# Data Visualization (CSCI 627/490)

## Color & Colormaps

Dr. David Koop

# Courselets

- Educational resources for visualization using notebooks
- Reviewed charts over the last couple of classes, how do we construct them?
- How do we use visualization libraries, including those in other contexts like Python?
  - matplotlib: charts-matplotlib.ipynb
  - pyobsplot: charts-obsplot.ipynb

# Midterm

- In-class, Wednesday, March 5, 9:30-10:45am
- Only need writing utensil (+eraser)
- Format:
  - Multiple Choice
  - Free Response
- CSCI 627 students will have an extra double-sided page with more research-focused questions

# Project

- What & Why
- Decide on dataset
- Analyze attributes
- Brainstorm Tasks

- Dataset ideas posted
- Research ideas also possible

- Proposal due March 7

# Color

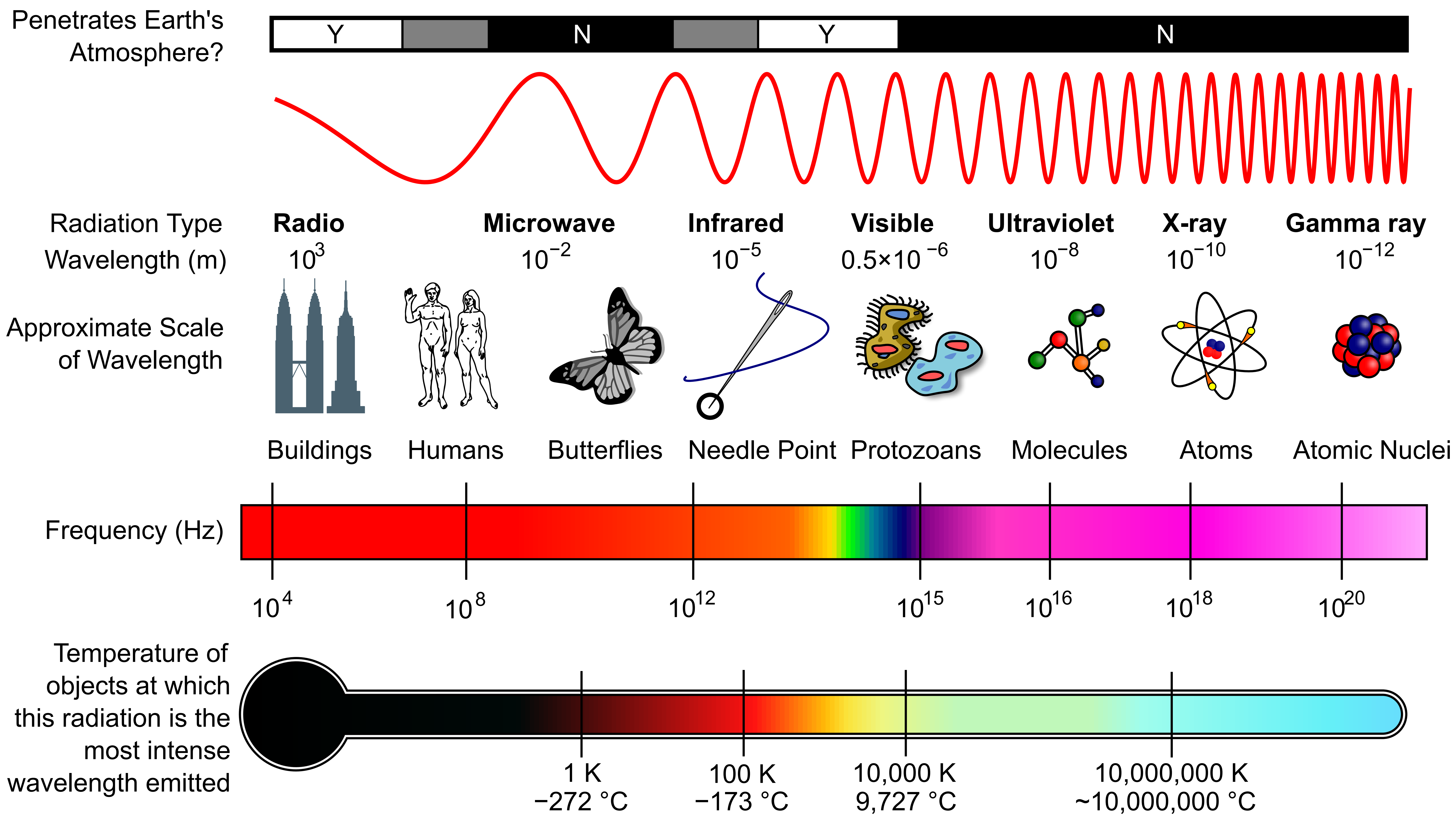
# Color

# Color

# Color and Light

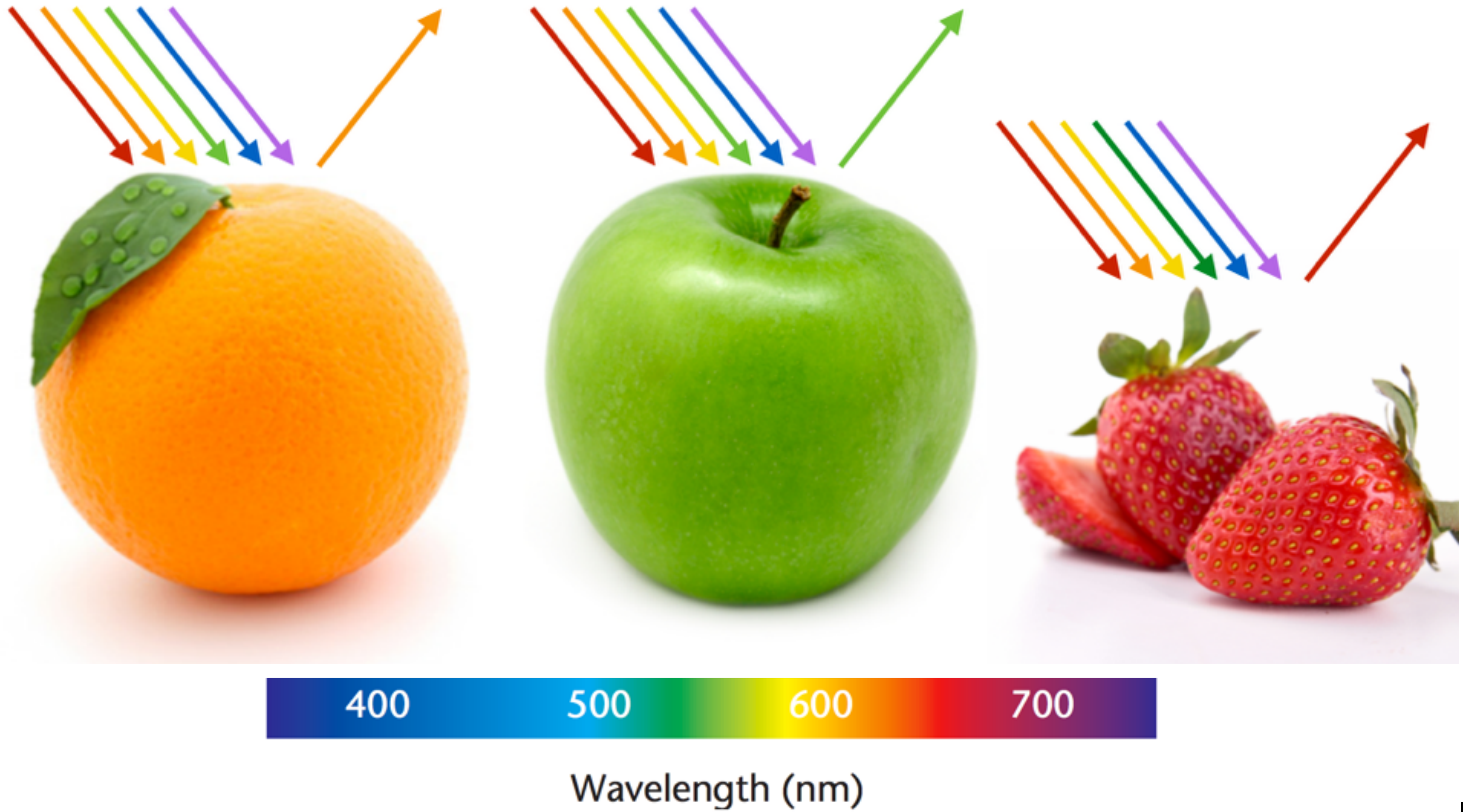
- Color is a **perceptive** property: color depends on the eyes and brain
- Visible light is a small portion of the **electromagnetic spectrum** which is composed of waves that at various frequencies (wavelengths), all traveling at the speed of light

# Electromagnetic Spectrum



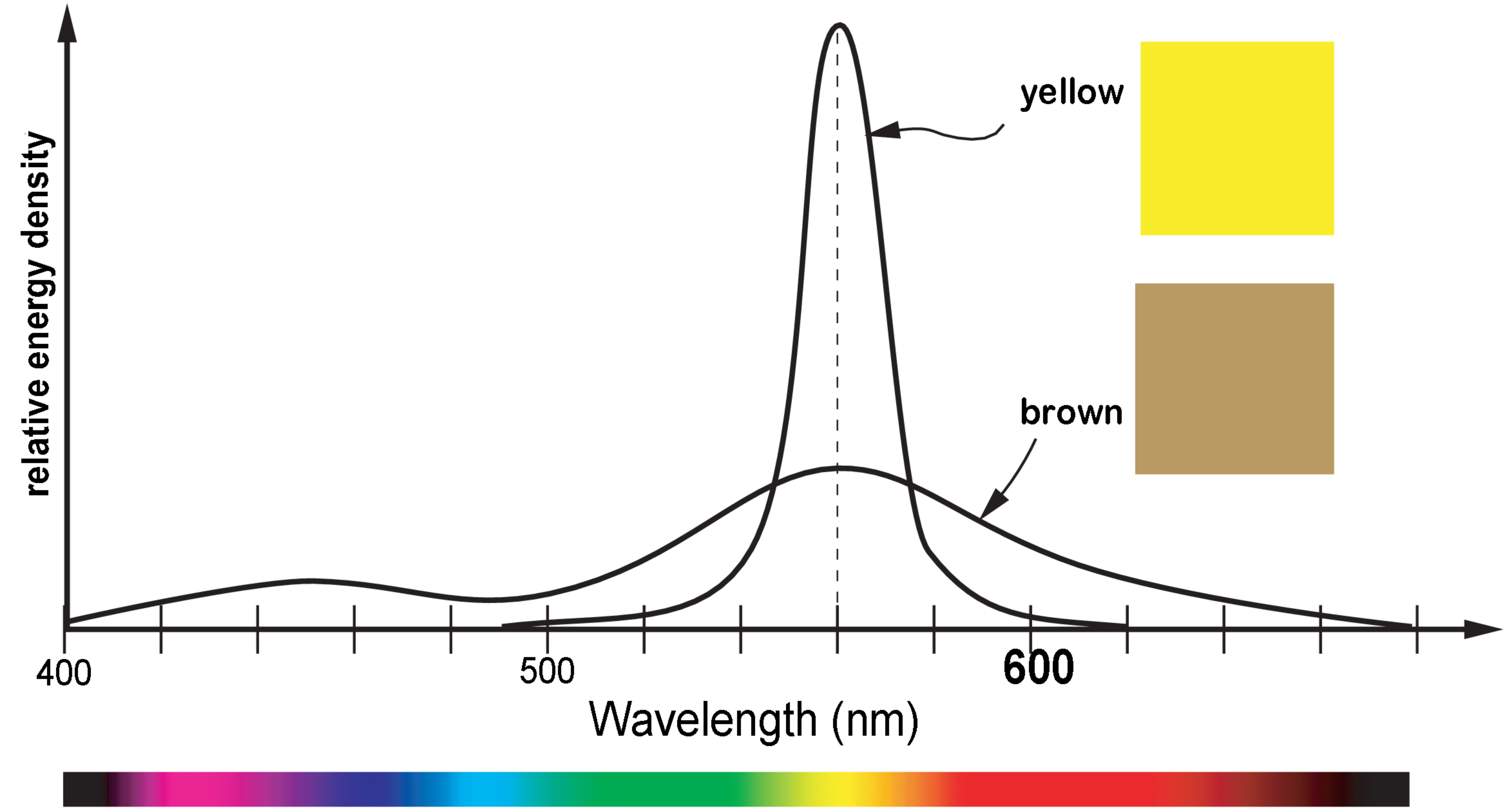

[Wikimedia, NASA]

# Light Reflection & Absorption




[via M. Meyer]

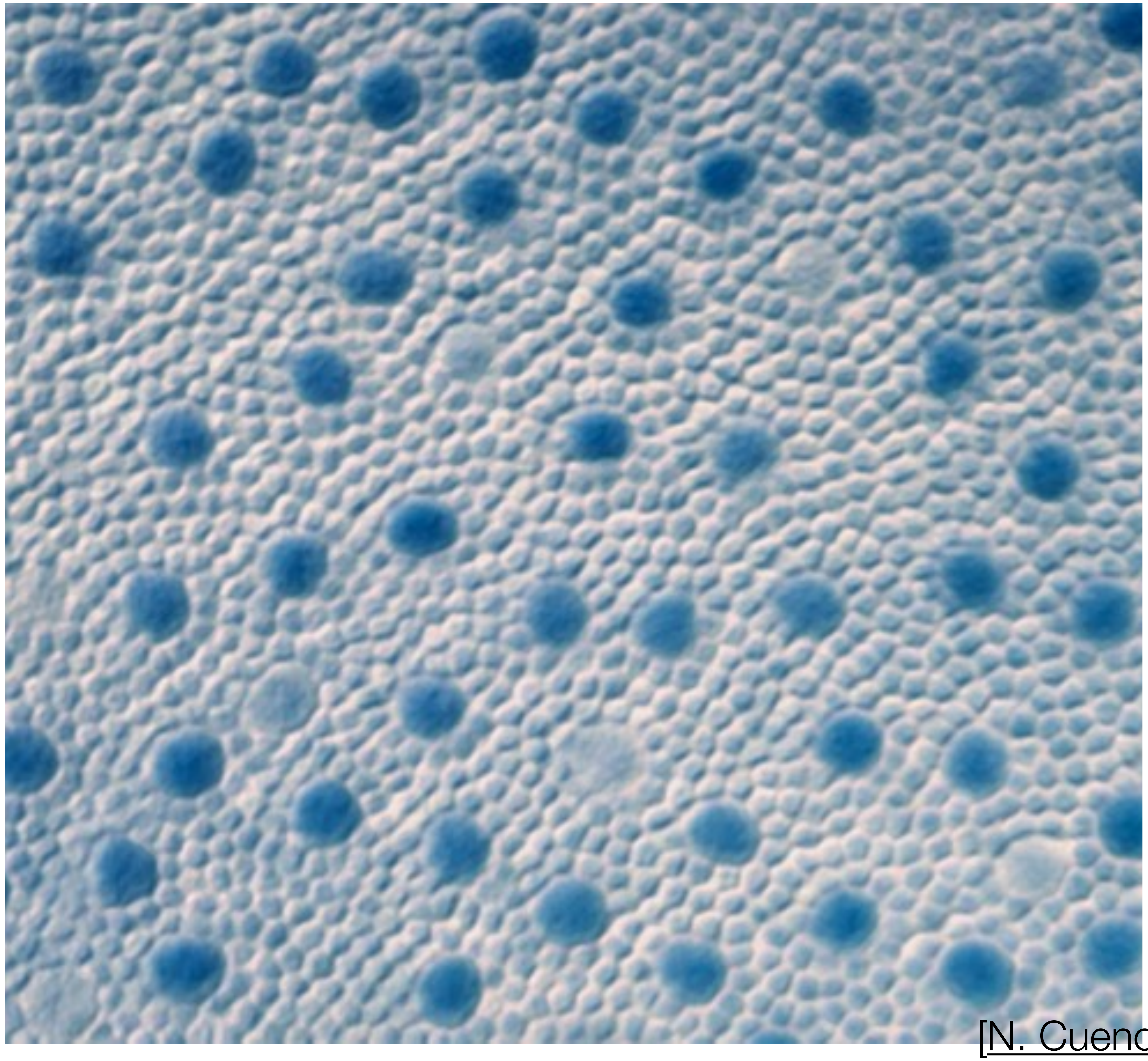
# Color != Wavelength




[via M. Meyer]

# Human Color Perception

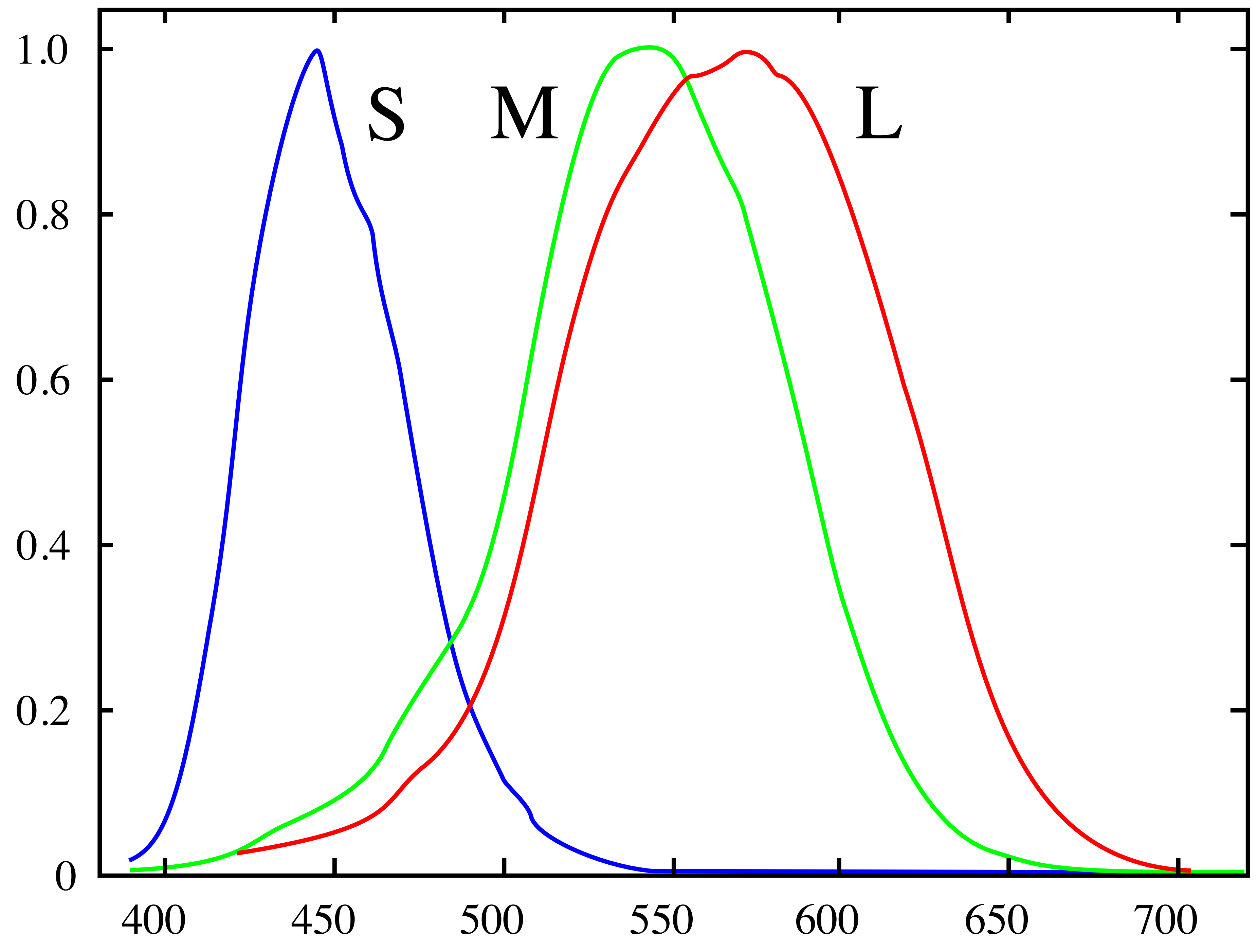
- Humans **do not** detect individual wavelengths of light
- Use **rods** and **cones** to detect light
  - rods capture intensity
  - cones capture color



[N. Cuenca]

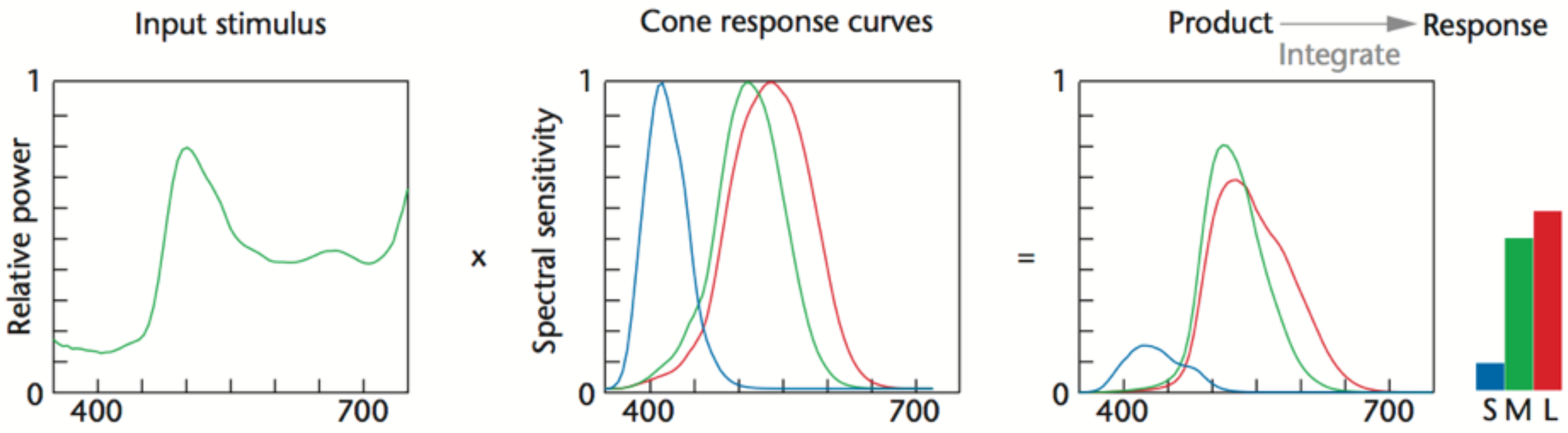
# Human Color Perception

- Humans are **trichromatic**—we have three different types of cones
  - S (430nm): blue
  - M (540nm): green
  - L (570nm): "red"
- Note that the response curves **overlap**
- Spectra of visible light are "covered" by these responses
- Three numbers -> color



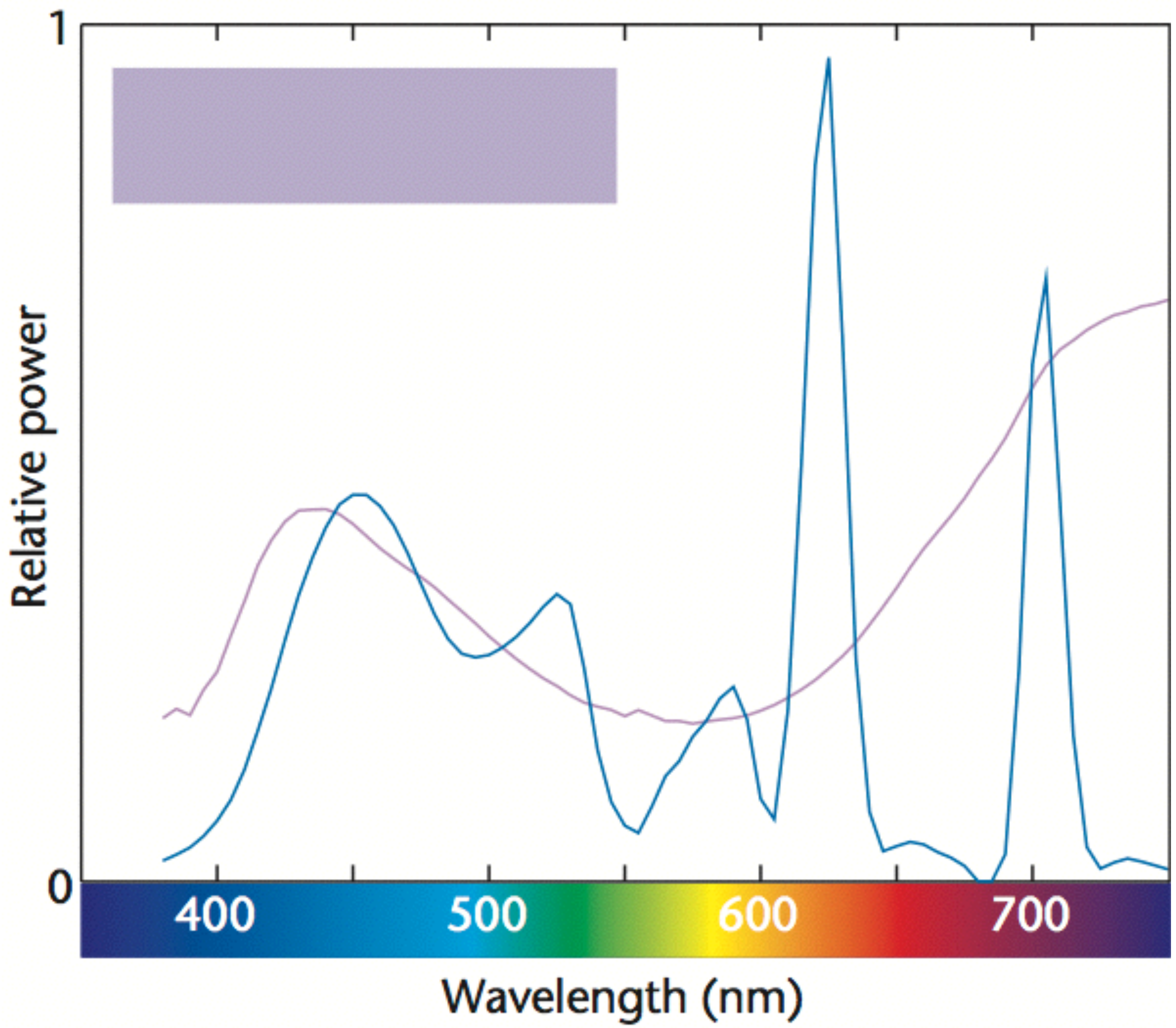

[Vanessaezekowitz at en.wikipedia]

# Human Color Perception




[via M. Meyer]

# Metamerism



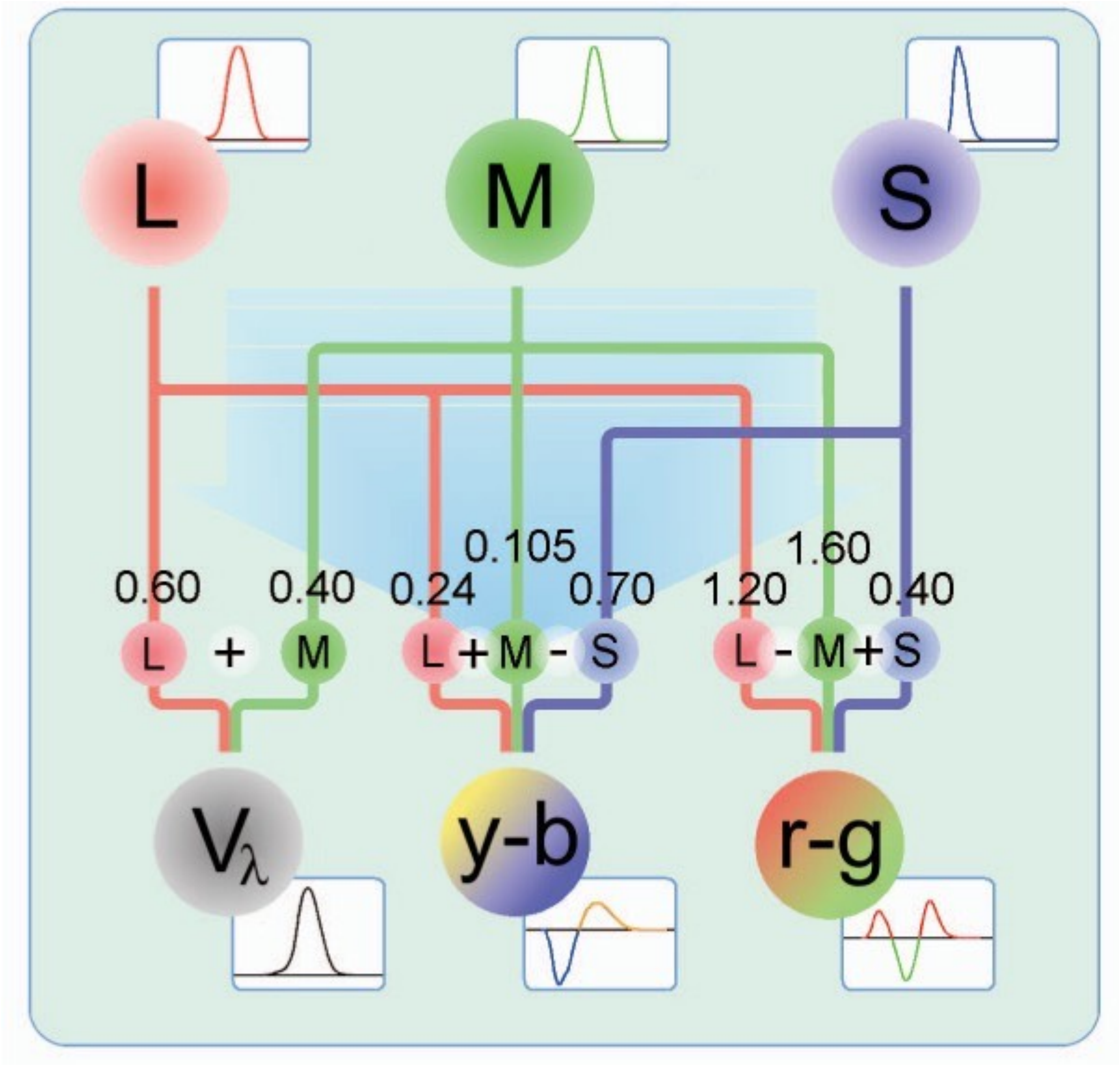

- Same responses == same color
- Humans are not spectrometers
- Do not get the whole function
- Three responses


[via M. Meyer]

# Color

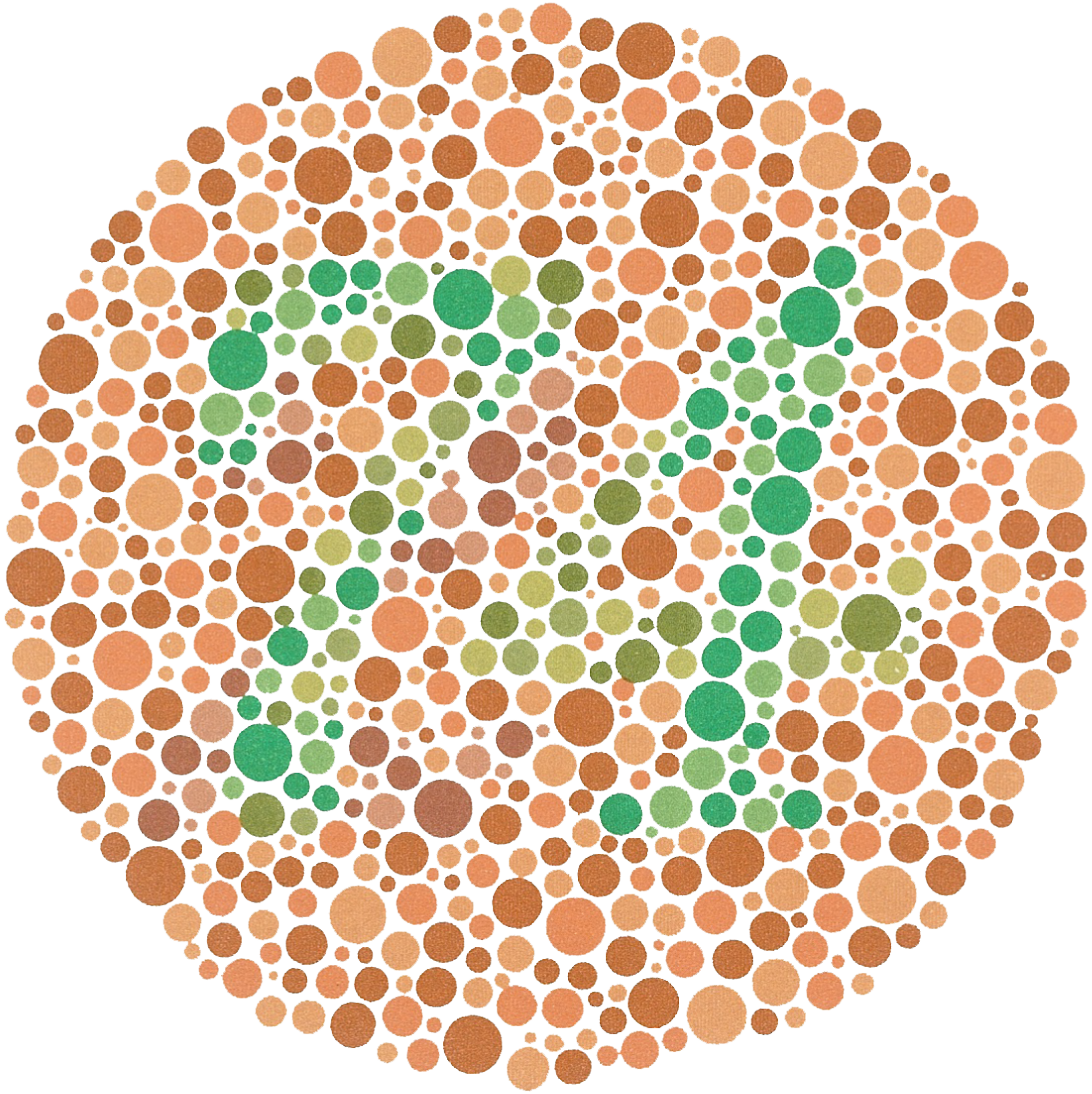
- Cones respond to different areas of the visible light spectrum
- Cover all wavelengths but certain wavelengths generate greater responses
- Color is determined by calculations based on the responses from the different cones
- Opponent Process Theory: three "opponent" channels
  - Light/Dark
  - Blue/Yellow
  - Red/Green
- Opposite colors are not perceived together

# Opponent Process Theory




[Machado et. al, 2009]

# Color Blindness

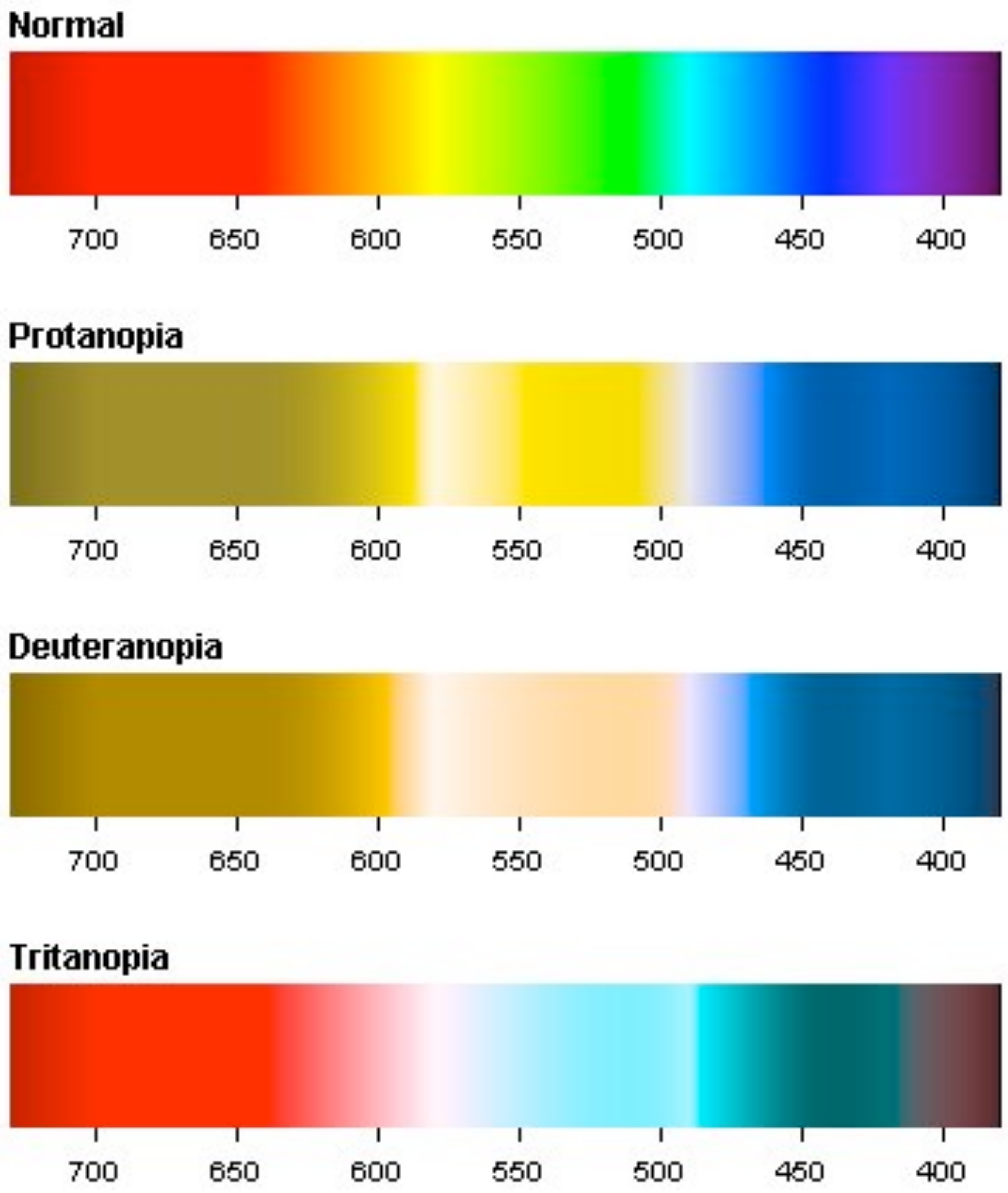


[Ishihara (Plate 9) via Wikipedia]

# Color Blindness

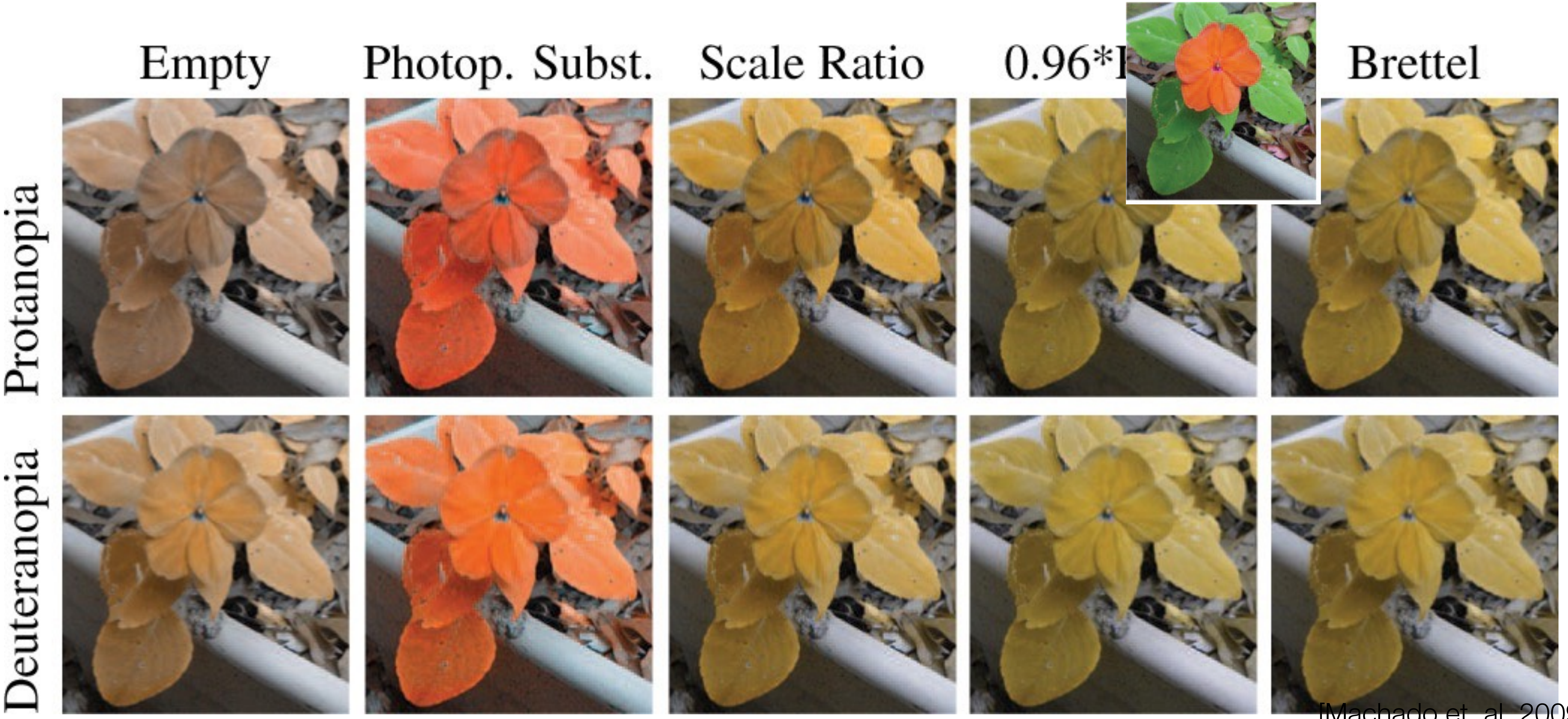
- Sex-linked: 8% of males and 0.4% of females of N. European ancestry
- Abnormal distribution of cones (e.g. missing the S, M, or L types)
- Either dichromatic (only two types of cones) or anomalous trichromatic (one type of cones has a defect)
  - Protanopia (L missing), Protanomaly (L defect)
  - Deuteranopia (M missing), Deuteranomaly (M defect) [Most Common]
  - Tritanopia (S missing), Tritanomaly (S defect) [Rare]
- Dichromacy is rarer than anomalous trichromacy
- Opponent process model explains why colors cannot be differentiated

# Color Blindness




[via M. Meyer]

# Simulating Color Blindness




[Machado et. al, 2009]

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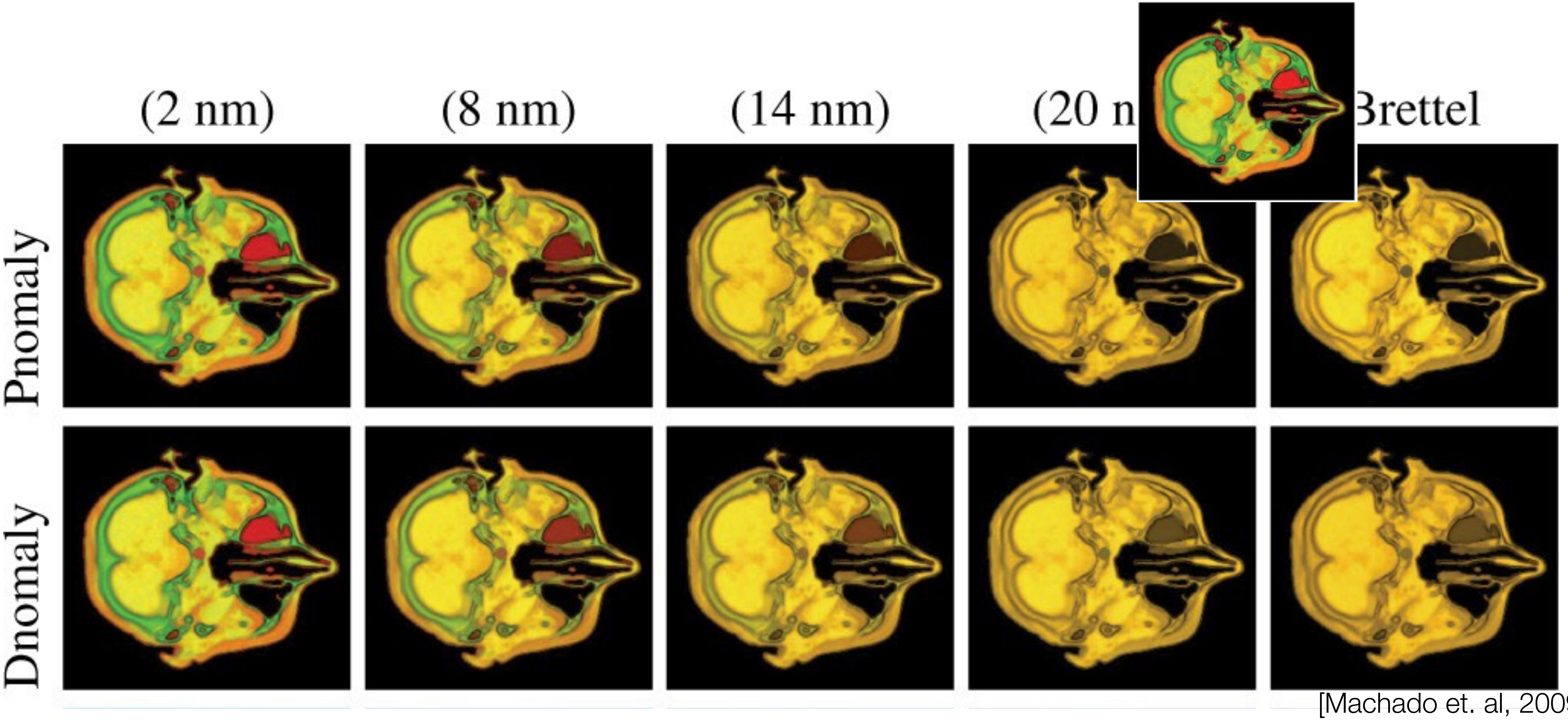


[Machado et. al, 2009]

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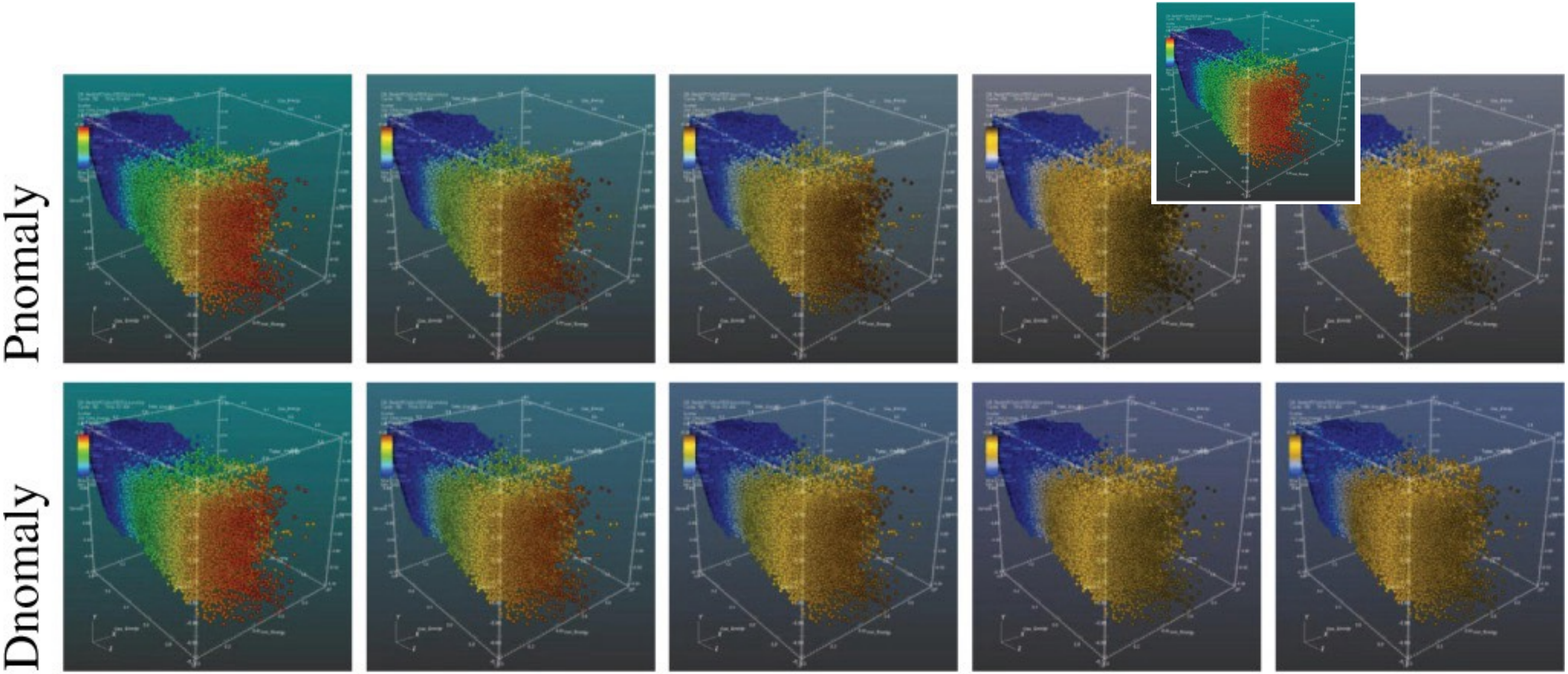
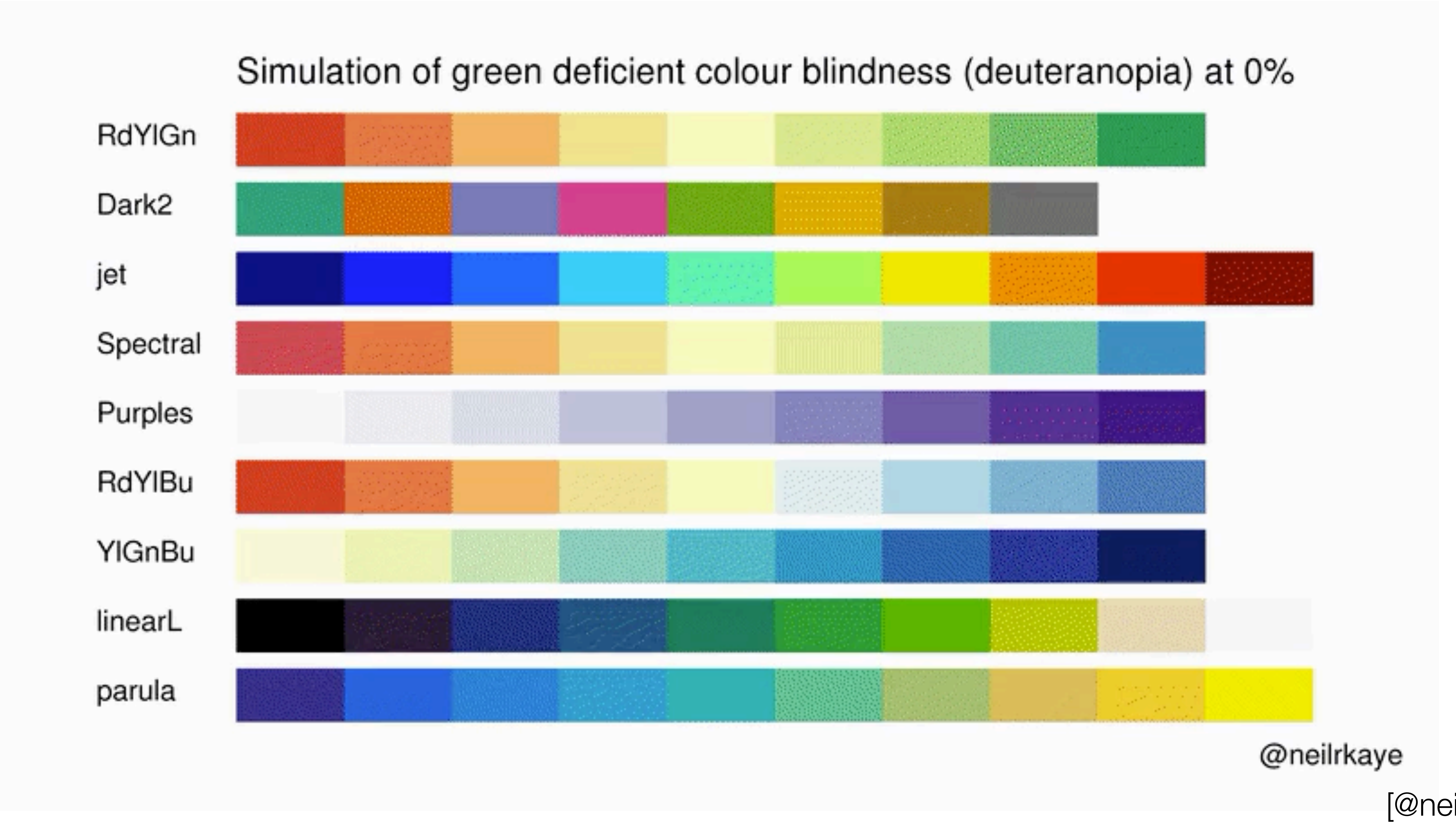



[Machado et. al, 2009]

# Simulating Deuteranopia (Colormaps)




[@neilrkaye, reddit]

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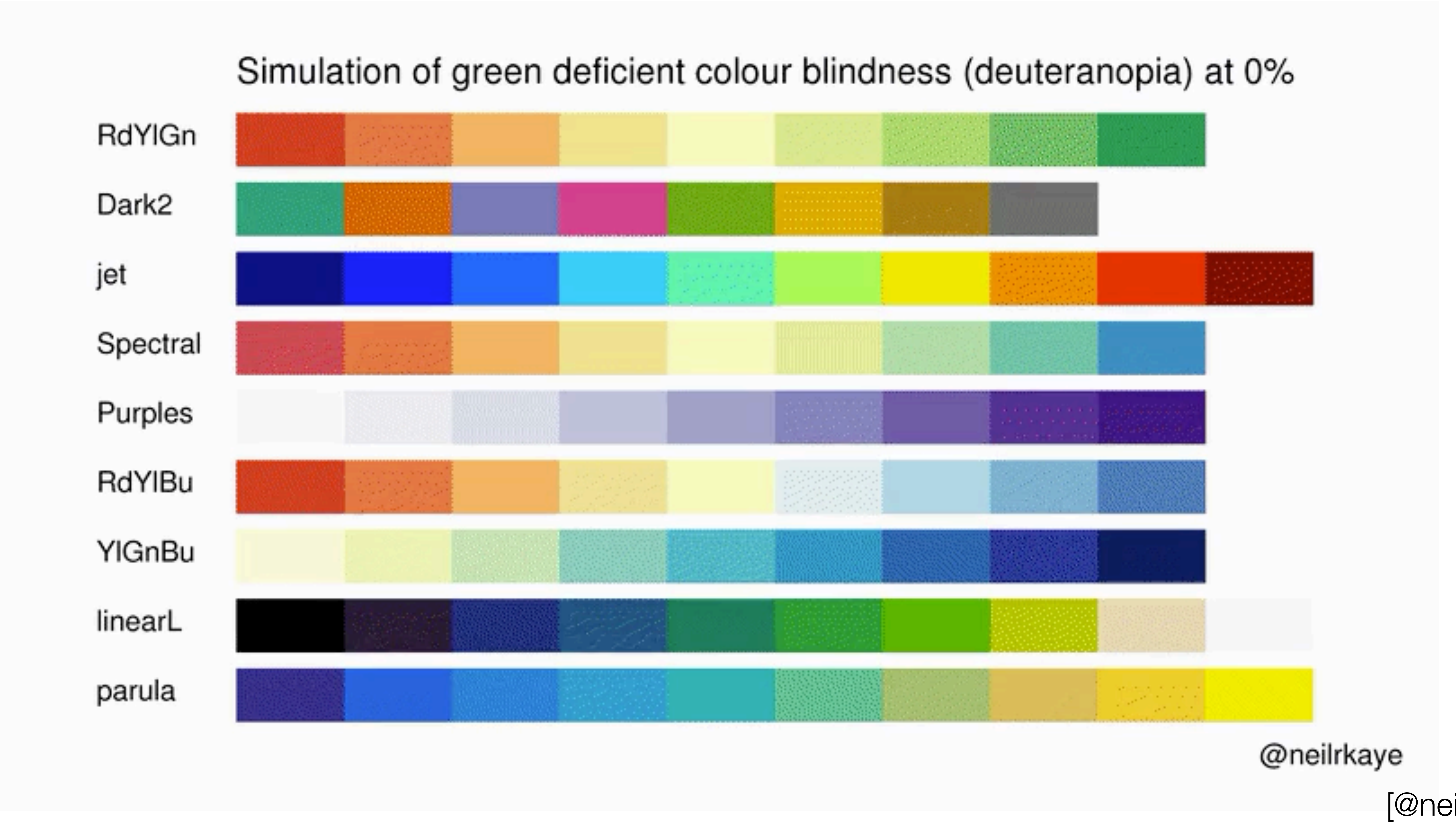



[@neilrkaye, reddit]

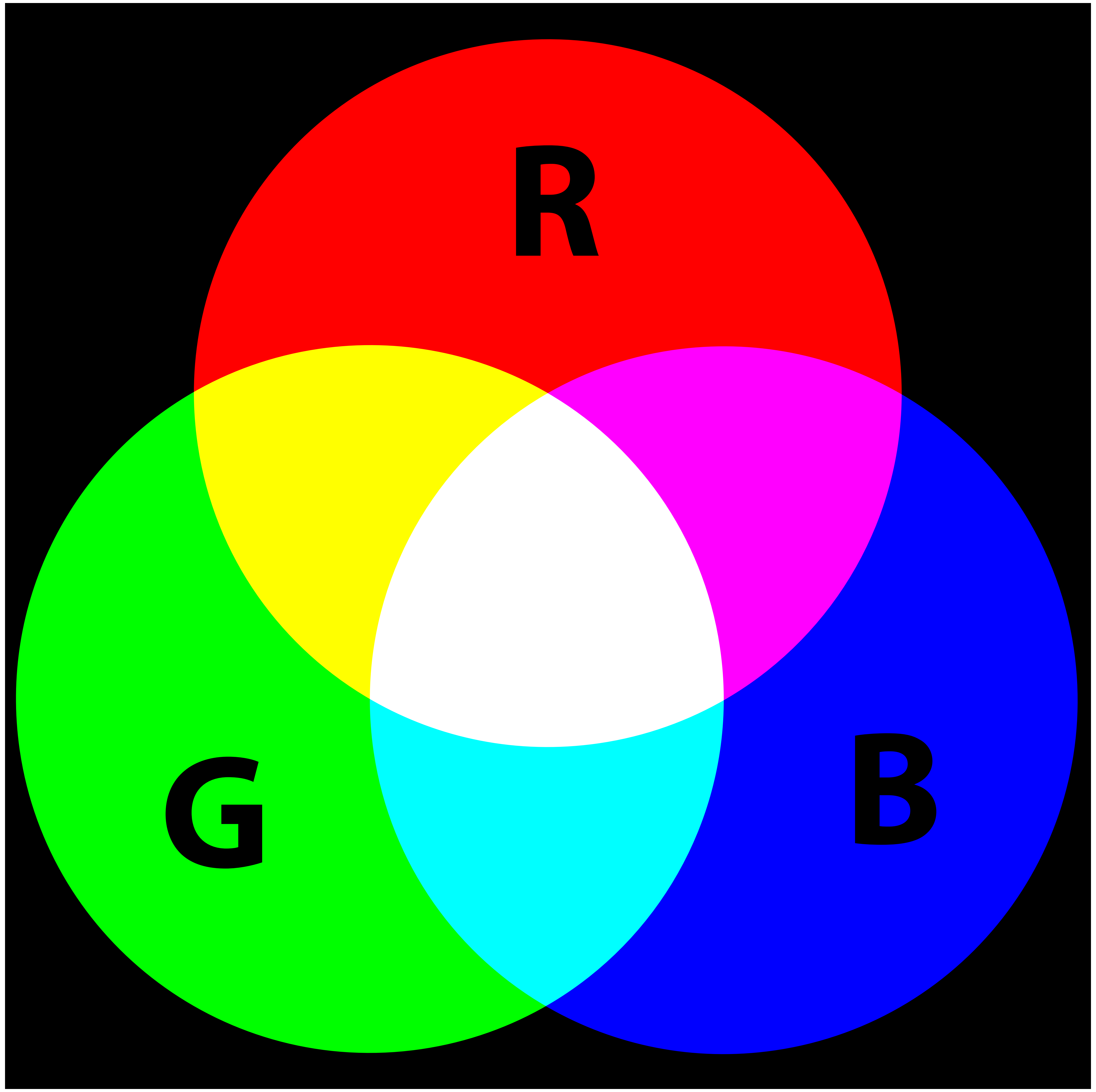
# Primary Colors?

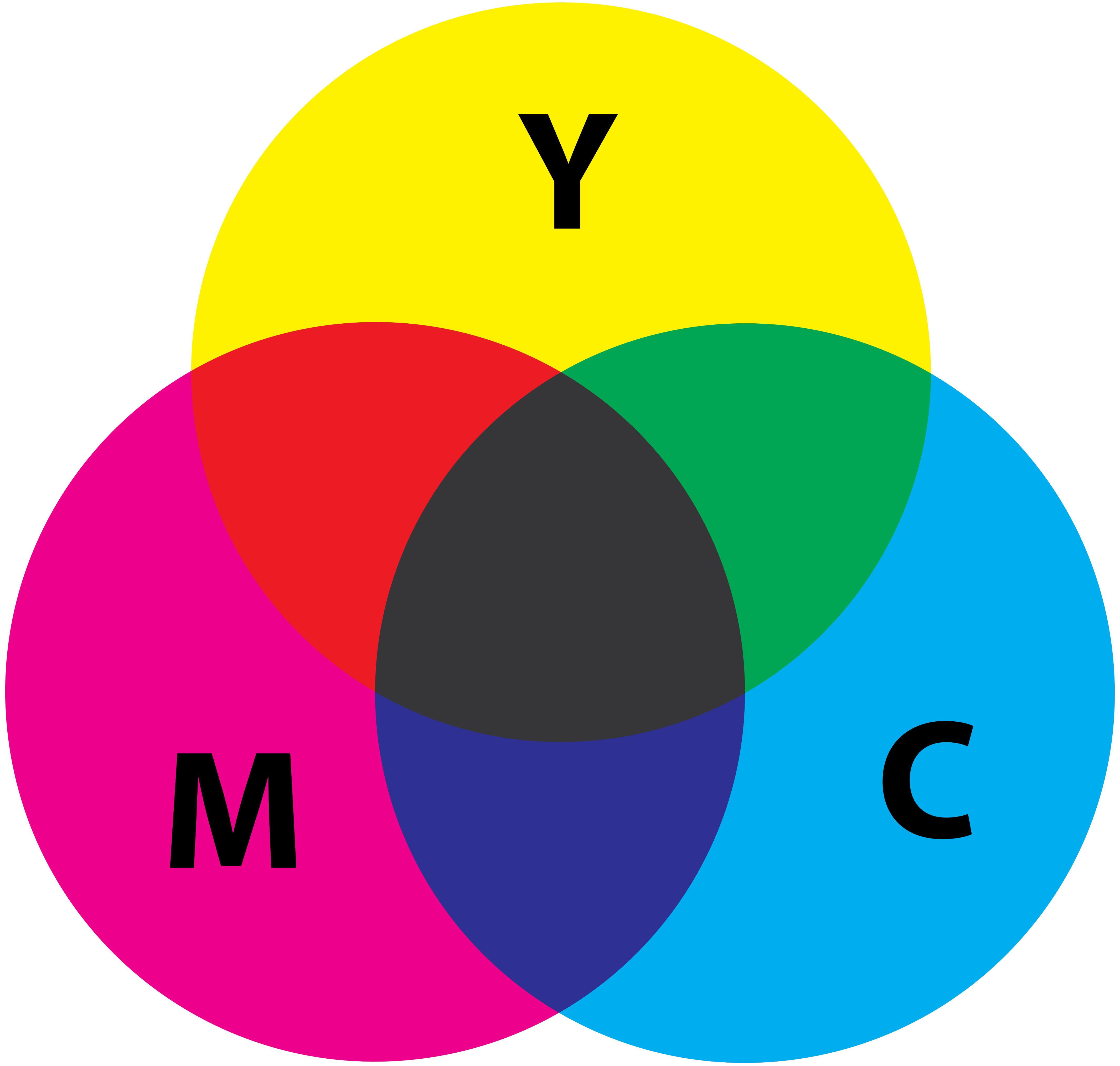
- Red, Green, and Blue
- Red, Yellow, and Blue
- Orange, Green, and Violet
- Cyan, Magenta, and Yellow

# Primary Colors?

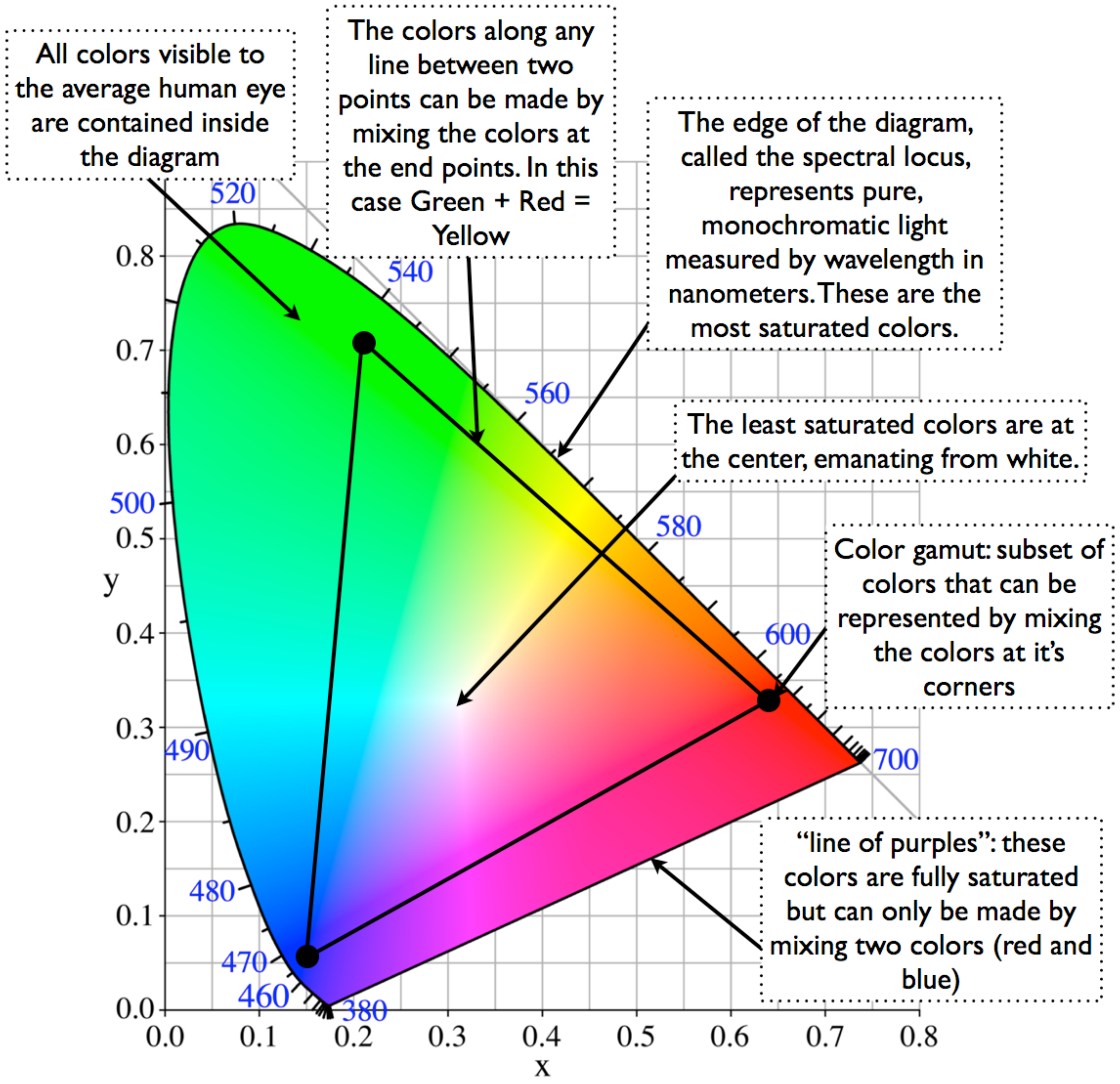
- Red, Green, and Blue
- Red, Yellow, and Blue
- Orange, Green, and Violet
- Cyan, Magenta, and Yellow
- **All of the above!**

# Color Addition and Subtraction



# Color Spaces and Gamuts




- **Color space**: the organization of all colors in space
  - Often human-specific, what we can see (e.g. CIELAB)
- **Color gamut**: a subset of colors
  - Defined by corners of color space
  - What can be produced on a monitor (e.g. using RGB)
  - What can be produced on a printer (e.g. using CMYK)
  - The gamut of your monitor != the gamut of someone else's or a printer

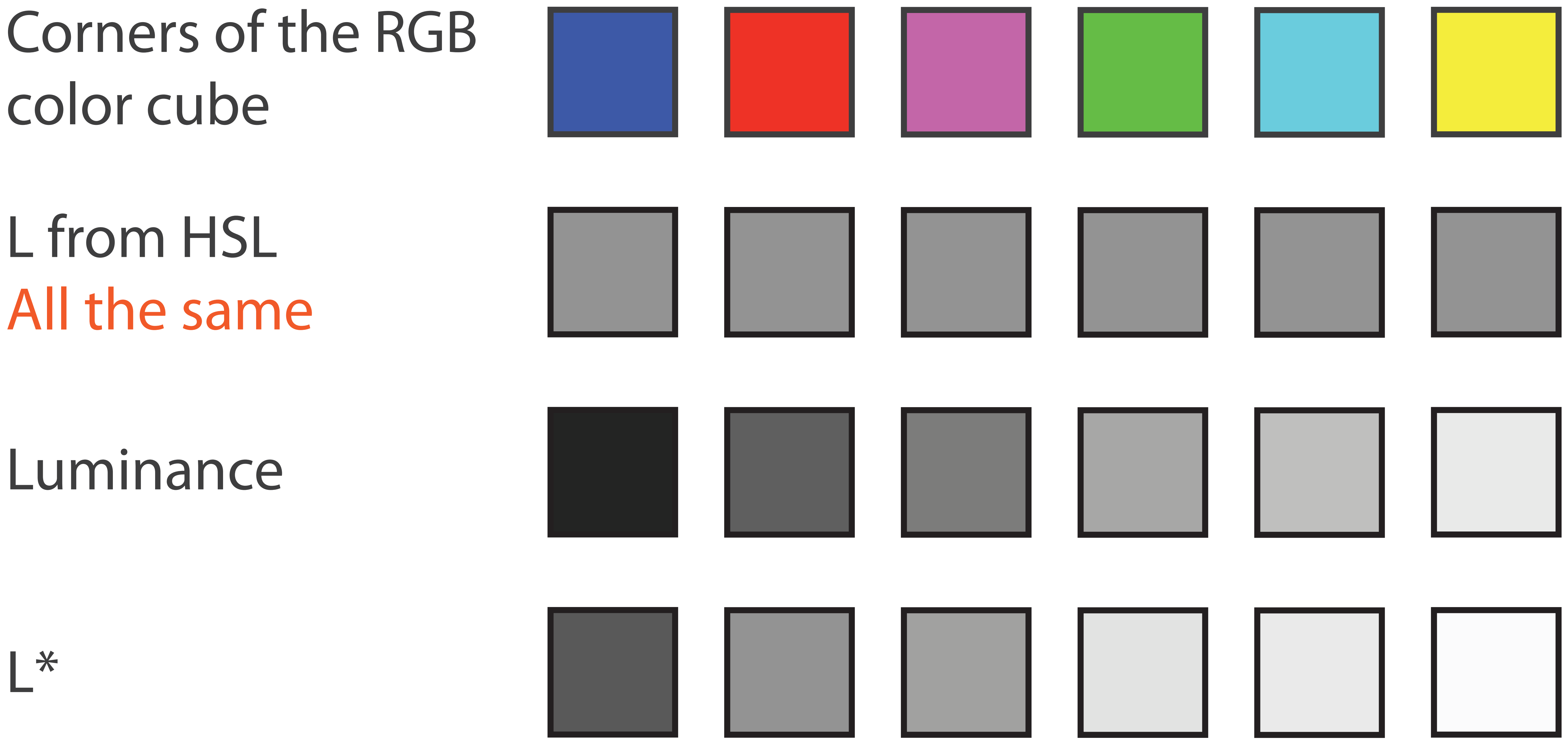
[Anatomy of a CIE Chromaticity Diagram]

# Color Models

- A **color model** is a representation of color using some basis
- RGB uses three numbers (red, blue, green) to represent color
- Color space ~ color model, but there can be many color models used in the same color space (e.g. OGV)
- Hue-Saturation-Lightness (HSL) is more intuitive and useful
  - Hue captures pure colors
  - Saturation captures the amount of white mixed with the color
  - Lightness captures the amount of black mixed with a color
  - HSL color pickers are often circular
- Hue-Saturation-Value (HSV) is similar (swap black with gray for the final value), linearly related

# Luminance

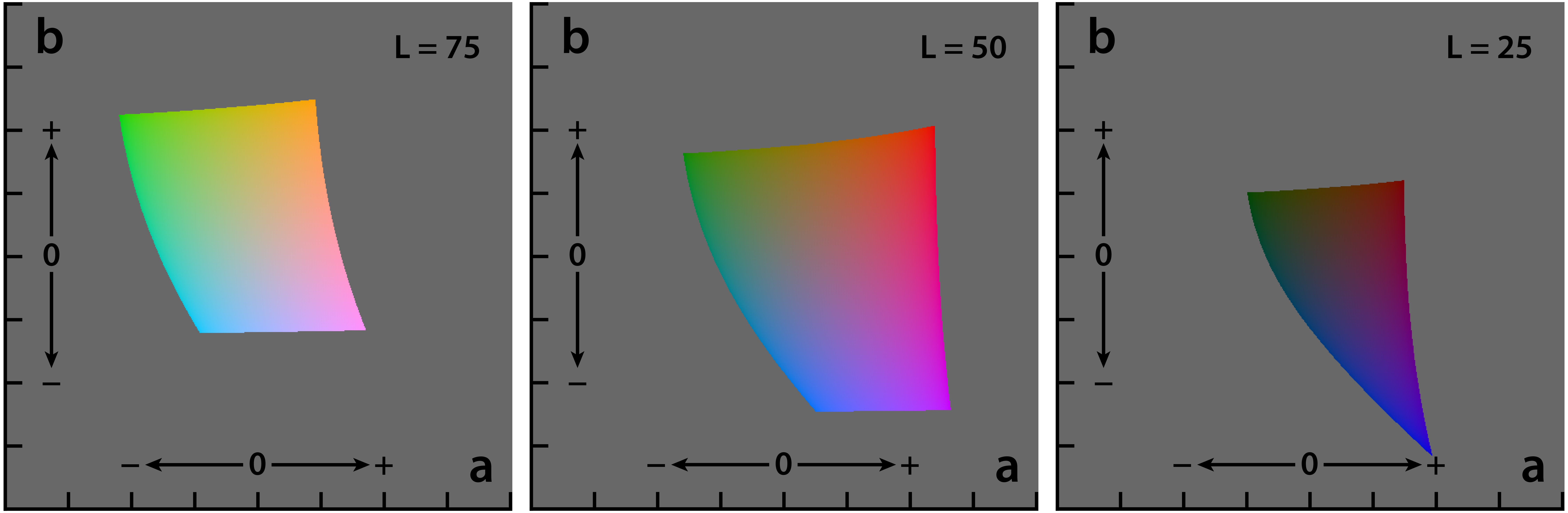
- HSL does not truly reflect the way we perceive color
- Even though colors have the same lightness, we perceive their luminance differently
- Our perception (L*) is **nonlinear**




[Munzner (ill. Maguire), 2014 (based on Stone, 2006)]

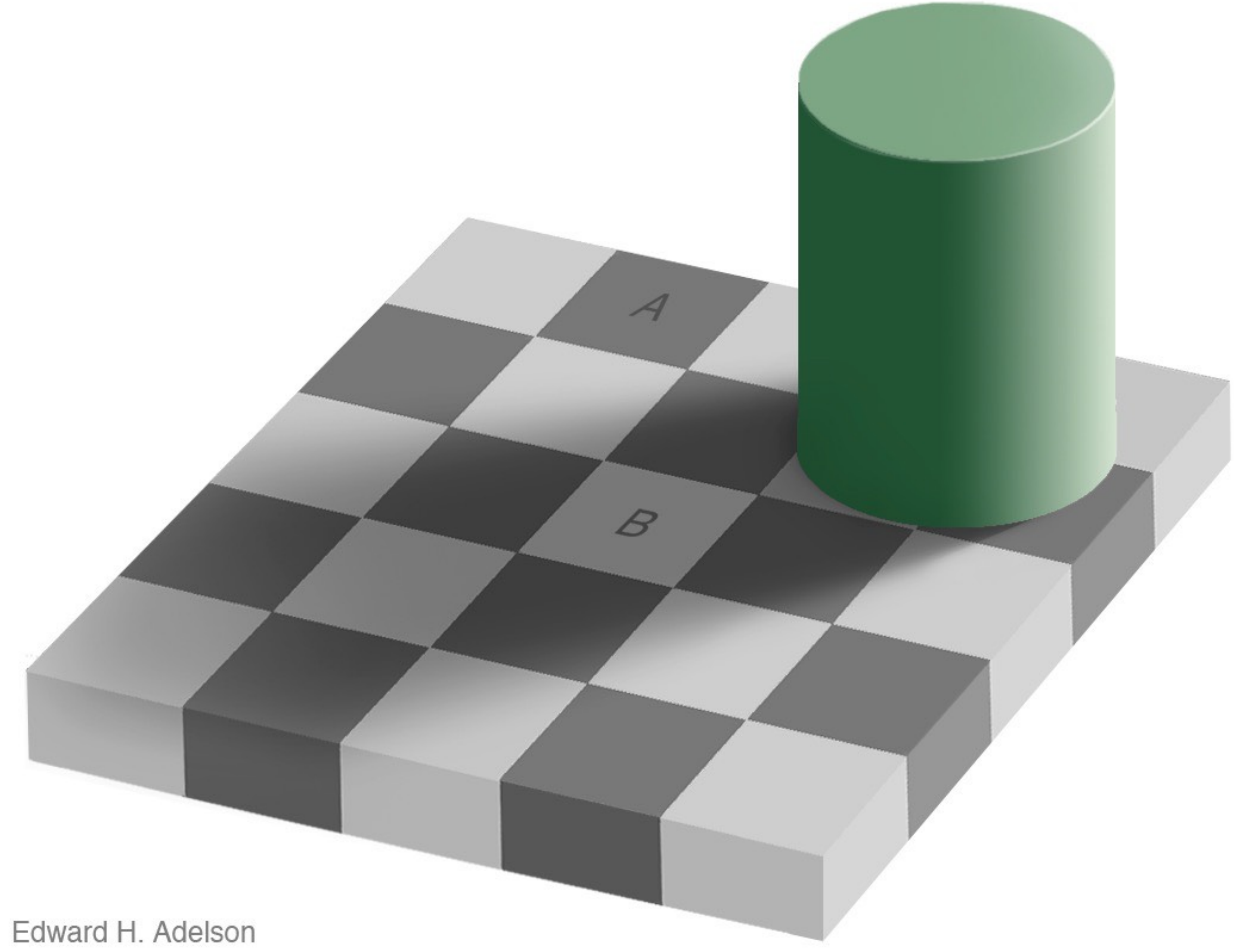
# Perceptually Uniform Color Spaces

- L*a*b* allows perceptually accurate comparison and calculations of colors




[J. Rus, CC-BY-SA (changed to horizontal layout)]

# Luminance Perception (Spatial Adaption)




[E. H. Adelson, 1995]

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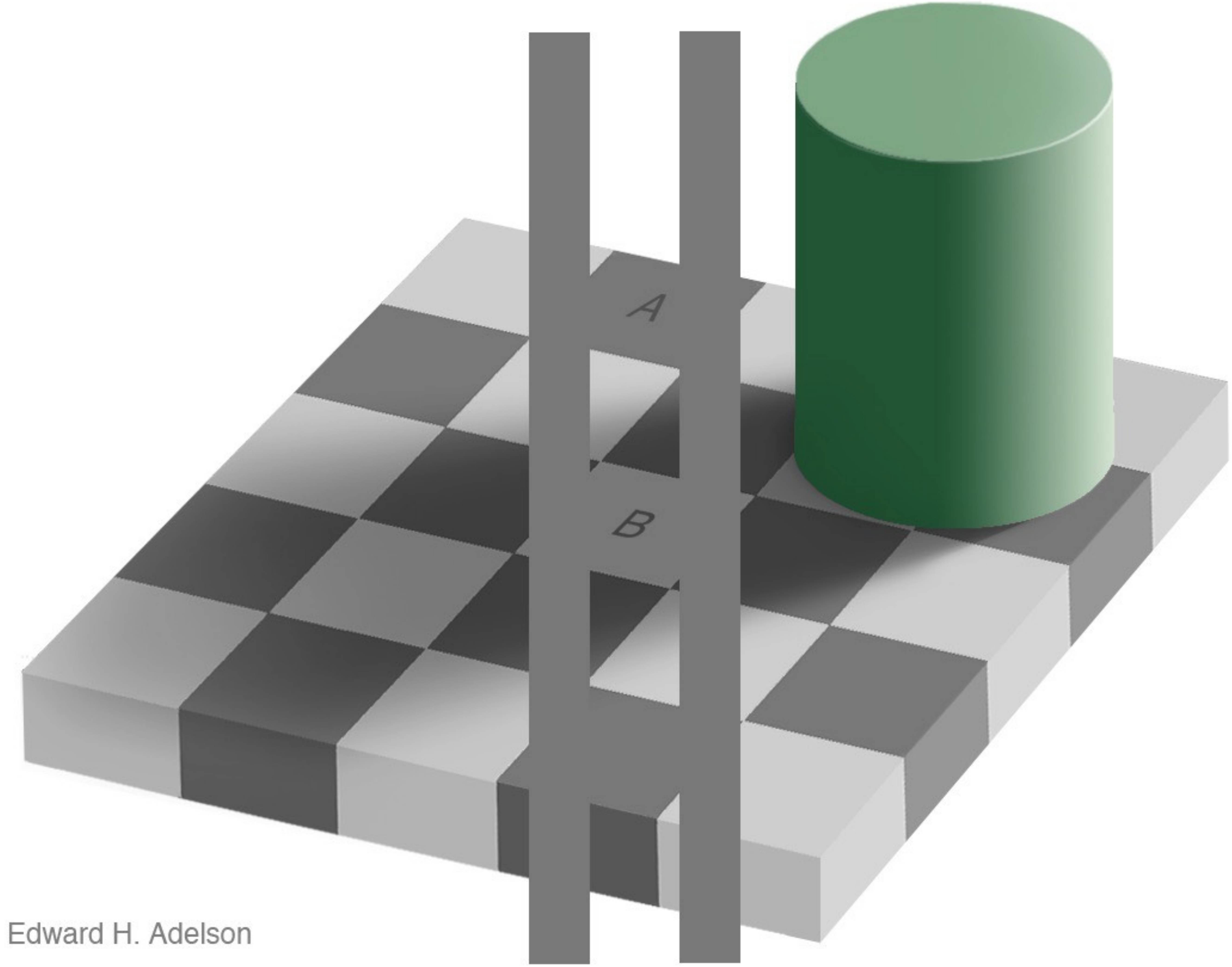
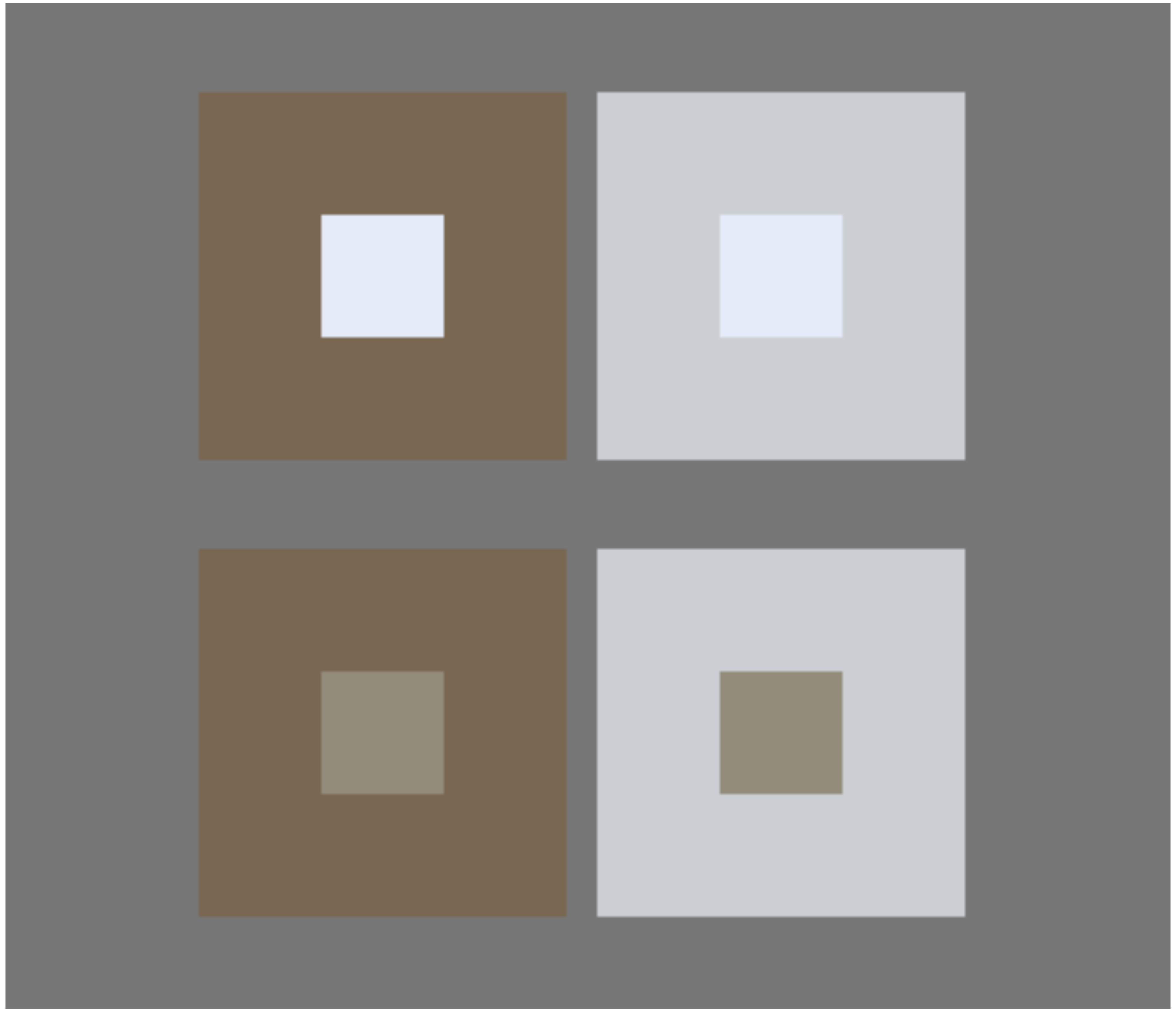



[E. H. Adelson, 1995]

# Simultaneous Contrast



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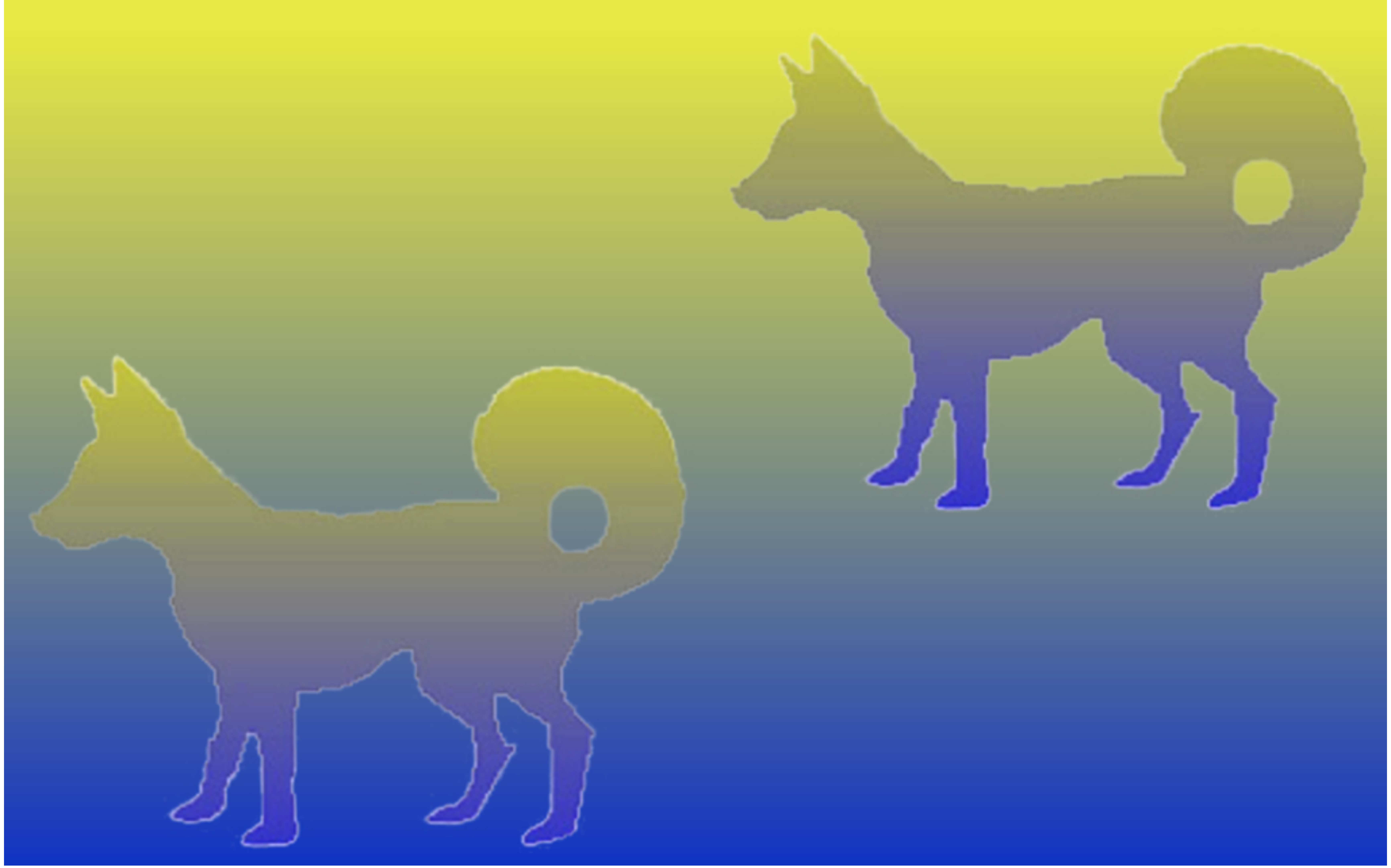

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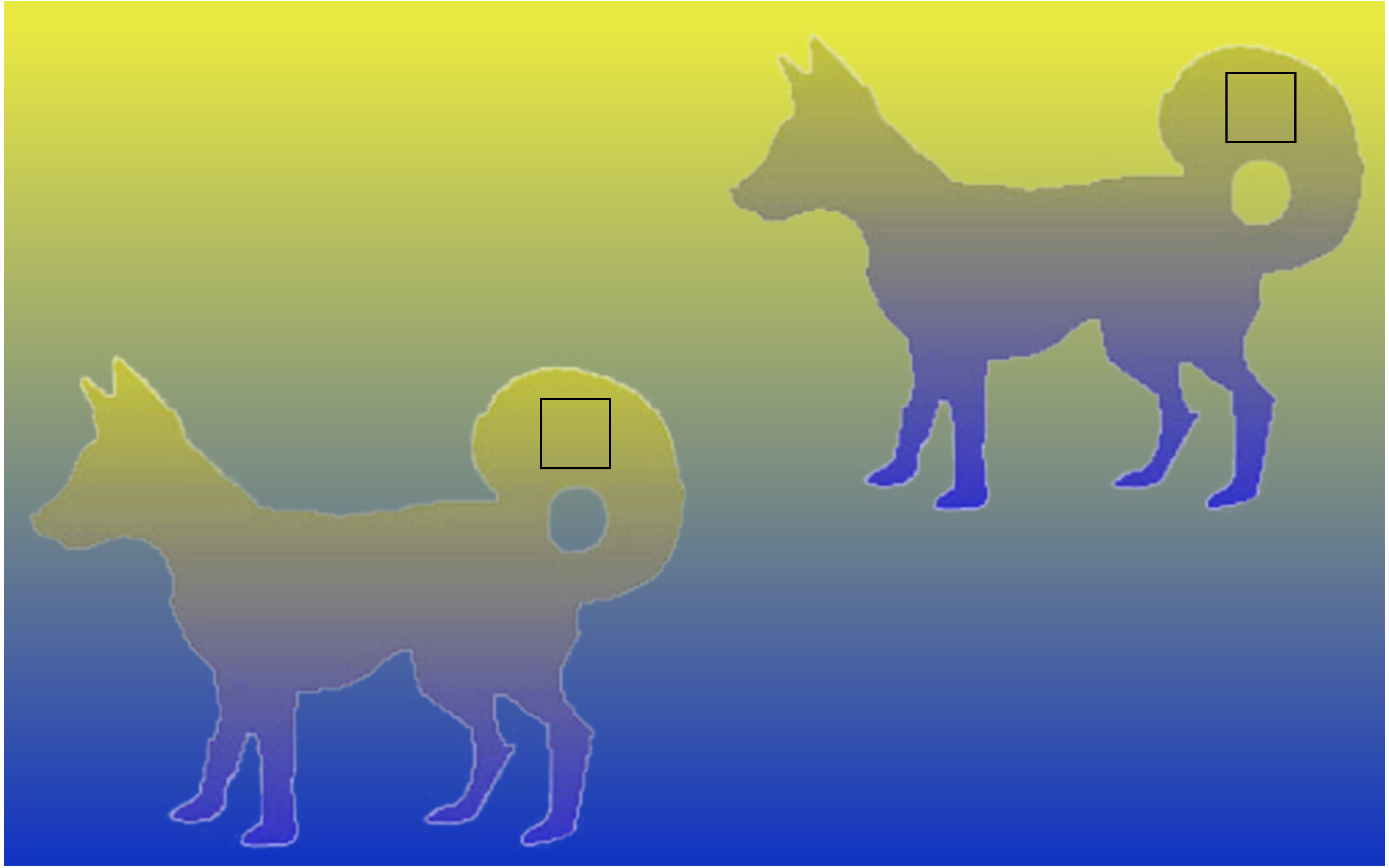
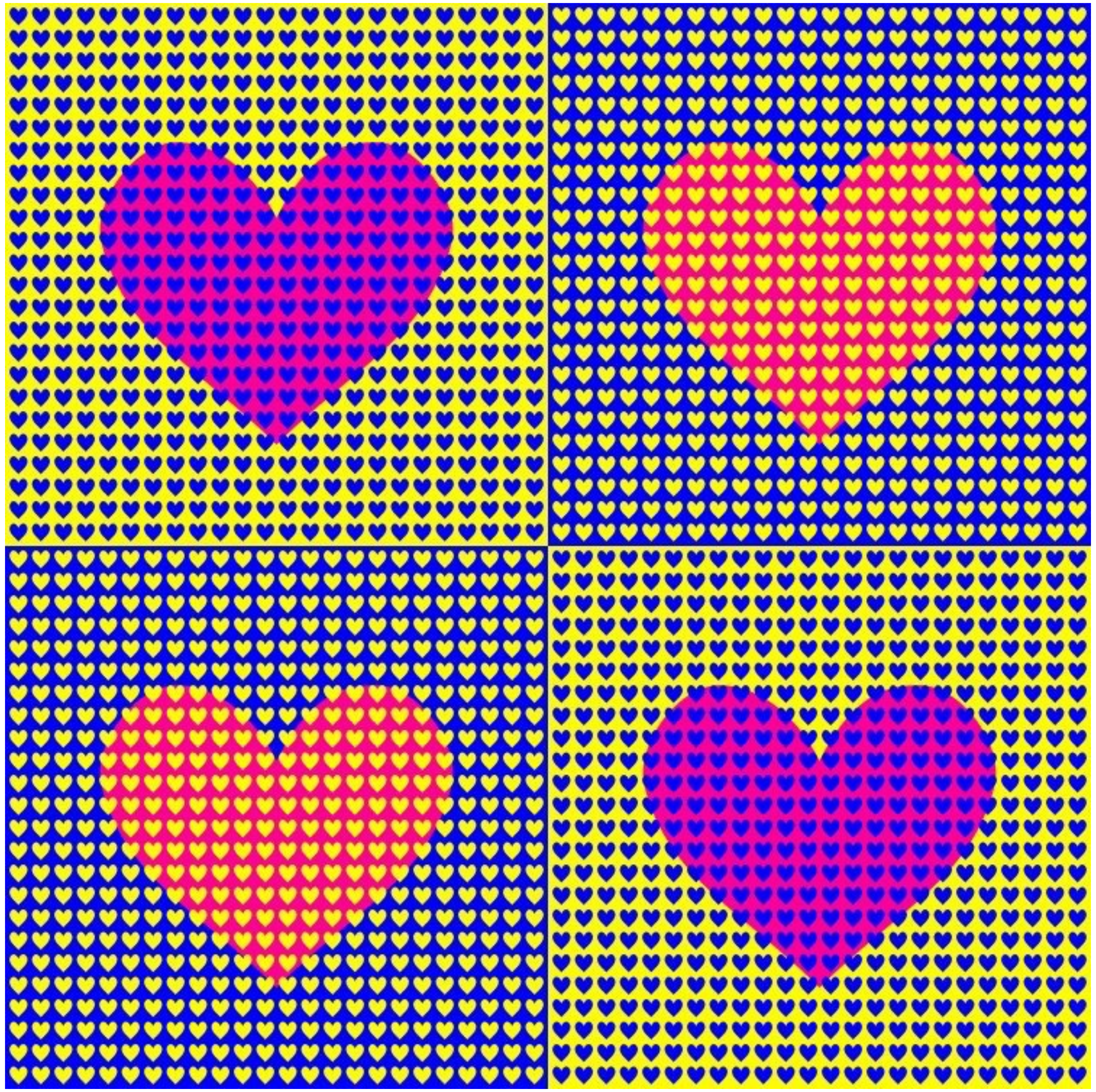


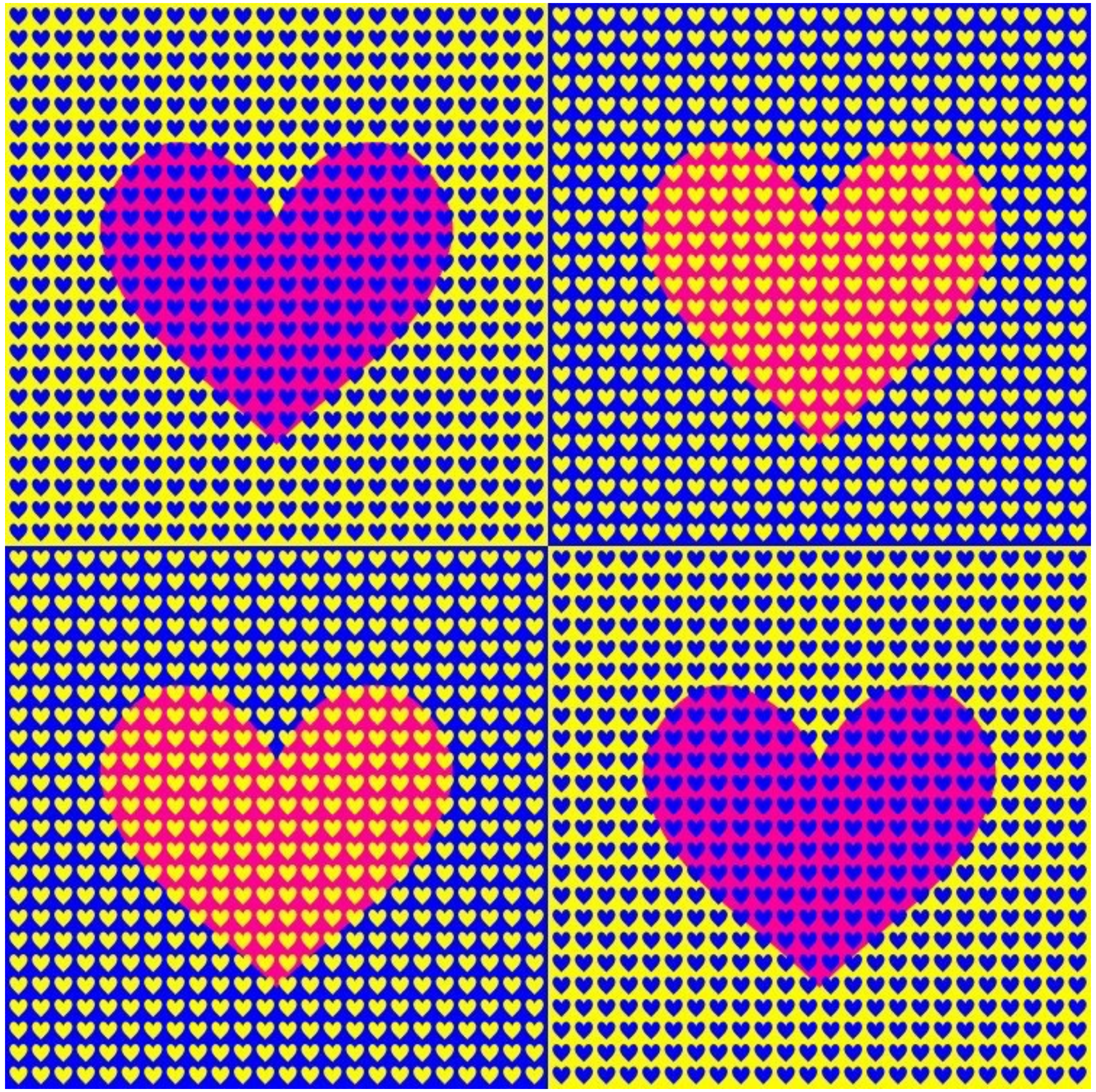
# Simultaneous Contrast

# What colors?



[A. Kitaoka]

# What colors?



Red, yellow, blue

Purple, orange do not exist!

[A. Kitaoka]

What does this mean for visualization?

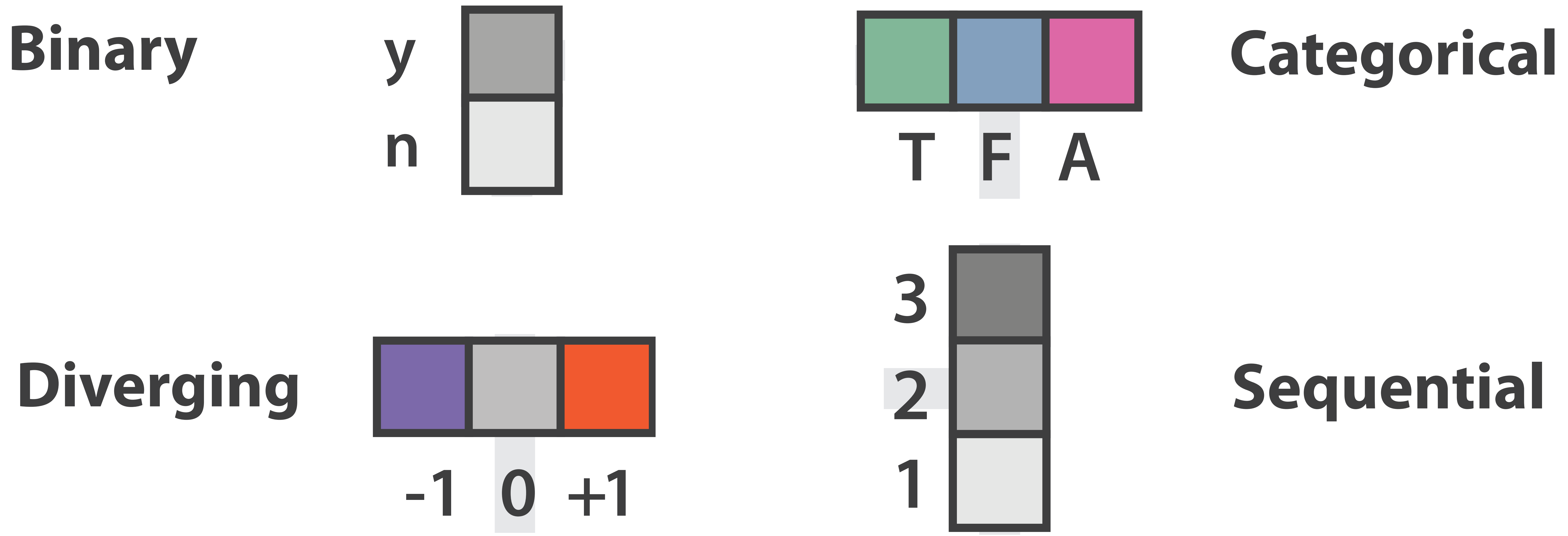
# What does this mean for visualization?

- We need to be aware of colorblindness when encoding via color
- Our brains may misinterpret color (surrounding colors matter!) even if we aren't colorblind
- Be careful! Don't assume that adding color always works the way you intended
- Use known colormaps when possible

# Colormaps

# Colormap

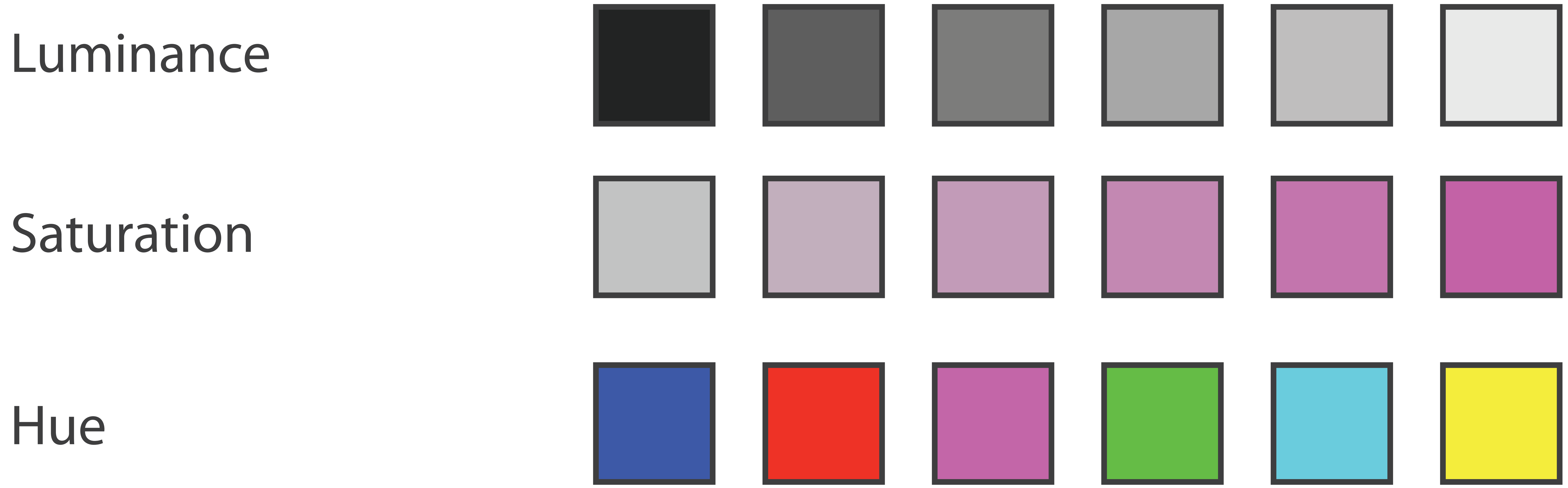
- A colormap specifies a mapping between colors and data values
- Colormap should follow the expressiveness principle
- Types of colormaps:




[Munzner (ill. Maguire), 2014]

# Categorical vs. Ordered

- Hue has no implicit ordering: use for categorical data
- Saturation and luminance do: use for ordered data

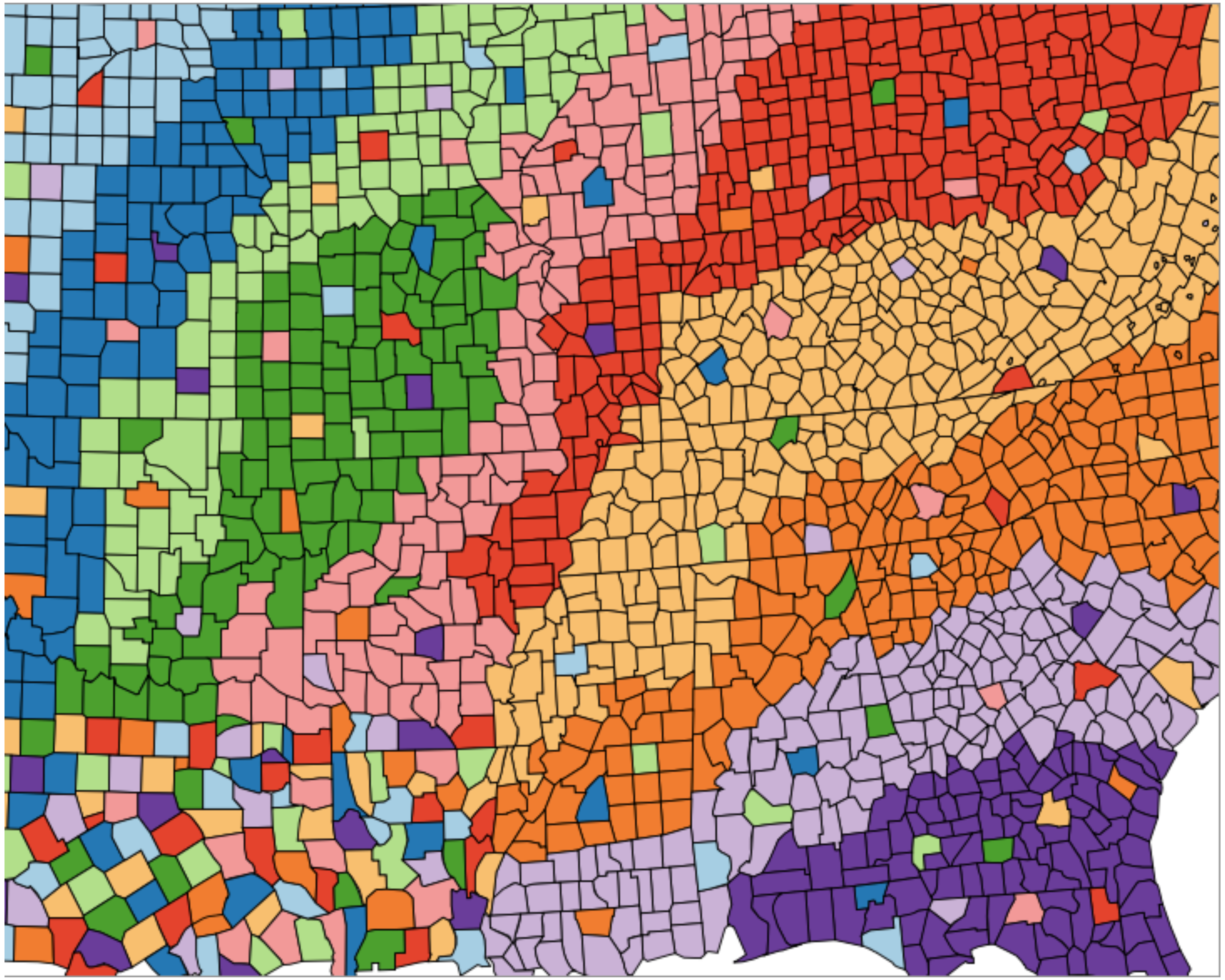



[Munzner (ill. Maguire), 2014]

# Categorical Colormap Guidelines

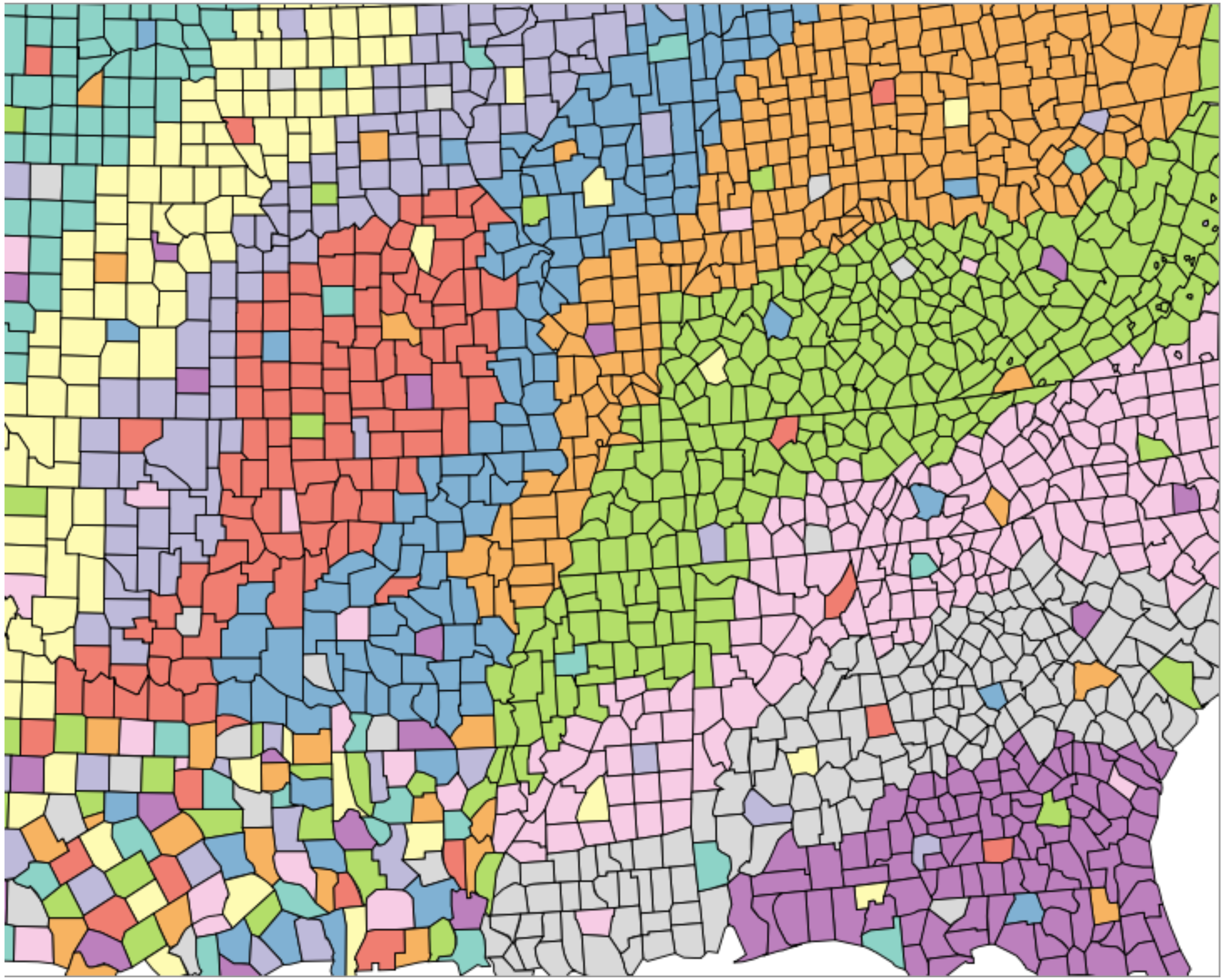
- Don't use too many colors (~12)
- Remember your background has a color, too
- Nameable colors help
- Be aware of luminance (e.g. difference between blue and yellow)
- Think about other marks you might wish to use in the visualization

# Categorical Colormaps



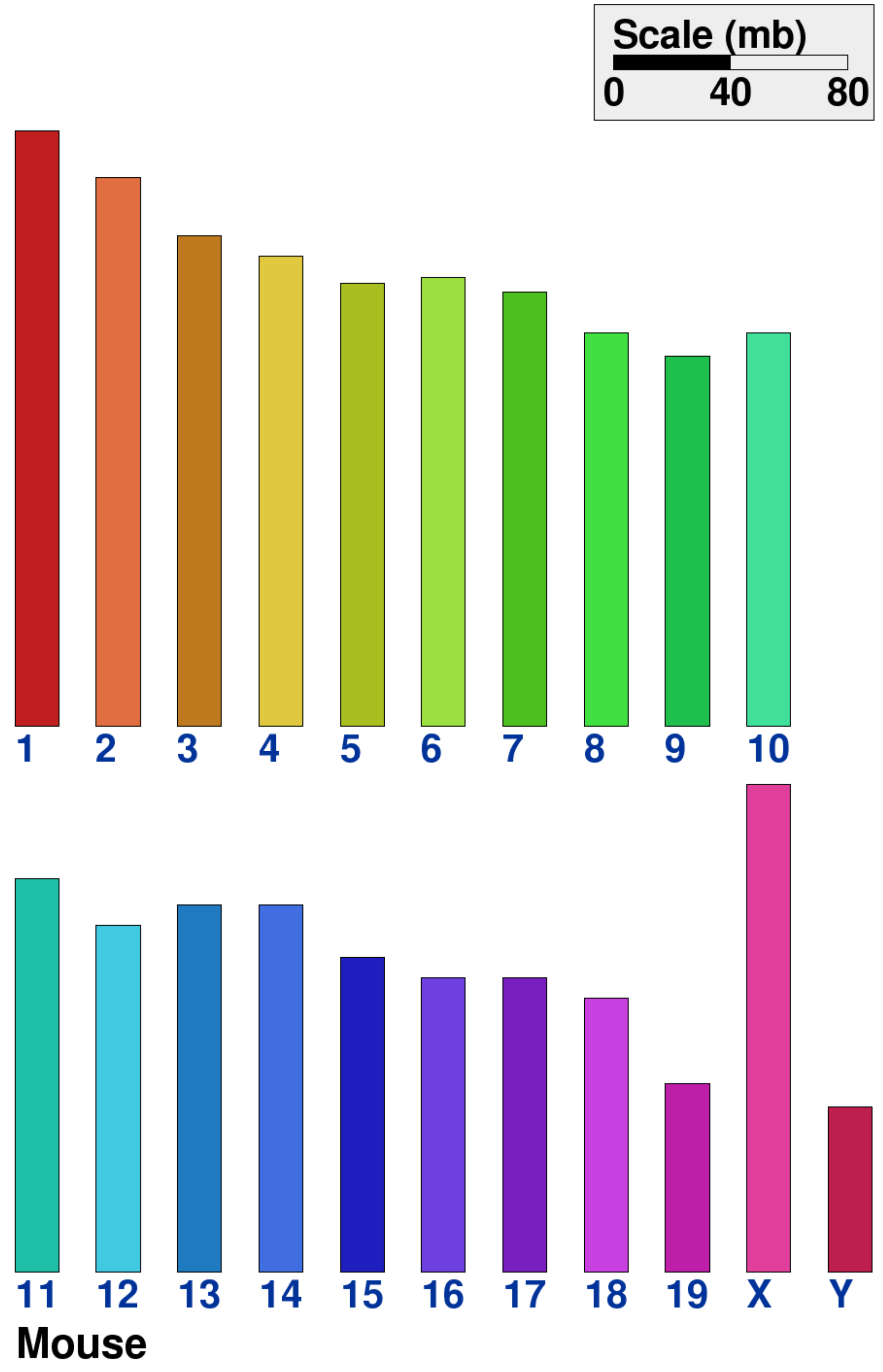
[colorbrewer2.org]

# Categorical Colormaps



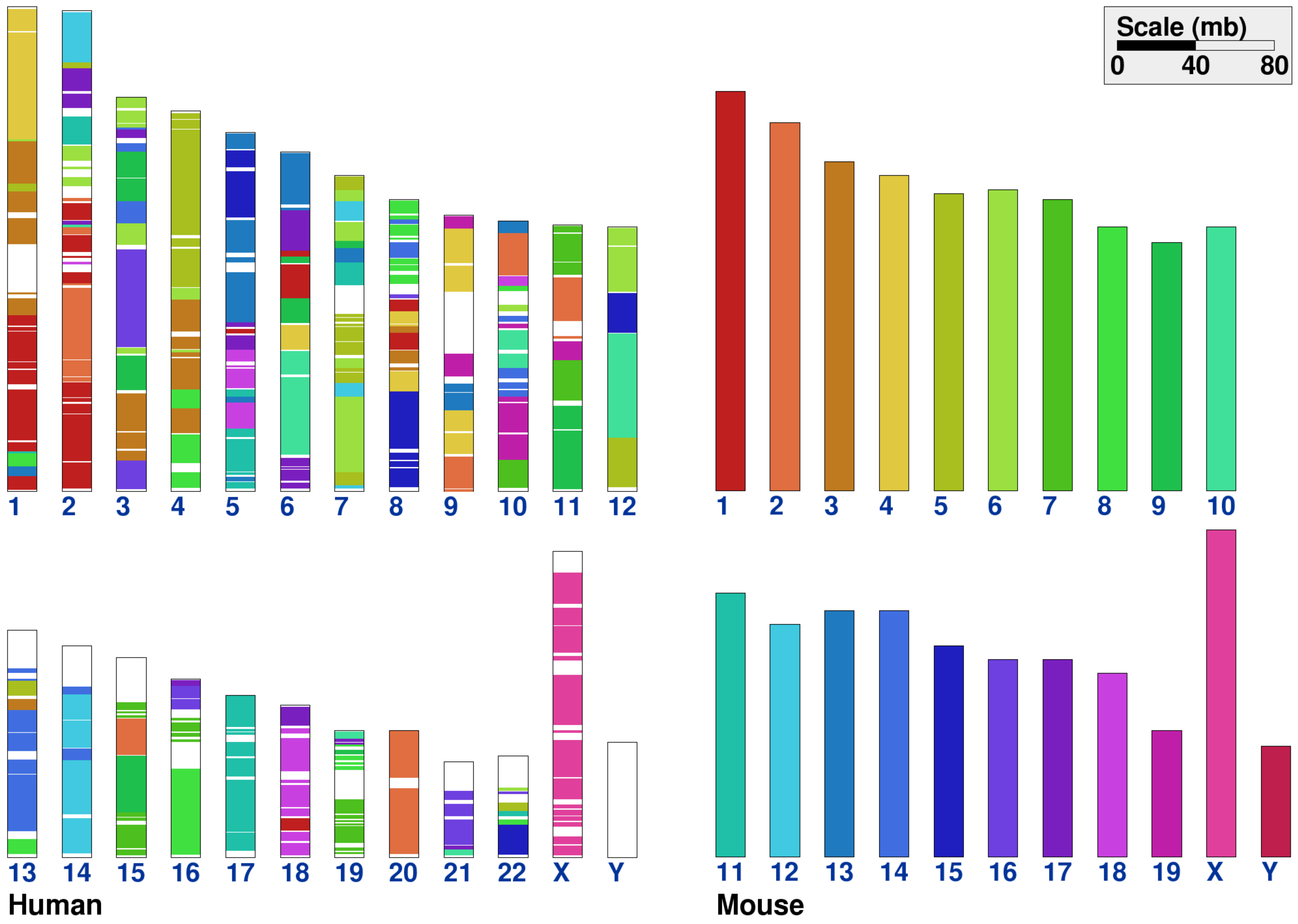
[colorbrewer2.org]

# Number of distinguishable colors?




[Sinha & Meller, 2007]

# Number of distinguishable colors?




[Sinha & Meller, 2007]

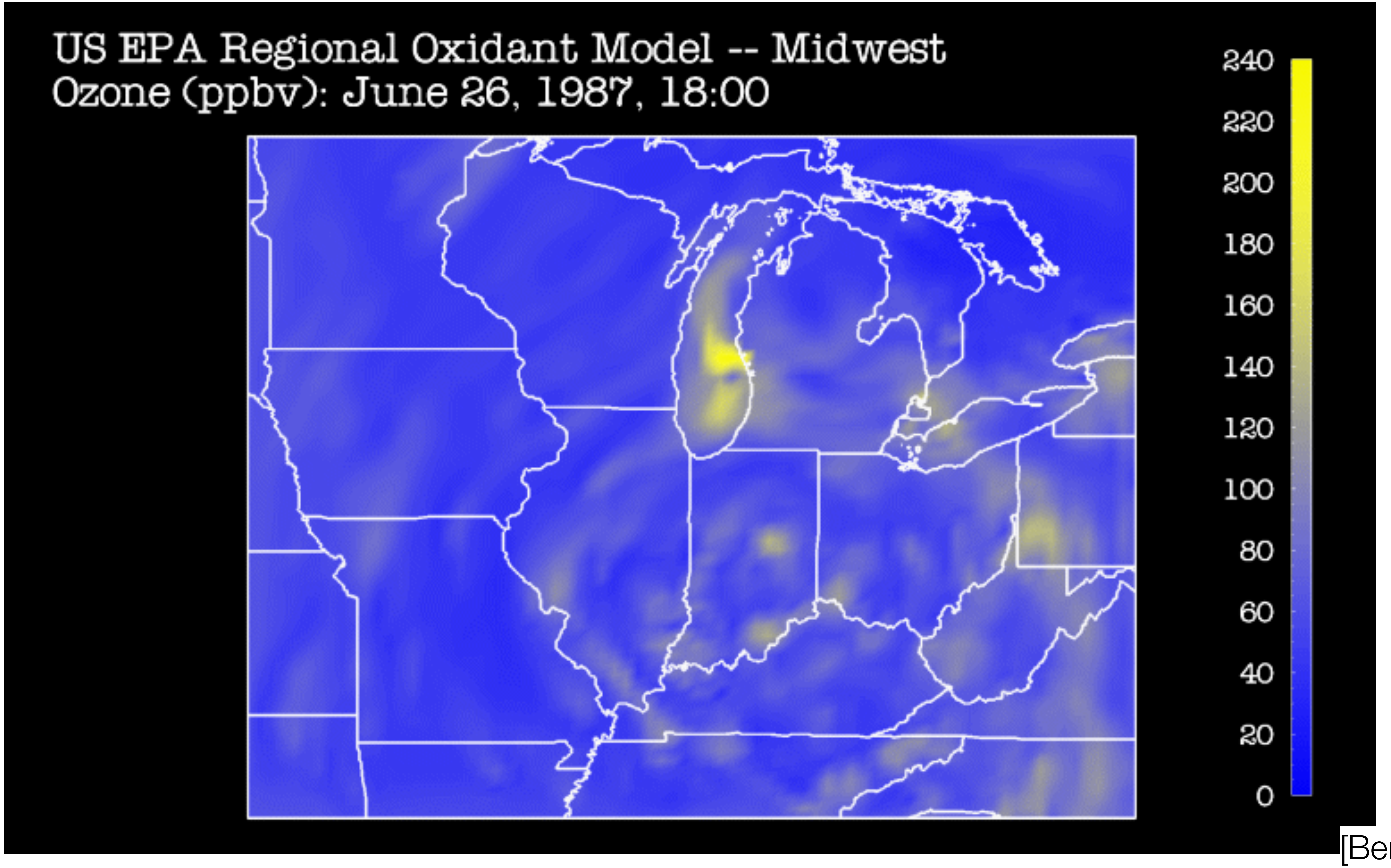
# Discriminability

- Often, fewer colors are better
- Don't let viewers combine colors because they can't tell the difference
- Make the combinations yourself
- Also, can use the "Other" category to reduce the number of colors

# Ordered Colormaps

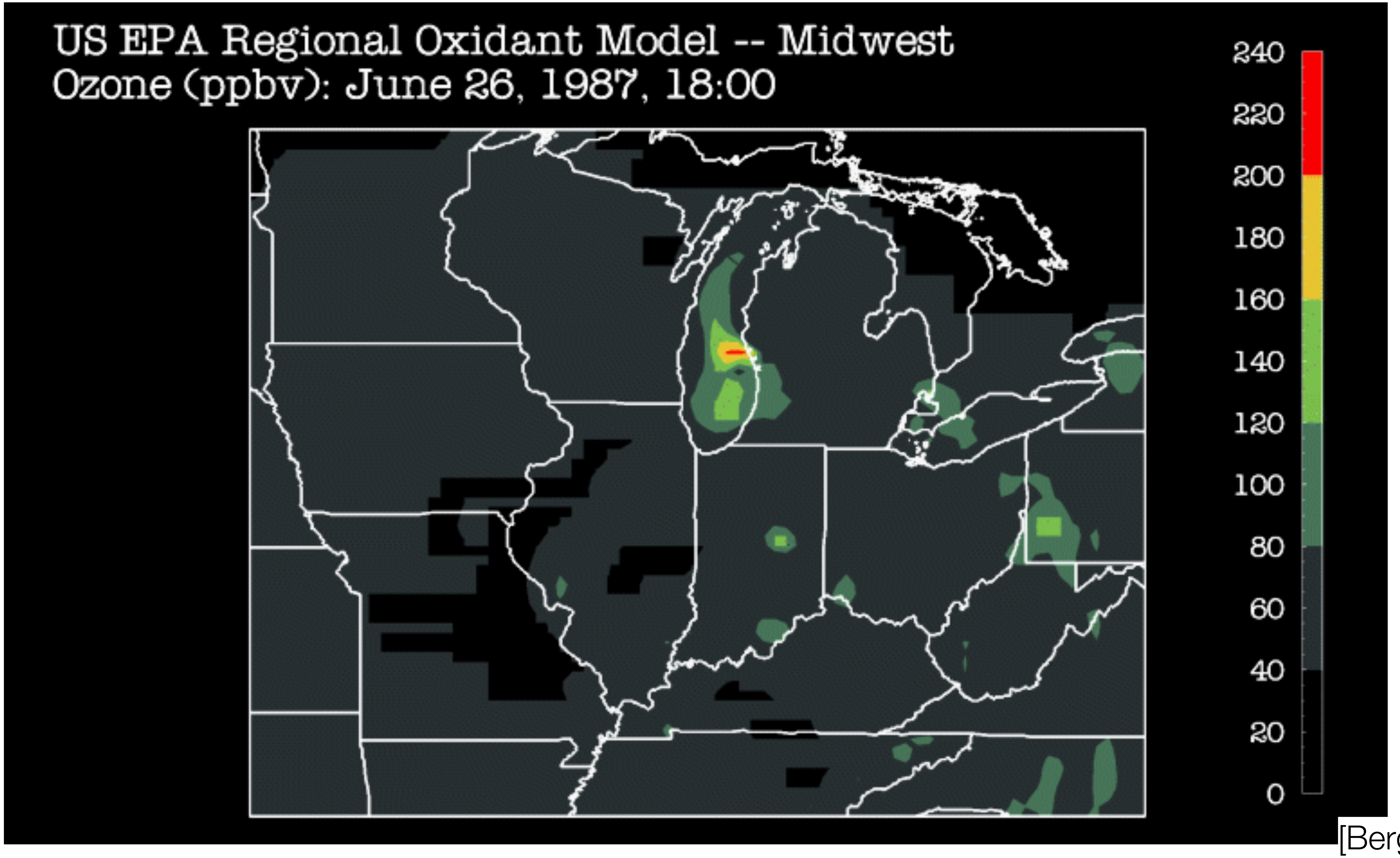
- Used for ordinal or quantitative attributes
- [0, N]: Sequential
- [-N, 0, N]: Diverging (has some meaningful midpoint)
- Can use hue, saturation, and luminance
- Remember hue is not a magnitude channel so be careful
- Can be **continuous** (smooth) or **segmented** (sharp boundaries)
  - Segmented matches with ordinal attributes
  - Can be used with quantitative data, too.

# Continuous Colormap




[Bergman et al., 1995]

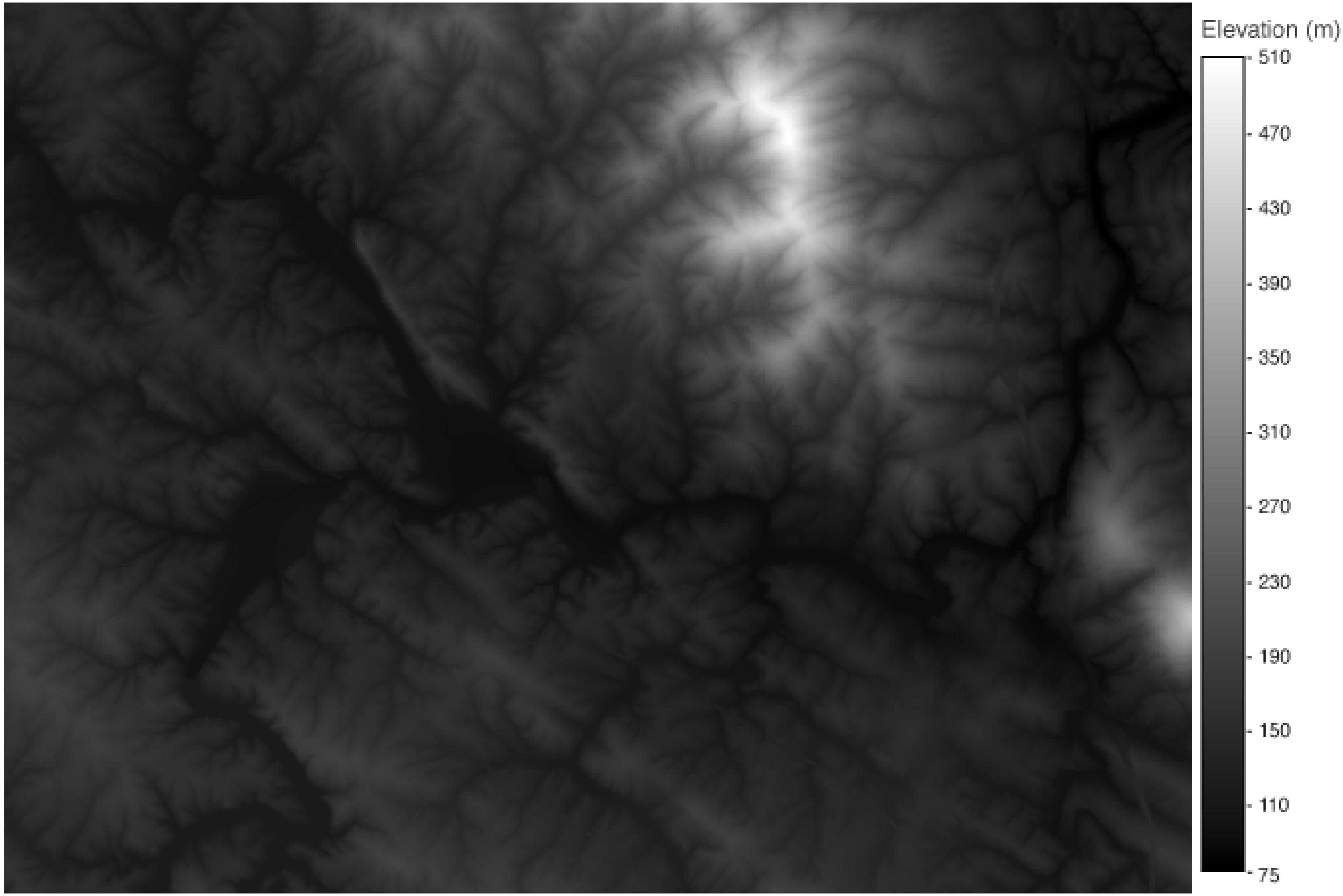
# Segmented Colormap




[Bergman et al., 1995]

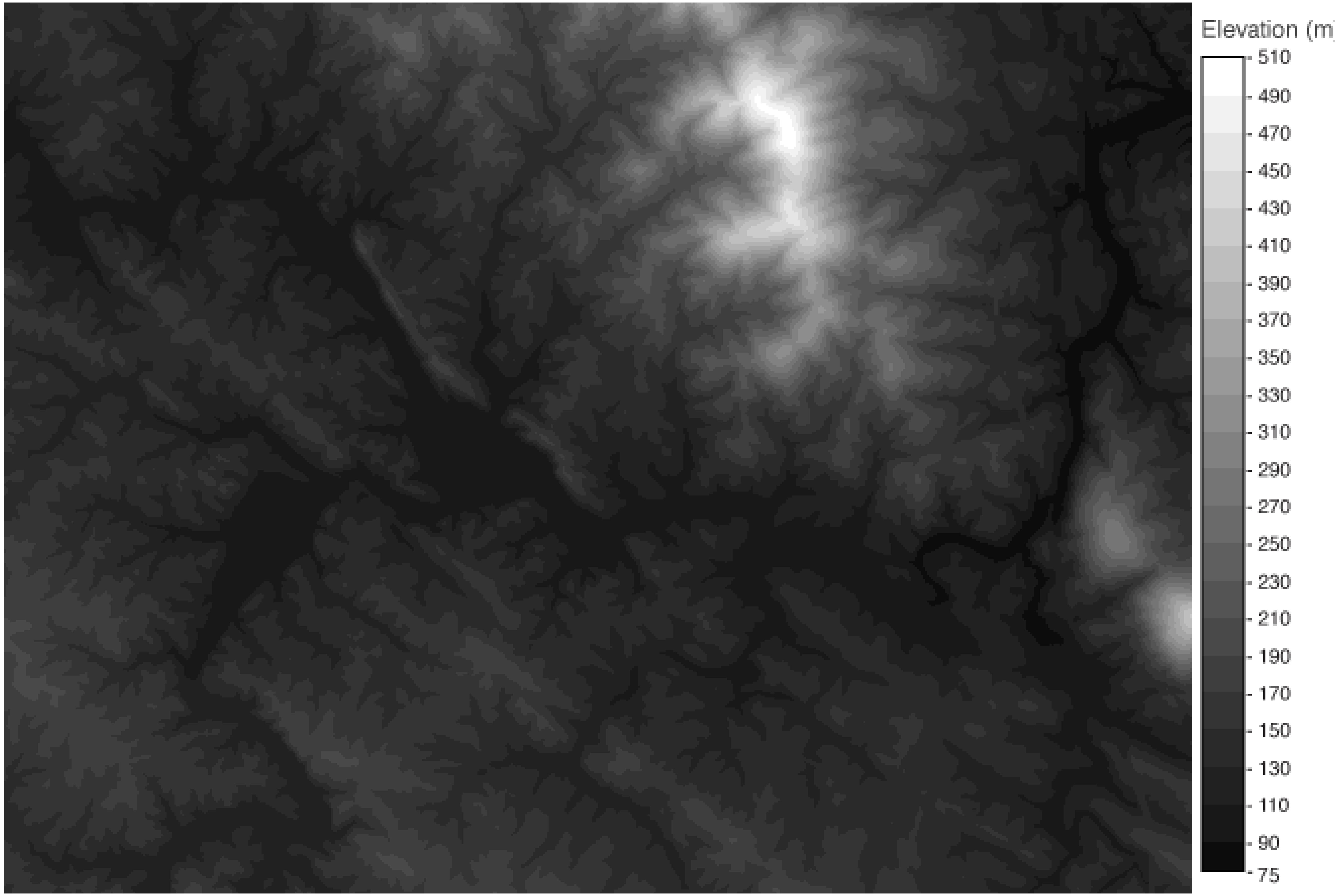
Is continuous better than segmented?

# Continuous




[Padilla et al., 2017]

# Many Segments




[Padilla et al., 2017]

# Fewer Segments


[Padilla et al., 2017]

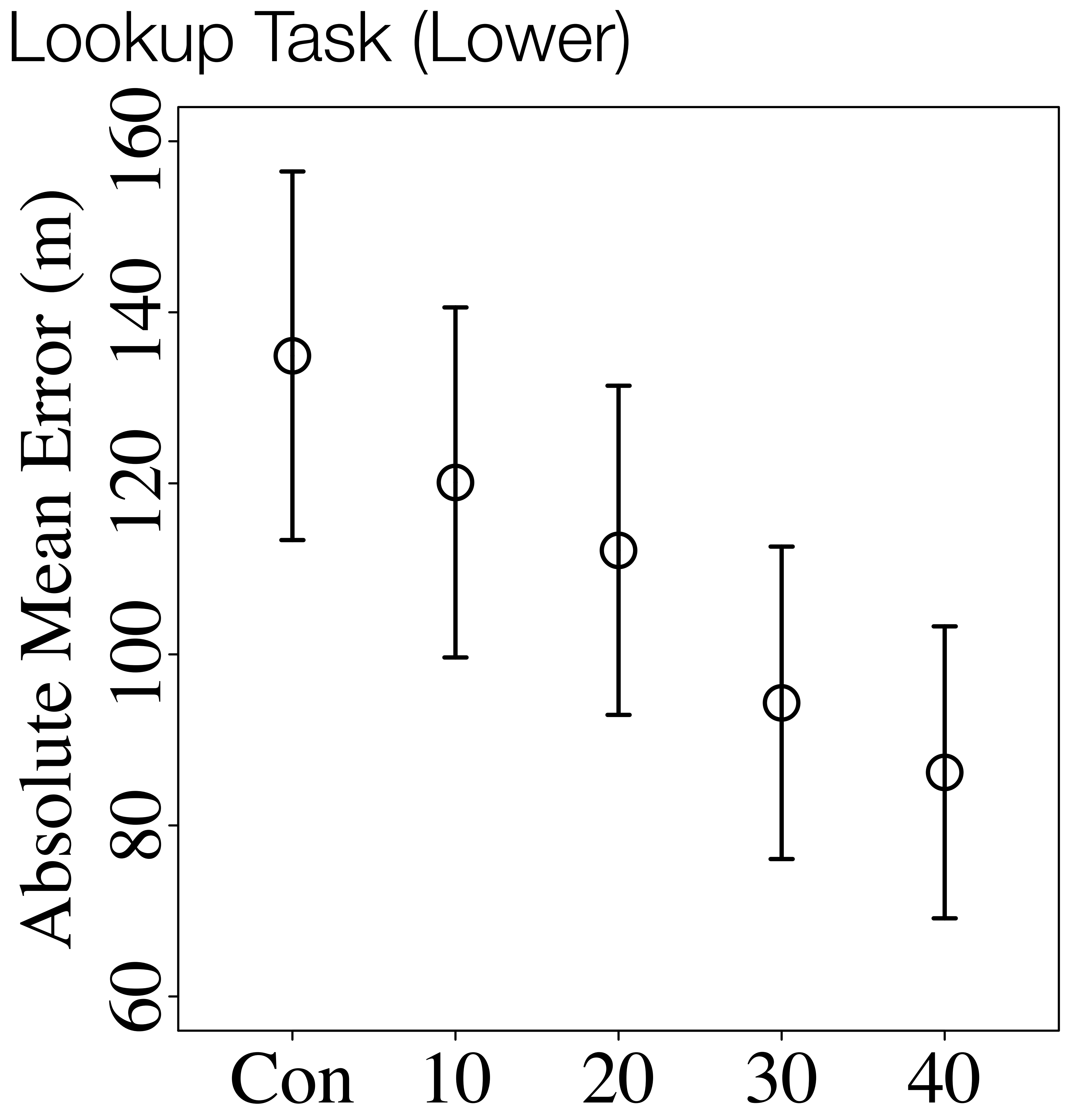
# Types of Tasks

- Locate/Explore & Identify: Highest Point (Global, In Region), 275m
- Locate/Explore & Compare: Height Compare/Rank
- Explore & Identify: Steepest
- Lookup & Identify: Lookup
- Explore & Compare: Steepness Compare/Rank
- Browse & Summarize: Average Height
- Browse & Compare: Compare Average Height
- Combination: Steepest at 355m

[Padilla et al., 2017]

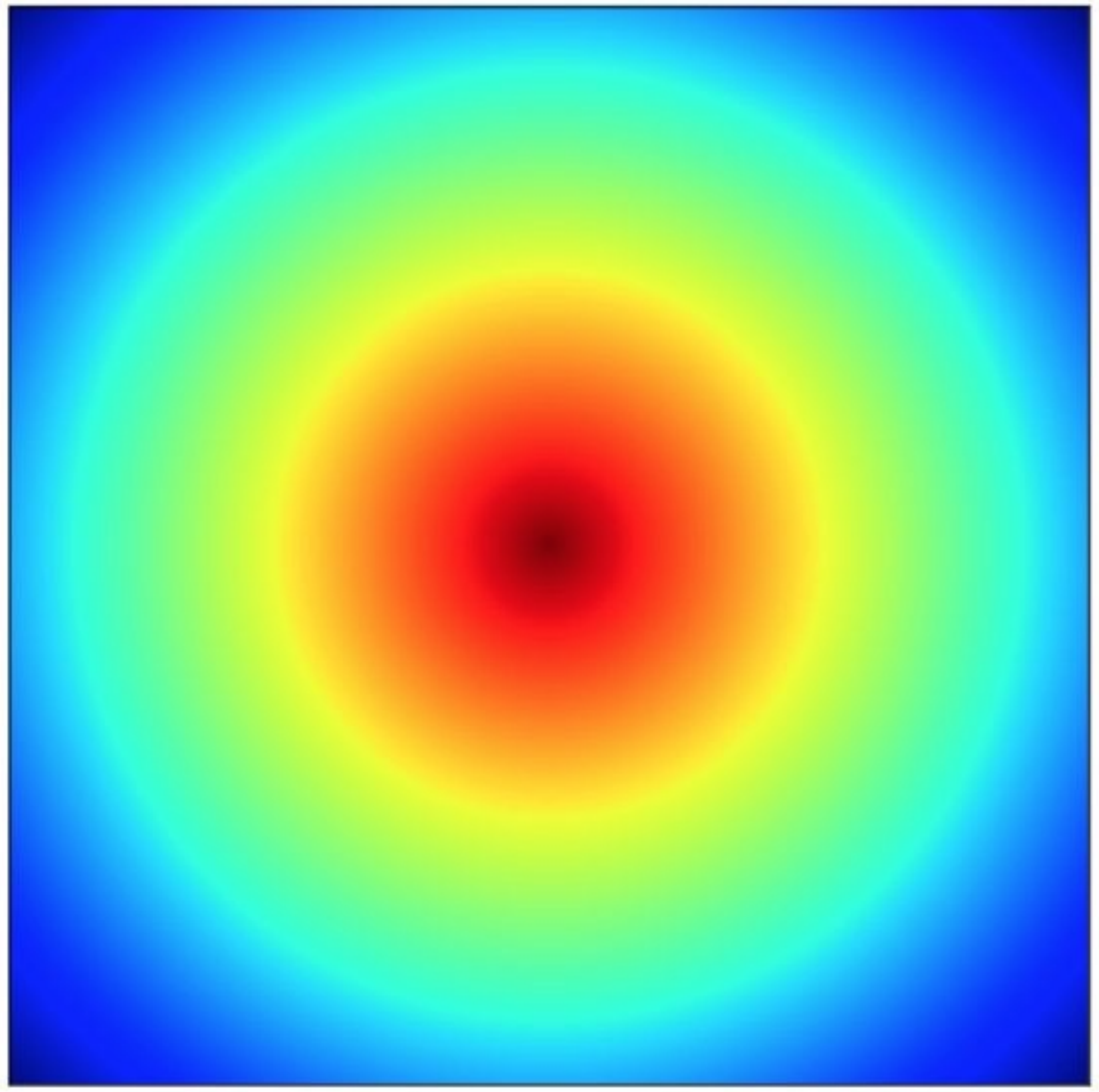
# Results

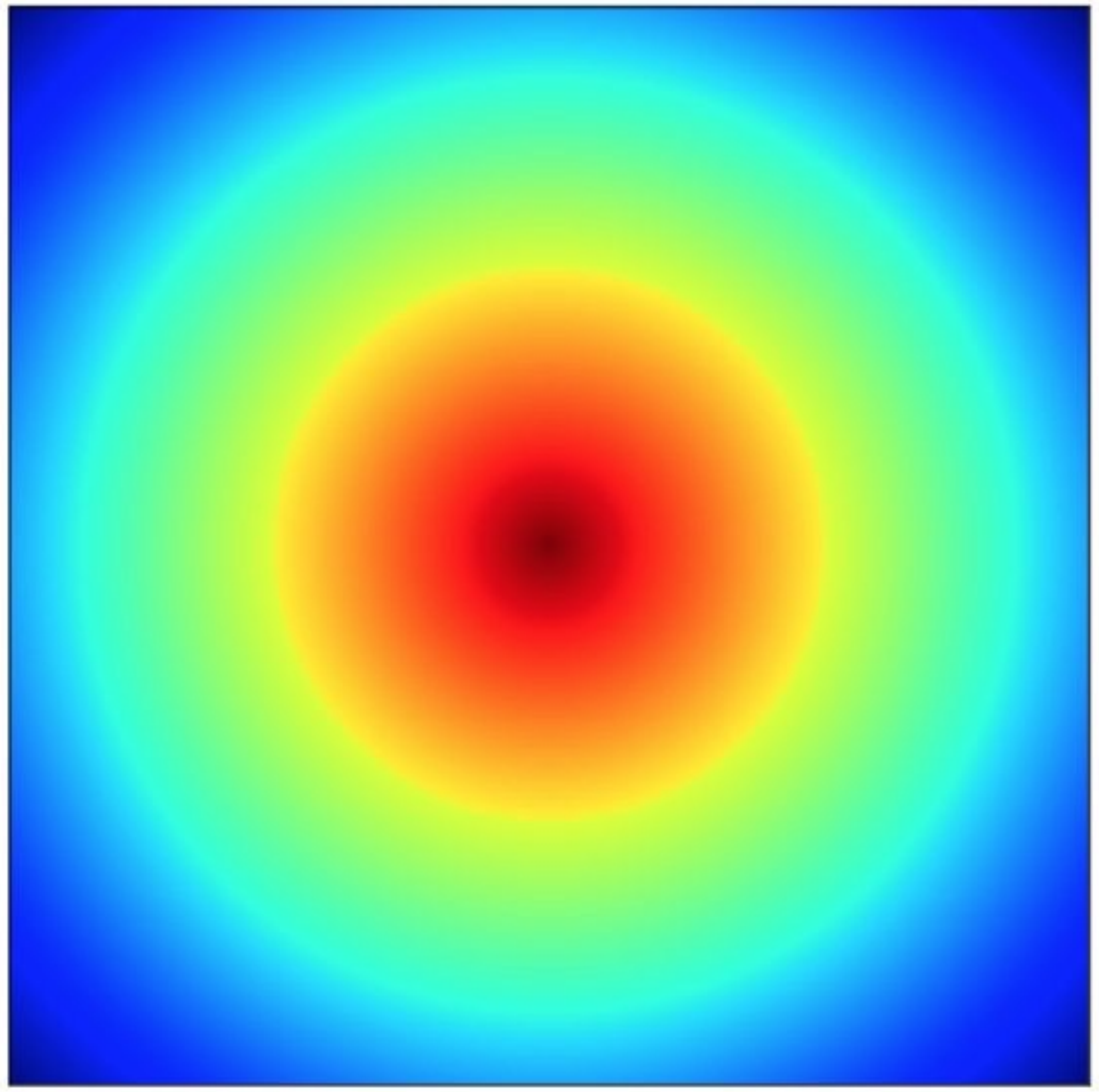
- "[C]ontrary to the expressiveness principle, no cases were found in which a continuous encoding of 2D scalar field data was advantageous for task accuracy, and for some tasks, specific binned encodings facilitated accuracy."
- "[S]upport for the counterintuitive finding that decisions with binned encoding were slower than those made with continuous encoding"
- Word of caution: single image!




[Padilla et al., 2017]

# Don't Use Rainbow Colormaps

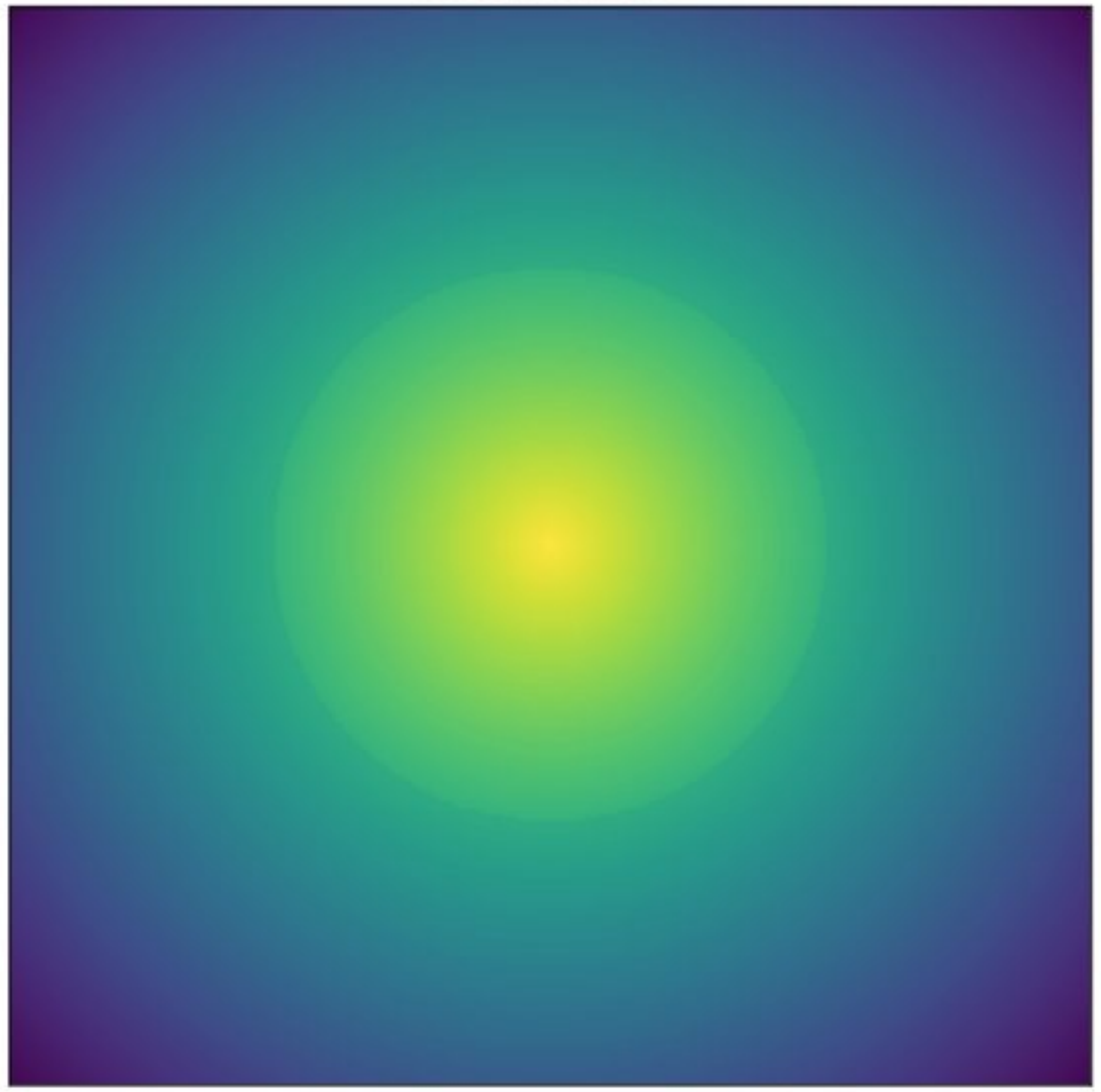


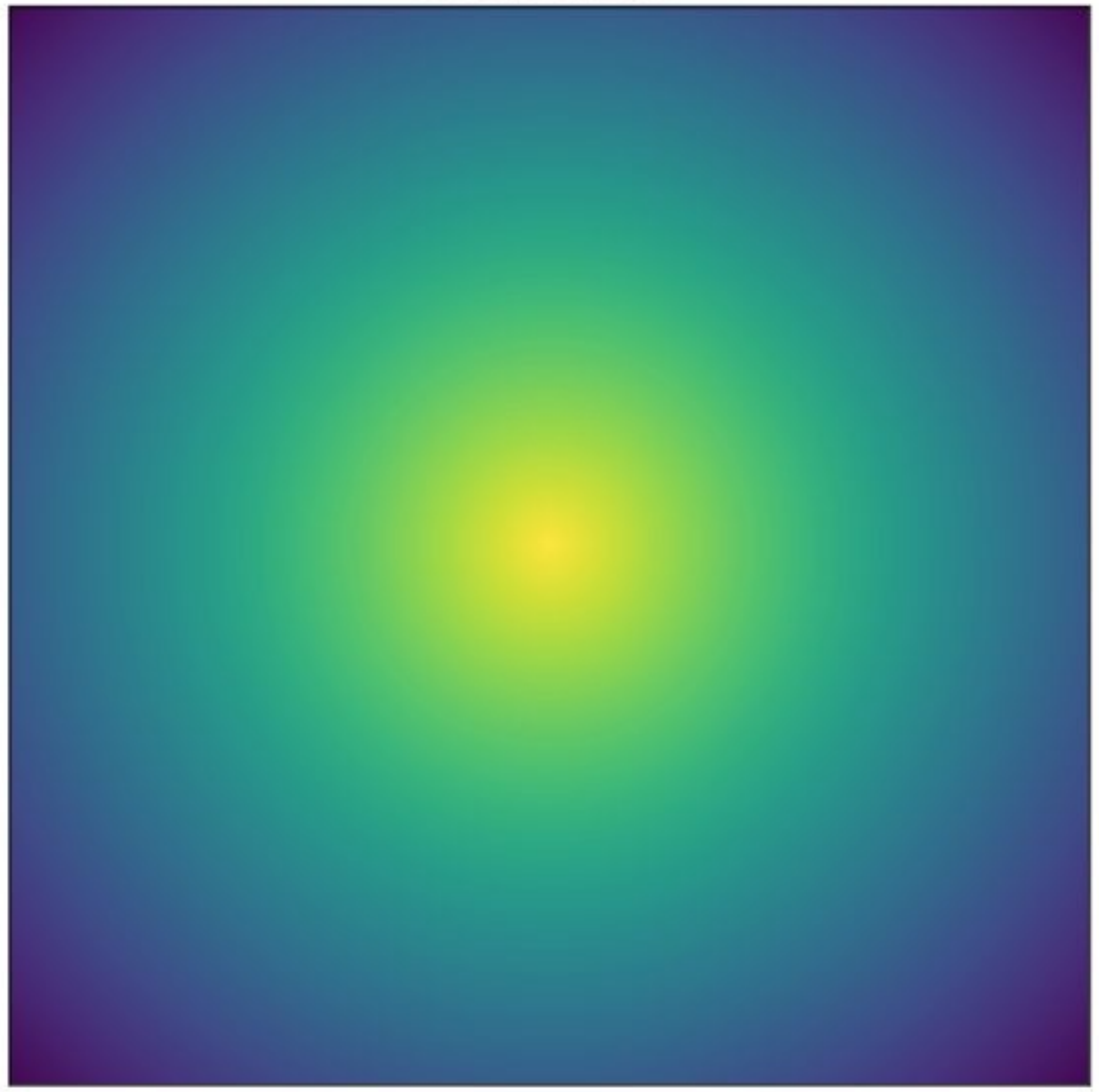


Which has a discontinuity?

[M. Bussonnier]

# Other Colormaps Work Better





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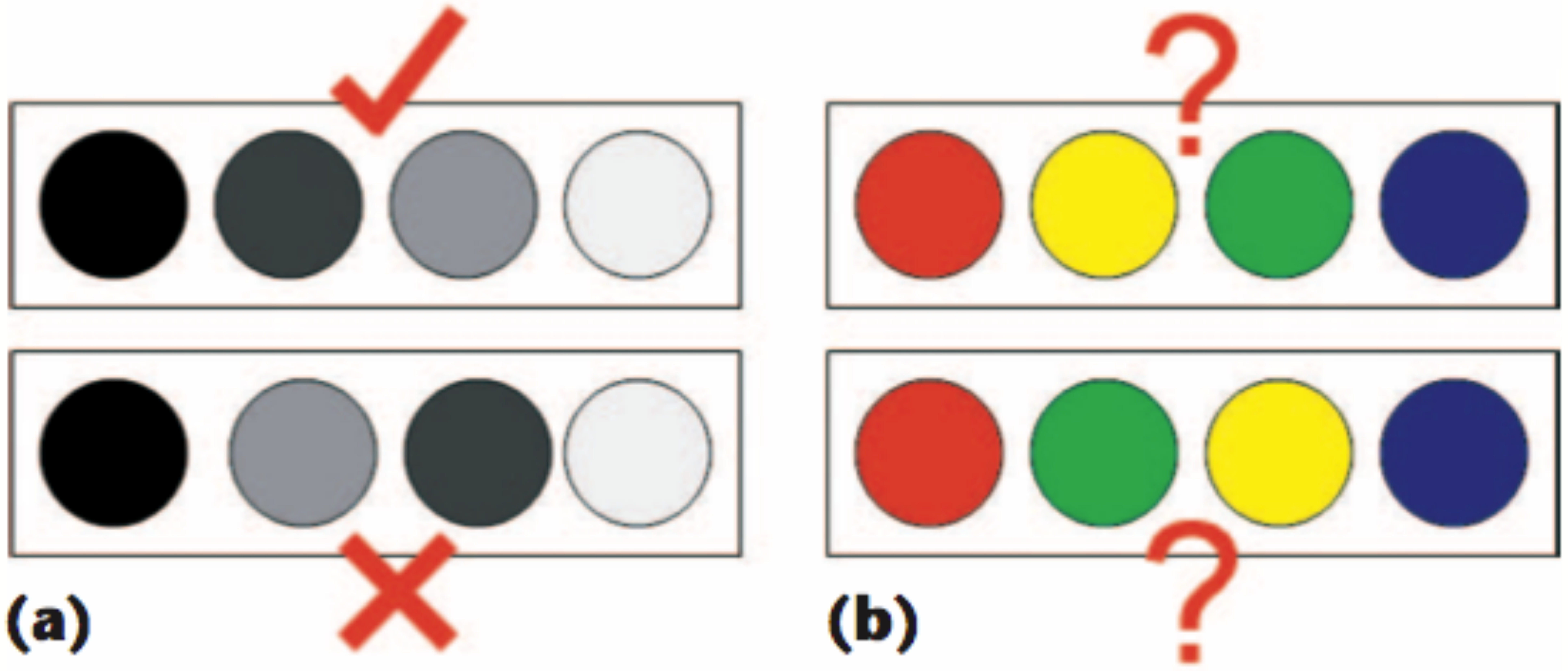
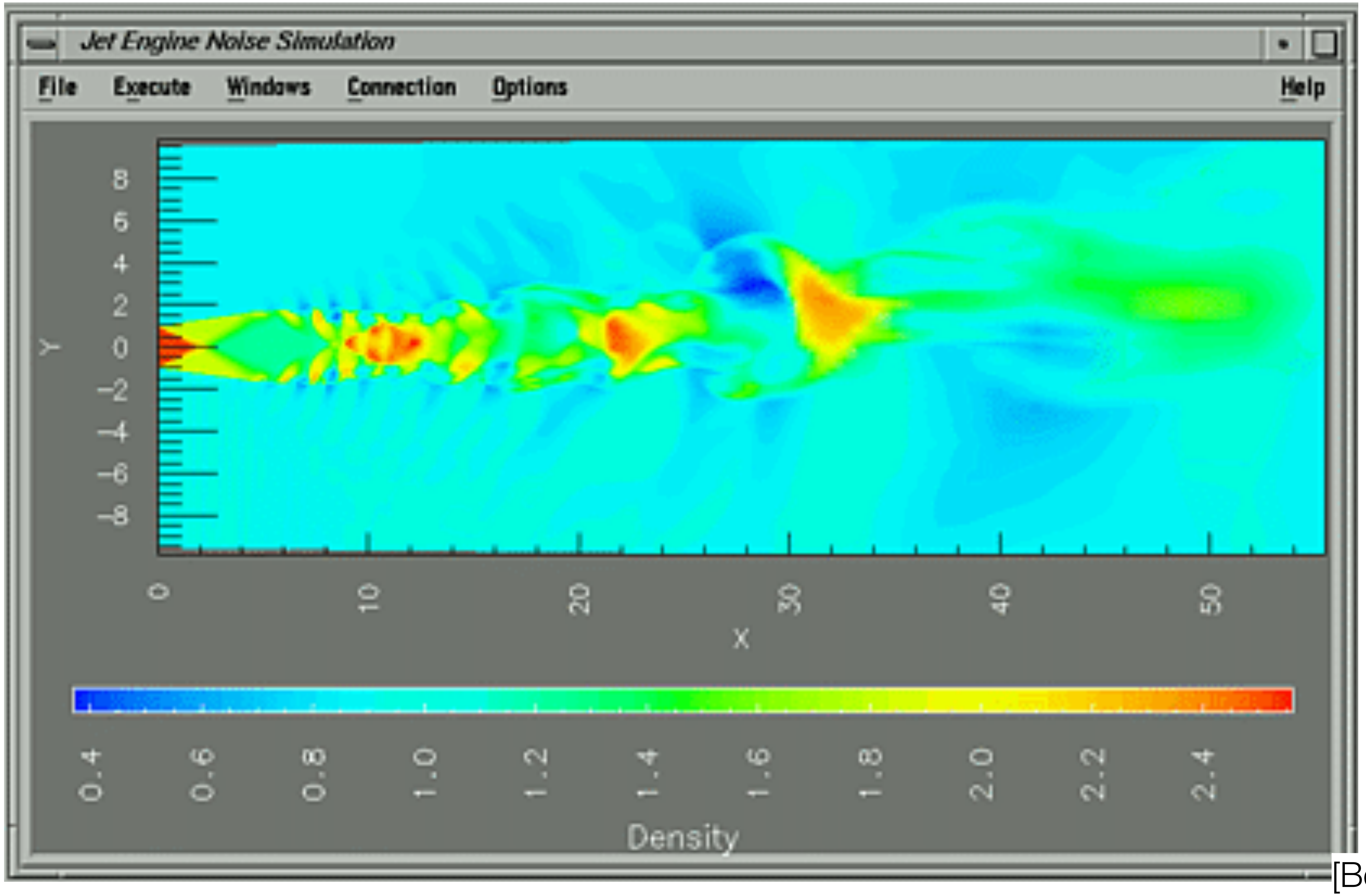
[M. Bussonnier]

# Ordering Color?



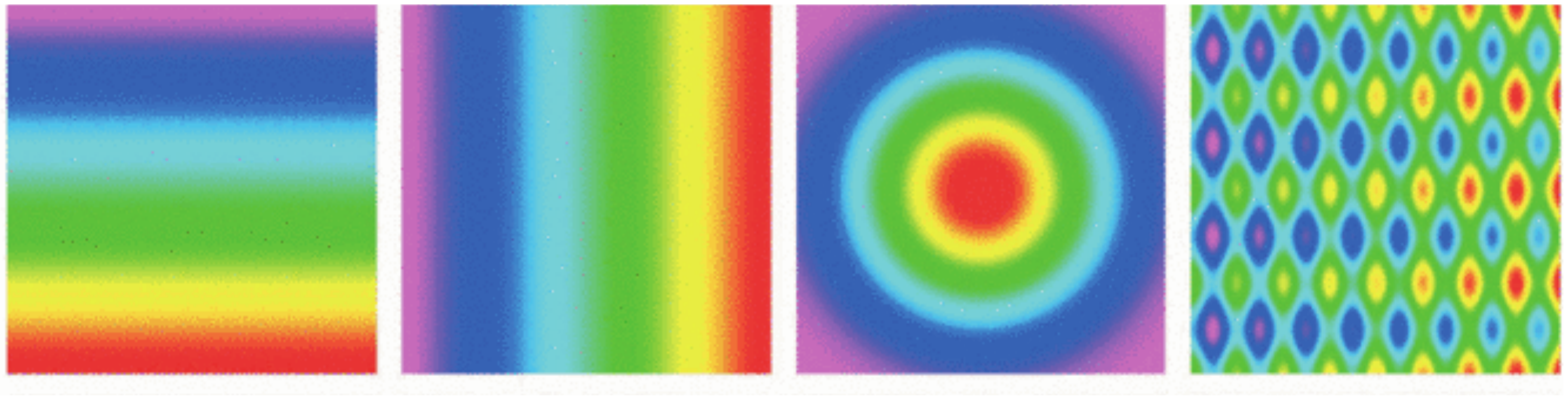

[Borland & Taylor, 2007]

# Rainbow Colormap




[Bergman et al., 1995]

# Artifacts from Rainbow Colormaps



[Borland & Taylor, 2007]

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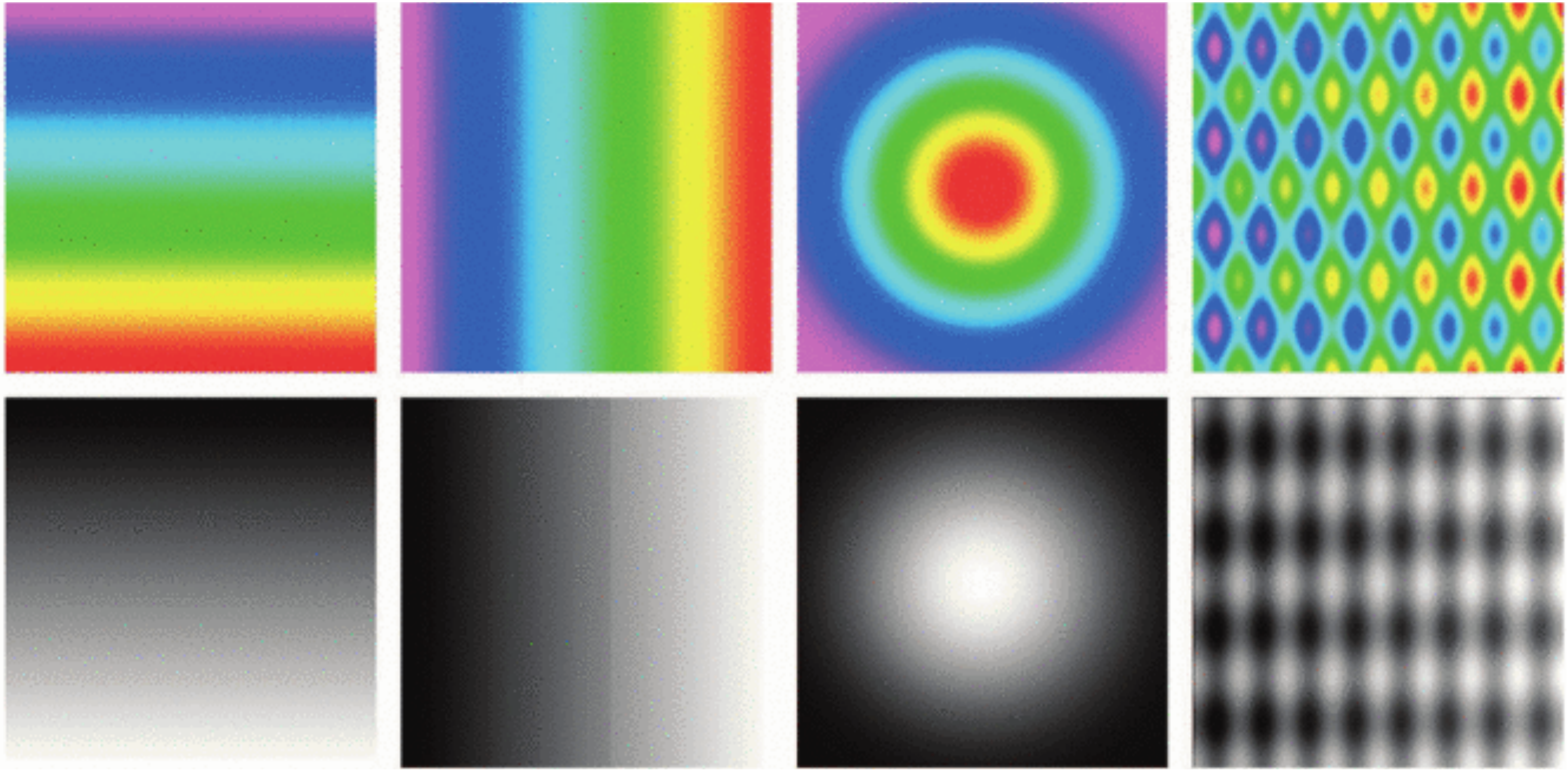
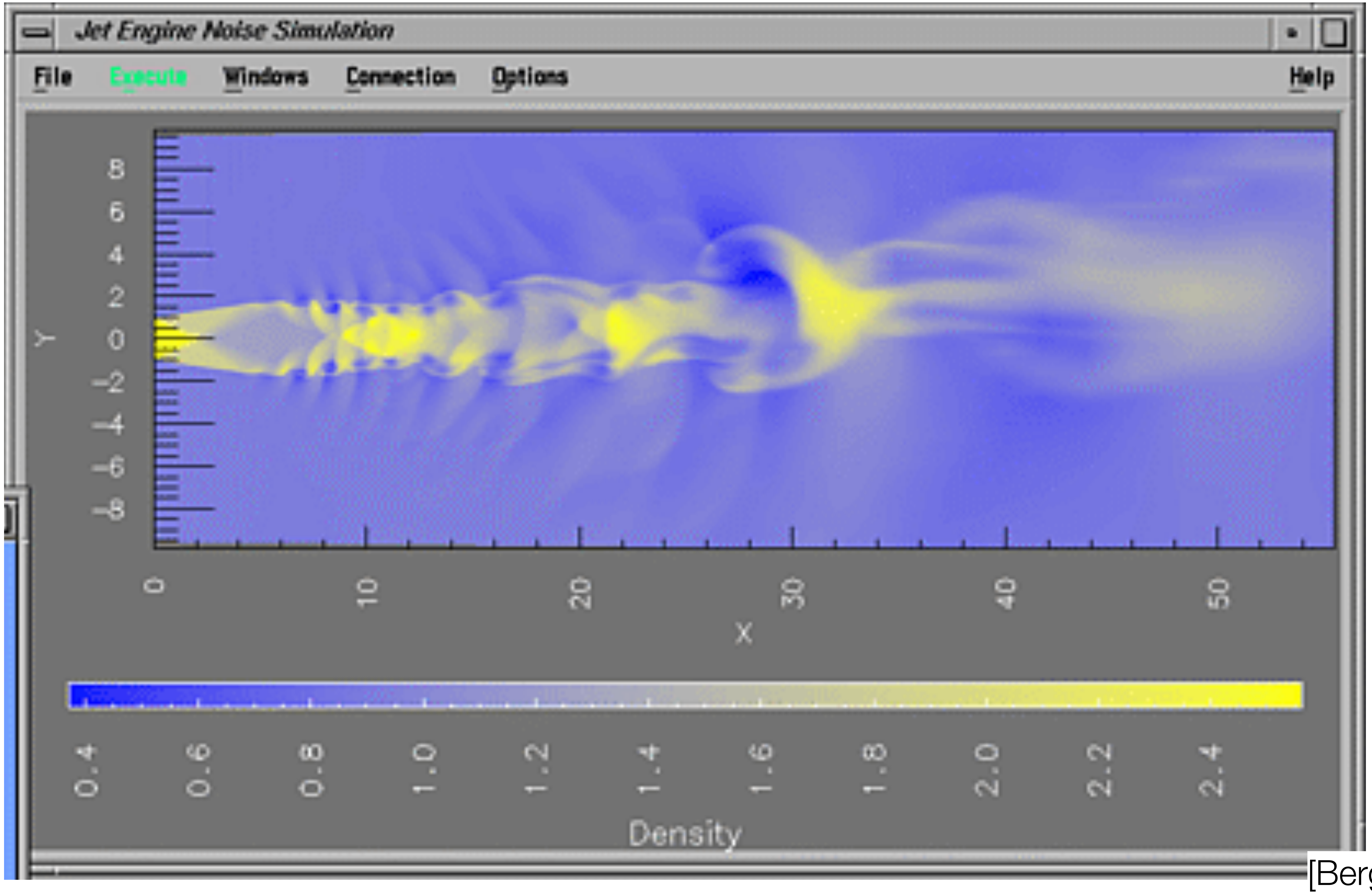


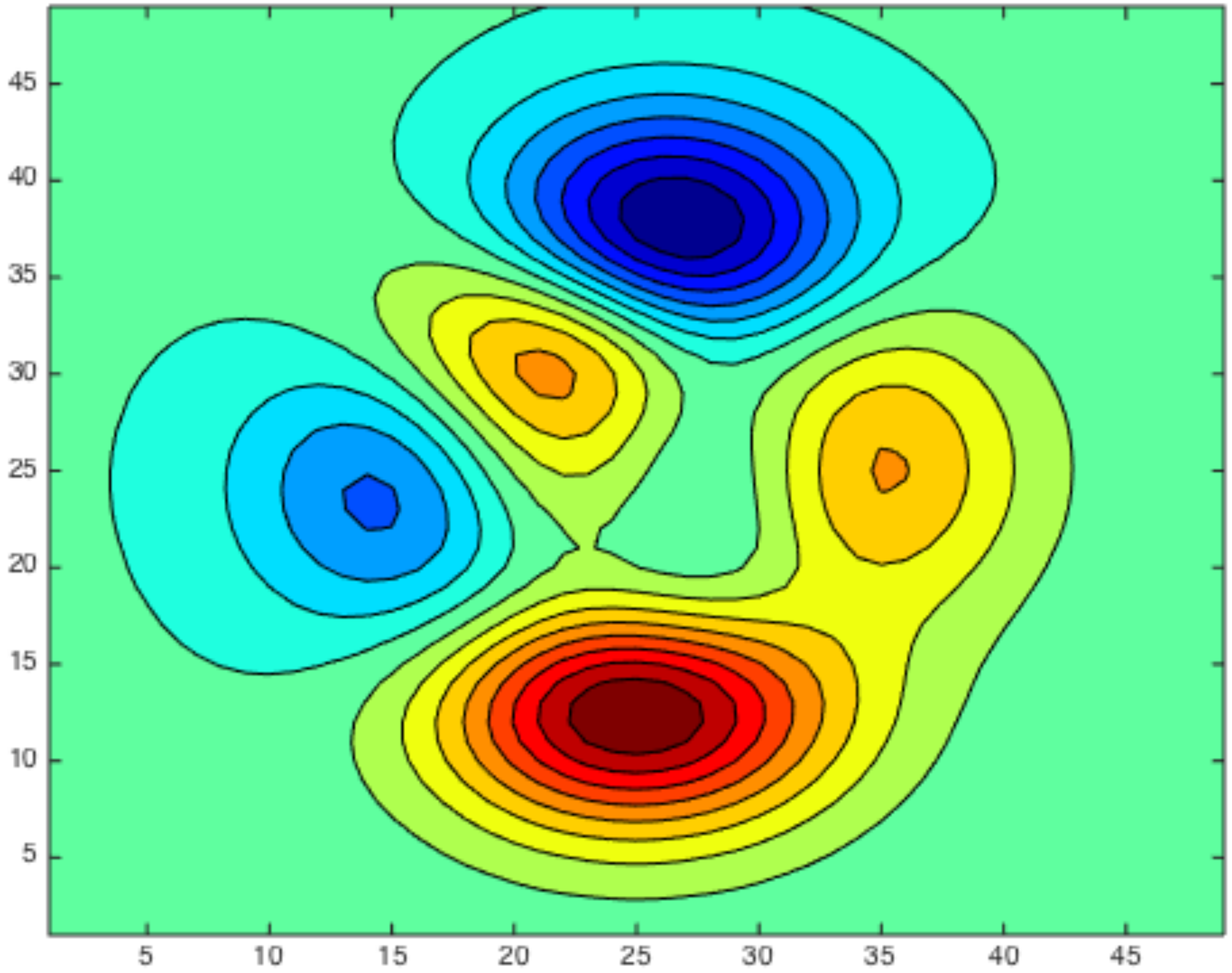
[Borland & Taylor, 2007]

# Two-Hue Colormap




[Bergman et al., 1995]

# "Get It Right in Black and White" - M. Stone




jet colormap

[S. Eddins (Matlab Blog), 2014]

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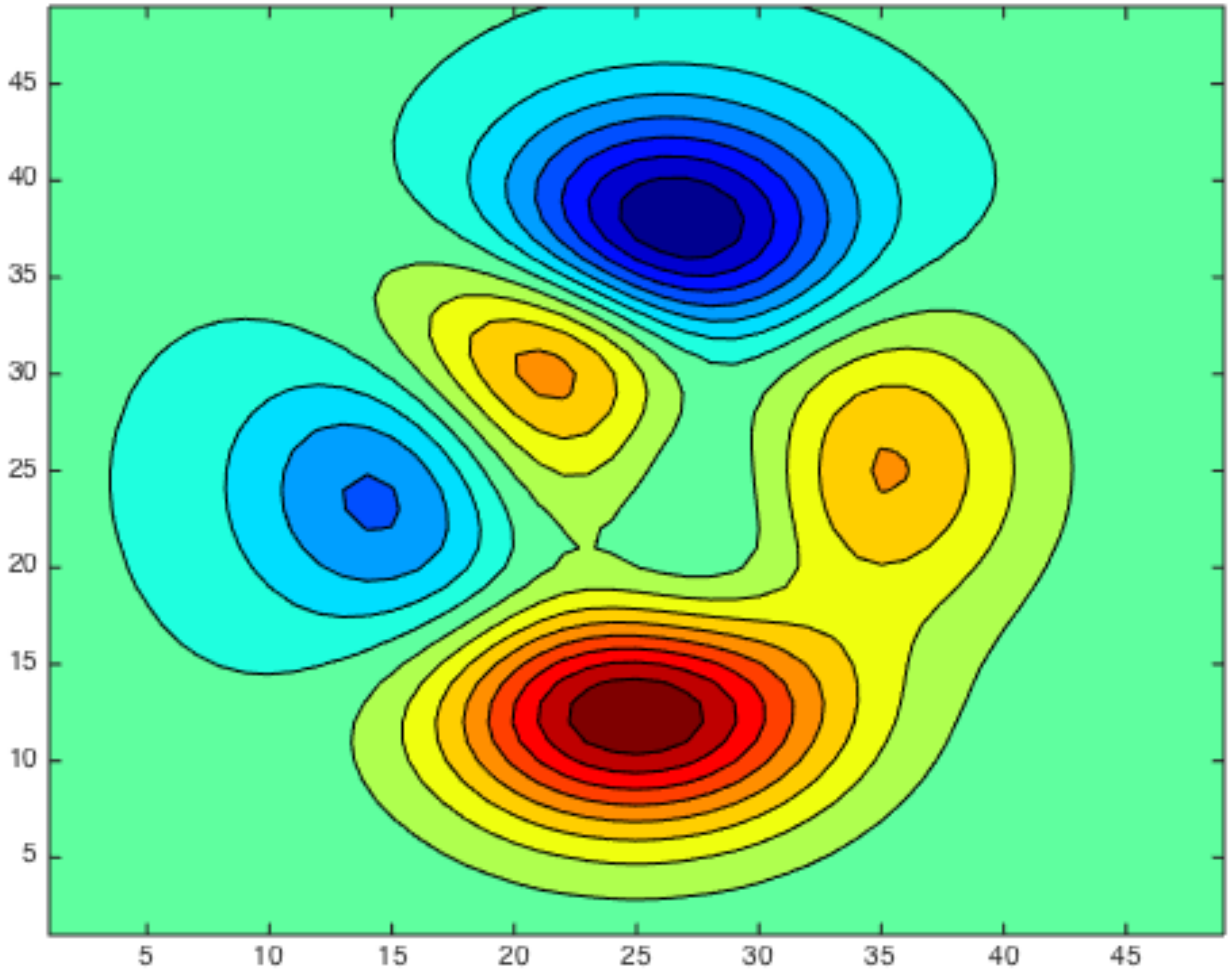


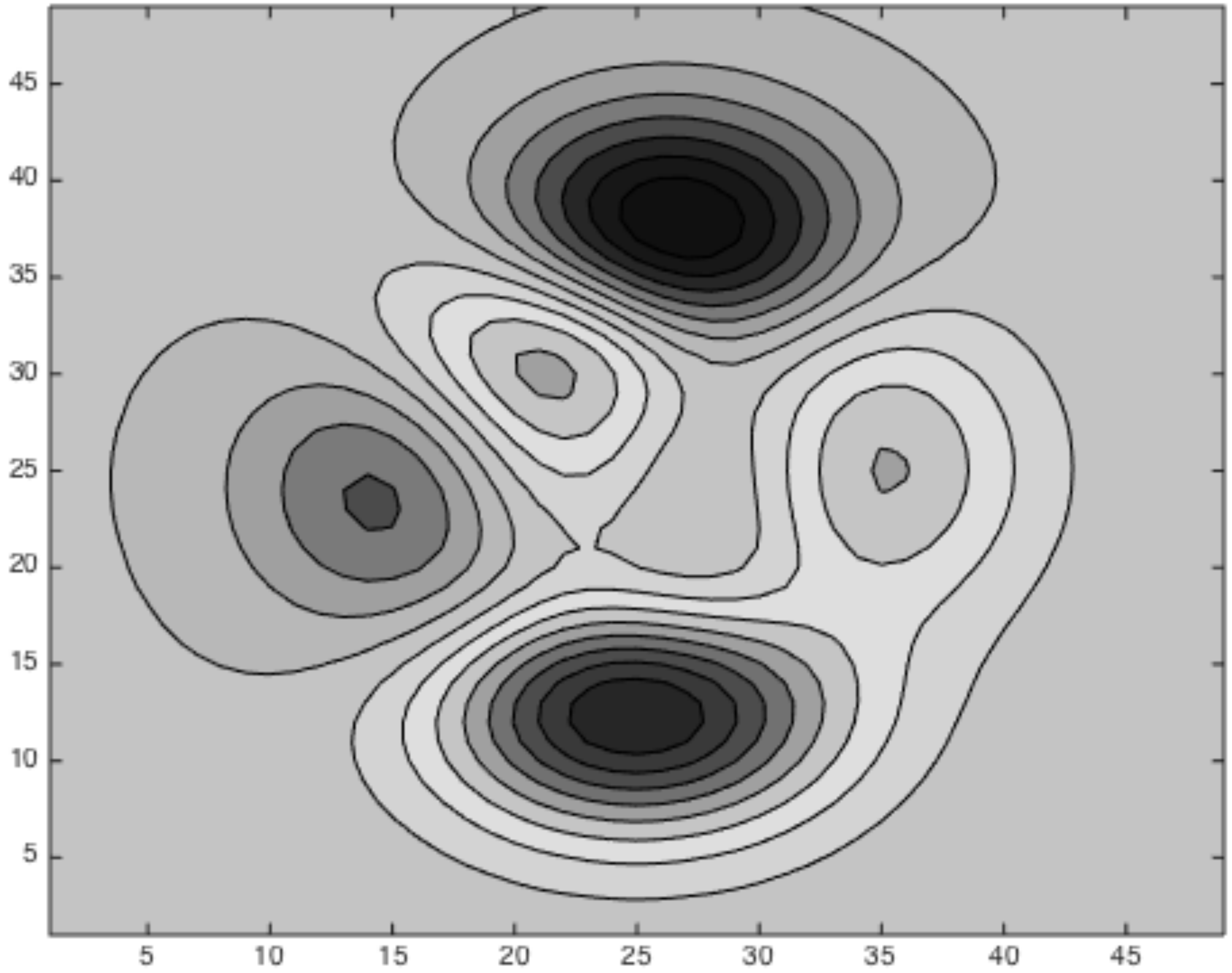


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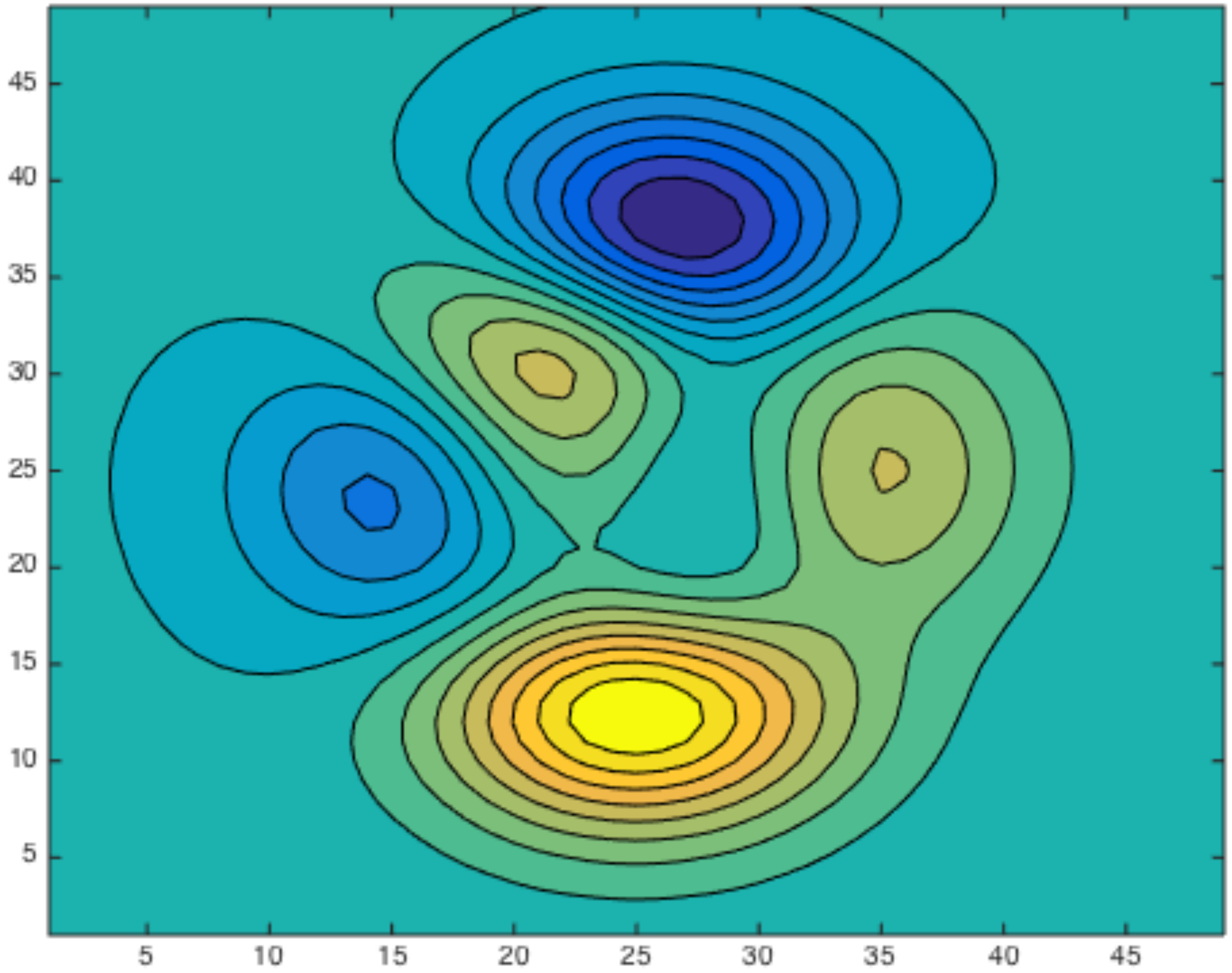
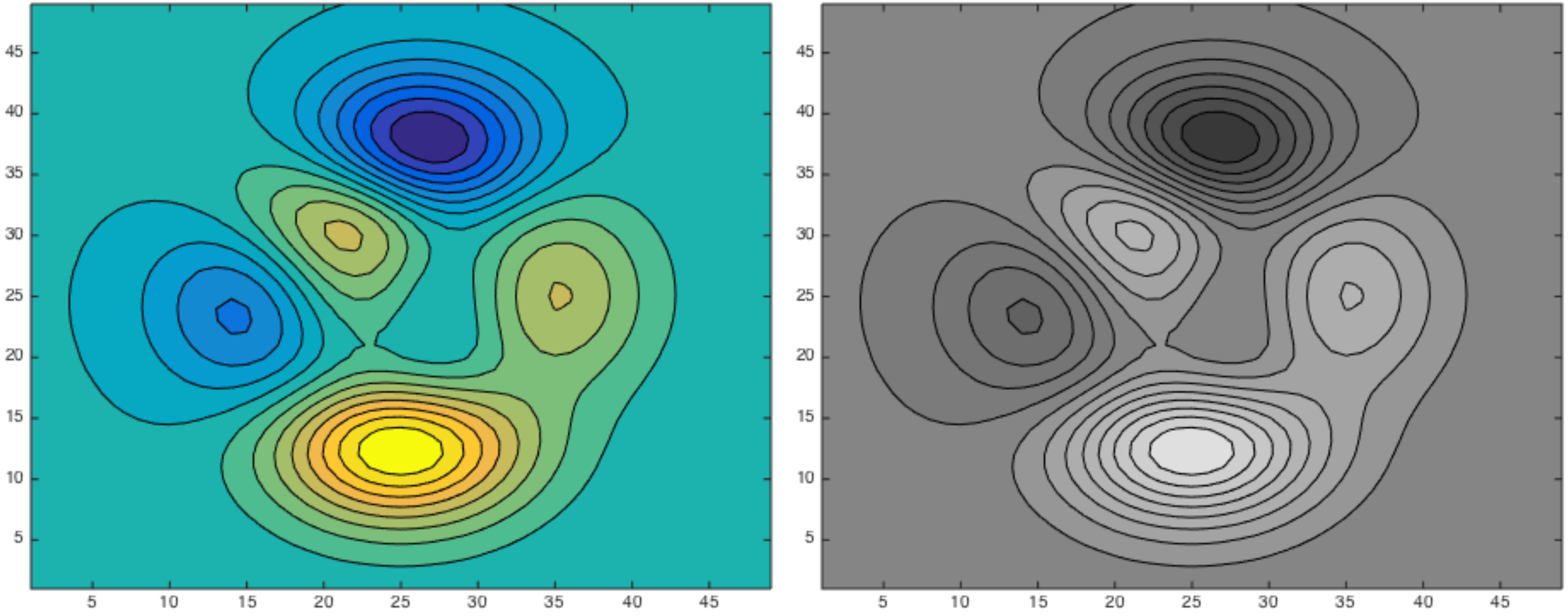



parula colormap

[S. Eddins (Matlab Blog), 2014]

# "Get It Right in Black and White" - M. Stone




parula colormap

[S. Eddins (Matlab Blog), 2014]

# Isoluminant Rainbow Colormap

Original

Isoluminant

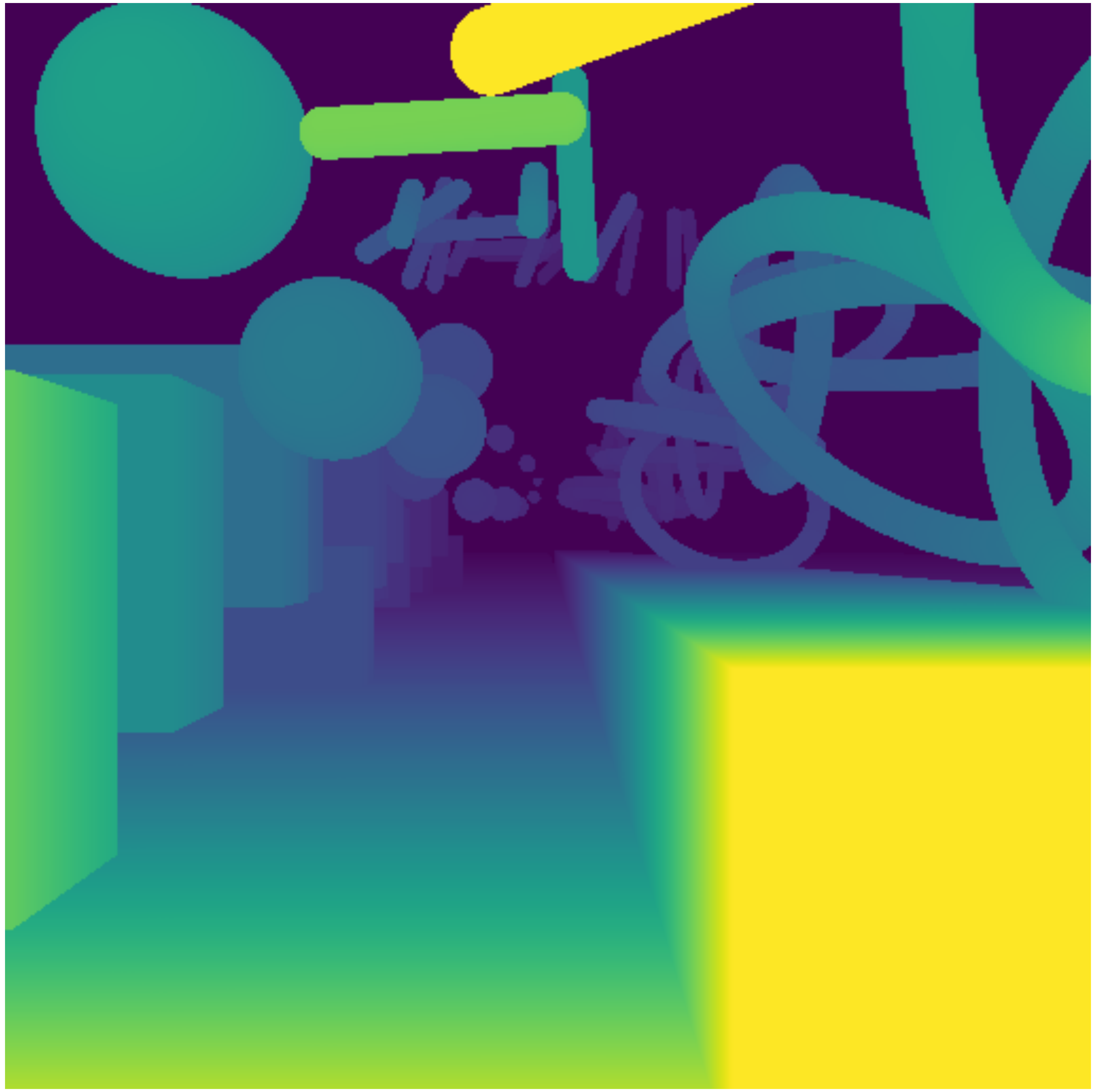
[Kindlmann et al., 2002]

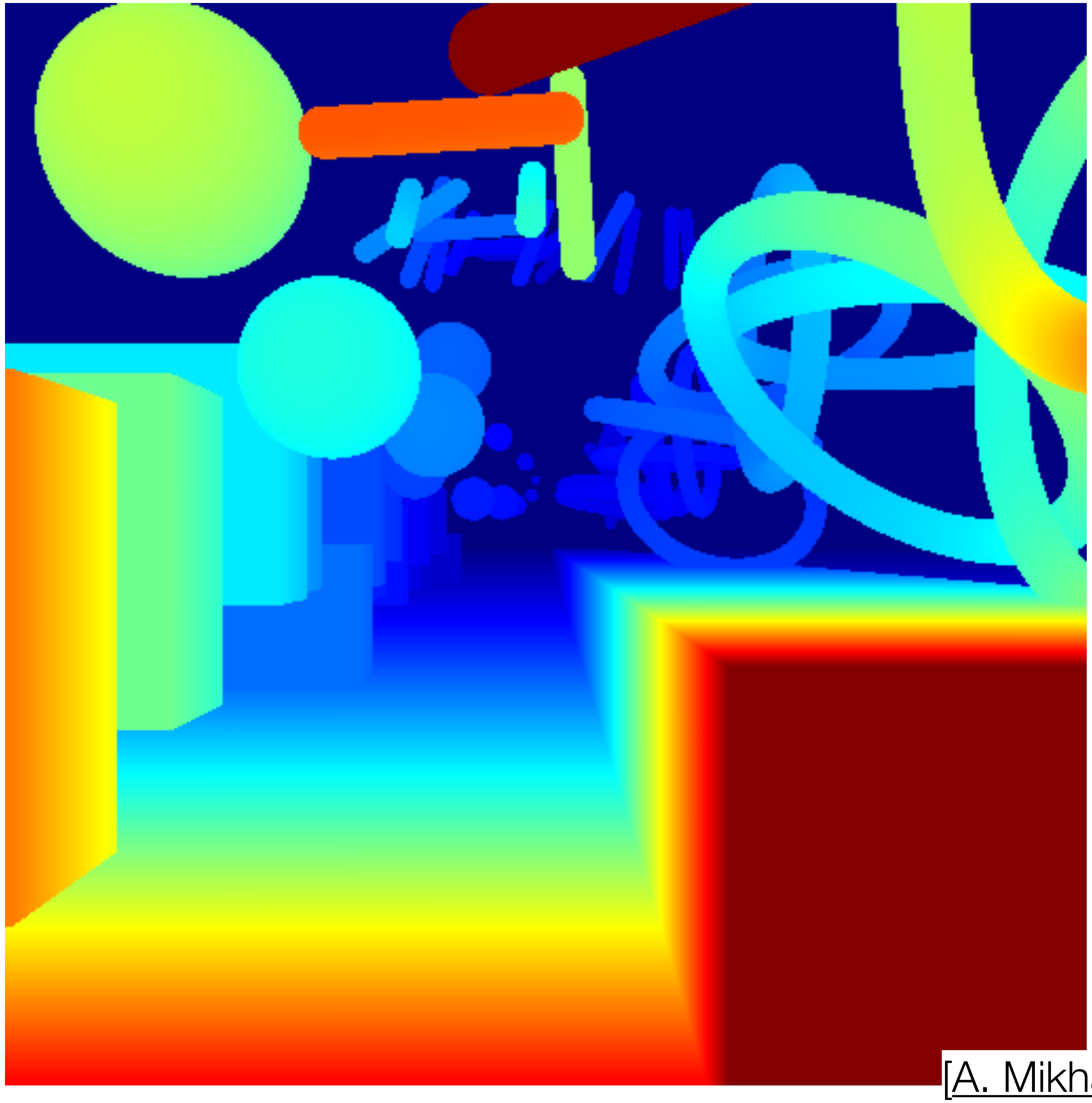
# Turbo Colormap (August 2019)

Jet

Turbo

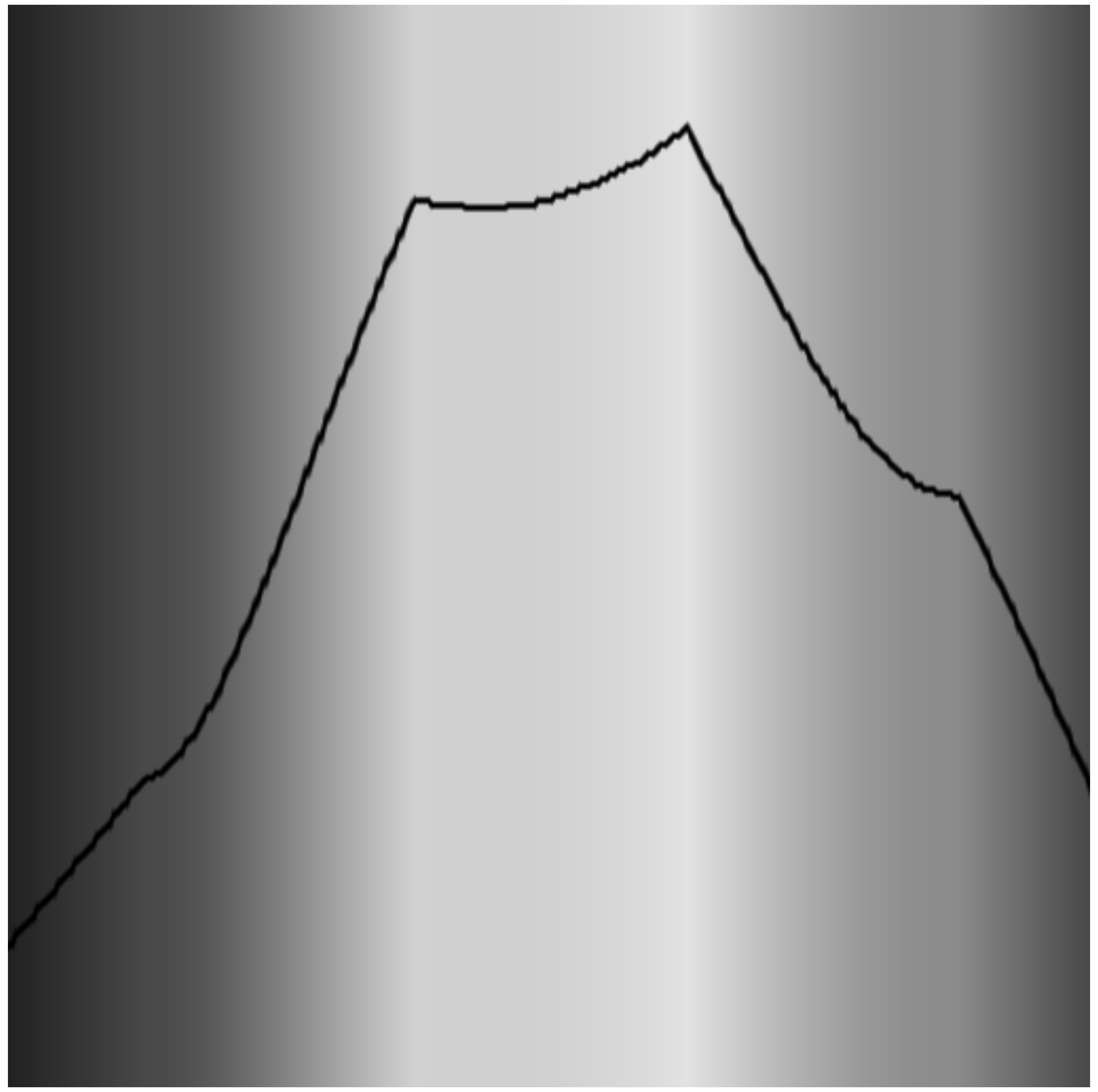
# Turbo: More Detail in Disparity Maps?



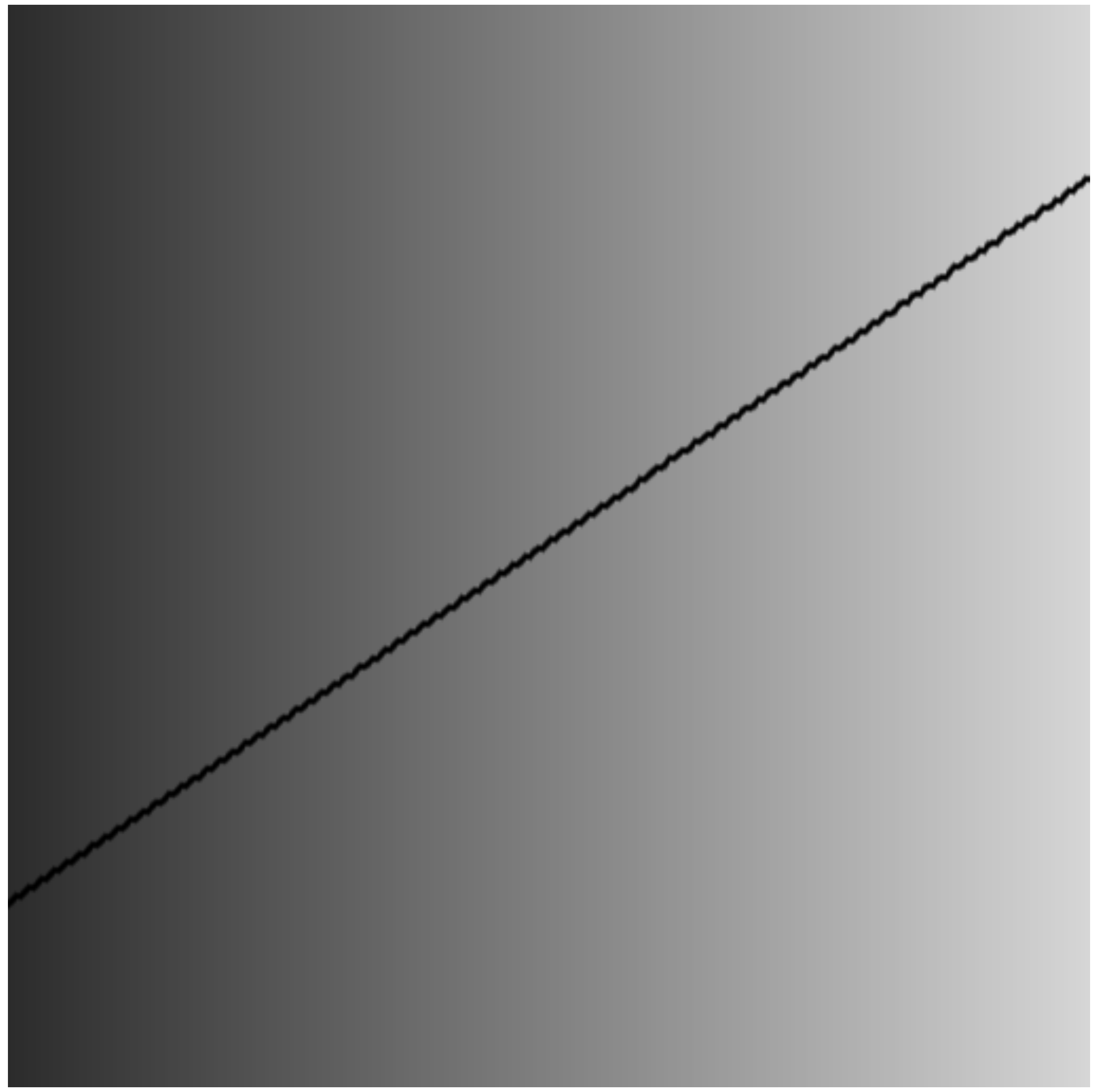


[A. Mikhailov]

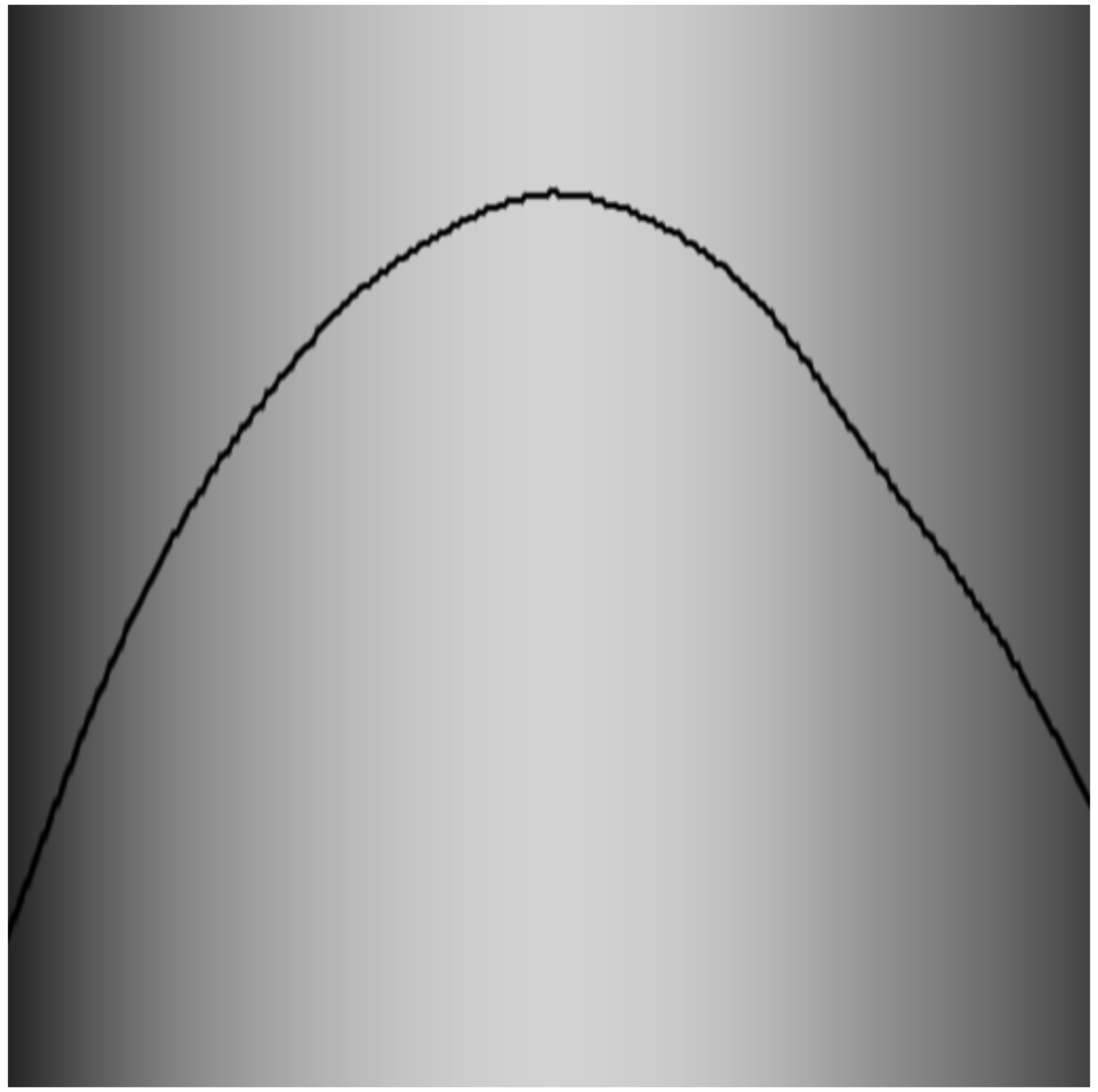
# Turbo: Lightness Profiles



Jet



Viridis



Turbo

[A. Mikhailov]

# Turbo Discussion

- Turbo is an improvement over jet
- Some fields (e.g. meteorology) have long used rainbow-like colormaps
- Argument is that segments are more easily located
- Turbo post claims that hue is prioritized in attention, but this seems to misinterpret the study…
- Brightness and saturation are more important than hue in attracting attention [Camgöz et al., 2004 h/t J. Stevens]