



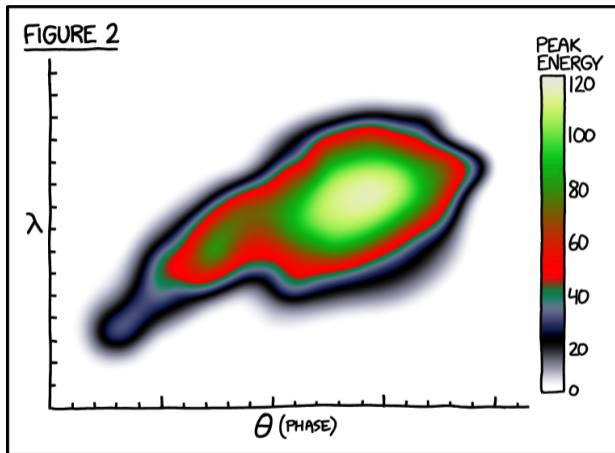
# colorspace

## Strategies and Software for Robust Color Palettes in Data Visualizations

Achim Zeileis

<https://colorspace.R-Forge.R-project.org/>

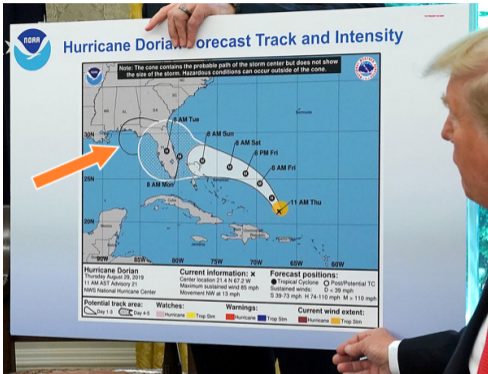
# Motivation



**Source:** <https://xkcd.com/2537/>

EVERY YEAR, DISGRUNTLED SCIENTISTS COMPETE FOR THE RAINBOW AWARD FOR WORST COLOR SCALE.

# Motivation



Source: White House (2019-09-04)

Donald J. Trump @realDonaldTrump · Sep 5, 2019

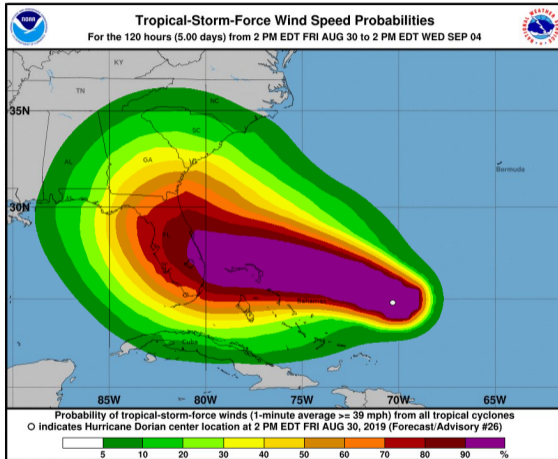
Just as I said, Alabama was originally projected to be hit. The Fake News denies it!

Four maps showing the earliest reasonable arrival time of tropical-storm-force winds for Hurricane Dorian. The maps show the storm's path and intensity over the Gulf of Mexico and Florida. The top two maps are labeled "Earliest Reasonable Arrival Time of Tropical-Storm-Force Winds" and "Tropical-Storm-Force Wind Speed Probabilities". The bottom two maps are also labeled "Earliest Reasonable Arrival Time of Tropical-Storm-Force Winds".

31.7K 10.8K 46.1K

Source: U.S. president via Twitter (2019-09-05)

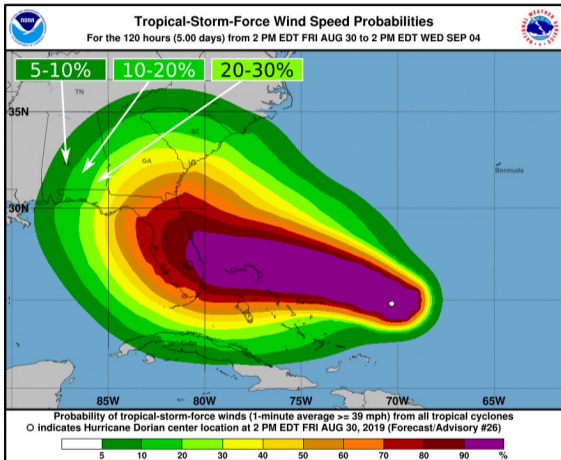
# Motivation



**Risk map:** Probability of wind speeds  $> 39$  mph ( $63 \text{ km h}^{-1}$ ), 2019-08-30–2019-09-04.

**Source:** National Oceanic and Atmospheric Administration.

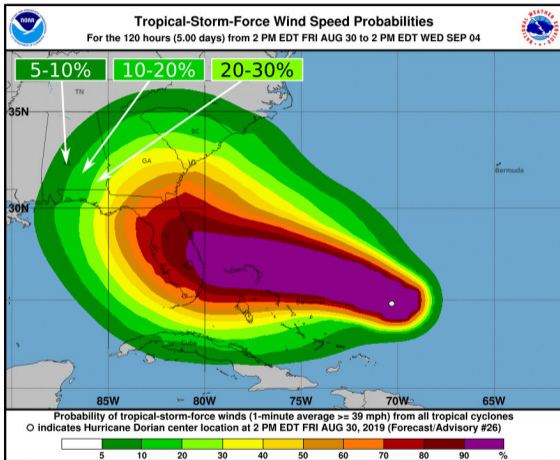
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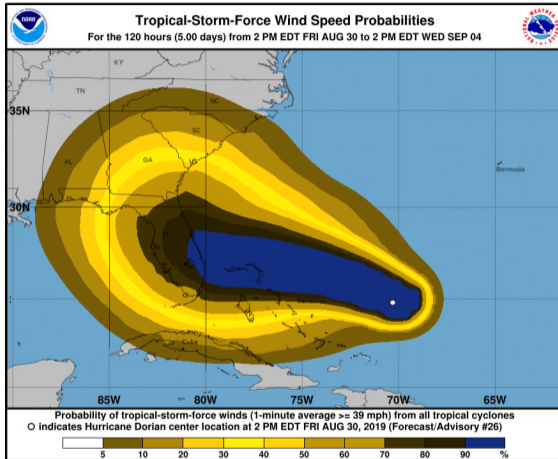


**Risk map:** Probability of wind speeds  $> 39$  mph ( $63 \text{ km h}^{-1}$ ), 2019-08-30–2019-09-04.

**Source:** National Oceanic and Atmospheric Administration.

**Problems:** Flashy.

# Motivation

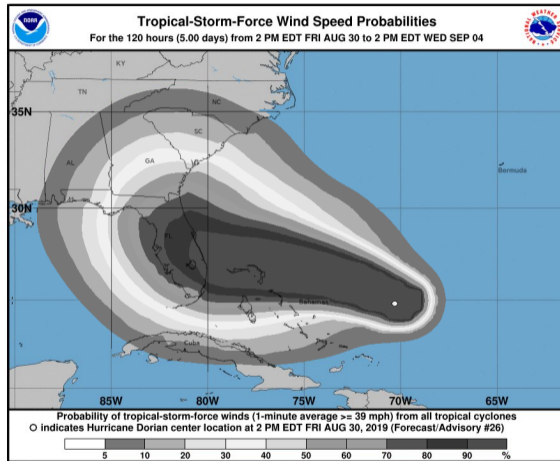


**Risk map:** Probability of wind speeds  $> 39$  mph ( $63 \text{ km h}^{-1}$ ), 2019-08-30–2019-09-04.

**Source:** National Oceanic and Atmospheric Administration.

**Problems:** Flashy. Color vision deficiency.

# Motivation



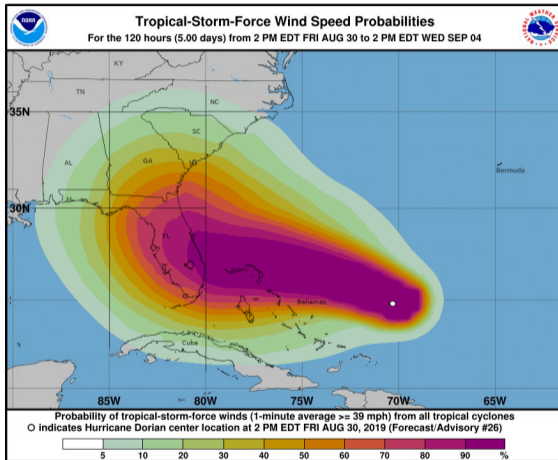
**Risk map:** Probability of wind speeds  $> 39$  mph ( $63 \text{ km h}^{-1}$ ), 2019-08-30–2019-09-04.

**Source:** National Oceanic and Atmospheric Administration.

**Problems:** Flashy. Color vision deficiency. Grayscale.



# Motivation



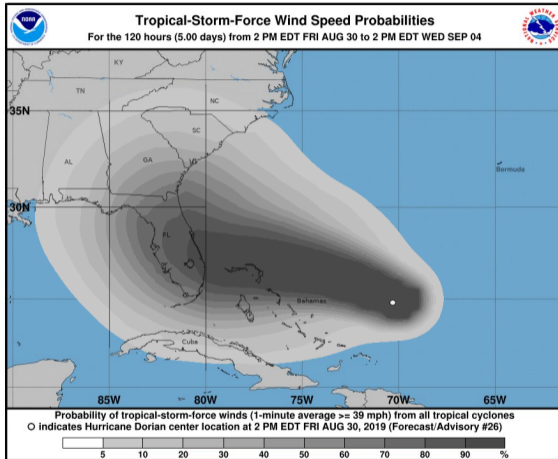
**Risk map:** Probability of wind speeds  $> 39$  mph ( $63 \text{ km h}^{-1}$ ), 2019-08-30–2019-09-04.

**Source:** National Oceanic and Atmospheric Administration.

**Problems:** Flashy. Color vision deficiency. Grayscale.

**Alternative:** HCL-based sequential palette.

# Motivation



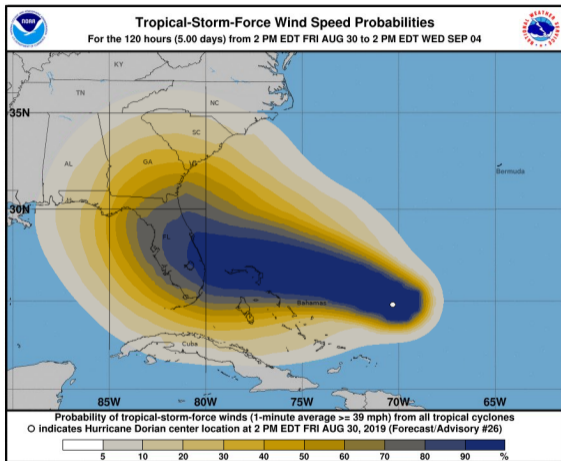
**Risk map:** Probability of wind speeds  $> 39$  mph ( $63 \text{ km h}^{-1}$ ), 2019-08-30–2019-09-04.

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# Motivation

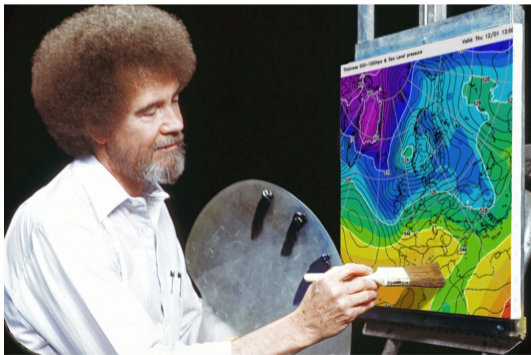
## **Need tools for:**

- Construction of palettes with better perceptual properties.
- Assessment of color palettes.
- Manipulation of colors.

# Motivation

## Need tools for:

- Construction of palettes with better perceptual properties.
- Assessment of color palettes.
- Manipulation of colors.



Because Bob Ross would not approve of this!

# Motivation

## **R package colorspace:**

- Flexible HCL-based color palettes (base graphics, ggplot2, shiny app, ...).
- Color manipulation tools (desaturation, lighten/darken, ...).
- Color vision deficiency emulation.
- Visualization of palette properties.

## **Base R:**

- New default color palette for base graphics.
- `hcl.colors()`: HCL-based color palettes (fixed/named).
- `palette.colors()`: Well-established qualitative color palettes.

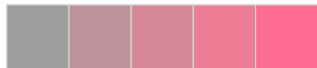
# HCL vs. RGB

**HCL:** Polar coordinates in CIELUV.  
Captures perceptual dimensions of  
the human visual system very well.

Hue  
(Type of color)



Chroma  
(Colorfulness)

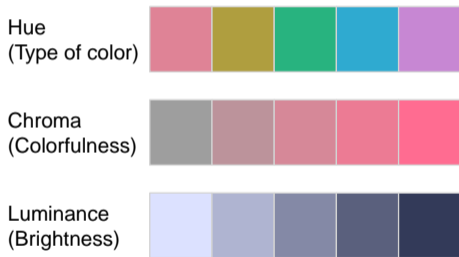


Luminance  
(Brightness)

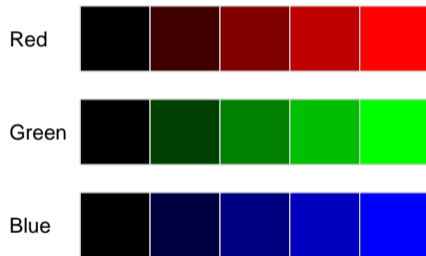


# HCL vs. RGB

**HCL:** Polar coordinates in CIELUV. Captures perceptual dimensions of the human visual system very well.

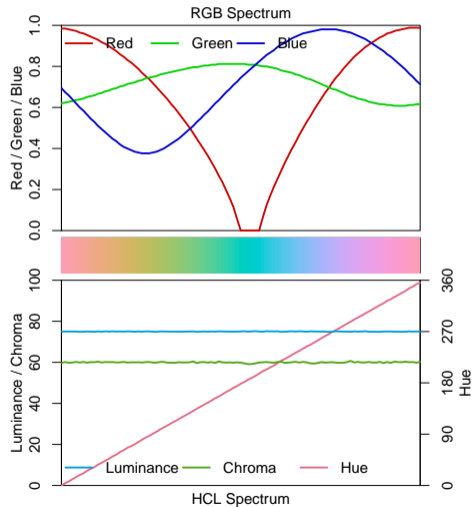


**RGB:** Motivated by how computers/TVs used to generate and still represent color.

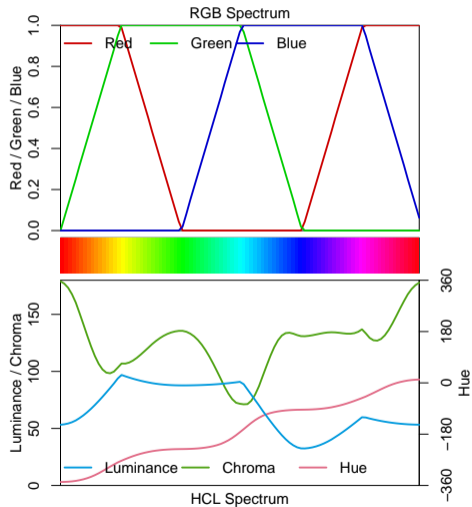
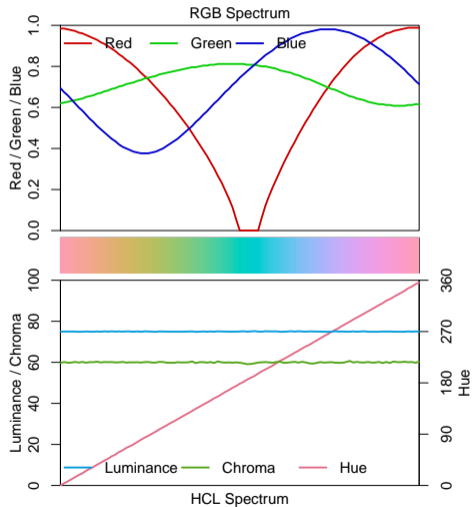




# HCL vs. RGB: The End of the Rainbow



# HCL vs. RGB: The End of the Rainbow



# Color palettes: Somewhere over the Rainbow

## Qualitative (Set 2)



## Sequential (Blues 3)



## Diverging (Green–Brown)



# Color palettes: Somewhere over the Rainbow

## Qualitative (Set 2)



## Sequential (Blues 3)



## Diverging (Green–Brown)



**Qualitative:** For categorical information with no particular ordering. Luminance differences should be limited.

# Color palettes: Somewhere over the Rainbow

## Qualitative (Set 2)



## Sequential (Blues 3)



## Diverging (Green–Brown)



**Qualitative:** For categorical information with no particular ordering. Luminance differences should be limited.

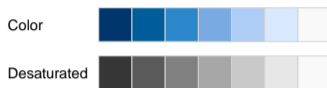
**Sequential:** For ordered/numeric information from high to low (or vice versa).

# Color palettes: Somewhere over the Rainbow

## Qualitative (Set 2)



## Sequential (Blues 3)



## Diverging (Green–Brown)



**Qualitative:** For categorical information with no particular ordering. Luminance differences should be limited.

**Sequential:** For ordered/numeric information from high to low (or vice versa).

**Diverging:** For ordered/numeric information diverging from a central neutral value to two extremes.

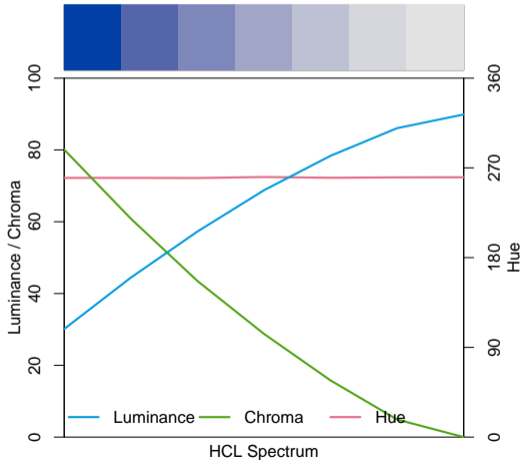
# Color palettes: Somewhere over the Rainbow

**Sequential:** Luminance contrast is crucial (dark to light or vice versa).



# Color palettes: Somewhere over the Rainbow

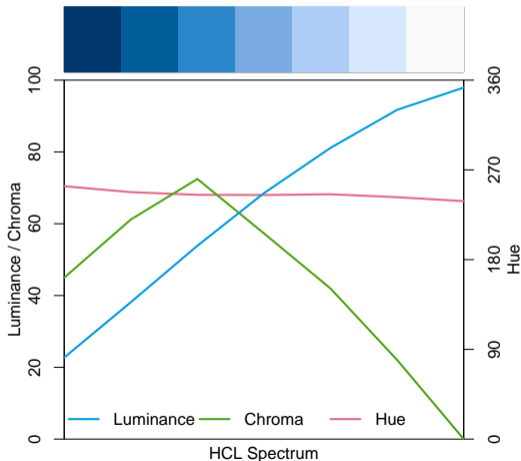
**Blues 2:** Single hue. Decreasing chroma with increasing luminance.





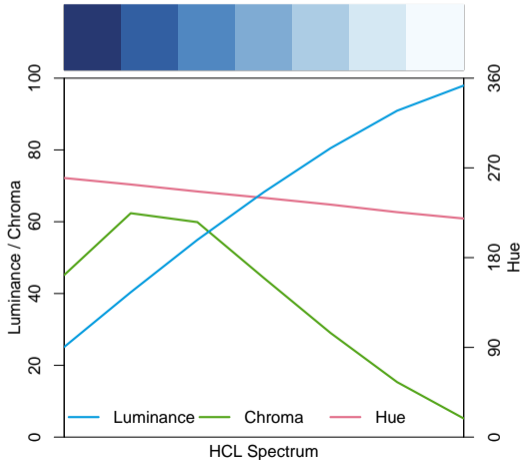
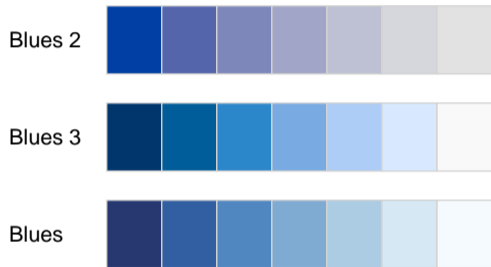
# Color palettes: Somewhere over the Rainbow

**Blues 3:** Single hue. Triangular chroma to achieve higher luminance contrast.

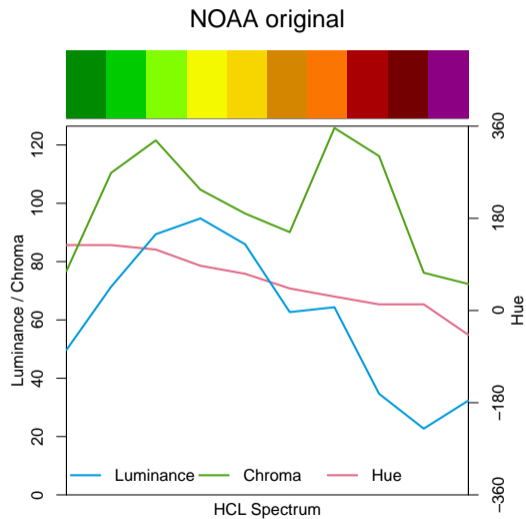


# Color palettes: Somewhere over the Rainbow

**Blues:** Multi hue. Triangular chroma. High luminance contrast.

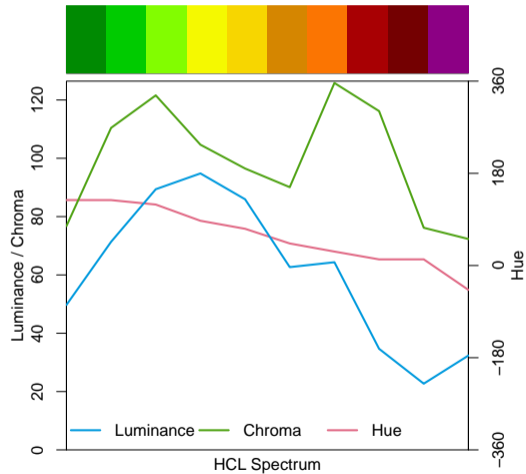


# Color palettes: Somewhere over the Rainbow

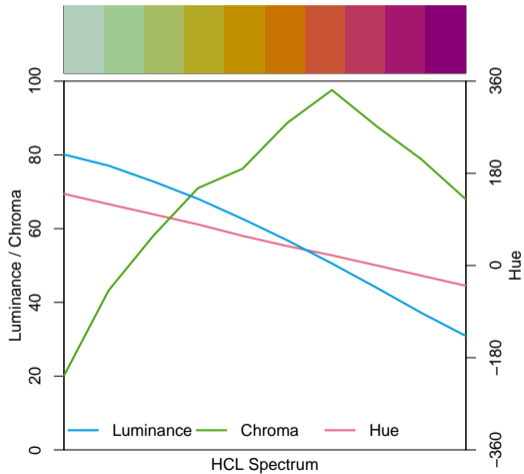


# Color palettes: Somewhere over the Rainbow

NOAA original

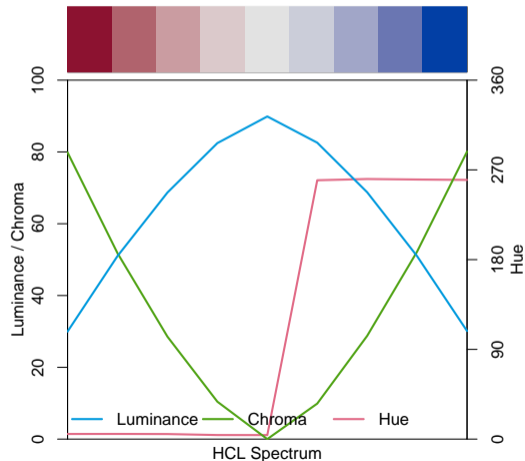


HCL-based alternative



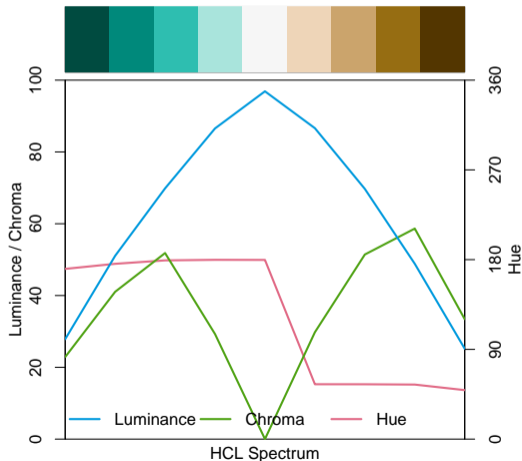
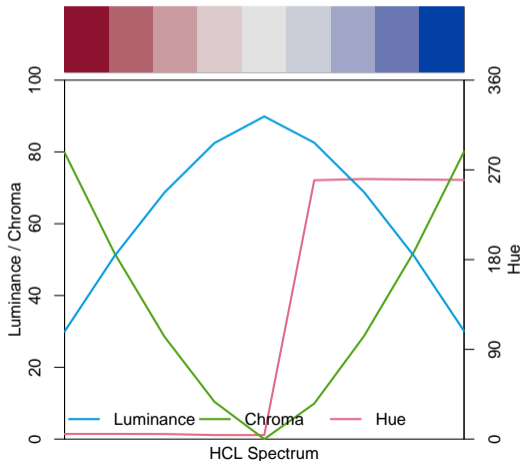
# Color palettes: Somewhere over the Rainbow

**Diverging:** Combine two sequential palettes with balanced chroma/luminance.



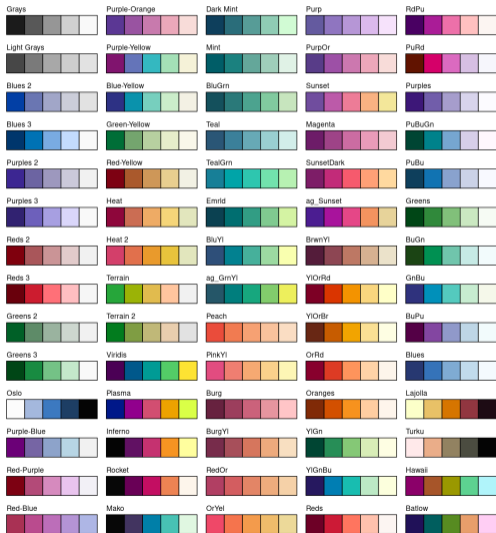
# Color palettes: Somewhere over the Rainbow

**Diverging:** Combine two sequential palettes with balanced chroma/luminance.

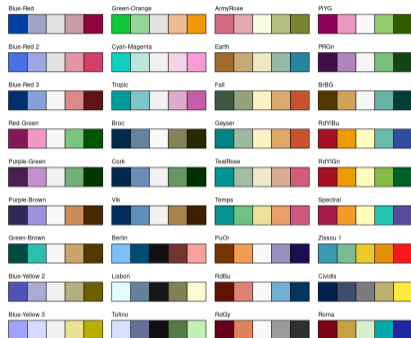


# Color palettes: Somewhere over the Rainbow

## Sequential (hcl.colors)

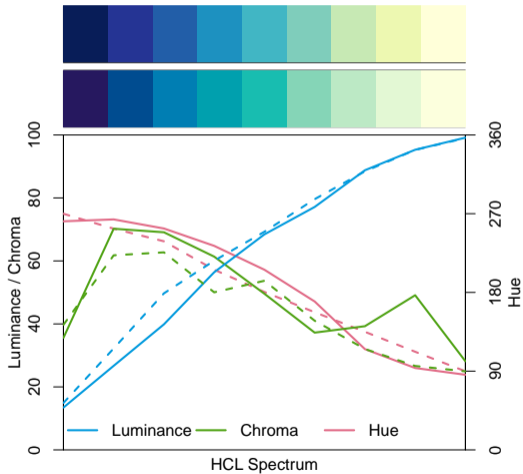


## Diverging (hcl.colors)



# Color palettes: Somewhere over the Rainbow

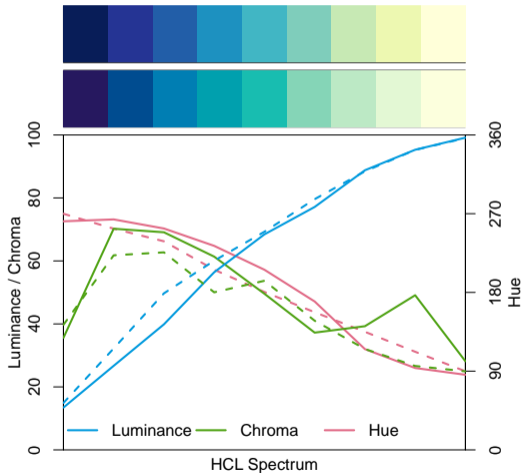
ColorBrewer.org: YlGnBu



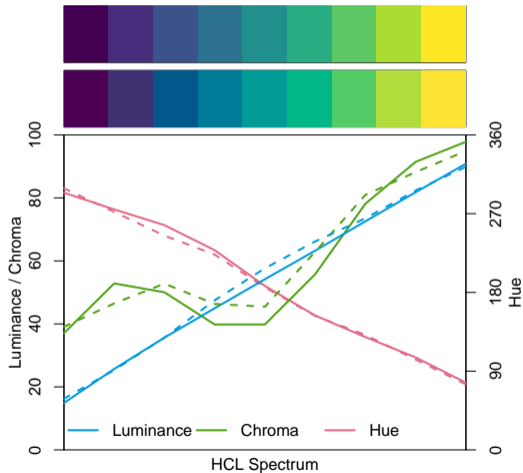


# Color palettes: Somewhere over the Rainbow

ColorBrewer.org: YlGnBu



Viridis



# Color palettes: Somewhere over the Rainbow

## **R package colorspace:**

- Flexible HCL-based palettes:  
`qualitative_hcl()`, `sequential_hcl()`, `diverging_hcl()`.
- Named palettes available, can be easily modified.
- ggplot2 scales: `scale_<aesthetic>_<datatype>_<colorscale>()`.

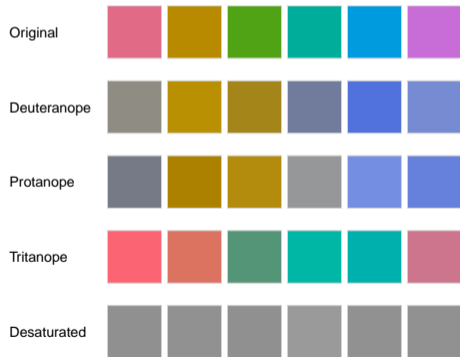
## **Base R:**

- `hcl.colors()`: Named HCL-based palettes, no modifications.
- `palette.colors()`: Well-established qualitative palettes.

# Color palettes: Somewhere over the Rainbow

**Qualitative:** Lack of luminance contrasts critical for color vision deficiencies.

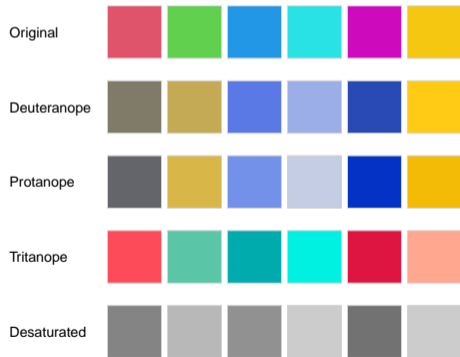
```
R> hcl.colors(6, palette = "Dark 3") |>  
+   swatchplot(cvd = TRUE)
```



# Color palettes: Somewhere over the Rainbow

**Qualitative:** New default base "R4" palette with limited luminance differences.

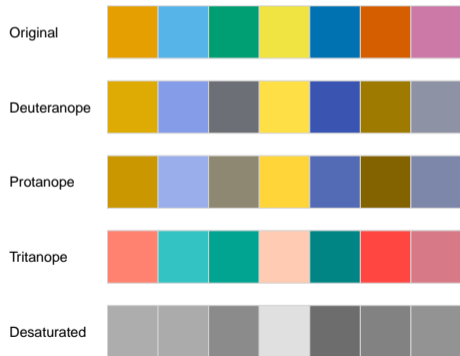
```
R> palette.colors(7, palette = "R4")[-1] |>  
+   swatchplot(cvd = TRUE)
```



# Color palettes: Somewhere over the Rainbow

**Qualitative:** "Okabe-Ito" palette very robust under color vision deficiencies.

```
R> palette.colors(8, palette = "Okabe-Ito")[-1] |>  
+   swatchplot(cvd = TRUE)
```



# Color palettes: Somewhere over the Rainbow

## Qualitative (palette.colors)

R4



ggplot2



Okabe-Ito



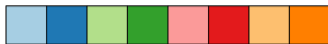
Accent



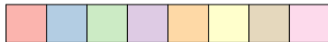
Dark 2



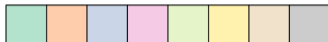
Paired



Pastel 1



Pastel 2



Set 1



Set 2



Set 3

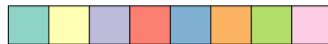


Tableau 10



Classic Tableau



Polychrome 36



Alphabet



# Colors by designers, painters, and directors?



**Movie:** *Todo sobre mi madre*  
(*All About My Mother*, 1999)

**Source:** Sony Pictures Classics  
via MoMA

# Colors by designers, painters, and directors?



**Movie:** *Todo sobre mi madre*  
(*All About My Mother*, 1999)

**Source:** Sony Pictures Classics  
via MoMA

**Palette:** Hadley Mendelsohn



# Colors by designers, painters, and directors?



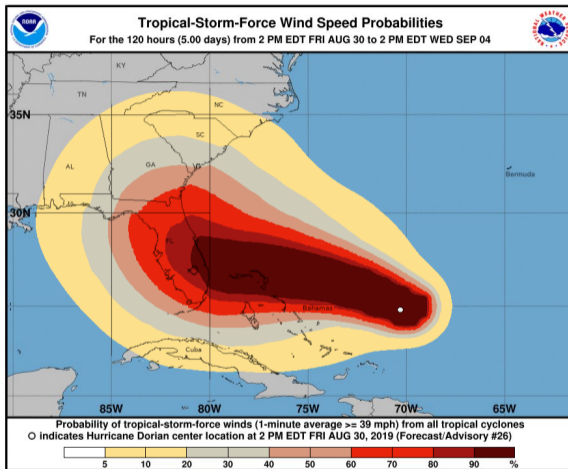
**Movie:** *Todo sobre mi madre*  
(*All About My Mother*, 1999)

**Source:** Sony Pictures Classics  
via MoMA

**Palette:** Hadley Mendelsohn

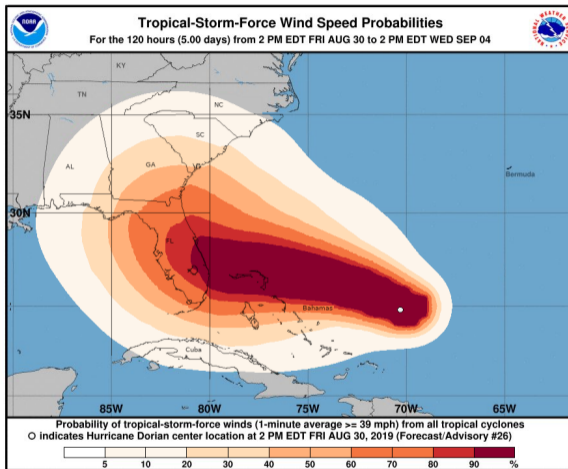


# Colors by designers, painters, and directors?



**Palette:** Todo sobre mi madre

# Colors by designers, painters, and directors?



**Palette:** OrRd (ColorBrewer.org, HCL version)

# Colors by designers, painters, and directors?



**Movie:** *Tacones lejanos* (*High Heels*, 1991)

**Source:** El Deseo S.A. via Twitter

# Colors by designers, painters, and directors?



**Movie:** *Tacones lejanos* (*High Heels*, 1991)

**Source:** El Deseo S.A. via Twitter

**Palette:** Bibiana Fernandez



# Colors by designers, painters, and directors?



**Movie:** *Tacones lejanos* (*High Heels*, 1991)

**Source:** El Deseo S.A. via Twitter

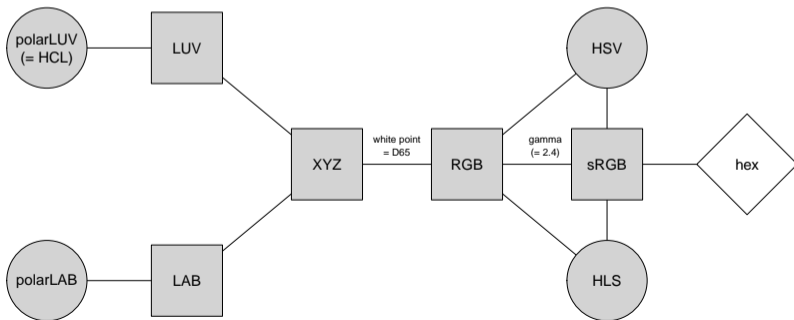
**Palette:** Bibiana Fernandez



# R package colorspace

**Origin of the package:** Convert colors between various three-dimensional representations of color.

**In particular:** From the perceptually-based HCL (Hue-Chroma-Luminance) to standard Red-Green-Blue (sRGB, and corresponding hex codes) space.



# Visualization and assessment

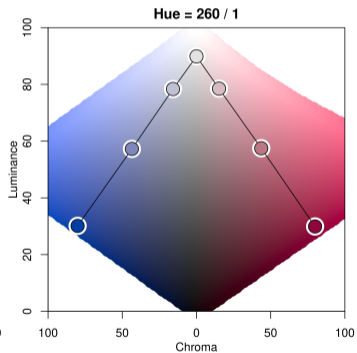
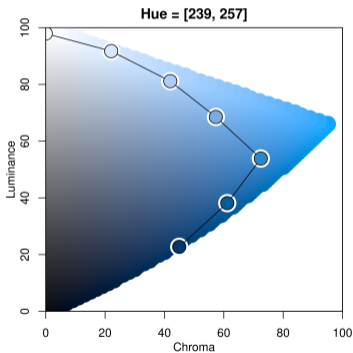
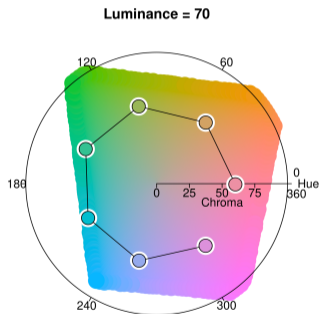
**Visualizations:** Based on vector of colors.

- `swatchplot()`: Color swatches.
- `specplot()`: Spectrum of HCL and/or RGB trajectories.
- `hclplot()`: Trajectories in 2-dimensional HCL space projections.
- `demoplot()`: Illustrations of typical (and simplified) statistical graphics.



# Visualization and assessment: hclplot()

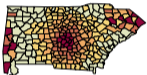
```
R> hclplot(qualitative_hcl(7, palette = "Set 2"))  
R> hclplot(sequential_hcl(7, palette = "Blues 3"))  
R> hclplot(diverging_hcl(7, palette = "Blue-Red"))
```



# Visualization and assessment: demoplot()

```
R> cl <- sequential_hcl(5, palette = "Heat")  
R> demoplot(cl, type = "...")
```

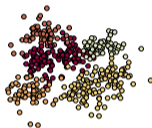
map



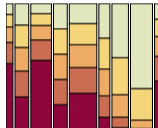
heatmap



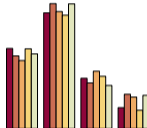
scatter



spine



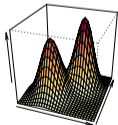
bar



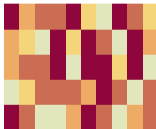
pie



perspective



mosaic



lines

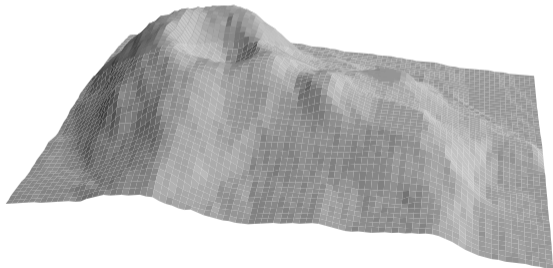


# Color vision deficiency

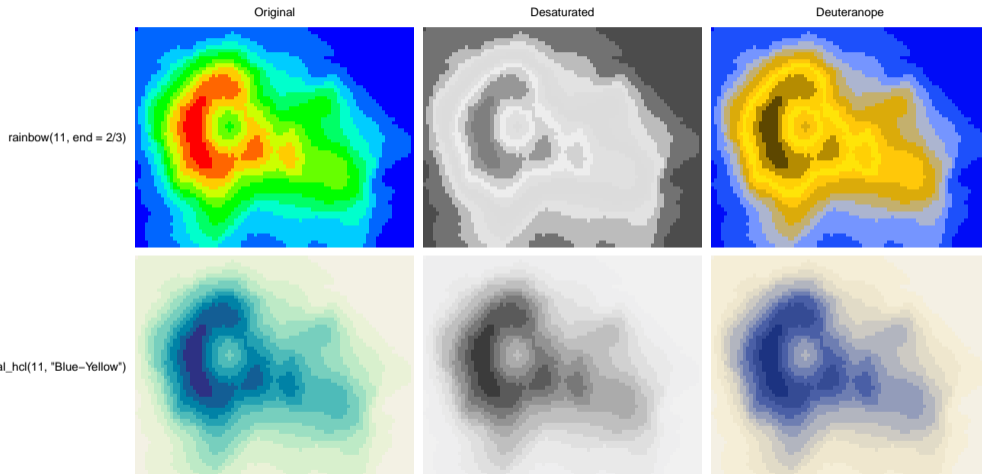
**Emulate:** Color vision deficiencies.

- `deutan()`: Deuteranopia (green deficient).
- `protan()`: Protanopia (red deficient).
- `tritan()`: Tritanopia (blue deficient).

**Example:** Maunga Whau volcano data.



# Color vision deficiency



# Color apps

**Facilitate exploration:** Graphical user interfaces as shiny apps.

- *Palette constructor:* `choose_palette()` or `hclwizard()` (also in `tcltk`).
- *Color picker:* `choose_color()` or `hcl_color_picker()`.
- *Color vision deficiency emulator:* `cvd_emulator()`.

**Online versions:** <https://hclwizard.org/>

# Color apps: choose\_palette() / hclwizard()

Mozilla Firefox

File Edit View History Bookmarks Tools Help

127.0.0.1:5604/ x +

127.0.0.1:5604

Search

Example Plot Spectrum Color Plane Export Info

**Base Options**

Type of palette  
Advanced: Sequential (single-hue)

Base color scheme  
Blues 3

Example  
Heatmap

**Control Options**

Reverse  
 Correct colors  
 Dark mode  
 Desaturated

**Vision**

Normal  
 Deutan  
 Protan  
 Tritan

**Color Settings**

HUE 1: 240 SET

CHROMA 1: 50 SET

MAX CHROMA: 90 SET

LUMN. 1: 20 SET

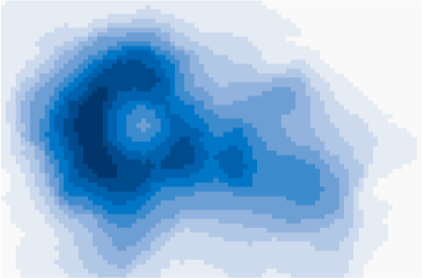
LUMN. 2: 95 SET

POWER 1: 1.2 SET

POWER 2: 1.4 SET

NUMBER: 11 SET

Return to R



R colorspace 1.4.5

# Color apps: choose\_color() / hcl\_color\_picker()

The screenshot shows a web-based color picker application running in Mozilla Firefox. The browser's address bar displays the URL 127.0.0.1:5604/. The application interface is divided into several sections:

- Left Panel:** Contains three sliders for adjusting color properties: Hue (set to 270), Chroma (set to 50), and Luminance (set to 60). Below the sliders is an input field for the RGB hex color, currently showing #9189C7, with a "Set" button. Further down, there is a "Selected color" preview bar and an "Actions" section with buttons for "Pick", "Unpick", "Clear", and "Return to R", along with a "Dark mode" checkbox.
- Right Panel:** Features a "Luminance-Chroma plane" diagram, which is a triangular color space plot. Below the plot are three horizontal scales: Hue (0 to 360), Chroma (0 to 150), and Luminance (0 to 100). Each scale has a circular marker indicating the current value.
- Bottom Panel:** A "Color palette" section displaying four color swatches with their corresponding hex codes: #E2E2E2, #B9B5D5, #9189C7, and #5F4FB1.

R colorspace 1.4.0

# Color apps: cvd\_emulator()

Mozilla Firefox


File Edit View History Bookmarks Tools Help

127.0.0.1:5604/ x +

127.0.0.1:5604

Upload Original Desaturated Deuteranope Protanope Tritanope


All Info



## Severity

0 10 20 30 40 50 60 70 80 90 100


Different levels of severity for the color vision deficiency can be emulated. A value of 100% means maximum deficiency, a value of 0% no deficiency at all. This value has to be adjusted before uploading the image.



## Upload Image

Browse... No file selected

Select an image from your local disc (PNG/JPG/JPEG) for which the color vision deficiency should be emulated. Please note that the file size is limited to 50.0 Megabyte.



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Mozilla Firefox

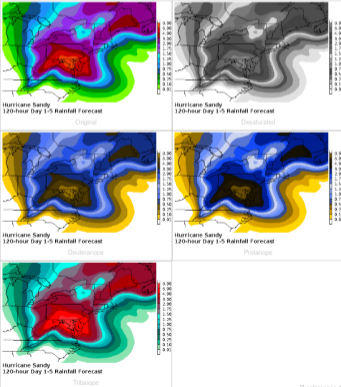
File Edit View History Bookmarks Tools Help

127.0.0.1:5604/ x +

127.0.0.1:5604

Upload Original Desaturated Deuteranope Protanope Tritanope

All Info



Hurricane Sandy 120-hour Day 1-5 Rainfall Forecast

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Hurricane Sandy 120-hour Day 1-5 Rainfall Forecast

Hurricane Sandy 120-hour Day 1-5 Rainfall Forecast

Hurricane Sandy 120-hour Day 1-5 Rainfall Forecast

© colorspace 1.4.0



# Recommendations

## **Colors and palettes:**

- Check whether color is appropriate for coding your information.
- Use appropriate type of palette.
- Don't reinvent the wheel, start out from well-established palettes.
- For areas use light colors (higher luminance, lower chroma).
- For points/lines darker colors are needed (lower luminance, higher chroma).
- Check robustness of palette.

# Recommendations

## Colors and palettes:

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## R:

- *colorspace* facilitates exploration, manipulation, and assessment.
- HCL approximations of palettes from *RColorBrewer*, *rcartocolor*, *scico*, ...
- Prespecified palettes are also easily available in base R.

# References

Zeileis A, Fisher JC, Hornik K, Ihaka R, McWhite CD, Murrell P, Stauffer R, Wilke CO (2020). “colorspace: A Toolbox for Manipulating and Assessing Colors and Palettes.” *Journal of Statistical Software*, **96**(1), 1–49. doi:10.18637/jss.v096.i01

Zeileis A, Murrell P, Maechler M, Sarkar D (2019). “A New palette() for R.” *R Foundation Blog*. <https://developer.R-project.org/Blog/public/2019/11/21/a-new-palette-for-r/>

Zeileis A, Murrell P (2019). “HCL-Based Color Palettes in grDevices.” *R Foundation Blog*/ <https://developer.R-project.org/Blog/public/2019/04/01/hcl-based-color-palettes-in-grdevices/>

Stauffer R, Mayr GJ, Dabernig M, Zeileis A (2015). “Somewhere over the Rainbow: How to Make Effective Use of Colors in Meteorological Visualizations.” *Bulletin of the American Meteorological Society*, **96**(2), 203–216. doi:10.1175/BAMS-D-13-00155.1

Zeileis A, Hornik K, Murrell P (2009). “Escaping RGBland: Selecting Colors for Statistical Graphics.” *Computational Statistics & Data Analysis*, **53**, 3259–3270. doi:10.1016/j.csda.2008.11.033.



# colorspace

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