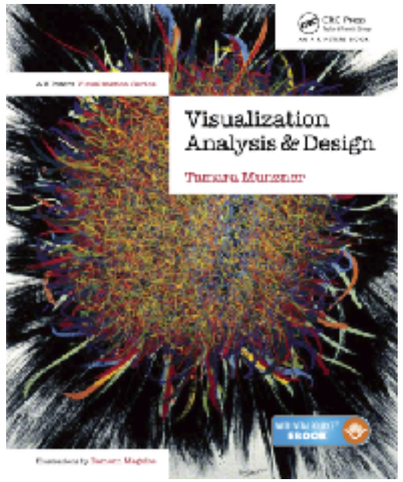
Visualization Analysis & Design



Color (Ch 10)

Tamara Munzner
Department of Computer Science
University of British Columbia
@tamaramunzner

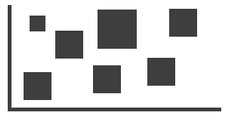
Idiom design choices: Visual encoding

Encode

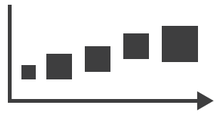
Arrange

- Express

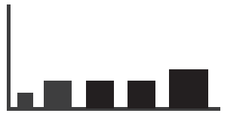
- Separate



- Order



- Align



- Use

Map

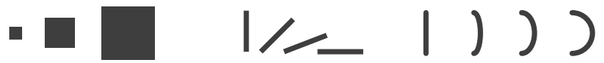
from categorical and ordered attributes

- Color
  - *Hue*

  - *Saturation*

  - *Luminance*

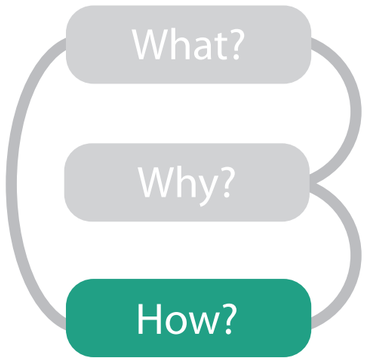
- Size, Angle, Curvature, ...



- Shape

- Motion

  Direction, Rate, Frequency, ...



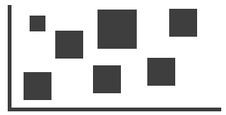
Idiom design choices: Beyond spatial arrangement

Encode

Arrange

- Express

- Separate



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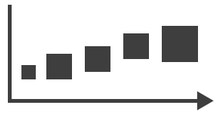

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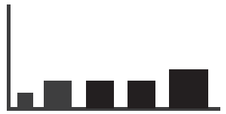

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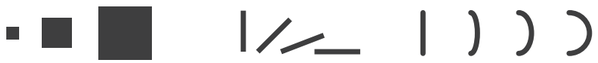

- Shape

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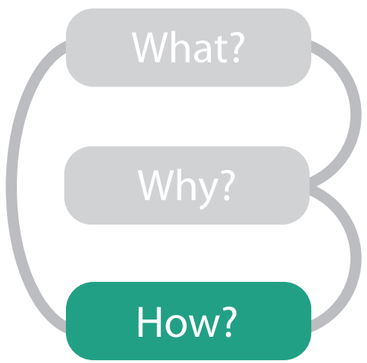
  Direction, Rate, Frequency, ...



Channels: What's up with color?

Magnitude Channels: Ordered Attributes

- Position on common scale
- Position on unaligned scale
- Length (1D size)
- Tilt/angle
- Area (2D size)
- Depth (3D position)
- Color luminance
- Color saturation
- Curvature
- Volume (3D size)

Effectiveness: Best ▲ … ▼ Least

Color luminance, Color saturation: Same

Curvature, Volume (3D size): Same

Identity Channels: Categorical Attributes

- Spatial region
- Color hue
- Motion
- Shape

Decomposing color

Decomposing color

- first rule of color: do not (just) talk about color!
  - color is confusing if treated as monolithic

Decomposing color

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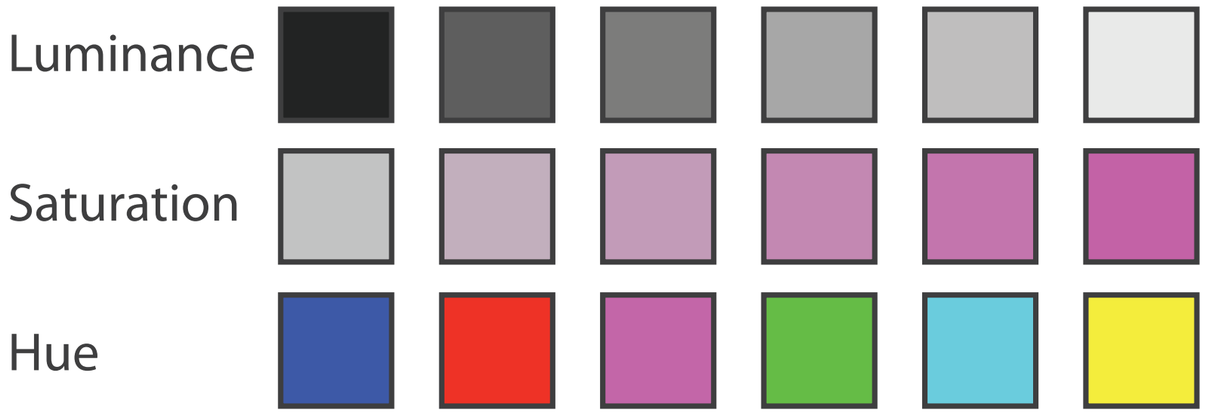
    - **luminance**: how bright (B/W)
    - **saturation**: how colourful
  - categorical can show identity
    - **hue**: what color



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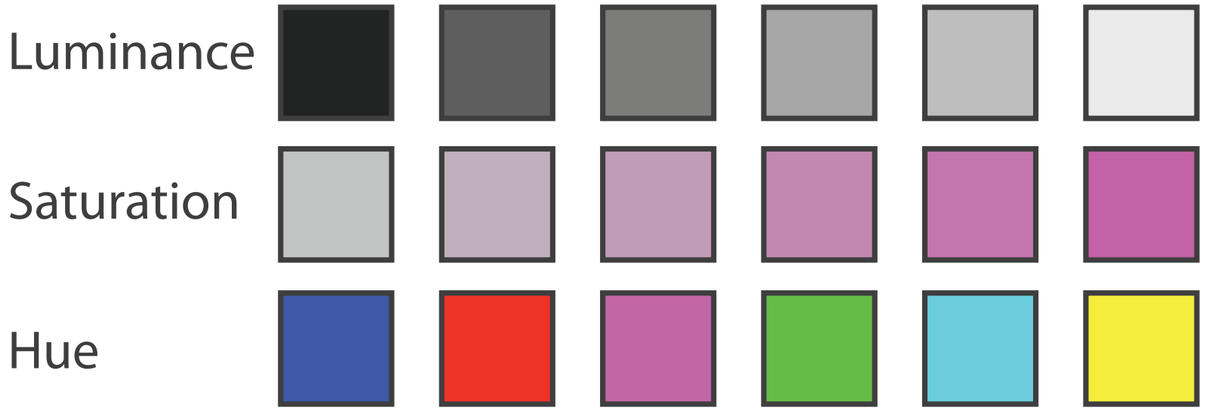
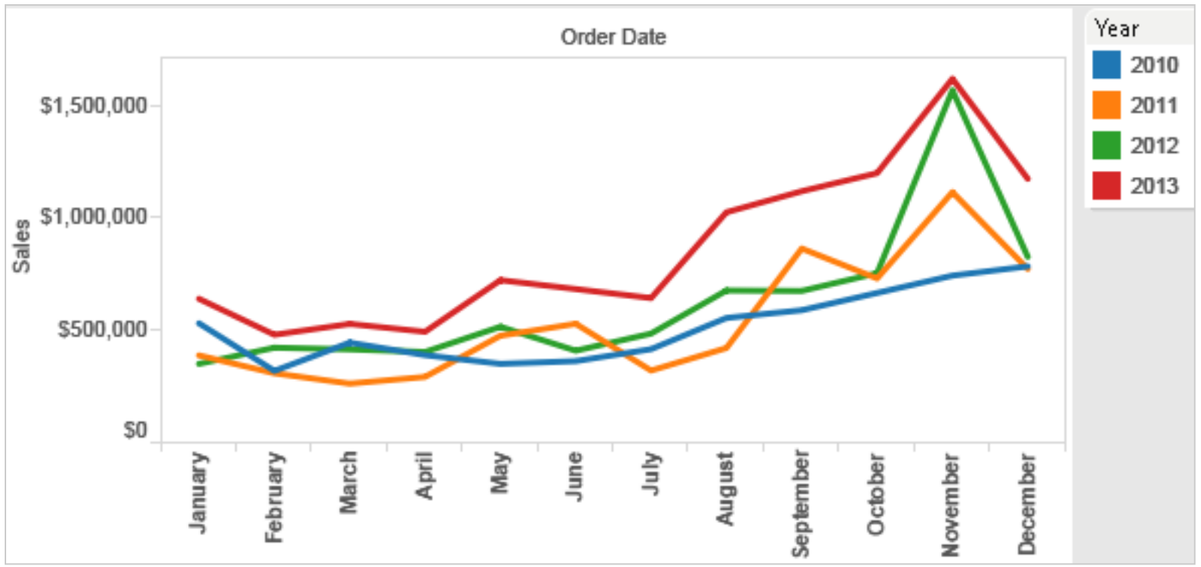
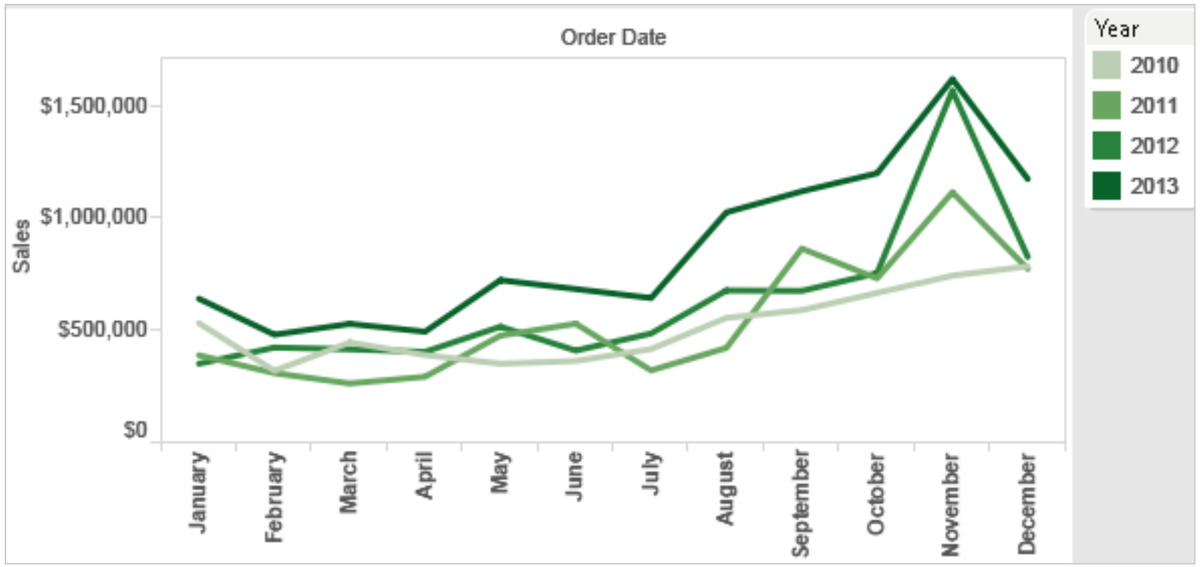


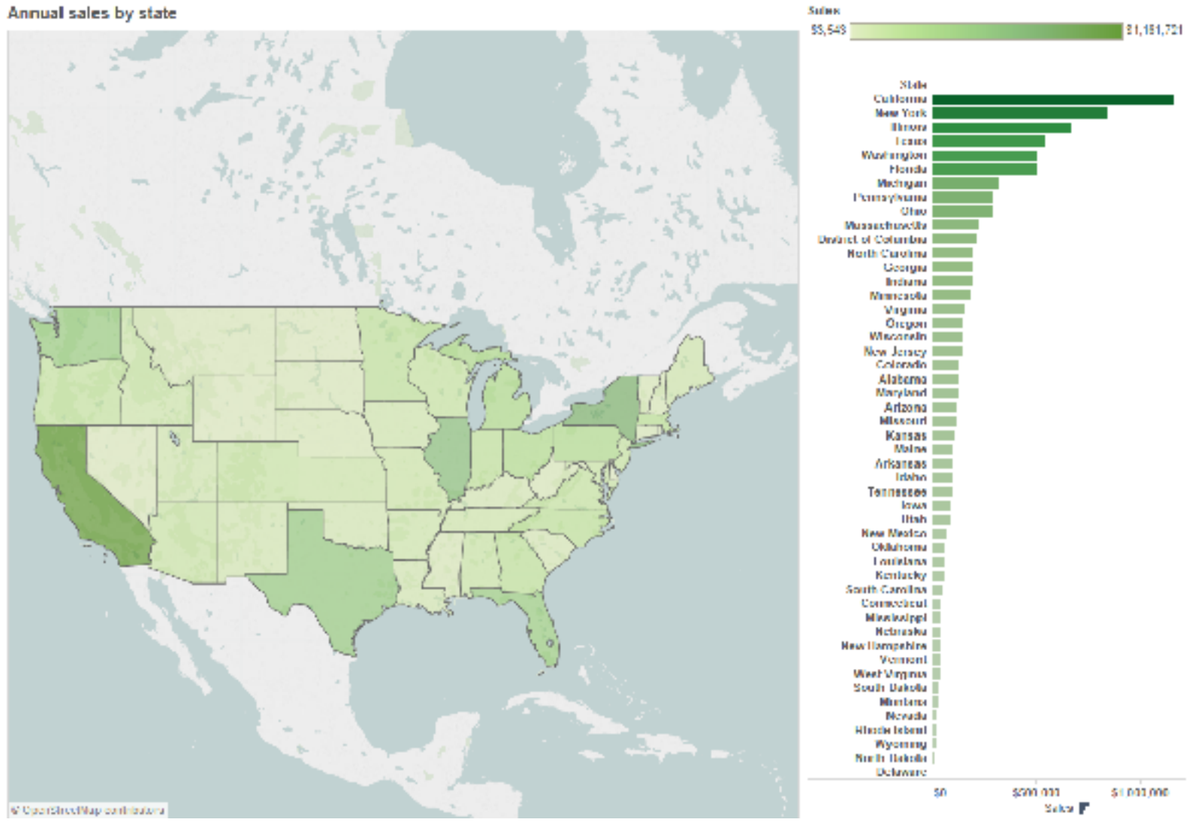
- channels have different properties
  - what they convey directly to perceptual system
  - how much they can convey
    - how many discriminable bins can we use?

Color Channels in Visualization

Categorical vs ordered color







[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

Categorical color: limited number of discriminable bins

- human perception built on relative comparisons

[Cinteny: flexible analysis and visualization of synteny and genome rearrangements in multiple organisms. Sinha and Meller. BMC Bioinformatics, 8:82, 2007.]

Categorical color: limited number of discriminable bins

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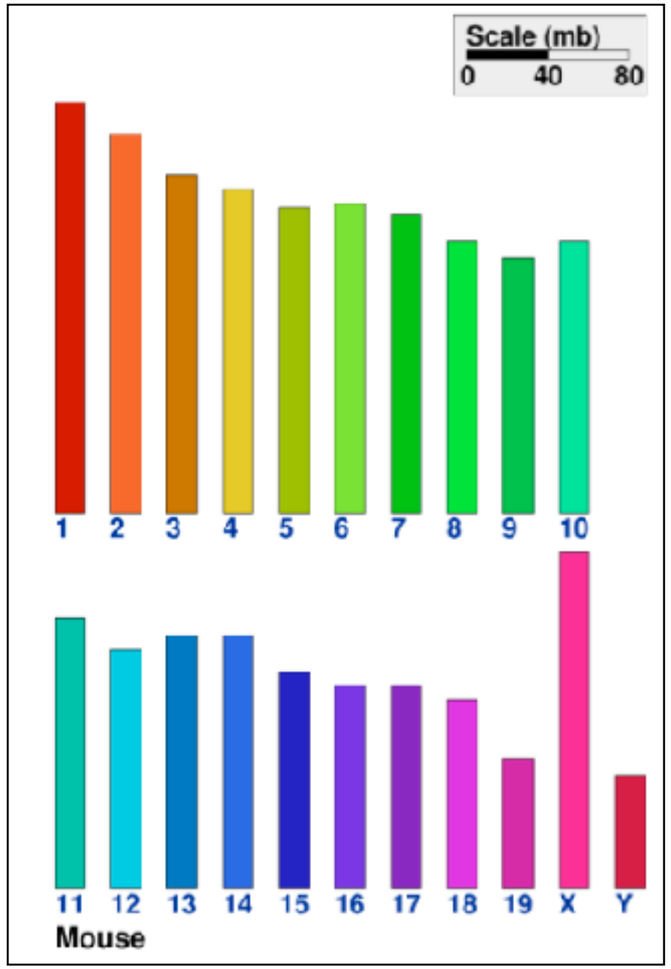
  - great if color contiguous



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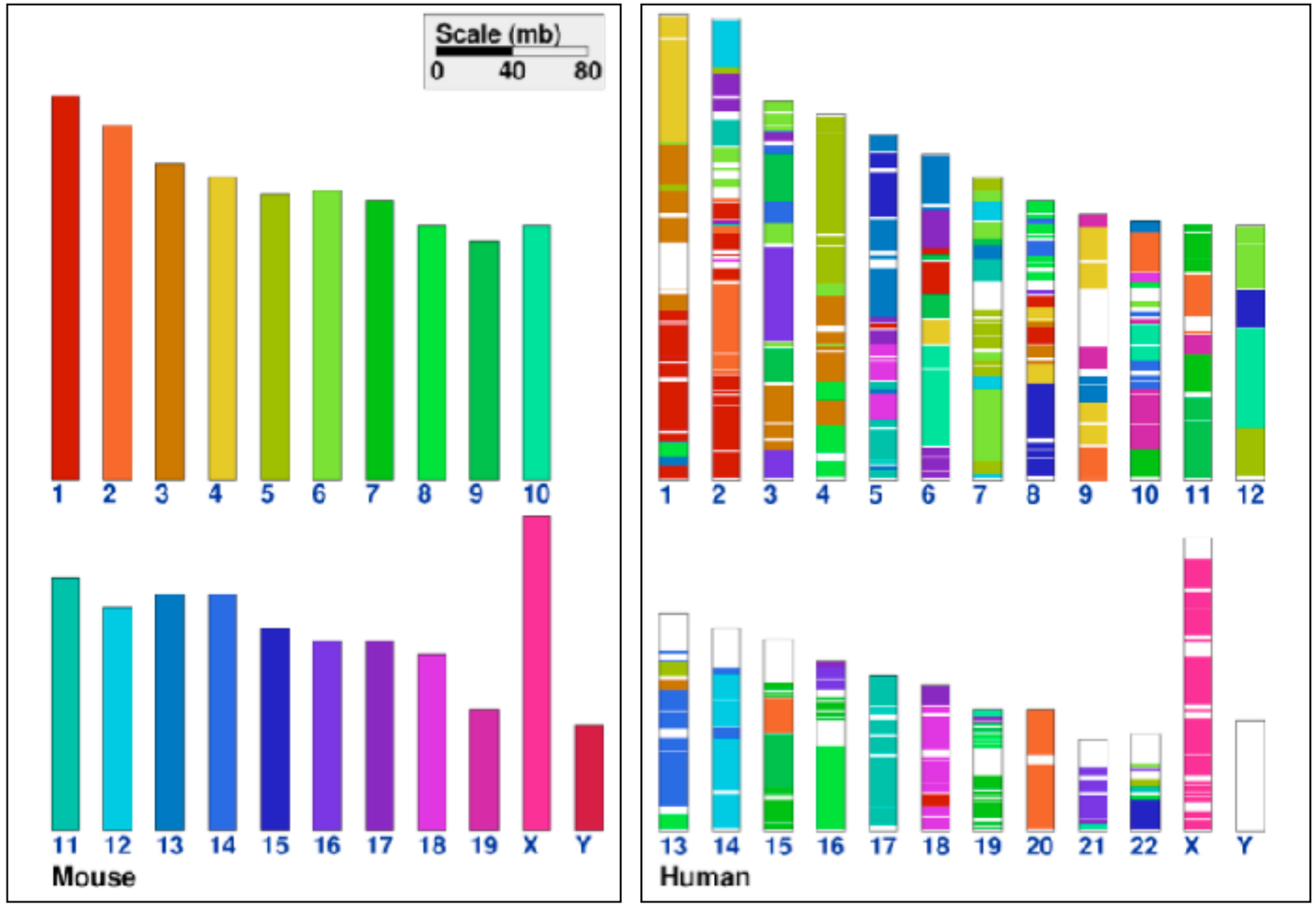

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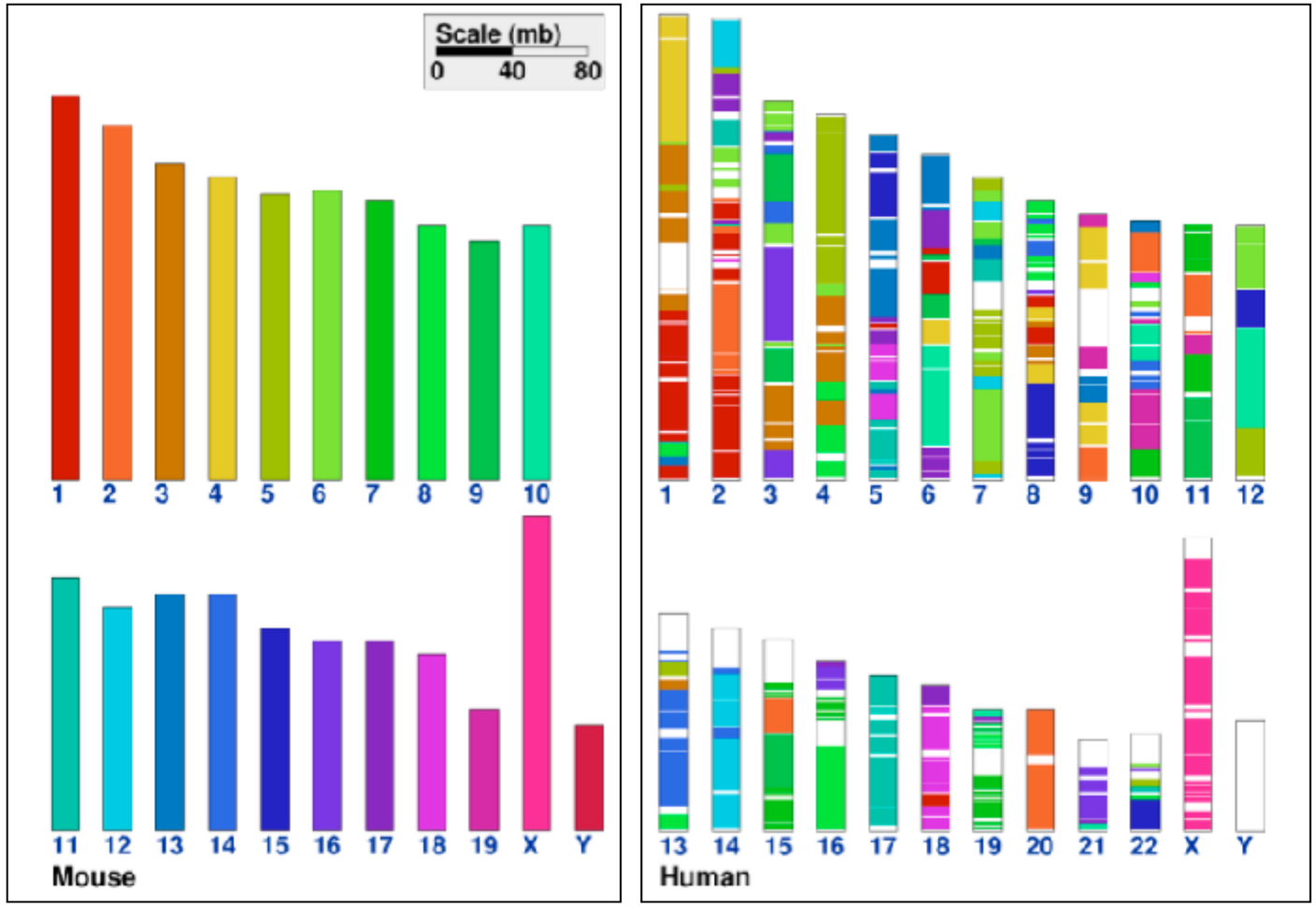
Categorical color: limited number of discriminable bins

- human perception built on relative comparisons
  - great if color contiguous
  - surprisingly bad for absolute comparisons
- noncontiguous small regions of color
  - fewer bins than you want
  - rule of thumb: 6-12 bins, including background and highlights



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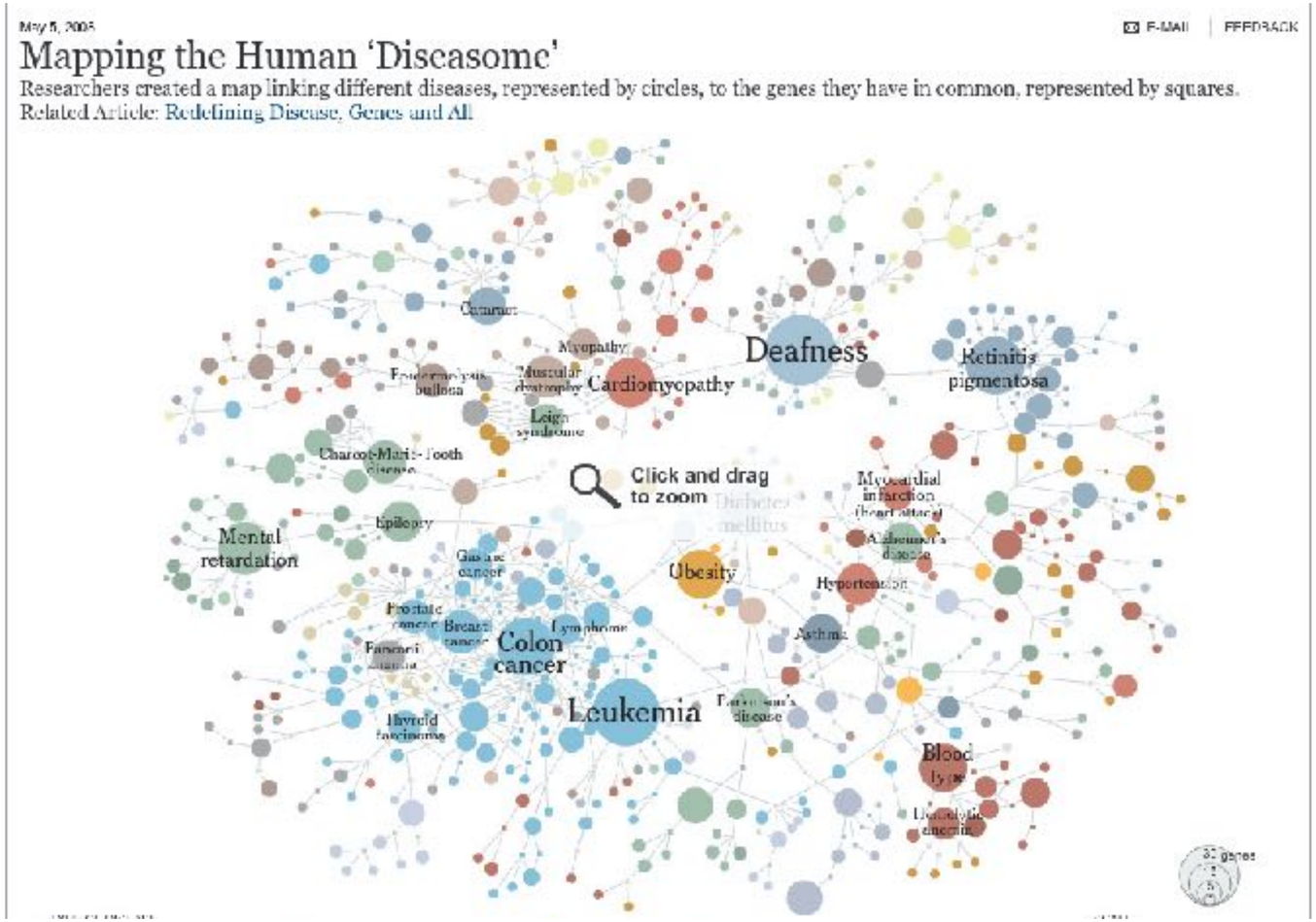
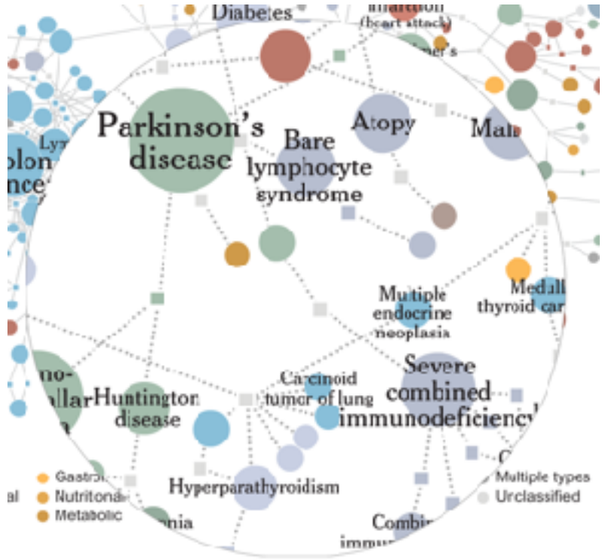
Categorical color: limited number of discriminable bins

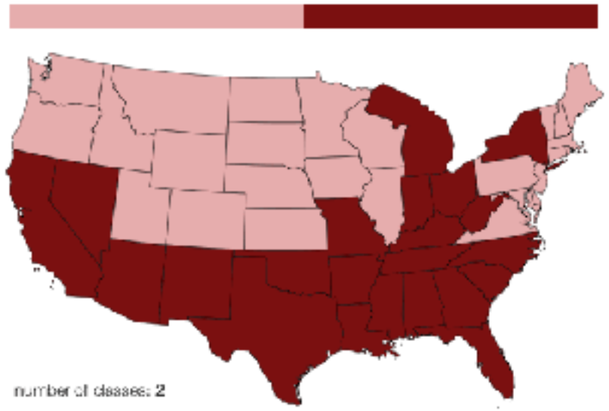
- Cancer
- Bone
- Skeletal
- Connective tissue
- Muscular
- Dermatological
- Cardiovascular
- Hematological
- Renal
- Endocrine
- Immunological
- Gastrointestinal
- Nutritional
- Metabolic
- Ear, nose, throat
- Ophthalmological
- Respiratory
- Developmental
- Neurological
- Psychiatric
- Multiple types
- Unclassified

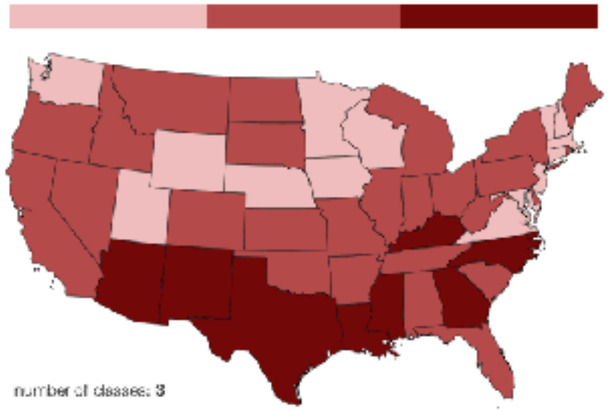


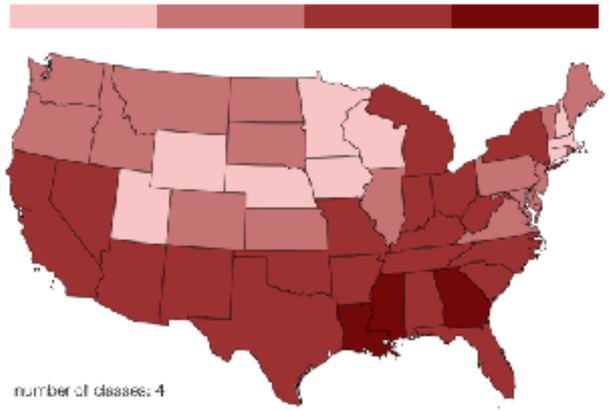


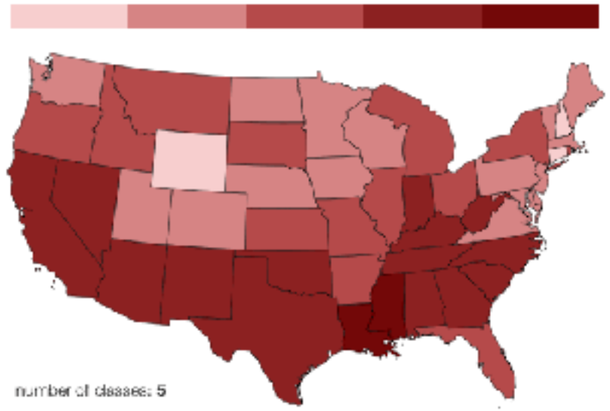
https://archive.nytimes.com/www.nytimes.com/interactive/2008/05/05/science/20080506_DISEASE.html

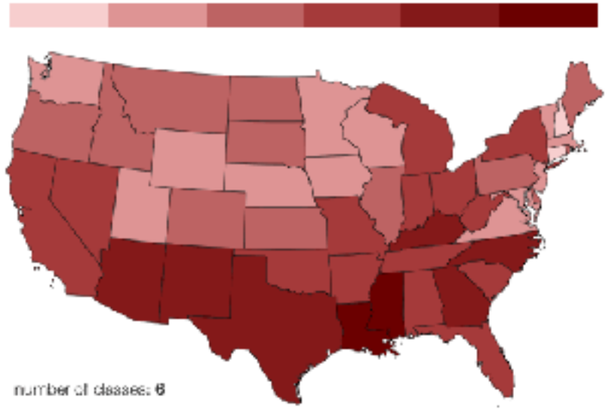
Ordered color: limited number of discriminable bins

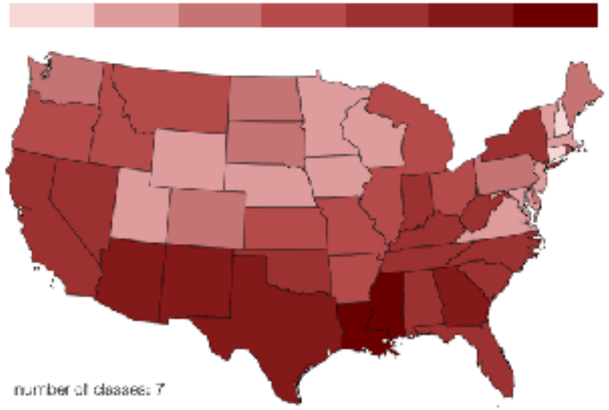


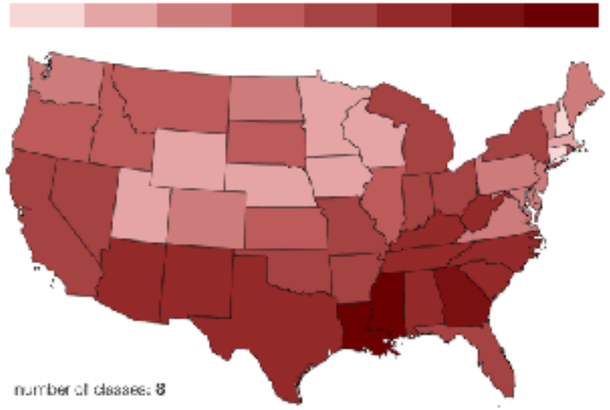










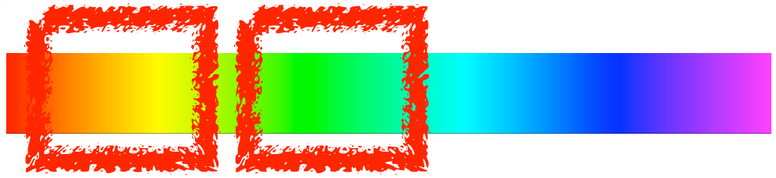


Gregor Aisch, vis4.net/blog/posts/choropleth-maps/

Ordered color: Rainbow is poor default

- problems
  - perceptually unordered
  - perceptually nonlinear

Ordered color: Rainbow is poor default



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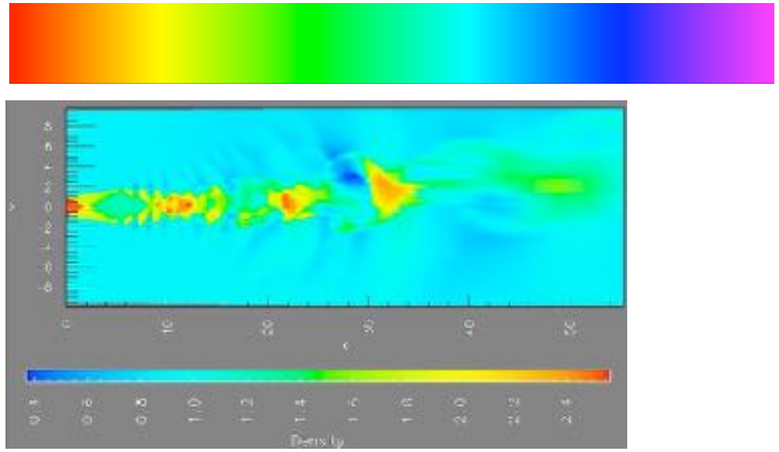
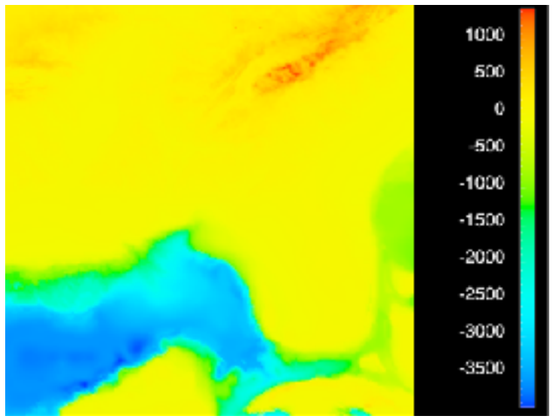
  - fine-grained structure visible and nameable



[A Rule-based Tool for Assisting Colormap Selection. Bergman,. Rogowitz, and. Treinish. Proc. IEEE Visualization (Vis), pp. 118–125, 1995.]



[Why Should Engineers Be Worried About Color? Treinish and Rogowitz 1998. http://www.research.ibm.com/people/l/lloydt/color/color.HTM]

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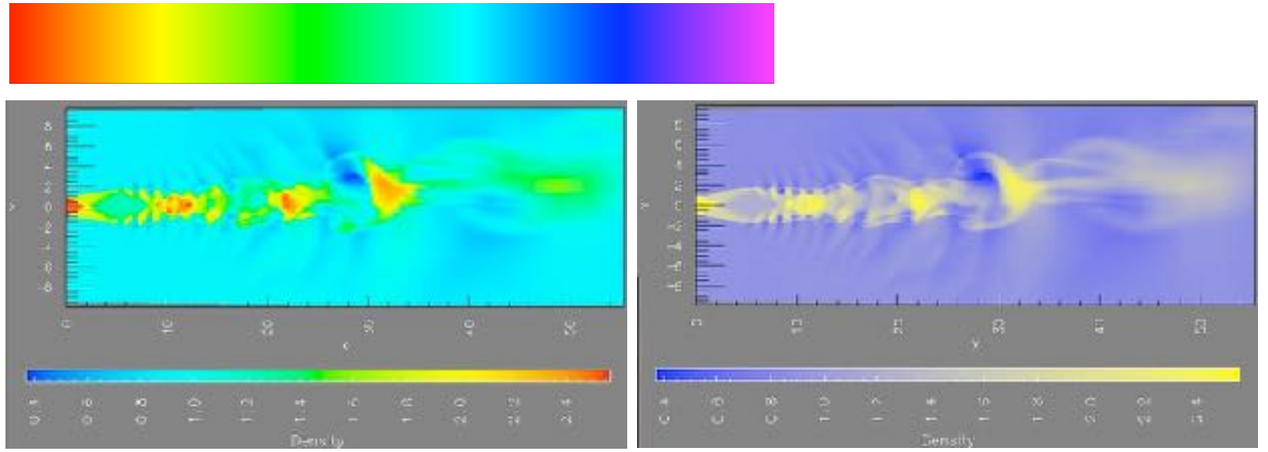
- alternatives
  - large-scale structure: fewer hues



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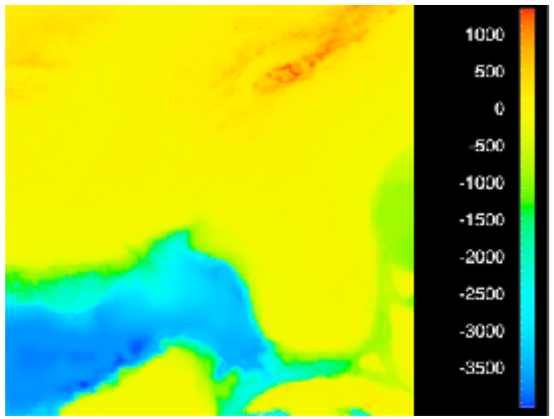

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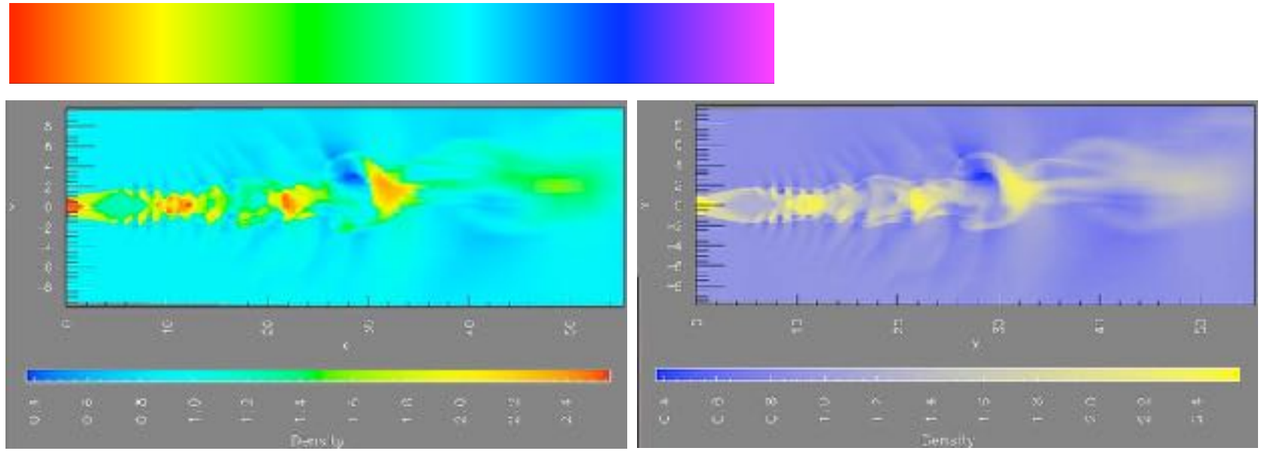
  - large-scale structure: fewer hues
  - fine structure: multiple hues with monotonically increasing luminance [eg viridis]



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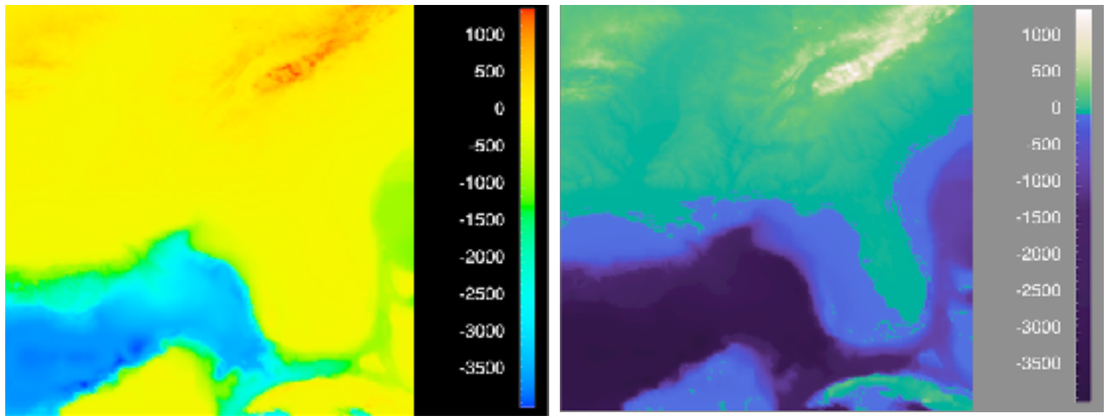

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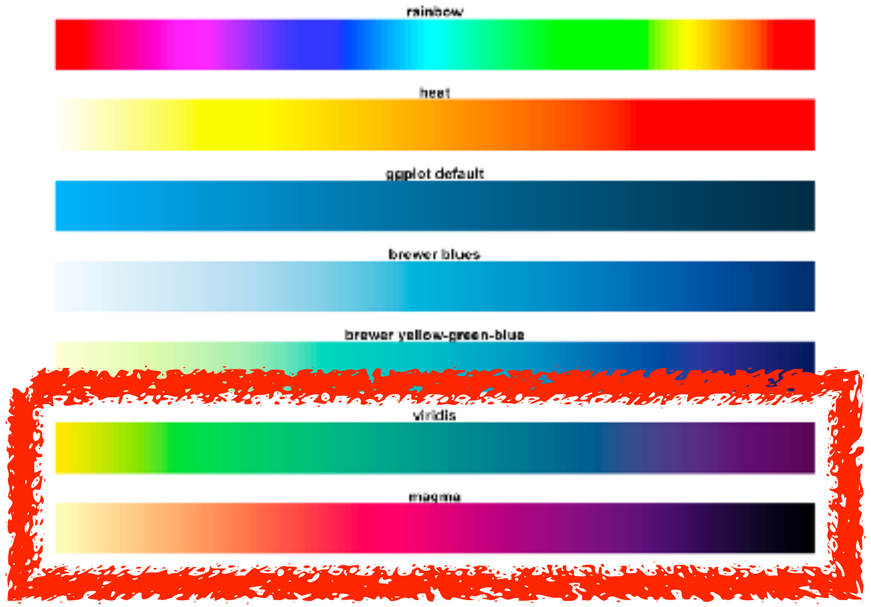
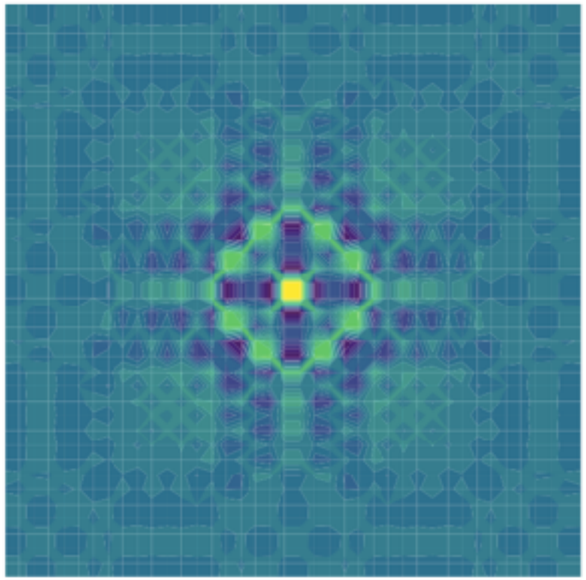
Viridis / Magma: sequential colormaps

- monotonically increasing luminance, perceptually uniform
- colorful, colorblind-safe
  - R, python, D3





https://cran.r-project.org/web/packages/viridis/vignettes/intro-to-viridis.html

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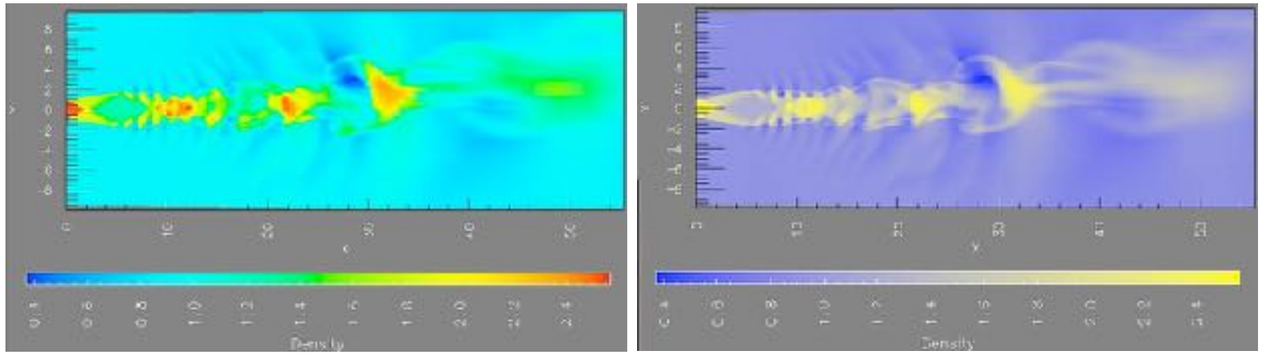
- benefits
  - fine-grained structure visible and nameable
- alternatives
  - large-scale structure: fewer hues
  - fine structure: multiple hues with monotonically increasing luminance [eg viridis]
- legit for categorical
  - segmented saturated rainbow is good!



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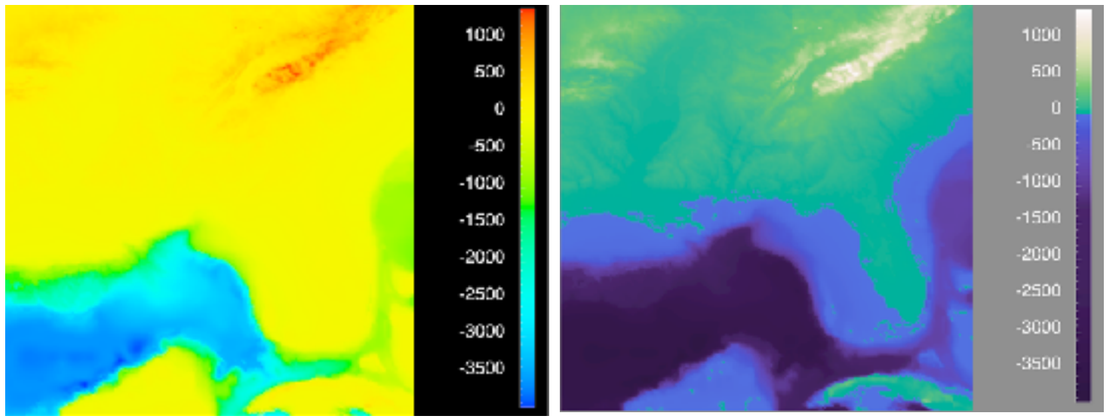
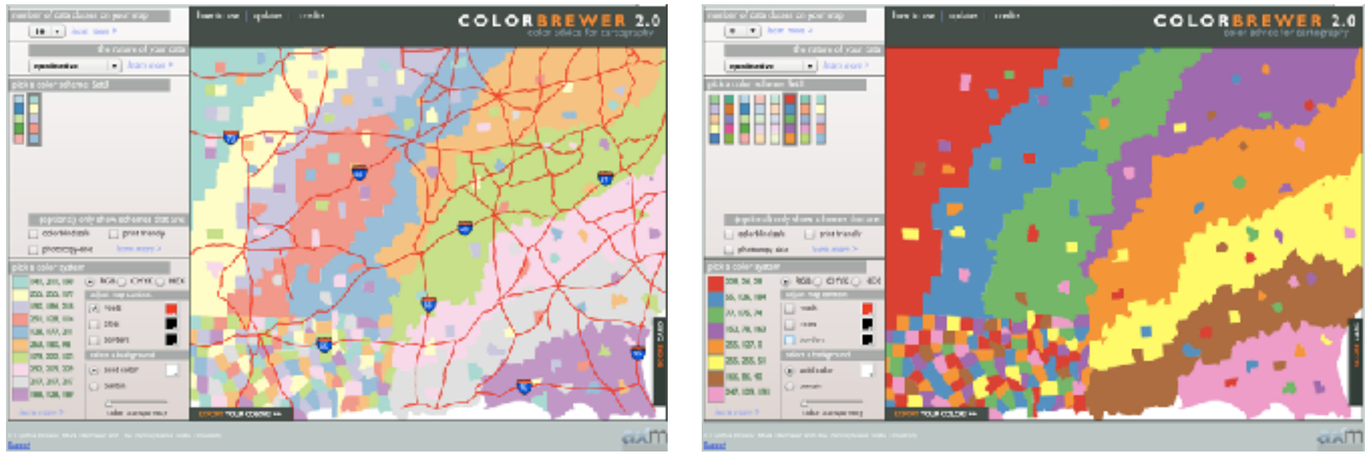


[Why Should Engineers Be Worried About Color? Treinish and Rogowitz 1998. http://www.research.ibm.com/people/l/lloydt/color/color.HTM]

[Transfer Functions in Direct Volume Rendering: Design, Interface, Interaction. Kindlmann. SIGGRAPH 2002 Course Notes]

Interaction between channels: Not fully separable

- color channel interactions
  - size heavily affects salience
  - small regions need high saturation
  - large regions need low saturation



http://colorbrewer2.org/

Interaction between channels: Not fully separable

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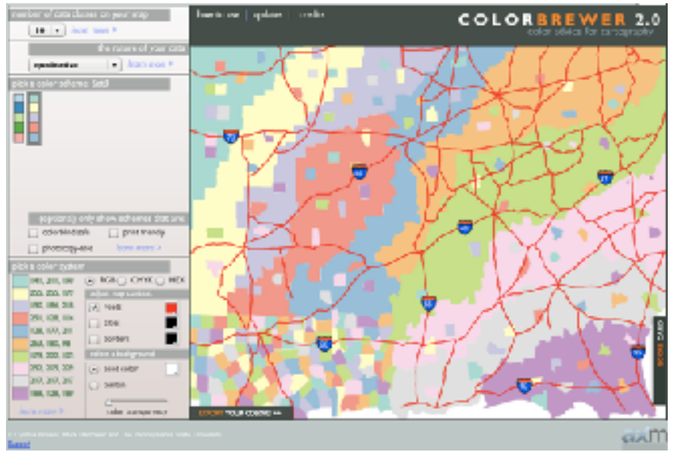
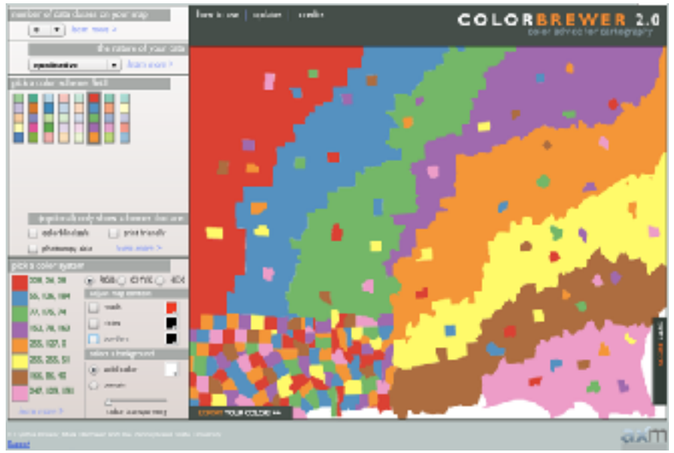
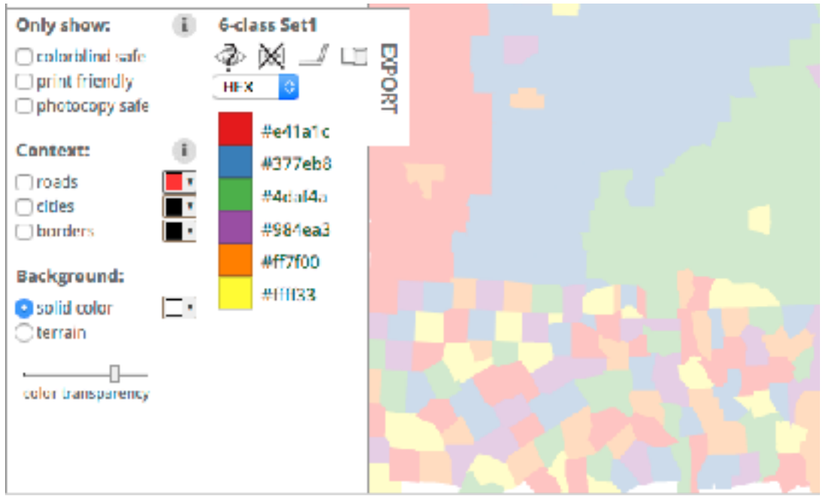
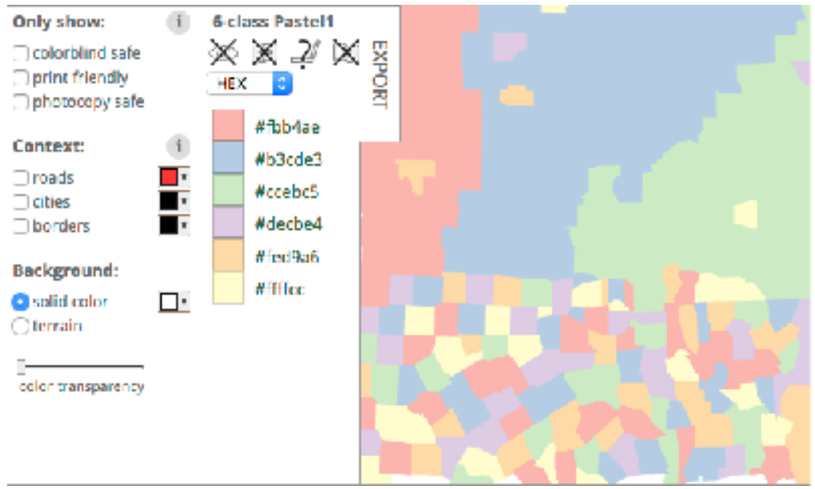
- saturation & luminance:
  - not separable from each other!
  - also not separable from transparency









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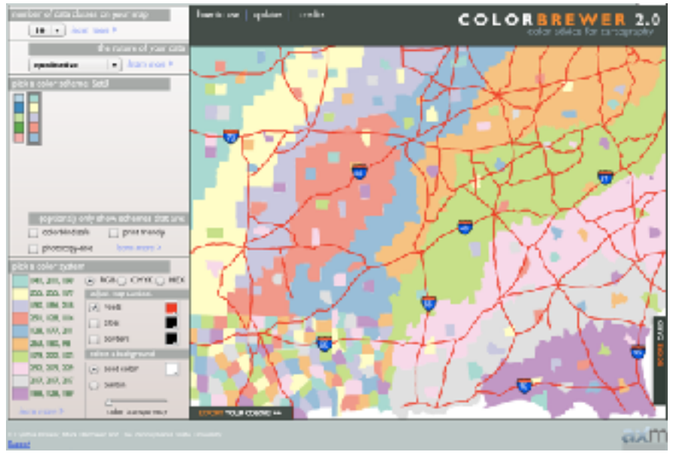
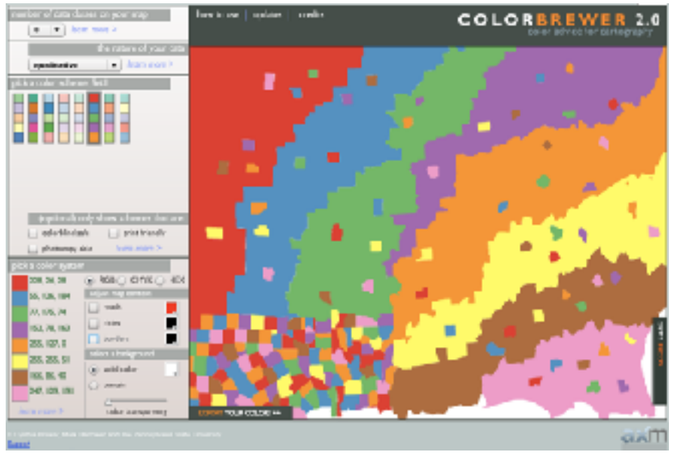
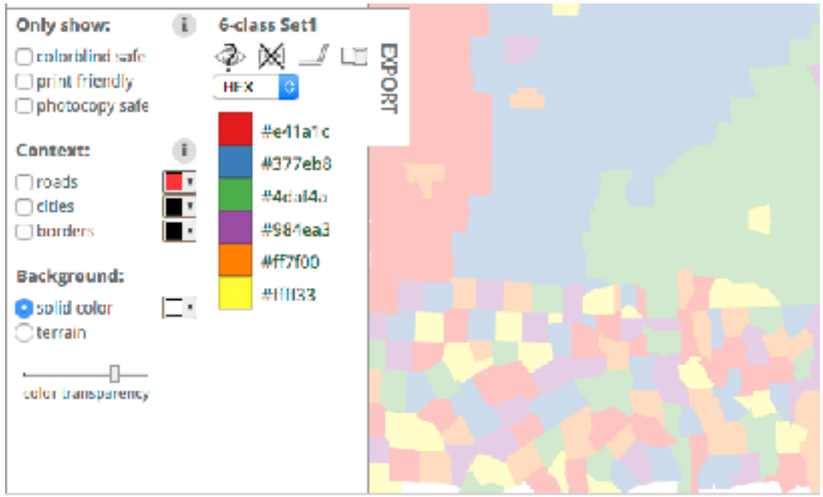
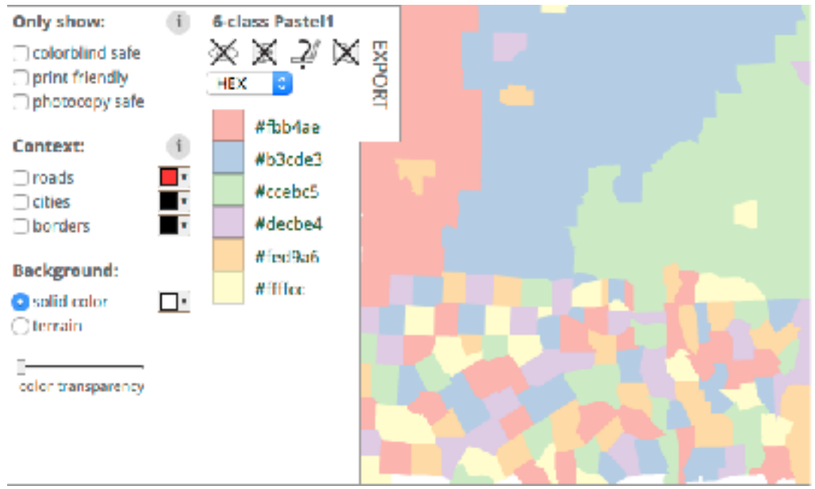
Interaction between channels: Not fully separable

- color channel interactions
  - size heavily affects salience
  - small regions need high saturation
  - large regions need low saturation
- saturation & luminance:
  - not separable from each other!
  - also not separable from transparency
  - small separated regions: 2 bins safest (use only one of these channels), 3-4 bins max
  - contiguous regions: many bins (use only one of these channels)









http://colorbrewer2.org/

Color Palettes

Color palettes: univariate

➔ Categorical

Categorical

categorical

- categorical
  - aim for maximum distinguishability
  - aka *qualitative*, *nominal*

after [Color Use Guidelines for Mapping and Visualization. Brewer, 1994. http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html]

Color palettes: univariate

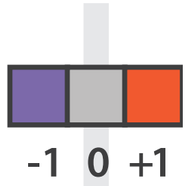
➔ Categorical

➔ Ordered

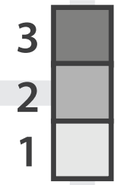
➔ *Sequential*

➔ *Diverging*

Categorical



Diverging



Sequential

- diverging
  - useful when data has meaningful "midpoint"
  - use neutral color for midpoint
    - white, yellow, grey
  - use saturated colors for endpoints
- sequential
  - ramp luminance or saturation

diverging

sequential

after [Color Use Guidelines for Mapping and Visualization. Brewer, 1994. http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html]

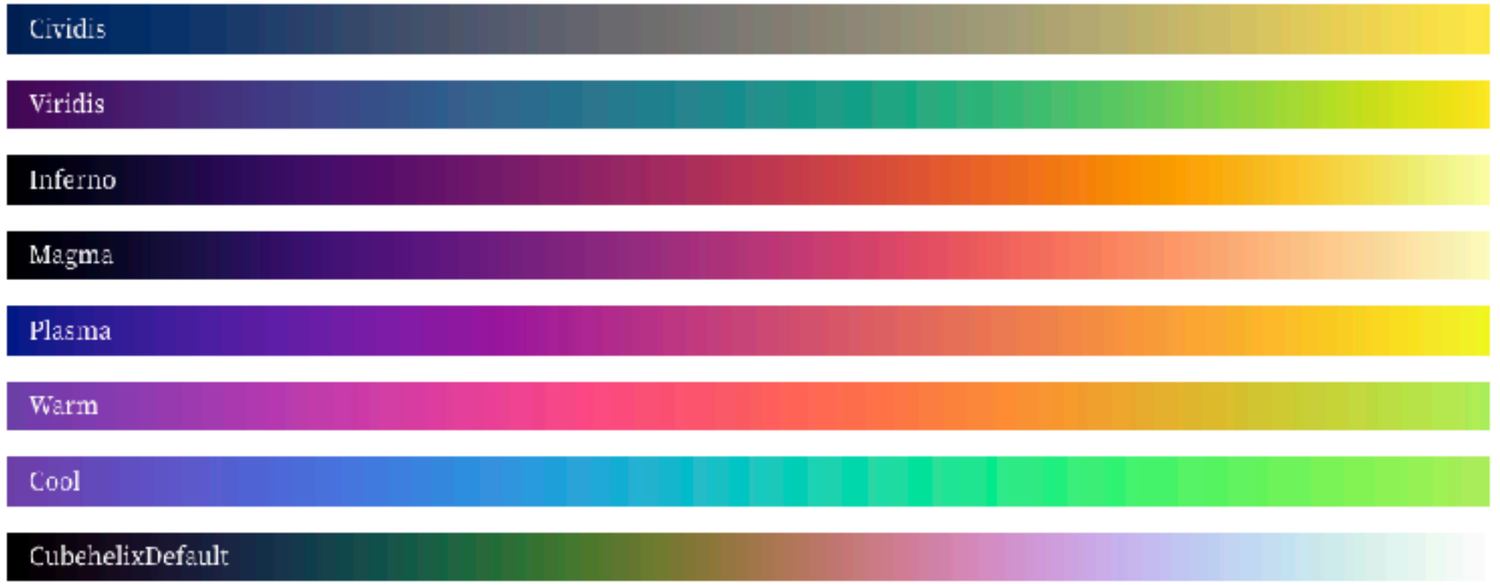
Color palettes: univariate

➔ Categorical

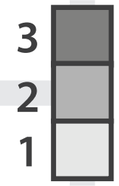
➔ Ordered

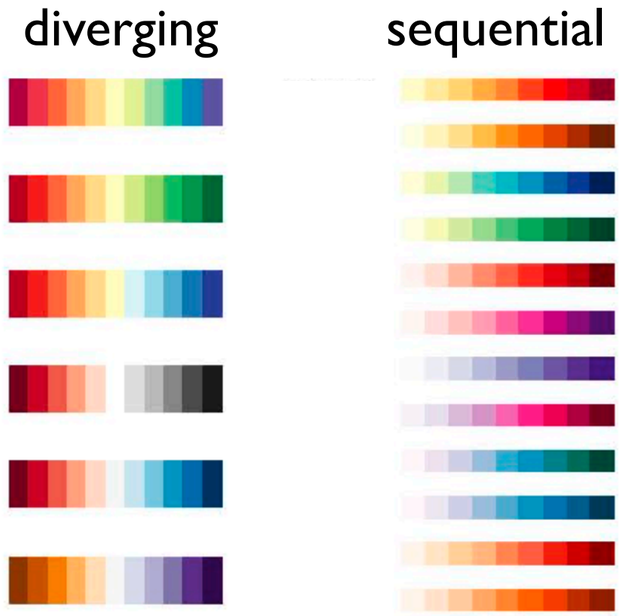
➔ *Sequential*

➔ *Diverging*



- diverging
  - useful when data has meaningful "midpoint"
  - use neutral color for midpoint
    - white, yellow, grey
  - use saturated colors for endpoints
- sequential
  - ramp luminance or saturation
  - if multi-hue, good to order by luminance





after [Color Use Guidelines for Mapping and Visualization. Brewer, 1994. http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html]

Color palettes: univariate

- Categorical

- Ordered
  - *Sequential*

  - *Diverging*

  - Cyclic

cyclic multihue

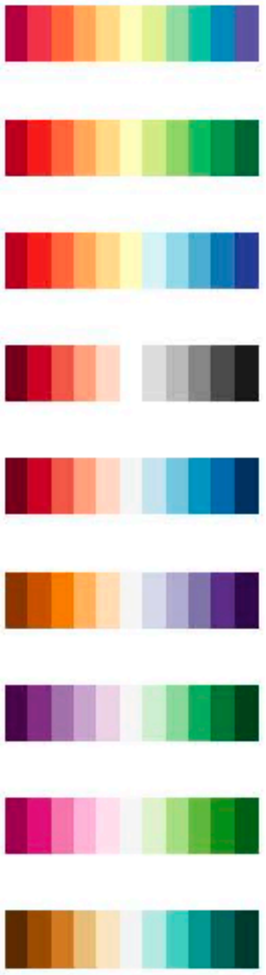
https://github.com/d3/d3-scale-chromatic

after [Color Use Guidelines for Mapping and Visualization. Brewer, 1994. http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html]

Color palette design considerations: univariate

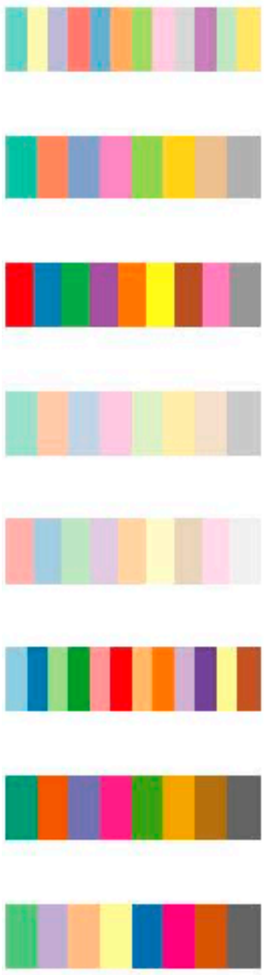
segmented

diverging



sequential

categorical



continuous

sequential single hue

diverging two hue

sequential multihue

cyclic multihue

- segmented or continuous?
- diverging or sequential or cyclic?
- single-hue or two-hue or multi-hue?
- perceptually linear?
- ordered by luminance?
- colorblind safe?

[A Study of Colormaps in Network Visualization. Karim et al. *Appl. Sci.* **2019**, *9*, 4228; doi:10.3390/app9204228]

https://github.com/d3/d3-scale-chromatic

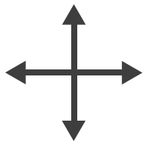
Colormaps: bivariate

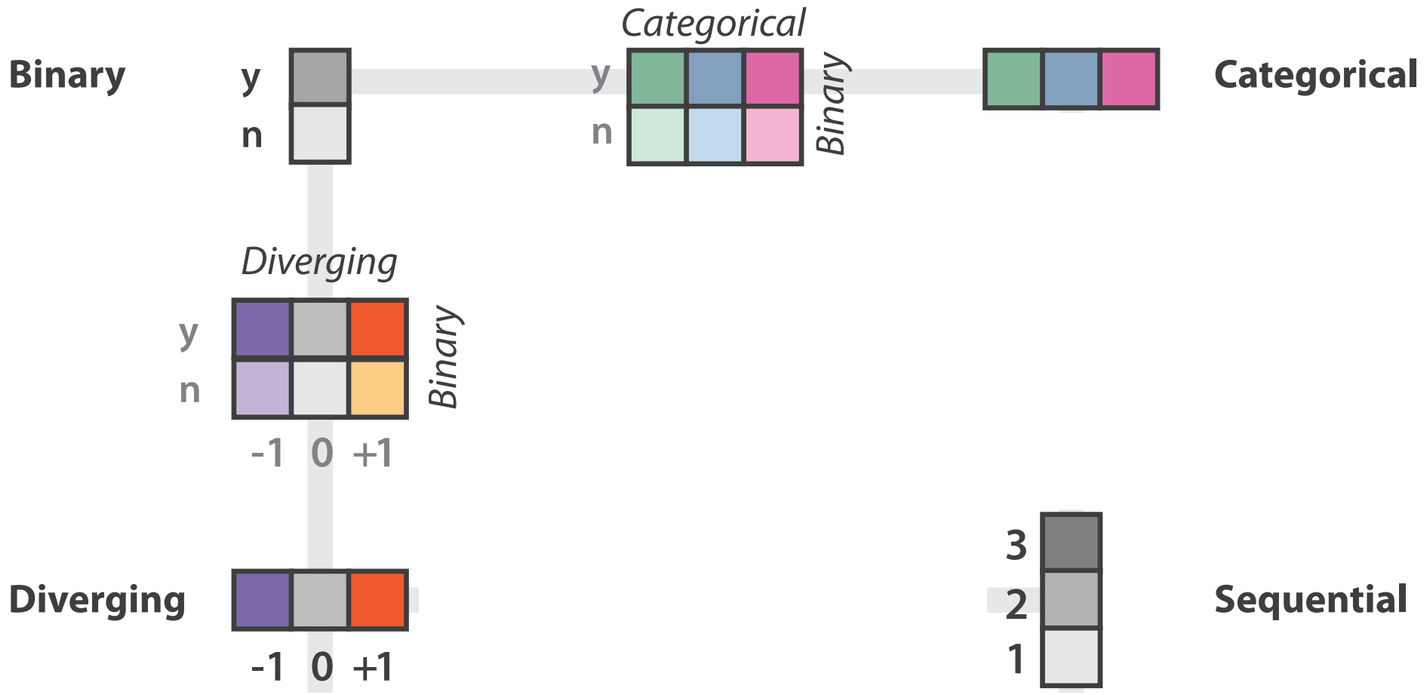
- Categorical

- Ordered
  - *Sequential*

  - *Diverging*

- Bivariate





- bivariate best case
  - binary in one of the directions

d3.schemePaired <>

binary saturation

categorical hue

after [Color Use Guidelines for Mapping and Visualization. Brewer, 1994. http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html]

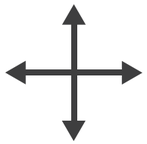
Colormaps: bivariate

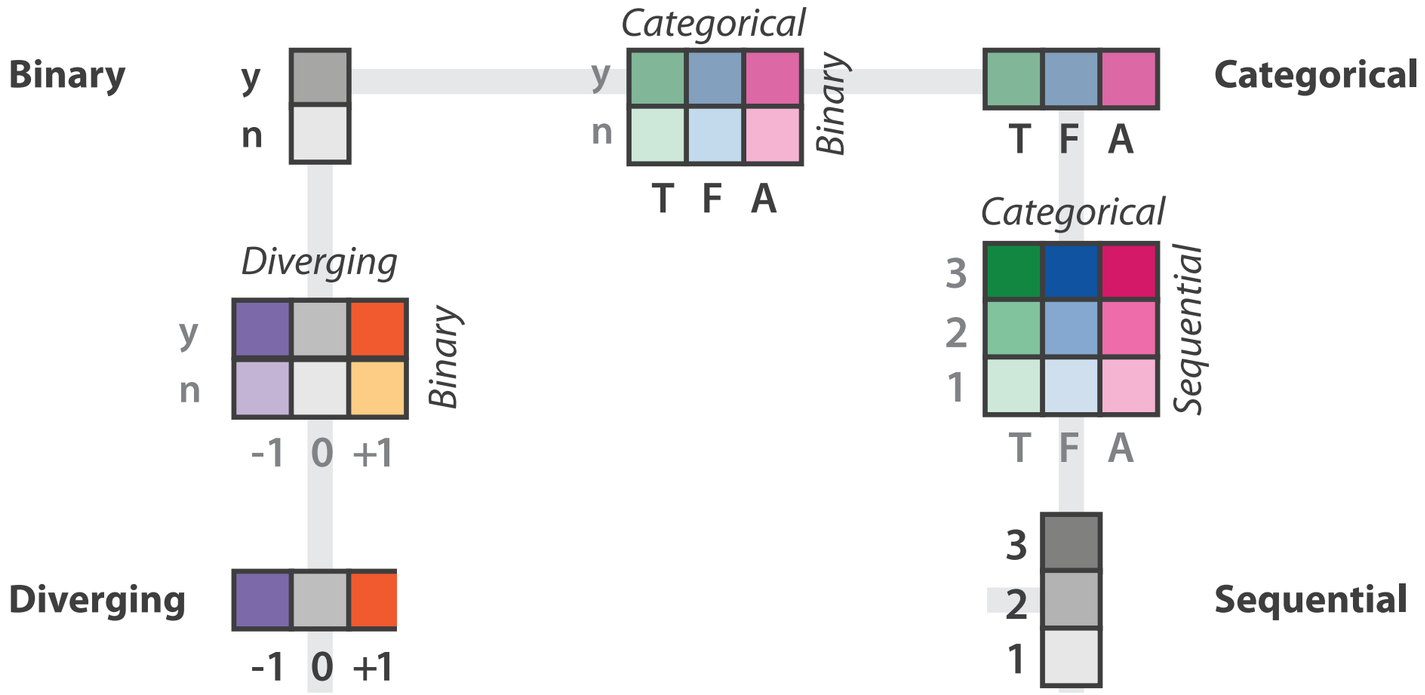
- Categorical

- Ordered
  - *Sequential*

  - *Diverging*

- Bivariate





after [Color Use Guidelines for Mapping and Visualization. Brewer, 1994. http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html]

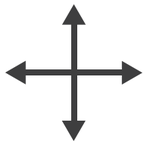
Colormaps

- Categorical

- Ordered
  - *Sequential*

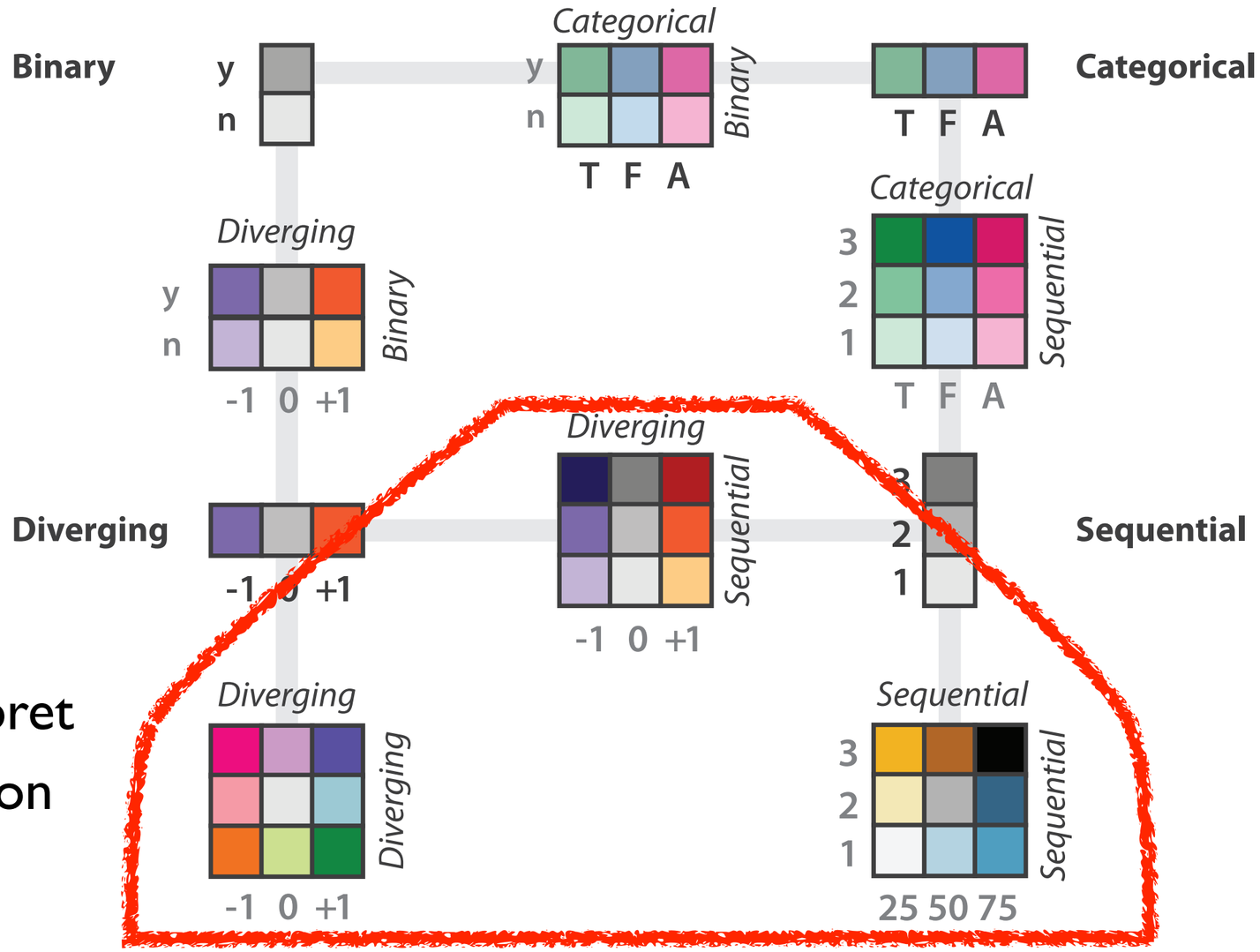
  - *Diverging*

- Bivariate



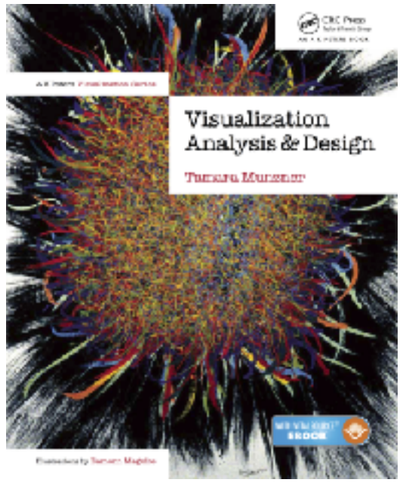
use with care!

- bivariate can be very difficult to interpret
  - when multiple levels in each direction



after [Color Use Guidelines for Mapping and Visualization. Brewer, 1994. http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html]

Visualization Analysis & Design



Color (Ch 10) II

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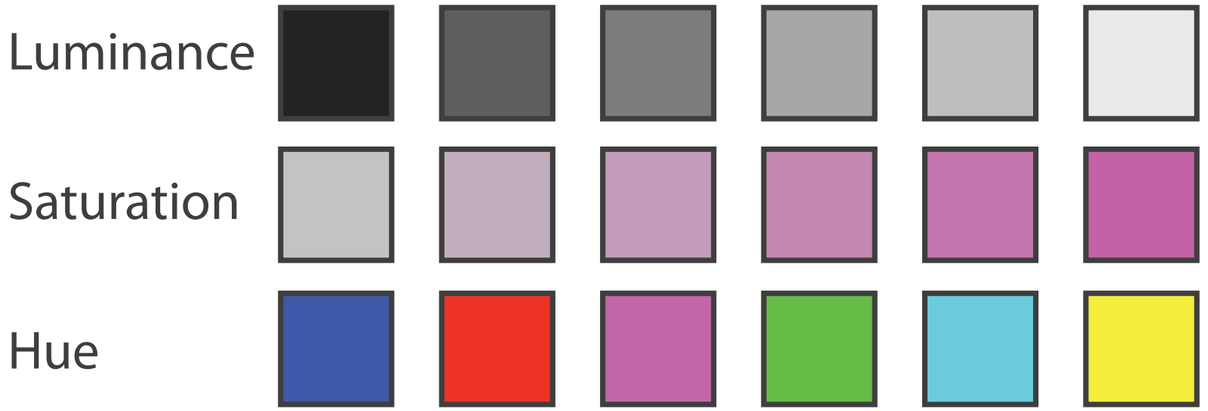
Decomposing color

- decompose into three channels
  - ordered can show magnitude
    - **luminance**: how bright (B/W)
    - **saturation**: how colourful
  - categorical can show identity
    - **hue**: what color



Color Deficiency

Luminance

- need luminance for edge detection
  - fine-grained detail only visible through luminance contrast
  - legible text requires luminance contrast!

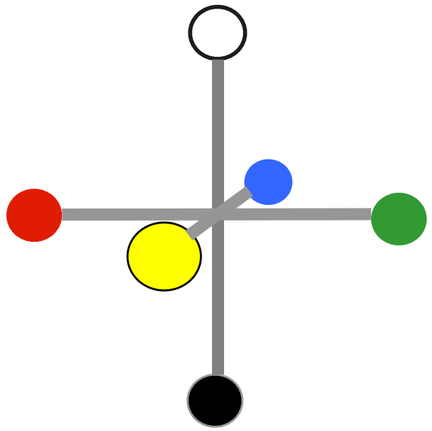
Luminance information

Saturation/hue information

[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

Opponent color and color deficiency

- perceptual processing before optic nerve
  - one achromatic luminance channel (L*)
    - edge detection through luminance contrast
  - 2 chroma channels
    - red-green (a*) & yellow-blue axis (b*)



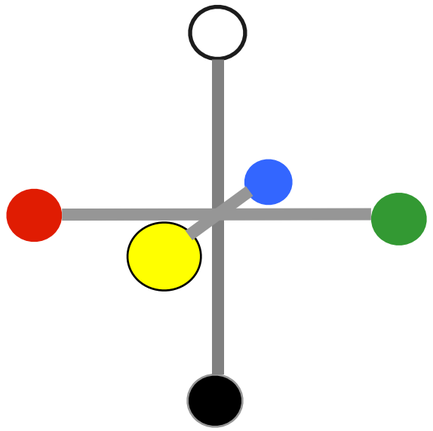
Luminance information

Chroma information

[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

Opponent color and color deficiency

- perceptual processing before optic nerve
  - one achromatic luminance channel (L*)
    - edge detection through luminance contrast
  - 2 chroma channels
    - red-green (a*) & yellow-blue axis (b*)
- "colorblind": degraded acuity, one axis
  - 8% of men are red/green color deficient
  - blue/yellow is rare



Luminance information

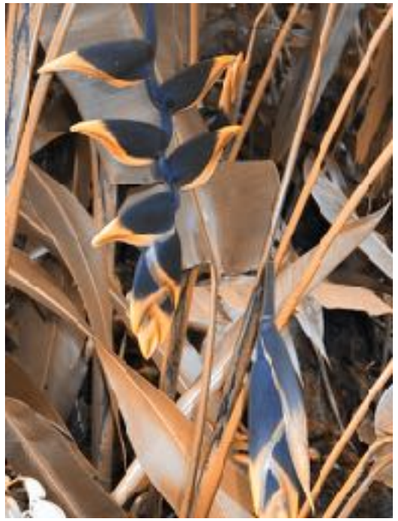
Chroma information

[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

Designing for color deficiency: Check with simulator

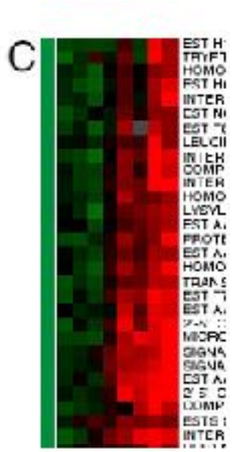
Normal vision

Deuteranope *green-weak*



Protanope *red-weak*

Tritanope *blue-weak*

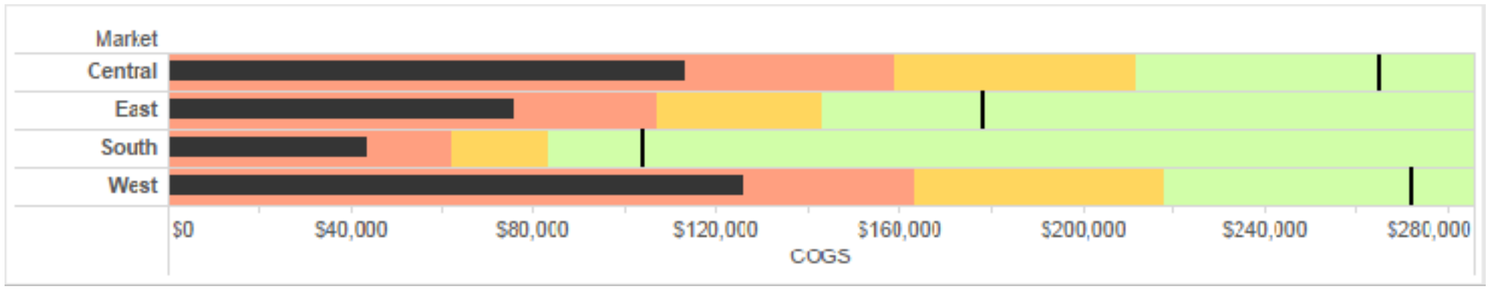


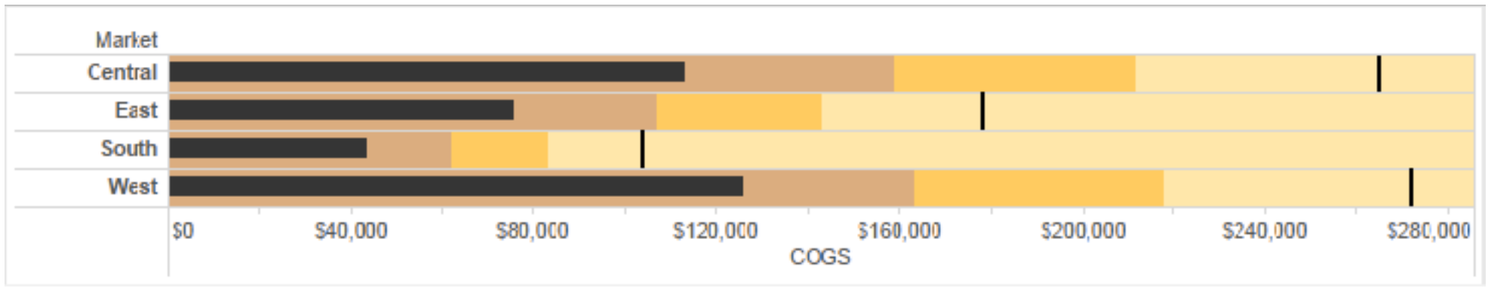
https://www.color-blindness.com/coblis-color-blindness-simulator/

[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

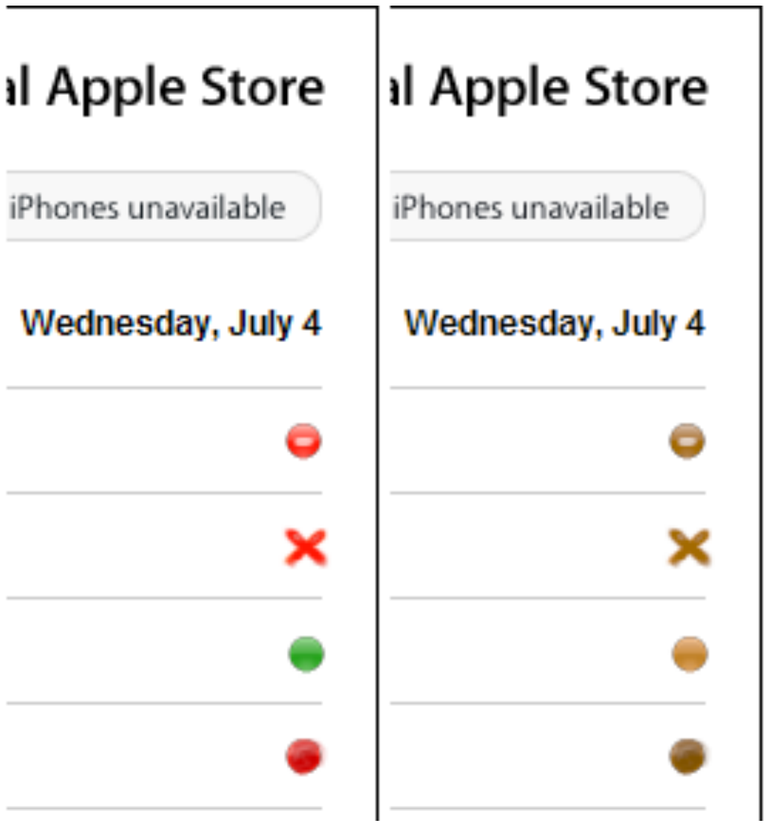
Designing for color deficiency: Avoid encoding by hue alone

- redundantly encode
  - vary luminance
  - change shape





Deuteranope simulation

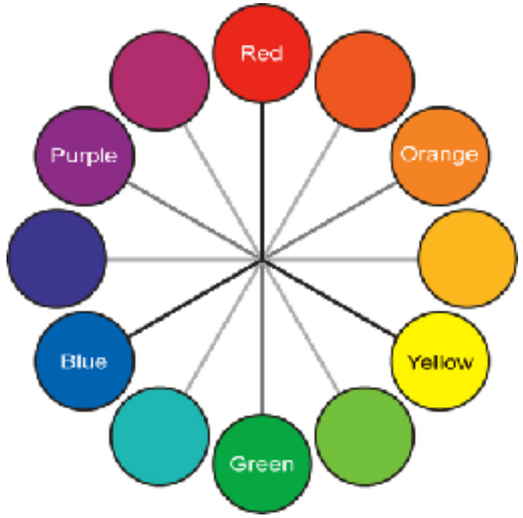


Change the shape

Vary luminance

[Seriously Colorful: Advanced Color Principles & Practices. Stone. Tableau Customer Conference 2014.]

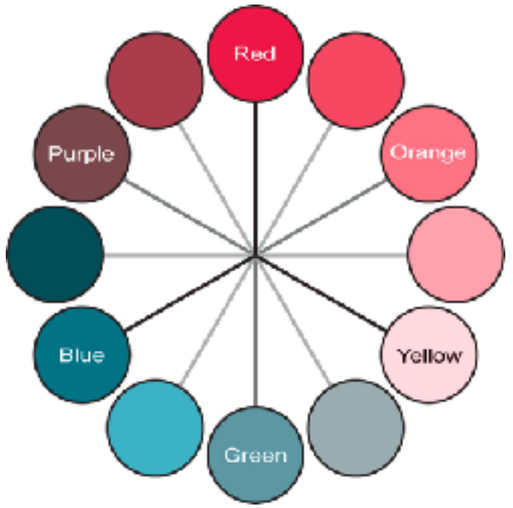
Color deficiency: Reduces color to 2 dimensions



Normal

Protanope

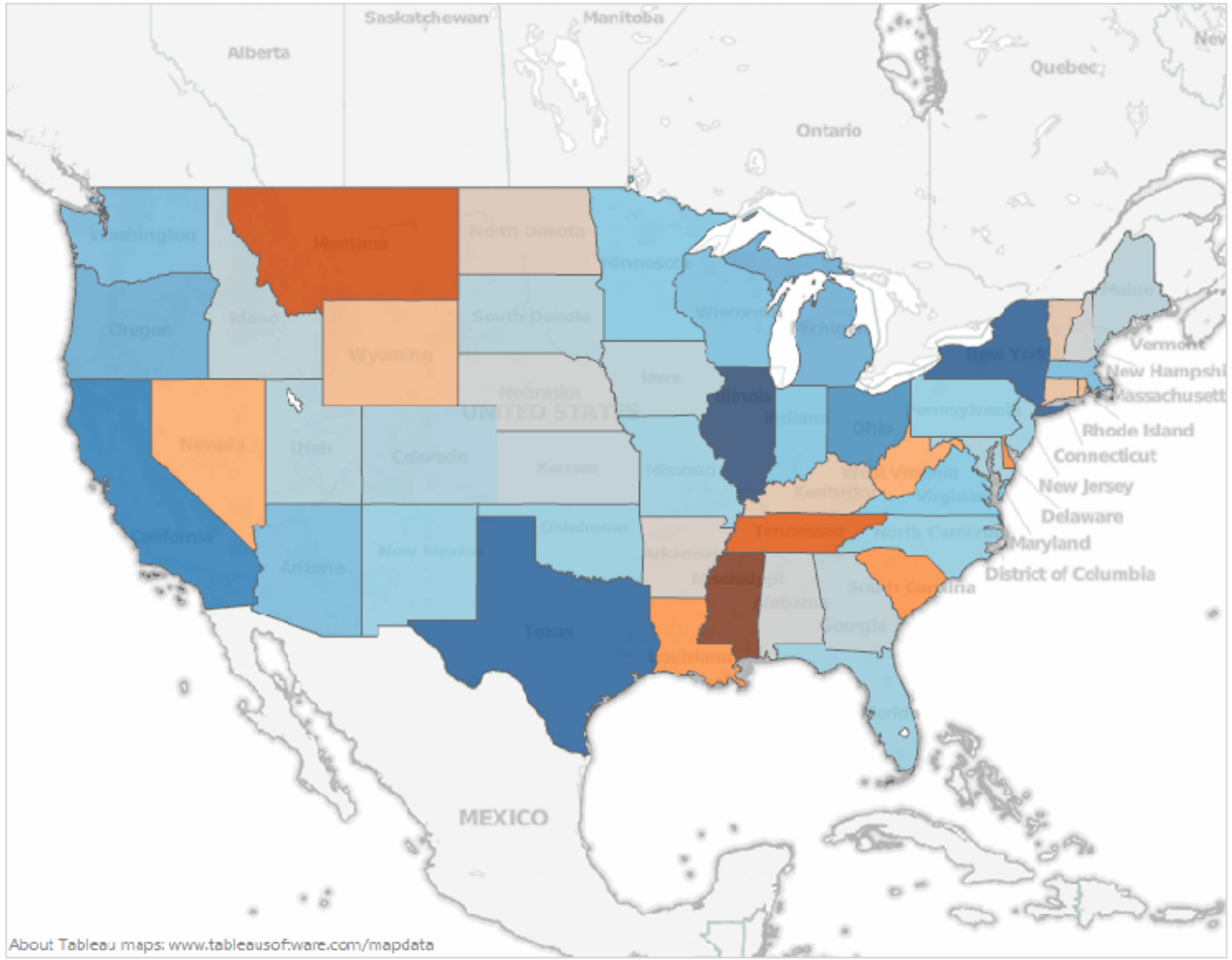
Deuteranope



Tritanope

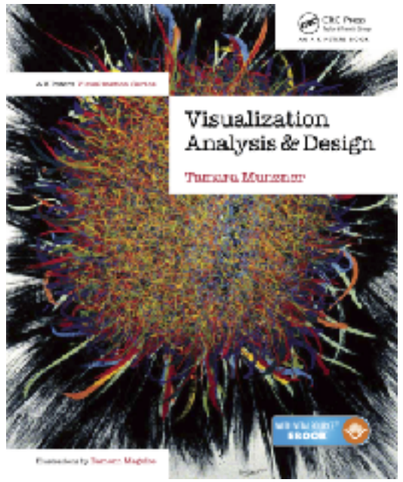
[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

Designing for color deficiency: Blue-Orange is safe



[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

Visualization Analysis & Design



Color (Ch 10) III

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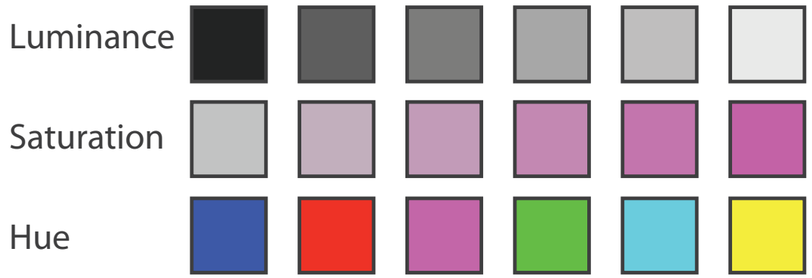
Color Spaces

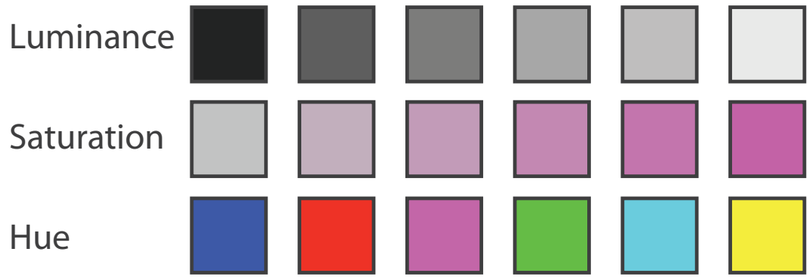
Many color spaces

- Luminance (L*), hue (H), saturation (S)
  - good for encoding



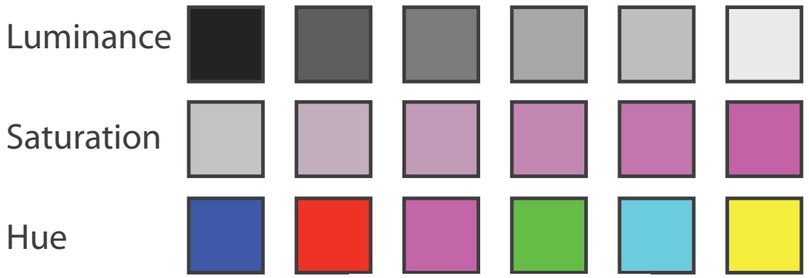
Many color spaces

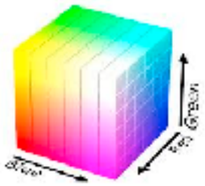
- Luminance (L*), hue (H), saturation (S)
  - good for encoding
  - but not standard graphics/tools colorspace



Many color spaces

- Luminance (L*), hue (H), saturation (S)
  - good for encoding
  - but not standard graphics/tools colorspace
- RGB: good for display hardware



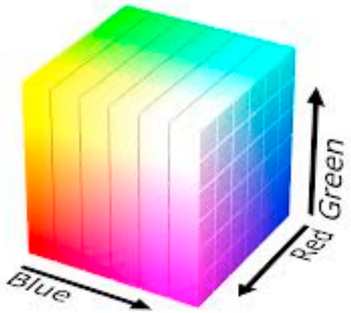


https://commons.wikimedia.org/wiki/File:RGB_color_solid_cube.png

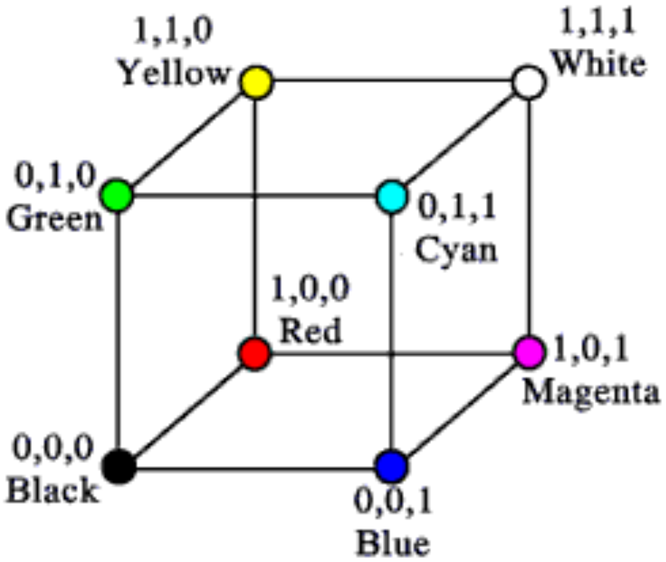
RGB

- RGB: good for display hardware

Corners of the RGB color cube



https://commons.wikimedia.org/wiki/File:RGB_color_solid_cube.png

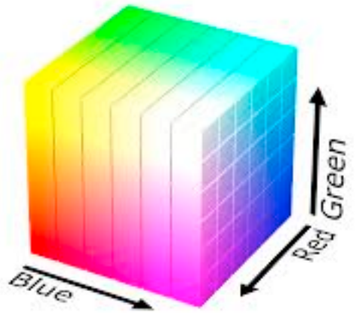


RGB

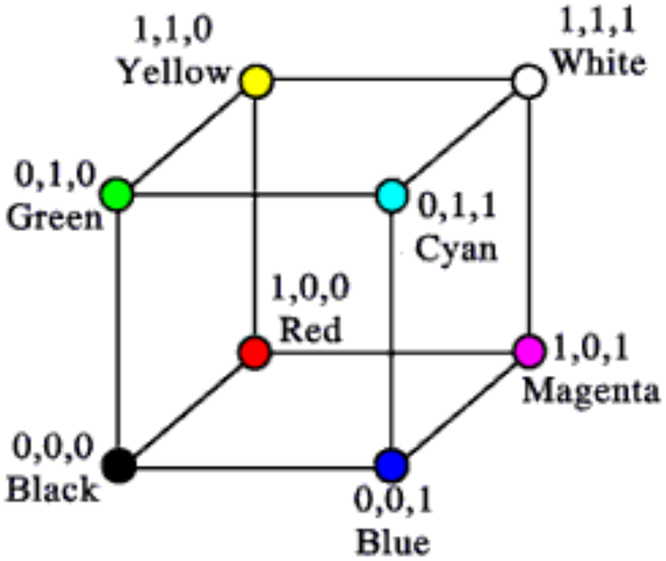
- RGB: good for display hardware

  – poor for encoding & interpolation

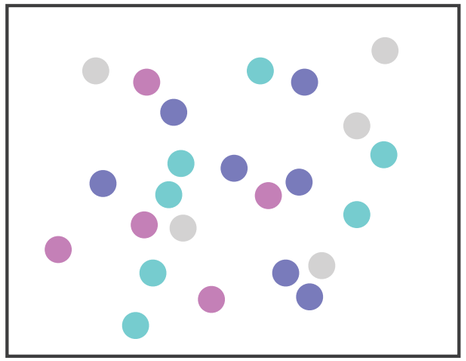
Corners of the RGB color cube



https://commons.wikimedia.org/wiki/File:RGB_color_solid_cube.png



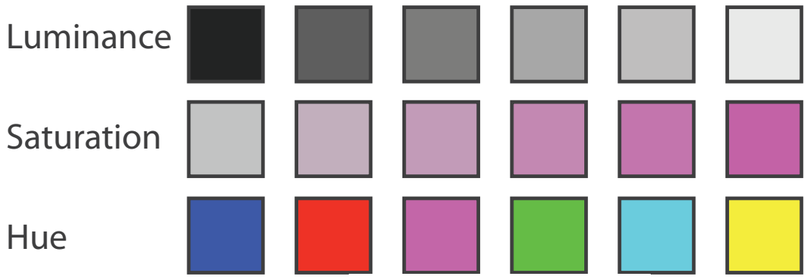
Red
+ Green

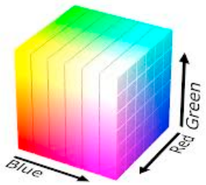


Major interference

Many color spaces

- Luminance (L*), hue (H), saturation (S)
  - good for encoding
  - but not standard graphics/tools colorspace
- RGB: good for display hardware
  - poor for encoding & interpolation

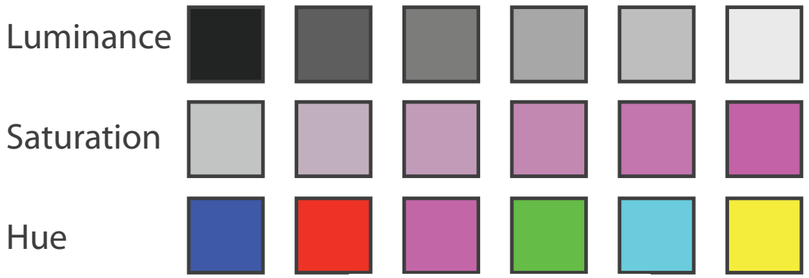


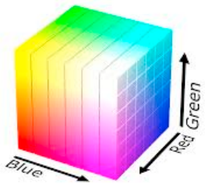


https://commons.wikimedia.org/wiki/File:RGB_color_solid_cube.png

Many color spaces

- Luminance (L*), hue (H), saturation (S)
  - good for encoding
  - but not standard graphics/tools colorspace
- RGB: good for display hardware
  - poor for encoding & interpolation
- CIE LAB (L*a*b*): good for interpolation

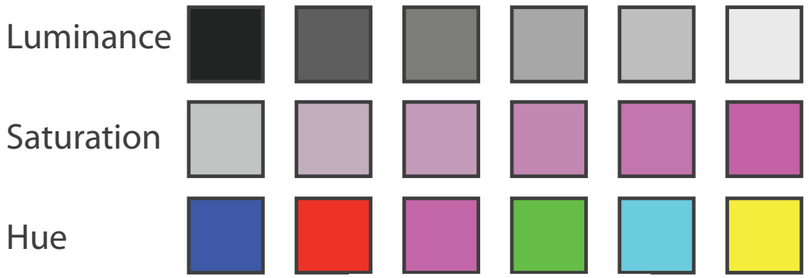


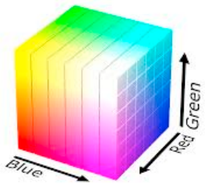


https://commons.wikimedia.org/wiki/File:RGB_color_solid_cube.png

Many color spaces

- Luminance (L*), hue (H), saturation (S)
  - good for encoding
  - but not standard graphics/tools colorspace
- RGB: good for display hardware
  - poor for encoding & interpolation
- CIE LAB (L*a*b*): good for interpolation
  - hard to interpret, poor for encoding

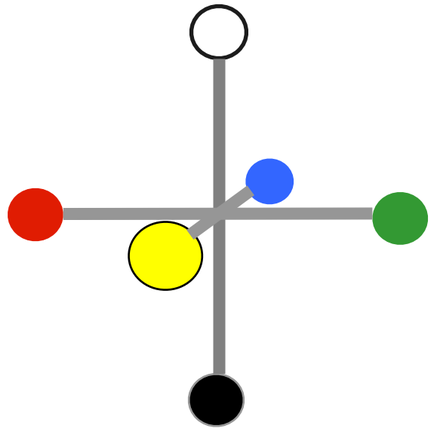




https://commons.wikimedia.org/wiki/File:RGB_color_solid_cube.png

Perceptual colorspace: L*a*b*

- perceptual processing before optic nerve
  - one achromatic luminance channel (L*)
    - edge detection through luminance contrast
  - 2 chroma channels
    - red-green (a*) & yellow-blue axis (b*)



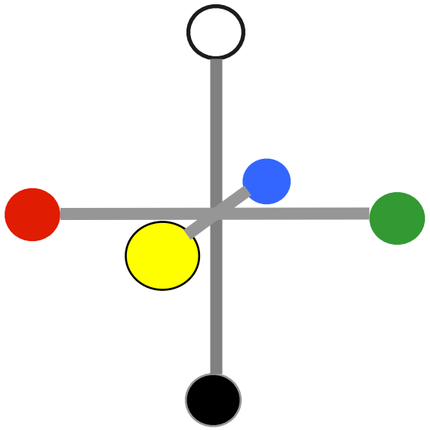
Luminance information

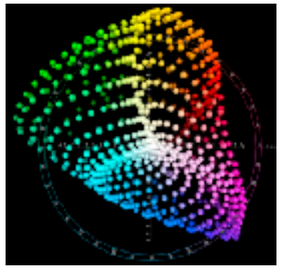
Chroma information

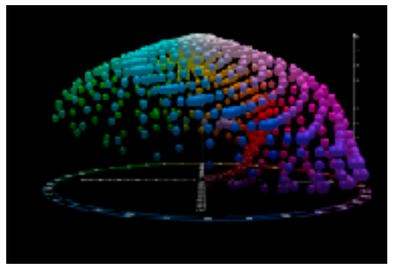
[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

Perceptual colorspace: L*a*b*

- perceptual processing before optic nerve
  - one achromatic luminance channel (L*)
    - edge detection through luminance contrast
  - 2 chroma channels
    - red-green (a*) & yellow-blue axis (b*)
- CIE LAB
  - perceptually uniform
    - great for interpolating
  - complex shape
    - poor for encoding







https://en.wikipedia.org/wiki/CIELAB_color_space

Luminance information

Chroma information

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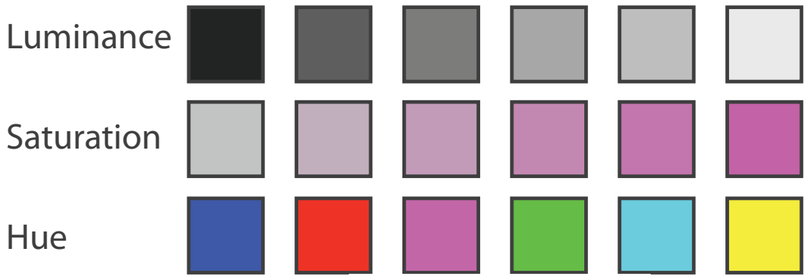
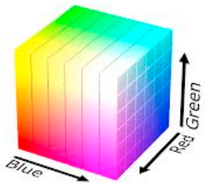
Many color spaces

- Luminance (L*), hue (H), saturation (S)
  - good for encoding
  - but not standard graphics/tools colorspace
- RGB: good for display hardware
  - poor for encoding & interpolation
- CIE LAB (L*a*b*): good for interpolation
  - hard to interpret, poor for encoding





https://commons.wikimedia.org/wiki/File:RGB_color_solid_cube.png

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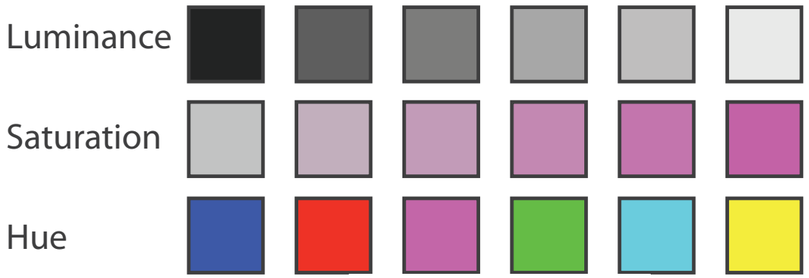
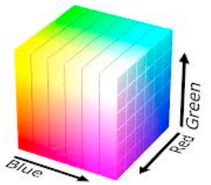
- HSL/HSV: somewhat better for encoding





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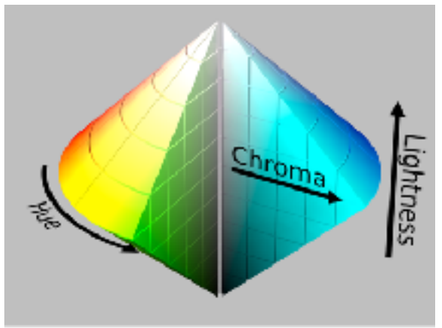
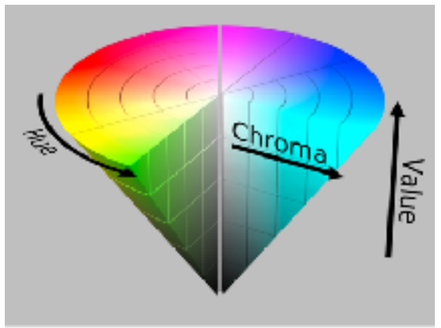
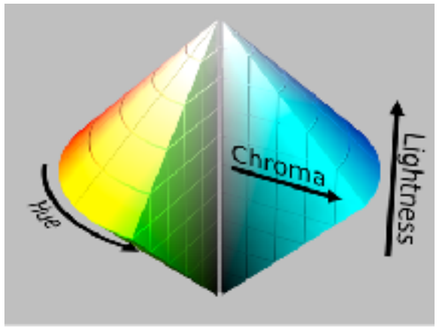
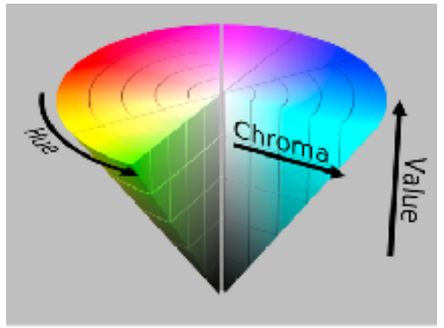


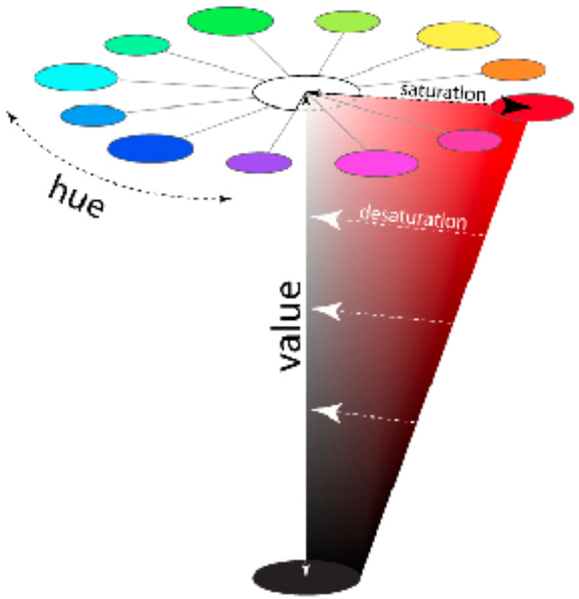


HSL/HSV

- HSL/HSV: somewhat better for encoding
  - hue/saturation wheel intuitive
- saturation
  - in HSV (single-cone) desaturated = white
  - in HSL (double-cone) desaturated = grey
-



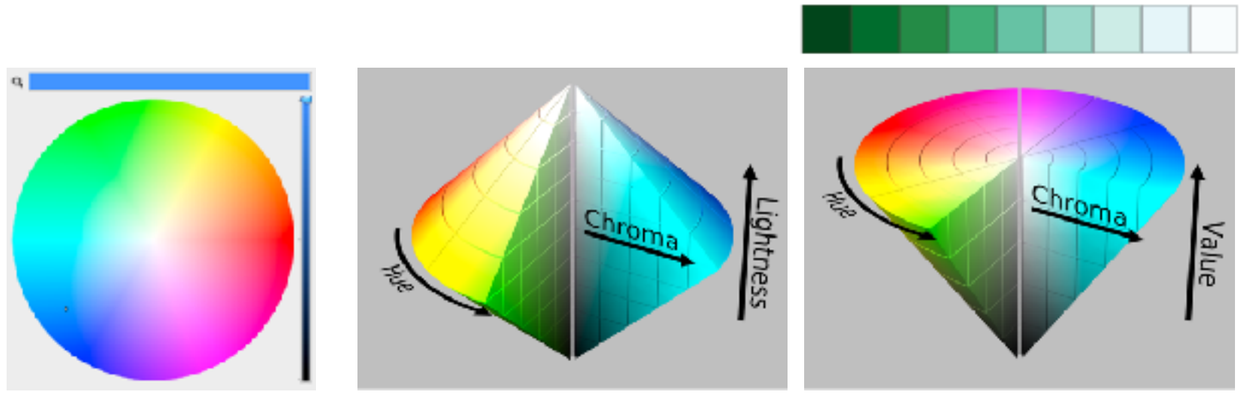


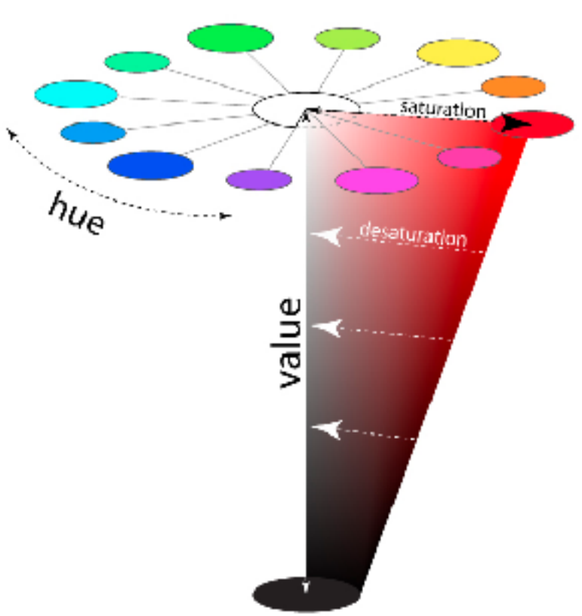


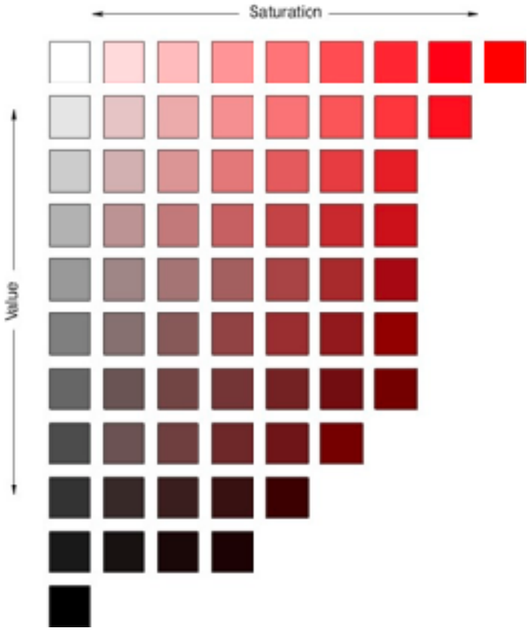
http://learn.leighcotnoir.com/artspeak/elements-color/hue-value-saturation/hsv8/

HSL/HSV

- HSL/HSV: somewhat better for encoding
  - hue/saturation wheel intuitive
- saturation
  - in HSV (single-cone) desaturated = white
  - in HSL (double-cone) desaturated = grey
- luminance vs saturation
  - channels **not** very separable
  - typically not crucial to distinguish between these with encoding/decoding
  - key point is hue vs luminance/saturation







http://learn.leighcotnoir.com/artspeak/elements-color/hue-value-saturation/hsv8/

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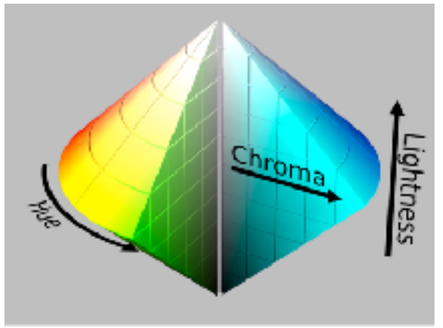
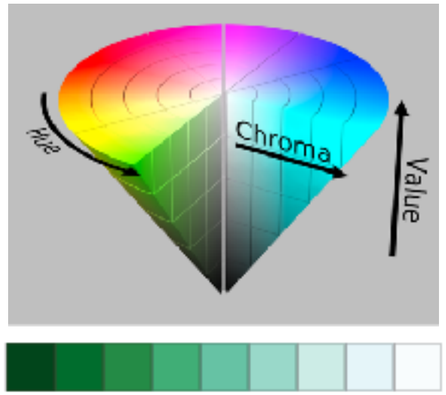
HSL/HSV: Pseudo-perceptual colorspace

- HSL better than RGB for encoding **but beware**
  - L lightness ≠ L* luminance

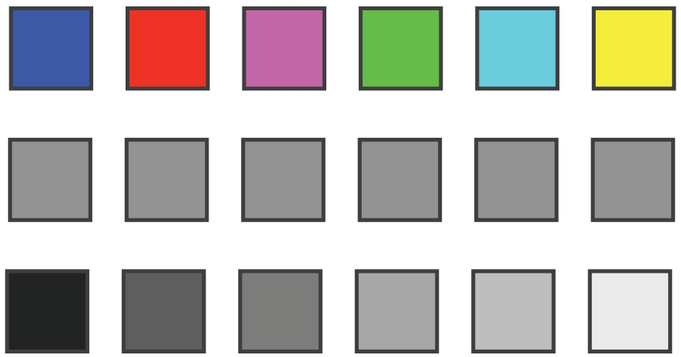




Corners of the RGB color cube

L from HLS
All the same

Luminance values



[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

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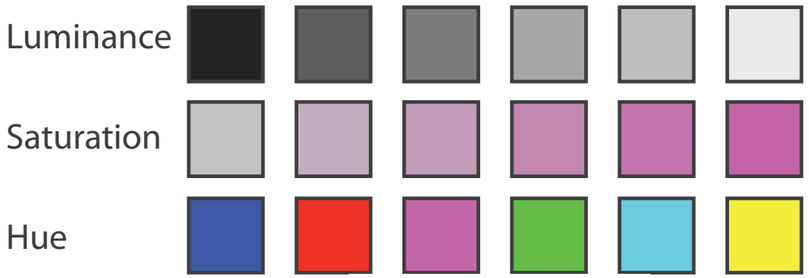
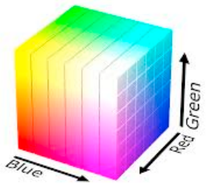
  - hard to interpret, poor for encoding
- HSL/HSV: somewhat better for encoding
  - hue/saturation wheel intuitive
  - beware: only pseudo-perceptual!
  - lightness (L) or value (V) ≠ luminance (L*)





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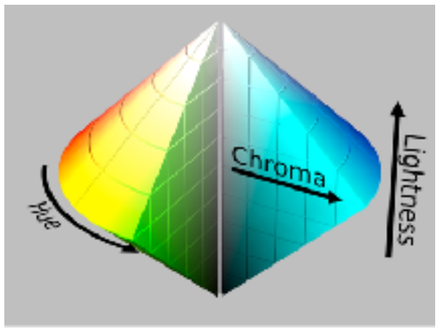
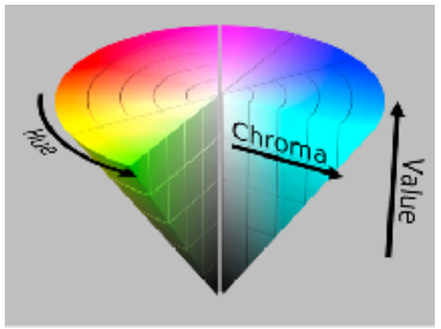
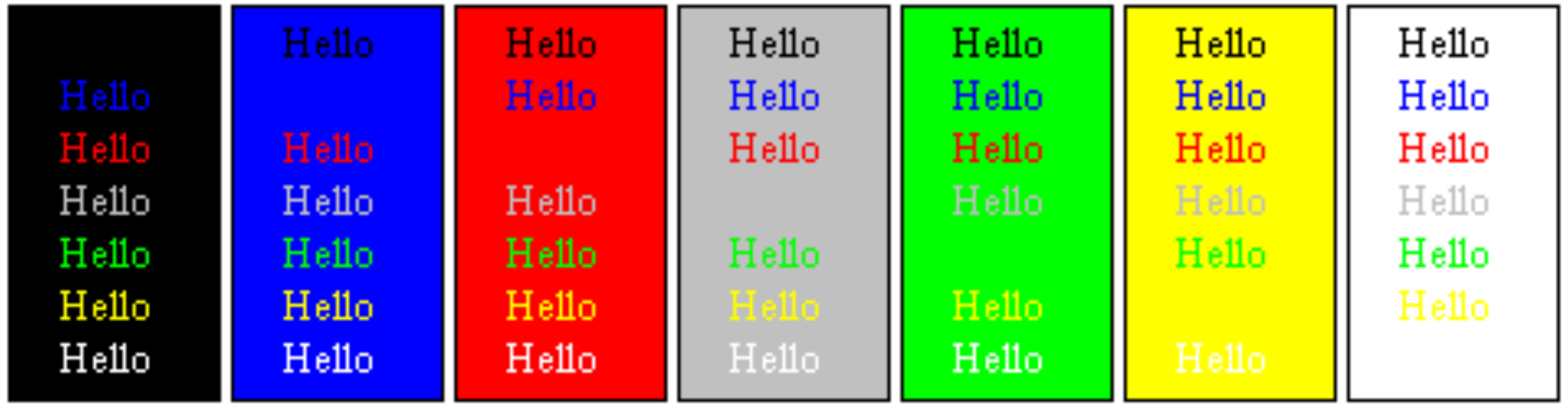




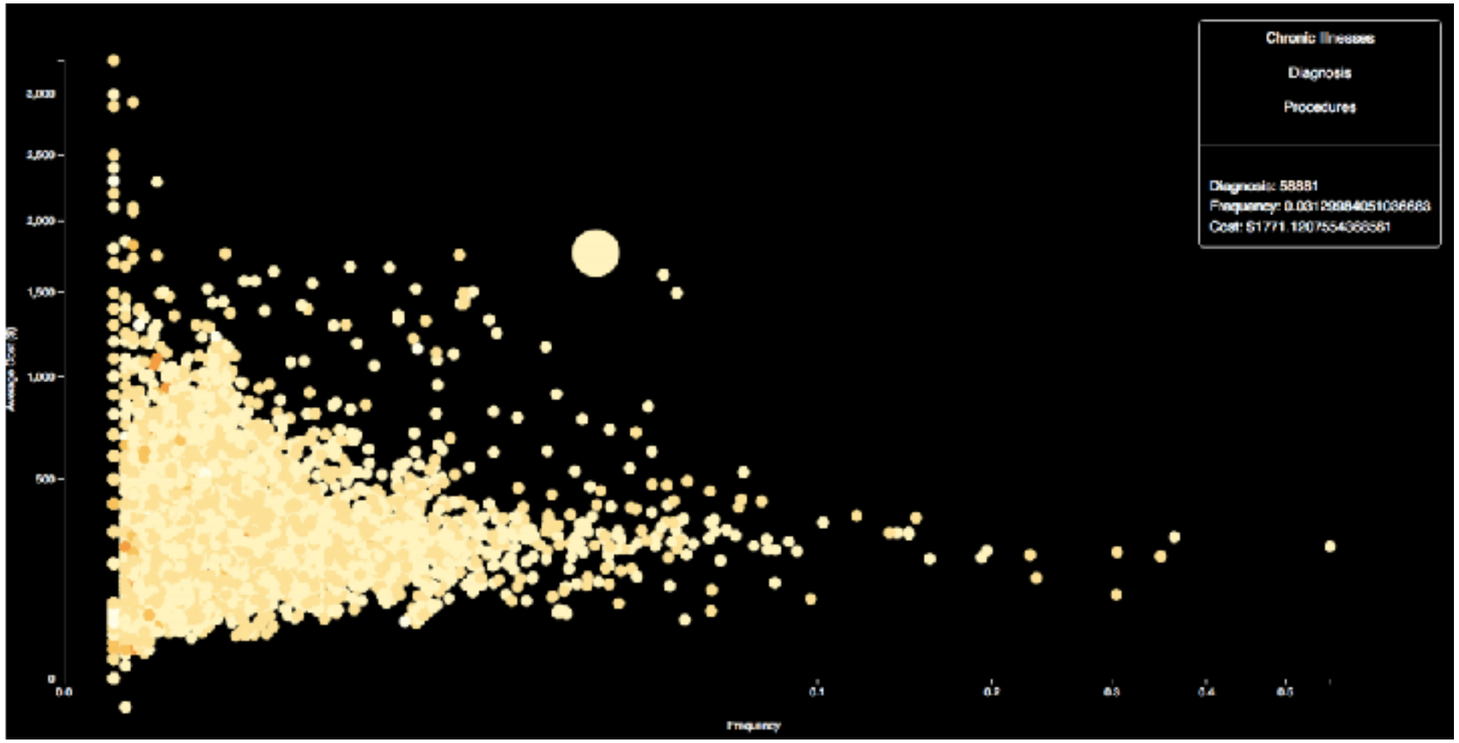
Color Constrast & Naming

Interaction with the background



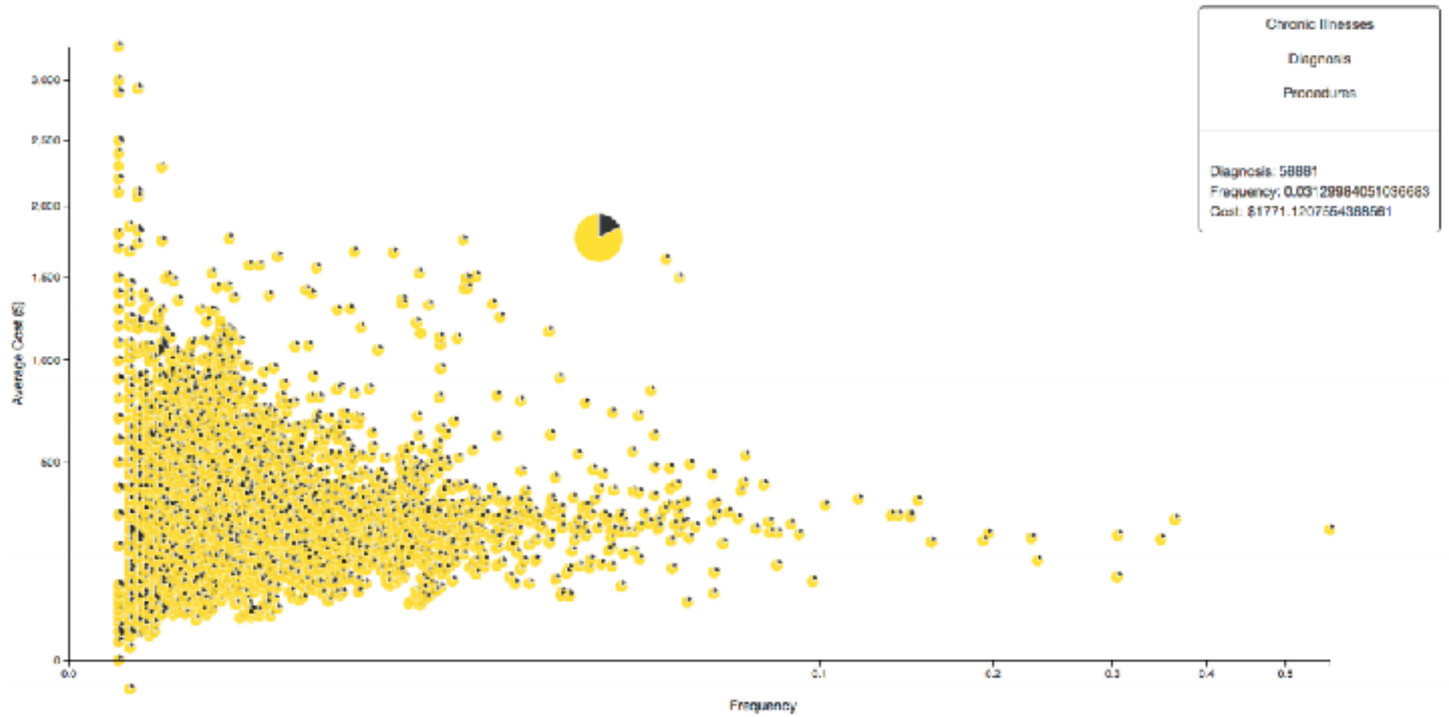
Interaction with the background: tweaking yellow for visibility

- marks with high luminance on a background with low luminance



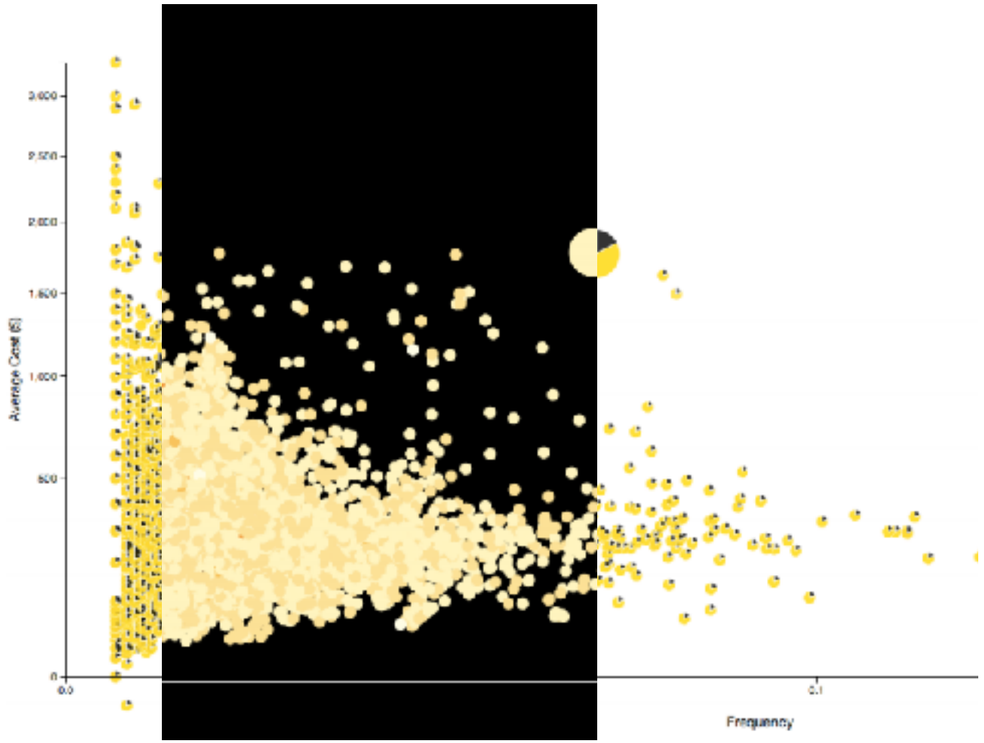
Interaction with the background: tweaking yellow for visibility

- marks with medium luminance on a background with high luminance



Interaction with the background: tweaking yellow for visibility

- change luminance of marks depending on background



Color/Lightness constancy: Illumination conditions

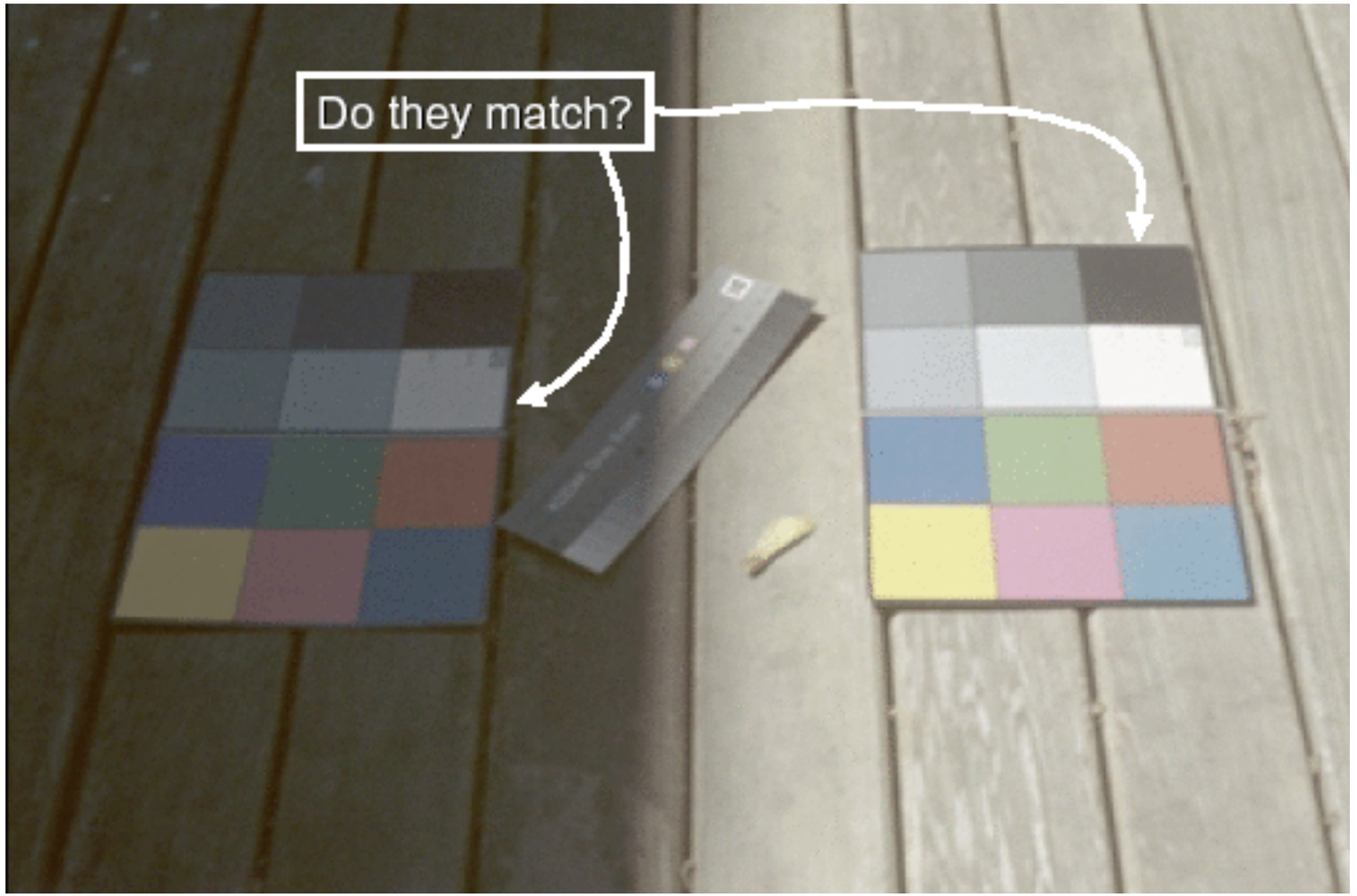


Image courtesy of John McCann via Maureen Stone

Color/Lightness constancy: Illumination conditions

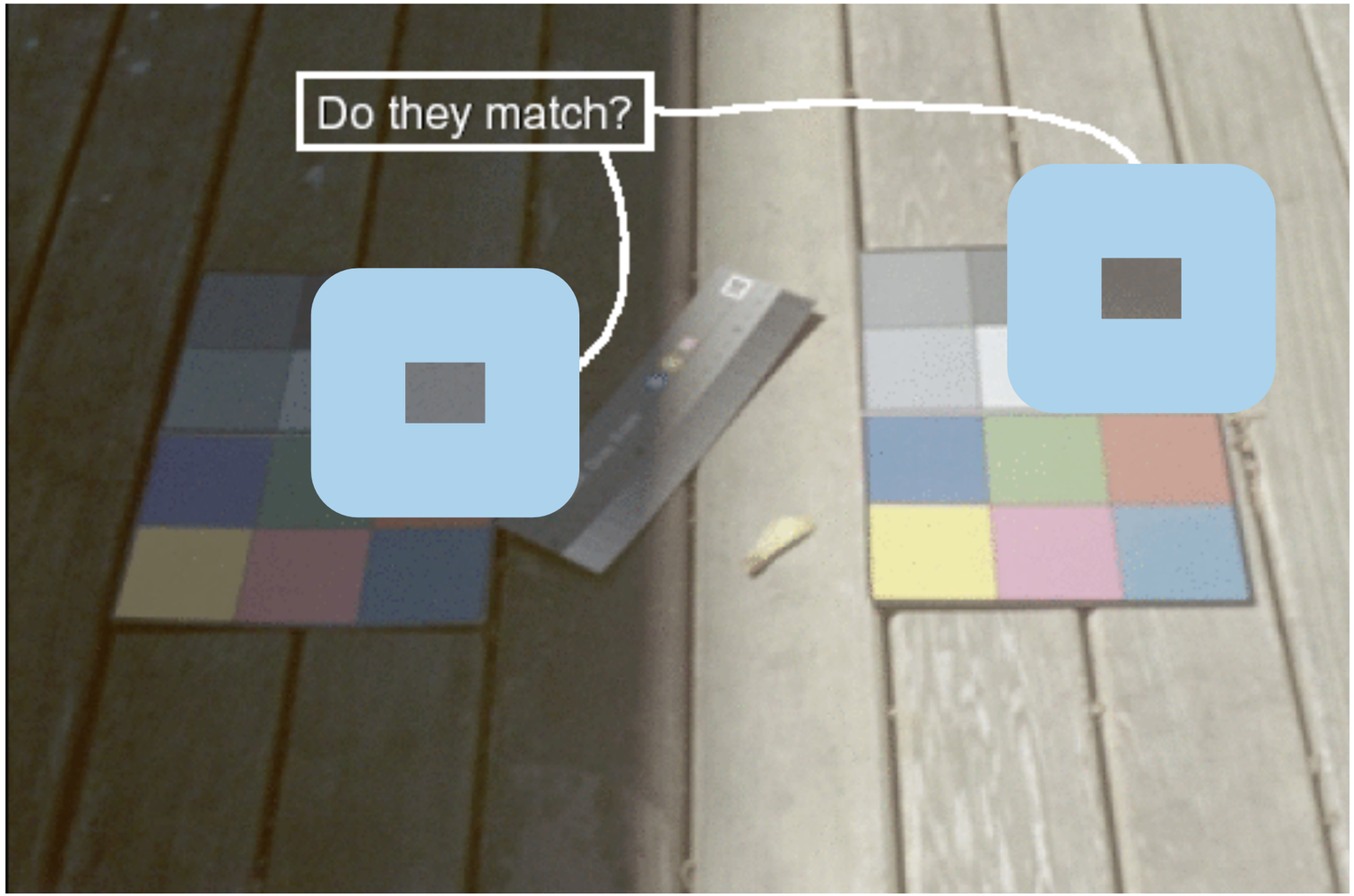
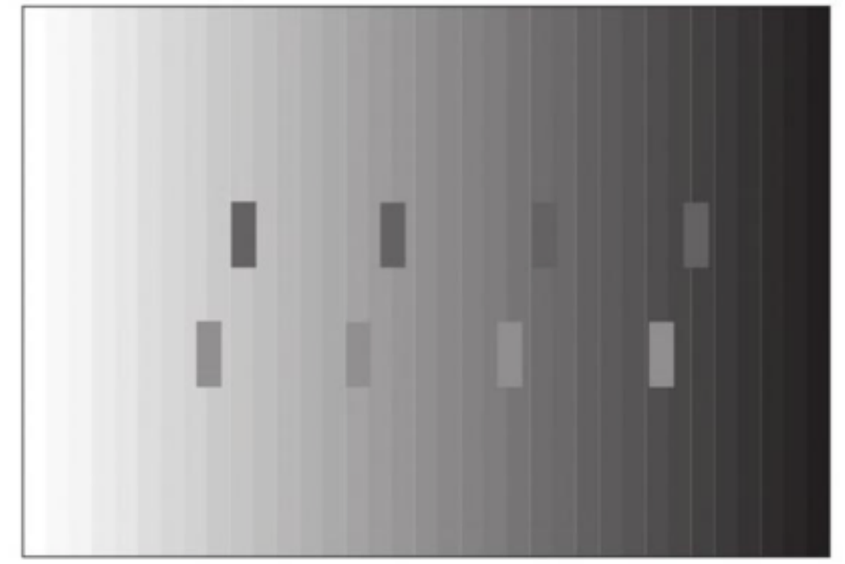
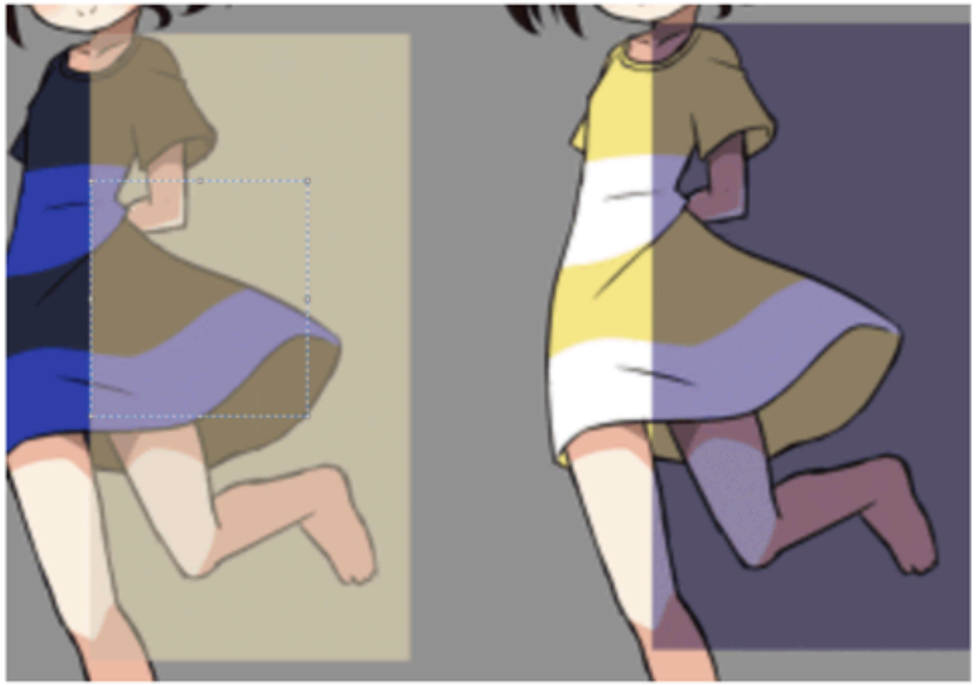


Image courtesy of John McCann via Maureen Stone

Contrast with background



Contrast with background

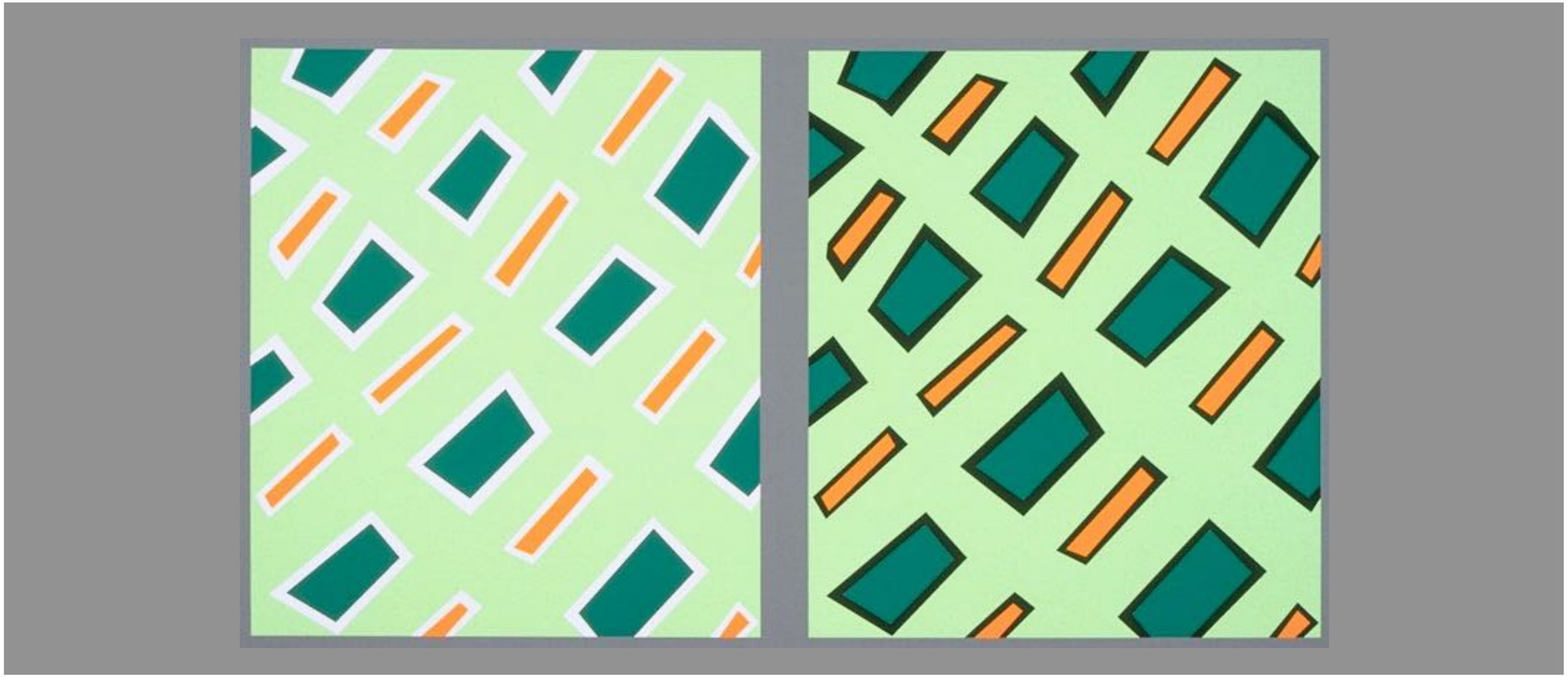


Black and blue? White and gold?

https://imgur.com/hxJjUQB

https://en.wikipedia.org/wiki/The_dress

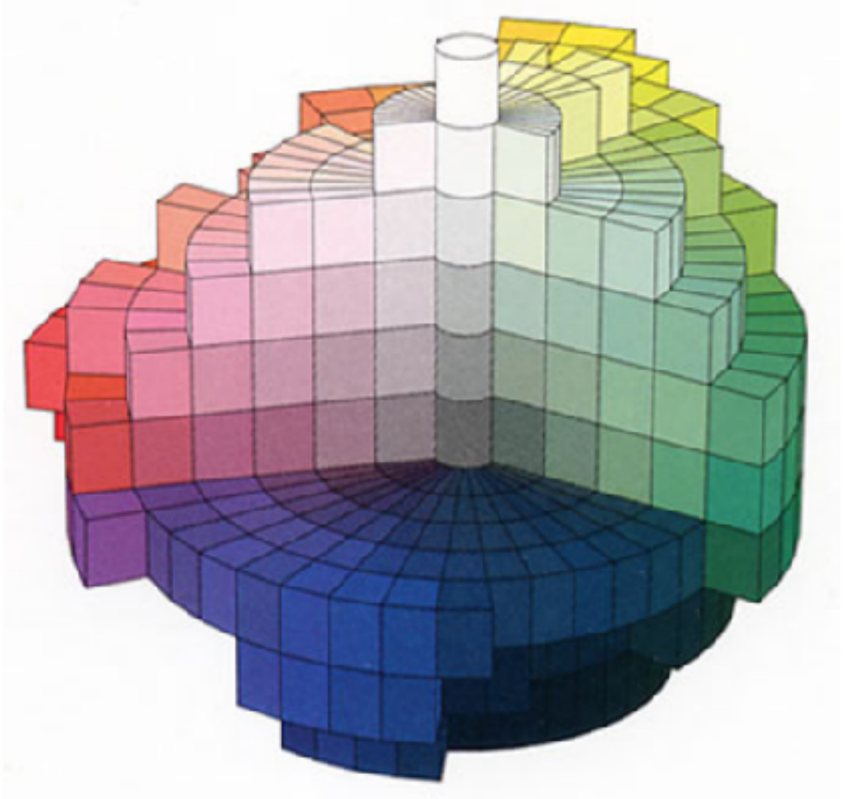
Bezold Effect: Outlines matter



[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

Color Appearance

- given L, a*, b*, can we tell what color it is?
  - no, it depends



- chromatic adaptation
- luminance adaptation
- simultaneous contrast
- spatial effects
- viewing angle
- …

Color naming

Color naming

http://www.thedoghousediaries.com/1406

Color naming

https://blog.xkcd.com/2010/05/03/color-survey-results/

Color naming

- nameability affects
  - communication
  - memorability
- can integrate into color models
  - in addition to perceptual considerations

https://blog.xkcd.com/2010/05/03/color-survey-results/

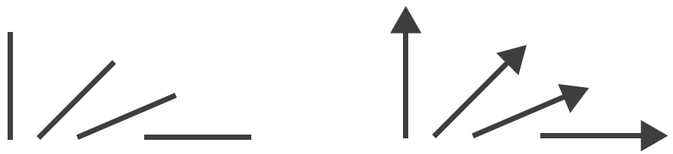
Color is just part of vision system

- Does not help perceive
  - Position
  - Shape
  - Motion
  - …

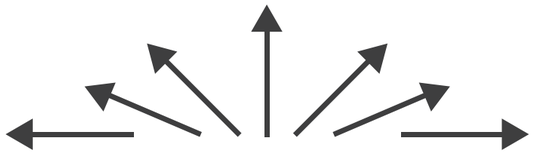
Map Other Channels

Angle / tilt / orientation channel

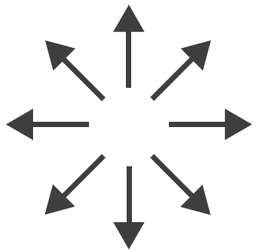
- different mappings depending on range used



Sequential ordered
line mark or arrow glyph



Diverging ordered
arrow glyph



Cyclic ordered
arrow glyph

- nonlinear accuracy
  - high: exact horizontal, vertical, diagonal (0, 45, 90 degrees)
  - lower: other orientations (eg 37 vs 38 degrees)

Map other channels

- size
  - aligned length best
  - length accurate
  - 2D area ok
  - 3D volume poor

Map other channels

- size
  - aligned length best
  - length accurate
  - 2D area ok
  - 3D volume poor
- shape
  - complex combination of lower-level primitives
  - many bins

Size

→ Length

→ Area

→ Volume

Shape

Map other channels

- size
  - aligned length best
  - length accurate
  - 2D area ok
  - 3D volume poor
- shape
  - complex combination of lower-level primitives
  - many bins
- motion
  - highly separable against static
    - great for highlighting (binary)
  - use with care to avoid irritation

➔ Size

➔ Length

➔ Area

➔ Volume

➔ **Shape**

➔ **Motion**

➔ Motion
Direction, Rate, Frequency, ...