

Rainbows & Research

The Science of Color Palettes

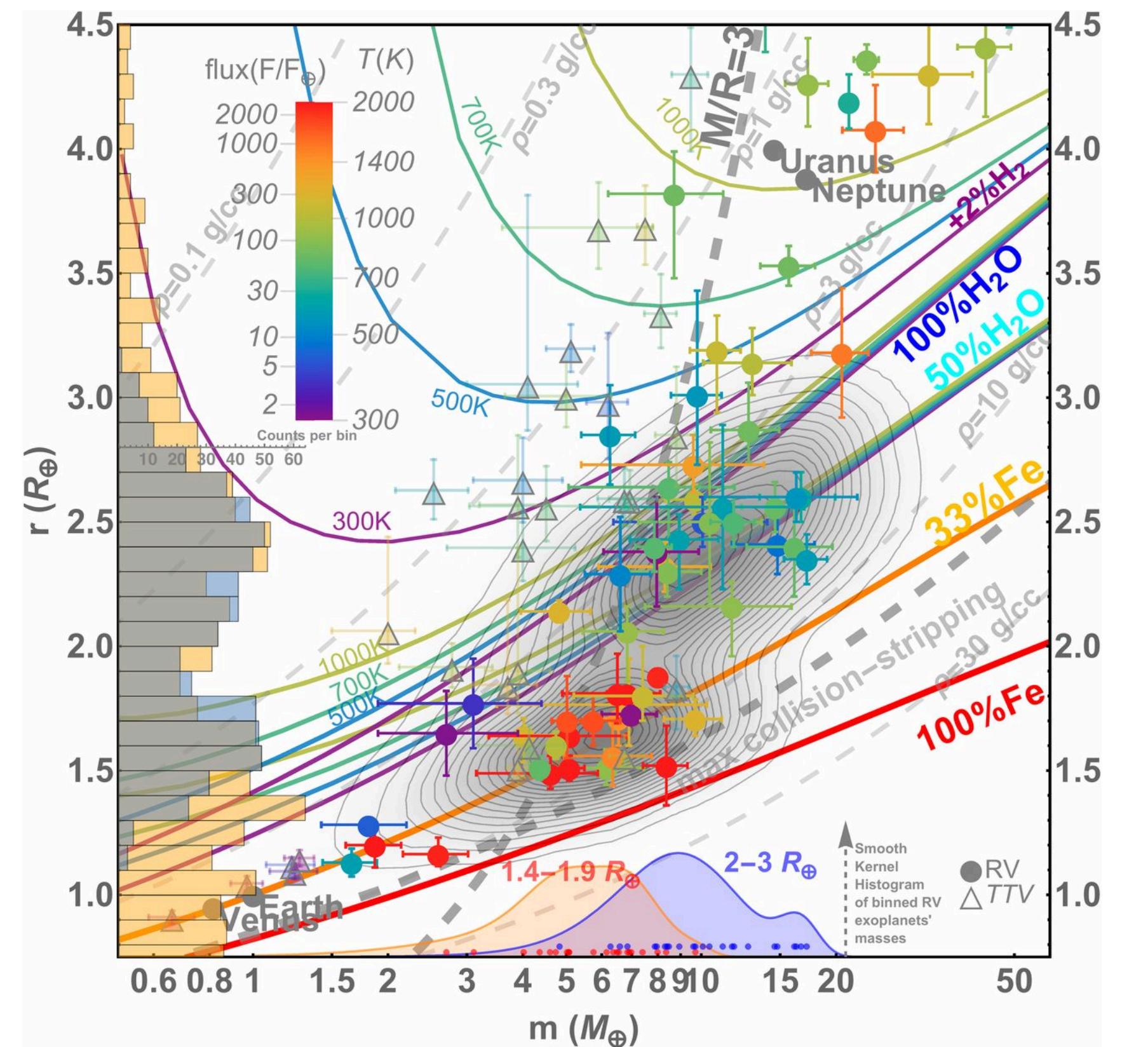
Marc Schlichting, May-The-Fourth-Be-With-You Day 2024

Clothes make the (wo)man.

Popular German Novella by Gottfried Keller

Clothes make the (wo)man.

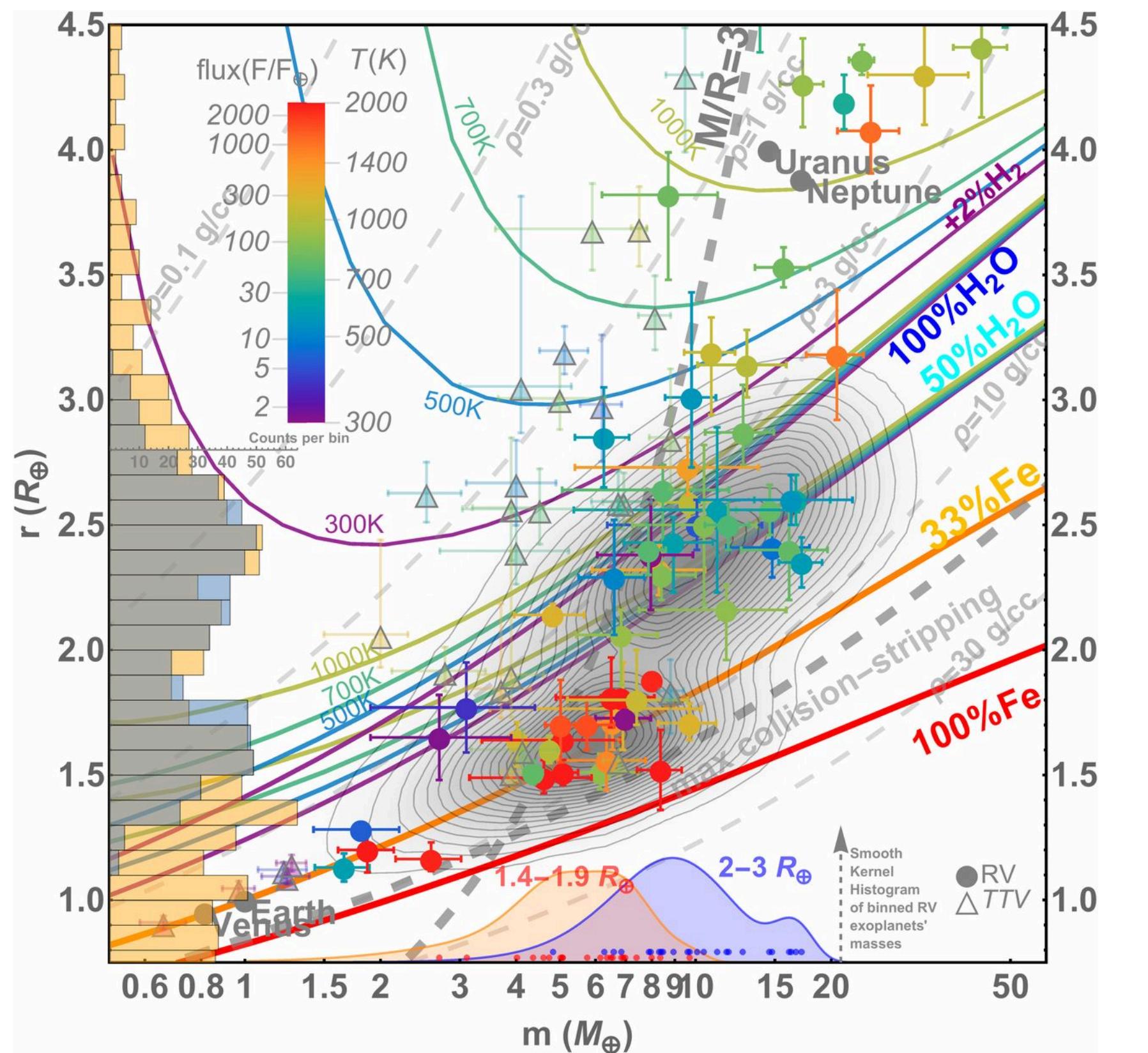
Popular German Novella by Gottfried Keller



Zeng et al. (2019)

Clothes make the (wo)man.

Popular German Novella by Gottfried Keller



Zeng et al. (2019)



Clothes make the (wo)man.

Popular German Novella by Gottfried Keller

Color Palette Criteria

Color Palette Criteria

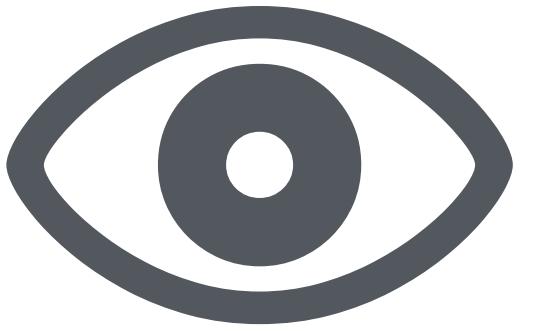


Distinguishable

Color Palette Criteria



Distinguishable

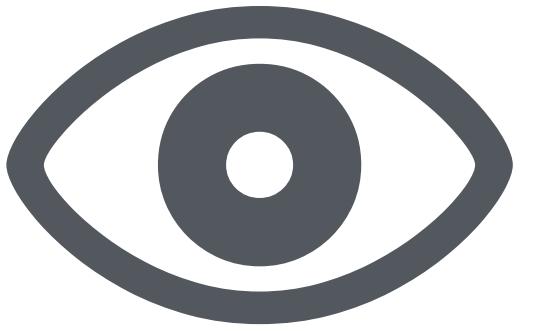


Accessible

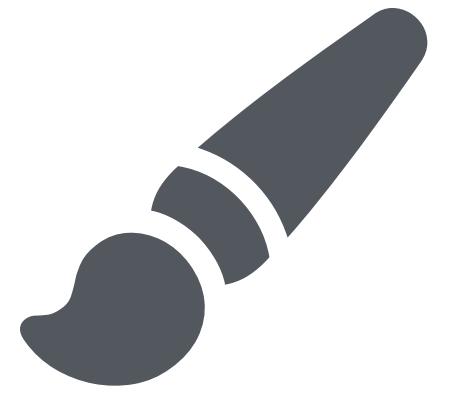
Color Palette Criteria



Distinguishable



Accessible



Aesthetic

Distinguishability

RGB Colorspace

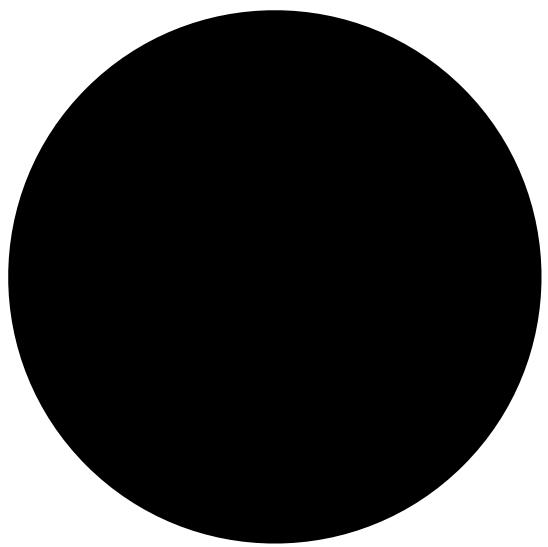
(R,G,B)

Additive Colorspace

RGB Colorspace

(R,G,B)

Additive Colorspace

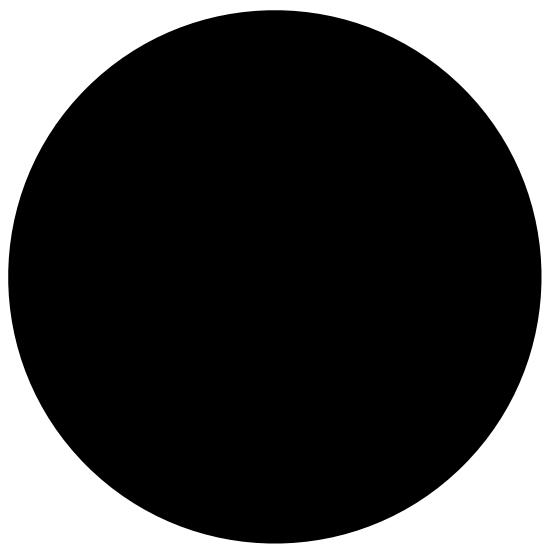


(0,0,0)

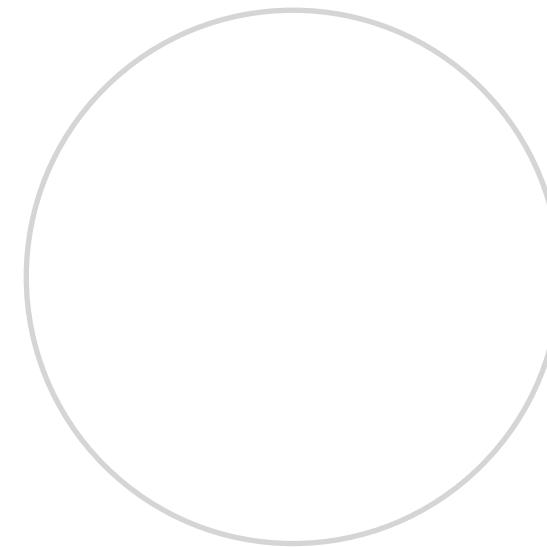
RGB Colorspace

(R,G,B)

Additive Colorspace



(0,0,0)

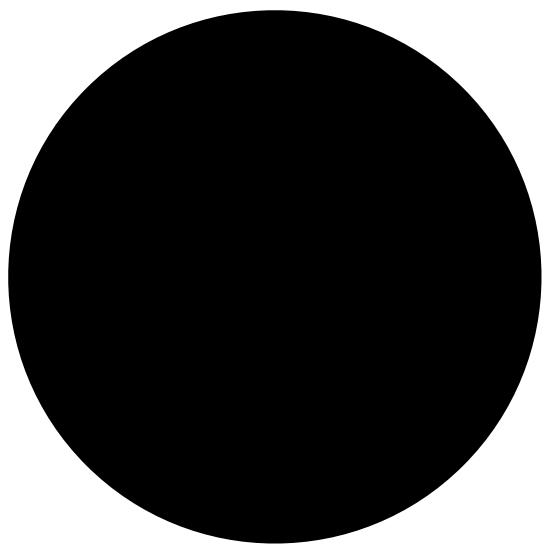


(1,1,1)

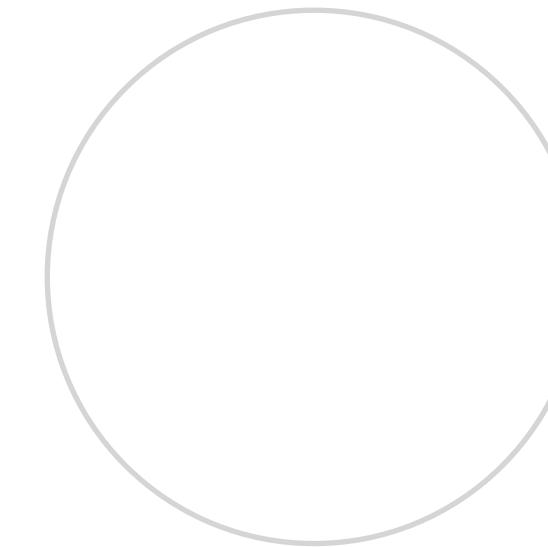
RGB Colorspace

(R,G,B)

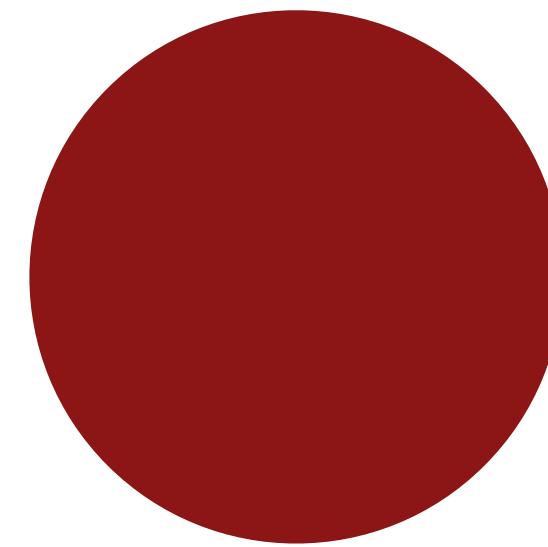
Additive Colorspace



(0,0,0)



(1,1,1)

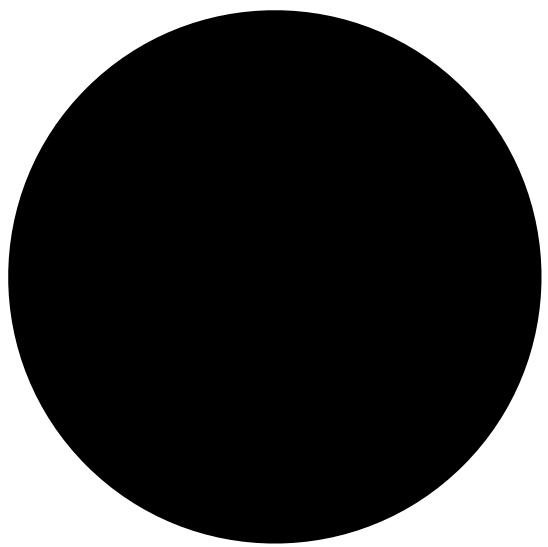


(0.55,0.08,0.08)

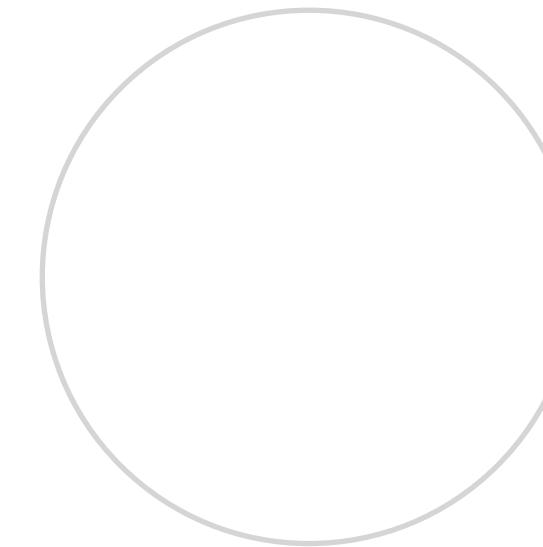
RGB Colorspace

(R,G,B)

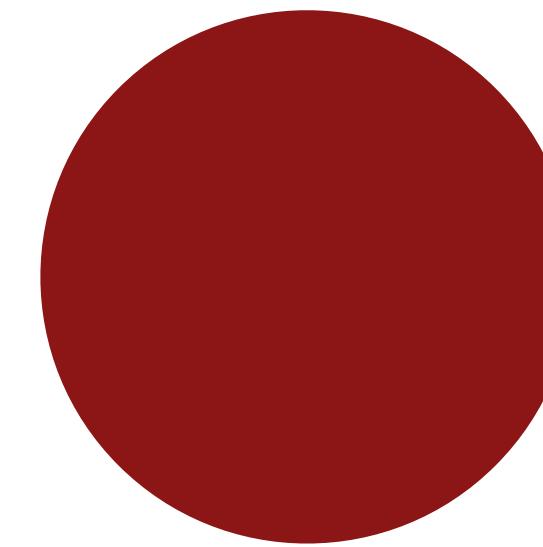
Additive Colorspace



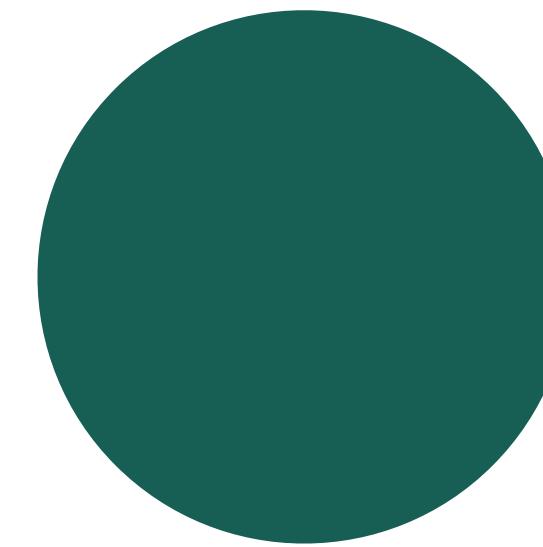
(0,0,0)



(1,1,1)



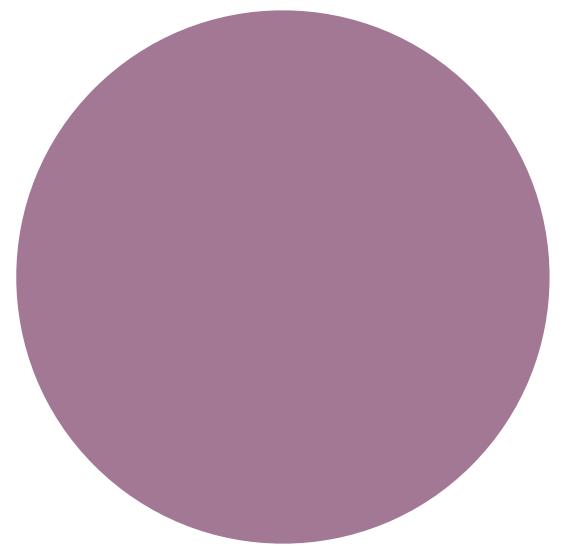
(0.55,0.08,0.08)



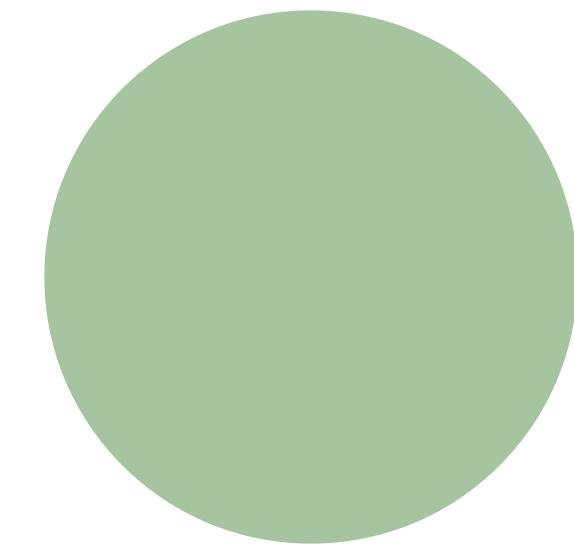
(0.09,0.37,0.33)

Distance in RGB Colorspace

Distance in RGB Colorspace

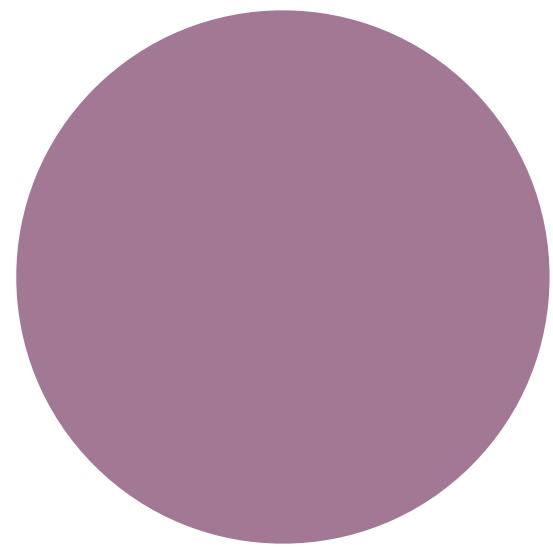


$c_1 = (0.64, 0.47, 0.58)$



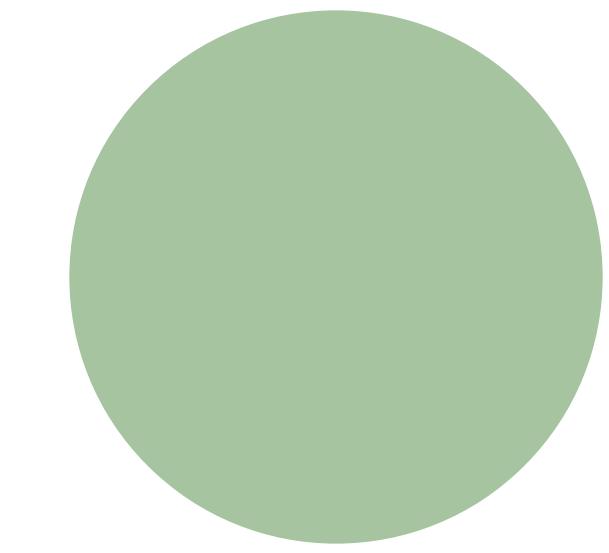
$c_2 = (0.65, 0.77, 0.63)$

Distance in RGB Colorspace



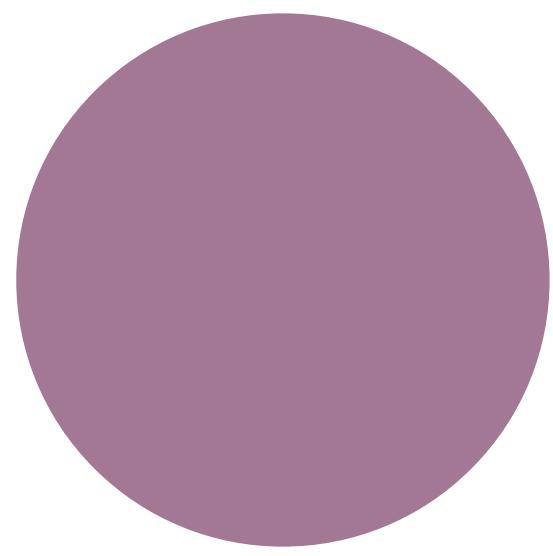
$$c_1 = (0.64, 0.47, 0.58)$$

$$c_2 = (0.65, 0.77, 0.63)$$

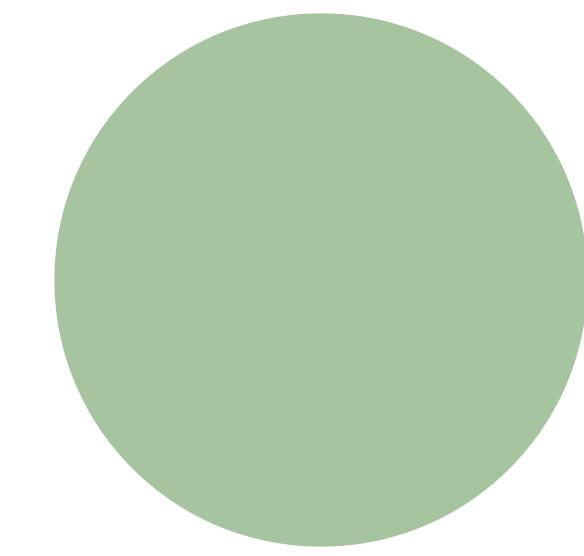


$$\|c_1 - c_2\|_2 = 0.3$$

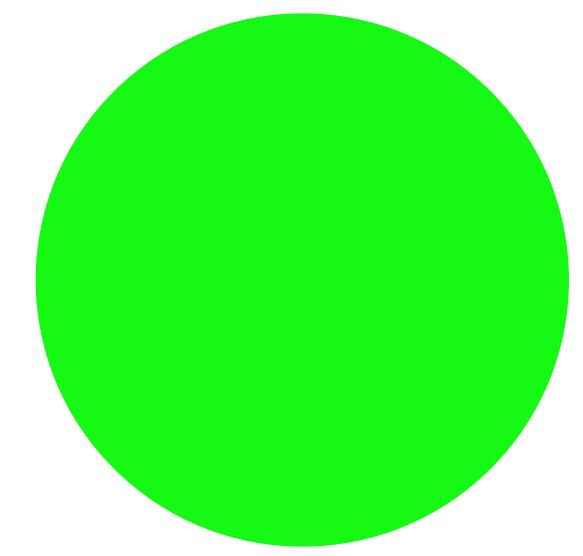
Distance in RGB Colorspace



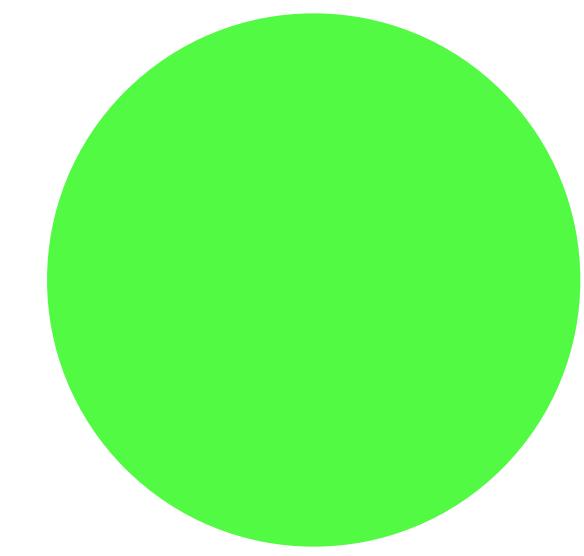
$c_1 = (0.64, 0.47, 0.58)$



$c_2 = (0.65, 0.77, 0.63)$



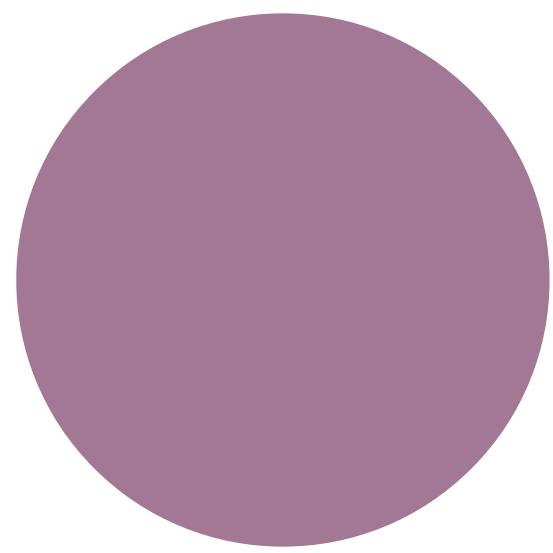
$c_3 = (0.09, 0.98, 0.08)$



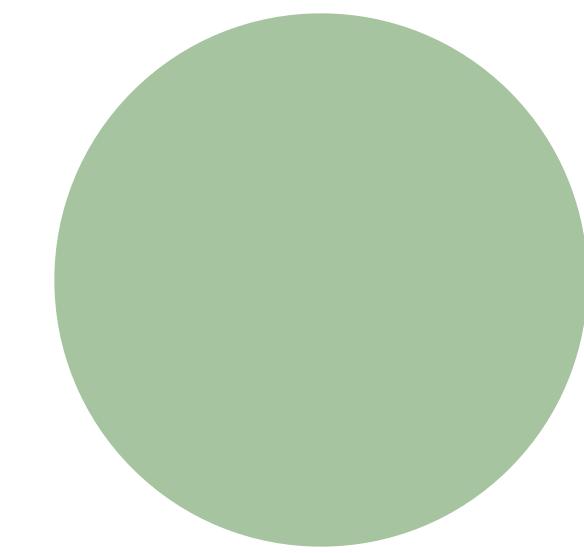
$c_4 = (0.32, 0.98, 0.27)$

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

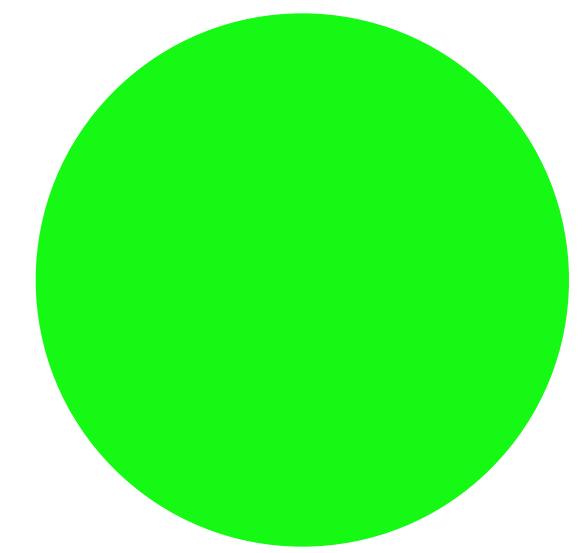
Distance in RGB Colorspace



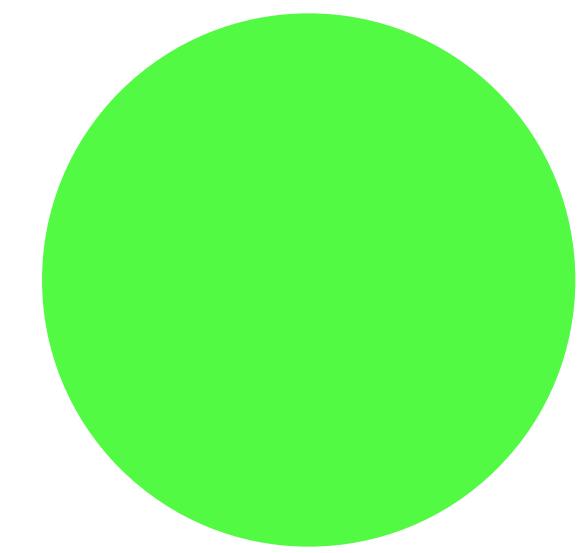
$c_1 = (0.64, 0.47, 0.58)$



$c_2 = (0.65, 0.77, 0.63)$



$c_3 = (0.09, 0.98, 0.08)$

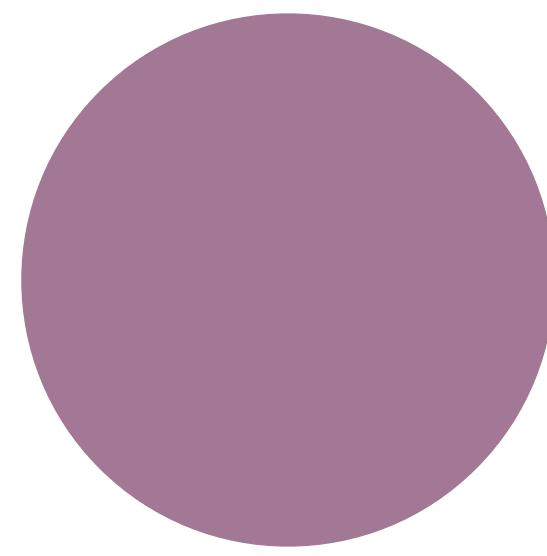


$c_4 = (0.32, 0.98, 0.27)$

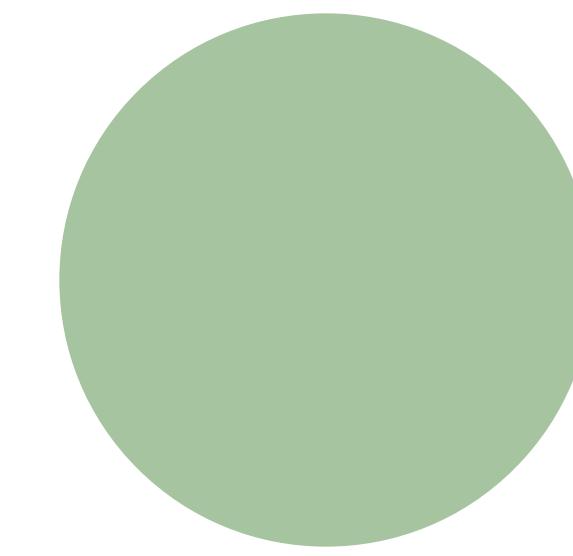
$$\|c_1 - c_2\|_2 = 0.3$$

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

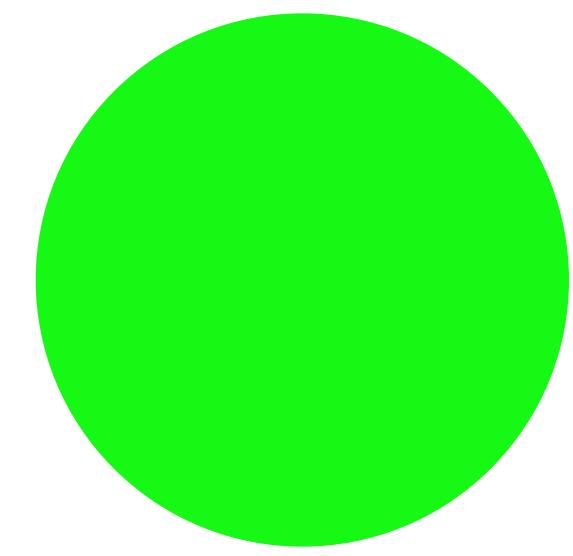
Distance in RGB Colorspace



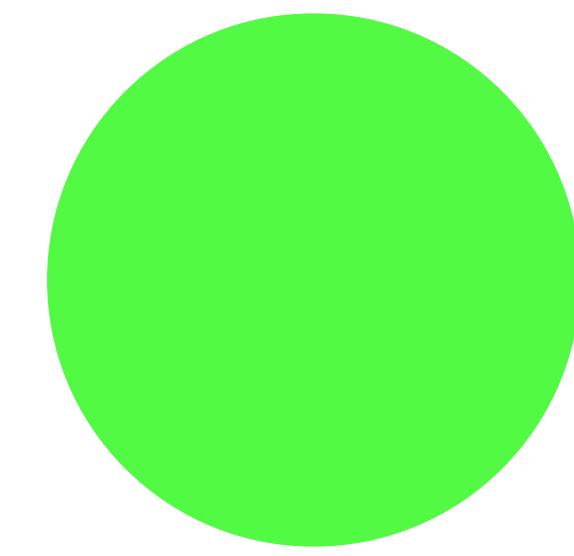
$$c_1 = (0.64, 0.47, 0.58)$$



$$c_2 = (0.65, 0.77, 0.63)$$



$$c_3 = (0.09, 0.98, 0.08)$$



$$c_4 = (0.32, 0.98, 0.27)$$

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

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

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)



0

100

-128

127

L



a

LAB Colorspace

(L,a,b)



0

100

L



-128

a



-128

b

127

127

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

Delta E 94

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

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

$$C_1^* = \sqrt{a_1^{*2} + b_1^{*2}}$$

$$C_2^* = \sqrt{a_2^{*2} + b_2^{*2}}$$

$$\Delta C_{ab}^* = C_1^* - C_2^*$$

$$\Delta H_{ab}^* = \sqrt{{\Delta E_{ab}^*}^2 - {\Delta L^*}^2 - {\Delta C_{ab}^*}^2} = \sqrt{{\Delta a^*}^2 + {\Delta b^*}^2 - {\Delta C_{ab}^*}^2}$$

$$\Delta a^* = a_1^* - a_2^*$$

$$\Delta b^* = b_1^* - b_2^*$$

$$S_L = 1$$

$$S_C = 1 + K_1 C_1^*$$

$$S_H = 1 + K_2 C_1^*$$

Still not good enough...apparently

Delta E Color Distance

Delta E 2000

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

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

$$a'_1 = a_1^* + \frac{a_1^*}{2} \left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right) \quad a'_2 = a_2^* + \frac{a_2^*}{2} \left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right)$$

$$\bar{C}' = \frac{C'_1 + C'_2}{2} \text{ and } \Delta C' = C'_2 - C'_1 \quad \text{where } C'_1 = \sqrt{a'^2_1 + b'^2_1} \quad C'_2 = \sqrt{a'^2_2 + b'^2_2}$$

$$h'_1 = \text{atan2}(b_1^*, a'_1) \mod 360^\circ, \quad h'_2 = \text{atan2}(b_2^*, a'_2) \mod 360^\circ$$

$$\Delta h' = \begin{cases} h'_2 - h'_1 & |h'_1 - h'_2| \leq 180^\circ \\ h'_2 - h'_1 + 360^\circ & |h'_1 - h'_2| > 180^\circ, h'_2 \leq h'_1 \\ h'_2 - h'_1 - 360^\circ & |h'_1 - h'_2| > 180^\circ, h'_2 > h'_1 \end{cases}$$

$$\Delta H' = 2\sqrt{C'_1 C'_2} \sin(\Delta h'/2), \quad \bar{H}' = \begin{cases} (h'_1 + h'_2 + 360^\circ)/2 & |h'_1 - h'_2| > 180^\circ \\ (h'_1 + h'_2)/2 & |h'_1 - h'_2| \leq 180^\circ \end{cases}$$

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

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

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

Delta E Color Distance

Delta E 2000

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

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

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

$$a'_1 = a_1^* + \frac{a_1^*}{2} \left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right) \quad a'_2 = a_2^* + \frac{a_2^*}{2} \left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right)$$

$$\bar{C}' = \frac{C'_1 + C'_2}{2} \text{ and } \Delta C' = C'_2 - C'_1 \quad \text{where } C'_1 = \sqrt{a'^2_1 + b'^2_1} \quad C'_2 = \sqrt{a'^2_2 + b'^2_2}$$

$$h'_1 = \text{atan2}(b_1^*, a'_1) \mod 360^\circ, \quad h'_2 = \text{atan2}(b_2^*, a'_2) \mod 360^\circ$$

$$\Delta h' = \begin{cases} h'_2 - h'_1 & |h'_1 - h'_2| \leq 180^\circ \\ h'_2 - h'_1 + 360^\circ & |h'_1 - h'_2| > 180^\circ, h'_2 \leq h'_1 \\ h'_2 - h'_1 - 360^\circ & |h'_1 - h'_2| > 180^\circ, h'_2 > h'_1 \end{cases}$$

$$\Delta H' = 2\sqrt{C'_1 C'_2} \sin(\Delta h'/2), \quad \bar{H}' = \begin{cases} (h'_1 + h'_2 + 360^\circ)/2 & |h'_1 - h'_2| > 180^\circ \\ (h'_1 + h'_2)/2 & |h'_1 - h'_2| \leq 180^\circ \end{cases}$$

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

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

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

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

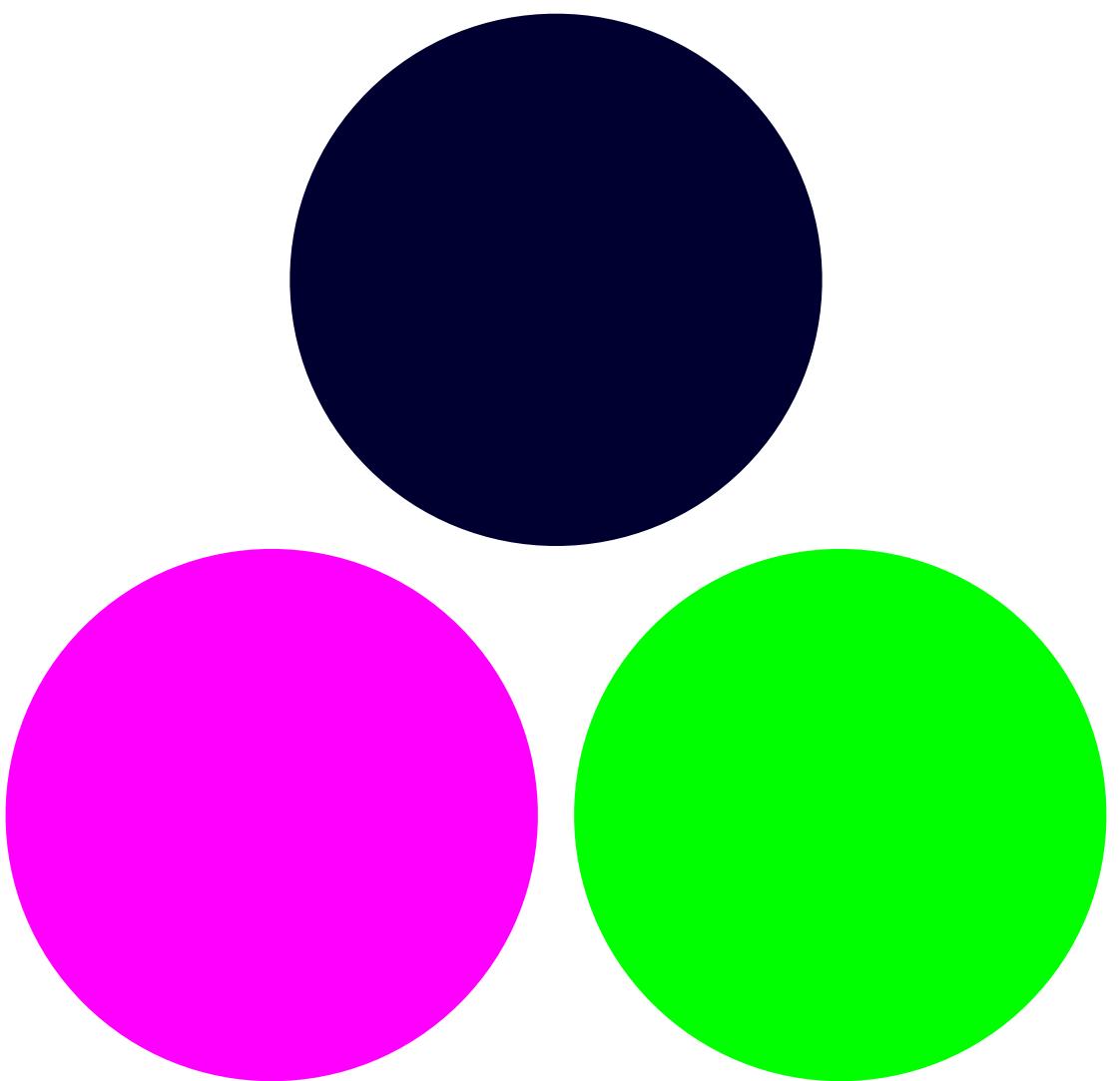
The Perfect Color Palette

A First Attempt

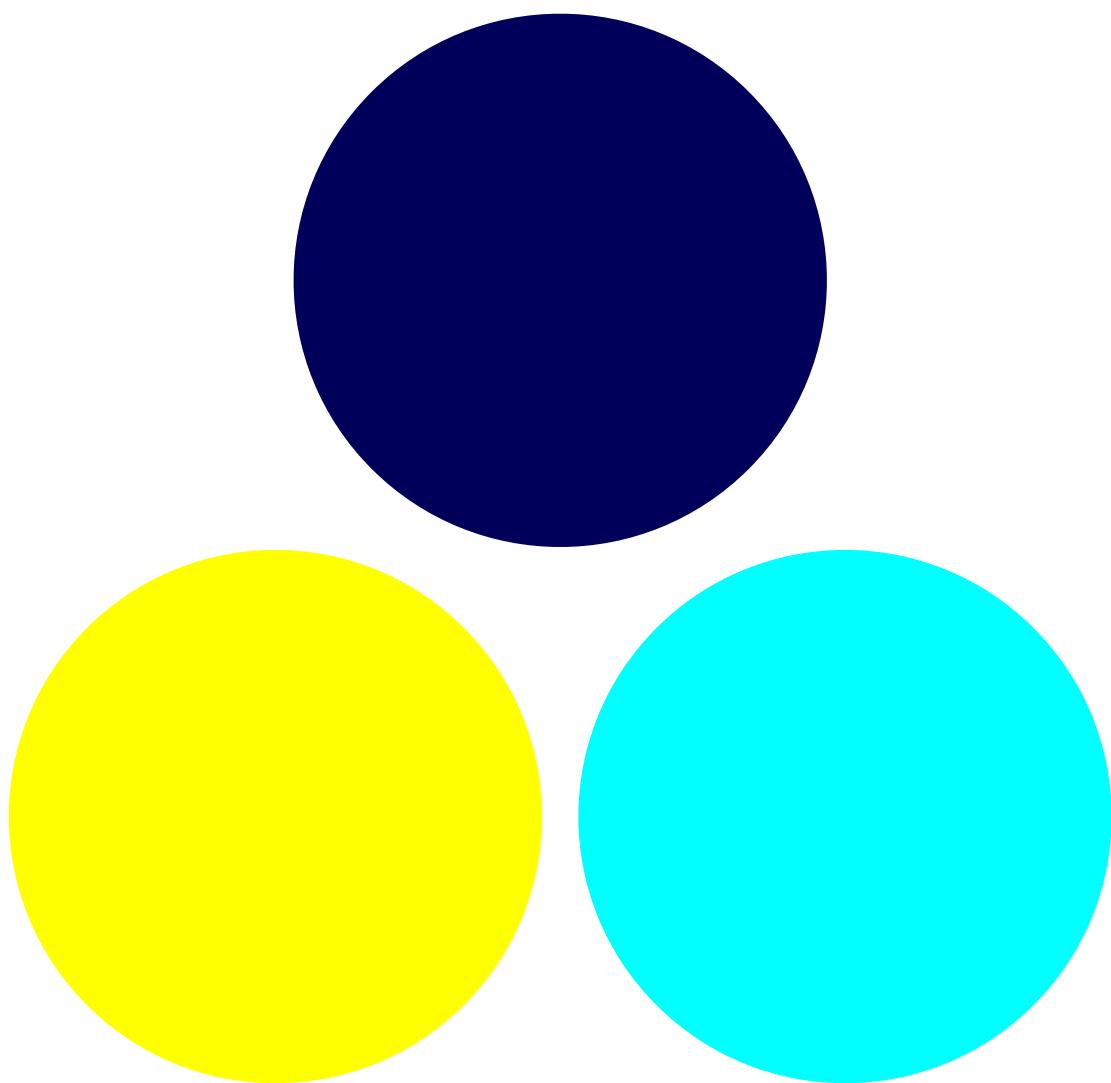
$$\underset{c_1, \dots, c_n}{\text{maximize}} \sum_{i=1}^{n-1} \left(\sum_{j=i+1}^n (\Delta E(c_i, c_j)) \right)$$

The Perfect Color Palette

A First Attempt



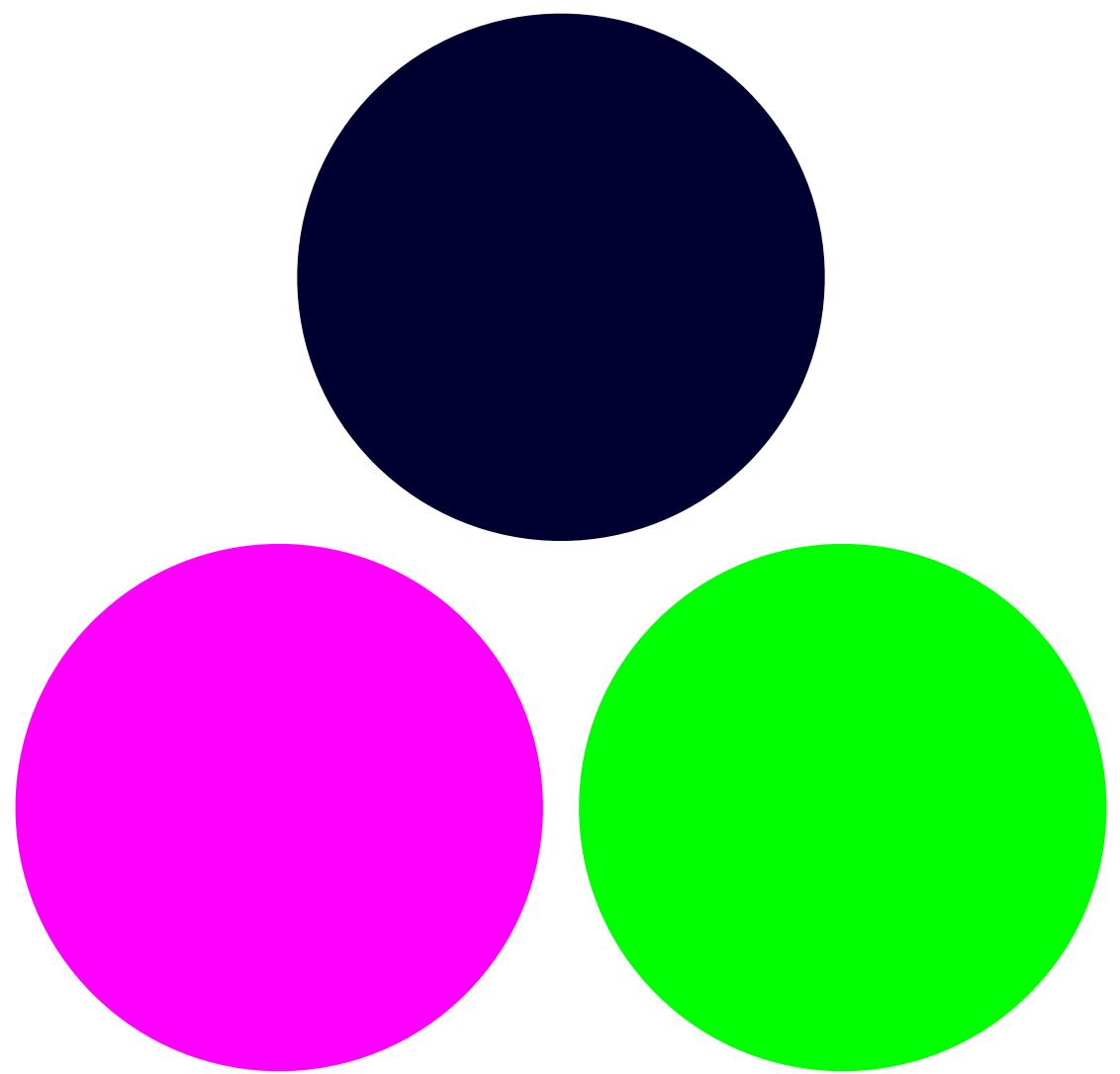
Mode 1



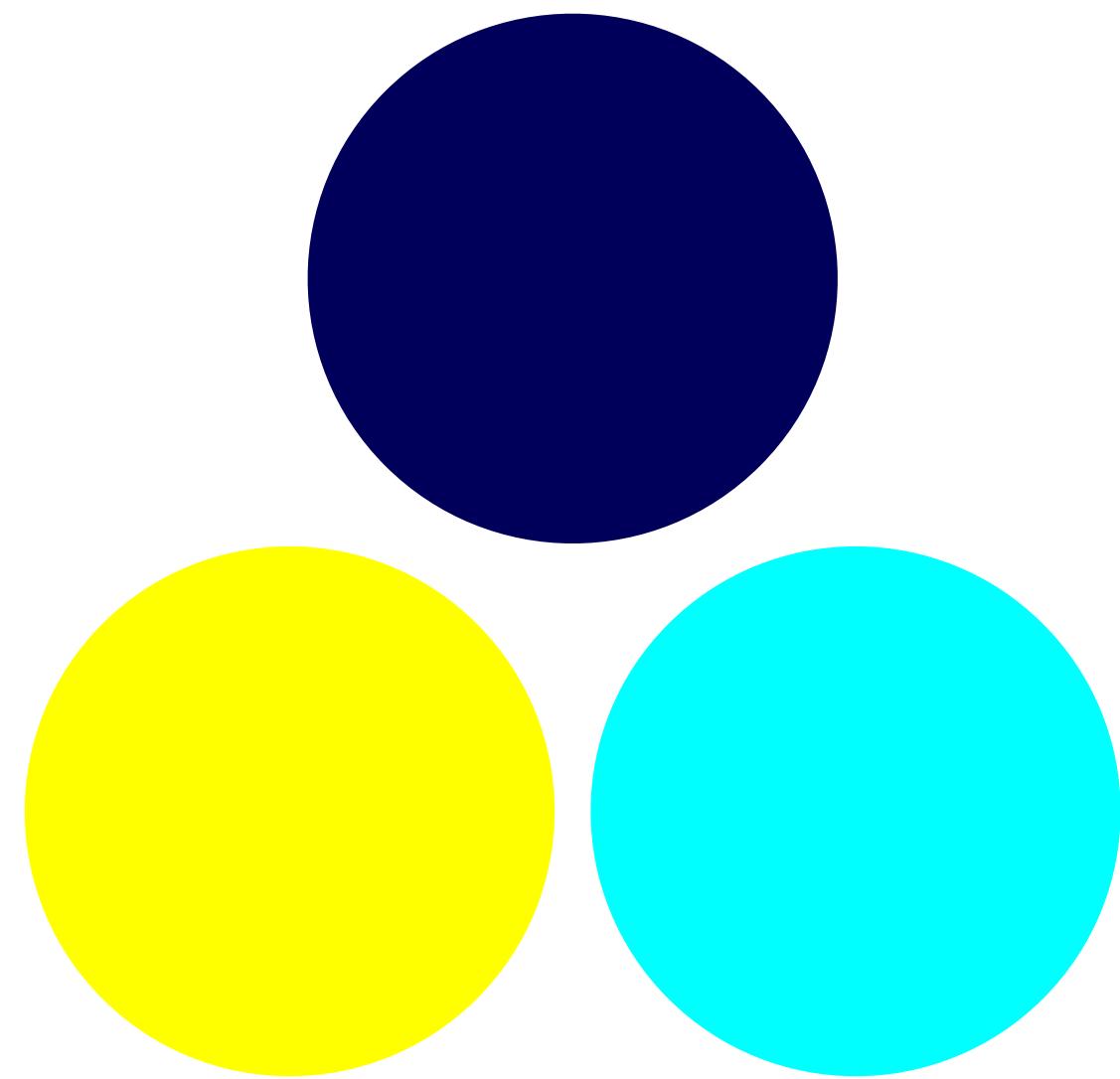
Mode 2

The Perfect Color Palette

A First Attempt



Mode 1



Mode 2

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

The Perfect Color Palette

A Second Attempt

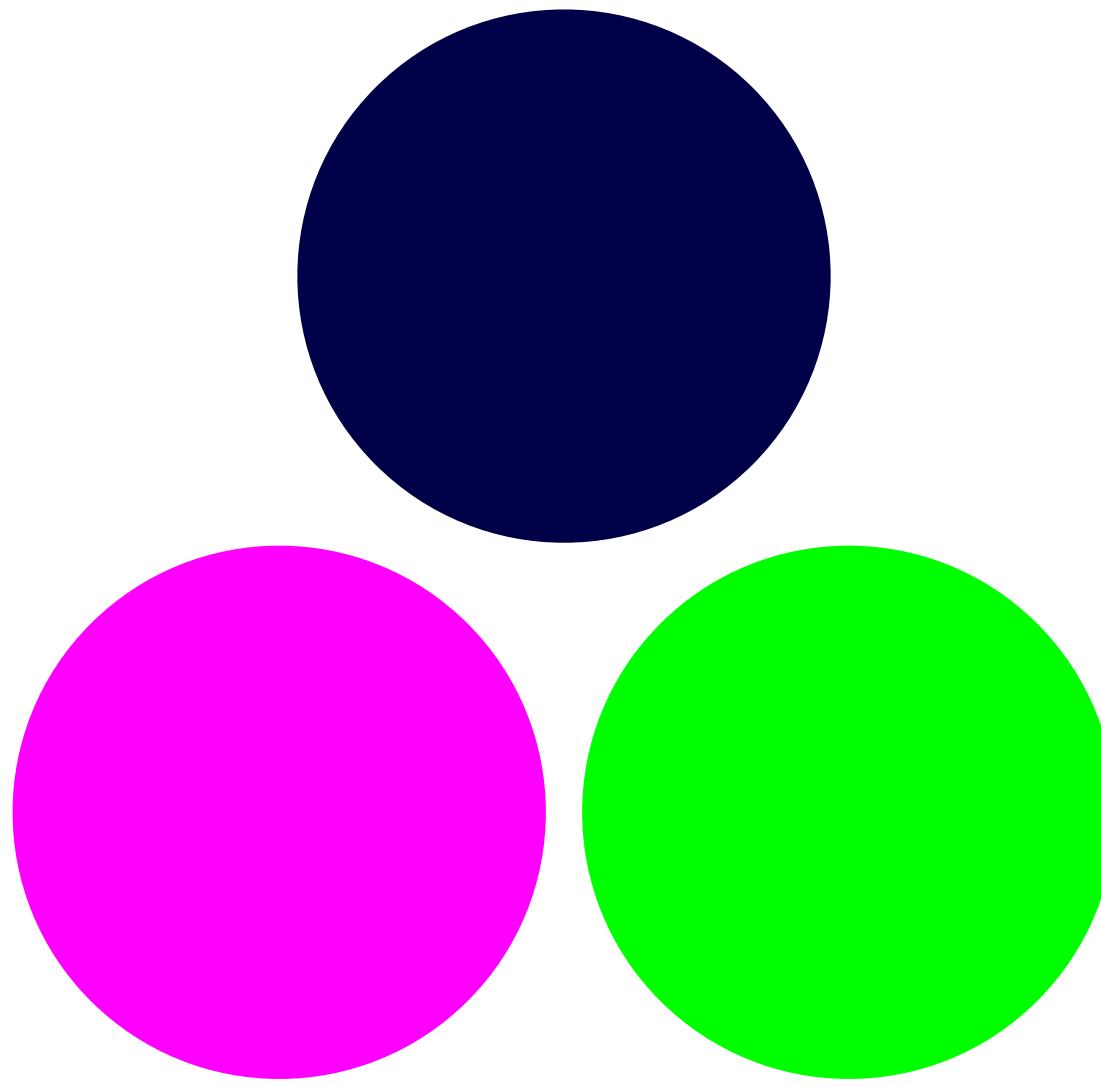
$$\underset{c_1, \dots, c_n}{\text{maximize}} \sum_{i=1}^{n-1} \left(\sum_{j=i+1}^n (\Delta E(c_i, c_j)) \right) + \sum_{i=1}^n (\Delta E(c_0, c_i))$$



Background Color

The Perfect Color Palette

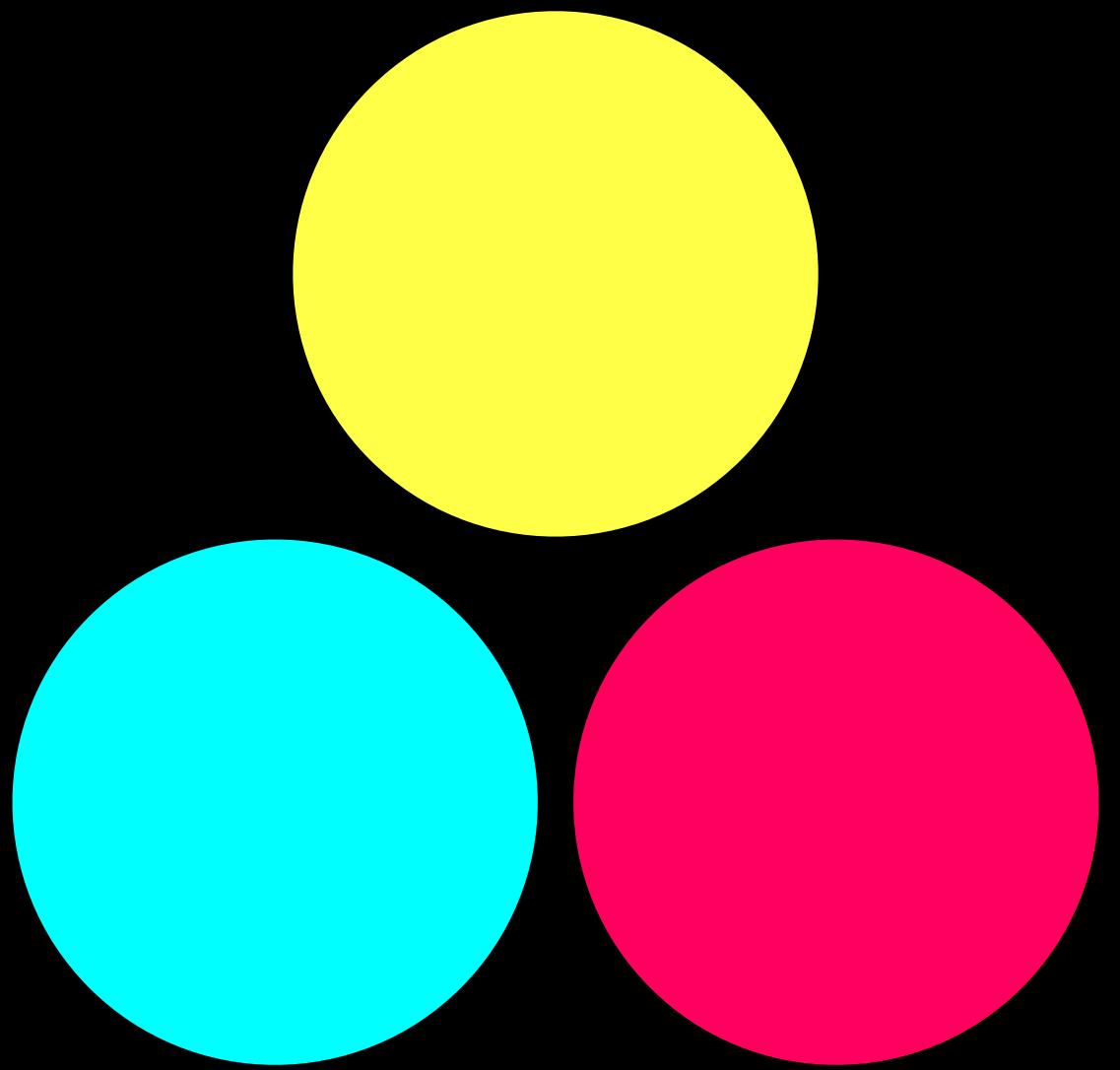
A Second Attempt



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

Blindness to Red

$\approx 1\%$

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

Normal Vision

Protanopia

Blindness to Red

Deuteranopia

Blindness to Green

Tritanopia

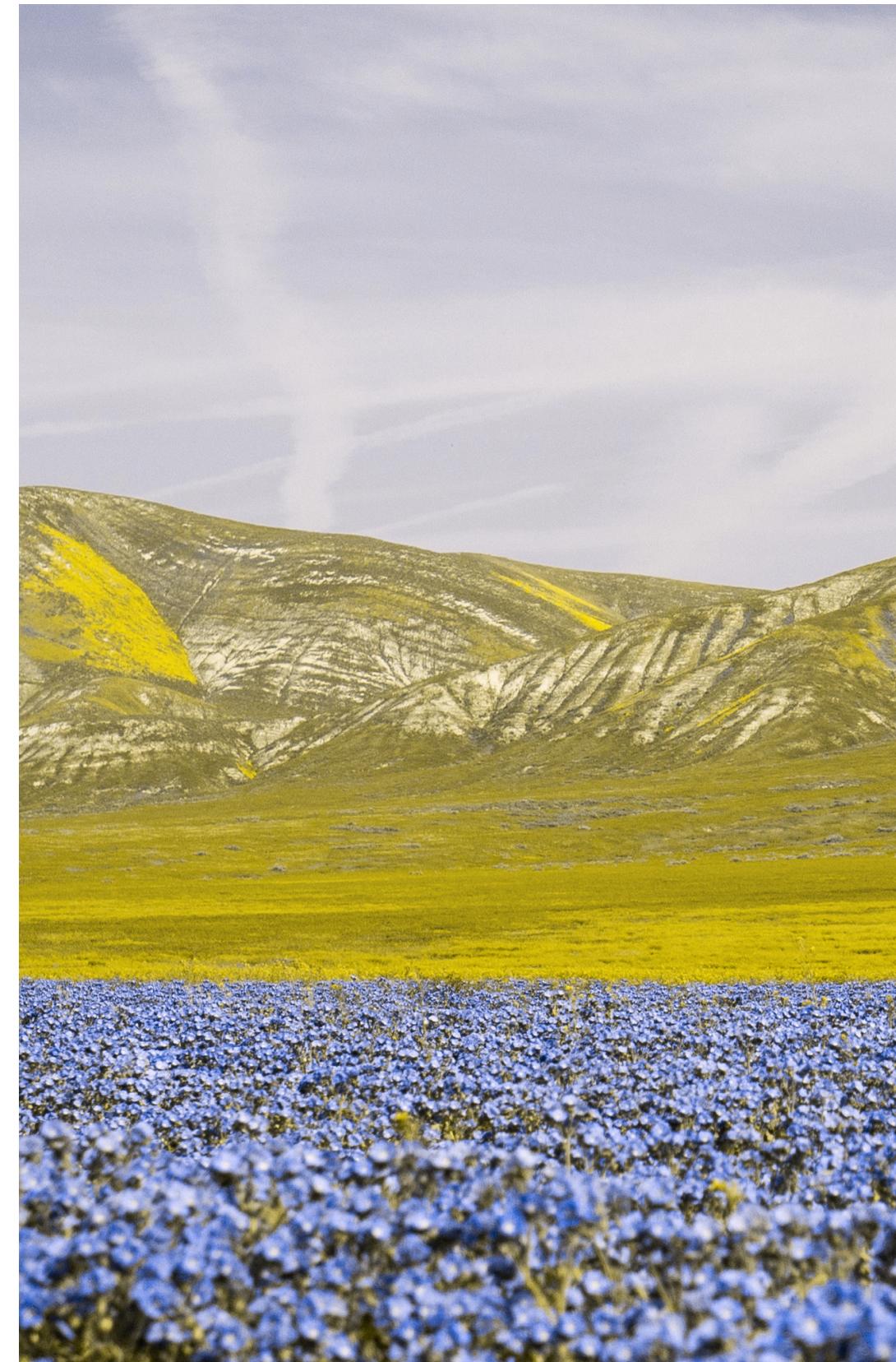
Blindness to Blue

Colorblindness Types



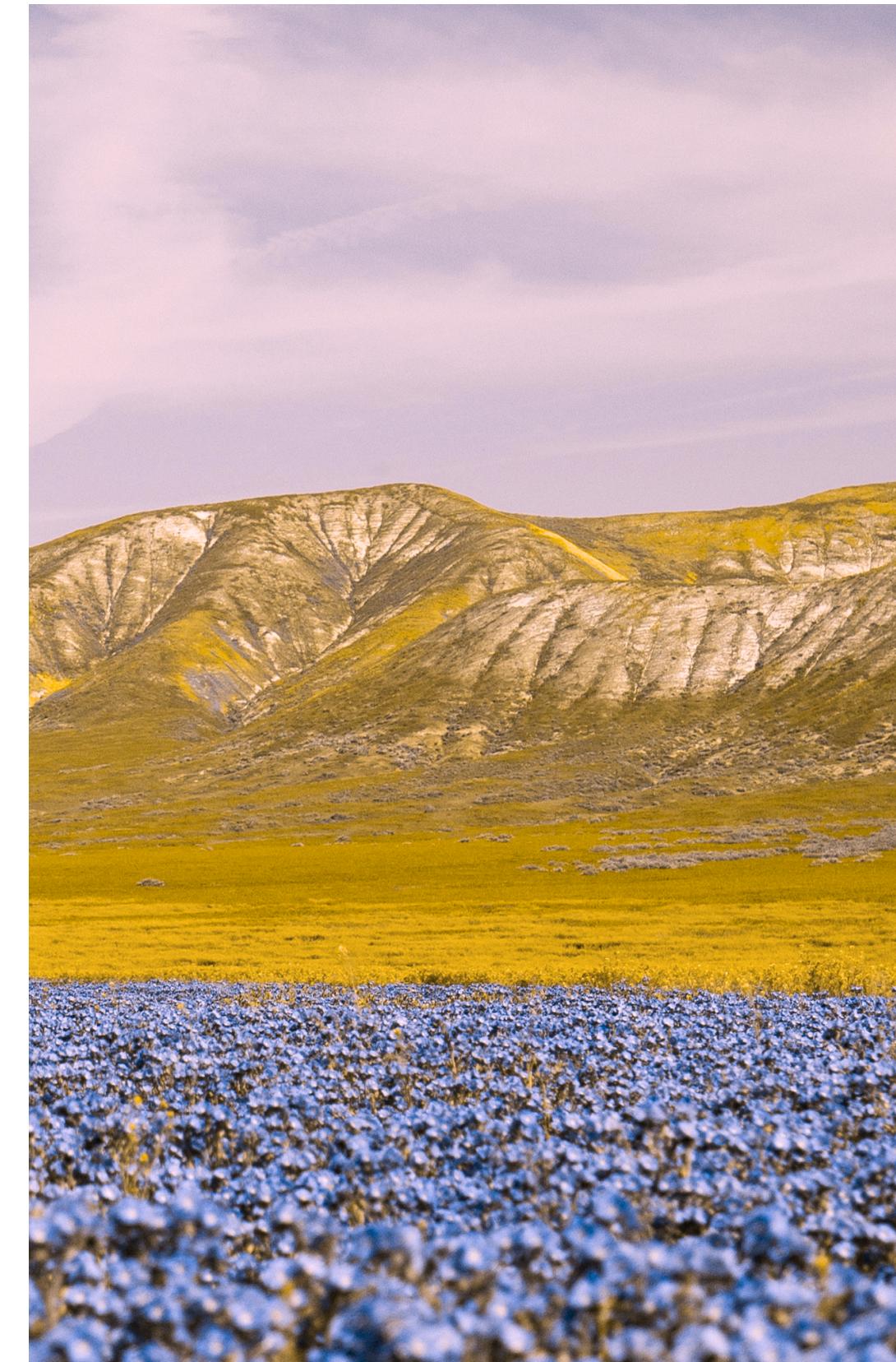
Trichromasy

Normal Vision



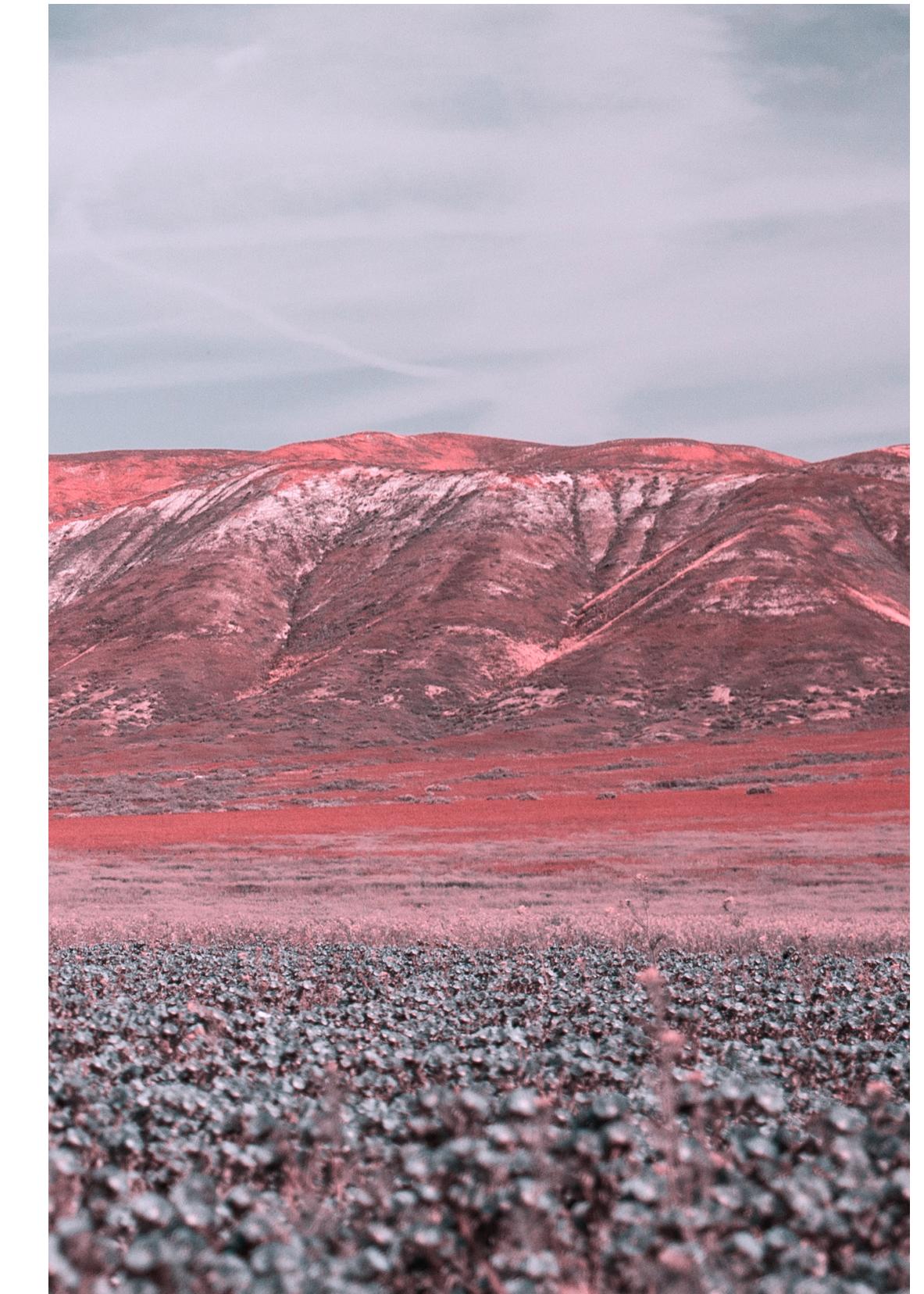
Protanopia

Blindness to Red



Deuteranopia

Blindness to Green



Tritanopia

Blindness to Blue

The Perfect Color Palette

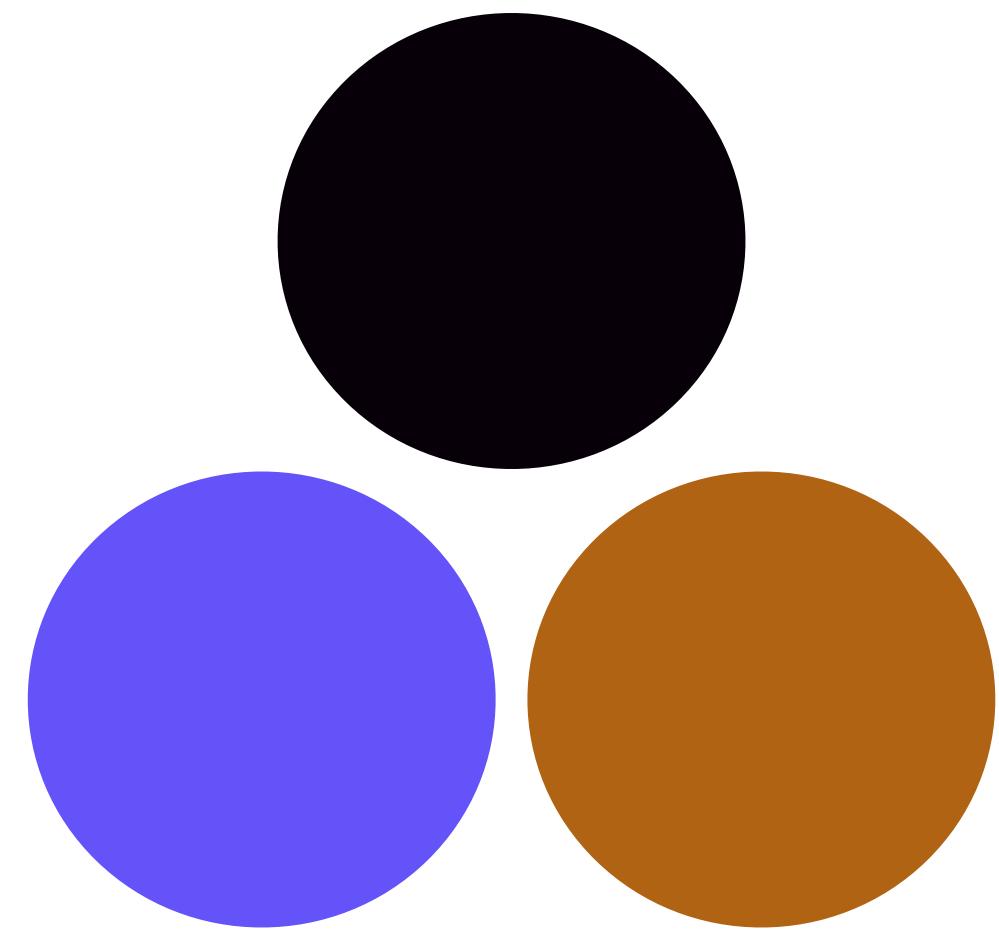
A Third Attempt

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

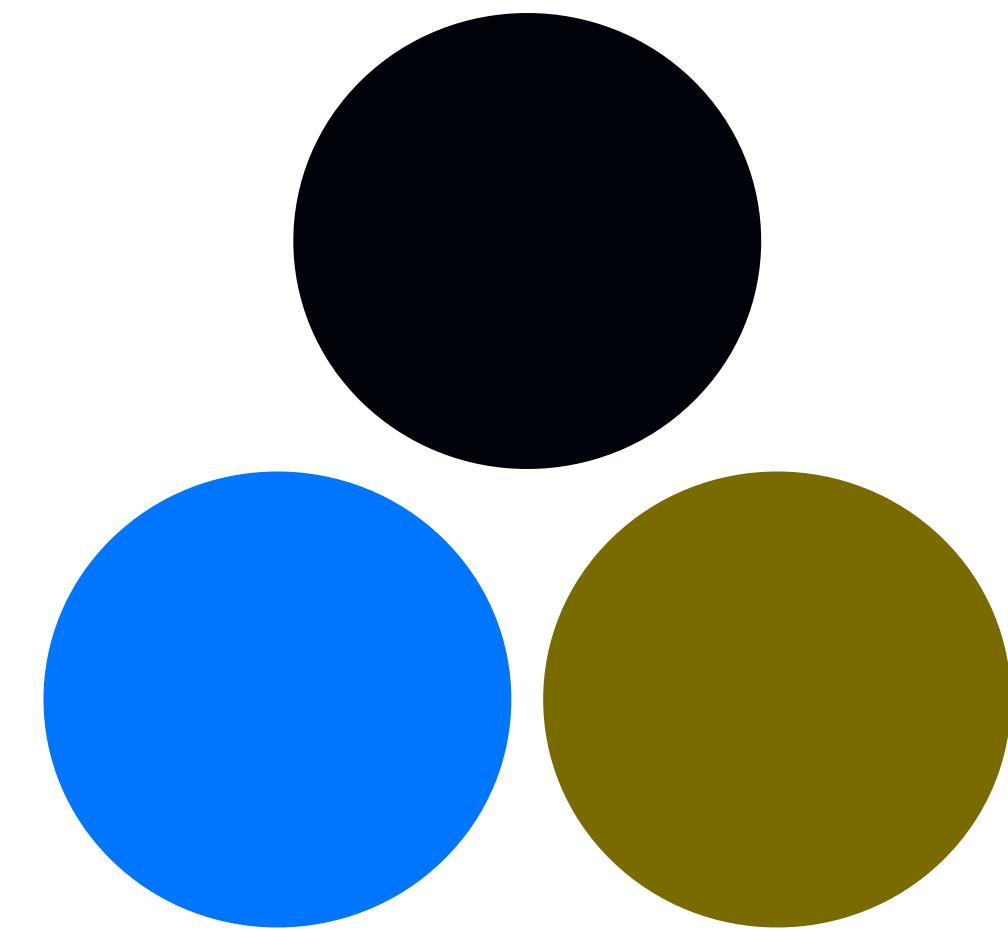
The diagram illustrates the components of the optimization equation. At the bottom, four labels represent different color vision types: 'Normal', 'Protanopia', 'Deuteranopia', and 'Tritanopia'. Arrows point from each of these labels upwards towards the summation term in the equation. The first arrow points from 'Normal' to the first term of the summation. The second arrow points from 'Protanopia' to the second term of the summation. The third arrow points from 'Deuteranopia' to the third term of the summation. The fourth arrow points from 'Tritanopia' to the fourth term of the summation.

The Perfect Color Palette

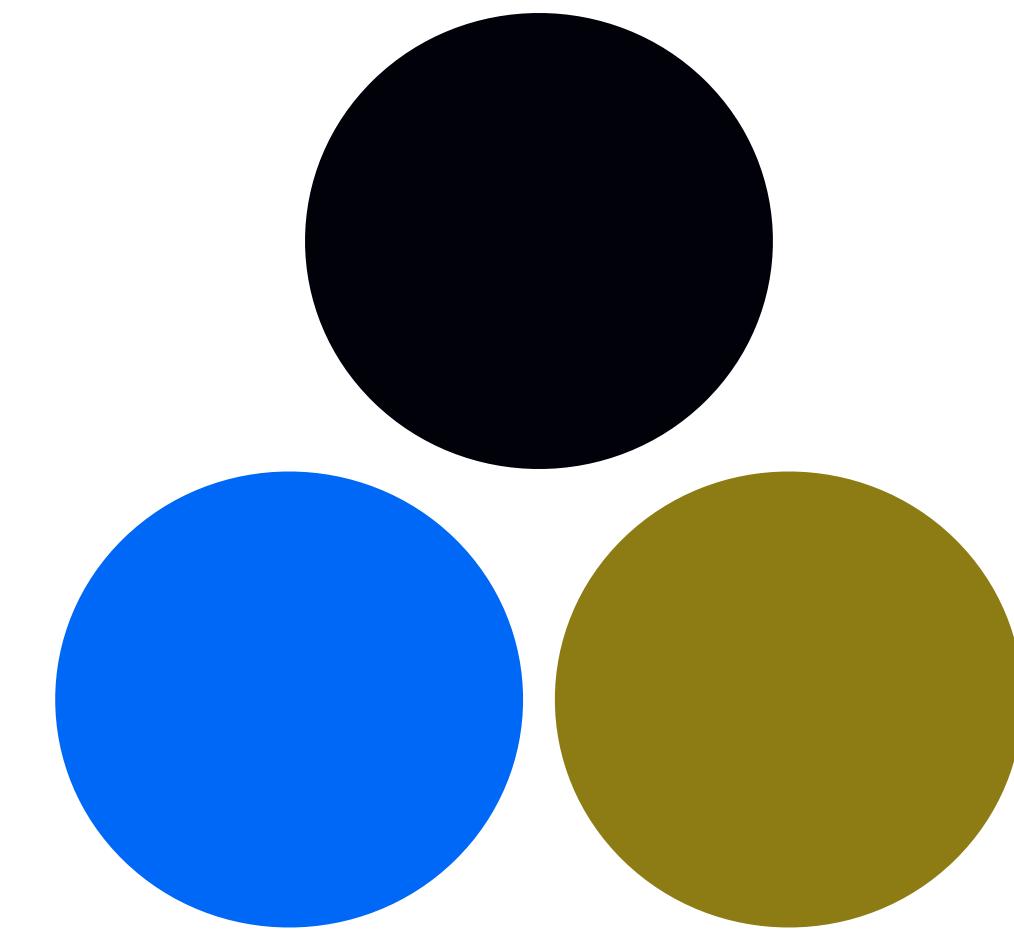
A Third Attempt



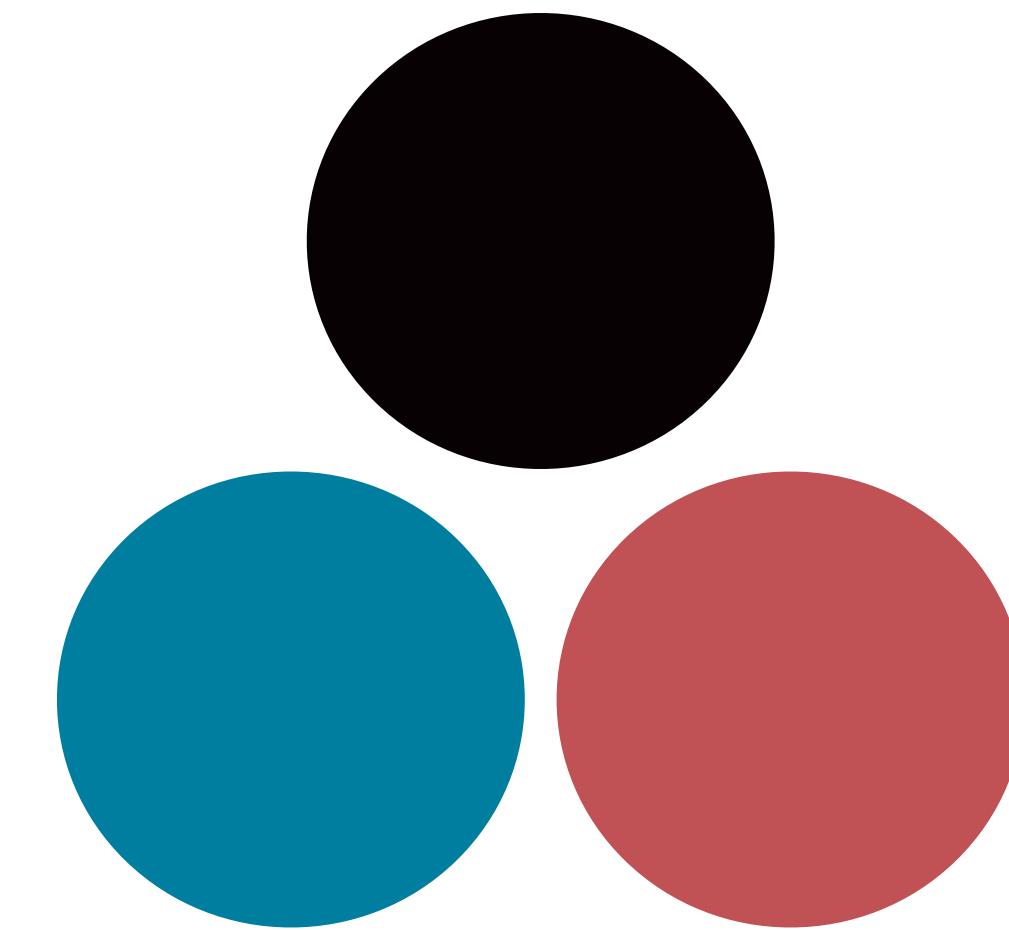
Normal Vision



Protanopia



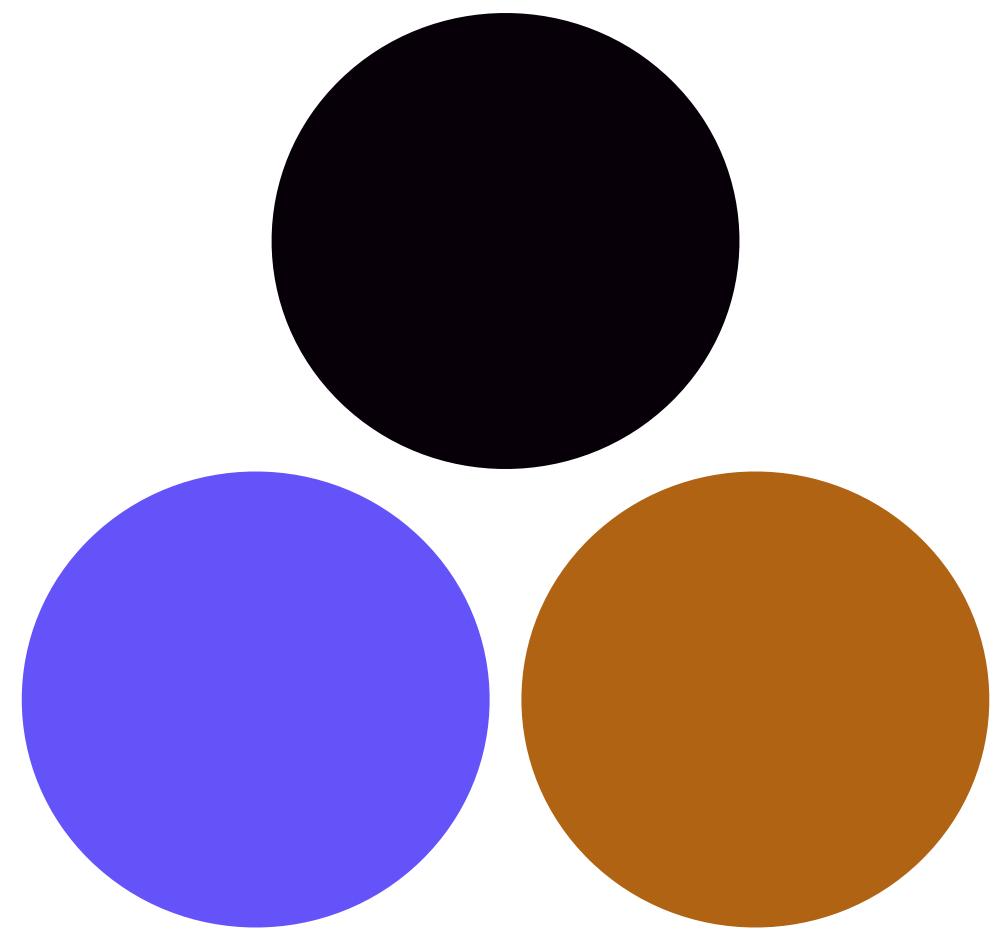
Deuteranopia



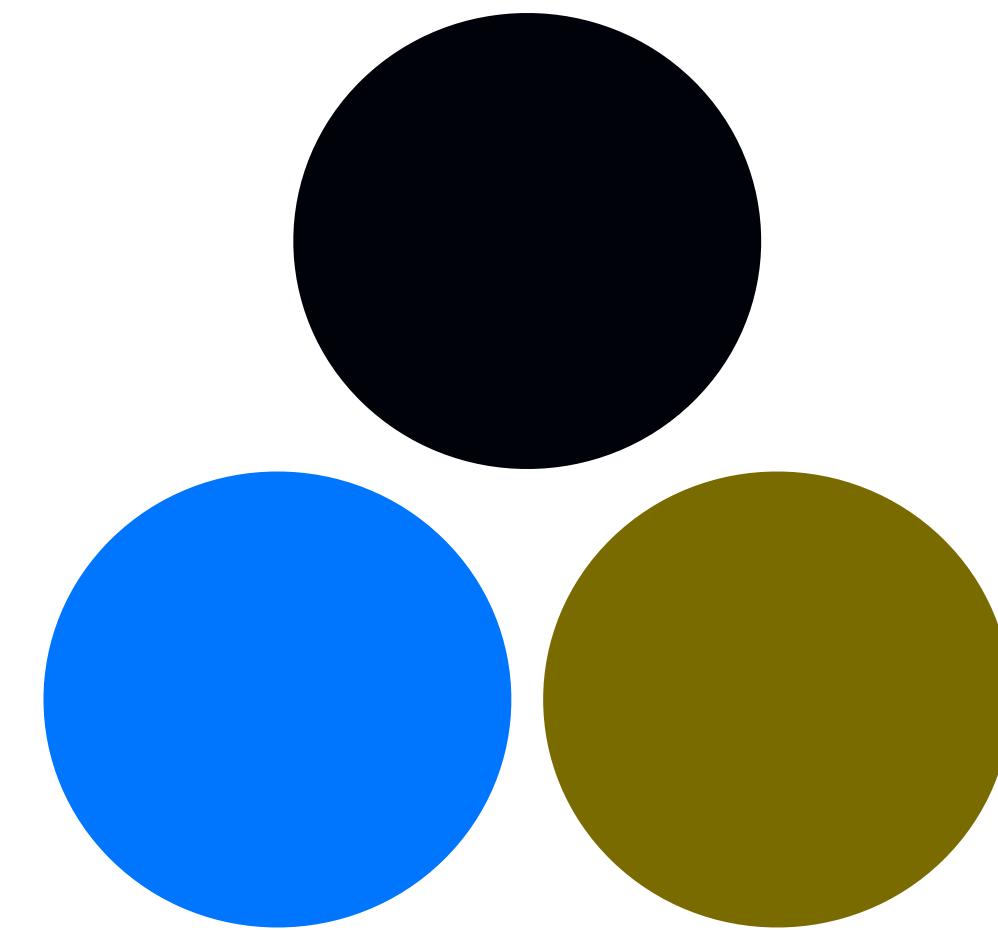
Tritanopia

The Perfect Color Palette

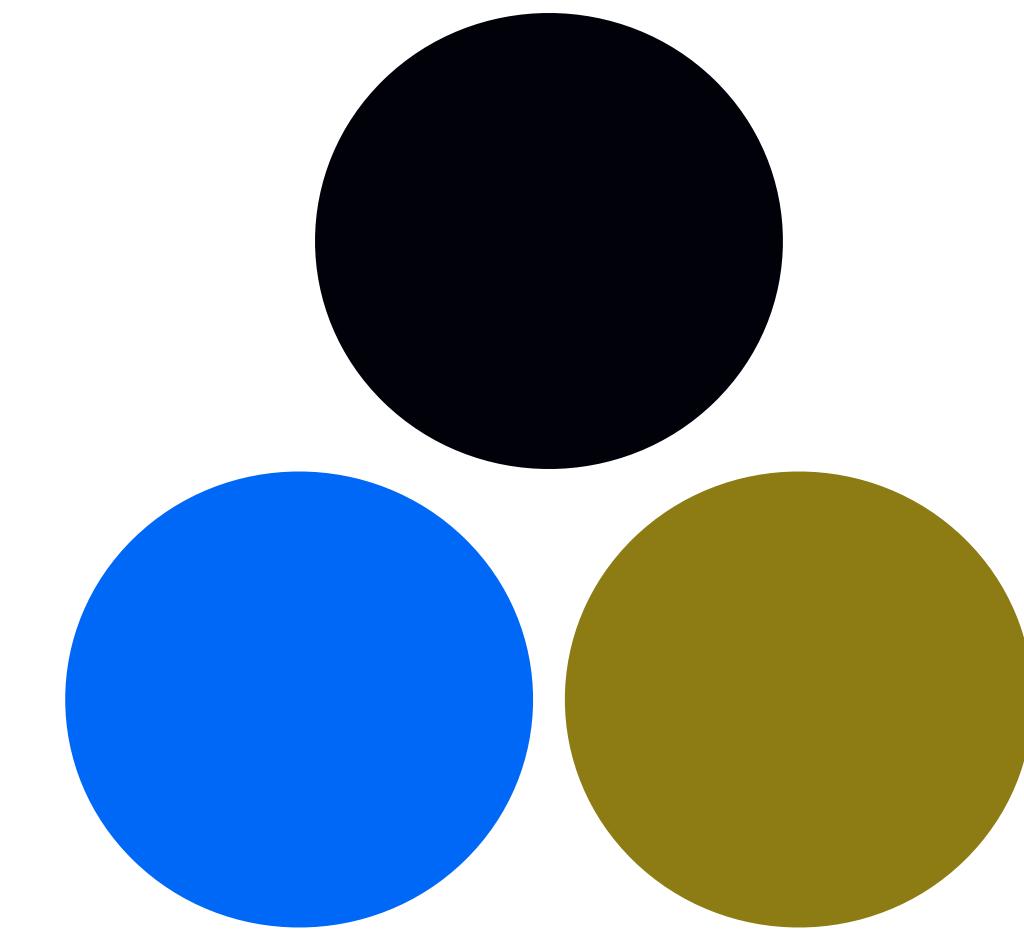
A Third Attempt



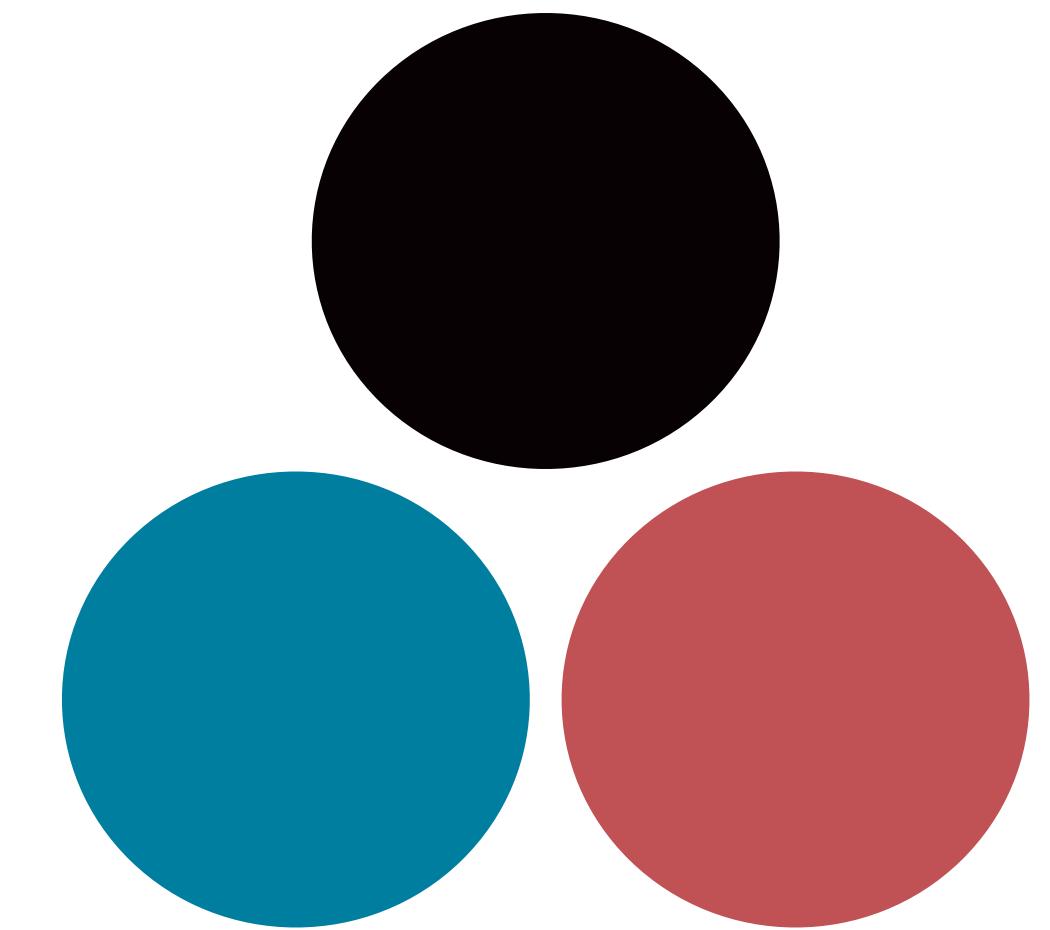
Normal Vision



Protanopia



Deuteranopia



Tritanopia

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

Aesthetics

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- 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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- Building **distinguishable** and **accessible** color palettes is just an optimization problem
- **LAB** colorspace and **ΔE** are useful to calculate how distinguishable colors are
- The three most common types of colorblindness are **protanopia**, **deutanopia**, and **tritanopia**
- Defining what is aesthetic is hard! **Survey!**

Thank You