Physical Basis of Color

光=不同波长的电磁辐射（可见光光谱范围内400~700nm）

不同波长的光具有不同的折射率

Spectrum 光谱：不同波长（频率）的光对应的类型

Spectral Power Distribution (SPD) 谱功率密度：描述一束光在所有波长的分布

- 线性：可叠加

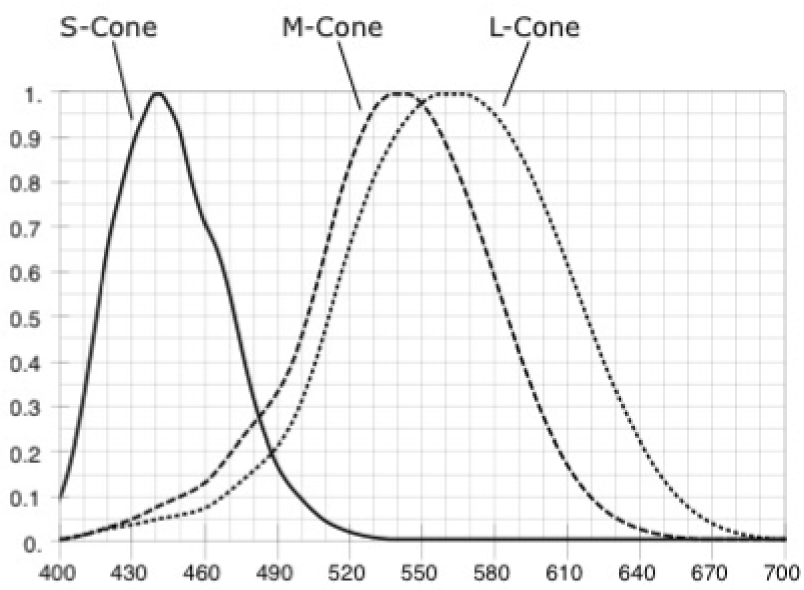
Color 颜色：是人的一种感知，不是光线的一种根本属性 a phenomenon of human perception; it is not a universal property of light

- 不同波长的光Different wavelengths of light are not “colors”

人眼的简单介绍：瞳孔=光圈，晶状体=透镜，视网膜=感光元件

视网膜上的感光细胞 Retinal Photoreceptor Cells

- Rods：视杆细胞，棒状，很多，感知光的强度（而非波长）
- Cones：视锥细胞，锥形，较少，产生“颜色”的感觉
    - Three types of cones S, M, and L (corresponding to peak response at short, medium, and long wavelengths), each with different spectral sensitivity

      不同视锥细胞对不同波长的光的响应曲线

    - 不同的人的视锥细胞分布大不一样 Fraction of Three Cone Cell Types Varies Widely

Tristimulus Theory of Color

Spectral Response of Human Cone Cells

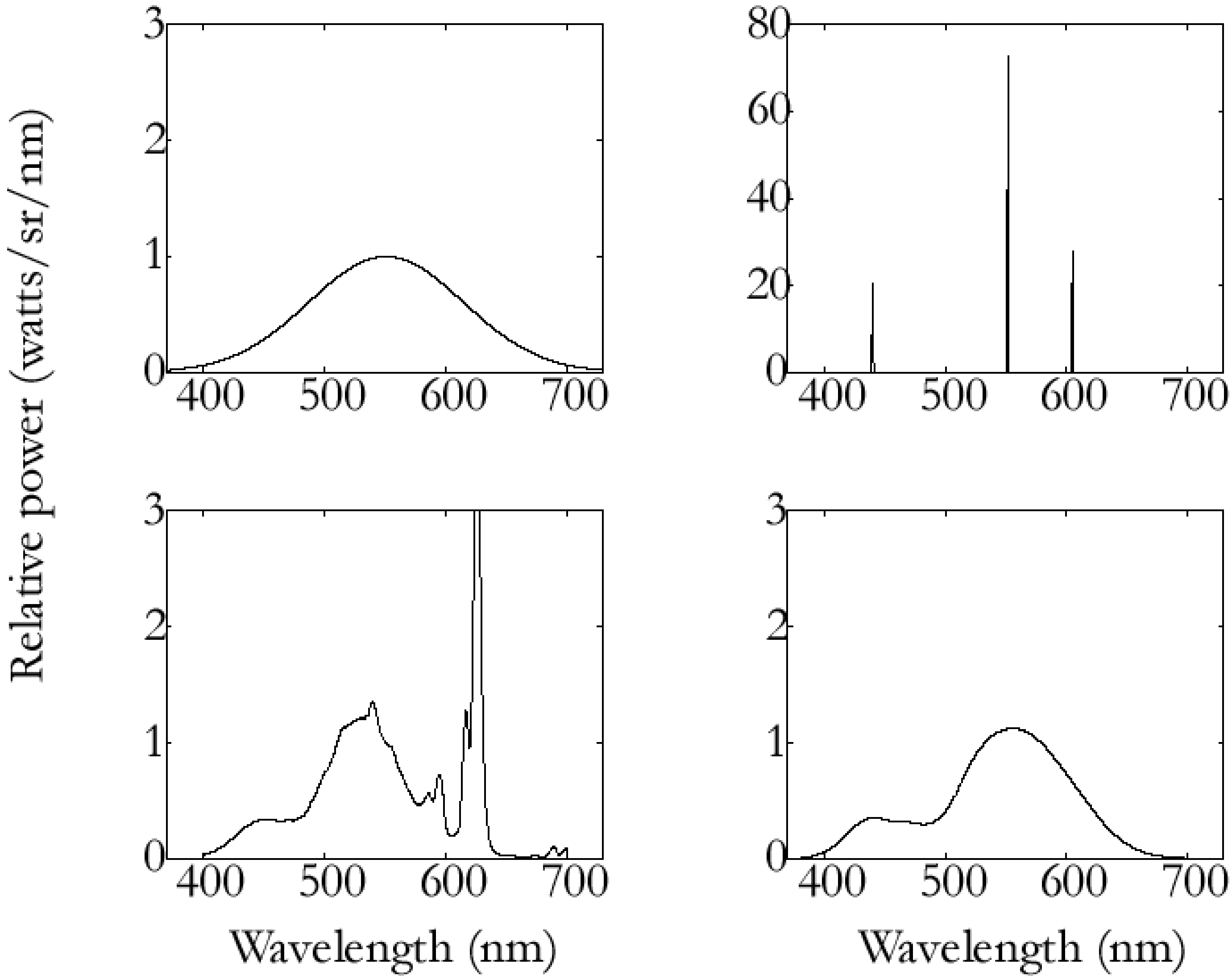
于是不同视锥细胞的信号强度=其对所有波长的光的响应的积分

$$S = \int r_S(\lambda)s(\lambda)d\lambda$$
$$M = \int r_M(\lambda)s(\lambda)d\lambda$$
$$L = \int r_L(\lambda)s(\lambda)d\lambda$$

于是有 任何一束光 → (S,M,L) → Color 的对应，人眼只知道(S,M,L)，不知道原来的光线分布（SPD）

Metamerism （同色异谱）

Metamerism （同色异谱）： 不同的SPD → 同样的(S,M,L) = 同样的Color



Metamers are two different spectra (∞-dim) that project to the same (S,M,L) (3-dim) response.

- These will appear to have the same color to a human The existence of metamers **is critical to color reproduction/**Matching
- Don't have to reproduce the full spectrum of a real world scene
- Example: A metamer can reproduce the perceived color of a real-world scene on a display with pixels of only three colors 通过显示器的三色光，也可以混合出现实中的种种色彩（虽然背后的光谱一般完全不一样）

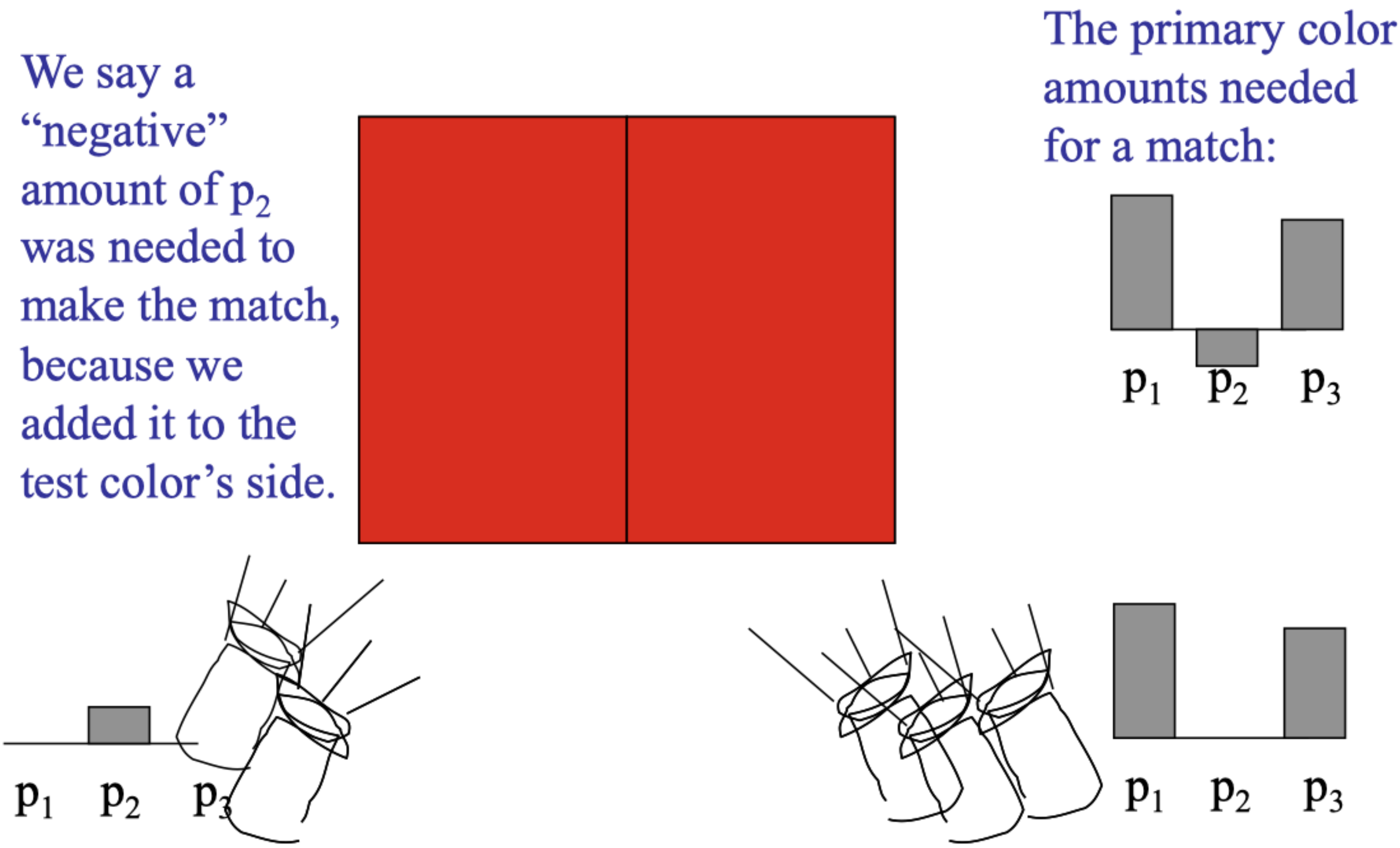
Color Reproduction / Matching 颜色匹配、重建

通过混合的方式

计算机的成像系统是加色系统：

- 给定一组主色（例如RGB）的光谱分布（S，M，L？）$s_R(\lambda), s_G(\lambda), s_B(\lambda)$
- 调整三种主色的强度并相加，得到一种颜色 $Rs_R(\lambda) + Gs_G(\lambda) + Bs_B(\lambda)$
- 于是这种颜色就可以用(R,G,B)这三个标量表示。
- 于是也可以通过实验确定不同颜色的(R,G,B)表示->Additive Color Matching Experiment

有些颜色怎么混合也混不出来，但是通过给原色加色，就可以混合出来，那么将最后混合的颜色中减去加上的颜色，就是对这种颜色的表示→系数会有负数！



CIE RGB Color Matching Experiment

CIE：一个组织

主光 RGB 都是单一波长的光

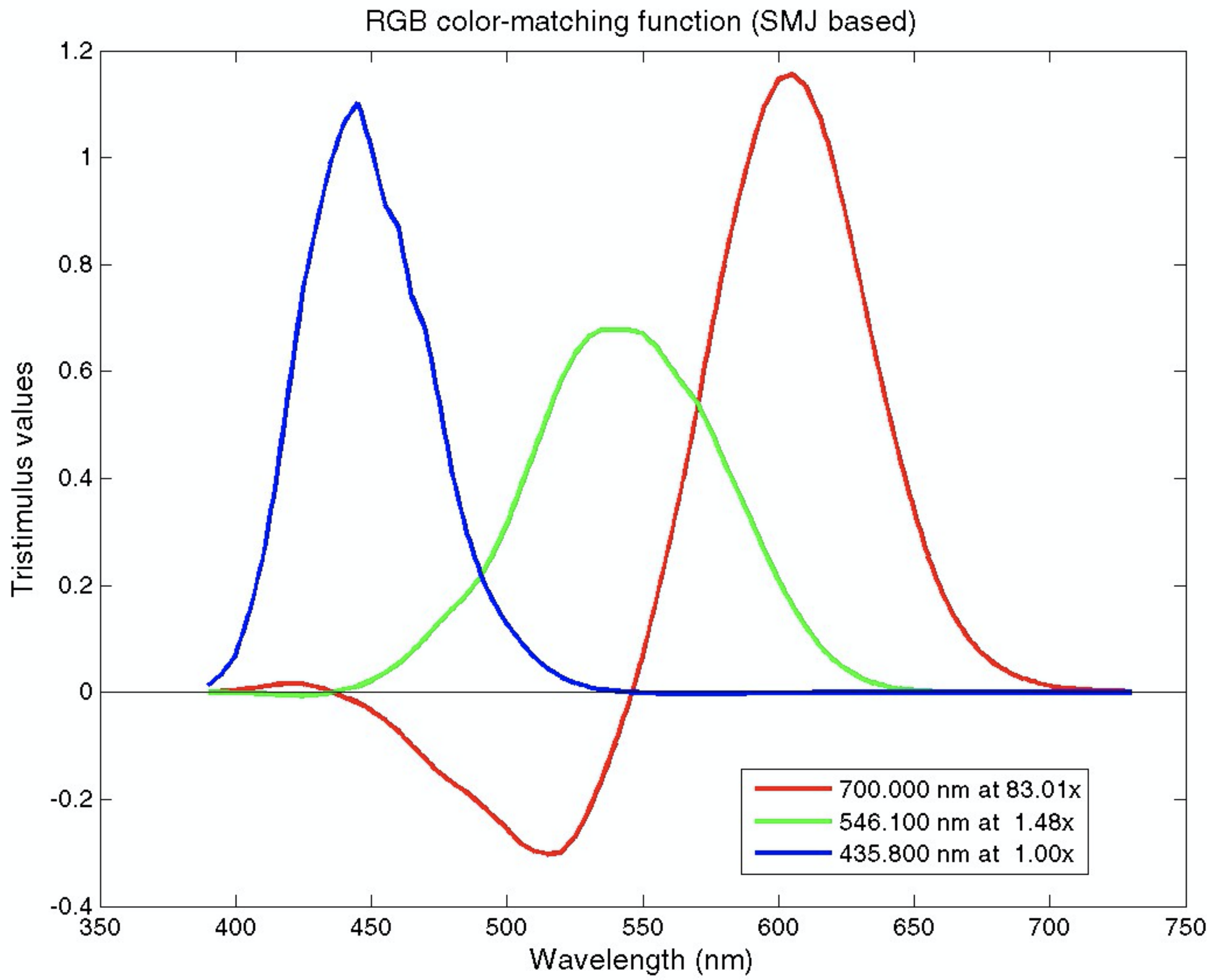
测试光也都是单一波长的光

做测试，测量多少强度的三种主光加起来会获得和测试光一样的颜色

颜色匹配函数 color matching functions 描述了三种主光各自多少强度加起来会获得和测试光一样的颜色。

Graph plots how much of each CIE RGB primary light must be combined to match a monochromatic light of wavelength given on x-axis

Careful: these are not response curves or spectra!



颜色匹配函数 color matching functions 横轴：单一波长光的波长，纵轴：主光强度

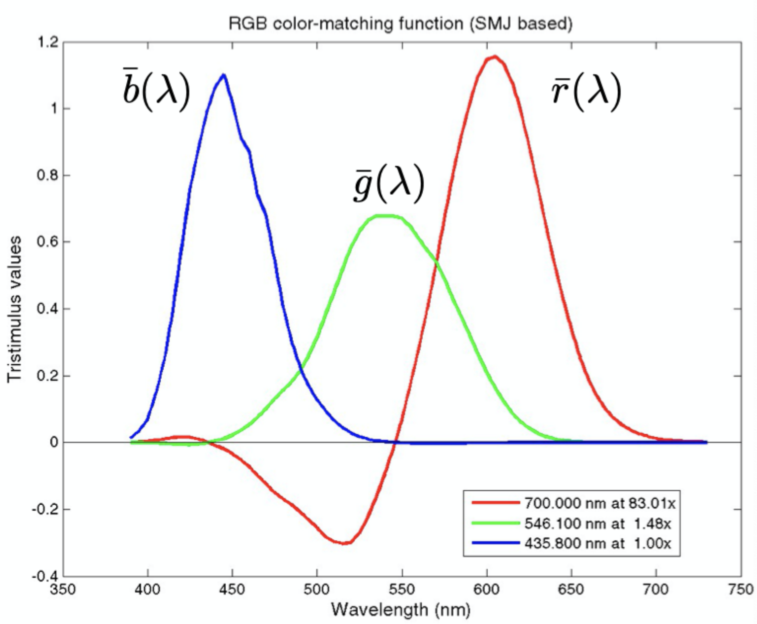
现实的光线 = 许多不同强度单一波长光的积分

现实的光线表示的颜色 = 许多不同强度单一波长光的Color Matching值的积分 → (R,G,B)

$$R_{\text{CIE RGB}} = \int_\lambda s(\lambda)\bar{r}(\lambda)\,d\lambda$$

$$G_{\text{CIE RGB}} = \int_\lambda s(\lambda)\bar{g}(\lambda)\,d\lambda$$

$$B_{\text{CIE RGB}} = \int_\lambda s(\lambda)\bar{b}(\lambda)\,d\lambda$$



Color Spaces 颜色空间

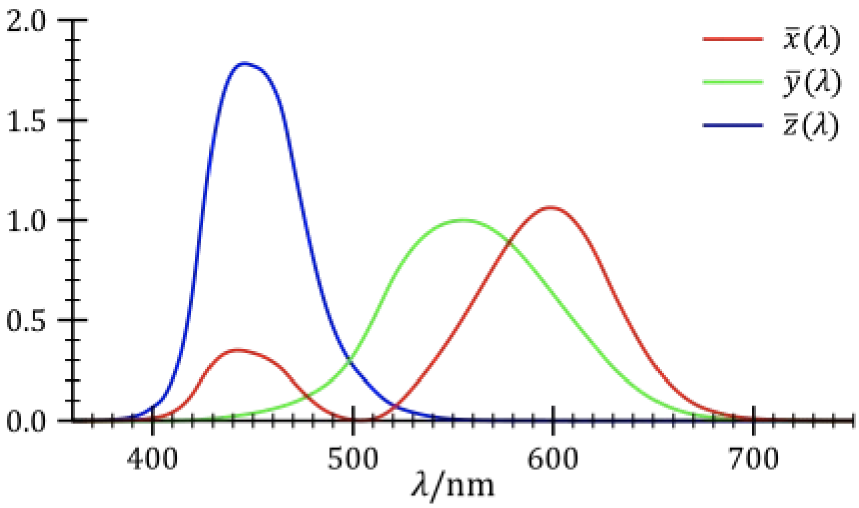
Standard Color Spaces

Standardized RGB (sRGB)

- makes a particular monitor RGB standard
- other color devices simulate that monitor by calibration
- widely adopted today
- gamut (色域) is limited

A Universal Color Space: CIE XYZ

同样定义了**CIE XYZ color matching functions**，但是并非实验测得，而是人造，虚拟的



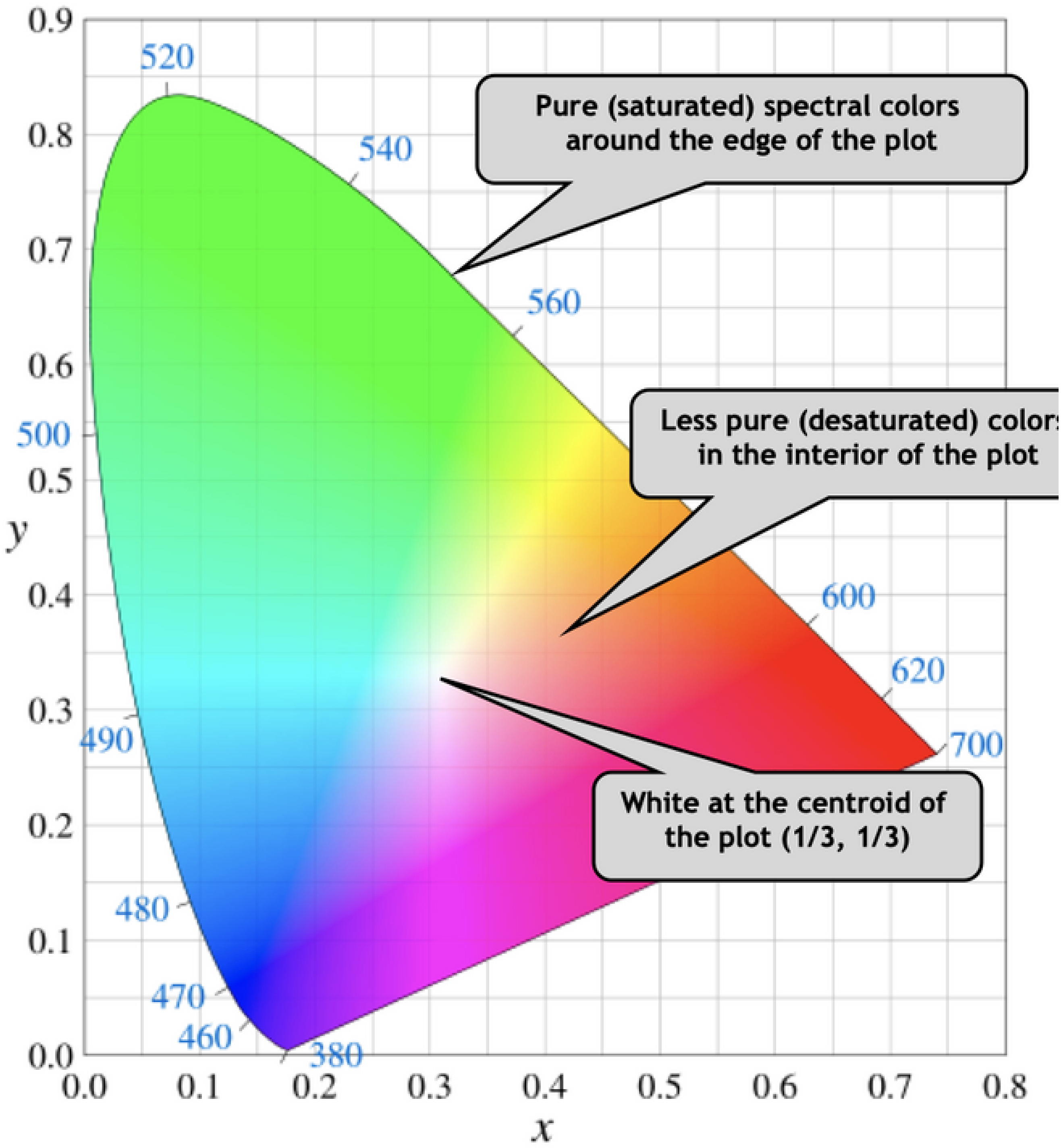
Imaginary set of standard color primaries X, Y, Z

- Primary colors with these matching functions do not exist
- **Y is luminance** (brightness regardless of color) (亮度)

为何如此设计?

- Matching functions are strictly positive 没有负数
- Span all observable colors 覆盖所有可见光

将(X,Y,Z) 归一化获得(x,y,z)（x + y + z = 1），然后对(x,y)做枚举，获得一张二维图像，表示在Y（亮度）固定的情况下，不同X，Z对应的颜色。

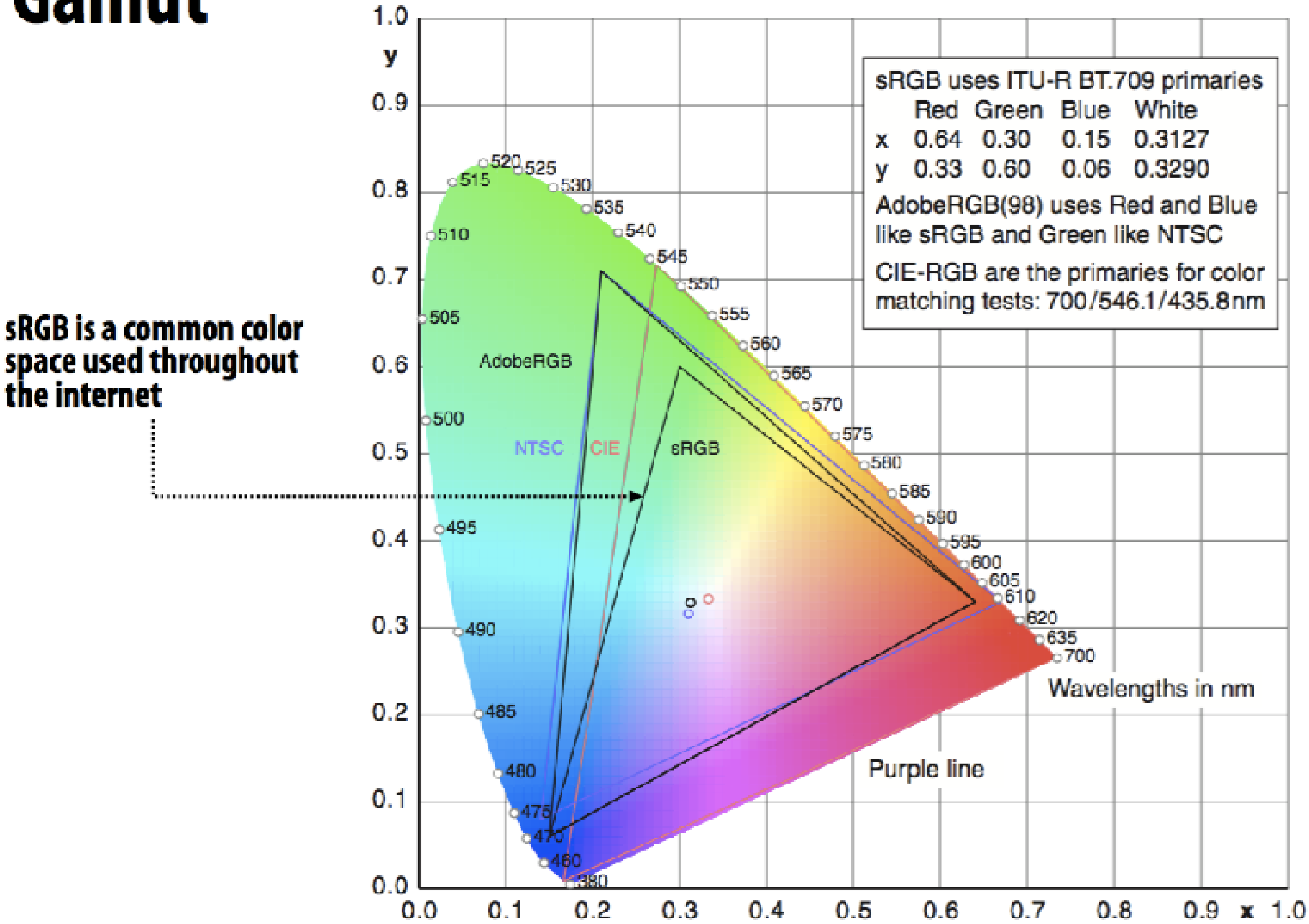


- since x + y + z = 1, we only need to record two of the three
- usually choose x and y, leading to (x, y) coords at a specific brightness Y
- The curved boundary: spectral locus
    - corresponds to monochromatic light (each point representing a pure color of a single wavelength)
- Any color inside is less pure, mixed

Gamut (色域)：the set of chromaticities generated by a set of color primaries

- Different color spaces represent different ranges of colors
- So they have different gamuts, i.e.
- they cover different regions on the chromaticity diagram

Gamut



Perceptually Organized Color Spaces

HSV Color Space (Hue-Saturation-Value)

Axes correspond to artistic characteristics of color

Widely used in a “color picker” 拾色器

Hue(色调)

- the “kind” of color, regardless of attributes
- colorimetric correlate: dominant wavelength
- artist’s correlate: the chosen pigment color

Saturation (饱和度)

- the “colorfulness”
- colorimetric correlate: purity
- artist’s correlate: fraction of paint from the colored tube

Lightness (or value) (亮度)

- the overall amount of light
- colorimetric correlate: luminance
- artist’s correlate: tints are lighter, shades are darker

CIELAB Space (AKA L_a_b*)

A commonly used color space that strives for perceptual uniformity

- L* is lightness (brightness)
- a *and b* are color-opponent pairs
- a* is red-green 正方向：红色，负方向：绿色
- b* is blue-yellow

基于互补色理论（Opponent Color Theory）

There’s a good neurological basis for the color space dimensions in CIE LAB

- the brain seems to encode color early on using three axes:
- white — black, red — green, yellow — blue
- the white — black axis is lightness; the others determine hue and saturation

one piece of evidence: you can have a light green, a dark green, a yellow-green, or a blue-green, but you can’t have a reddish green (just doesn’t make sense)

• thus red is the opponent to green

another piece of evidence: afterimages (following slides)

人眼是奇怪的

- 视觉暂留
- 视错觉
- 颜色的相对性

减色系统

典型：CMYK: A Subtractive Color Space

墨水越混越黑

- Cyan, Magenta, Yellow, and Key
- 靛蓝、品红、黄色、黑色

什么没有提

- HDR
- Gamma Correction矫正：Radiance → 颜色，因为显示器上颜色显示是非线性的，需要抵消