Development and implementation of perceptually uniform colormaps

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This presentation available at

http://www.ppenteado.net/idl/penteado_visualize2010.pdf

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Outline

The problem
 Why perceptually uniform maps need to be developed

Human color vision
 Light detection
 Color coding at the eye
 Color perception
 Human color space
 Spatial effects

Limitations of standard colormaps
 Why rainbows are bad
 Limitations of other common maps

Development of uniform colormaps
 Standard color maps in different color spaces

Defintion of maps from CIE Lab space
 Fully uniform maps
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Examples

Summary

The problem

Displaying a 2D array as 1-channel images is one of the most common visualization tasks.

It is one of the most basic facilities provided by any data analysis environment.

This requires choosing a colormap, that goes from the 1D range of data values, to some trajectory in the 3D display colorspace (the RGB cube, with 256^3 uniformly distributed points).

IDL comes with 41 8-bit (256 levels) maps:

```
        B-W LINEAR            BLUE/WHITE       GRN-RED-BLU-WHT        RED TEMPERATURE BLUE/GREEN/RED/YELLOW
      STD GAMMA-II                PRISM           RED-PURPLE     GREEN/WHITE LINEAR    GRN/WHT EXPONENTIAL
        GREEN-PINK             BLUE-RED             16 LEVEL               RAINBOW                  STEPS
     STERN SPECIAL                 Haze    Blue - Pastel - Red              Pastels    Hue Sat Lightness 1
 Hue Sat Lightness 2    Hue Sat Value 1     Hue Sat Value 2     Purple-Red + Stripes                Beach
         Mac Style                Eos A                Eos B             Hardcandy                 Nature
             Ocean            Peppermint               Plasma             Blue-Red                Rainbow
        Blue Waves              Volcano                Waves             Rainbow18        Rainbow + white
     Rainbow + black
```

Why not just pick any one of those?

The standard colormaps (in IDL or anything else) are simple curves through a device space (RGB, CMYK) or a simple abstraction (HLS, HSV).

They do not take into consideration the shape of the human color space, and several spatial effects that alter perceived color.
    Create artifacts, supressing some data structures, and creating false ones.
They are limited to 256 values
    Remnant from the days of 8-bit colormapped displays.
    Low dynamic range saturates the ends of the range, or supresses small variations.

Human color vision - Light detection

The retina has 4 different kinds of light-sensitive cells:
- 1 type of rod cell
    - Single type of pigment
    - High sensitivity
    - Concentrated on the periphery of the retina
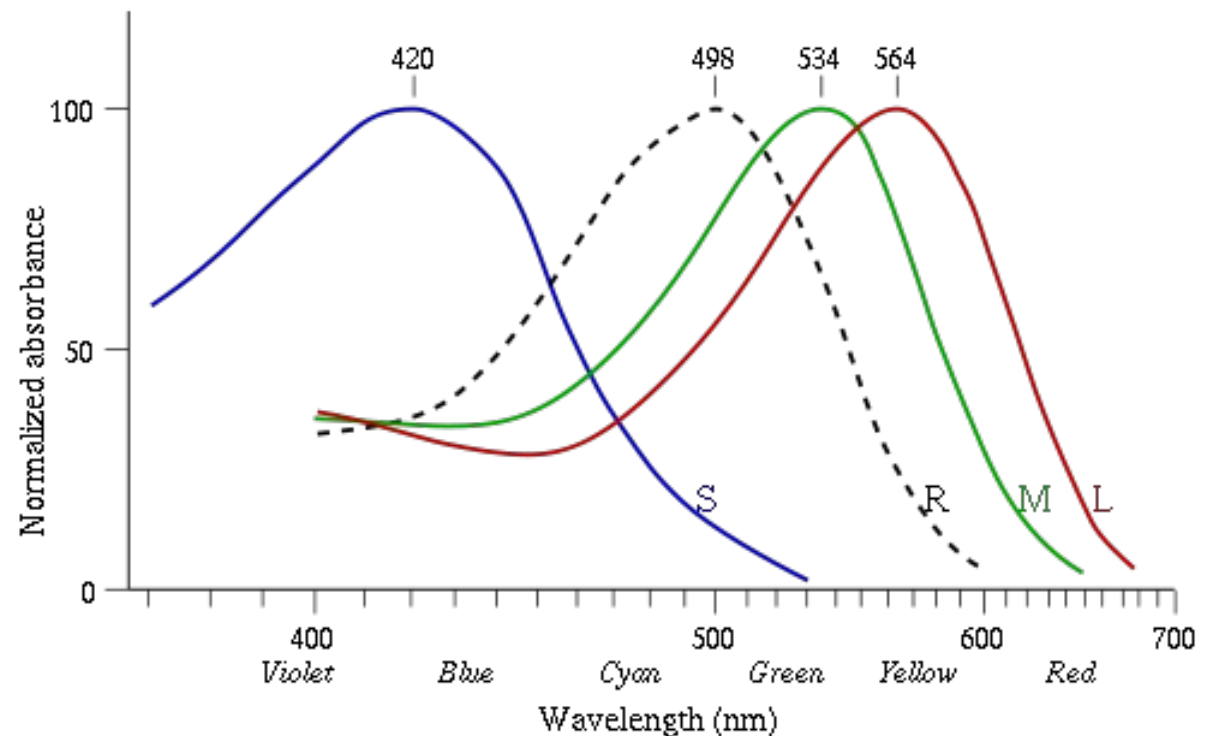- 3 types of cone cells
    - Differ in the pigment (L, M, S)
    - Concentrated on the fovea (hi-res center of the field of view).

Rods are more poorly studied and not relevant at high light levels and high resolution.
The cones have different, broad and overlapping spectral responses.
Cones are L,M,S (for Long, Medium, Short wavelength) – They are **not** R,G,B

Human color vision - Color coding at the eye

The brain does not get a camera-like signal of the intensities of the 3 colors at each location.

The first transformations happen at the retinal neurons:

  They change the color from L,M,S space to 3 color-opponent channels
    "Luminance" - from black to white
    Two chromaticity channels:
      Blue-yellow
      Red-green
Channels get encoded differently, all resulting from the combination of the signals from several cone cells.
  Similar to different wavelet transforms for each channel.
  Luminance is sensitive to high spatial frequencies.
  Chromaticity is sensitive to low spatial frequencies.

To brain

Cones, rods

Light
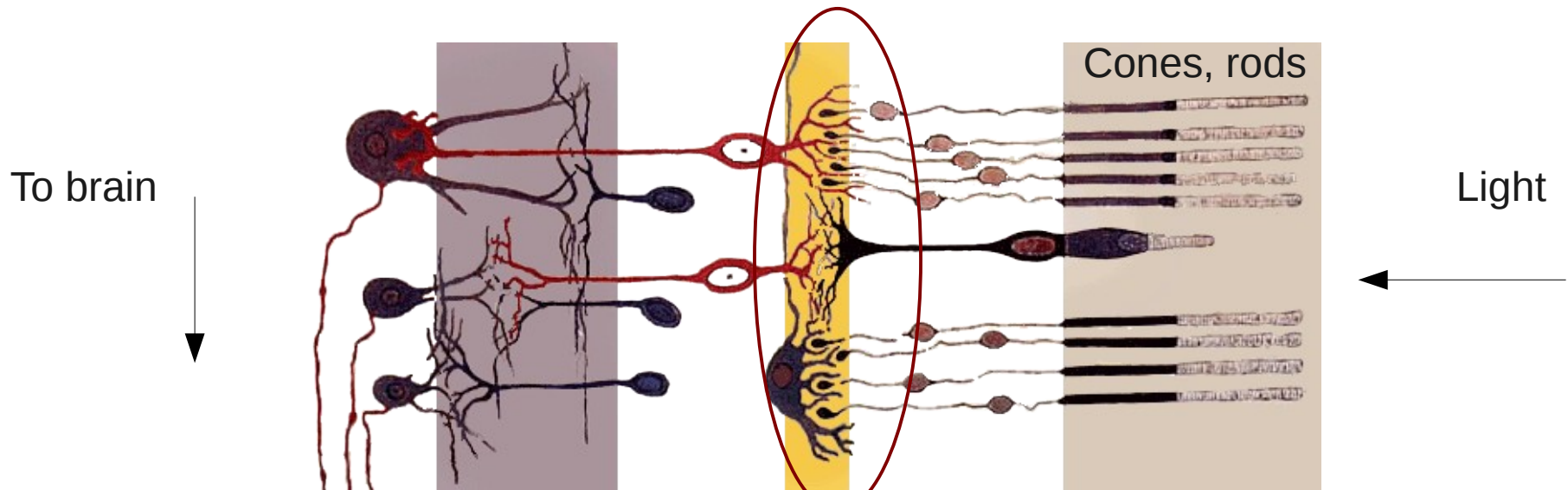
Human color vision - Color perception

Black/white, blue/yellow, red/green are the opponent colors of our perception:
There is reddish yellow (orange), but no reddish green, and no bluish yellow.

We can also naturally think of chromaticities in terms of hue and saturation.

Hues are perceived as cyclical, so the two chromaticity channels are naturally the x/y axes of a plane where the hue is the angle around the (achromatic) origin, and saturation is the distance from the origin.

This may remind of HLS and HSV spaces, but they are **not** the same:

HLS and HSV use combinations of R,G,B, which lead to a different hue distribution:
Red is 180° from cyan, not green

HLS and HSV are regular, our perceptual colorspace is not.
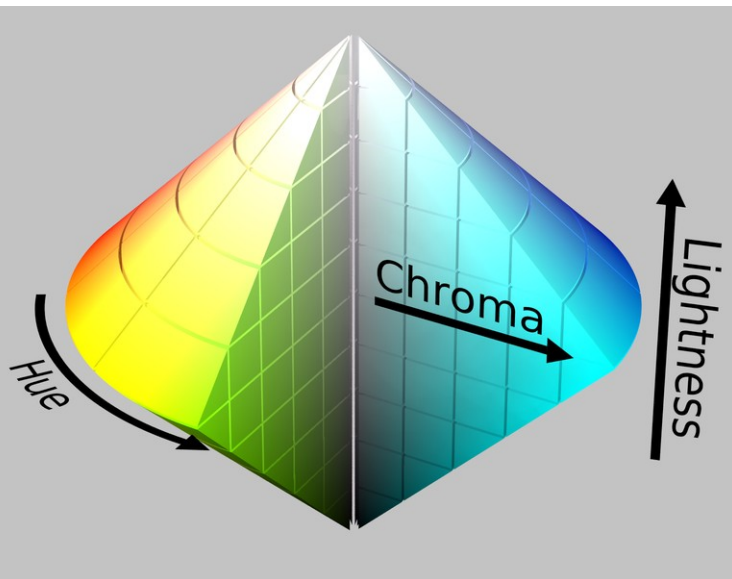
HLS

HSV
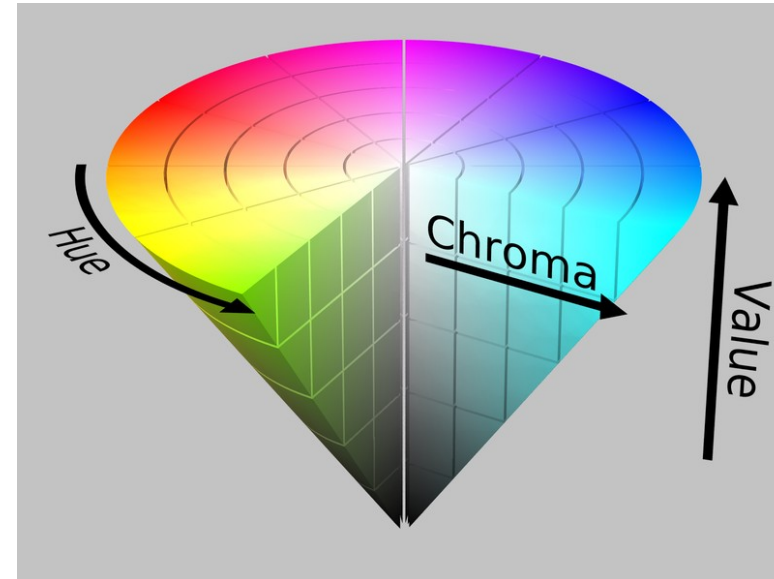
Human color vision - Human color space

Munsell (~1900) : first perceptually uniform color catalog

   Discrete color chips mapped into regular distances in its 3 independent dimensions: perceived hue, value and chroma

   Map showed that the human gamut is not regular (it is not curves of constant H/V/C)

   The Munsell Book of Color became the standard for color specification in industry and science.

   Founded the Munsell Color Company (now X-Rite), the Munsell Color Science Laboratory (at RIT), and the Munsell Foundation.
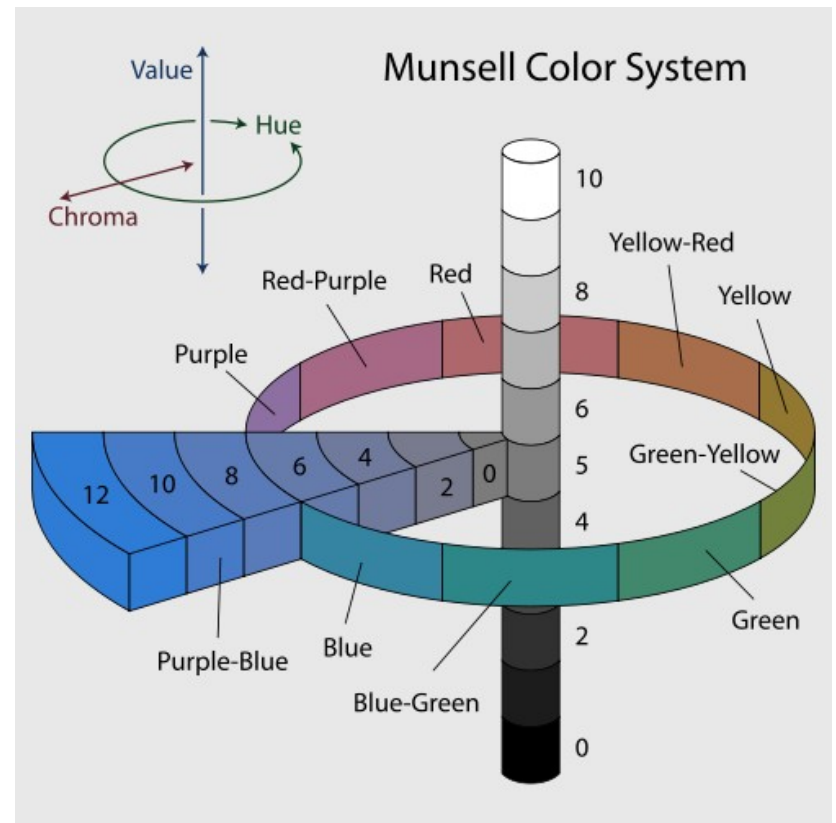
Human color vision - Munsell color space
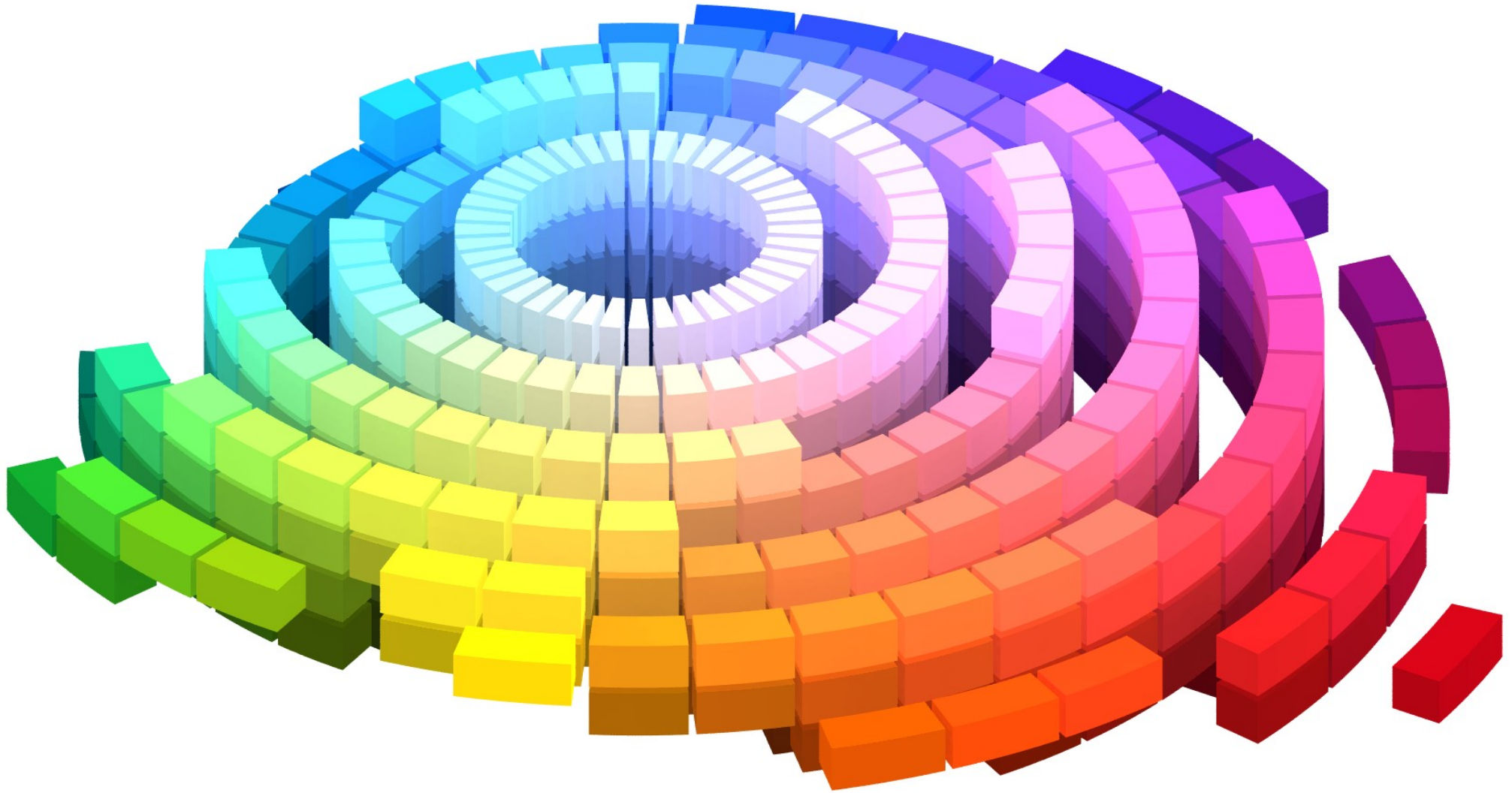
Human color vision

CIE (Commission Internationale de l'Eclairage – International Commission on Illumination) work

The Munsell space is empirically defined through physical samples

The CIE has established many commissions to review the current research and arrive at quantitative measurements and mathematical definitions for human perception:

CIE 1931 color space (define the CIE 1931 standard observer)

   Result from color matching experiments, that measured the cone spectral sensitivities.

   Based on the X,Y,Z tristimulus - the integrals of the 3 color matching functions over the spectrum of a light source.

   Quickly became the standard for measurements in research and applications, even after the advent of the CIE 1964 standard observer.

Human color vision

CIE 1931 xy chromaticity diagram with the RGB primaries and monochormatic wavelengths
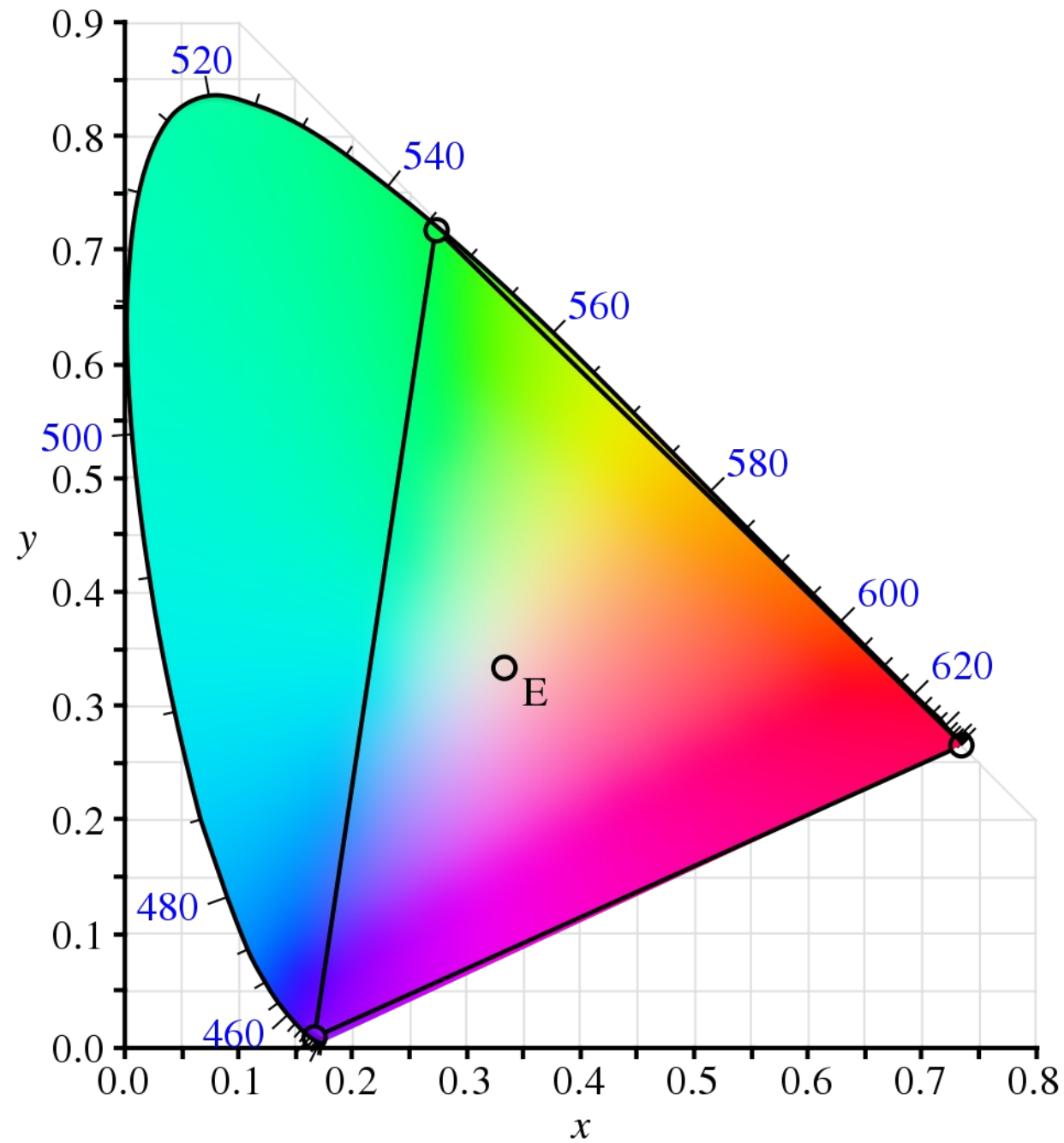
Human color vision

The CIE XYZ space is photometric, to predict color matching, it does not predict perceived color distances.

CIE 1976 Lab and Luv spaces:

Reviewed the research on perceived color differences to define and recommend perceptually uniform colors spaces.
Color opponent space, conceptually similar to Munsell space.
One dimension for Luminance, and one orthogonal pair for chromaticity (a/b, or u/v).
Cartesian distances in these spaces should correspond to perceived color distances.
CIE could not decide between the relatively similar Lab and Luv.

Lab has been more commonly adopted, and has been refined from further research (Bradford correction).

Lab has been the base for most research on other color appearance phenomena.

Human color vision - Human gamut in CIE Lab

L=60

L* b*

a*

L=40

L* b*

a*

L=20

L* b*

a*

a,b axes to +/- 200

Hoffman,
http://www.fho-emden.de/~hoffmann/cielab03022003.pdf
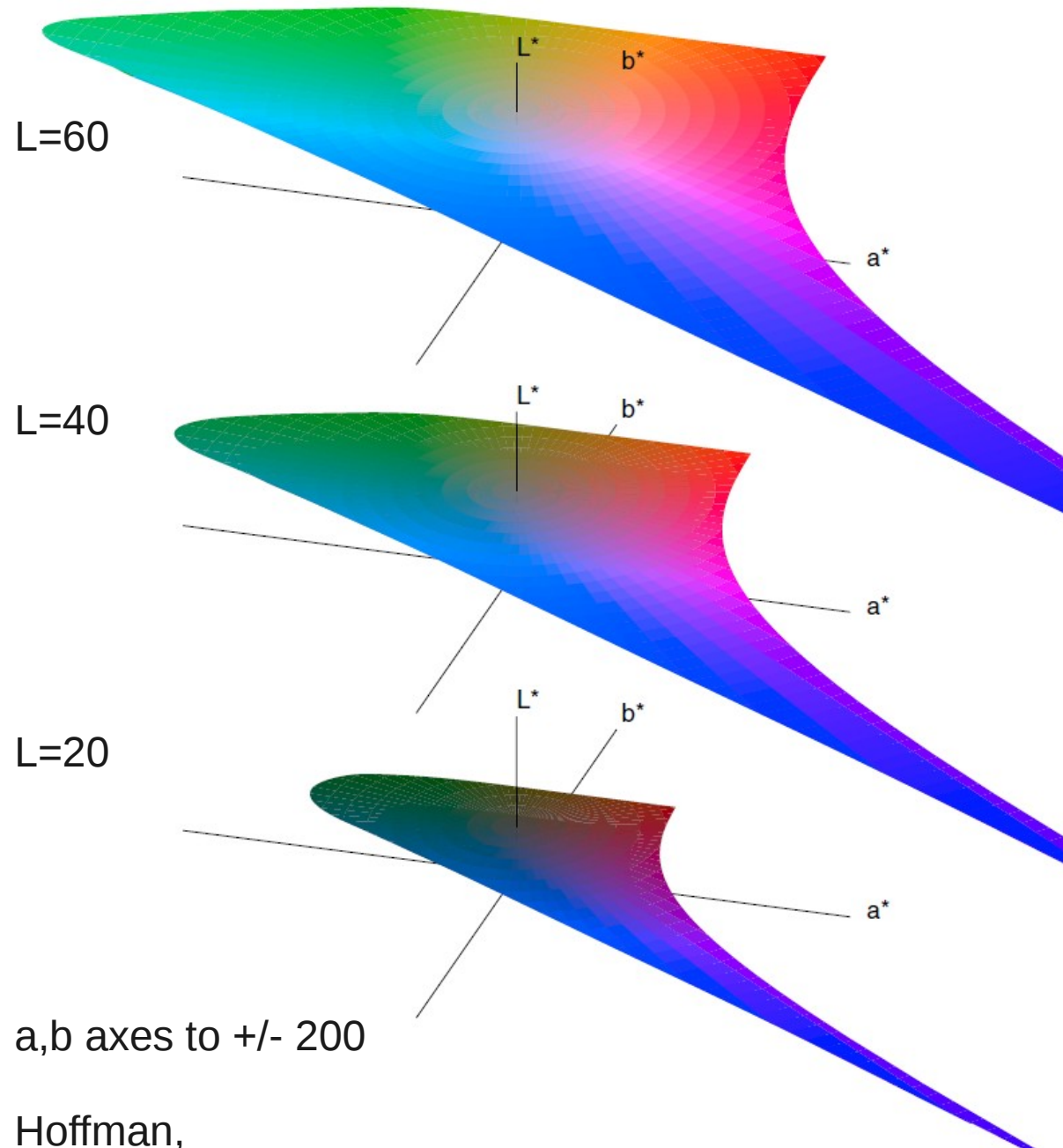
Human color vision - sRGB gamut in CIE Lab
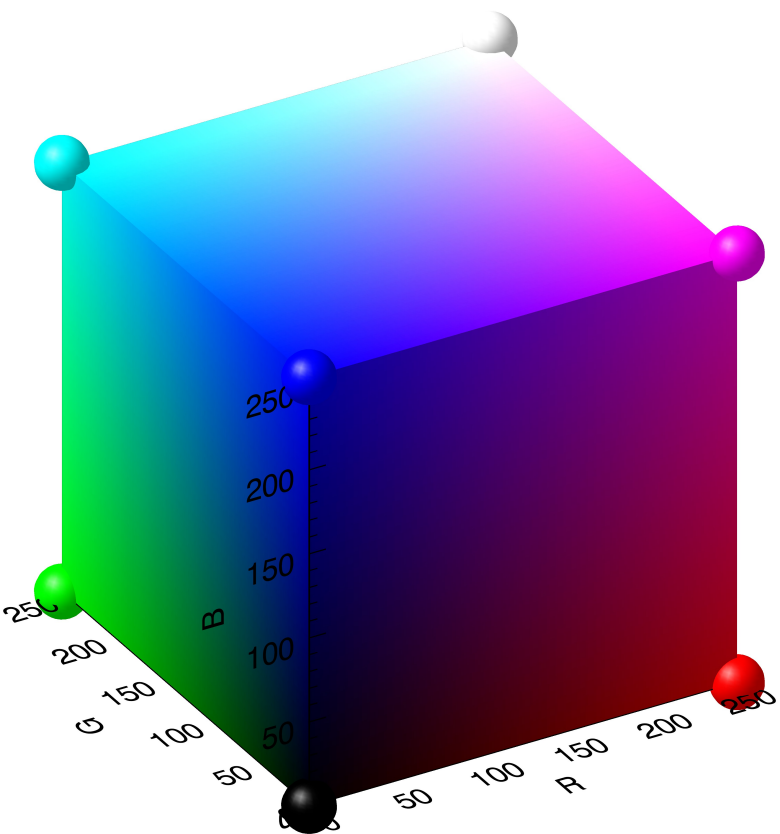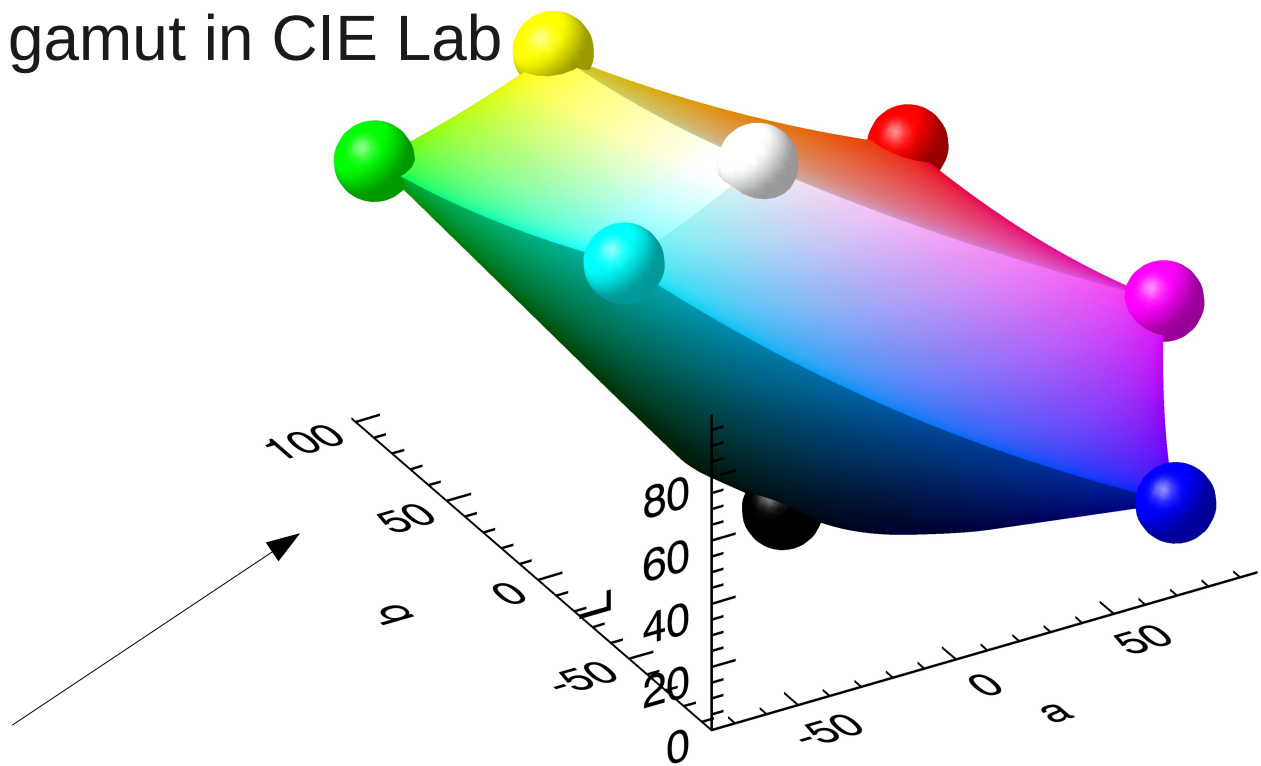
Transformed to Lab space

RGB cube
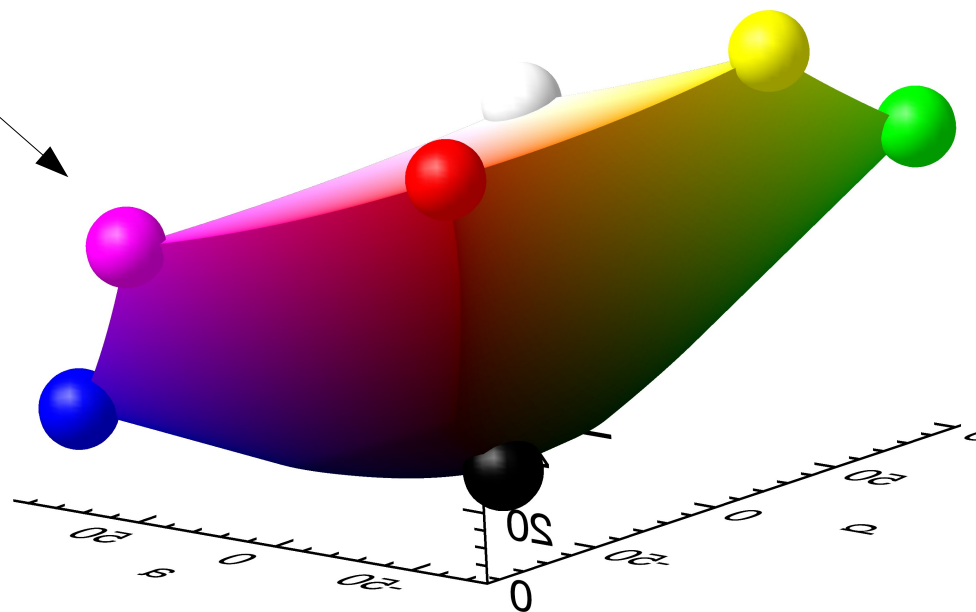
Human color vision - Spatial effects

Color spaces are not everything:

Only predict color matching, gamut and perceptual distance, on controlled observing conditions.

Spatial and temporal effects change perceived color:

Illumination of the surrounding field
State of chromatic adaptation
Color being perceived as object or illuminant
Spatial effects

Only Color-Appearance Models (CAM) account for those.

Different models vary widely in the range of modeled phenomena and applicable conditions. The most complete are so complex that have been rarely used.

The only relatively standard model is the CIECAM02 (2002, derived from CIECAM 97s).

Given (a large amount of) information on the stimulus and the viewing conditions, predicts how it will be perceived.

Can be used to correct for the modeled phenomena, to obtain an image that will be perceived as inteded.

Human color vision

Spatial effects examples
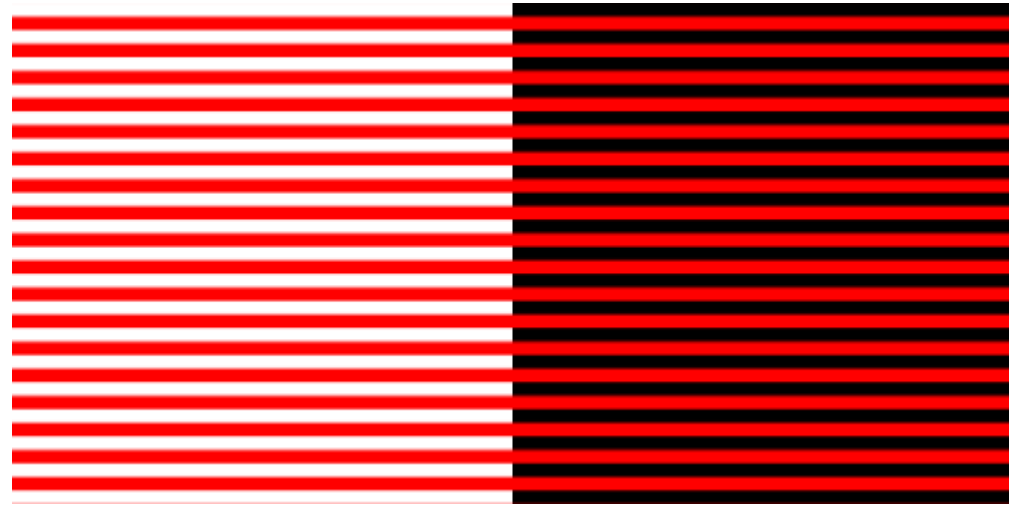
The red lines are of constant color
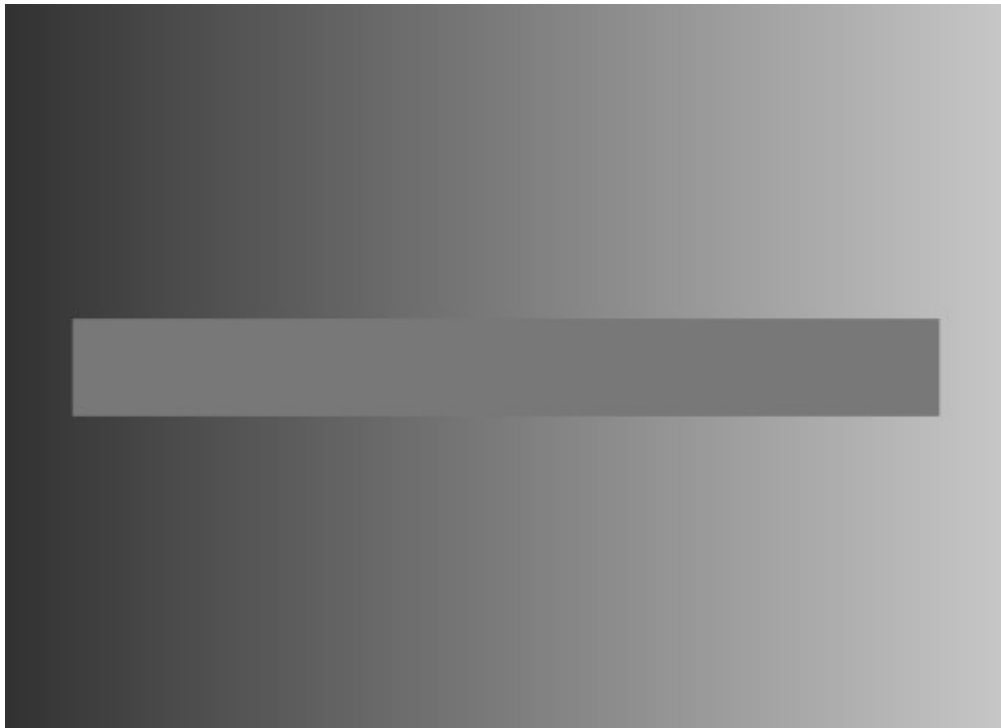
The bar is of constant color
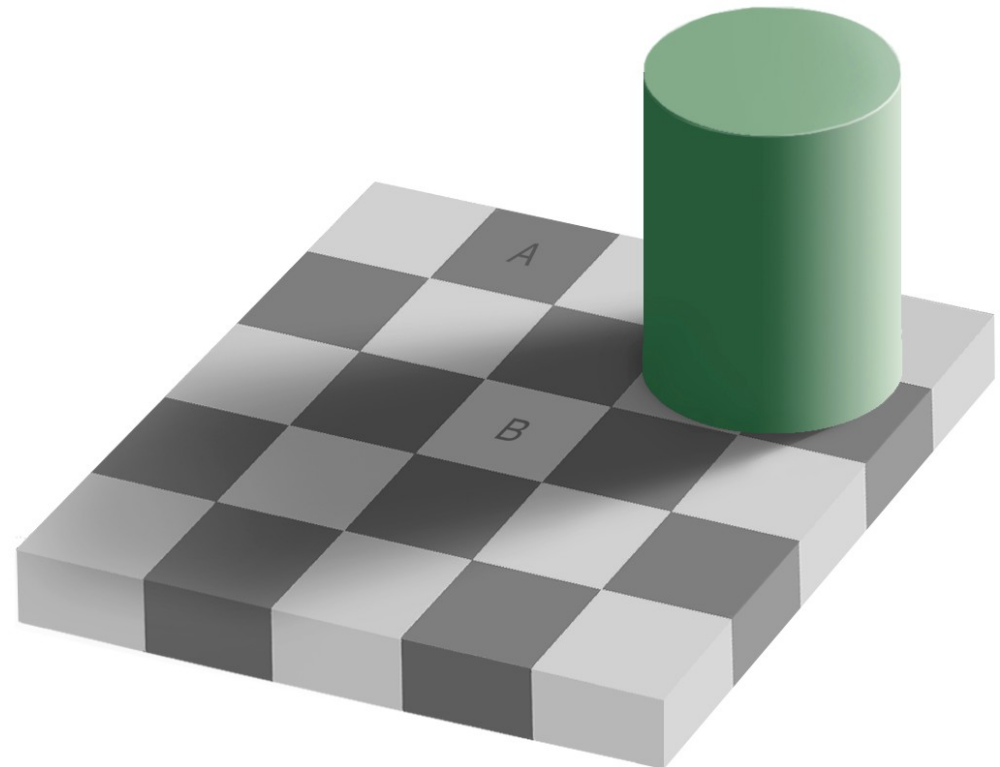
Squares A and B are of the same color

Limitations of standard colormaps

Rainbow colormaps are as evil as goto:

"Rainbow Color Map (Still) Considered Harmful" - Borland and Taylor, 2007
IEEE Computer Graphics and Applications, vol. 27, no. 2:

The goal is to make the rainbow color map as rare in visualization as the goto statement is in programming (...)

"Go To Statement Considered Harmful" - Dijkstra, 1968
Communications of the ACM, vol. 11, no. 3

Still very commonly used:

Table 1. Statistics from the 2001 through 2005 IEEE Visualization Conference proceedings papers implementing pseudocoloring to display data and that use the rainbow color map.

Year	Relevant Papers Including Medical Images (%)	Relevant Papers Excluding Medical Images (%)	Number of Pages
2001	47	62	8
2002	40	45	18
2003	52	71	32
2004	59	68	62
2005	52	59	61
Total	51	61	181

Limitations of standard colormaps

Rainbow creates false steps and hides real steps.
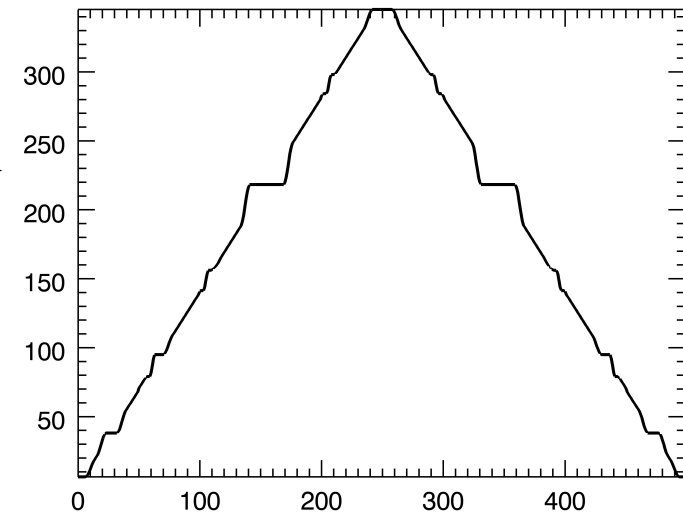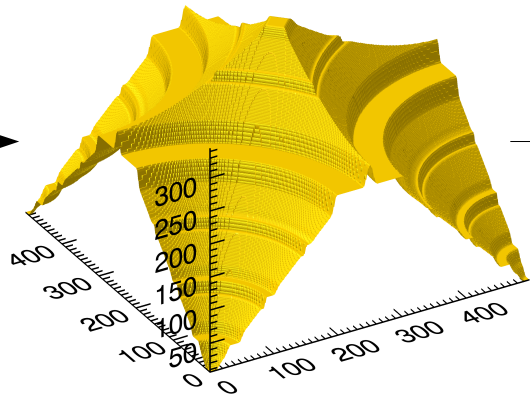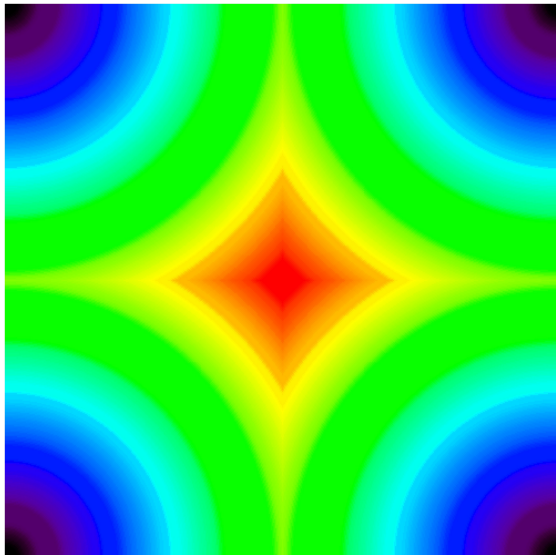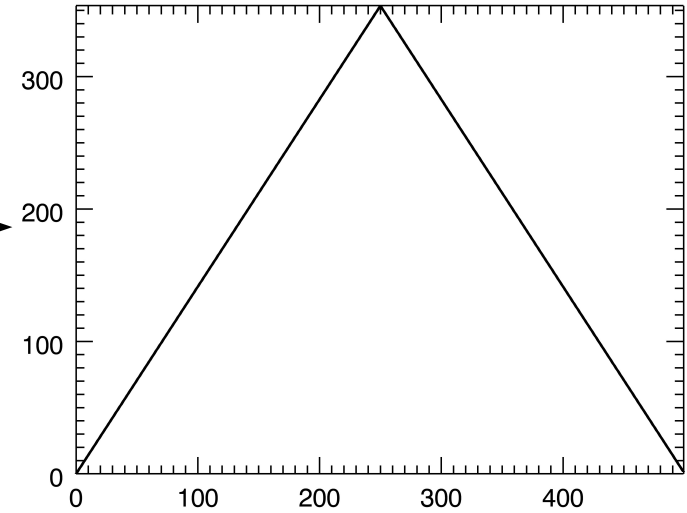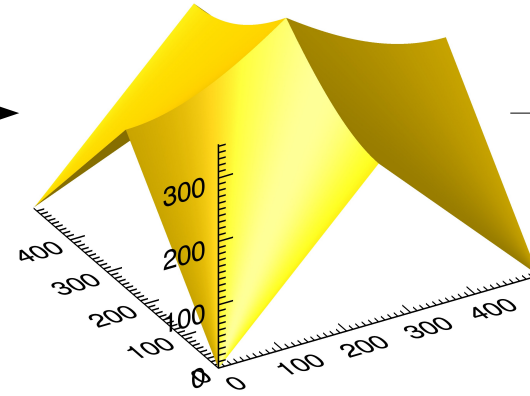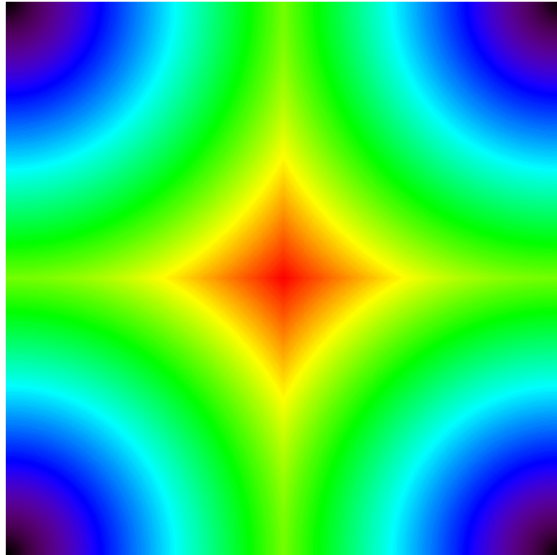
Limitations of standard colormaps - Same 4 images, in 4 colormaps

Rainbow creates false steps

Rainbow hides the real step in the middle of the images in the second row.

Borland and Taylor, 2007
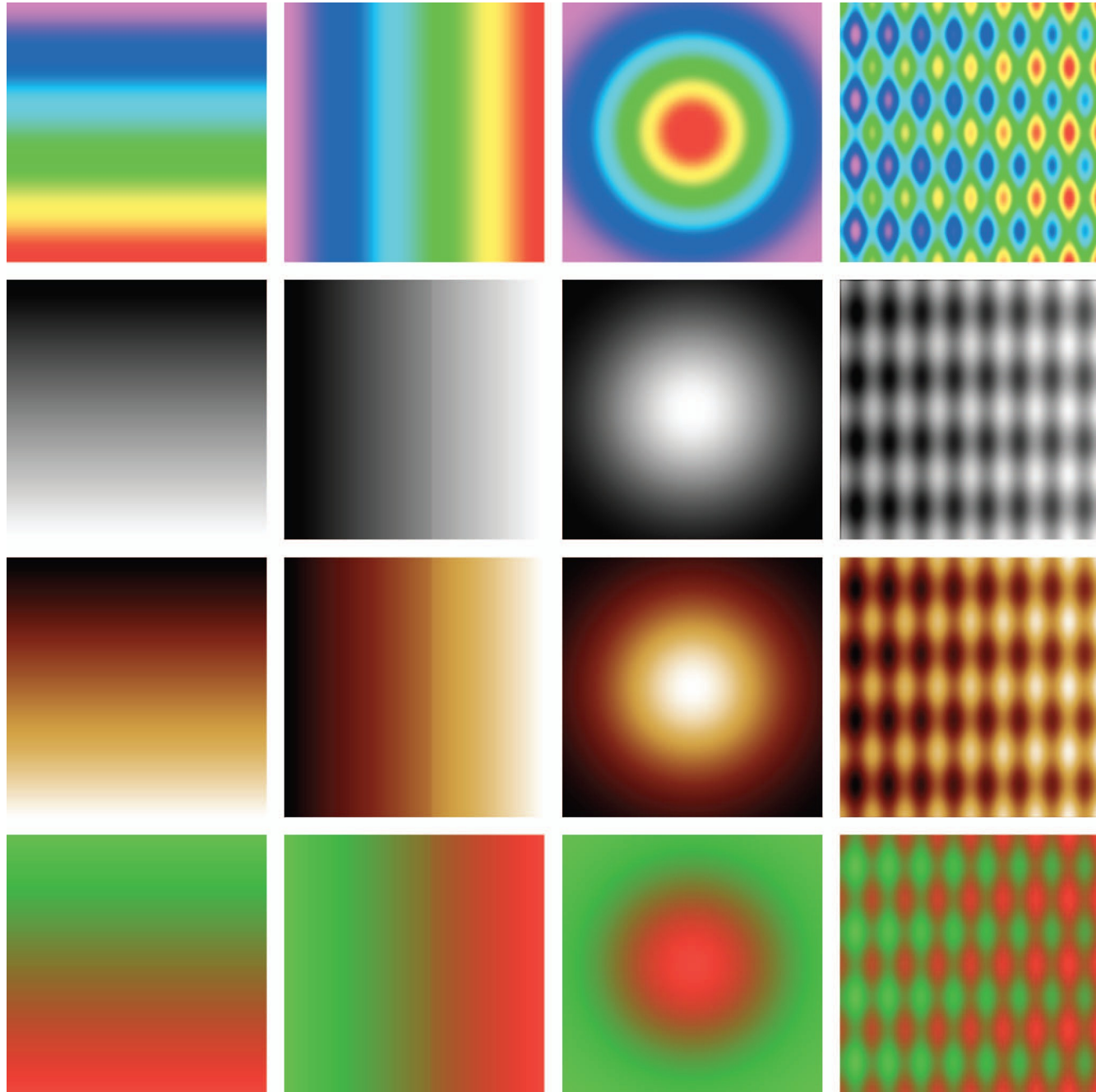
Limitations of standard colormaps

Same 5 images, in a 3D surface, and 2 colormaps.

Rainbow creates false steps

Rainbow hides the high frequency structure.

From

Rogowitz and Treinish,

Why Should Engineers and Scientists Be Worried About Color?

http://www.research.ibm.com/people/l/lloydt/color/color.HTM
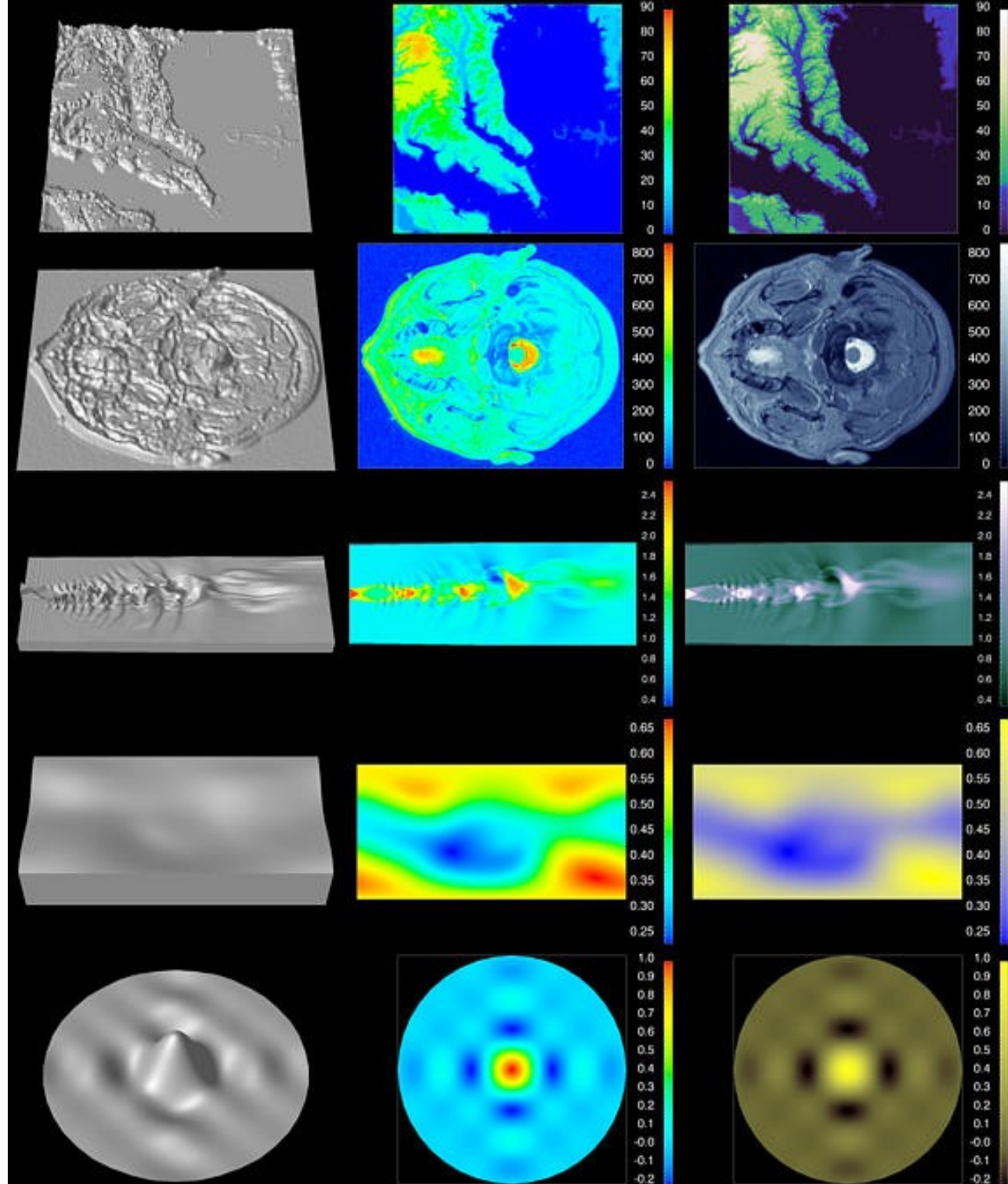
Limitations of standard colormaps

Then use what in place of the rainbow?
B-W Linear (grayscale), Blue/White, and Red Temperature, are more uniform, not introducing such strong artifacts, but:
    B-W Linear only varies luminance.
    Blue/White and Red Temperature are still single hue, and are less uniform.

All IDL maps are limited to a low dynamic range (only 256 levels):
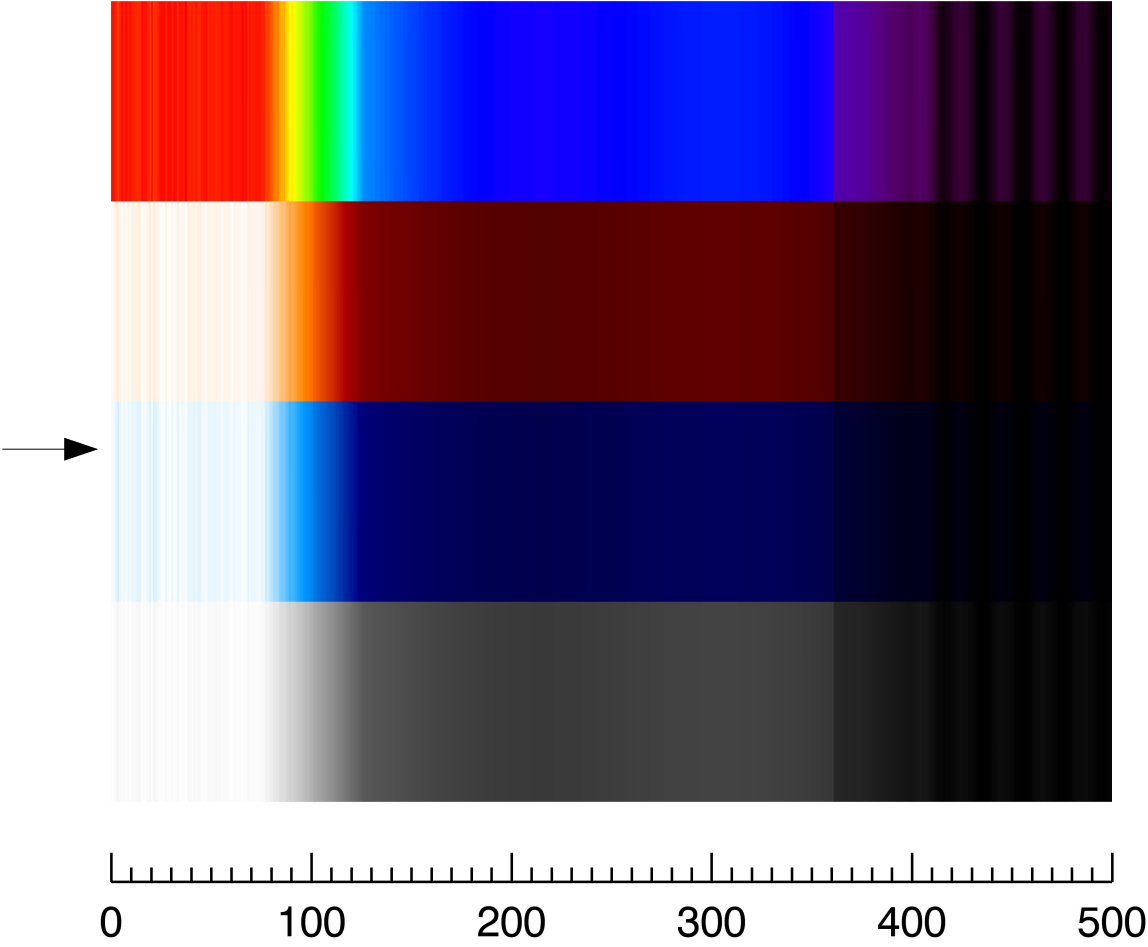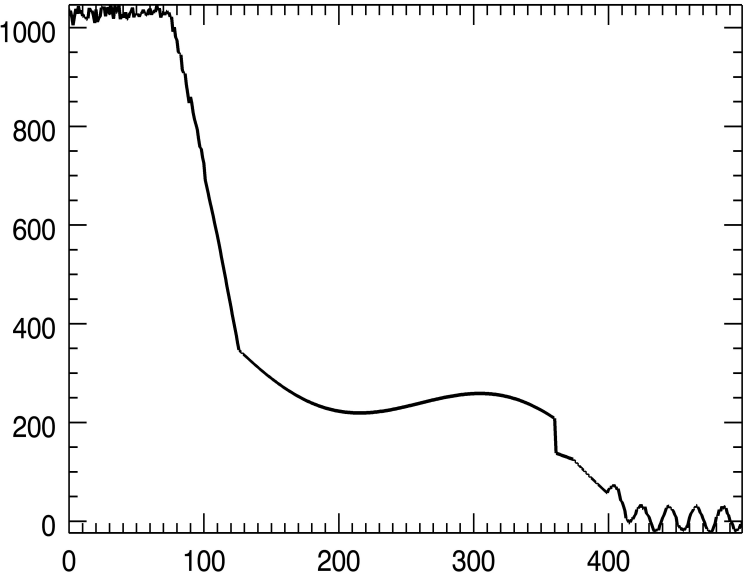
Rainbow (13)

Red Temperature (3)

Blue/White (1)

B-W Linear (0)

0   50   100 150 200 250

Limitations of standard colormaps

Development of uniform colormaps - Standard color maps in RGB
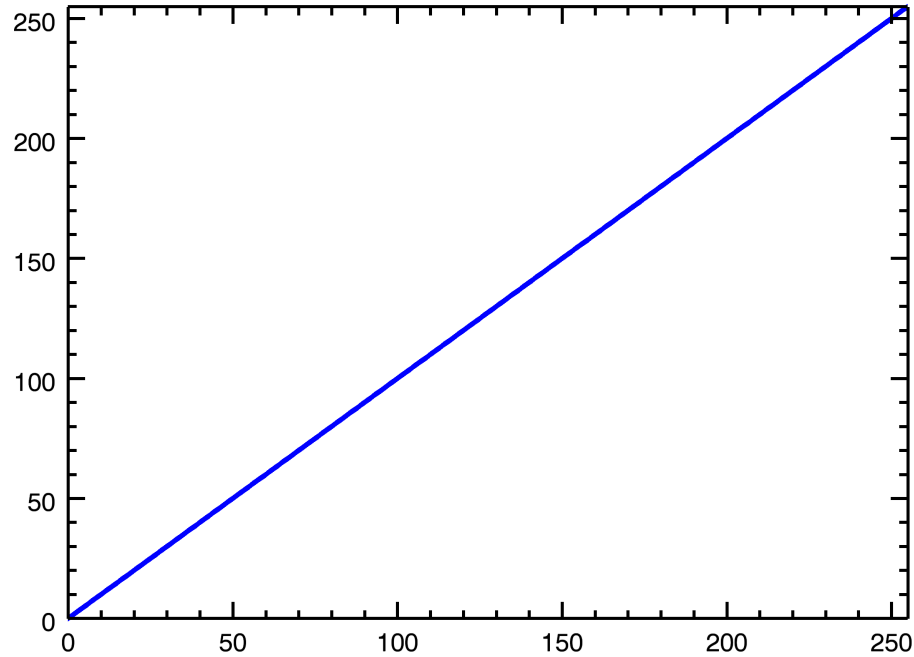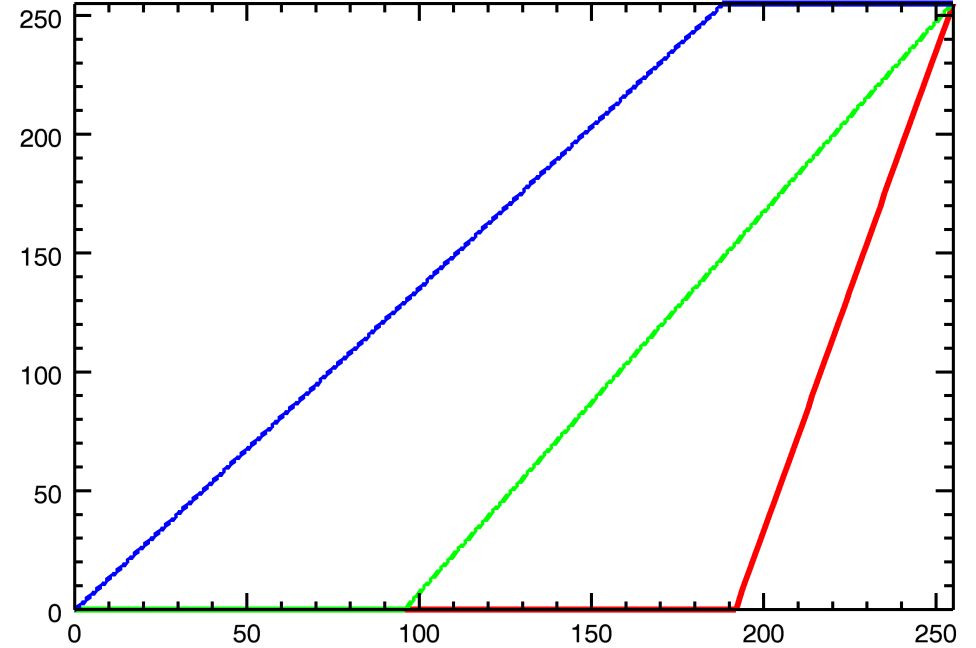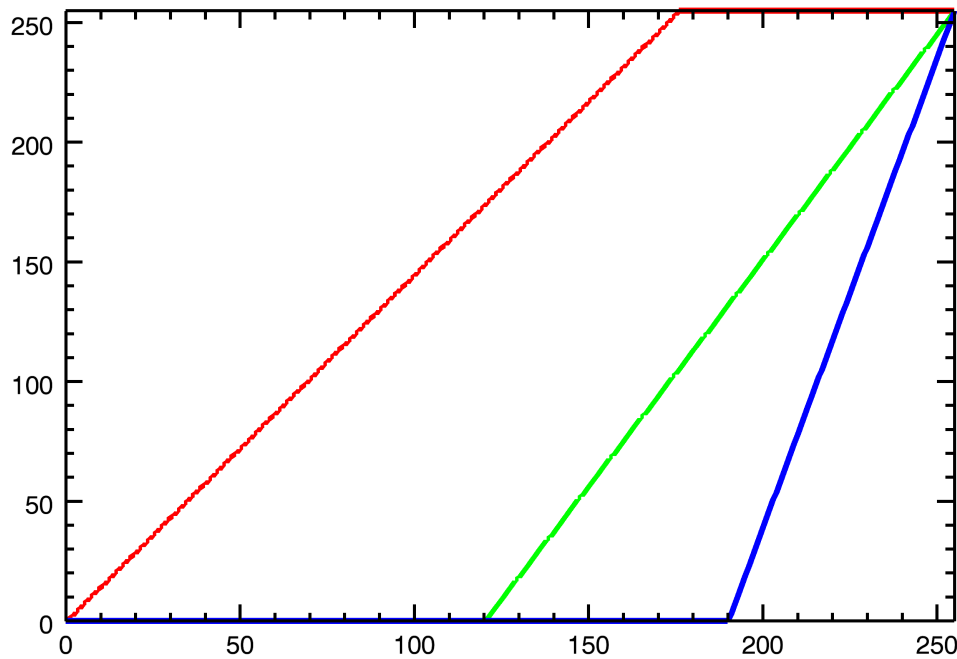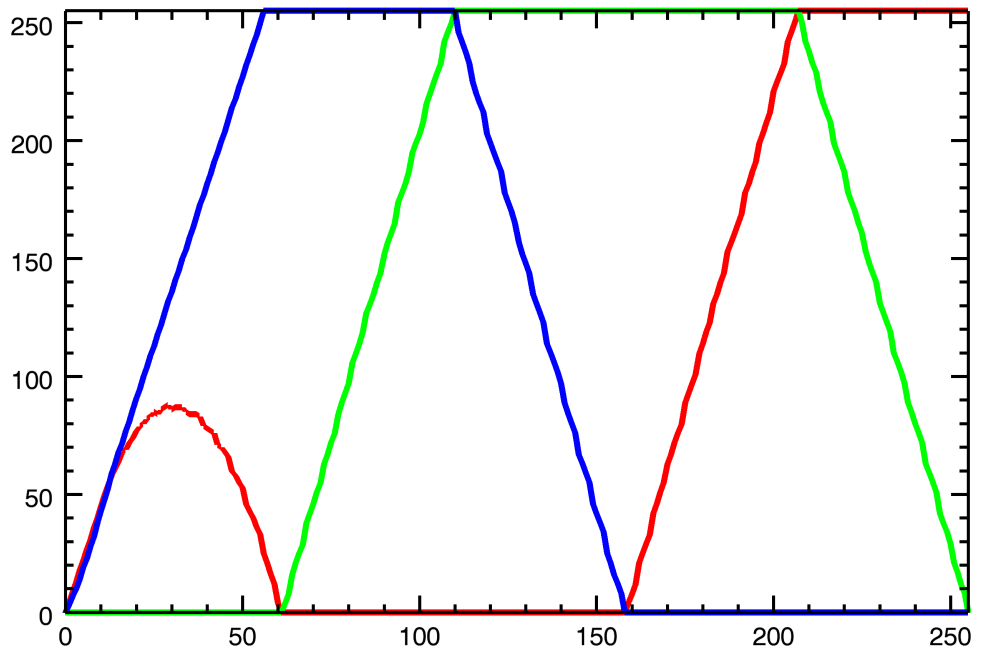
Development of uniform colormaps - Standard color maps in Lab
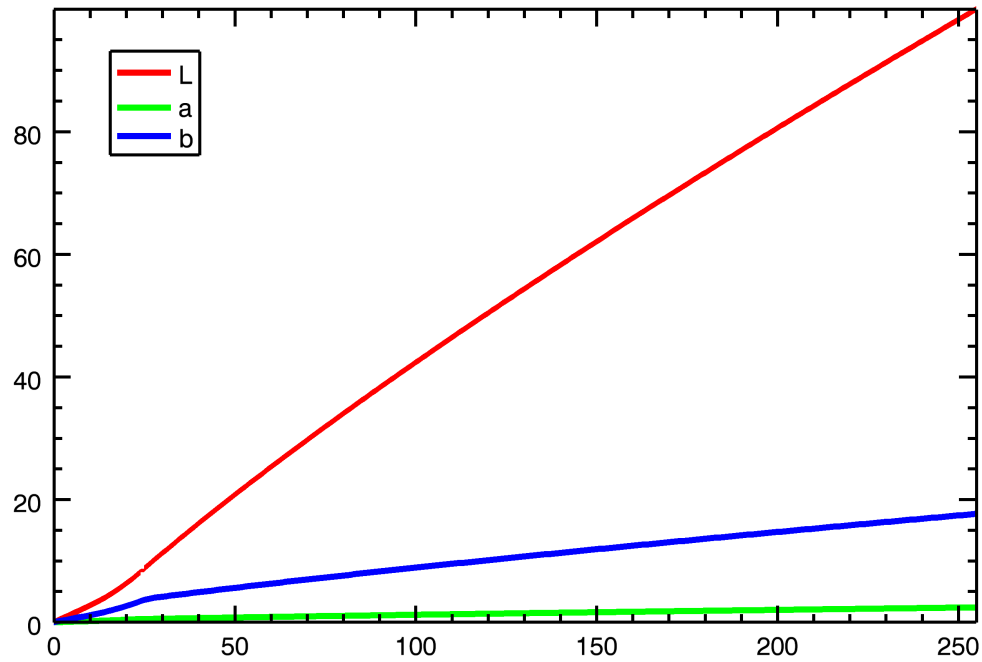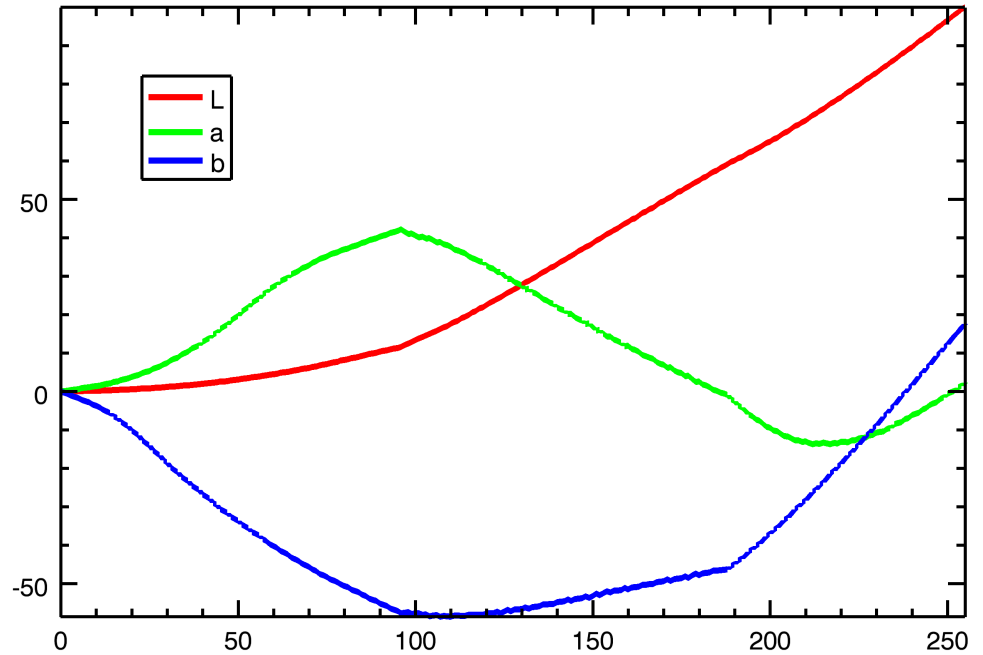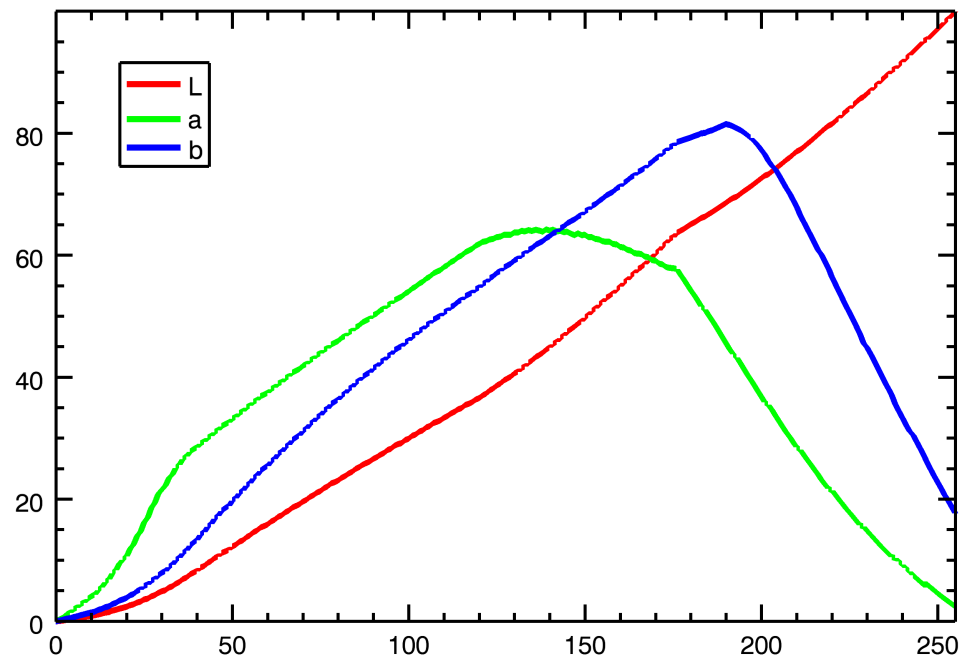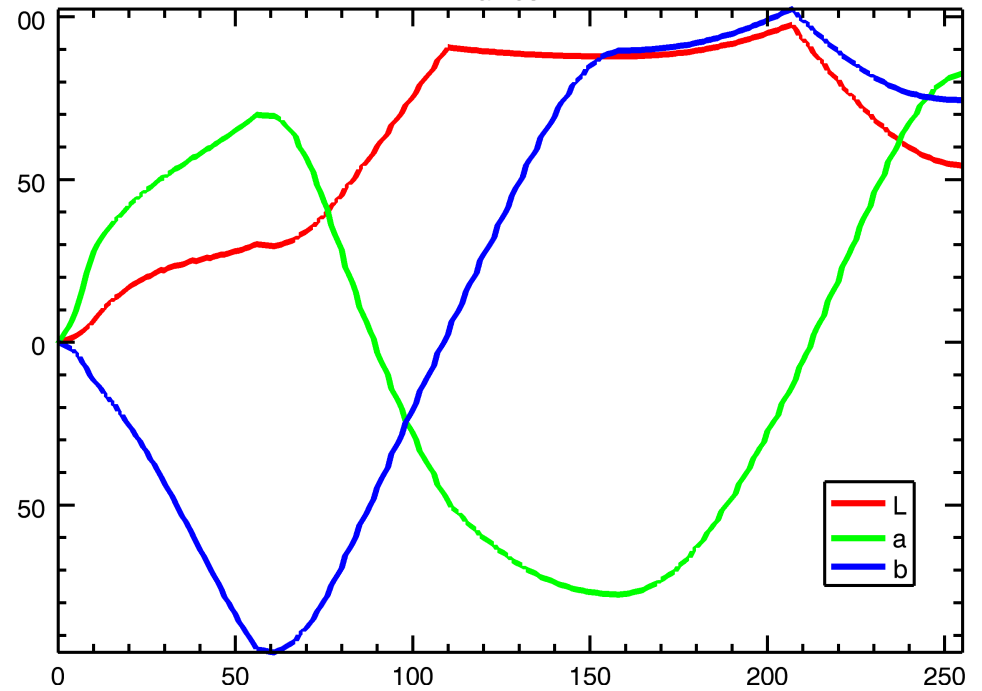
Development of uniform colormaps - Standard color maps in Lab
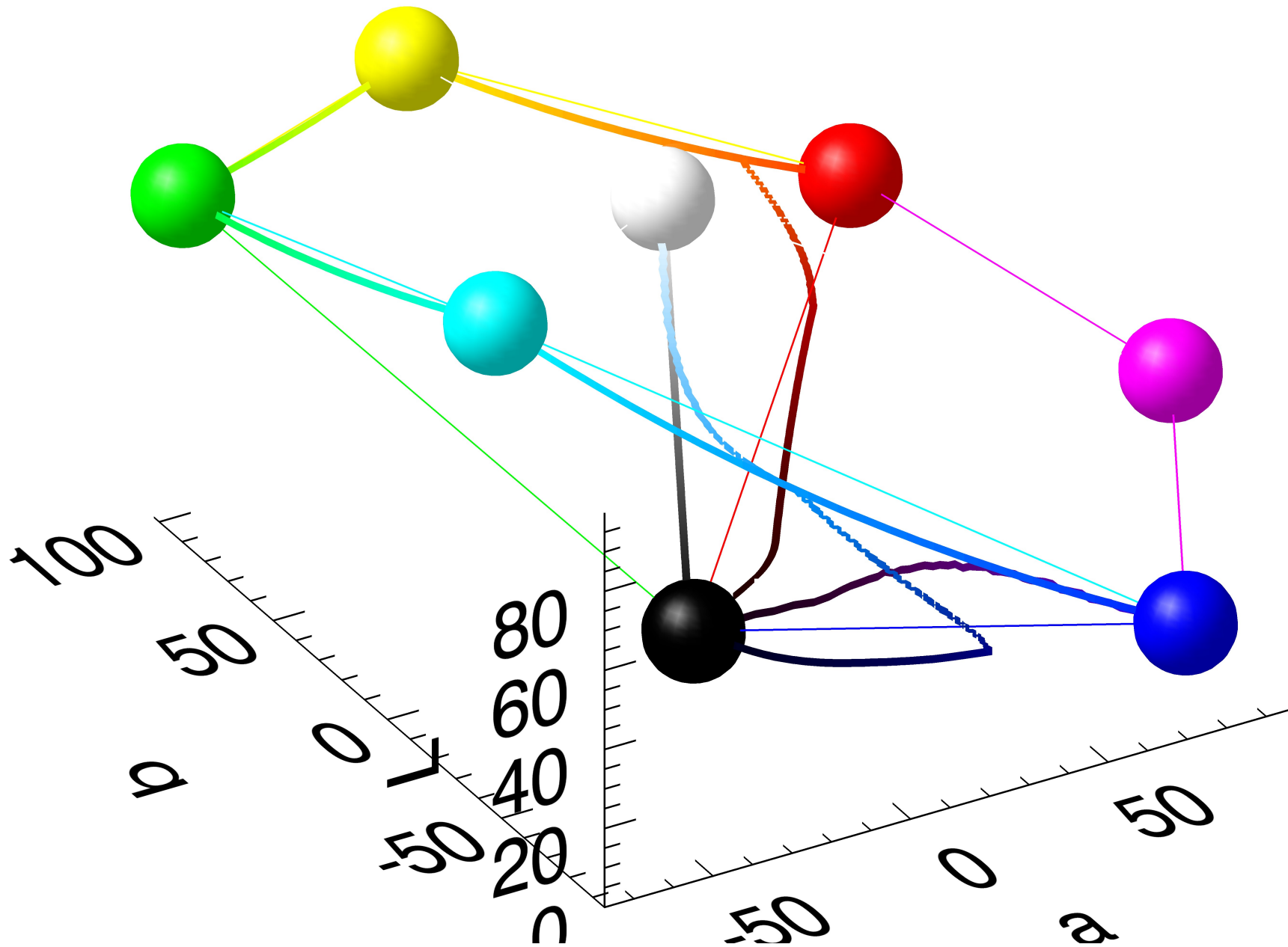
Development of uniform colormaps - Distances from the map origin
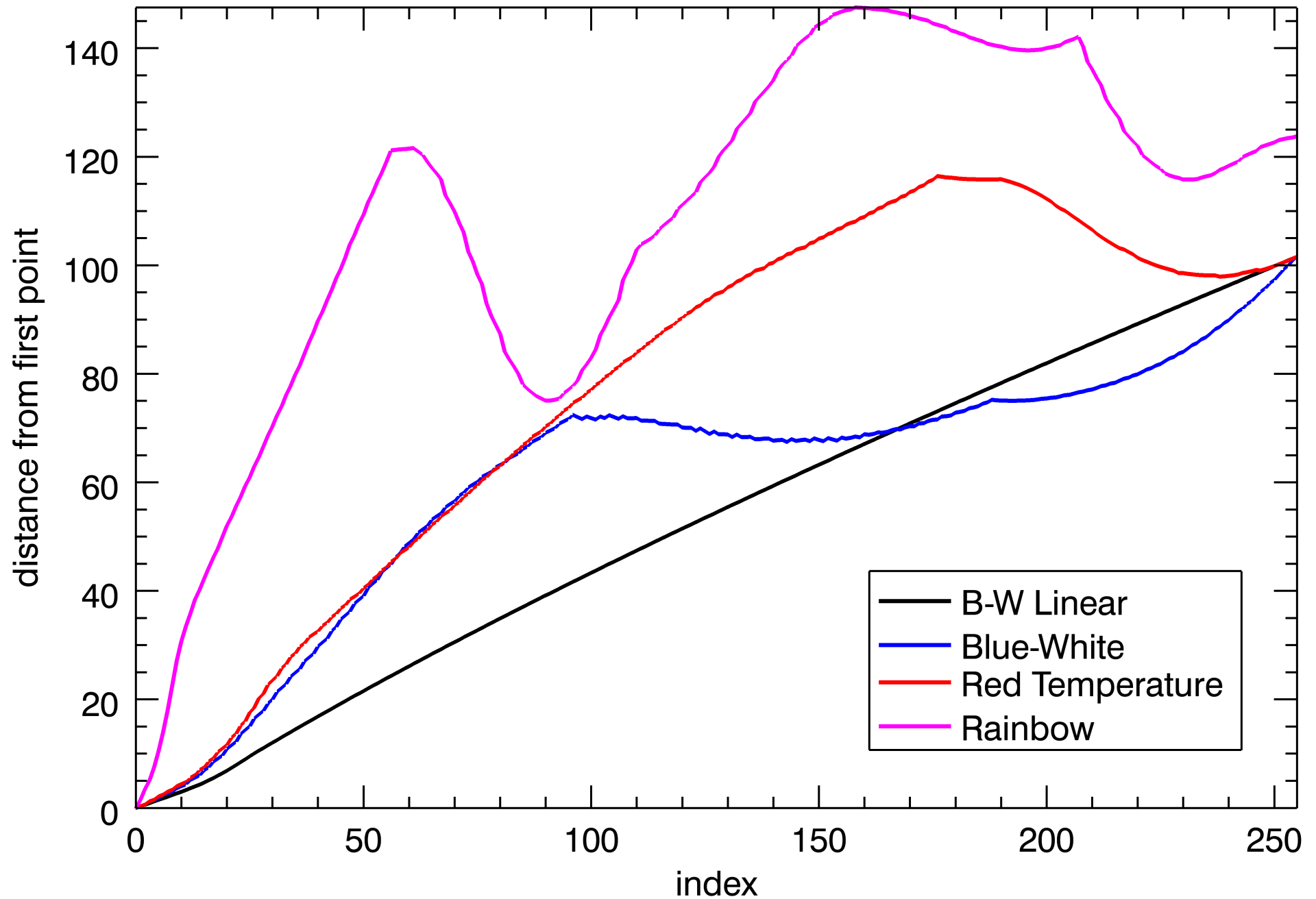
Defintion of maps from CIE Lab space - Fully uniform acyclic maps
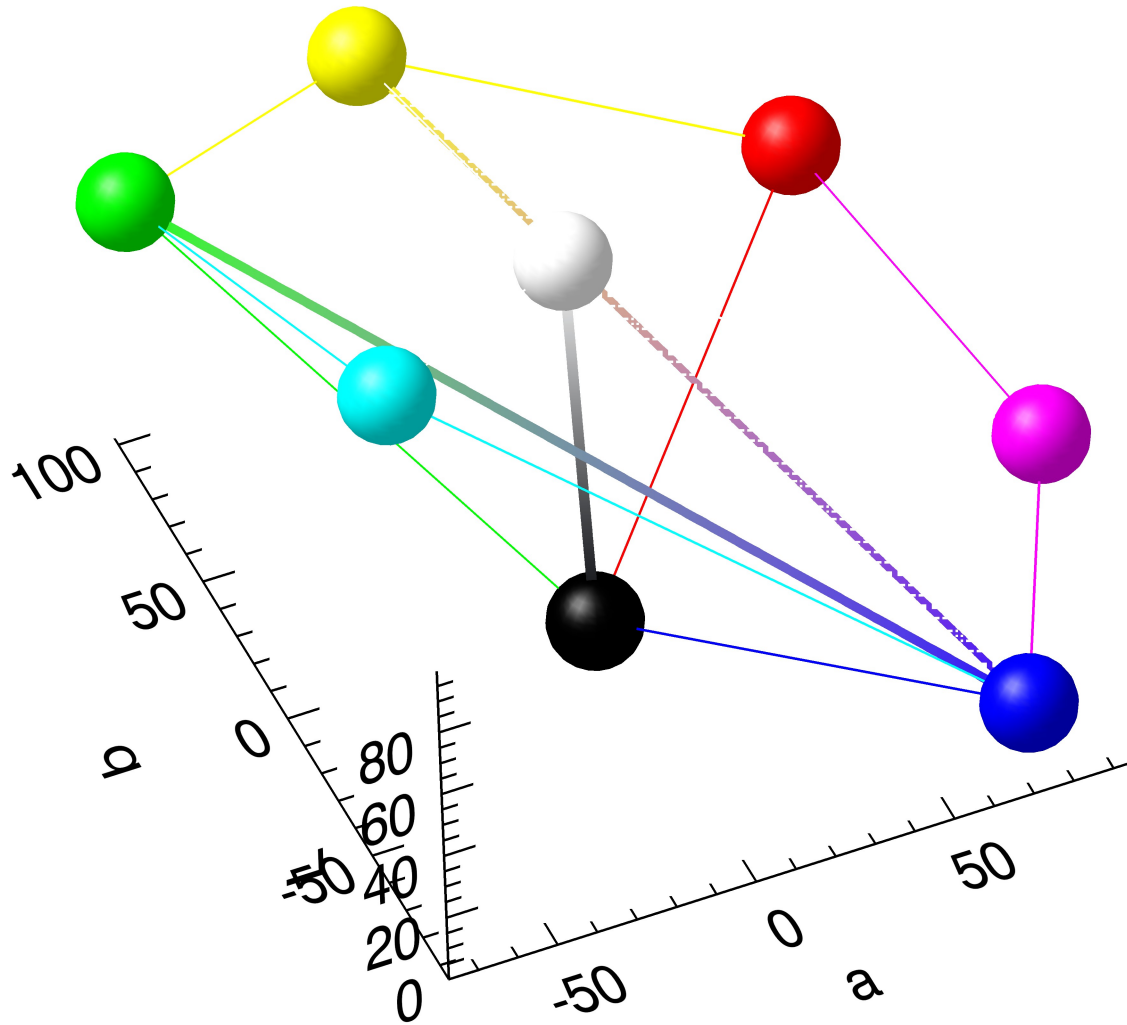
Defintion of maps from CIE Lab space - Fully uniform acyclic maps
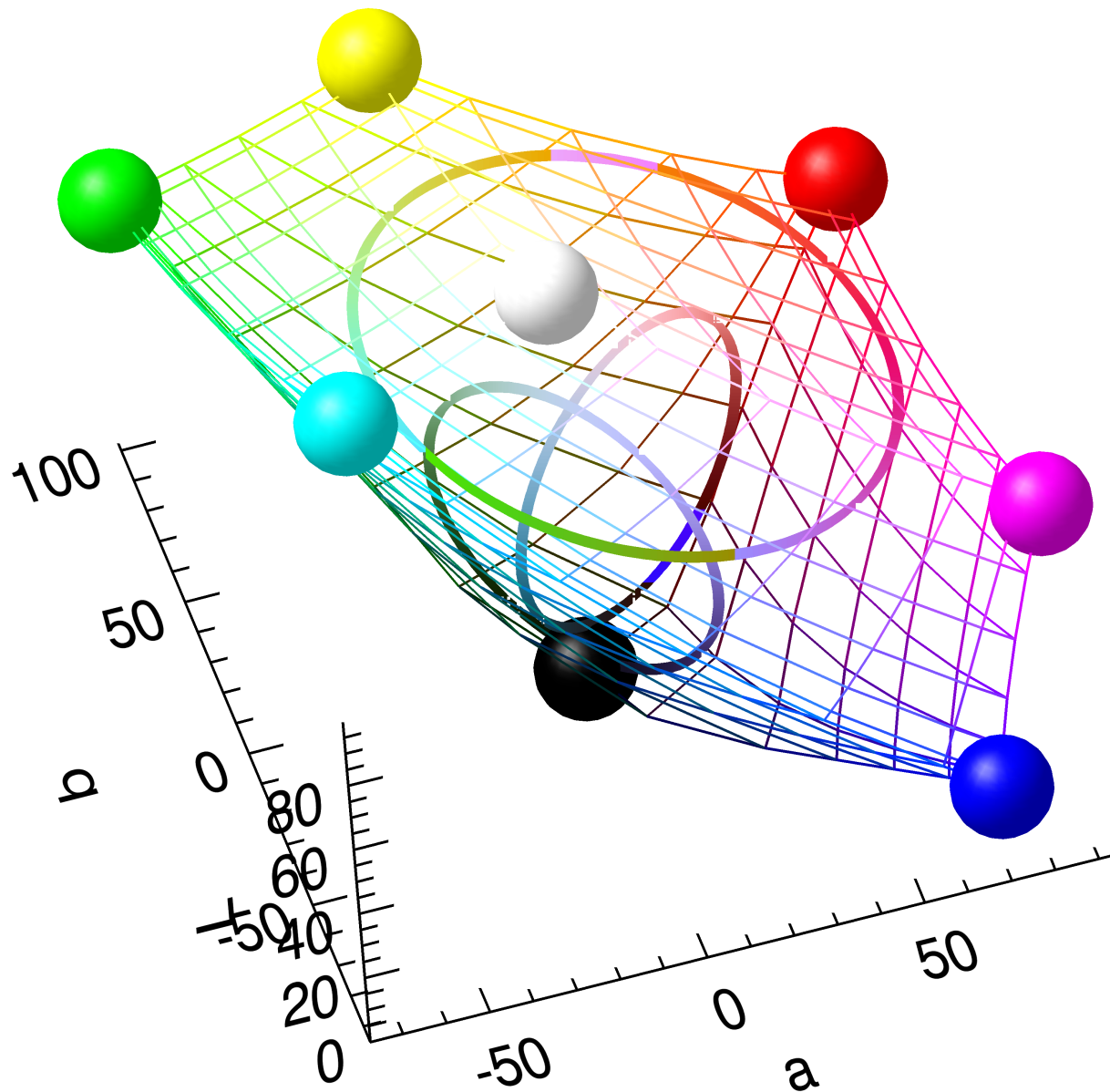
Defintion of maps from CIE Lab space - Smooth acyclic maps
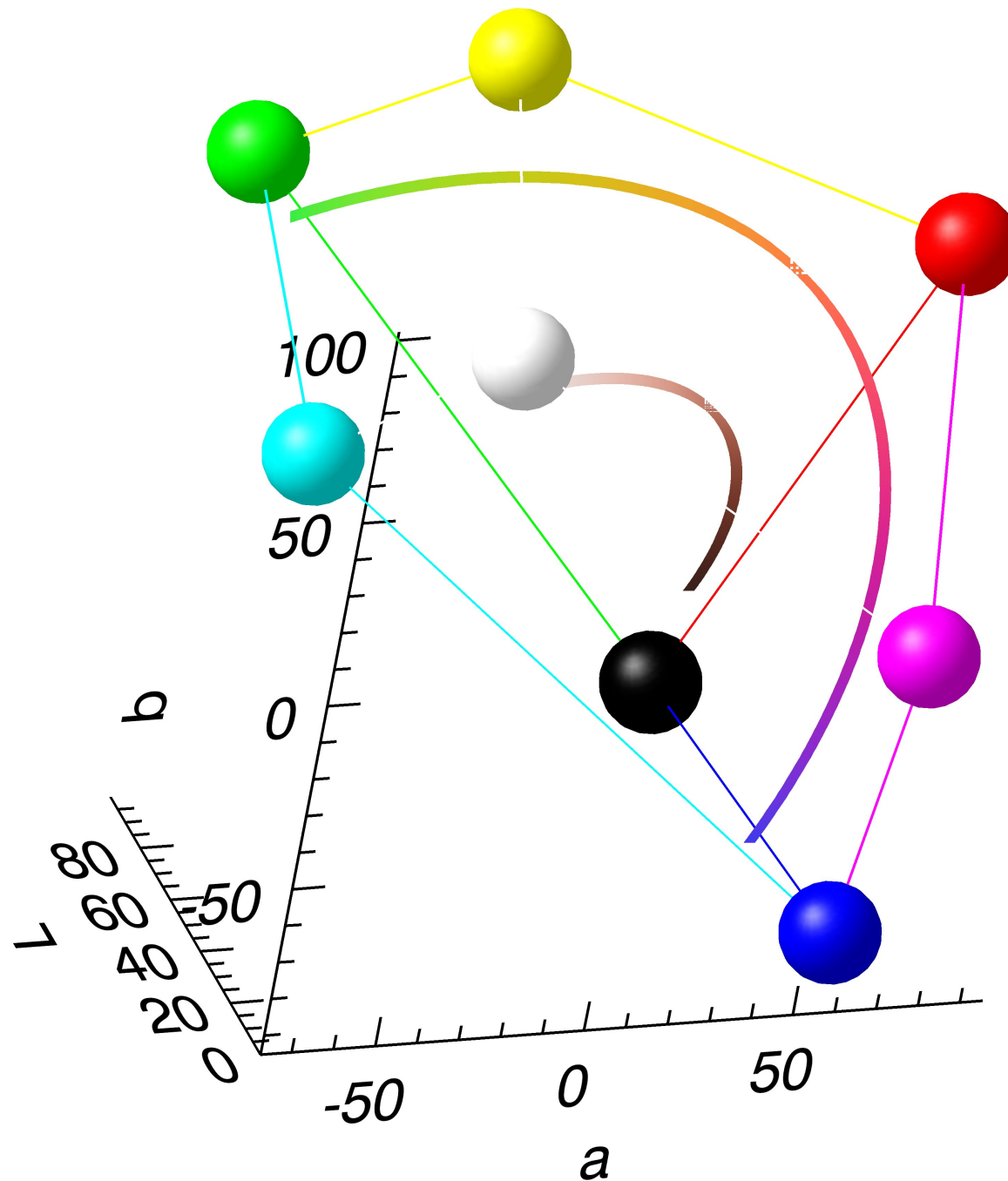
Defintion of maps from CIE Lab space - Smooth cyclic maps
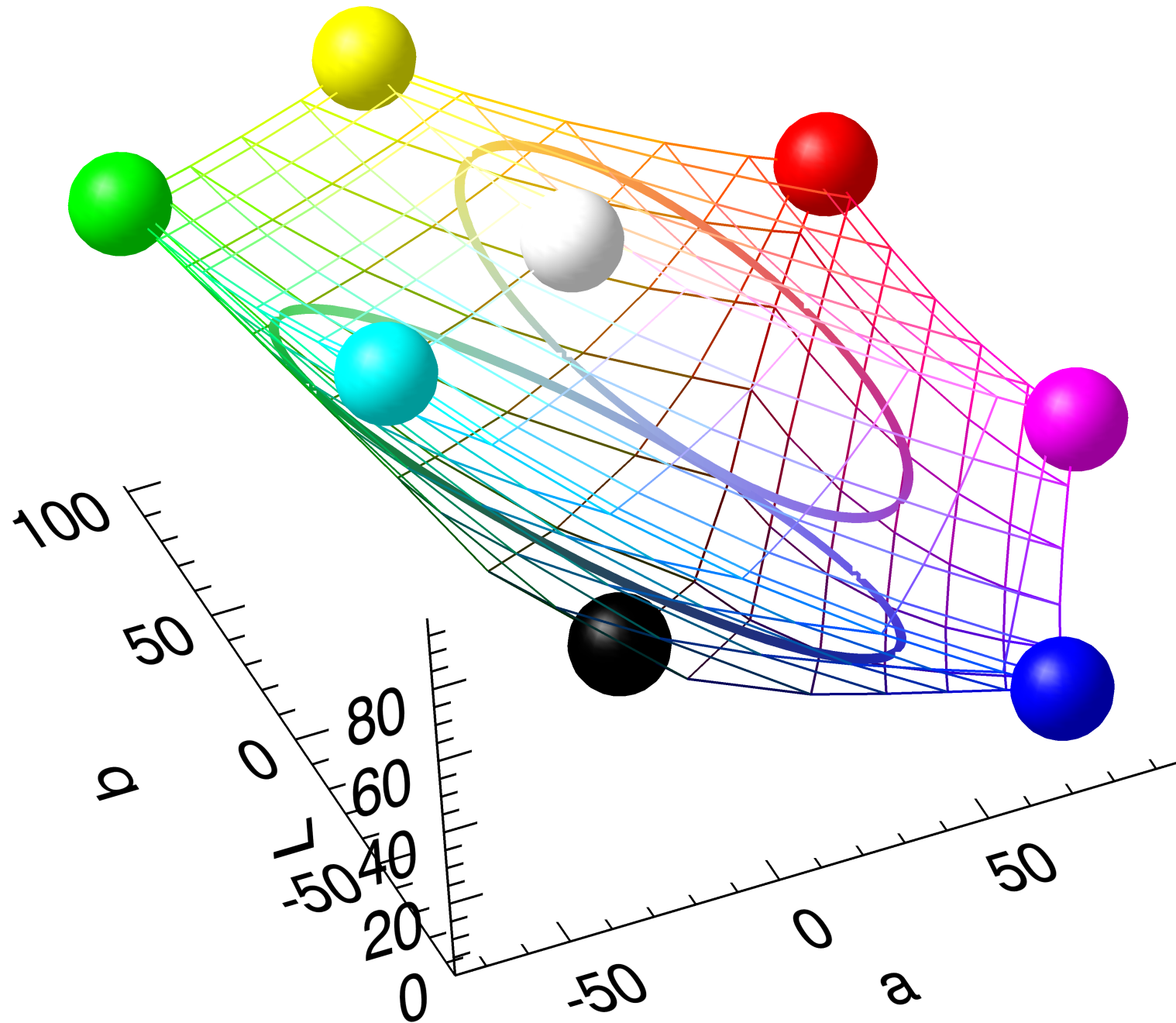
Examples

Uniform maps, plus B-W Linear
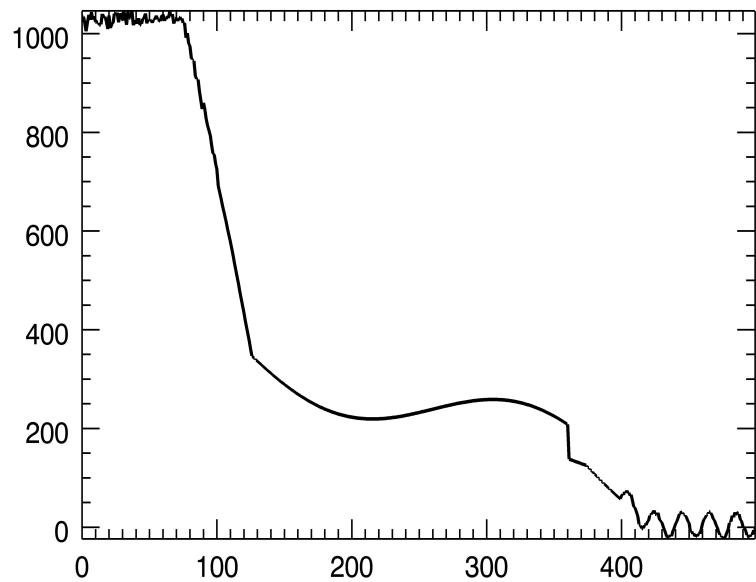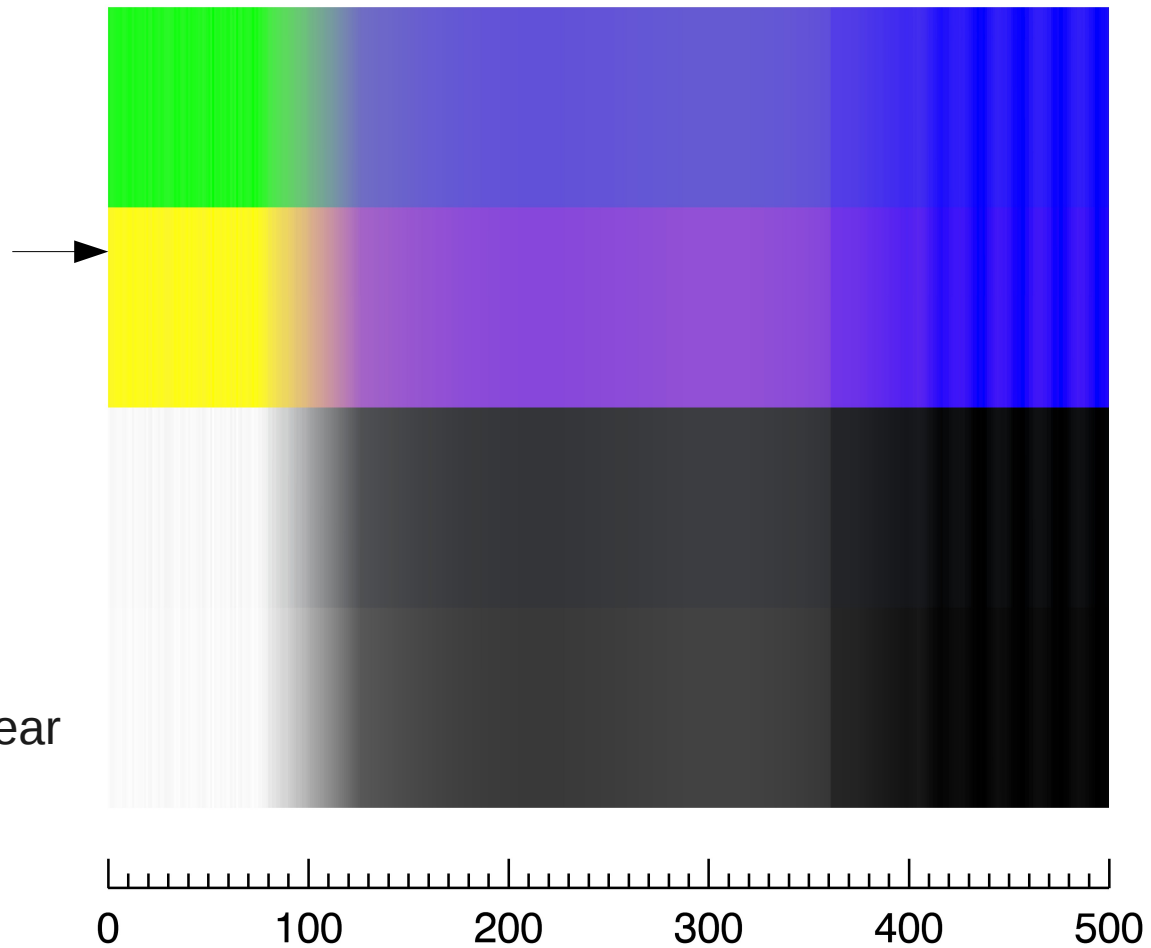
B-W Linear

Examples

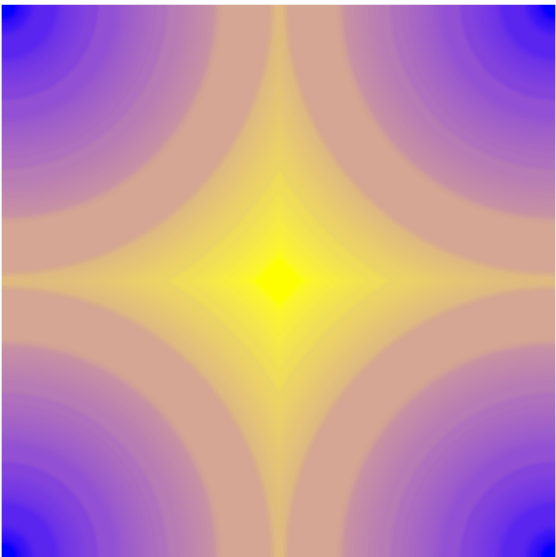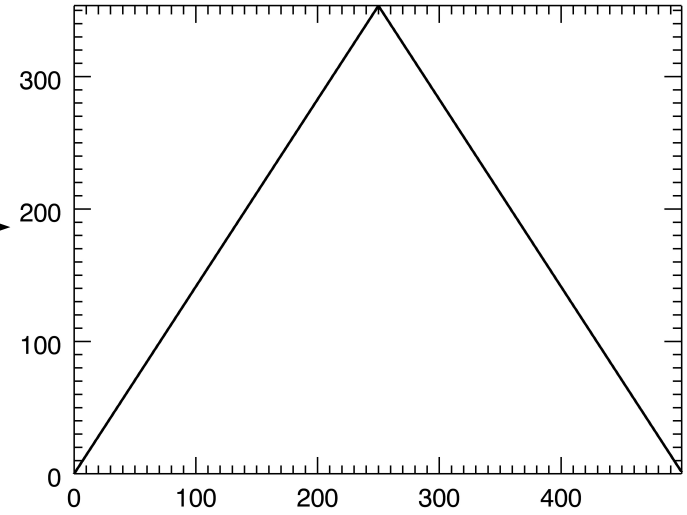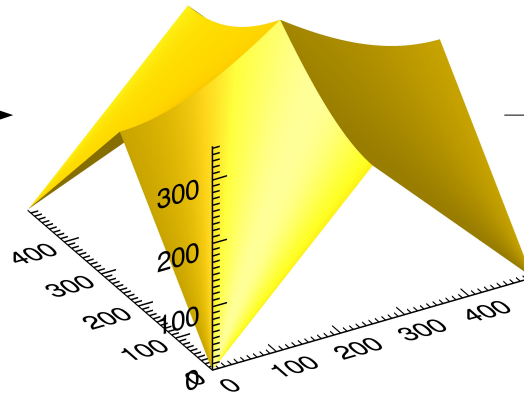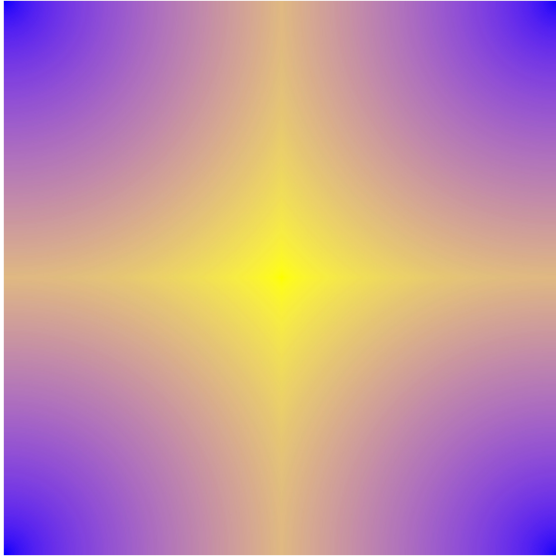## Smooth maps, plus B-W Linear
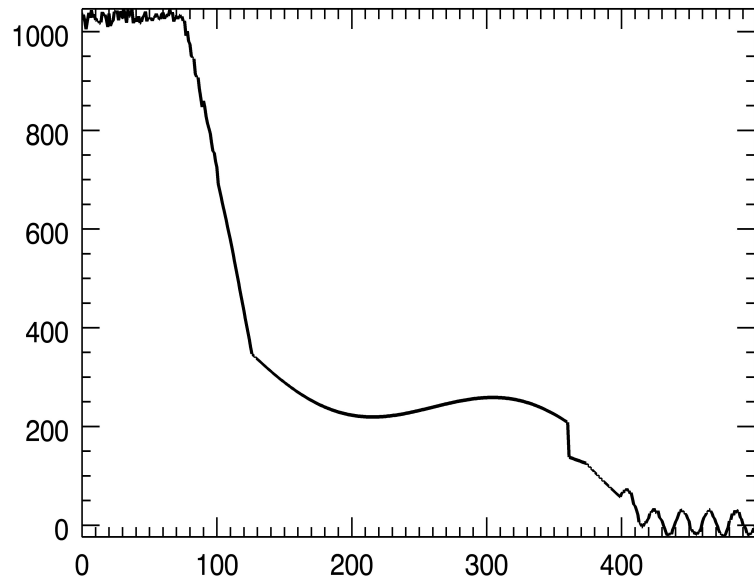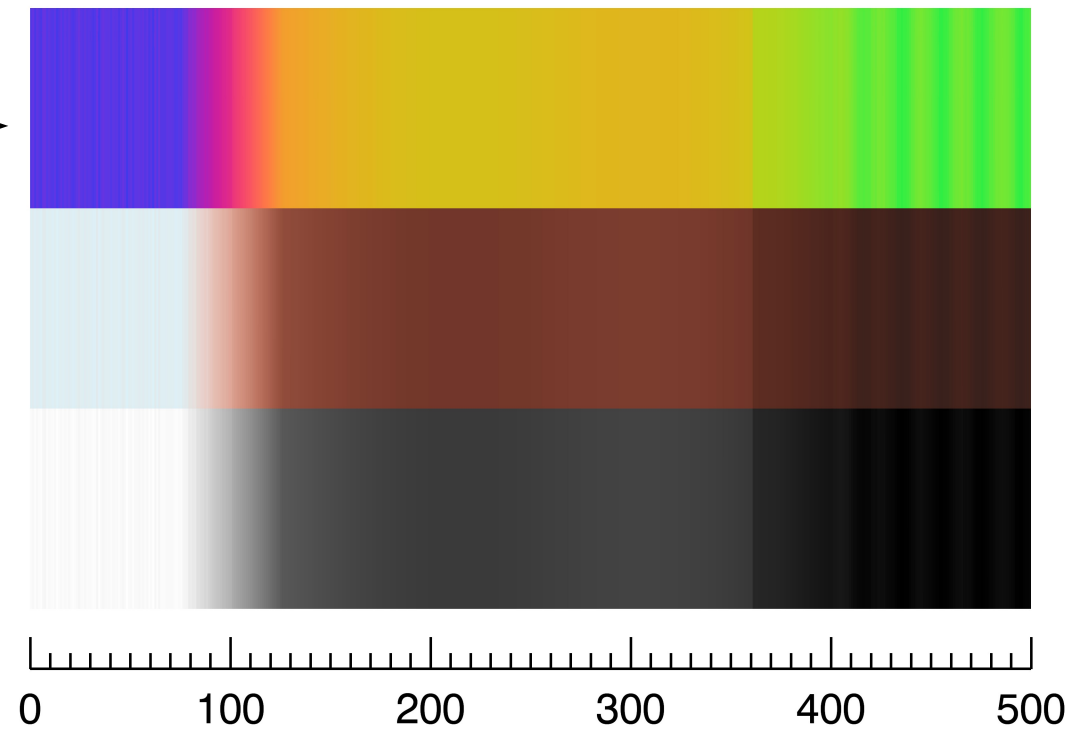
B-W Linear

Examples

B-W Linear
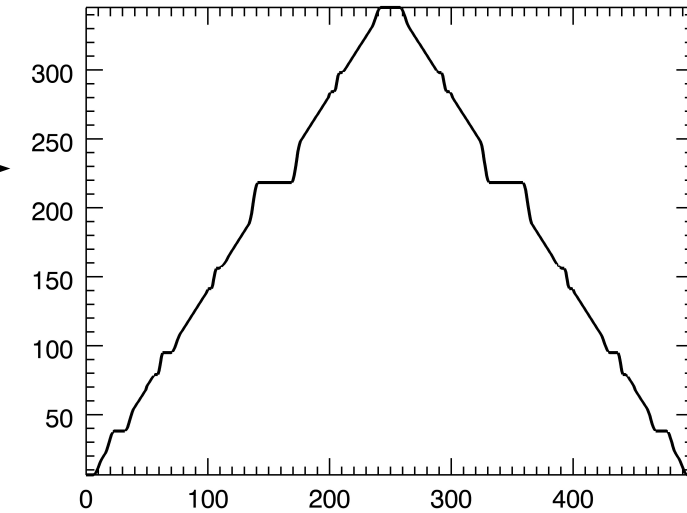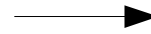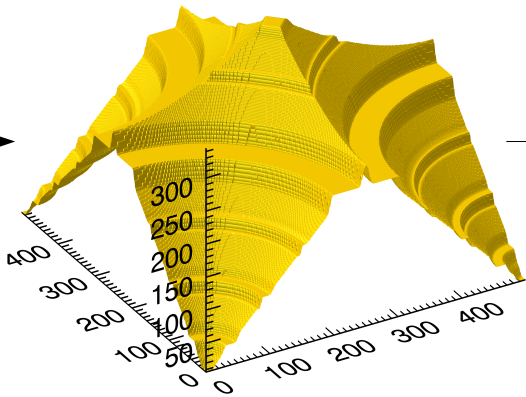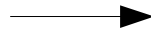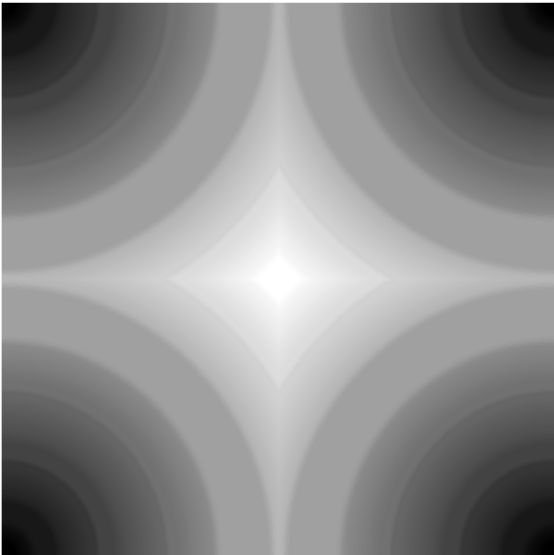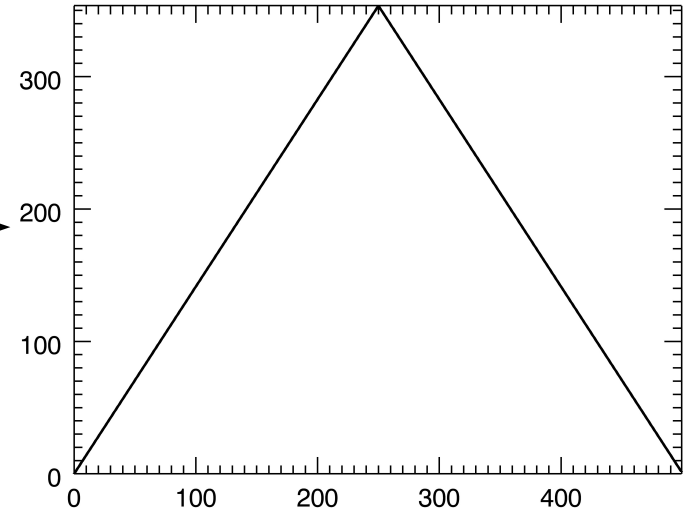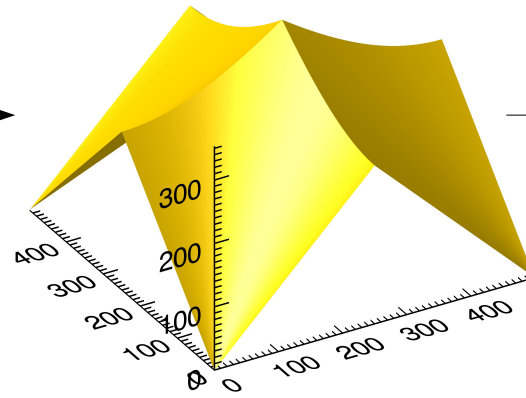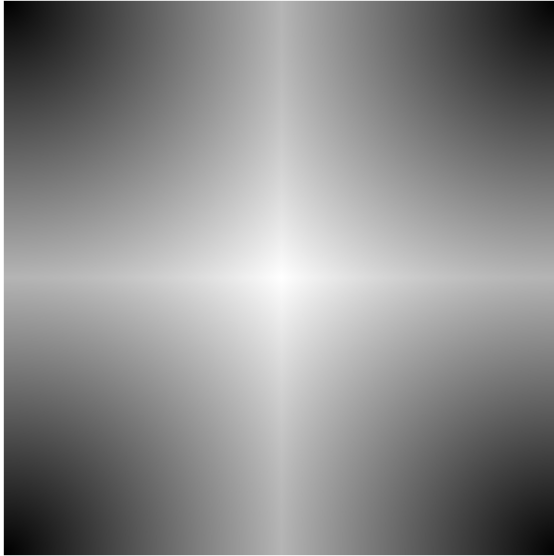
Examples

Blue-yellow uniform
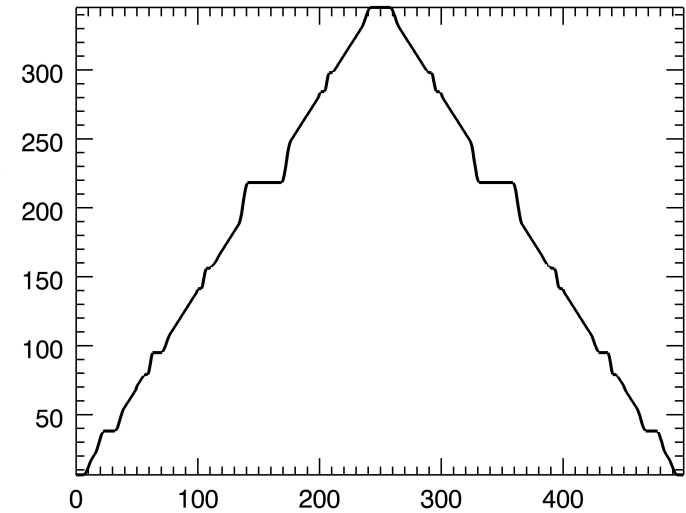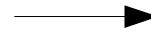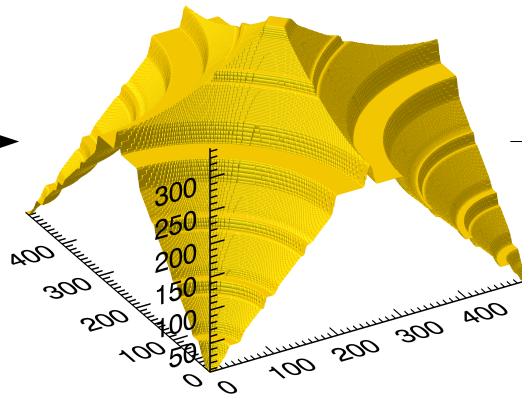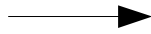
Summary

Standard colormaps found in IDL and other environments tend to be too simple.

Rainbow maps are particularly inadequate.

CIE Lab space provides a framework to measure color differences and define maps.

This work defines maps in CIE Lab for:
    Low, high, or mixed spatial frequencies.
    Cyclic or acyclic variables.
    Standard (8-bit) or wider dynamic range.
    Completely uniform, or (wider) smooth color variations.

Maps definitions are still being experimented with. Other trajectories need to be tested, more work on their optimization is needed.

Future work will consider color appearance models (CAM), and other media.

As the maps mature, source code, color maps and articles on them will soon be made public, and announced on the IDL newsgroup.

Questions, suggestions, requests for maps/software/references: pp.penteado@gmail.com