Rainbows & Research

The Science of Color Palettes

Marc Schlichting, *May-The-Fourth-Be-With-You Day 2024*

Clothes make the (wo)man.

Popular German Novella by Gottfried Keller

Clothes make the (wo)man.

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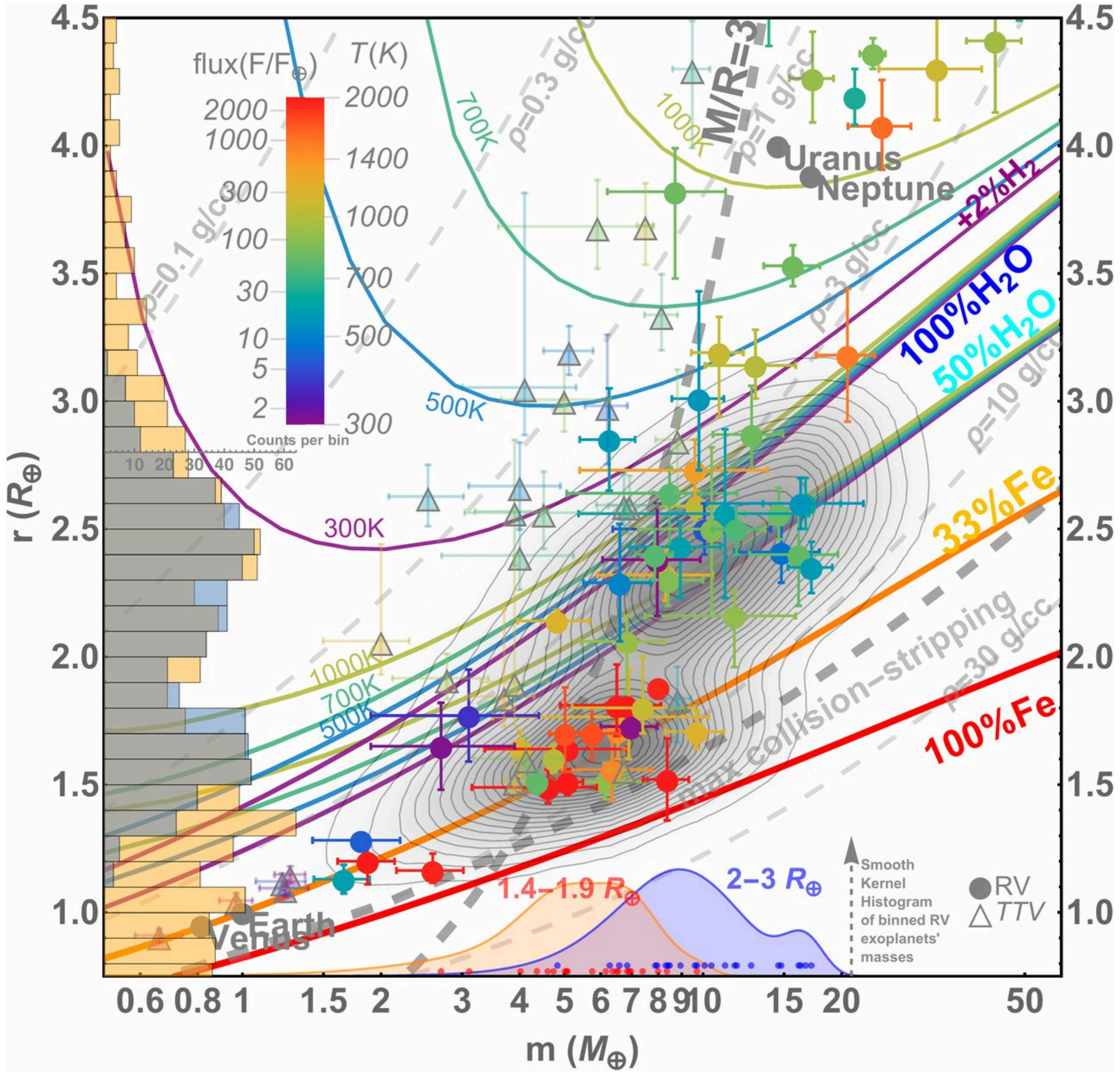

Zeng et al. (2019)

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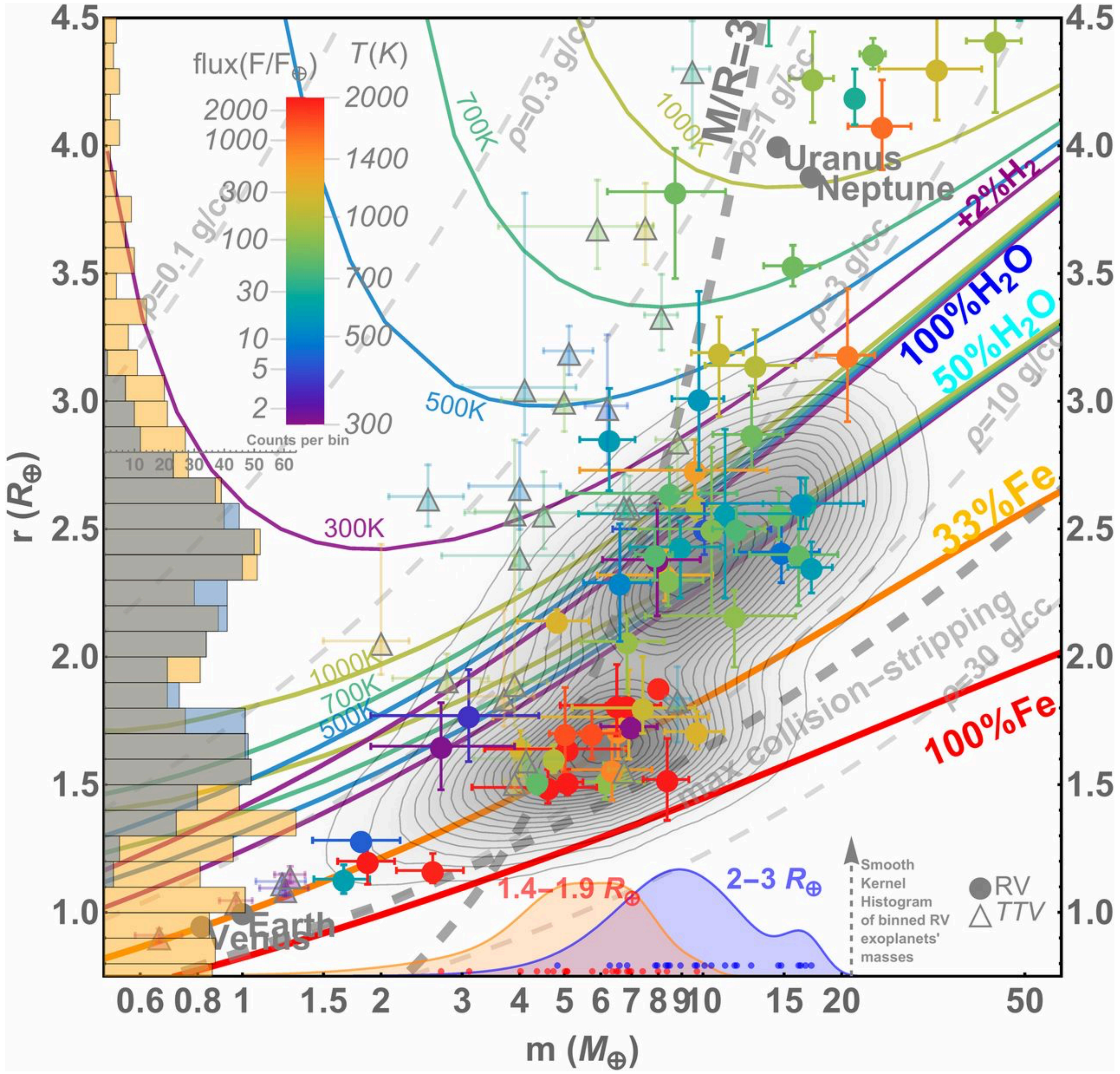


Zeng et al. (2019)

?

Clothes make the (wo)man.

Popular German Novella by Gottfried Keller

Color Palette Criteria

Color Palette Criteria

Distinguishable

Color Palette Criteria

Distinguishable

Accessible

Color Palette Criteria

Distinguishable

Accessible

Aesthetic

Distinguishability

RGB Colorspace

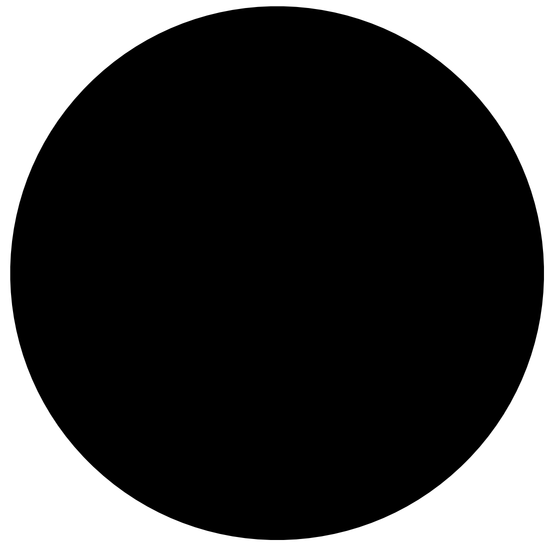
(R,G,B)

Additive Colorspace

RGB Colorspace

(R,G,B)

Additive Colorspace

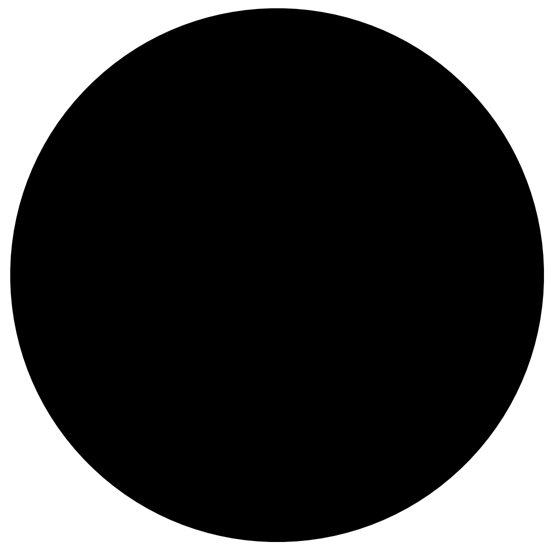


(0,0,0)

RGB Colorspace

(R,G,B)

Additive Colorspace



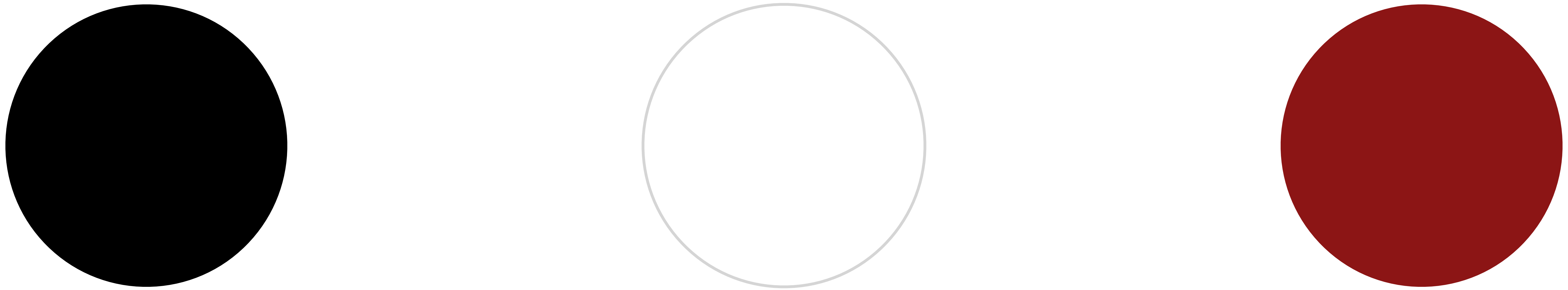
(0,0,0)

(1,1,1)

RGB Colorspace

(R,G,B)

Additive Colorspace



(0,0,0) (1,1,1) (0.55,0.08,0.08)

RGB Colorspace

(R,G,B)

Additive Colorspace

(0,0,0) (1,1,1) (0.55,0.08,0.08) (0.09,0.37,0.33)

Distance in RGB Colorspace

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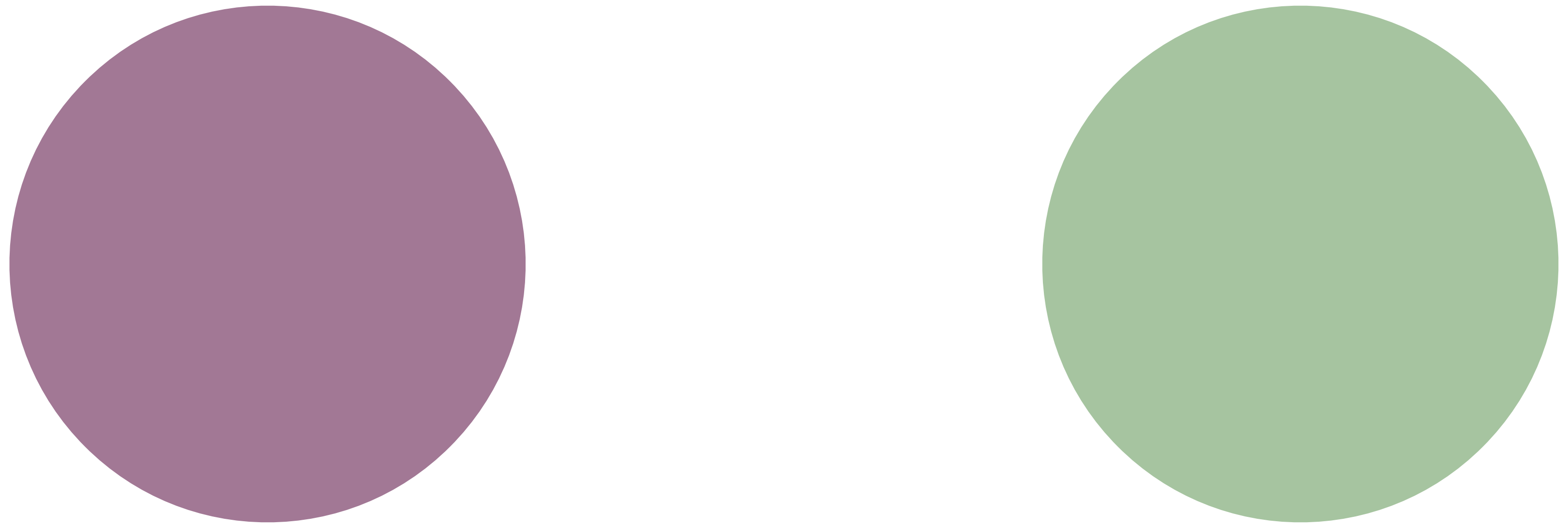
$c_1 = (0.64, 0.47, 0.58)$ $c_2 = (0.65, 0.77, 0.63)$

Distance in RGB Colorspace



$c_1 = (0.64, 0.47, 0.58)$ $c_2 = (0.65, 0.77, 0.63)$

$$\|c_1 - c_2\|_2 = 0.3$$

Distance in RGB Colorspace

$c_1 = (0.64, 0.47, 0.58)$ $c_2 = (0.65, 0.77, 0.63)$ $c_3 = (0.09, 0.98, 0.08)$ $c_4 = (0.32, 0.98, 0.27)$

$$\|c_1 - c_2\|_2 = 0.3$$

Distance in RGB Colorspace

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$\|c_1 - c_2\|_2 = 0.3$ $\|c_3 - c_4\|_2 = 0.3$

Takeaway: Euclidean distances in RGB are $\neq$ perceptual distances

LAB Colorspace

(L,a,b)

LAB Colorspace

(L,a,b)

0 100

L

LAB Colorspace

(L,a,b)

LAB Colorspace

(L,a,b)

Delta E Color Distance

Delta E 76

$$\Delta E = \sqrt{(L_2 - L_1)^2 + (a_2 - a_1)^2 + (b_2 - b_1)^2}$$

Delta E Color Distance

Delta E 76

$$\Delta E = \sqrt{(L_2 - L_1)^2 + (a_2 - a_1)^2 + (b_2 - b_1)^2}$$

Unfortunately: Even the LAB colorspace is not perceptually uniform

Delta E Color Distance

Delta E 94

$$\Delta E_{94}^* = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C_{ab}^*}{k_C S_C}\right)^2 + \left(\frac{\Delta H_{ab}^*}{k_H S_H}\right)^2}$$

$$\Delta L^* = L_1^* - L_2^*$$
$$C_1^* = \sqrt{{a_1^*}^2 + {b_1^*}^2}$$
$$C_2^* = \sqrt{{a_2^*}^2 + {b_2^*}^2}$$
$$\Delta C_{ab}^* = C_1^* - C_2^*$$
$$\Delta H_{ab}^* = \sqrt{{\Delta E_{ab}^*}^2 - {\Delta L^*}^2 - {\Delta C_{ab}^*}^2} = \sqrt{{\Delta a^*}^2 + {\Delta b^*}^2 - {\Delta C_{ab}^*}^2}$$
$$\Delta a^* = a_1^* - a_2^*$$
$$\Delta b^* = b_1^* - b_2^*$$
$$S_L = 1$$
$$S_C = 1 + K_1 C_1^*$$
$$S_H = 1 + K_2 C_1^*$$

Delta E Color Distance

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$$\begin{aligned}
&\Delta L^* = L_1^* - L_2^* \\
&C_1^* = \sqrt{a_1^{*2} + b_1^{*2}} \\
&C_2^* = \sqrt{a_2^{*2} + b_2^{*2}} \\
&\Delta C_{ab}^* = C_1^* - C_2^* \\
&\Delta H_{ab}^* = \sqrt{{\Delta E_{ab}^*}^2 - {\Delta L^*}^2 - {\Delta C_{ab}^*}^2} = \sqrt{{\Delta a^*}^2 + {\Delta b^*}^2 - {\Delta C_{ab}^*}^2} \\
&\Delta a^* = a_1^* - a_2^* \\
&\Delta b^* = b_1^* - b_2^* \\
&S_L = 1 \\
&S_C = 1 + K_1 C_1^* \\
&S_H = 1 + K_2 C_1^*
\end{aligned}$$

Still not good enough...apparently

Delta E Color Distance

Delta E 2000

$$\Delta E_{00}^* = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_H S_H}}$$

$$\Delta L' = L_2^* - L_1^*$$

$$\bar{L} = \frac{L_1^* + L_2^*}{2} \quad \bar{C} = \frac{C_1^* + C_2^*}{2}$$

$$a_1' = a_1^* + \frac{a_1^*}{2}\left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right) \quad a_2' = a_2^* + \frac{a_2^*}{2}\left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right)$$

$$\bar{C}' = \frac{C_1' + C_2'}{2} \text{ and } \Delta C' = C_2' - C_1' \quad \text{where } C_1' = \sqrt{a_1'^2 + b_1^{*2}} \quad C_2' = \sqrt{a_2'^2 + b_2^{*2}}$$

$$h_1' = \operatorname{atan2}(b_1^*, a_1') \mod 360^\circ, \quad h_2' = \operatorname{atan2}(b_2^*, a_2') \mod 360^\circ$$

$$\Delta h' = \begin{cases} h_2' - h_1' & |h_1' - h_2'| \leq 180^\circ \\ h_2' - h_1' + 360^\circ & |h_1' - h_2'| > 180^\circ, h_2' \leq h_1' \\ h_2' - h_1' - 360^\circ & |h_1' - h_2'| > 180^\circ, h_2' > h_1' \end{cases}$$

$$\Delta H' = 2\sqrt{C_1' C_2'} \sin(\Delta h'/2), \quad \bar{H}' = \begin{cases} (h_1' + h_2' + 360^\circ)/2 & |h_1' - h_2'| > 180^\circ \\ (h_1' + h_2')/2 & |h_1' - h_2'| \leq 180^\circ \end{cases}$$

$$T = 1 - 0.17\cos(\bar{H}' - 30^\circ) + 0.24\cos(2\bar{H}') + 0.32\cos(3\bar{H}' + 6^\circ) - 0.20\cos(4\bar{H}' - 63^\circ)$$

$$S_L = 1 + \frac{0.015\left(\bar{L} - 50\right)^2}{\sqrt{20 + \left(\bar{L} - 50\right)^2}} \quad S_C = 1 + 0.045\bar{C}' \quad S_H = 1 + 0.015\bar{C}'T$$

$$R_T = -2\sqrt{\frac{\bar{C}'^7}{\bar{C}'^7 + 25^7}} \sin\left[60^\circ \cdot \exp\left(-\left[\frac{\bar{H}' - 275^\circ}{25^\circ}\right]^2\right)\right]$$

Delta E Color Distance

Delta E 2000

$$\Delta E_{00}^{*} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C} \frac{\Delta H'}{k_H S_H}}$$

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We still use this today…so hopefully good enough

Delta E Color Distance

Delta E 2000

Delta E	Perception
< 1	Not distinguishable by humans
1 - 2	Difference can only be seen through close observation
2 - 10	Distinguishable
11 - 49	Colors are more similar than opposite
100	Colors are the exact opposite

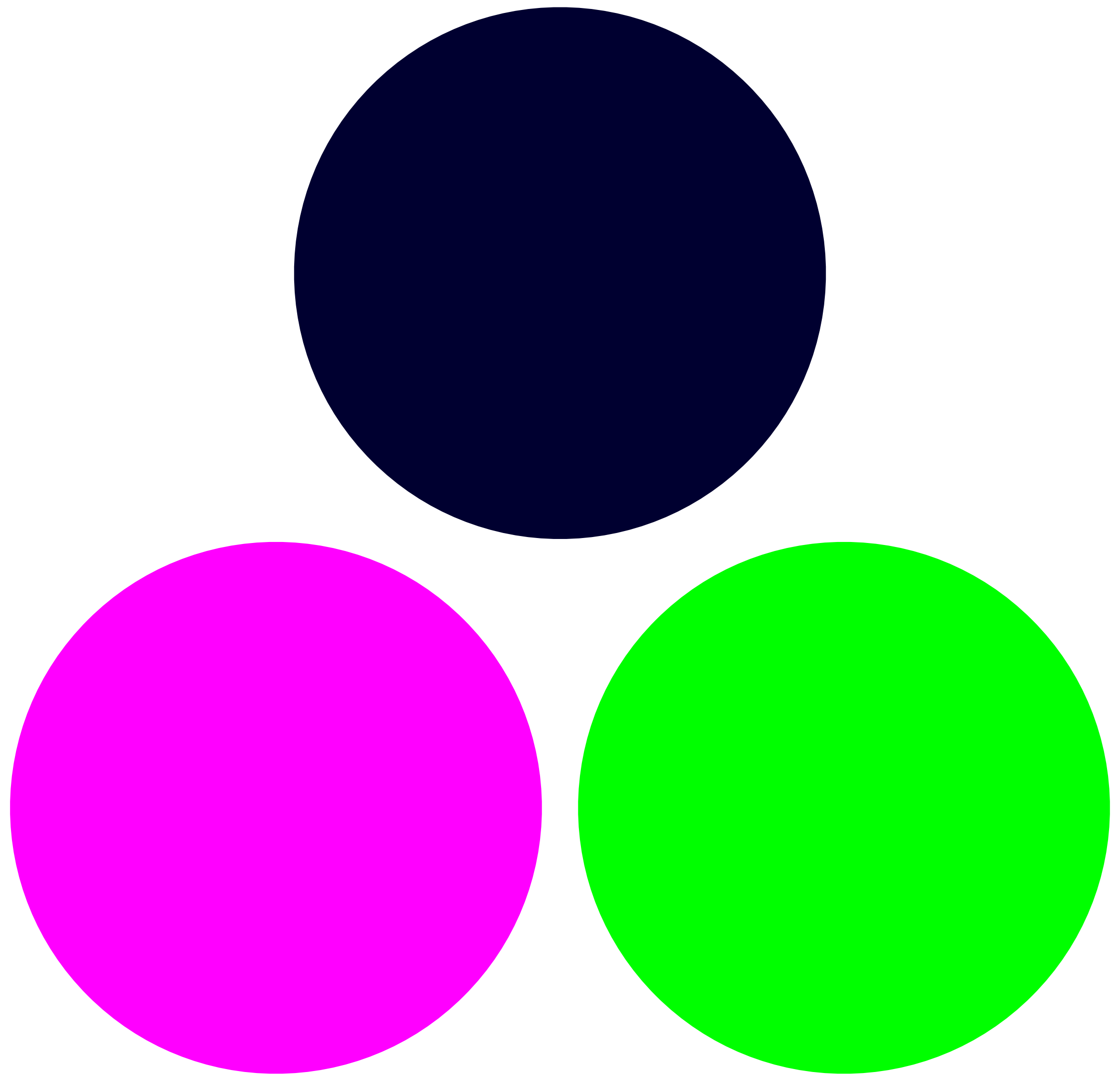
The Perfect Color Palette

A First Attempt

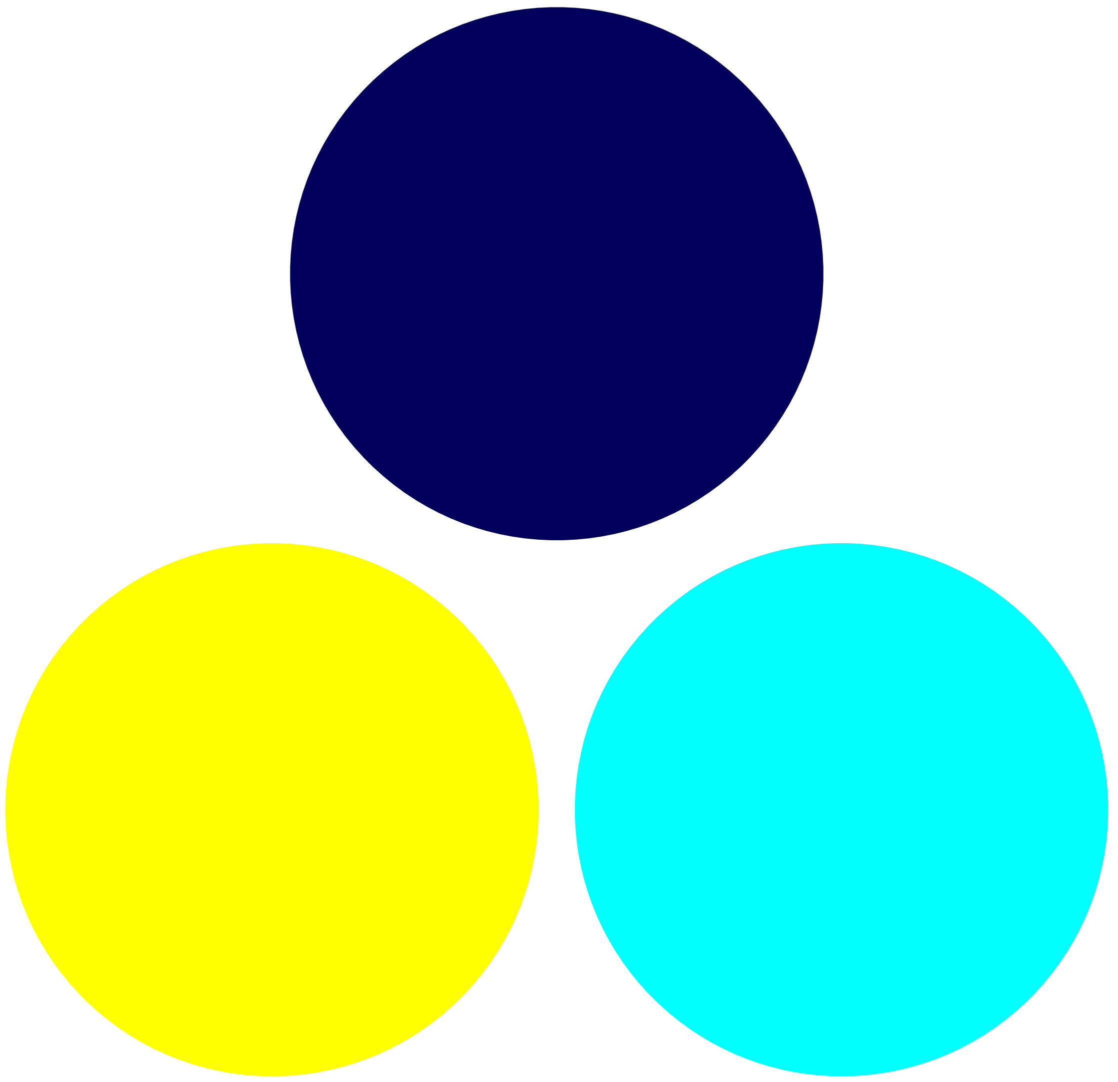
$$\underset{c_1,\ldots,c_n}{\text{maximize}} \sum_{i=1}^{n-1} \left(\sum_{j=i+1}^{n} \left(\Delta E(c_i, c_j \right) \right)$$

The Perfect Color Palette

A First Attempt



Mode 1



Mode 2

The Perfect Color Palette

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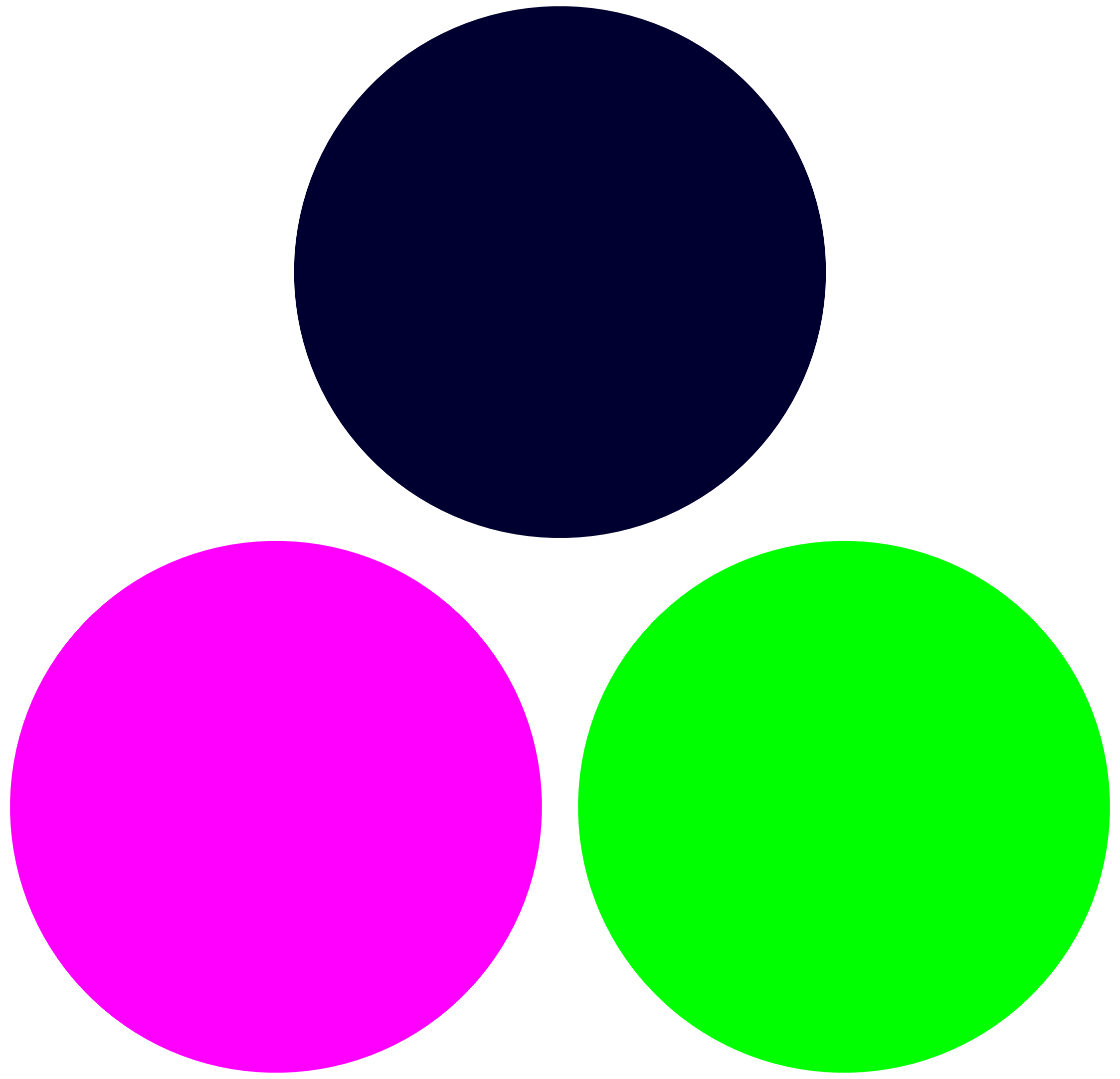
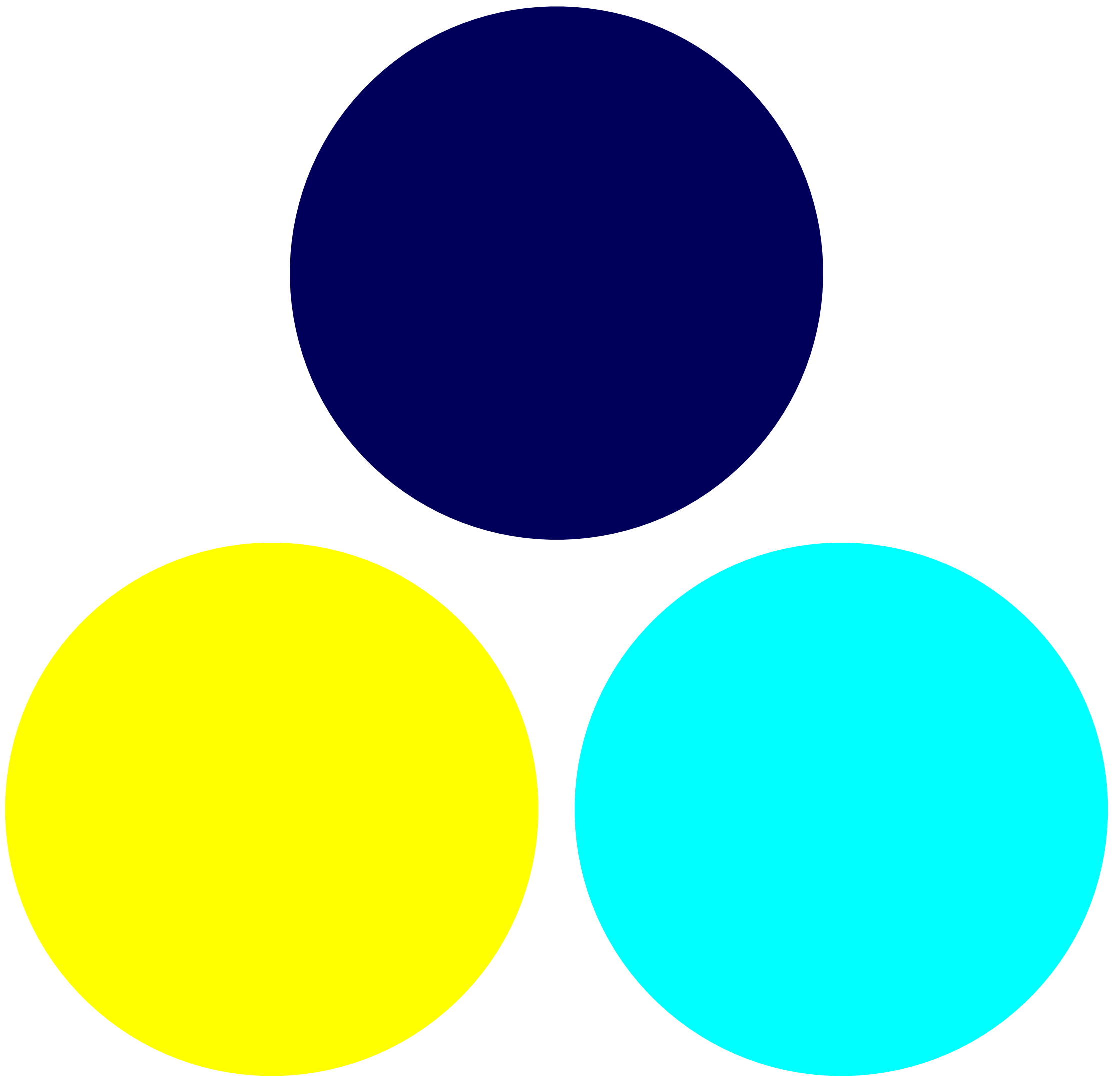


Mode 1



Mode 2

Especially mode 2 is visually hard to distinguish from a white background

The Perfect Color Palette

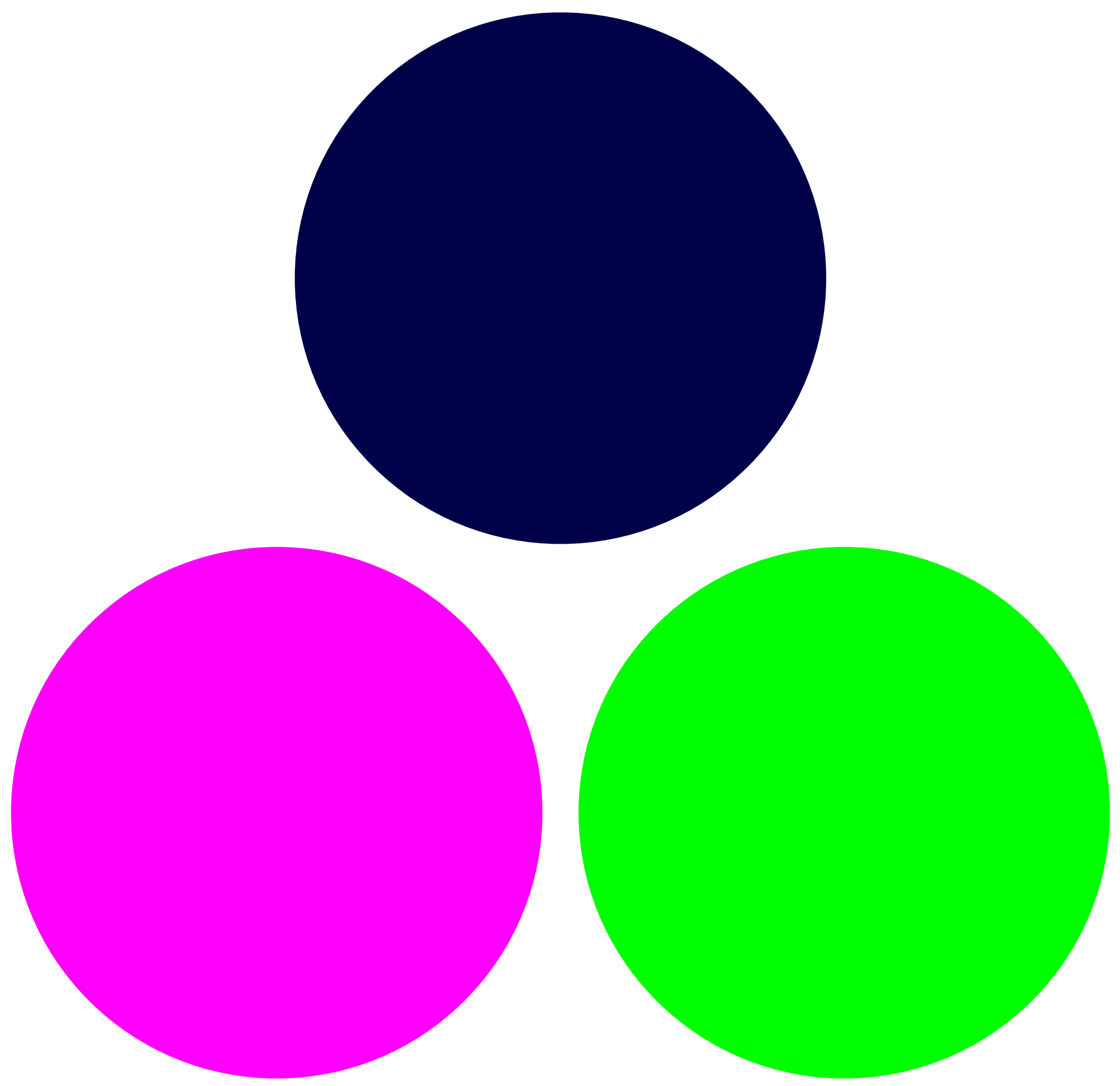
A Second Attempt

$$\underset{c_1,\ldots,c_n}{\text{maximize}} \sum_{i=1}^{n-1} \left(\sum_{j=i+1}^{n} \left(\Delta E(c_i, c_j) \right) \right) + \sum_{i=1}^{n} \left(\Delta E(c_0, c_i) \right)$$

Background Color

The Perfect Color Palette

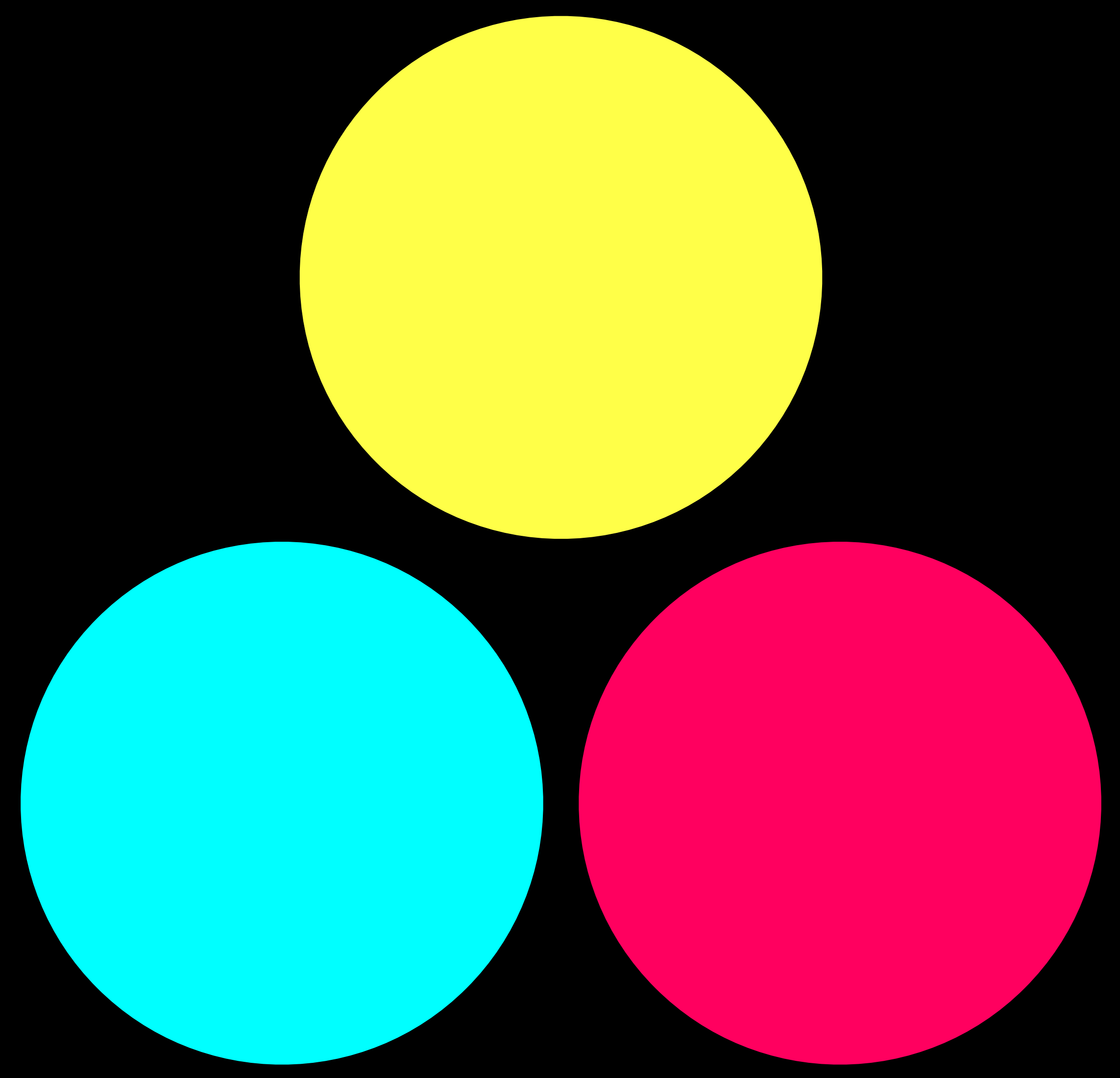
A Second Attempt



Mode 1

The Perfect Color Palette

A Second Attempt



Mode 1

Accessibility

Colorblindness Types

Colorblindness Types

Protanopia

Deuteranopia

Tritanopia

Colorblindness Types

Protanopia

Blindness to Red

$\approx 1\,\%$

Deuteranopia

Tritanopia

Colorblindness Types

Protanopia

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$\approx 1\,\%$

Deuteranopia

Blindness to Green

$\approx 1.5 - 5\,\%$

Tritanopia

Colorblindness Types

Protanopia

Blindness to Red

$\approx 1\,\%$

Deuteranopia

Blindness to Green

$\approx 1.5 - 5\,\%$

Tritanopia

Blindness to Blue

$< 0.01\,\%$

Colorblindness Types

Trichromasy	Protanopia	Deuteranopia	Tritanopia
Normal Vision	Blindness to Red	Blindness to Green	Blindness to Blue

Colorblindness Types

Trichromasy

Normal Vision

Protanopia

Blindness to Red

Deuteranopia

Blindness to Green

Tritanopia

Blindness to Blue

The Perfect Color Palette

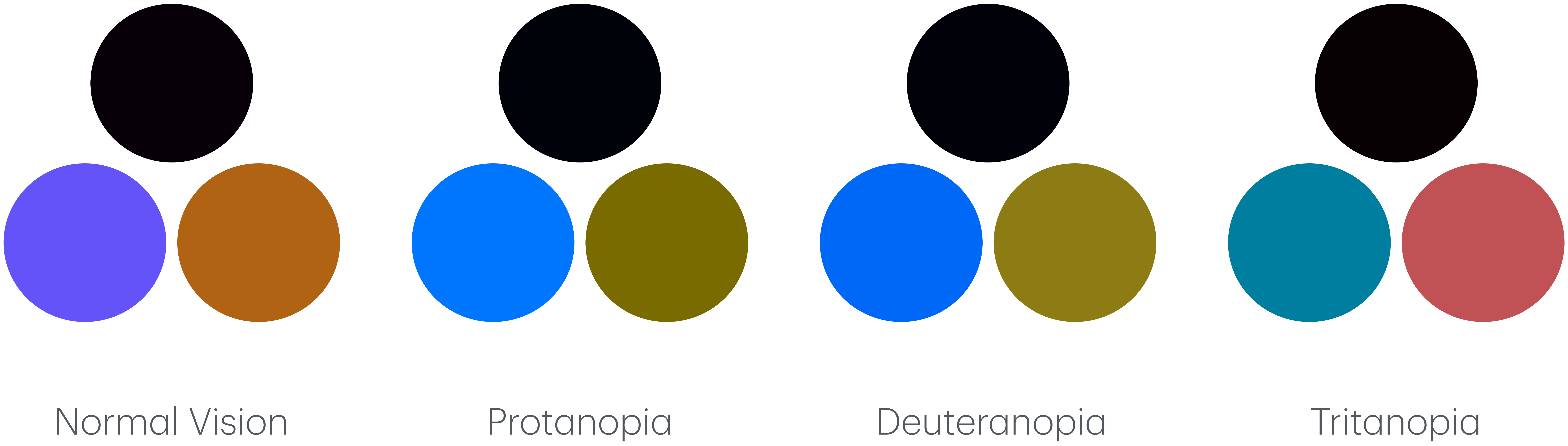
A Third Attempt

$$\underset{c_1,\ldots,c_n}{\text{maximize}} \sum_{a \in \{\text{norm.},\text{pro.},\text{deu.},\text{tri.}\}} \lambda^a \left(\sum_{i=1}^{n-1} \left(\sum_{j=i+1}^{n} \left(\Delta E(c_i^a, c_j^a \right) \right) + \sum_{i=1}^{n} \left(\Delta E(c_0^a, c_i^a) \right) \right)$$

Normal Protanopia Deuteranopia Tritanopia

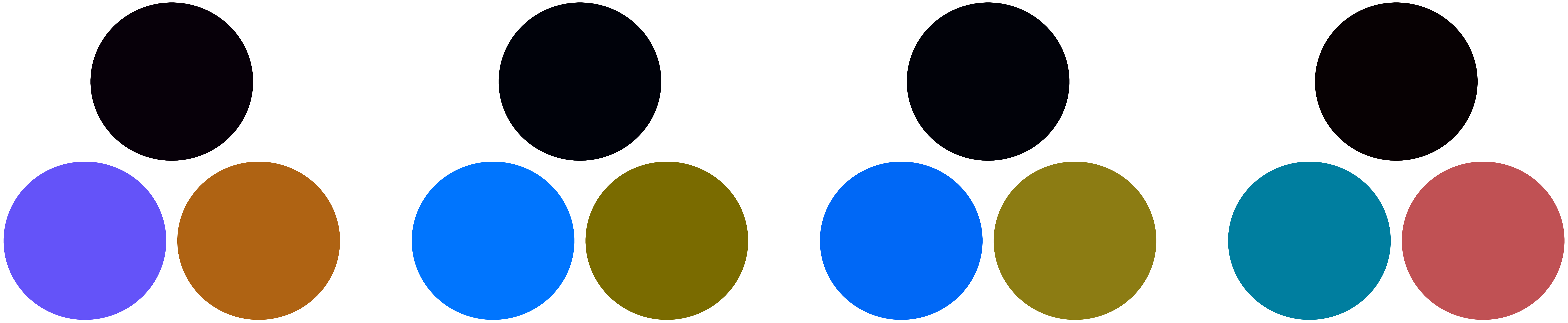
The Perfect Color Palette

A Third Attempt



The Perfect Color Palette

A Third Attempt



Normal Vision | Protanopia | Deuteranopia | Tritanopia

Let's be honest, this color palette doesn't look that nice

Aesthetics

What is aesthetic?

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What is aesthetic?

- Human preferences are highly subjective and common mechanisms are poorly understood
- We need a ΔE for aesthetics!
- Sadly, this doesn't exist 😭
- Data-driven approach: learn a function (i.e., neural network) that given two input colors predicts how aesthetically pleasing someone finds the combination of colors
- We need your help! Will be sending out a questionnaire early next week. As incentive: stylish color palettes for presentations and publications!

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- **LAB** colorspace and $\Delta\mathbf{E}$ are useful to calculate how distinguishable colors are
- The three most common types of colorblindness are **protanopia**, **deuteranopia**, and **tritanopia**

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- Building **distinguishable** and **accessible** color palettes is just an optimization problem
- It works with an **arbitrary number** of colors and you can use **seed colors**
- **LAB** colorspace and $\mathbf{\Delta E}$ are useful to calculate how distinguishable colors are
- The three most common types of colorblindness are **protanopia**, **deuteranopia**, and **tritanopia**
- Defining what is aesthetic is hard! **Survey!**

Thank You