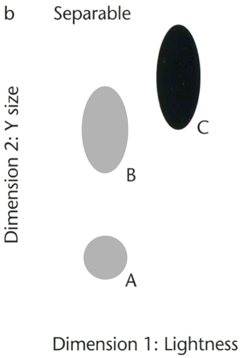
Quick! Pick out the **gray squares**

Source: Ware, *Information Visualization*

This may be an acceptable price for structured comparison across many dimensions

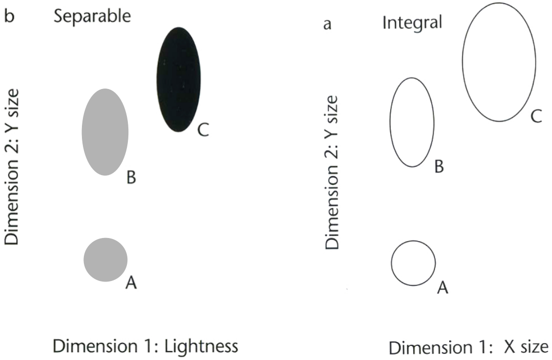
Sometimes, the best graphic – which is the simplest one that makes the desired point – still takes a bit of study to fully comprehend

Glyphs and Data Display



Take care to choose glyph dimensions that can be cleanly separated

Glyphs and Data Display



Take care to choose glyph dimensions that can be cleanly separated

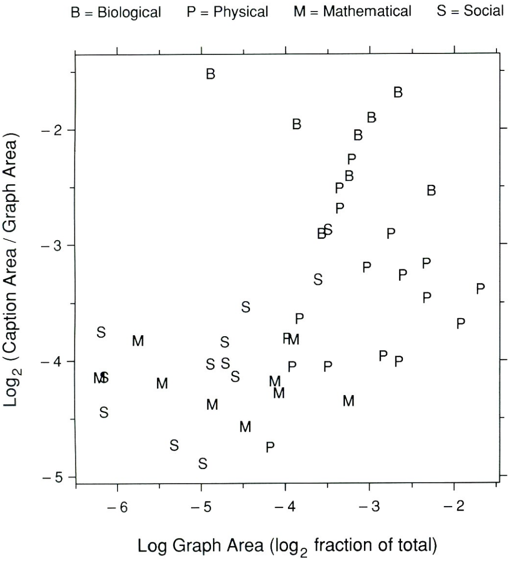
Sometimes, dimensions are reinforcing – and tend to blur together.
This makes it harder to extract information from the plot

Glyphs and Data Display

Glyphs most effective for encoding *discrete* data

Which glyphs should we use?

Glyphs and Data Display



Glyphs most effective for encoding *discrete* data

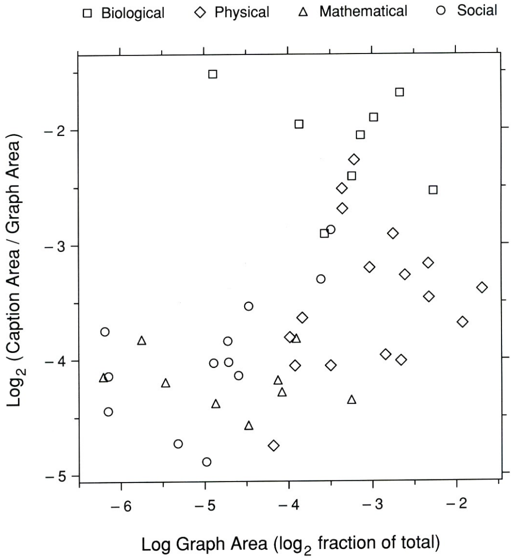
Which glyphs should we use?

First letter of each category?

Easiest to remember; hardest to preattentively distinguish

Source:
Cleveland, *Elements of Graphing Data*

Glyphs and Data Display



Glyphs most effective for encoding *discrete* data

Which glyphs should we use?

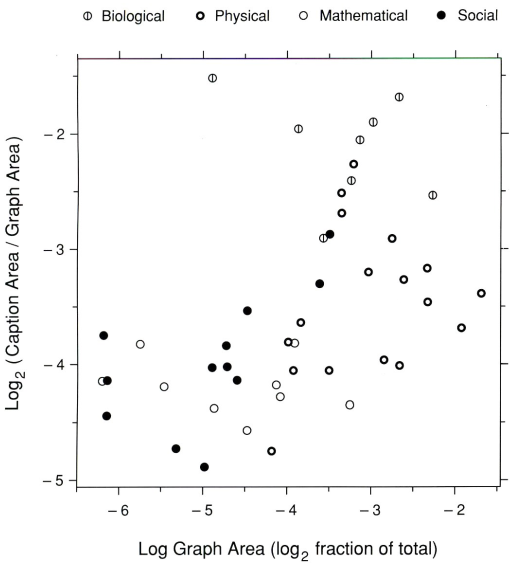
Random open symbols?

Reveal overlaps; still hard to preattentively distinguish

Source:

Cleveland, *Elements of Graphing Data*

Glyphs and Data Display



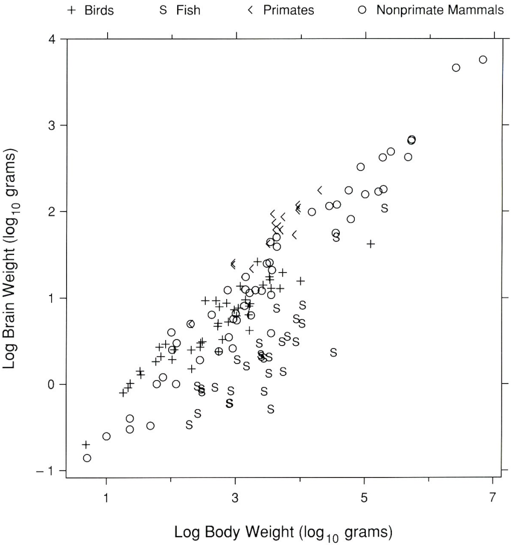
Not too many overlapping datapoints?

Then Cleveland recommends these glyphs:

Hard to remember;
Easy to preattentively distinguish and mentally group

Source:
Cleveland, *Elements of Graphing Data*

Glyphs and Data Display



Lots of overlapping datapoints?

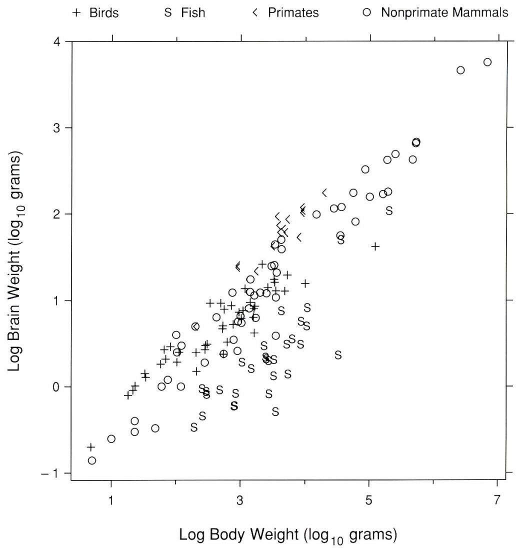
Then Cleveland recommends these glyphs:

○ + < S W

Hard to remember;
Easy to preattentively distinguish, even in pieces

Source:
Cleveland, *Elements of Graphing Data*

Glyphs and Data Display



Glyphs most effective for encoding *discrete* data

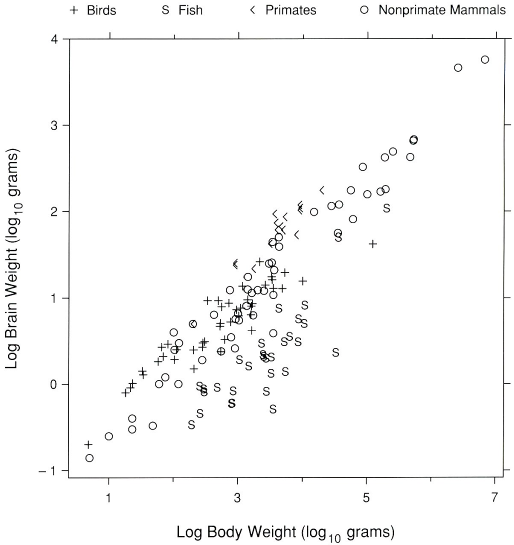
Which glyphs should we use? *It depends*

Always tradeoffs between preattentive distinctions and category recall

What matters will vary by display

Source:
Cleveland, *Elements of Graphing Data*

Glyphs and Data Display



Glyphs most effective for encoding *discrete* data

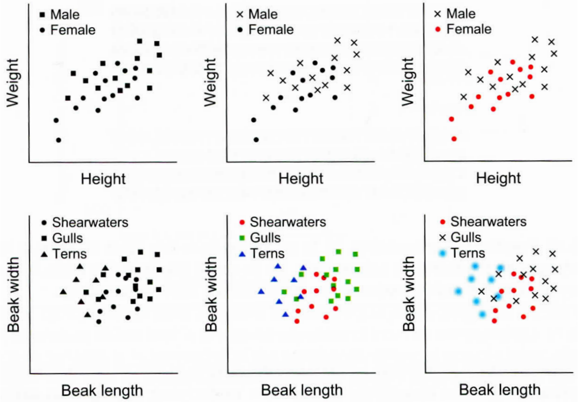
Which glyphs should we use? *It depends*

Note we haven't used color or transparency.

If we add these features, we can differentiate even identical, overlapping glyphs.

Source:
Cleveland, *Elements of Graphing Data*

Glyphs and Data Display



Source: Ware, *Information Visualization*

The dimensions of a glyph need not always code different variables

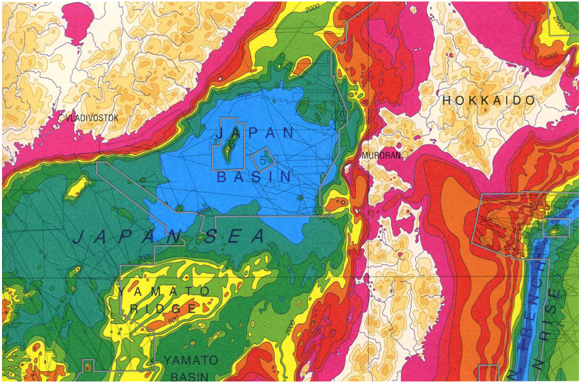
Coding the same variables to multiple pre-attentive features can help emphasize distinctions and pull apart distributions, even when points are strongly overlapping

Using Color (In)effectively

While striking and colorful, this map is not clear or useful

The color scale is so ineffectively chosen that we likely wouldn't *know* this was a map if the place names were missing

Source:
Tufte, *Information Visualization*



Using Color (In)effectively

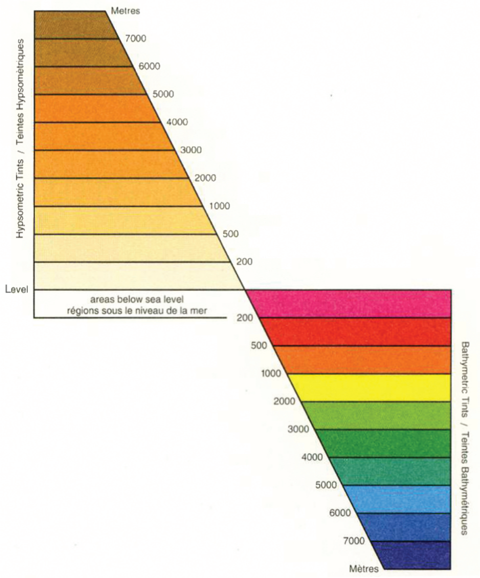
The mapmaker used a rainbow scale for underwater depth

Normally, mapmakers maintain a constant hue for a terrain type, and vary its brightness and saturation

Our eyes can order brightness, but not the rainbow

Source:

Tufte, *Information Visualization*



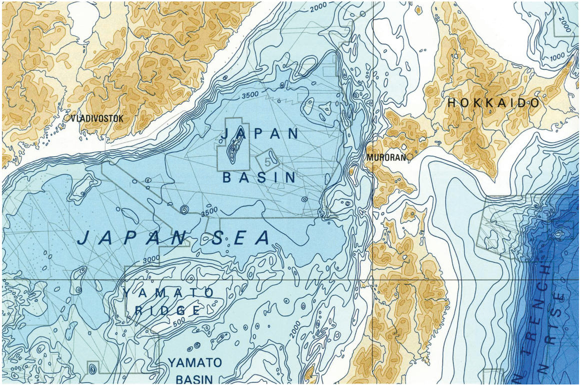
Using Color Effectively

For centuries, cartographers have effectively used color on maps

While not as flashy as a rainbow scale, this map is far more effective for both lookup and comparison

Source:

Tufte, *Information Visualization*



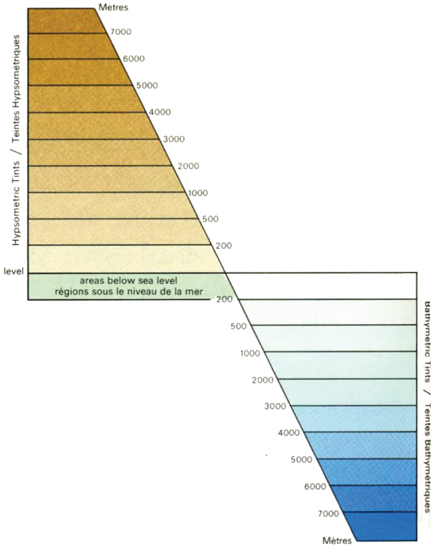
Using Color Effectively

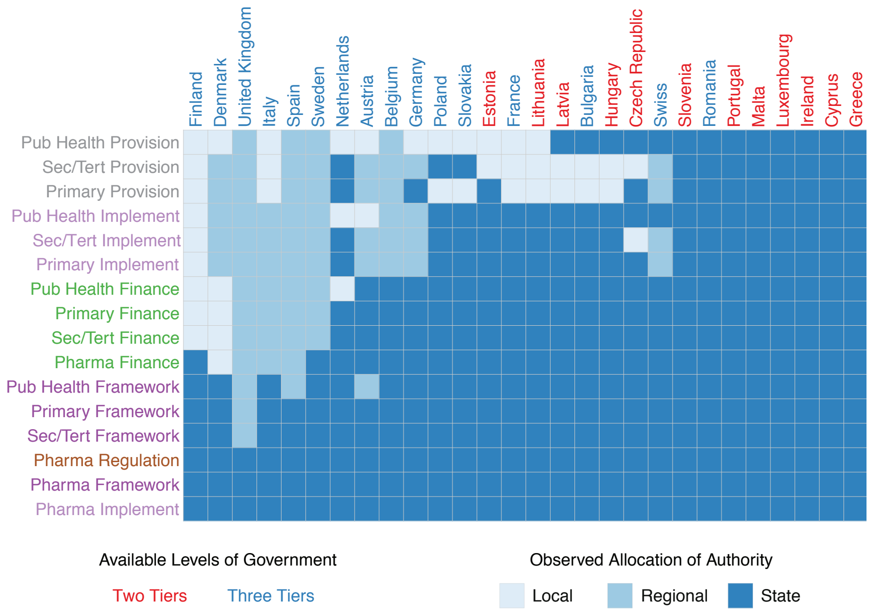
Humans are bad at precise reading of color

When plotting a quantitative variable on a color scale, care should be taken to find pre-attentively smooth gradients

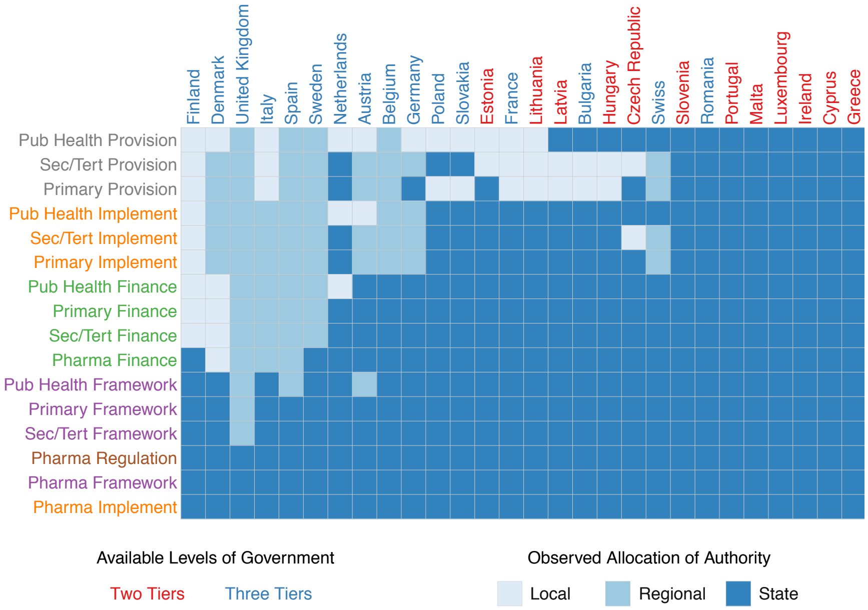
Source:

Tufte, *Information Visualization*

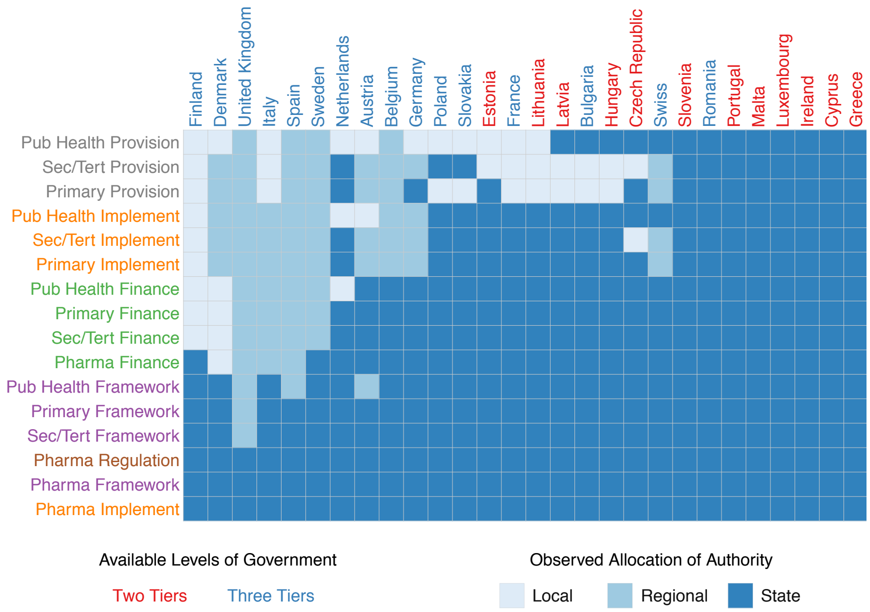




What if I'd drawn my heatmap with *these* colors



Poor choice of colors for categorical data can distort the data



Choose colors for categories to achieve equal pairwise distinctions

Color advice

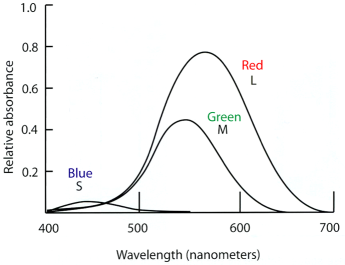
If you only learn four things about using color in graphs, it should be to:

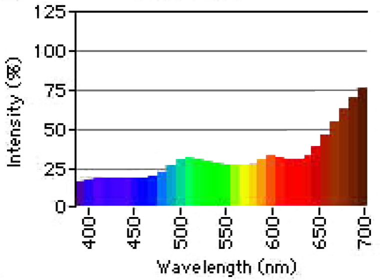
1. Choose colors for quantities using pre-attentively smooth gradients
2. Choose colors for categories to achieve equal pairwise distinctions
3. Avoid overlapping colors with similar brightness (value)
4. Use pastels for large-area colors and saturated colors for small points

To understand and implement the above,
we need to know something about the science of color

Color is

- a measure of the wavelength of light
- something we perceive
- a mixture of red, blue, and green
- a mixture of hue, luminosity, and saturation
- broadly categorical; also continuous
- hard to perceive accurately
- hard to reproduce accurately
- an element of many visuals





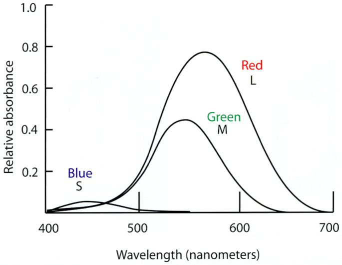
Color Science Vastly Oversimplified by an Outsider

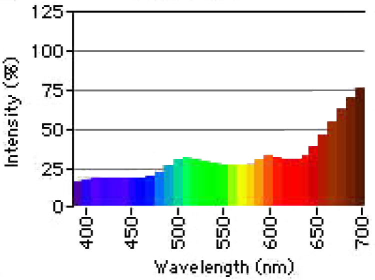
Human eyes contain two kinds of photo-receptive elements:

Rods. Sensitive to brightness
Single photon receptors
Little use in sunlight

Cones. Come in three varieties...

1. Short wavelength (red); most sensitive
2. Medium wavelength (green); moderately sensitive
3. Long wavelength (blue); weak





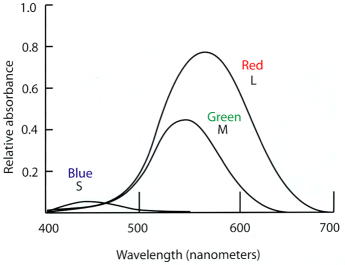
Color Science Vastly Oversimplified by an Outsider

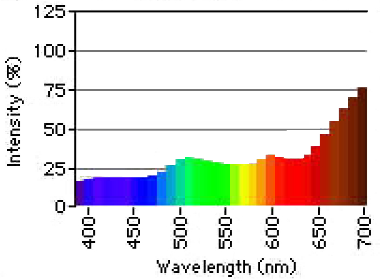
Humans are best at seeing red;
worst at seeing blue

Species vary in color vision ability:

- dogs have only two cones,
  are red-green colorblind,
  and see less detail in daylight
- birds have more cones than humans –
  chickens have 12!

Number of cones = number of primary colors a species perceives
Mixing the three (human) primaries in different amounts makes any color humans can see.



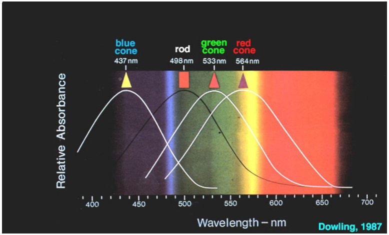


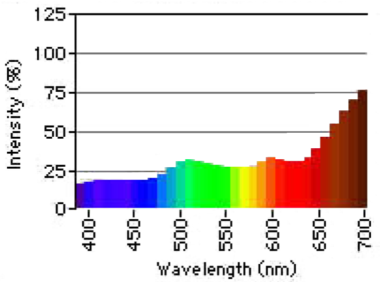
Color Science Vastly Oversimplified by an Outsider

Suppose we used scientific equipment to measure the number of photons received at each of *N* wavelengths throughout the visible spectrum

Clearly, we could choose *N* to be arbitrarily large, and still learn more about the distribution of photon wavelenghts by sampling in still more places

Just like adding bins to a histogram, this gives us a finer view of the distribution

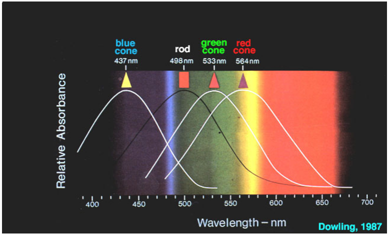


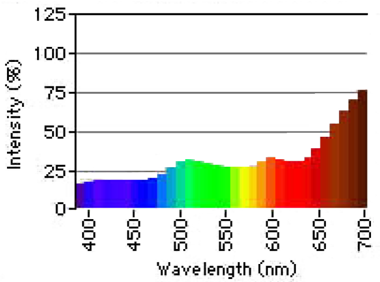


Color Science Vastly Oversimplified by an Outsider

The human eye has cones tuned to just three wavelengths, so our eyes approximate complex histogram as mixture of three densities

Many different colors (that is, distinct histograms on the visual spectrum) that look the "same" to us would look different to a chicken, which samples the distribution in 12 places!





Color Spaces

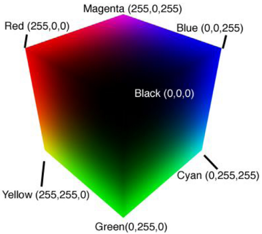


Figure 3a: The black corner (0,0,0) of the RGB Cube

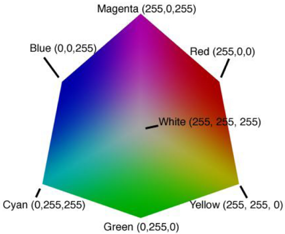


Figure 3b: The white corner (255,255,255) of the RGB Cube

Primaries and color can be expressed in many equivalent ways.

These are different **colorspaces**: mappings from 3 variables to a color

Computer space · **RGB**
Red, Green, Blue

Printer space · **CMYK**
Cyan, Magenta, Yellow, Black

Artist space · **HSV**
Hue, Saturation, Value

Brain space · **CIElab**
Lightness, blue/yellow, red/green

Color Spaces: RGB

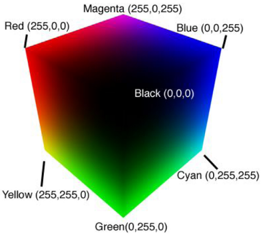


Figure 3a: The black corner (0,0,0) of the RGB Cube

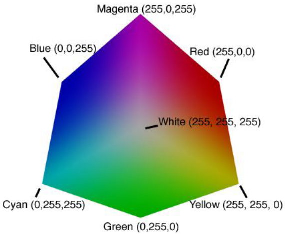


Figure 3b: The white corner (255,255,255) of the RGB Cube

RGB is mainly useful for telling a computer what color of light to display

If you want to tell a printer what color of ink to print, it is easier to use CMYK: cyan, magenta, yellow, and black

But neither color space is useful for choosing colors, either aesthetically or scientifically

Color Spaces: HSV

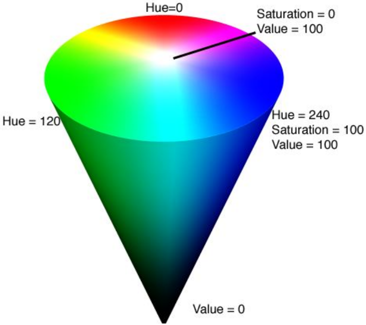


Figure 2: The HSV Cone

Source: Darrin Cardani, "Adventures in HSV Space"

Artists find RGB an inconvenient space to think about color

Instead, they often use HSV:
hue is the "name" of the color

think rainbow

saturation is the richness of the color; desaturated colors have been mixed with gray

think solids vs pastels

value is the brightness of the color; how much white or black is mixed in

think stop sign vs. red wine

Color Spaces: HSV

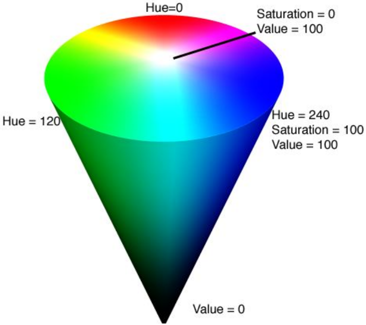


Figure 2: The HSV Cone

Source: Darrin Cardani, "Adventures in HSV Space"

HSV is useful for constructing beautiful complementary colors for artistic palettes

Colors on opposite sides of the cone are aesthetically harmonious contrasting colors

Colors 120 degrees apart (color triads) are too

Any HSV color can also be represented in RGB and CMYK, and vice versa

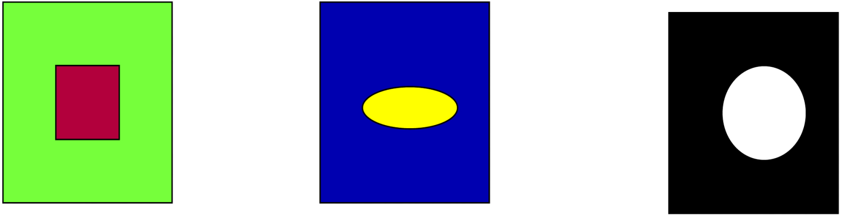
Does your brain read off RGB values from your cones? Or maybe HSV values?

Probably not.

Opponent color theory:

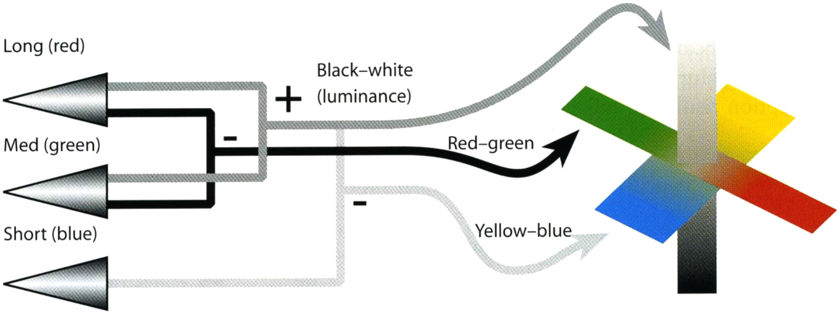
Human optical system converts {S,M,L} cone readouts to three channels

- Redness vs. greenness
- Blueness vs. yellowness
- Brightness



Source: Maya Gupta, Electrical Engineering, UW

Color Spaces: Opponent Color Theory



Source: Colin Ware, *Information Visualization*

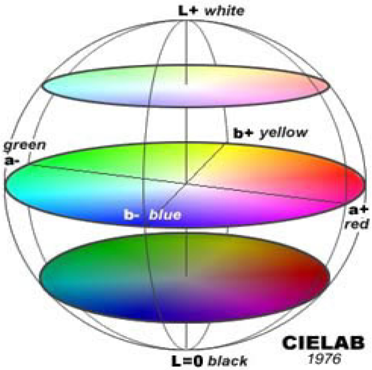
In other words, red/green and blue/yellow are "opponent colors"

They appear in zero-sum combinations
(no one ever says "the yellowish-blue sweater")

Color blindness: absence or weakness of one set of cones

Most common are people who can't distinguish red & green

Color Spaces: CIElab



Opponent color theory suggests a new color space, CIElab
(CIE stands for *Commission internationale de l'éclairage*,
or International Commission on Illumination)

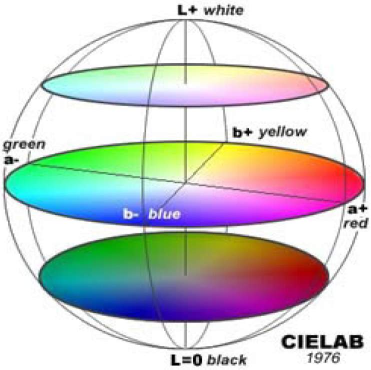
l = luminance (white vs. black)

a = red vs. green

b = blue vs. yellow

Equal Euclidian distances in CIElab space are (approximately) perceptually "equal" to humans

Color Spaces: CIElab



Equal Euclidian distances in CIElab space are (approximately) perceptually "equal" to humans

If CIElab is the brain's color space,
it's the best one for choosing colors to convey precise scientific information

If you want to convey distinct categories, choose colors that are well separated in CIElab space

If you want to convey precise numerical steps, choose equal stpes through CIElab space

Does this mean you need to learn a lot of cognitive science before you can make a color graphic?

Not really.

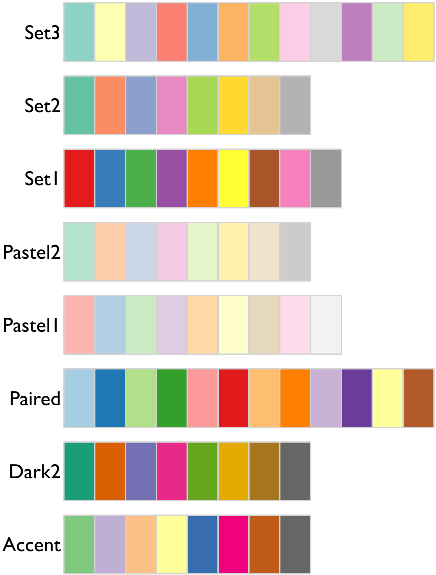
Easy shortcuts available: `RColorBrewer` will choose appropriate colors for you

The Cognitive Science of Visual Displays of Information

At left are perceptually equal gradients for different color hues, as suggested by `RColorBrewer`

```
library(RColorBrewer)
display.brewer.all(type="seq")
```

Pick one horizontal strip for your color scale to plot quantitative data



`RColorBrewer` will also suggest colors for qualitative variables

Goal here is to make each category equally distinct from the others

```
library(RColorBrewer)
display.brewer.all(type="qual")
```

Why so many choices? Not for aesthetics, but because they solve different color cognition problems

Color Cognition Problem 1 *Saturation and Size*

Suppose we use `Pastel1` to encode categories to glyphs

Can you easily tell which color is which?

Suppose we use `Pastel1` to encode categories to glyphs

Can you easily tell which color is which?

Hard to distinguish the hue of small areas of desaturated color

Don't use pastels to color small glyphs

Suppose we use `Pastel1` to encode categories to regions

Can you easily tell which color is which?

Suppose we use `Pastel1` to encode categories to regions

Can you easily tell which color is which?

Easy to distinguish the hue of large areas of desaturated color

Use pastels to color large regions

Suppose we use `Set1` to encode categories to glyphs

Can you easily tell which color is which?

Color Cognition Problem 1 *Saturation and Size*

Suppose we use `Set1` to encode categories to glyphs

Can you easily tell which color is which?

Easy to distinguish the hue of small areas of saturated color

Use jewel tones to color large regions

Suppose we use `Set1` to encode categories to regions

Would a graph with large bright regions be readable?

Suppose we use `Set1` to encode categories to regions

Would a graph with large bright regions be readable?

Large areas of saturated color command attention – distract from small details

Avoid jewel tones when coloring large regions

Color Cognition Problem 1 *Saturation and Size*

Use jewel tones for glyphs *Use pastels for regions*

Color Cognition Problem 1 *Saturation and Size*

Use jewel tones for glyphs *Use pastels for regions*

Avoid pastel glyphs and saturated regions!

Color Cognition Problem 1 *Saturation and Size*

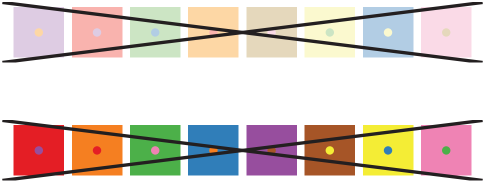
Use jewel tones for glyphs *Use pastels for regions*

Avoid pastel glyphs and saturated regions!

Color Cognition Problem 1 *Saturation and Size*

Use jewel tones for glyphs *Use pastels for regions*

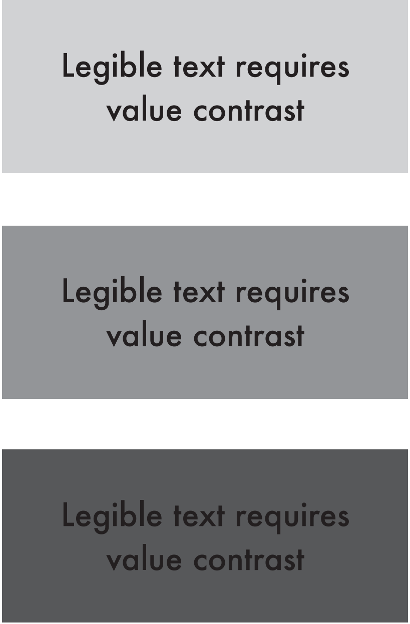
Avoid pastel glyphs and saturated regions!



Color Cognition Problem 2
Background Contrast

Text is only readable when it differs significantly from the background in *value*

Dark text only works on light backgrounds



Color Cognition Problem 2
Background Contrast

Text is only readable when it differs significantly from the background in *value*

Dark text only works on light backgrounds

Light text only works on dark backgrounds

Legible text requires value contrast

Legible text requires value contrast

Legible text requires value contrast

Color Cognition Problem 2
Background Contrast

Text is only readable when it differs significantly from the background in *value*

Dark text only works on light backgrounds

Light text only works on dark backgrounds

Mid-value backgrounds make muddy images: *avoid*

Legible text requires value contrast

Avoid mid gray backgrounds

Legible text requires value contrast

Color Cognition Problem 2
Background Contrast

Text is only readable when it differs significantly from the background in *value*

Mid-value backgrounds make muddy images: *avoid*

Applies to graphs generally: don't use a gray background to your plot

Warning: gray backgrounds are default in `ggplot2` and `Excel`!

Legible text requires value contrast

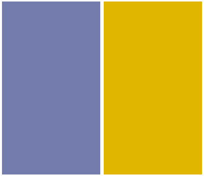
Avoid mid gray backgrounds

Legible text requires value contrast

Common mistaken intuition:
Different hues ("colors") are sufficient to distinguish background and foreground

Color Cognition Problem 2 *Background Contrast*

It is very difficult to read text that is isoluminant with its background color. If clear text material is to be presented it is essential that there be sustantial luminance contrast with the background color. Color contrast is not enough. This particular example is especially difficult because the chromatic difference is in the yellow blue direction. The only exception to the requirement for luminance contrast is when the purpose is artistic effect and not clarity.



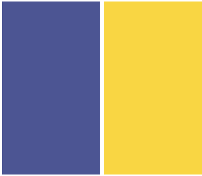
Common mistaken intuition:

Different hues ("colors") are sufficient to distinguish background and foreground

Even two color opposites (blue and yellow) can blend
when they have similar values (brightness)

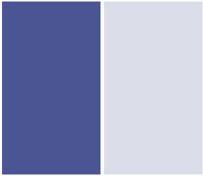
Color Cognition Problem 2 *Background Contrast*

It is very difficult to read text that is isoluminant with its background color. If clear text material is to be presented it is essential that there be sustantial luminance contrast with the background color. Color contrast is not enough. This particular example is especially difficult because the chromatic difference is in the yellow blue direction. The only exception to the requirement for luminance contrast is when the purpose is artistic effect and not clarity.



To avoid unreadable text,
make sure background and foreground have different values

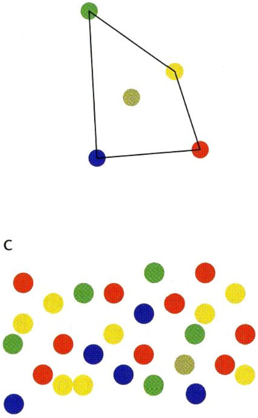
It is very difficult to read text that is isoluminant with its background color. If clear text material is to be presented it is essential that there be sustantial luminance contrast with the background color. Color contrast is not enough. This particular example is especially difficult because the chromatic difference is in the yellow blue direction. The only exception to the requirement for luminance contrast is when the purpose is artistic effect and not clarity.



To avoid unreadable text,
make sure background and foreground have different values

With a large value contrast,
even background and foreground of the same hue can be effective

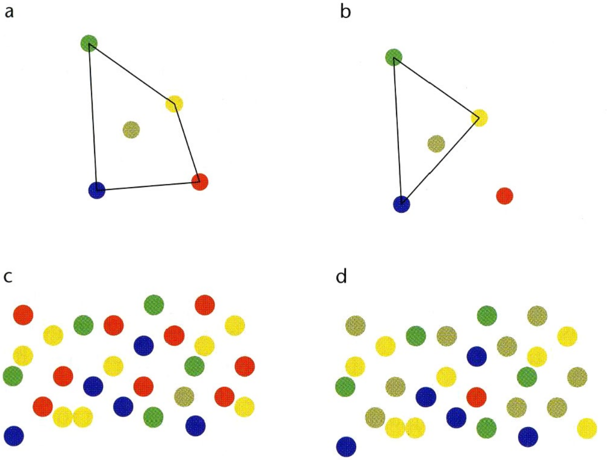
a



c

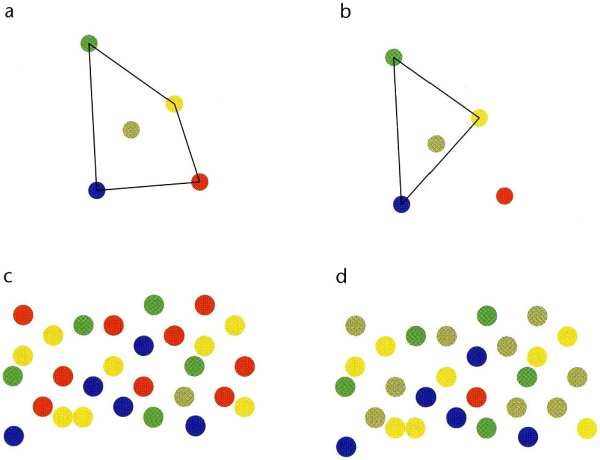
RColorBrewer chooses "equally distinct" colors. How?

Colors in a are plotted in CIElab space: Interior colors blend in



`RColorBrewer` chooses "equally distinct" colors. How?

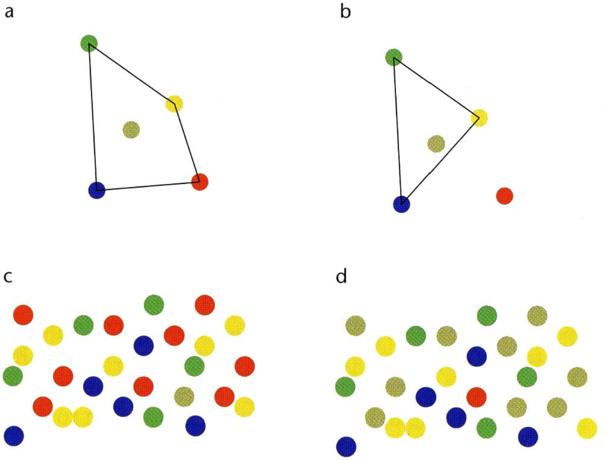
Colors outside the *convex hull* of the other colors *stand out*



`RColorBrewer` chooses "equally distinct" colors. How?

`RColorBrewer` "`qual`" colors are equidistant from each other on the convex hull

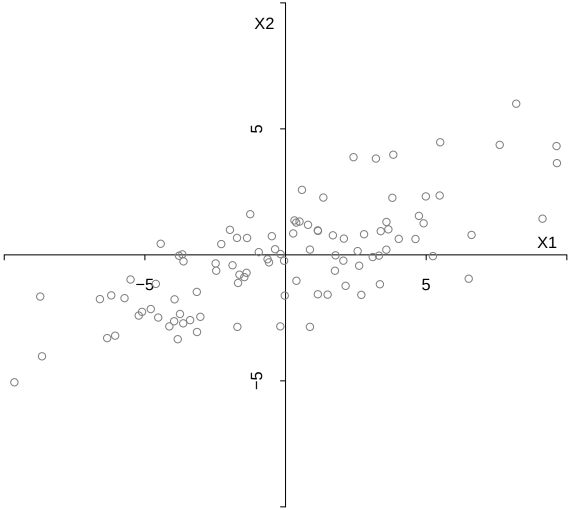
Color Cognition Problem 3 *Choosing Colors as Highlights*



If your goal is to *highlight* a point or category,
choose something outside the convex hull of the other colors

Aside: Convex Hulls

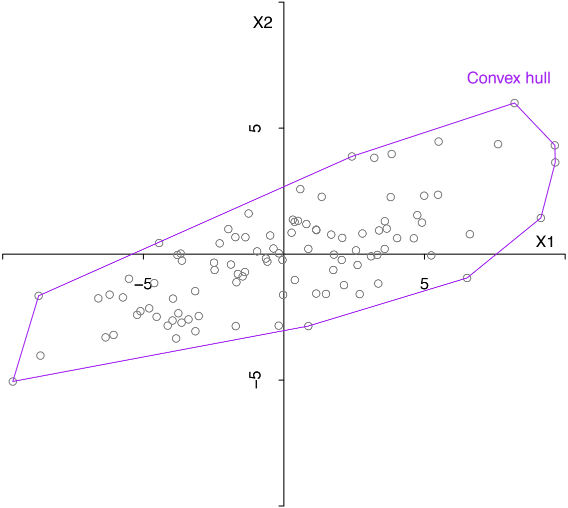
What is a convex hull?



Aside: Convex Hulls

What is a convex hull?

An elastic band wrapped around the cloud of points such that it contains the smallest convex set containing those points



Aside: Convex Hulls

What is a convex hull?

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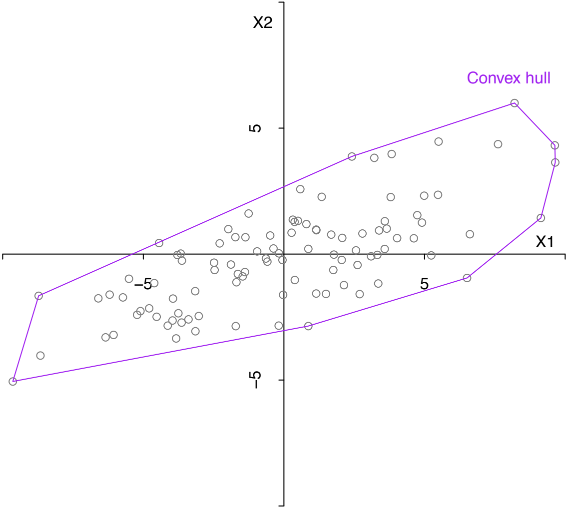
What is a convex set?



Aside: Convex Hulls

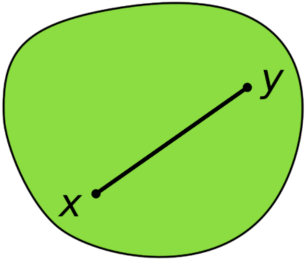
What is a convex hull?

An elastic band wrapped around the cloud of points such that it contains the smallest convex set containing those points

What is a convex set?

If a straight line between any two points in a region remains within that region, that region is a convex set

A Convex Set



Aside: Convex Hulls

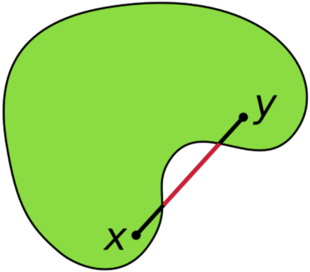
What is a convex hull?

An elastic band wrapped around the cloud of points such that it contains the smallest convex set containing those points

What is a convex set?

If a straight line between any two points in a region remains within that region, that region is a convex set

Not a Convex Set

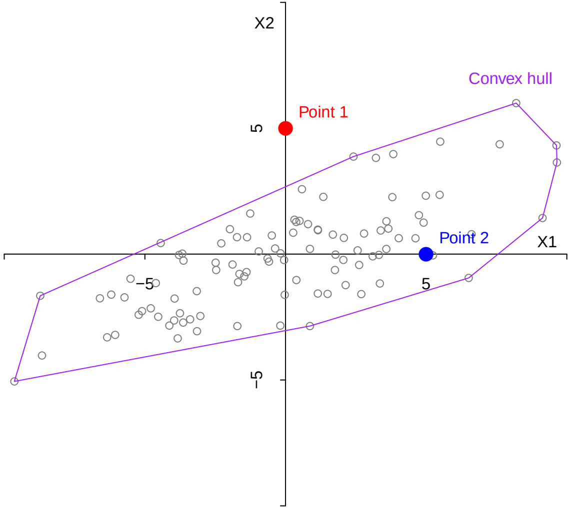


Aside: Convex Hulls

Convex hulls will come up again later when we discuss the difference between extrapolation from a dataset and interpolation from a dataset

Point 2 is interpolated

Point 1 is extrapolated



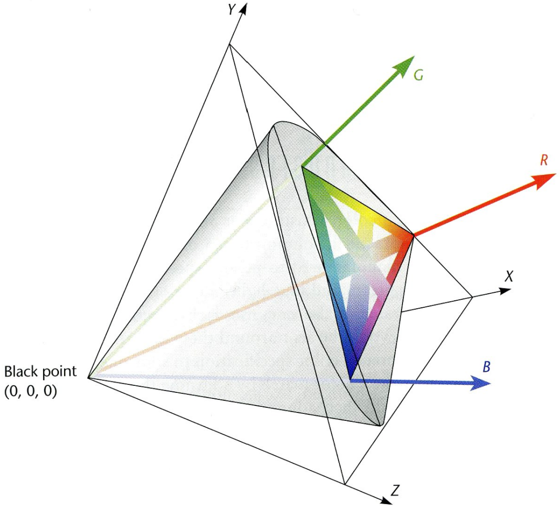
Color Cognition Problem 4 *Color Reproduction & Color Gamuts*

LCD displays can't capture all the colors humans can see

Or all the colors a good printer can print

$ and fancy chemistry needed to get all perceived colors

Fascinating history of science topic:
discovery of pigments for various colors took centuries



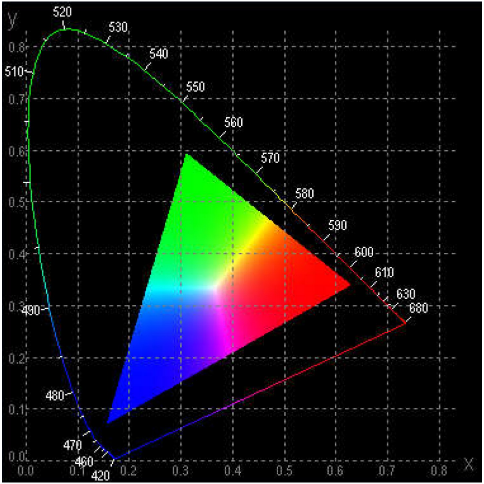
Focus on the LCD display versus human perception problem

Most greens and blues are missing!

OLED helps, but rarely available

Bigger problem: device dependence

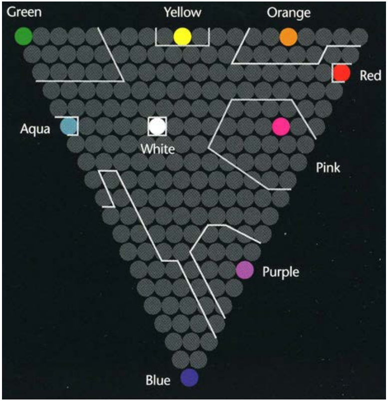
This LCD projector $\neq$ my computer $\neq$ your computer *ne* your printer

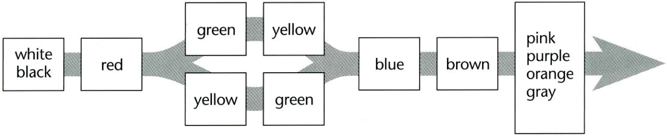


Why colors work for categories:

Humans recognize certain hues as categorically distinct

Note the misclassification of red and orange in terms of primaries





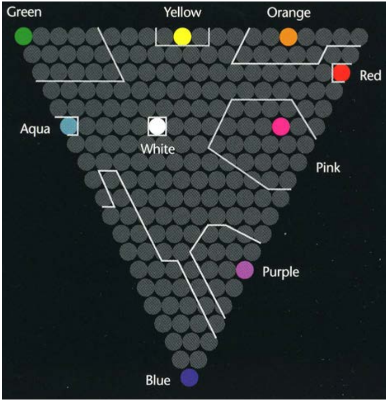
Note:

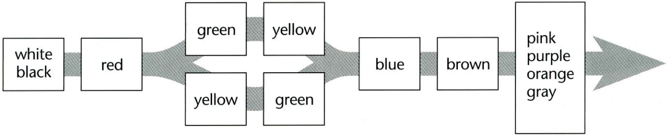
misclassification of red and orange in terms of primaries

narrow range of reds

wide range of blues

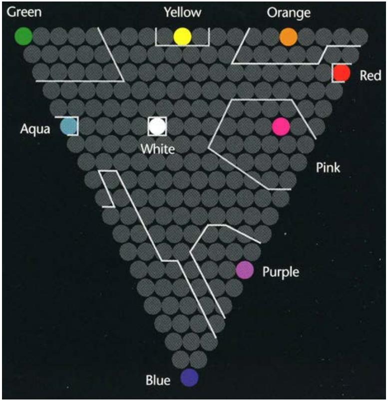
Result of strong red cones/weak blue cones

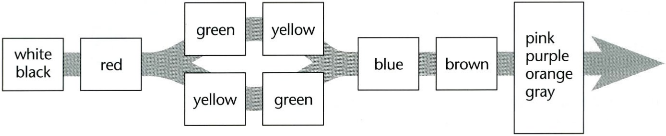




Where is brown on this chart?

For that matter, where is brown in the color spectrum?



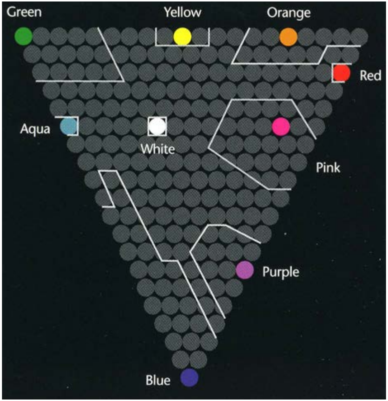


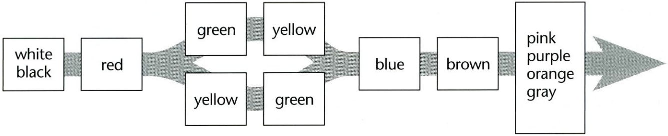
Where is brown on this chart?

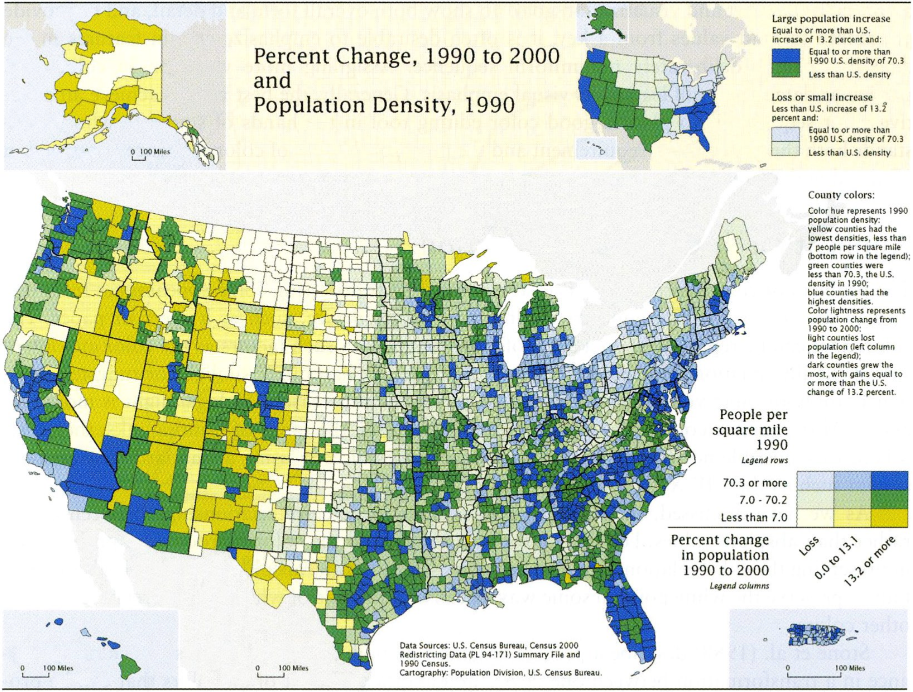
For that matter, where is brown in the color spectrum?

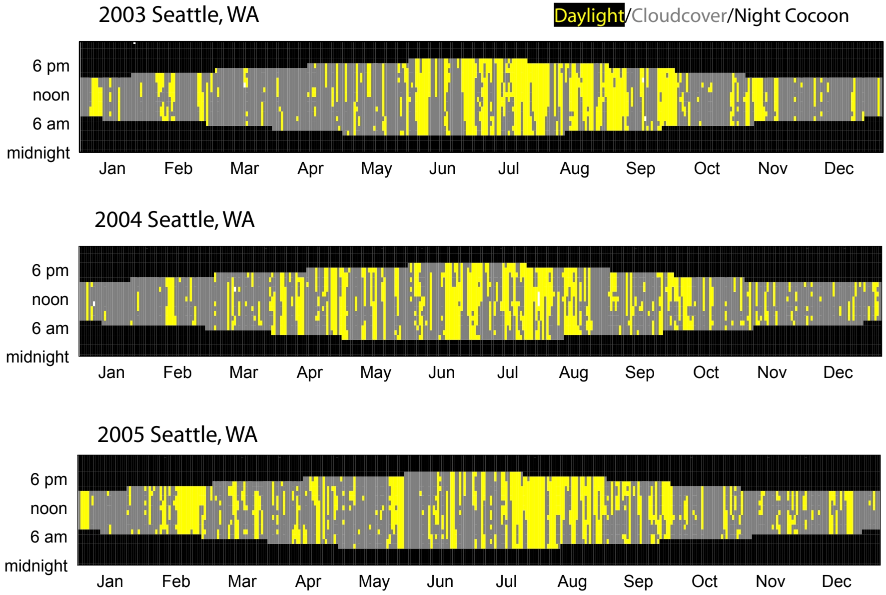
Browns are dark yellows and dark oranges

An imperfection in mapping of hue to human color perception






Percent Change, 1990 to 2000
and
Population Density, 1990
Large population increase
Equal to or more than U.S. increase of 13.2 percent and:
Equal to or more than 1990 U.S. density of 70.3
Less than U.S. density
Loss or small increase
Less than U.S. increase of 13.2 percent and:
Equal to or more than 1990 U.S. density of 70.3
Less than U.S. density
0 100 Miles
County colors:
Color hue represents 1990 population density: yellow counties had the lowest densities, less than 7 people per square mile (bottom row in the legend); green counties were less than 70.3, the U.S. density in 1990; blue counties had the highest densities.
Color lightness represents population change from 1990 to 2000: light counties lost population (left column in the legend); dark counties grew the most, with gains equal to or more than the U.S. change of 13.2 percent.
People per square mile 1990
Legend rows
70.3 or more
7.0 - 70.2
Less than 7.0
Percent change in population 1990 to 2000
Legend columns
Loss
0.0 to 13.1
13.2 or more
Data Sources: U.S. Census Bureau, Census 2000 Redistricting Data (PL 94-171) Summary File and 1990 Census.
Cartography: Population Division, U.S. Census Bureau.
0 100 Miles
0 100 Miles
0 100 Miles



Graphic: Christopher Adolph (www.chrisadolph.com); Data:NOAA and US Naval Observatory.