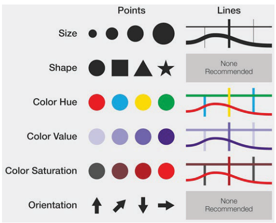
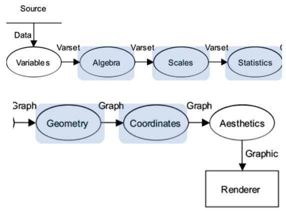




The Language of Graphs: from Bertin to GoG to ggplot2

Michael Friendly

Psych 6135

http://euclid.psych.yorku.ca/www/psy6135/

Topics

- Idea: Graphs as visual language
  - Early attempts at standardization of graphs
- Jacques Bertin: *Semiology of Graphics*
  - Mapping of visual properties to data relations
- Graphics programming languages:
  - Goal: power & elegance
- Lee Wilkinson: *Grammar of Graphics*
- Hadley Wickham: ggplot2




Metaphor: Graphs as visual language

- Playfair, Guerry, Minard and others described their fundamental insight that graphical displays convey quantitative data more directly than numbers.
- Playfair (1802)
  - *"Regarding numbers and proportions, the best way to catch the imagination is to speak to the eyes"*
- Minard (1861)
  - *"The aim of my carte figurative is … to convey promptly to the eye the relation not given quickly by numbers requiring mental calculation."*

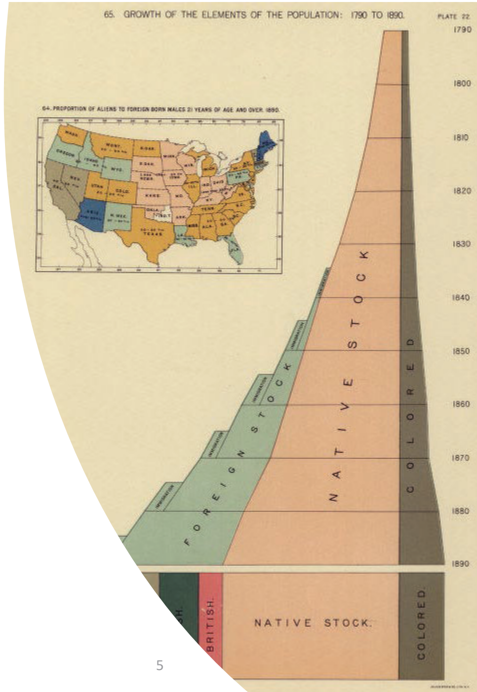
Metaphor: Graphs as visual language

- Émile Cheysson (1890) took this further:
  - *"When a law is contained in figures, it is buried like metal in an ore; it is necessary to extract it. This is the work of graphical representation.*
  - *It points out the coincidences, the relationships between phenomena, their anomalies, and we have seen what a powerful means of control it puts in the hands of the statistician to verify new data, discover and correct errors with which they have been stained."*

Context: Statistical albums, 1870-1910

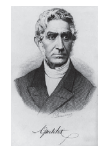
From ~ 1870—1910, statistical albums of official statistics on topics of population, trade, moral & political issues became widespread throughout Europe and the U.S.

- France: *Album de Statistique Graphique*: 1879-1899 (trade, commerce & other topics)
- USA: Census atlases: 1870/80/90--
- Switzerland: *Atlas graphique de la Suisse*:1897, 1914

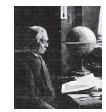


Need for standardization

- Beautiful graphics: Yes, but all separate designs
  - Can anything be compared across countries?
- Émile Cheysson (1878)
  - *"The time will come when Science has to lay down general principles and decide on well-defined standards. We can no longer tolerate this sort of anarchy"*
- International statistical meetings (ISI)
  - 1852 (Brussels), 1857 (Vienna), 1869 (The Hague), 1872 (St. Petersburg), 1876 (Budapest) …
  - Participants: Quetelet, Cheysson, Levasseur (France), Ernest Engel, Gustav von Mayr, Hans Schwabe (Germany), Francis Walker (U.S.), …




Cheysson


Levasseur


von Mayr


Walker

No consensus

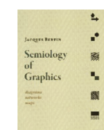
- St. Petersburg (1872) resolutions:
  - *"The Congress accepts that it is not worth going into details about the choice of methods or facts for graphical representation".*
  - *"no strict rule can be imposed on authors, because the only real problem is that of applying the graphical method to data that is comparable".*

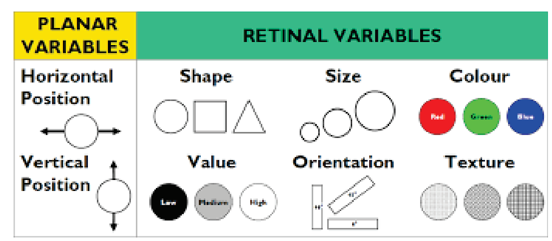
Standardize the data before the graphs!

- Most of the debate had to do with thematic maps
  - number of class intervals for a quantitative variable
  - number and variety of shading colors
- Yet, the idea of a visual language had been accepted, along with the need for some theory of graphs

Bertin: *Semiology of graphics* (1967)

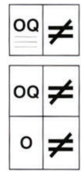
- Defines a system of "grammatical elements" of graphs and relations among visual attributes that give meaning (semantics) from perceptual features
  - Planar variables: (x,y) coordinates
  - Retinal variables: shape, size, color, …



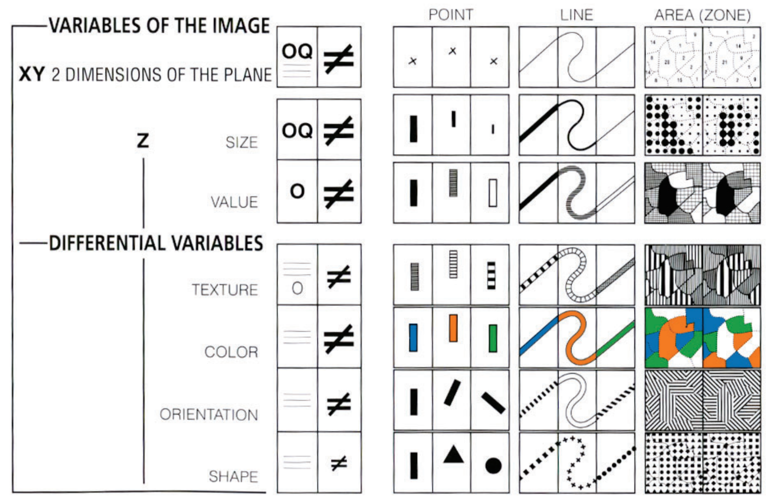


Bertin: *Semiology of graphics*

- Defines a system of mapping of retinal variables to properties of data variables for perception of relations
  - Association (≡) – marks are perceived as similar
  - Selection (≠) – marks are perceived as forming classes
  - Order (O) – marks are perceived as showing order
  - Quantity (Q) – marks are perceived as proportional
- This is the first theory of graphs relating visual attributes (encoding) to perceptual characteristics (decoding).
- It comprises nearly all known graph and thematic map types in a general system



The retinal variables and relationship types can be implanted in various symbol types in the plane (X,Y)



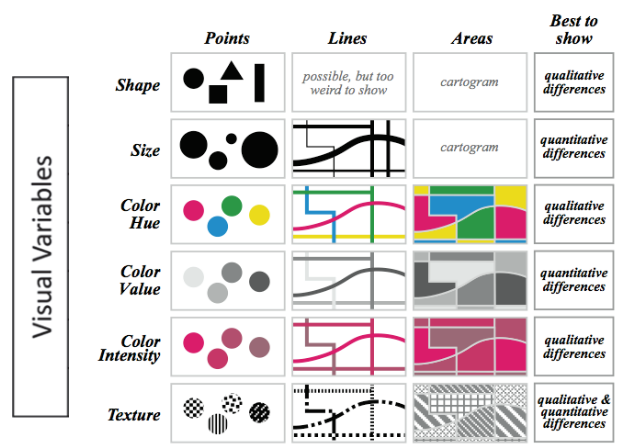
Visual variables & data characteristics

Visual variables differ in the kinds of information they can convey

Visual Variables	Selective (≠)	Associative (≡)	Quantitative (Q)	Order (O)	Length
Position					Theoretically Infinite
Size					Selection: ~5 Distinction: ~20
Shape					Theoretically Infinite
Value					Selection: <7 Distinction: ~10
Color					Selection: <7 Distinction: ~10
Orientation					Theoretically Infinite
Texture					Theoretically Infinite

Some recommendations

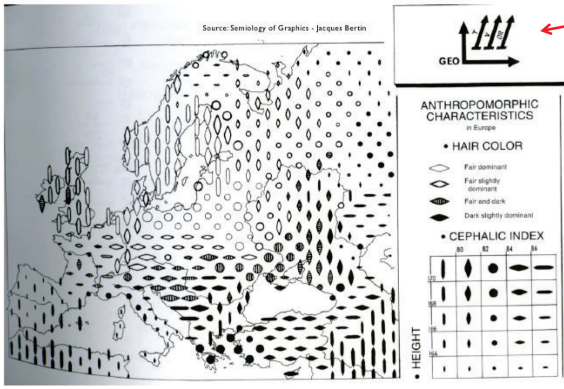
Various authors have used Bertin's system to make recommendations for the best attributes to use with different symbol types



Retinal variables allow several variables to be encoded.

Bertin's system provides a general framework for thematic mapping, allowing multiple variables to shown simultaneously in a single map.

Map for height, hair color and cephalic index distribution



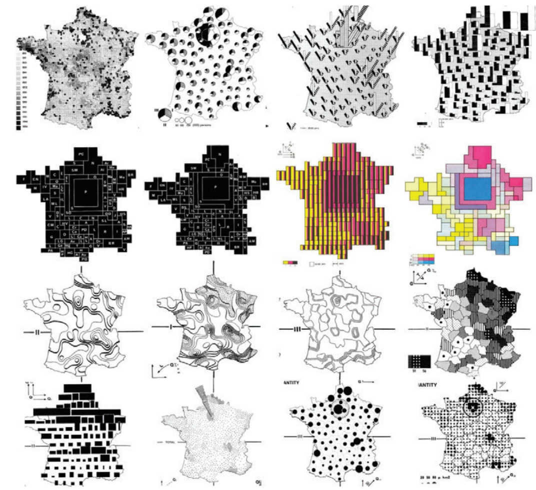
Legend:
GEO: (x,y)
T, V, OR: ordered

For Bertin, the legend is a symbolic description of the coordinate system and the variables displayed.

Various maps of France, encoding quantitative and categorical variables in a wide number of different ways.

This semiology is productive, as is the semiology of language.

Allows one to think of new graphic encodings.



Decoding: Reading a graphic

How successful is a graph for transmitting information?

Bertin defines three stages for reading a graphic:

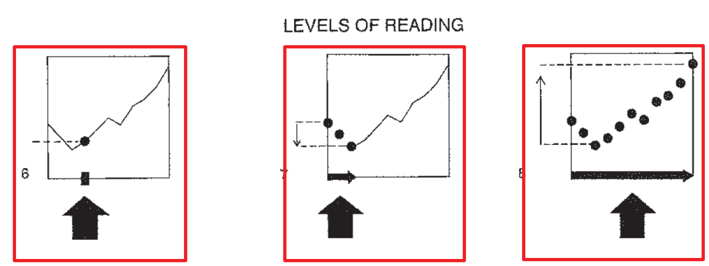
- **External**: What is the overall context?
  - Graph title, axis labels
- **Internal**: What visual variables are used to represent the components in the graphic?
  - points, lines, …
  - size, shape, color:hue, color:intensity, texture, …
- **Relationships**:
  - How are these components related?
  - What questions can I ask of this graphic?
  - What can I learn?

Research topic: Have there been any studies of this ordering in graph perception?

Reading levels

Questions a graph should answer:

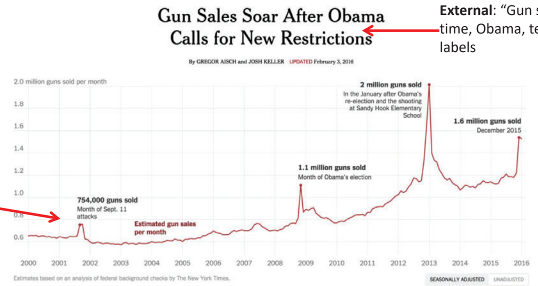
- Elementary: find some specific value
- Intermediate: make comparisons, see a trend
- Overall: what is the general message or overall trend?



These ideas provided the beginnings of a theory of graphs related to graph perception.

Reading levels: Example

Graph from the NY Times, Feb. 3, 2016



External: "Gun sales", time, Obama, text labels

Internal: lines, points for labeled events

Relationships: what is the message?

Reading tasks:

- Elementary: "How many guns were sold in January of 2013?"
- Intermediate: "What's the trend in gun sales since President Obama was elected?"
- Overall: "What's the overall trend in gun sales in America since the year 2000?"

From: https://medium.com/@karlsluis/before-tufte-there-was-bertin-63af71ceaa62

Bertin: The reorderable matrix

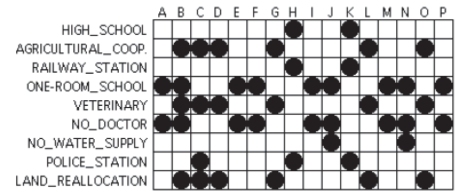
A data table: objects by characteristics

n		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	High School	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
2	Agricultural Cooperative	0	1	1	1	0	0	1	0	0	0	0	1	0	0	1	0
3	Railway Station	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
4	One Room School	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	1
5	Veterinary	0	1	1	1	0	0	1	0	0	0	0	1	0	0	1	0
6	No Doctor	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	1
7	No Water Supply	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
8	Police Station	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0
9	Land Reallocation	0	1	1	1	0	0	1	0	0	0	0	1	0	0	1	0

Both rows and columns are reorderable (≠≠)

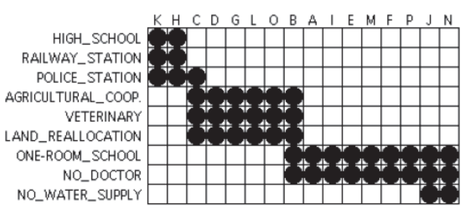
Overall relation can be discovered by permuting rows, cols

Encode each value by visual attributes



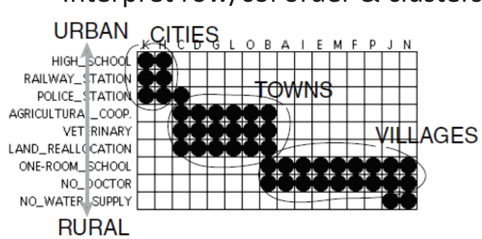
The reorderable matrix

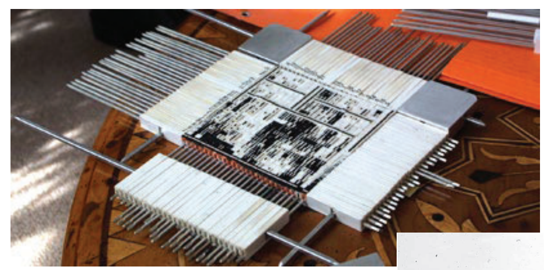
Permute rows and columns to put like with like



This is an early example of what I called "effect ordering" for data display

Interpret row/col order & clusters

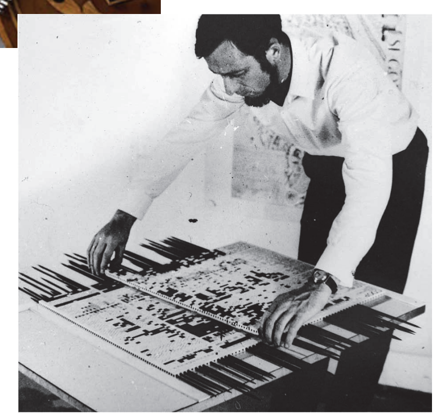




A physical device implementing matrix reordering

This was used by Bertin and others in a large number of applied projects

Bertin was to visual data analysis in France what Tukey was to EDA in N. America



Bertifier

Bertifier: A web app implementing Bertin's idea of the reorderable matrix
See: http://www.aviz.fr/bertifier

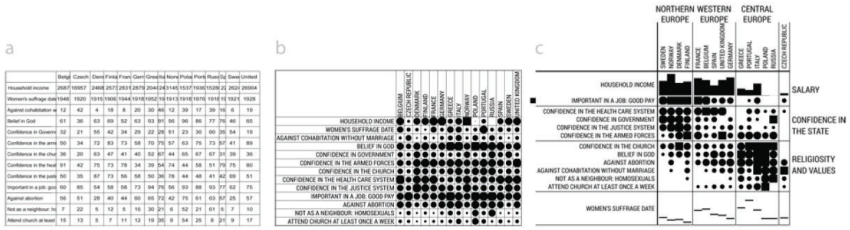


table: Attitudes and attributes by country
Values encoded by size and shape
Sorted and grouped by themes and country regions

Watch: Youtube video of Bertifier, http://youtu.be/tJxAF_a_yBQ

Heatmaps

Heatmaps are a re-invention of Bertin's ideas:

- Cluster analysis to reorder rows/cols
- Shading cells to show some variable

This example shows a microarray analysis of 128 leukemia patients using 12625 genes.

- The goal is to distinguish two types of leukemia
- The shading variable is a *z*-score for how well a given gene distinguishes the two types.
- Several clusters of high association are discovered!

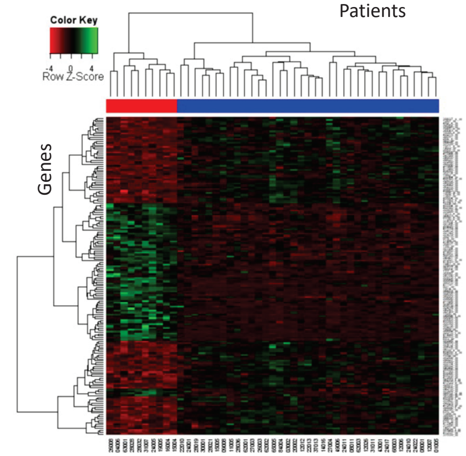


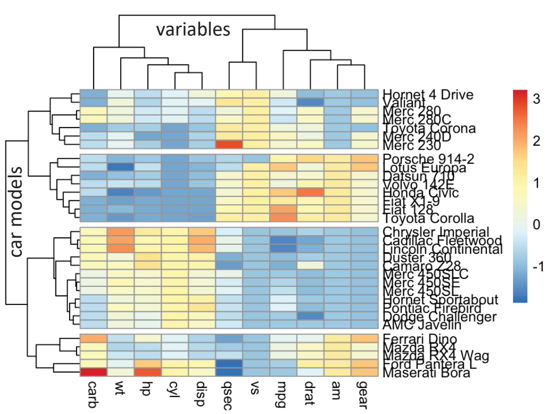
Image source: https://warwick.ac.uk/fac/sci/moac/people/students/peter_cock/r/heatmap/
See also: Wilkinson & Friendly, The History of the Cluster Heat Map, *The American Statistician*, 2009, 63, 179-184

Heatmaps: the devil is in the details

There are many implementations of "heatmaps"
They differ importantly in the details of: clustering, shading scheme

This example shows a data set of 11 measures on 32 cars from the 1974 Motor Tends magazine

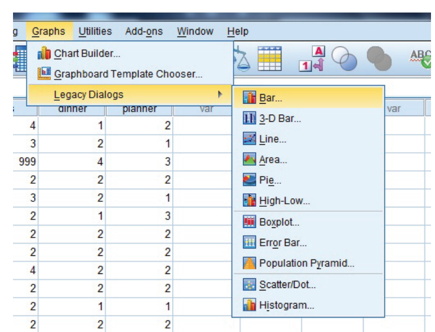
- Each variable was converted to z-scores
- The value was shaded using a bipolar color scheme
- Clusters of cars are slightly separated
- The very high and low values stand out

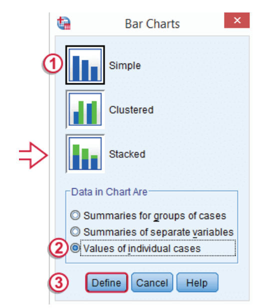


From: http://www.sthda.com/english/articles/28-hierarchical-clustering-essentials/93-heatmap-static-and-interactive-absolute-guide/

Making graphs: menus vs. syntax

Menu-driven graphics provide a wide range of graph types, with options
What's wrong with that?



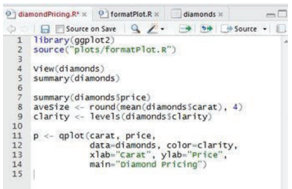


WYSIAYG: What you see is **all** you get. No way to do something different
Not reproducible: Change the data → Re-do manually from scratch
Often designed by programmers with little sense of data vis

Programming languages: Power & elegance

- **CS view**: All programming languages can be proved to be equivalent (to a Turing machine)
- **Cognitive view**: Languages differ in:
  - expressive power: ease of translating what you want to do into the results you want
  - elegance: how well does the code provide a human-readable description of what is done?
  - extensibility: ease of generalizing a method to wider scope
  - learn-ability: your learning curve (rate, asymptote)

+



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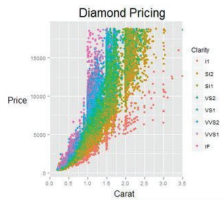


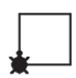
Programming languages: Power & elegance

Language	Features:Tools for thinking?
FORTRAN	Subroutines – reusable code Subroutine libraries (e.g., BLAS)
APL, APL2STAT	N-way arrays, nested arrays Generalized reduction, outer product Function operators
Logo	Turtle graphics Recursion, list processing
Lisp, LispStat, *ViSta*	Object-oriented computing Functional programming
Perl	Regular expressions Search, match, transform, apply
SAS	Data steps, PROC steps, BY processing SAS macros, Output Delivery system
R	Object-oriented methods, tidyverse: dplyr, ggplot2, …

Programming languages: Elegance - *Logo*

Features:

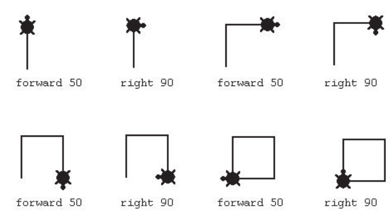
- Based on Lisp, but tuned to young minds
  - Papert: *Mindstorms: Children, Computers, and Powerful Ideas* (1980)
- Turtle graphics: draw by directing a turtle, not by (x,y) coordinates
  - Analytic geometry rests on a coordinate system.
  - Turtle geometry is "body syntonic": Tell turtle what to do.



- Data types:
  - words, lists, arrays, property lists
- Lists & list processing: inherited from Lisp, but with gentler syntax.
  - Lists are infinitely expandable & nestable.
- Recursion rather than iteration is the natural method to process lists
- Extensions:
  - multiple, animated turtles (sprites);
  - object-oriented programming (message passing) -> SmallTalk

Logo : Turtle graphics

Turtle primitives: forward, back, left, right, penup, pendown, ...

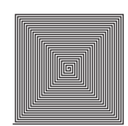


Logo procedures: teach the turtle a new word

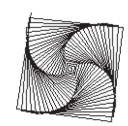
```
> to square :side
  repeat 4 [fd :side rt 90]
  end

> square 100
```

Recursive procedures:

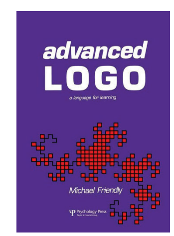
```
> to spiral :size :angle
  if :size > 100 [stop]
  forward :size
  right :angle
  spiral (:size + 2) :angle
  end
```



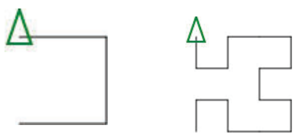
> spiral 0 90



> spiral 0 91



Logo : Hilbert curves



Logo was more than just pretty pictures

It was graphics & mathematics for young minds: **A language for learning**

```
to Hilbert0 :turn :size
 right :turn
 forward :size
 left :turn
 forward :size
 left :turn
 forward :size
 right :turn
end
```

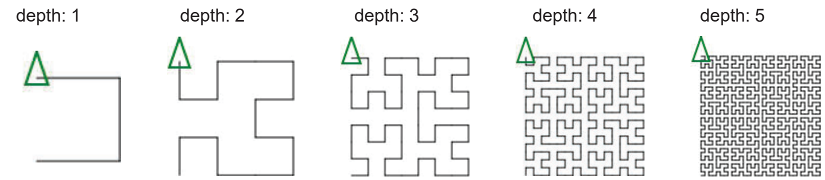
Start with some basic shape

What happens if you replace each line with a smaller copy of the basic shape?

What happens if you continue this process?

What happens if you choose a different basic shape?

Logo : Hilbert curves




```
to Hilbert :depth :turn :size
 if :depth = 0 [stop]
 right :turn
  Hilbert (:depth-1) -:turn :size
 forward :size
 left :turn
  Hilbert (:depth-1)  :turn :size
 forward :size
  Hilbert (:depth-1)  :turn :size
 left :turn
 forward :size
  Hilbert (:depth-1) -:turn :size
 right :turn
end
```

Hilbert curve: A continuous, space-filling fractal, of Hausdorff dimension 2

Theorem (Hilbert, 1891): The euclidean length of the n-th depth Hilbert curve, H_n is $2^n - \frac{1}{2^n}$

Proof (by enumeration): Redefine forward to calculate total turtle path length

```
to forward.length :size
  make "total.length :total.length + :size
  forward :size
  end
```

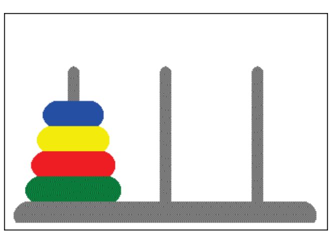
Logo: Tower of Hanoi

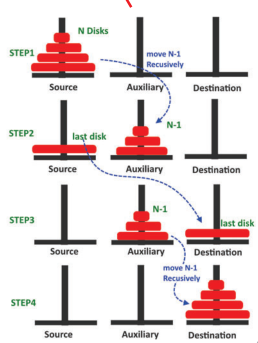
Move N disks from one pole to another, with no disk ever resting on a disk smaller than itself.

```
to Hanoi :n :start :goal :spare        # move disks 1:n from START to GOAL
if :n=0 [stop]                          # are we done?
Hanoi :n-1 :start :spare :goal          # move disks 1:n-1 from START to SPARE
move :n :start :goal                    # move disk n from START to GOAL
Hanoi :n-1 :spare :goal :start          # move disks 1:n-1 from SPARE to GOAL
end
```

A direct translation of an algorithm into code

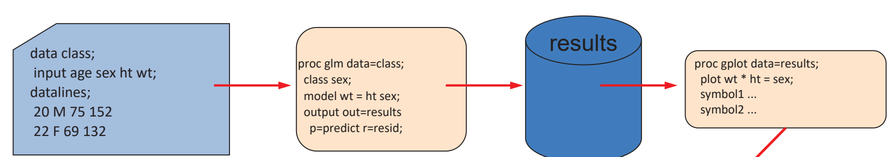
The Tower of Hanoi problem has an elegant solution in Logo
Change the 'move' instruction to render on screen or by a robot!

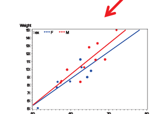




Graphics programming languages: SAS

- SAS: procedures + annotate facility + macros
  - PROC GPLOT (x,y plots), PROC GCHART, PROC GMAP, …
  - Annotate: data set with instructions (move, draw, text, fonts, colors)
  - Macros: Create a new, generic plot type, combining PROC steps and DATA steps.





Why I gave up SAS: This works well, and is very powerful, but lacks elegance

SAS thinking : many languages

ODS graphics
- template language

Output delivery system (ODS)

%macro language

proc iml
- matrix language, graphics

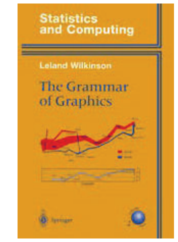
- procs, Annotate language

SAS/Graph:

Base SAS, SAS/STAT
- data step, proc steps

Wilkinson: Grammar of Graphics

- Natural language:
  - **Grammar**/syntax: What are the minimal, complete set of rules to describe all well-formed sentences?
    - John ate the big red apple ✓
    - John big apple red apple ate the ×
  - **Semantics**: How to distinguish meaning, nonsense, poetry in well-formed sentences?
    - Large green trucks carry garbage ✓
    - Colorless green ideas sleep furiously ??
- How to apply these ideas to graphics?
  - Grammar: Algebra, scales, statistics, geometry, …
  - Semantics: Space, time, uncertainty, …
  - Needed: a complete formal theory of graphs & computational graphics language



Wilkinson: Grammar of Graphics

- A complete system, describing the components of graphs and how they combine to produce a finished graphic
  - *"The grammar of graphics takes us beyond a limited set of charts (words) to an almost unlimited world of graphical forms (statements)"* (Wilkinson, 2005, p. 1).
  - *"… describes the meaning of what we do when we construct statistical graphics … more than a taxonomy"*
  - *"This system is capable of producing some hideous graphics … This system cannot produce a meaningless graphic, however."*
- This is a general theory for producing graphs.
  - the foundation of most modern software systems;
  - not connected with a theory for reading graphs à la Bertin.

Wilkinson: Grammar of Graphics

- Components:
  - specification: a formal language for composing graphs
  - assembly: coordination of attributes
    - internal: a data structure for a graphical "object"
  - rendering: producing a graphic on a display system
    - low level: device drivers for screen, PDF, PNG, SVG, …

```
ELEMENT: point(position(x*y)),
COORD: rect(dim(1,2))
SCALE: linear(dim(1))
SCALE: linear(dim(2))
GUIDE: axis(dim(1), label("Sepa
GUIDE: axis(dim(2), label("Sepa
```

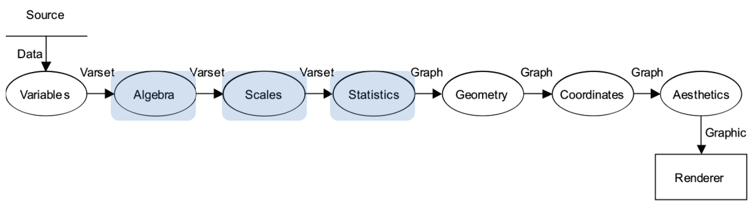
code

data structure

graphical output

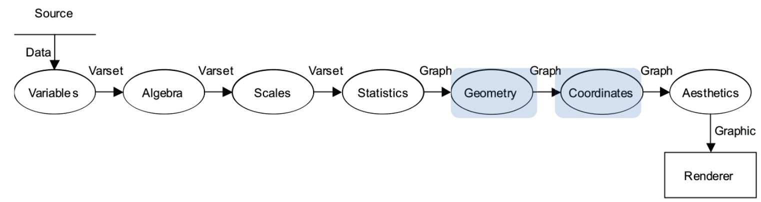
Grammar of Graphics: Specification

- **Algebra**: combine variables into a data set to be plotted
  - cross (A*B), nest (A/B), blend (A+B), filter, subset, …
- **Scales**: how variables are represented
  - categorical, linear, log, power, logit, …
- **Statistics**: computations on the data
  - binning, summary (mean, median, sd), region (CI), smoothing



Grammar of Graphics: Specification

- **Geometry**: Creation of geometric objects from variables
  - Functions: point, line, area, interval, path, …
  - Partitions: polygon, contour,
  - Networks: edge
  - Collision modifiers: stack, dodge, jitter
- **Coordinates**: Coordinate system for plotting
  - transformations: translation, rotation, dilation, shear, projection
  - mappings: Cartesian, polar, map projections, warping, Barycentric
  - 3D+: spherical, cylindrical, dimension reduction (MDS, SVD, PCA)



Grammar of Graphics: Specification

- **Aesthetics**: mapping of qualitative and quantitative scales to sensory attributes (extends Bertin)
  - Form: position, size, shape (polygon, glyph, image), rotation, …
  - Surface: color (hue, saturation, brightness), texture (pattern, orientation), blur, transparency
  - Motion: direction, speed, acceleration
  - Sound: tone, volume, rhythm, voice, …
  - Text: label, font, size, …
- **Facets**: Construct multiplots (“small multiples”) by partitioning, blending or nesting
- **Guides**: Allow for reading the encodings of variables mapped to aesthetics
  - scales: axes, legend (labels: size, shape, color, …)
  - annotations (title, footnote, line, arrow, ellipse, text, …)

Grammar of Graphics: Implementation

- Wilkinson illustrates the GoG with a programming language (GPL: the *G*raphics *P*roduction *L*anguage)
- GPL statements
  - **DATA**: expressions that create variables to display from data sets
  - **TRANS**: variable transformations prior to plotting (e.g., ranking the data points)
  - **ELEMENT**: define graphical elements (e.g., points, lines, …) and their aesthetic attributes (e.g., shape, color, …) to use in the display
  - **SCALE**: apply scale transformations to the plot (e.g., square root or log)
  - **COORD**: select the coordinate system for use in the graphic (e.g., Cartesian, polar)
  - **GUIDE**: guides to aid interpretation (axes, legends)

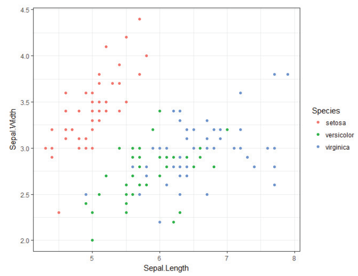
GPL example: scatterplot

A simple scatterplot of the Iris data, points colored by species

```
DATA: x = "SepalLength"
DATA: y = "SepalWidth"
DATA: z = "Species"
TRANS: x = x
TRANS: y = y
ELEMENT: point(position(x*y), color(z))
COORD: rect(dim(1,2))
SCALE: linear(dim(1))
SCALE: linear(dim(2))
GUIDE: axis(dim(1), label("Sepal Length"))
GUIDE: axis(dim(2), label("Sepal Width"))
```

TRANS, SCALE, COORD and GUIDE all show the defaults & aren't necessary here.
The key one is ELEMENT, specifying points, positioned by (x*y) and colored by z

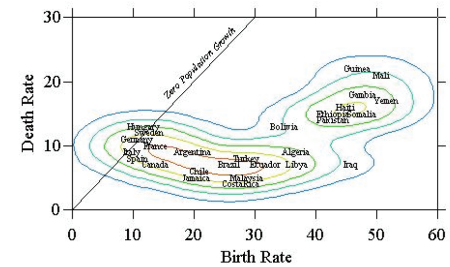
SPSS graphics now use GPL as the backend (syntax) for their graphics engine



GPL example: contour plot

A smoothed contour plot of birth rate vs. death rate for selected countries

ELEMENT: point(position(birth*death), label(country))
ELEMENT: contour(position(smooth.kernel.density(birth*death)), color.hue())
GUIDE: form.line(position((0,0), (30,30)), label("Zero population growth"))
GUIDE: axis(dim(1), label("Birth rate"))
GUIDE: axis(dim(2), label("Death rate"))



Wilkinson, *Grammar of Graphics*, Fig 1.1

GPL syntax

The essential features of a graph are described by **ELEMENT**
- The geometrical objects (point, line, interval, …) are specified within this
- Their visual properties (position, color) and statistical summaries are given as well

Some typical graph types:

Graph	*Syntax*
scatterplot	ELEMENT: *point* (*position* (d*r))
line chart	ELEMENT: *line* (*position* (d*r))
bar chart	ELEMENT: *interval* (*position* (d*r))
hor. bar chart	COORD: *rotate* (270) ELEMENT: *point* (*position* (d*r))
clustered bar chart	ELEMENT: *interval.dodge* (*position* (d*r), *color* (c))
stacked bar chart	ELEMENT: *interval.stack* (*position* (*summary.proportion* (r), *color* (c)))
histogram	ELEMENT: *interval* (*position* (*summary.count* (*bin.rect* (y))))

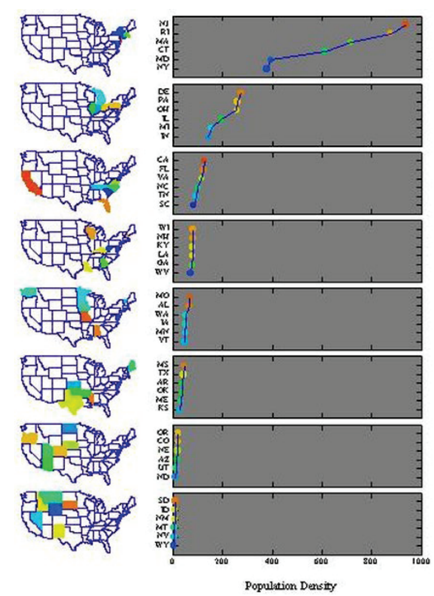
From: Pere Milán, *Imagining data with ggplot2*, QM Forum presentation, Nov. 23, 2015

Facets & frames

Tables of graphs:
- Facets: → graphs of subset
- Frames: → separate graphs

Linked micromap:
- Population density of US, divided in octiles
- States in each octile shown separately

GoG was a coherent language for specifying and producing nearly all known graphic forms.



Colorless green graphs sleep furiously

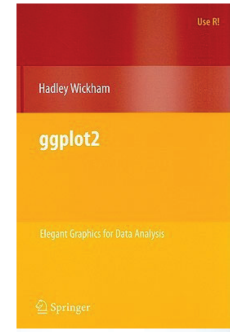
- JSM 2017: Dinner with Lee Wilkinson, Howard Wainer, Paul Vellman, & others
- The great debate:
  - LW: The GoG is a complete theory, a formal mathematical model comprehending all graphs.

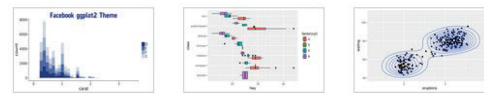
"Beauty is truth, truth beauty,"--that is all Ye know on earth, and all ye need to know.

  - MF: There is more--
    - Implementation matters: translating a graphic idea into a finished graph should be facilitated by the language of graphic code.
    - A productive language for graphs should encompass the steps of data analysis
  - Pere Milán: A truly expressive graphic language should recommend the right graphic(s) to "get the message home"

Wickham: ggplot2

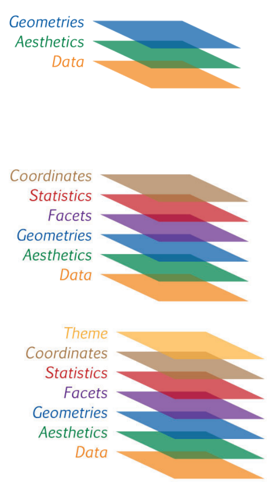
- ggplot2: *Elegant graphics for data analysis*
  - a computational language for thinking about & constructing graphs
  - sensible, aesthetically pleasing defaults
    - + themes: default, bw, journal, tufte, …
  - infinitely extendable
    - ggplot extensions: https://exts.ggplot2.tidyverse.org/





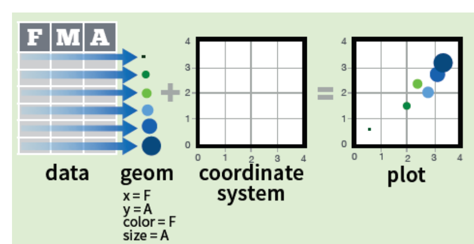
Wickham: ggplot2

- Implementation of GoG in R as layers of a graphic
  - Basic layers:
    - Data,
    - Aesthetics (data → plot mapping)
    - Geoms (points, lines, bars, …),
  - Statistics: summaries & models
  - Coordinates: plotting space
  - Facets: partition into sub-plots
  - Themes: define the general features of all graphical elements



ggplot2: data + geom = graph

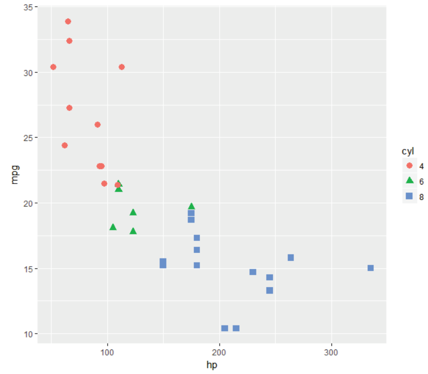
- Every graph can be described as a combination of independent building blocks, connected by "+" (read: "and")
  - data: a data frame: quantitative, categorical; local or data base query
  - aesthetic mapping of variables into visual properties: size, color, x, y
  - geometric objects ("geom"): points, lines, areas, arrows, …
  - coordinate system ("coord"): Cartesian, log, polar, map,




```
ggplot(FMA,
       aes(x=F, y=A, color=F, size=A) +
  geom_point()
```

ggplot2: data + geom = graph

```
ggplot(data=mtcars,
       aes(x=hp, y=mpg,
           color=cyl, shape=cyl)) +
  geom_point(size=3)
```



In this call:

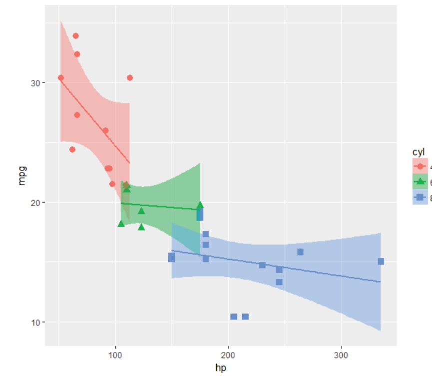
- data=mtcars: data frame
- aes(x=, y=): plot X,Y variables
- aes(color=, shape=): attributes
- + geom_point(): what to plot
- the coordinate system is taken to be the standard Cartesian (x,y)
- a corresponding legend is automatically generated

ggplot2: geoms

Wow! I can really see something there.

How can I enhance this visualization?

Easy: add a geom_smooth() to fit linear regressions for each level of cyl



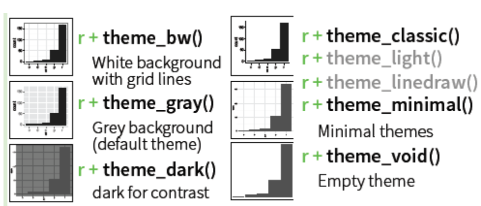

```
ggplot(mtcars, aes(x=hp, y=mpg, color=cyl, shape=cyl)) +
  geom_point(size=3) +
  geom_smooth(method="lm", aes(fill=cyl))
```


ggplot2: GoG -> graphic language

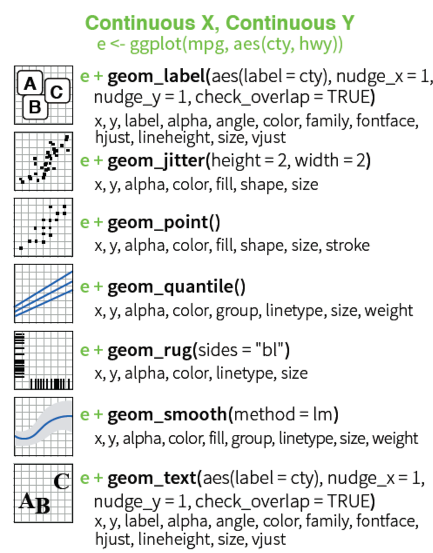
- The implementation of GoG ideas in ggplot2 for R created a more expressive language for data graphs
  - layers: graph elements combined with “+” (read: “and”)

```
ggplot(mtcars, aes(x=hp,  y=mpg)) +
  geom_point(aes(color = cyl)) +
  geom_smooth(method ="lm") +
```

  - themes: change graphic elements consistently



ggplot2: more geoms



ggplot2 facilitates graphical thinking by making a clear separation among:

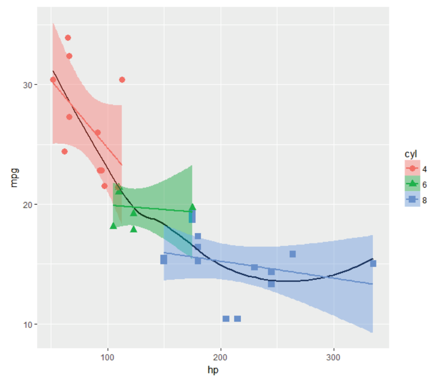
- mapping data variables to plot features (aes());
- geometric objects (geom_())
- statistical summaries (stat_())

ggplot2: layers & aes()

Aesthetic attributes in the ggplot() call are passed to geom_() layers

Other attributes can be passed as constants (size=3, color="black") or with aes(color=, …) in different layers

This plot adds an overall loess smooth to the previous plot




```
ggplot(mtcars, aes(x=hp, y=mpg)) +
  geom_point(size=3, aes(color=cyl, shape=cyl)) +
  geom_smooth(method="lm", aes(color=cyl, fill=cyl)) +
  geom_smooth(method="loess", color="black", se=FALSE)
```

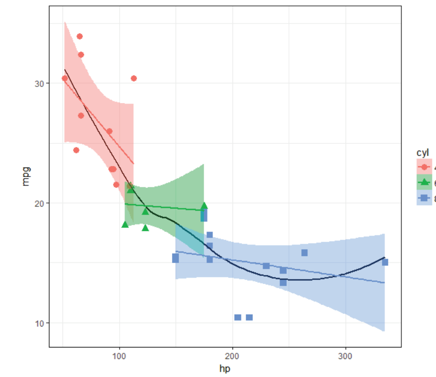

ggplot2: themes

All the graphical attributes of ggplot2 are governed by themes – settings for all aspects of a plot

A given plot can be rendered quite differently just by changing the theme

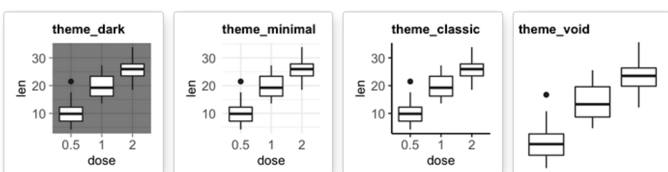
If you haven't saved the ggplot object, last_plot() gives you something to work with further

```
last_plot() + theme_bw()
```

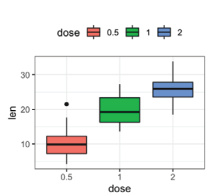


ggplot2: themes

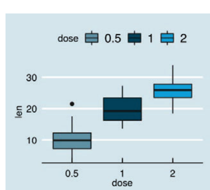
Built-in ggplot themes provide a wide variety of basic graph styles



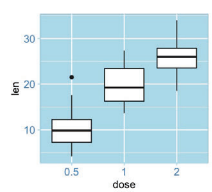
Other packages provide custom themes, or you can easily define your own



theme_hc()



theme_economist()



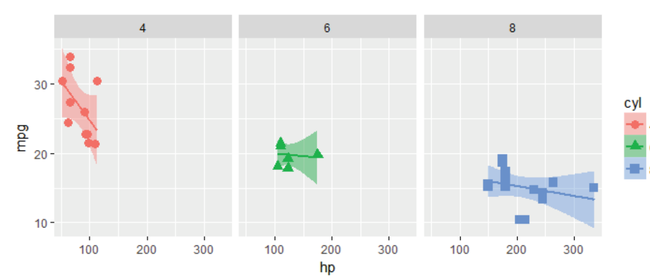
theme_bluewhite()

ggplot2: facets

Facets divide a plot into separate subplots based on one or more discrete variables

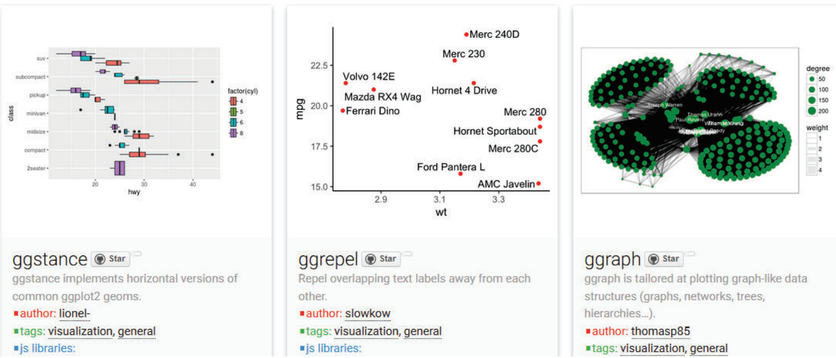
```
plt <-
ggplot(mtcars, aes(x=hp, y=mpg, color=cyl, shape=cyl)) +
        geom_point(size=3) +
        geom_smooth(method="lm", aes(fill=cyl))

plt + facet_wrap(~gear)
```

Syntax:
facet_wrap(rowvar ~ colvar)



ggplot2: extensions

ggplot2 provides a prototype system for implementing new geoms, stats, themes, …
Many of these are listed at https://exts.ggplot2.tidyverse.org/



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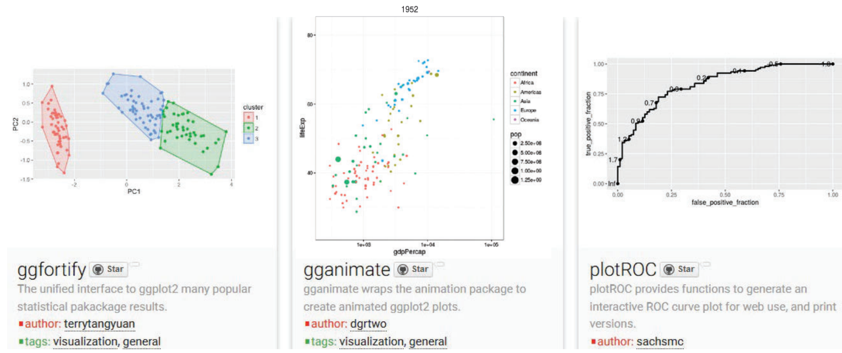
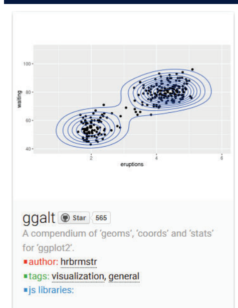
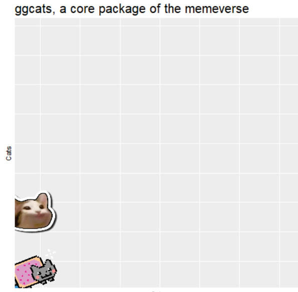


ggplot2: extensions

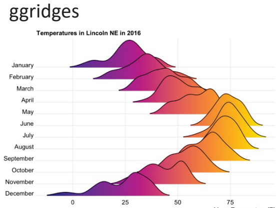


ggcats, a core package of the memeverse

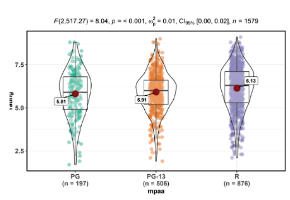


ggwordcloud

ggridges



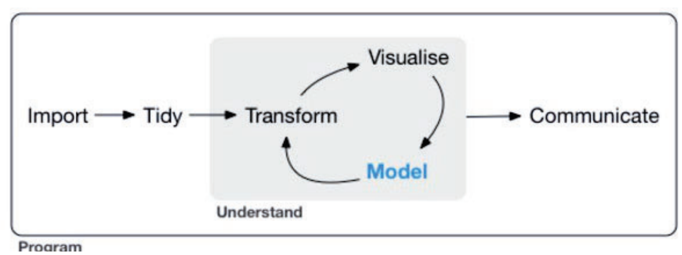
ggstatsplot



The wide range of extensions indicates the power of ggplot2 as a general framework for data graphics

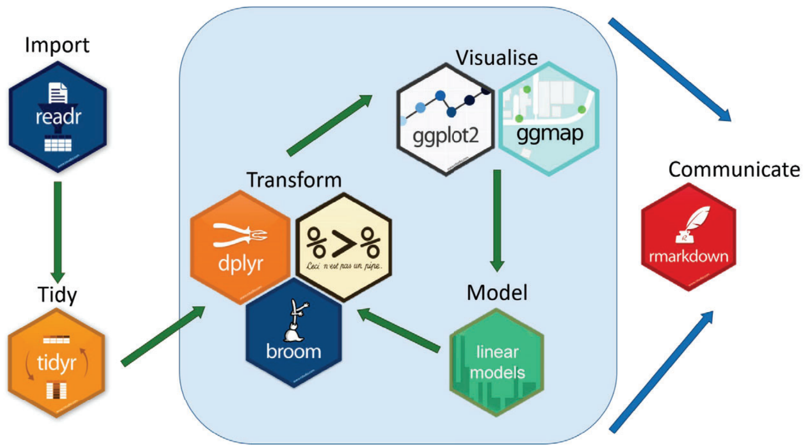
A larger view: Data science

- Data science treats statistics & data visualization as parts of a larger process
  - Data import: text files, data bases, web scraping, …
  - Data cleaning → "tidy data"
  - Model building & visualization
  - Reproducible report writing



The tidyverse of R packages

These ideas inspire a larger view of data analysis and graphics based on tidy principles.



Summary

- Graphical developers in the Golden Age recognized the idea of "graphic language," but could not define it.
- Bertin first formalized the relations between graphical features ("retinal variables"), data attributes (O, Q, ≠, ≡), and "reading levels"
- Wilkinson, in GoG, created a comprehensive syntax and algebra to define any graph
- Wickham, in ggplot2, created an expressive language to ease the translation of graphic ideas into plots.
- Tidyverse ideas place data analysis & graphics within a communication-oriented, reproducible research framework.