

Correspondence analysis



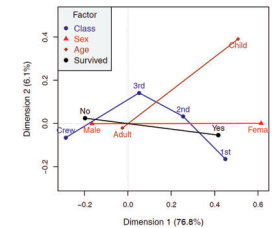
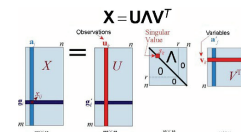
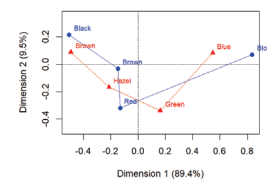
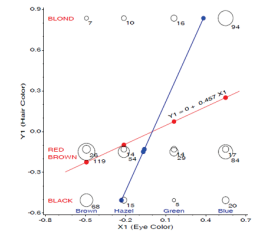
Michael Friendly
Psych 6136

<https://friendly.github.io/psy6136>



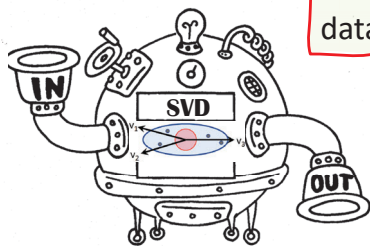
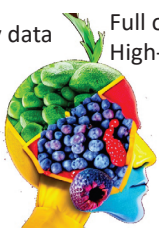
Today's topics

- Correspondence analysis: Basic ideas
- Singular value decomposition (SVD)
- Optimal category scores
- Multiway tables: MCA



Multivariate Juicers

My data Full of flavor
High-dimensional



Squeeze the most flavor from your data in low-D space

Insight



Examples:

- ❖ PCA/Biplot: Data juicer
- ❖ CDA plots: MANOVA juicer
- ❖ CA/plot: The categorical juicer

Correspondence analysis: Basic ideas

Analog of PCA for frequency data

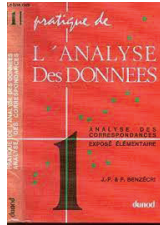
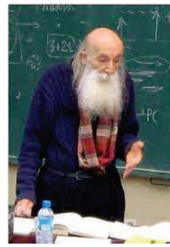
- Account for **maximum** % of χ^2 in few (2-3) dimensions
- Finds **scores** for row (x_{im}) and col (y_{jm}) categories on these dimensions
- Uses **Singular Value Decomposition** of residuals from independence,

$$d_{ij} = (n_{ij} - \hat{m}_{ij}) / \sqrt{\hat{m}_{ij}} \quad \longrightarrow \quad d_{ij} = \sqrt{n} \sum_{m=1}^M \lambda_m x_{im} y_{jm} \quad \leftrightarrow \quad D = X \Lambda Y^T \quad (\text{SVD})$$

- **Optimal scaling**: each pair of scores for rows (x_{im}) and col (y_{jm}) have highest possible correlation (= λ_m)
- **Plots** of the row and column scores show associations
 - Row point (x_{im}) **near** col point (y_{jm}) \rightarrow positive association $d_{ij} > 0$

Correspondence analysis: History

- Mathematical foundations:
 - “Geometric data analysis”, J. P. Benzecri, ~ 1960s
 - The French school: L’Analyse des Données
 - Popularized in European social science
- Multidimensional EDA
 - More descriptive than inferential
 - “models should follow the data, not vice versa”
 - High-D phenomena → Low-D approximations
- CARME conferences: every 4 years



CA software for R

- [ca package](#)
 - `ca()` – two-way tables; `plot(ca())` for graphs
 - `mjca()` – multiple & joint CA; `vcdExtra::mcaplot()` for plots
- [FactoMineR](#), [factoextra](#) & [Factoshiny](#) packages
 - `CA()` – many options for graphical displays
 - `fviz_ca()` – uses `ggplot2`; can `ggrepel` point labels
- [ade4](#) & `ade4shiny` packages
 - `dudi.coa()` – very nice graphics, but somewhat quirky



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Example: Hair color, eye color

```
> library(ca)
> haireye <- margin.table(HairEyeColor, 1:2)
> (haireye.ca <- ca(haireye))
```

Principal inertias (eigenvalues):

	1	2	3
Value	0.208773	0.022227	0.002598
Percentage	89.37%	9.52%	1.11%

χ^2 % for dimensions

Rows:

	Black	Brown	Red	Blond
Mass	0.1824	0.4831	0.1199	0.215
ChiDist	0.5512	0.1595	0.3548	0.838
Inertia	0.0554	0.0123	0.0151	0.151
Dim. 1	-1.1043	-0.3245	-0.2835	1.828
Dim. 2	1.4409	-0.2191	-2.1440	0.467

} Hair category scores, Dim1-2

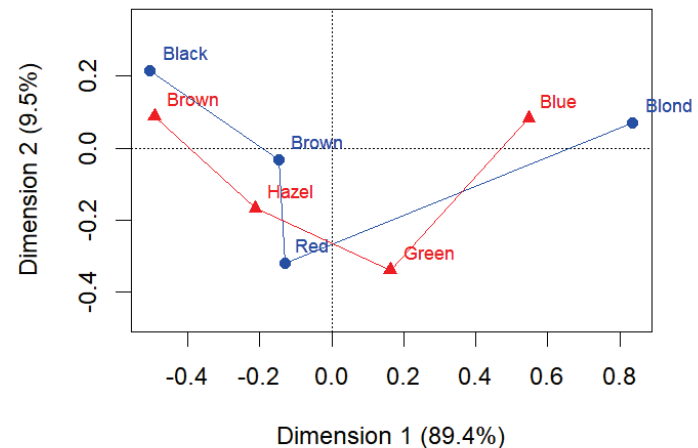
Columns:

	Brown	Blue	Hazel	Green
Mass	0.3716	0.363	0.1571	0.1081
ChiDist	0.5005	0.554	0.2887	0.3857
Inertia	0.0931	0.111	0.0131	0.0161
Dim. 1	-1.0771	1.198	-0.4653	0.3540
Dim. 2	0.5924	0.556	-1.1228	-2.2741

} Eye category scores, Dim1-2

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```
plot(haireye.ca, lines=TRUE)
```

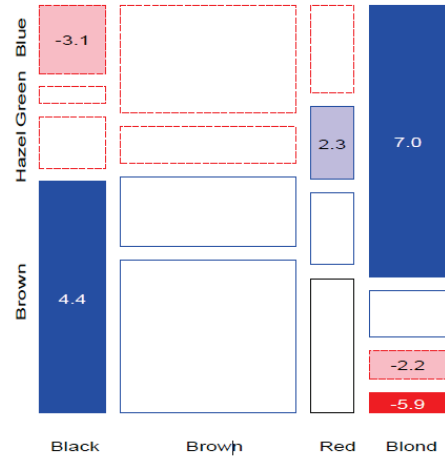


- Rough interpretation: row/col points “near” each other are positively associated (independence residuals $d_{ij} >> 0$)
- Dim 1: 89.4% of χ^2 (dark → light)
- Dim 2: 9.5% of χ^2 (Red/Green vs. others)

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Row & column profiles

Hair color, Eye color data: Compare with mosaic display



- The main dark–light dimension is reflected in the opposite-corner pattern of residuals
- The 2nd dimension is reflected in deviations from this pattern (e.g., Red hair–Green eyes)
- CA is “accounting for” residuals (deviations) from independence

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- For a two-way table, row profiles & column profiles give **relative** proportions of the categories
- An association is present to the extent that the row/col profiles differ
- Profiles add to 1.0 (100%), and can be visualized in profile space

Example: Toothpaste purchases by region

120 people in three regions where asked which of four brands of toothpaste, A–D, they had most recently purchased. Is there a difference among regions?

toothpaste

```
##           Region
## Brand    R1 R2 R3
## Brand A    5  5 30
## Brand B    5 25  5
## Brand C   15  5  5
## Brand D   15  5  0
```

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- Row profiles pertain to the differences among **brand** preference
- Column profiles pertain to the differences among **regions**

Region	→			Sum
Brand	R1	R2	R3	
Brand A	12.5	12.5	75.0	100
Brand B	14.3	71.4	14.3	100
Brand C	60.0	20.0	20.0	100
Brand D	75.0	25.0	0.0	100
Sum	100.0	100.0	100.0	

There is clearly an association: → the row (& column) profiles differ

```
> chisq.test(toothpaste)
```

Pearson's Chi-squared test

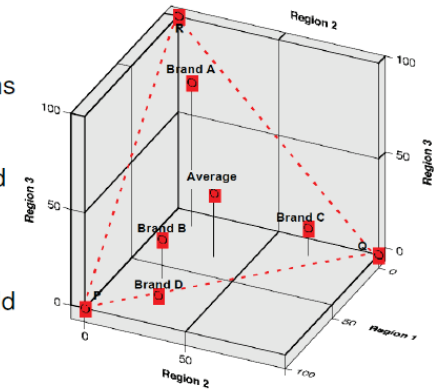
```
data: toothpaste
X-squared = 79.6, df = 6, p-value = 4.3e-15
```

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Plotting profiles

In this simple example we can plot the row profiles as points in 3D space, with axes corresponding to regions, R1, R2, R3

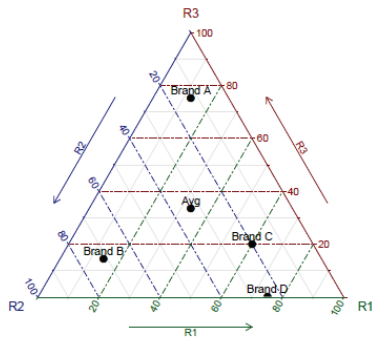
- Each brand is positioned in this space according to its proportions for the regions
- Because proportions sum to 100%, all points lie in the dashed plane PQR
- The Average profile is at the (weighted) centroid
- If no association, all brands would appear at the centroid



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Plotting profiles

Analogous 2D plot is a **trilinear plot** that automatically scales the R1–R3 values so they sum to 100%



- The Avg profile has coordinates of 33.3% for each region
- Brand preferences by region can be seen by their positions wrt the R1–R3 axes
- This suggests that differences among brands can be measured by their (squared) distances from the centroid, weighted by their row margins (**mass**)
- Physical analogy suggests the term **inertia** for this weighted variation

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CA solution

The CA solution has at most $\min(r - 1, c - 1)$ dimensions
The 2D solution here is **exact**, i.e., accounts for 100% of Pearson χ^2

```
> tp.ca <- ca(toothpaste)
> summary(tp.ca, rows=FALSE, columns=FALSE)

Principal inertias (eigenvalues):

dim  value      %  cum%  scree plot
1    0.410259  61.8  61.8  *****
2    0.253134  38.2  100.0 *****
-----
Total: 0.663393 100.0
```

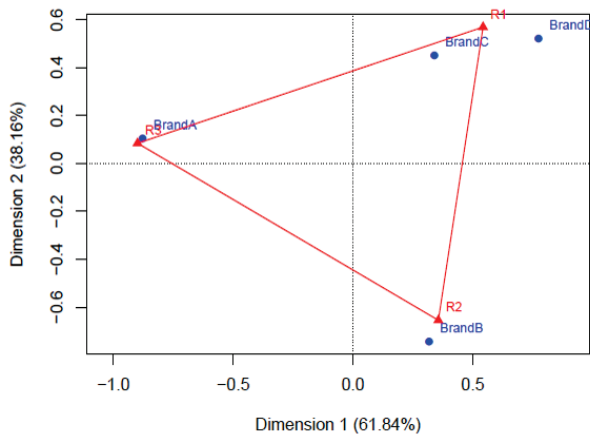
$$\text{Pearson } \chi^2 = N \sum \lambda^2$$

```
> # reproduce chi-square
> sum(tp.ca$sv^2) * sum(toothpaste)
[1] 79.607
```

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CA solution

```
res <- plot(tp.ca)
polygon(res$cols, border="red", lwd=2)
```

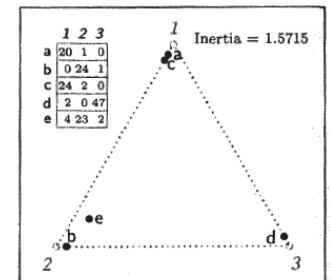
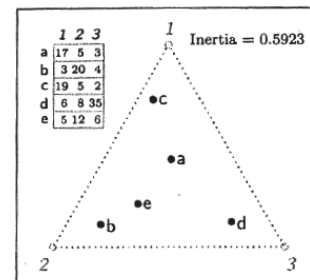
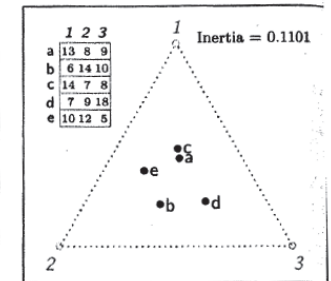
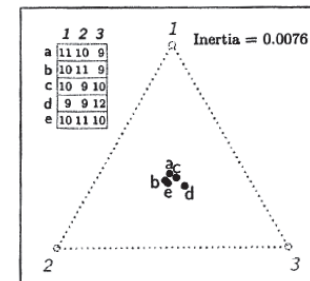


Brand A: most in R3
Brand B: most in R2
Brands C, D: most in R1

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Profiles & inertia

Exhibit 4.2:
A series of data tables with increasing total inertia. The higher the total inertia, the greater is the association between the rows and columns, displayed by the higher dispersion of the profile points in the profile space. The values in these tables have been chosen specifically so that the column sums are all equal, so the weights in the χ^2 -distance formulation are the same, and hence distances we observe in these maps are true χ^2 -distances.



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Housetasks: Who does what?

```
data(housetasks, package = "factoextra")
# Convert the data.frame to a table
dt <- as.table(as.matrix(housetasks))
names(dimnames(dt)) <- c("Task", "Who_does?")
dt
```

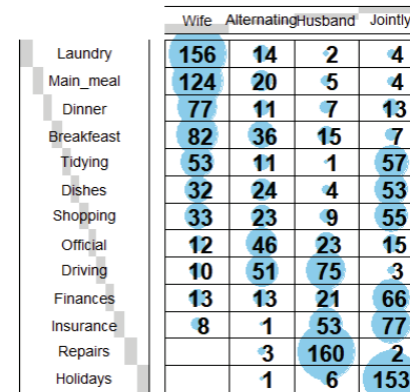
Task	Who_does?			
	Wife	Alternating	Husband	Jointly
Laundry	156	14	2	4
Main_meal	124	20	5	4
Dinner	77	11	7	13
Breakfast	82	36	15	7
Tidying	53	11	1	57
Dishes	32	24	4	53
Shopping	33	23	9	55
Official	12	46	23	15
Driving	10	51	75	3
Finances	13	13	21	66
Insurance	8	1	53	77
Repairs	0	3	160	2
Holidays	0	1	6	153

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Housetasks: Semi-graphic tables

```
library("gplots")
balloonplot(t(dt),
            label.size = 5, ...)
```

housetasks data: Who does What?



```
vcdExtra::color_table(dt)
```

	Who_does?				Total
	Wife	Alternating	Husband	Jointly	
Laundry	156	14	2	4	176
Main_meal	124	20	5	4	153
Dinner	77	11	7	13	108
Breakfast	82	36	15	7	140
Tidying	53	11	1	57	122
Dishes	32	24	4	53	113
Shopping	33	23	9	55	120
Official	12	46	23	15	96
Driving	10	51	75	3	139
Finances	13	13	21	66	113
Insurance	8	1	53	77	139
Repairs	0	3	160	2	165
Holidays	0	1	6	153	160
Total	600	254	381	509	1744

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CA with FactoMineR

```
house.ca <- CA(housetasks, graph = FALSE) # ugly default graph
summary(house.ca, ncp = 2)
```

```
Call:
CA(X = housetasks, graph = FALSE)

The chi square of independence between the two variables is equal to 1944.456 (p-value = 0 ).
```

```
Eigenvalues
          Dim.1  Dim.2  Dim.3
Variance   0.543  0.445  0.127
% of var.  48.692 39.913 11.395
Cumulative % of var. 48.692 88.605 100.000

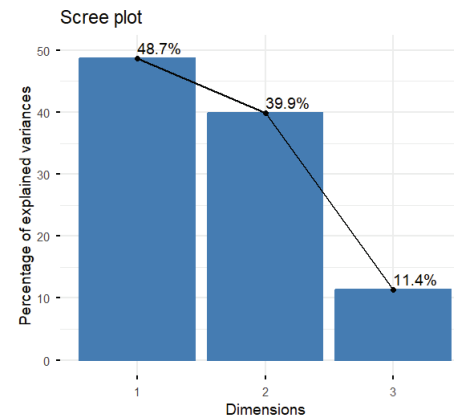
Rows (the 10 first)
      Iner*1000  Dim.1  ctr  cos2  Dim.2  ctr  cos2
Laundry | 134.160 | -0.992 18.287 0.740 | 0.495 5.564 0.185 |
Main_meal | 90.692 | -0.876 12.389 0.742 | 0.490 4.736 0.232 |
Dinner | 38.246 | -0.693 5.471 0.777 | 0.308 1.321 0.154 |
Breakfast | 41.124 | -0.509 3.825 0.505 | 0.453 3.699 0.400 |
Tidying | 24.667 | -0.394 1.998 0.440 | -0.434 2.966 0.535 |
Dishes | 19.587 | -0.189 0.426 0.118 | -0.442 2.844 0.646 |
Shopping | 14.970 | -0.118 0.176 0.064 | -0.403 2.515 0.748 |
Official | 53.300 | 0.227 0.521 0.053 | 0.254 0.796 0.066 |
Driving | 101.509 | 0.742 8.078 0.432 | 0.653 7.647 0.335 |
Finances | 29.564 | 0.271 0.875 0.161 | -0.618 5.559 0.837 |

Columns
      Iner*1000  Dim.1  ctr  cos2  Dim.2  ctr  cos2
Wife | 301.019 | -0.838 44.462 0.802 | 0.365 10.312 0.152 |
Alternating | 117.824 | -0.062 0.104 0.005 | 0.292 2.783 0.105 |
Husband | 381.373 | 1.161 54.234 0.772 | 0.602 17.787 0.208 |
Jointly | 314.725 | 0.149 1.200 0.021 | -1.027 69.118 0.977 |
```

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How many dimensions to consider?

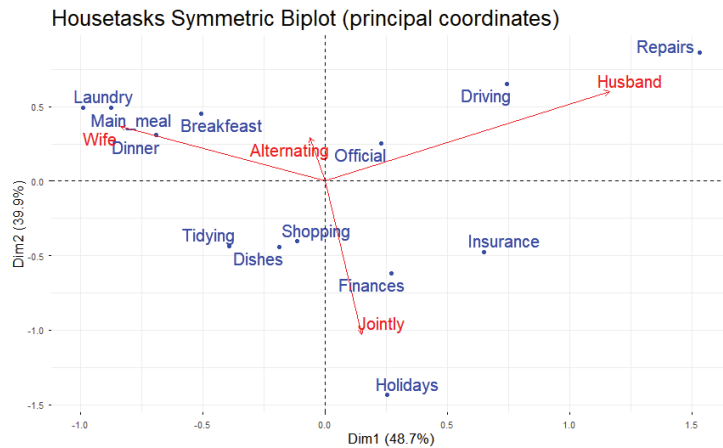
```
fviz_screplot(house.ca,
              addLabels = TRUE, ylim = c(0, 50),
              ggtheme = theme_minimal(base_size = 16))
```



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CA biplot

```
fviz_ca_biplot(house.ca,
  repel = TRUE, labelsize = 6, arrows = c(FALSE, TRUE),
  title = "Housetasks Symmetric Biplot (principal coordinates)")
```



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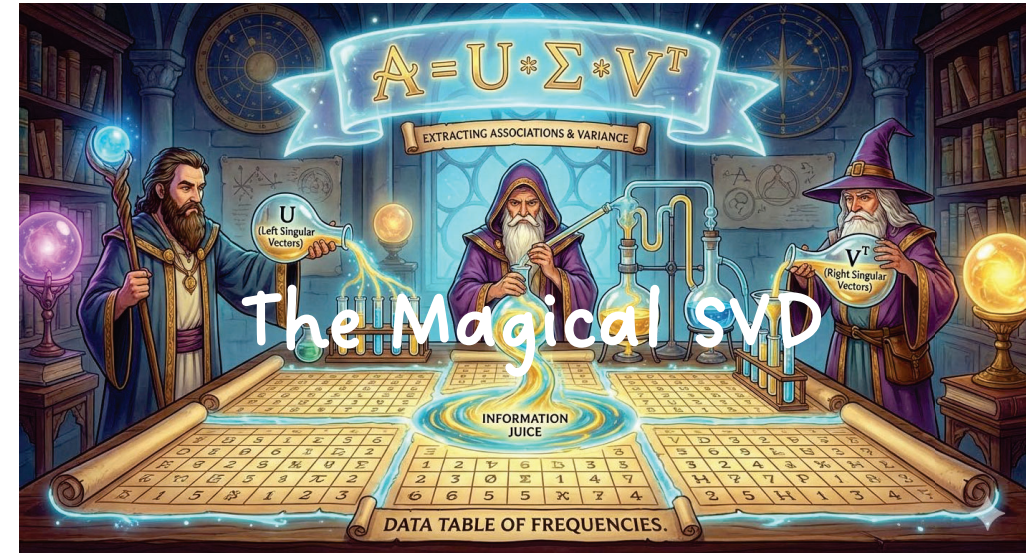
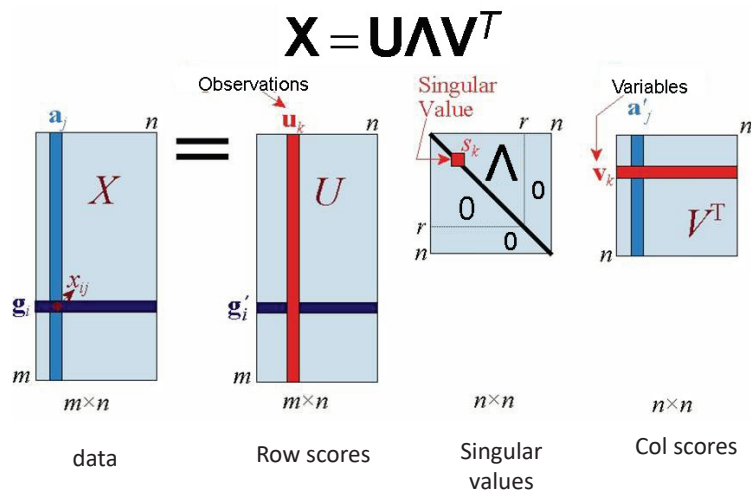


Image source: Gemini (Nano Banana) imagines the "magic of the SVD for extracting juice from frequency tables"

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Singular value decomposition

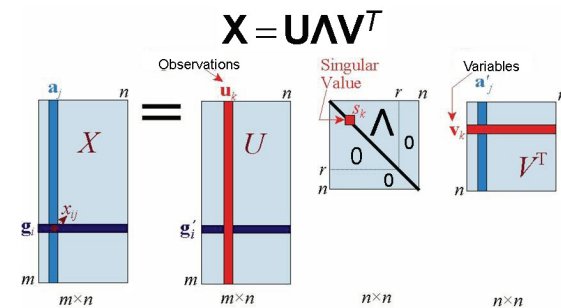
The singular value decomposition (SVD) is a basic technique for factoring a matrix and for matrix approximation
 For an $m \times n$ matrix X of rank $r \leq \min(m, n)$ the SVD of X is:



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Properties of the SVD

- U : columns are **eigenvectors** of XX^T and form an orthonormal basis for observation profiles such that $U^T U = I$
- Λ : diagonal, r singular values = sqrt eigenvalues of both XX^T and $X^T X$
- V : columns are eigenvectors of $X^T X$, orthonormal: $V^T V = I$



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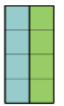
SVD: Matrix approximation

- Let \mathbf{X} be an $m \times n$ matrix such that $\text{rank}(\mathbf{X}) = r$
- If $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_r$ are the singular values of \mathbf{X} , then $\hat{\mathbf{X}}$, the rank q approximation of \mathbf{X} that minimizes $\|\mathbf{X} - \hat{\mathbf{X}}\|$, is


$$\hat{\mathbf{X}}_{m \times n} = \sum_{i=1}^q \lambda_i \begin{pmatrix} u_{i1} \\ \vdots \\ u_{im} \end{pmatrix} \begin{pmatrix} v_{i1} & \dots & v_{in} \end{pmatrix} = \lambda_1 u_1 v_1^T + \dots + \lambda_q u_q v_q^T$$

column scores row scores


a sum of rank 1 (outer) products.
Variance acct'd for by each term = λ_i^2



\mathbf{U}_r
 $m \times r$



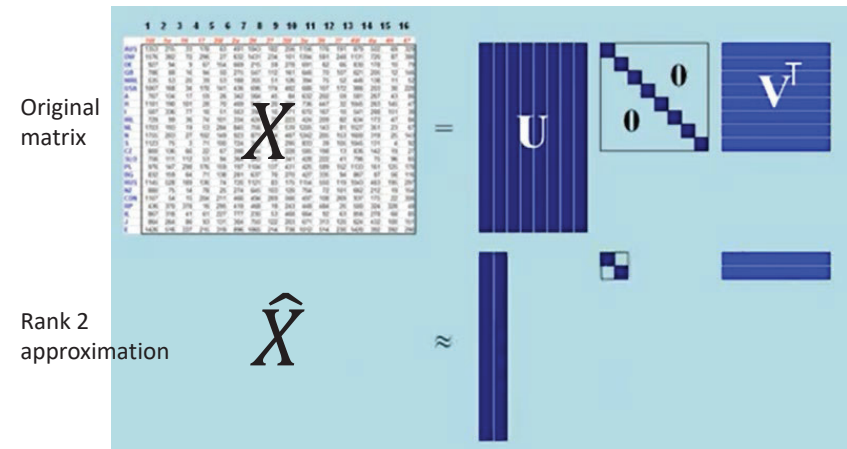
Λ_r
 $r \times r$



\mathbf{V}_r^*
 $r \times n$

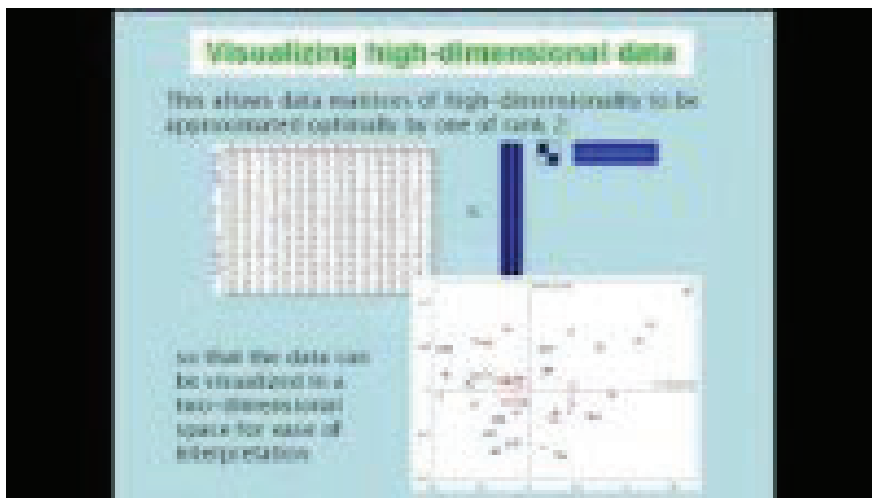
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SVD: Matrix approximation



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SVD song: It had to be U ...



Michael Greenacre, *It had to be U - the SVD song*, <https://www.youtube.com/watch?v=JEYLFivvR9I>

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CA notation & terminology

Notation:

- Contingency table: $\mathbf{N} = \{n_{ij}\}$
- Correspondence matrix (cell probabilities): $\mathbf{P} = \{p_{ij}\} = \mathbf{N}/n$
- Row/column masses (marginal probabilities): $\mathbf{r} = \sum_j p_{ij}$ and $\mathbf{c} = \sum_i p_{ij}$
- Diagonal weight matrices: $\mathbf{D}_r = \text{diag}(\mathbf{r})$ and $\mathbf{D}_c = \text{diag}(\mathbf{c})$

The SVD is then applied to the correspondence matrix of cell probabilities as:

$$\mathbf{P} = \mathbf{A} \mathbf{D}_\lambda \mathbf{B}^T$$

where

- Singular values: $\mathbf{D}_\lambda = \text{diag}(\lambda)$ is the diagonal matrix of singular values $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_M$
- Row scores: $\mathbf{A}_{I \times M}$, normalized so that $\mathbf{A} \mathbf{D}_r^{-1} \mathbf{A}^T = \mathbf{I}$
- Column scores: $\mathbf{B}_{J \times M}$, normalized so that $\mathbf{B} \mathbf{D}_c^{-1} \mathbf{B}^T = \mathbf{I}$

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Principal & standard coordinates

Two types of coordinates are used in CA, based on re-scalings of A and B. **Principal coordinates** are most commonly used in plotting CA solutions.

Principal coordinates

Coordinates of the row (**F**) and column (**G**) profiles *wrt* their own principal axes

$$\begin{aligned} \mathbf{F} &= \mathbf{D}_r^{-1} \mathbf{A} \mathbf{D}_\lambda \quad \text{scaled so that} \quad \mathbf{F}^T \mathbf{D}_r \mathbf{F} = \mathbf{D}_\lambda \\ \mathbf{G} &= \mathbf{D}_c^{-1} \mathbf{B} \mathbf{D}_\lambda \quad \text{scaled so that} \quad \mathbf{G}^T \mathbf{D}_c \mathbf{G} = \mathbf{D}_\lambda \end{aligned}$$

- Defined so that the **inertia** along each axis is the corresponding singular value, λ_i ,
- i.e., weighted average of squared principal coordinates = λ_i on dim. i
- The joint plot in principal coordinates, **F** and **G**, is called the **symmetric map** because both row and column profiles are overlaid in the same coordinate system.

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Standard coordinates

Standard coordinates

The standard coordinates (Φ, Γ) are a rescaling of the principal coordinates to **unit inertia** along each axis,

$$\begin{aligned} \Phi &= \mathbf{D}_r^{-1} \mathbf{A} \quad \text{scaled so that} \quad \Phi^T \mathbf{D}_r \Phi = \mathbf{I} \\ \Gamma &= \mathbf{D}_c^{-1} \mathbf{B} \quad \text{scaled so that} \quad \Gamma^T \mathbf{D}_c \Gamma = \mathbf{I} \end{aligned}$$

- The weighted average of squared standard coordinates = 1 on each dimension
- An **asymmetric map** shows one set of points (say, the rows) in principal coordinates and the other set in standard coordinates.
-

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Geometric & statistical properties

- **Nested solutions:** CA solutions are **nested**, meaning that the first two dimensions of a 3D solution will be identical to the 2D solution (similar to PCA)
- **Centroids at origin:** In both principal coordinates and standard coordinates the points representing the row and column profiles have their centroids (weighted averages) at the origin.
 - The origin represents the (weighted) average row profile and column profile.
- **Chi-square distances:** In principal coordinates, distances between two row profiles, r_i and r_j , are χ^2 distances
 - The squared difference $(r_{ij} - r_{ij'})^2$ between two row profiles is inversely weighted by the column frequency, to account for the different relative frequency of the column categories.
- **Plotting:** For distances to be interpretable, it's crucial to scale the axes equally, so 1^{cm} is the same on both axes (**aspect ratio = 1**). This is standard in most packages.

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The ca package in R

ca() calculates CA solutions, returning a "ca" object with all the details

```
> names(haireye.ca)
[1] "sv"          "nd"          "rownames"   "rowmass"    "rowdist"
[6] "rowinertia" "rowcoord"   "rowsup"     "colnames"   "colmass"
[11] "coldist"    "colinertia" "colcoord"   "colsup"     "N"
[16] "call"
```

The result contains the standard row coordinates (**rowcoord**: Φ) and column coordinates (**colcoord**: Γ) used in plotting

```
> haireye.ca$rowcoord
      Dim1 Dim2 Dim3
Black -1.104 1.441 -1.089
Brown -0.324 -0.219 0.957
Red   -0.283 -2.144 -1.631
Blond 1.828 0.467 -0.318
```

```
> haireye.ca$colcoord
      Dim1 Dim2 Dim3
Brown -1.077 0.592 -0.4240
Blue  1.198 0.556 0.0924
Hazel -0.465 -1.123 1.9719
Green 0.354 -2.274 -1.7184
```

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ca plots

The `plot()` method provides a wide variety of scalings (`map=`), with different interpretative properties. Some of these:

- "symmetric" – both rows & cols in principal coordinates (default)
- "rowprincipal" or "colprincipal" – asymmetric maps with rows in principal coordinates and cols in std coordinates, or vice versa
- "symbiplot" – scales both rows and cols to have variances equal to the singular value

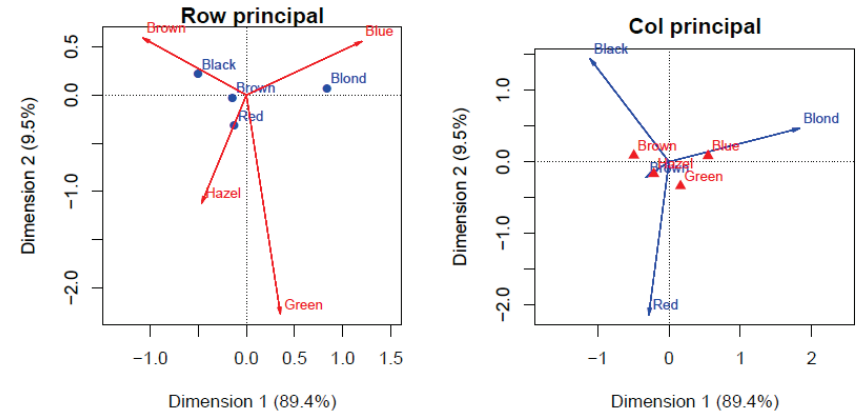
The `mjca()` function is used for multiple correspondence analysis (MCA) for 3+ way tables. Has analogous `print()`, `summary()` and `plot()` methods

- `vcdExtra::mcaplot()` does a nicer job of plotting MCA solutions

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Asymmetric row/col principal plots are **biplots** – can interpret the projection of points on vectors for the other variable

```
plot(haireye.ca, map="rowprincipal", arrows=c(FALSE, TRUE))
plot(haireye.ca, map="colprincipal", arrows=c(TRUE, FALSE))
```



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Optimal category scores

- CA has a close relation to **canonical correlation analysis**, applied to dummy variables representing the categories
- The singular values, λ_i , are the **correlations** between the category scores
 - Assign Dim 1 scores, **X1** and **Y1** to the row/column categories: → Max. possible correlation, λ_1
 - Assign Dim 2 scores, **X2** and **Y2** to the row/column categories: → Max. possible correlation, λ_2 , but uncorrelated with **X1**, **Y1**
 - All association between row/col categories is captured by the scores
- This **optimal scaling** interpretation can be used to quantify categorical variables, particularly if Dim 1 is large
- Mosaics: Permute rows / cols by Dim 1 scores

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Optimal category scores

```
> haireye.ca <- ca(haireye)
> round(haireye.ca$sv, 3)
[1] 0.457 0.149 0.051
```

The singular values λ_i = canonical correlations

To demonstrate category scores, extract row/col coordinates to a data frame

```
HE.df <- as.data.frame(haireye)

RC <- haireye.ca$rowcoord # row coordinates
CC <- haireye.ca$colcoord # col coordinates

Y1 <- RC[match(HE.df$Hair, haireye.ca$rownames), 1] # Dim 1
X1 <- CC[match(HE.df$Eye, haireye.ca$colnames), 1]
Y2 <- RC[match(HE.df$Hair, haireye.ca$rownames), 2] # Dim 2
X2 <- CC[match(HE.df$Eye, haireye.ca$colnames), 2]

HE.df <- cbind(HE.df, X1, Y1, X2, Y2)
```

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Optimal category scores

```
> HE.df <- cbind(HE.df, X1, Y1, X2, Y2)
> print(HE.df, digits=3)
  Hair Eye Freq   X1   Y1   X2   Y2
1 Black Brown  68 -1.077 -1.104 0.592 1.441
2 Brown Brown 119 -1.077 -0.324 0.592 -0.219
3 Red Brown  26 -1.077 -0.283 0.592 -2.144
4 Blond Brown  7 -1.077 1.828 0.592 0.467
. . .
13 Black Green  5 0.354 -1.104 -2.274 1.441
14 Brown Green 29 0.354 -0.324 -2.274 -0.219
15 Red Green  14 0.354 -0.283 -2.274 -2.144
16 Blond Green 16 0.354 1.828 -2.274 0.467
```

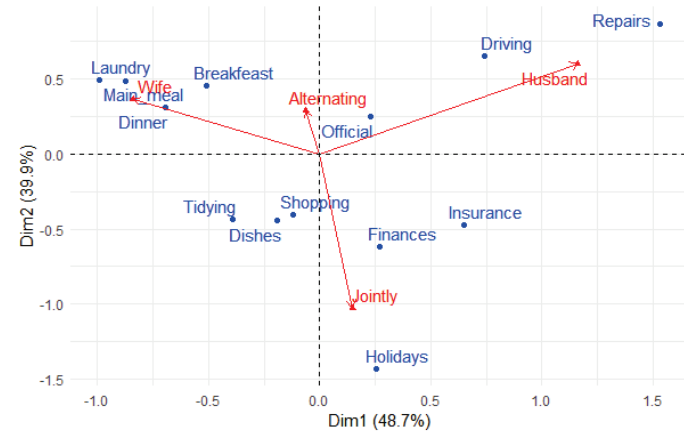
Calculate Freq-weighted correlations. All are zero except $r(X1, Y1) = \lambda_1$ & $r(X2, Y2) = \lambda_2$

```
> corr <- cov.wt(HE.df[,4:7], wt=HE.df$Freq, cor=TRUE)$cor
> round(zapsmall(corr), 3)
      X1   Y1   X2   Y2
X1 1.000 0.457 0.000 0.000
Y1 0.457 1.000 0.000 0.000
X2 0.000 0.000 1.000 0.149
Y2 0.000 0.000 0.149 1.000
```

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Permuting for a mosaic

```
data(housetasks, package="factoextra")
res.ca <- FactoMiner::CA(housetasks, graph=FALSE)
fviz_ca(res.ca, repel = TRUE,
        geom.col = c("point", "text", "arrow") +
        theme_minimal())
```



Dim1: H vs Wife

Dim2: single vs jointly

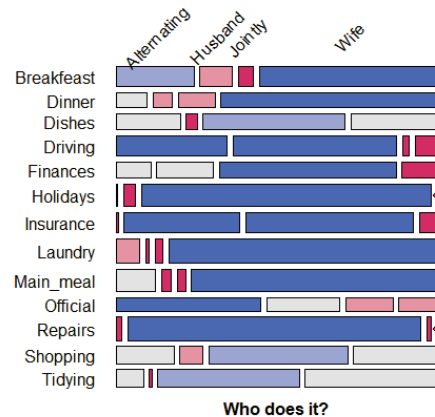
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Permuting for a mosaic

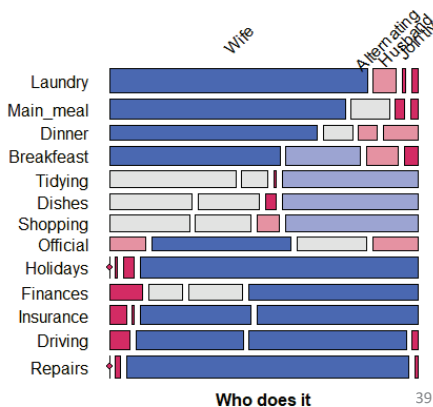
The seriate package has a CA method to permute rows/cols of a df or matrix

```
library(seriation)
order <- seriate(housetasks, method = "CA")
ht <- permute(housetasks, order, margin=1)
mosaic(ht, shade = TRUE, ...)
```

Alpha ordered



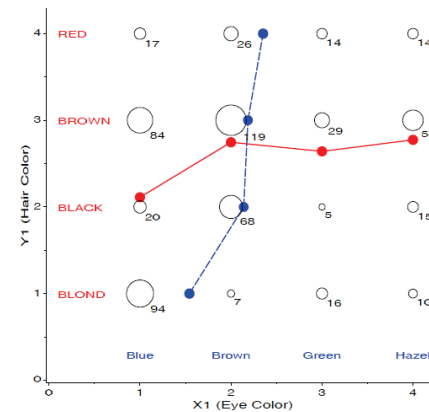
CA ordered



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Simultaneous linear regression

Assign linear scores (1-4) X1 to eye color and Y1 to hair color

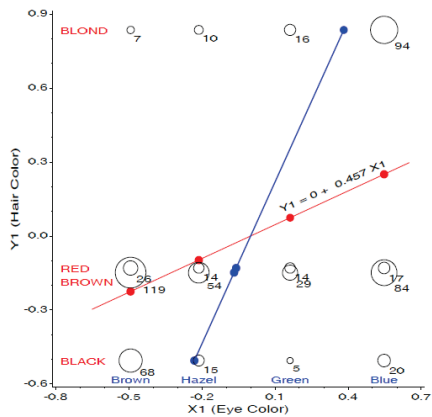


- Lines connecting the weighted (conditional) means of $Y1 | X1$ and $X1 | Y1$ are not-linear
- The scatterplot uses bubble symbols showing frequency in each cell
- Is it possible to assign row and column scores so that both regressions are linear?

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Simultaneous linear regressions

Yes, use CA scores on the first dimension



- The regression of Y1 on X1 is linear, with slope λ_1
- The regression of X1 on Y1 is linear, with slope $1/\lambda_1$
- λ_1 is the (canonical) correlation between X1 and Y1
- The angle between the two lines would be 0 if perfect correlation
- The conditional means (dots) are the principal coordinates

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Example: Mental impairment & parent' SES

Data on mental health status of 1660 young NYC residents, by parents' SES, a 6 x 4 table. Is higher SES associated with better kids' mental health?

```
> data("Mental", package="vcdExtra")
> str(Mental)
'data.frame': 24 obs. of 3 variables:
 $ ses : Ord.factor w/ 6 levels "1"<"2"<"3"<"4"<...: 1 1 1 2 2 2 2 3 3 ...
 $ mental: Ord.factor w/ 4 levels "Well"<"Mild"<...: 1 2 3 4 1 2 3 4 1 2 ...
 $ Freq : int 64 94 58 46 57 94 54 40 57 105 ...
```

Both ses and mental are ordered factors in a frequency data frame

- For ca(), convert this to a table using xtabs()

```
> (mental.tab <- xtabs(Freq ~ ses + mental, data=Mental))
mental
ses Well Mild Moderate Impaired
1 64 94 58 46
2 57 94 54 40
3 57 105 65 60
4 72 141 77 94
5 36 97 54 78
6 21 71 54 71
```

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Mental data: CA solution

```
> mental.ca <- ca(mental.tab)
> summary(mental.ca, rows=FALSE, columns=FALSE)
```

Principal inertias (eigenvalues):

dim	value	%	cum%	scree plot
1	0.026025	93.9	93.9	*****
2	0.001379	5.0	98.9	*
3	0.000298	1.1	100.0	

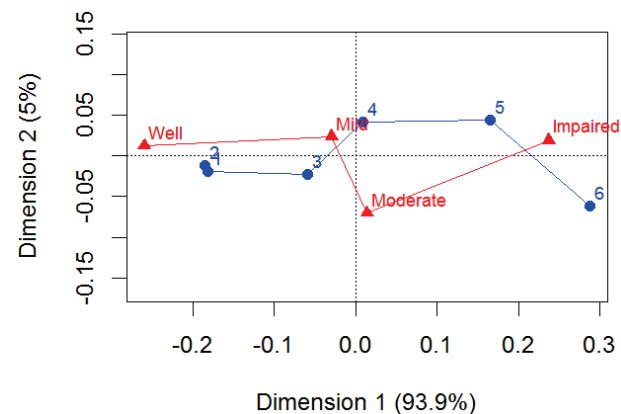
Total:	0.027702	100.0		

- The exact CA solution requires $\min(r-1, c-1) = 3$ dimensions
- Total Pearson χ^2 is $n \sum \lambda_i^2 = 1660 \times 0.0277 = 45.98$ with 15 df
- Of this, 93.9% is accounted for by the 1st dimension

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Mental data: CA plot

```
plot(mental.ca, lines = TRUE)
```



Category spacing:
 SES: perhaps collapse categories (1,2) ??
 Mental: Smaller diff betw. Mild, Moderate ??

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Looking ahead

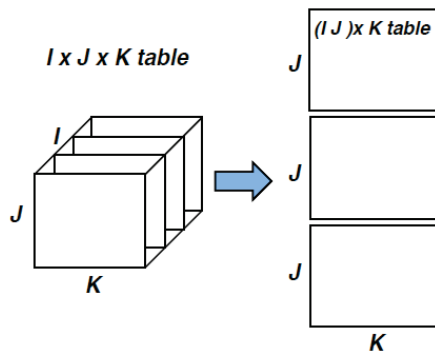


- CA is largely an exploratory method — row/column scores are not **parameters** of a statistical model; no **confidence intervals**
- Only rough tests for the number of CA dimensions
- Can't test a **hypothesis** that the row/column scores have some particular spacing (e.g., are `mental` and `ses` equally spaced?)
- These questions can be answered with specialized loglinear models
- Nevertheless, `plot(ca(table))` gives an excellent quick view of associations

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Multi-way tables: Stacking

A 3-way table of size $I \times J \times K$ can be sliced and stacked as a two-way table in several ways



- The variables combined are treated “interactively”
- Each way of stacking corresponds to a loglinear model
 - $(I \times J) \times K \rightarrow [AB][C]$
 - $I \times (J \times K) \rightarrow [A][BC]$
 - $J \times (I \times K) \rightarrow [B][AC]$
- Only the associations in separate `[]` terms are analyzed and displayed
- The stacked table is analyzed with ordinary CA of the two-way stacked table

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Multi-way tables

Correspondence analysis can be extended to n -way tables in several ways:

Stacking approach

- n -way table flattened to a 2-way table, combining several variables “interactively”
- Each way of stacking corresponds to a *loglinear model*
- Ordinary CA of the flattened table \rightarrow visualization of that model
- Associations among stacked variables are *not visualized*

Multiple correspondence analysis (MCA)

- Extends CA to n -way tables
- Analyzes all **pairwise bivariate** associations
- Can plot all factors in a single plot
- An extension, **joint correspondence analysis**, gives a better account of inertia for each dimension

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Interactive coding in R

- Data in table or array form: use

```
as.matrix(structable(rows ~ cols))
```

```
mat1 <- as.matrix(structable(A + B ~ C, data=mytable)) # [A B][C]
mat2 <- as.matrix(structable(A + C ~ B + D, data=mytable)) # [A C][B D]
ca(mat2)
```

- Data as frequency data frame: use **interaction()** or **paste()** followed by **xtabs()**

```
mydf$AB <- interaction(mydf$A, mydf$B, sep='.') # levels: A.B
mydf$AB <- paste(mydf$A, mydf$B, sep=':') # levels: A:B
...
mytab <- xtabs(Freq ~ AB + C, data=mydf) # [A B] [C]
```

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Example: Suicide rates in Germany

- `vcd::Suicide` gives a 2 x 5 x 8 table of `sex` by `age.group` by `method` for 53,158 suicides in Germany, in a frequency data frame
- Use `paste()` to join `age.group` and `sex` → `age_sex` in the form '10-20 M'

```
> Suicide <- within(Suicide, {
  age_sex <- paste(age.group, toupper(substr(sex,1,1)))
})
> head(Suicide)
  Freq sex method age age.group method2 age_sex
1     4 male  poison  10    10-20  poison 10-20 M
2     0 male cookgas  10    10-20    gas 10-20 M
3     0 male toxicgas 10    10-20    gas 10-20 M
4    247 male  hang  10    10-20  hang 10-20 M
5     1 male  drown  10    10-20  drown 10-20 M
6    17 male   gun  10    10-20   gun 10-20 M
```

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Suicide rates in Germany

```
> suicide.tab <- xtabs(Freq ~ age_sex + method2, data=Suicide)
> suicide.tab
      method2
age_sex  poison  gas hang drown  gun  knife jump other
10-20 F    921   40  212   30   25   11  131  100
10-20 M   1160  335 1524   67  512   47  189  464
25-35 F   1672  113  575   139  64   41  276  263
25-35 M   2823  883 2751   213  852  139  366  775
40-50 F   2224   91 1481   354   52   80  327  305
40-50 M   2465  625 3936   247  875  183  244  534
55-65 F   2283   45 2014   679   29  103  388  296
55-65 M   1531  201 3581   207  477  154  273  294
70-90 F   1548   29 1355   501   3   74  383  106
70-90 M    938   45 2948   212  229  105  268  147
```

- The CA analysis will be that of the loglinear model [\[Age Sex\]](#) [\[Method\]](#)
- It will show associations between the age–sex combinations and method of suicide
- Associations between age and sex will **not be shown** in this analysis

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Suicide rates in Germany

```
> suicide.ca <- ca(suicide.tab)
> summary(suicide.ca, rows=FALSE, columns = FALSE)

Principal inertias (eigenvalues):

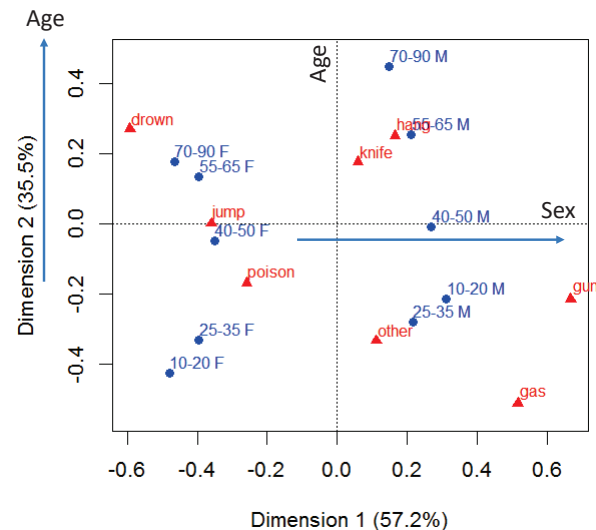
dim  value      %  cum%  scree plot
1    0.096151  57.2  57.2  *****
2    0.059692  35.5  92.6  *****
3    0.008183   4.9  97.5  *
4    0.002158   1.3  98.8
5    0.001399   0.8  99.6
6    0.000557   0.3 100.0
7    6.7e-050   0.0 100.0

-----
Total: 0.168207 100.0
```

For this table $\chi^2(63) = 8946$. Of this, 92.6% is accounted for in the first two dimensions

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```
> plot(suicide.ca)
```



- Dim 1: Sex
- Dim 2: Age
- Can interpret method use by age-sex combination
- young M: gas, gun,
- young F: poison

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Compare with a mosaic plot, also fitting the model [Age Sex][Method]

```
suicide.tab3 <- xtabs(Freq ~ sex + age.group + method2, data=Suicide)
mosaic(suicide.tab3, shade=TRUE, legend=FALSE,
       expected=~age.group*sex + method2, ...)
```



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Marginal tables & supplementary variables

- **Supplementary variables** provide a way to include more info in CA
 - An n -way table is collapsed to a marginal table by ignoring factors
 - Omitted variables can be included by treating them as supplementary
 - These are **projected** into the space of the marginal CA
- E.g., age by method, ignoring sex as the main analysis

```
> suicide.tab2 <- xtabs(Freq ~ age.group + method2, data=Suicide)
> suicide.tab2
      method2
age.group poison  gas hang  drown  gun  knife  jump  other
10-20      2081  375 1736    97  537    58   320   564
25-35      4495  996 3326   352  916   180   642  1038
40-50      4689  716 5417   601  927   263   571   839
55-65      3814  246 5595   886  506   257   661   590
70-90      2486   74 4303   713  232   179   651   253
```

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Also have data on relation of sex and method

```
> (suicide.sup <- xtabs(Freq ~ sex + method2, data=Suicide))
      method2
sex      poison  gas  hang  drown  gun  knife  jump  other
male      8917 2089 14740  946  2945  628  1340  2214
female     8648  318  5637  1703  173  309  1505  1070
> suicide.tab2s <- rbind(suicide.tab2, suicide.sup)
```

age.group	poison	gas	hang	drown	gun	knife	jump	other
10-20	2081	375	1736	97	537	58	320	564
25-35	4495	996	3326	352	916	180	642	1038
40-50	4689	716	5417	601	927	263	571	839
55-65	3814	246	5595	886	506	257	661	590
70-90	2486	74	4303	713	232	179	651	253

Main analysis table

sex	poison	gas	hang	drown	gun	knife	jump	other
male	8917	2089	14740	946	2945	628	1340	2214
female	8648	318	5637	1703	173	309	1505	1070

Supplementary rows

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Supplementary variables

Call `ca(table, suprow =)` to treat some rows as supplementary variables

```
> suicide.ca2s <- ca(suicide.tab2s, suprow=6:7)
> summary(suicide.ca2s, rows=FALSE, columns = FALSE)
```

Principal inertias (eigenvalues):

dim	value	%	cum%	scree plot
1	0.060429	93.9	93.9	*****
2	0.002090	3.2	97.1	*
3	0.001479	2.3	99.4	*
4	0.000356	0.6	100.0	

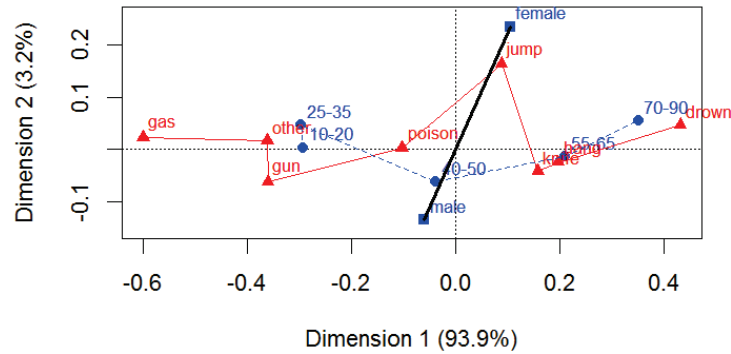
Total:	0.064354	100.0		

The relation of age and method is now essentially 1 dimensional
The inertia of Dim 1 here (0.604) is nearly the same as that of Dim 2 (0.596) for age in the stacked table

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```
res <- plot(suicide.ca2s,
           pch=c(16, 15, 17, 24),
           lines = c(FALSE, TRUE))
lines(res$rows[1:5,], col = "blue", lty=2)
lines(res$rows[6:7,], col = "black", lwd=3)
```

Plotting the solution shows points for row, col & supplementary rows



Ignoring Sex has collapsed Sim 1 (Sex) of the [Age Sex][Method] analysis
Supp. points for Sex show the association of Method with Sex in this space

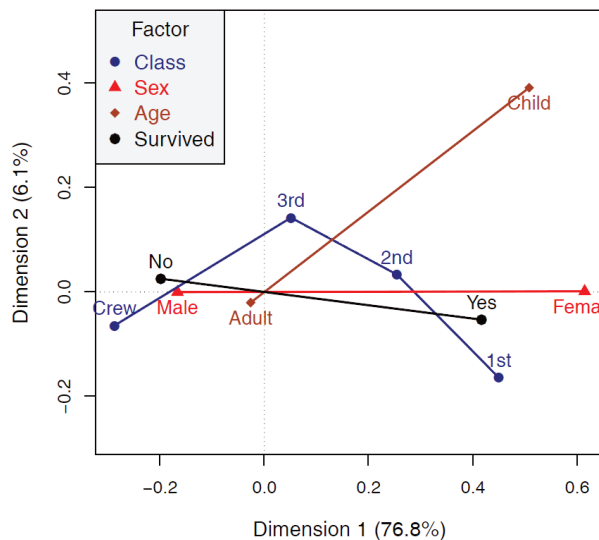
57

Multiple correspondence analysis

- Extends CA to n -way tables
- Useful when simpler stacking approach doesn't work well, e.g., 10 categorical attitude items
- Analyzes all **pairwise bivariate** associations. Analogous to:
 - Correlation matrix (numbers)
 - Scatterplot matrix (graphs)
 - All pairwise χ^2 tests (numbers)
 - Mosaic matrix (graphs)
- Provides an **optimal scaling** of the category scores for each variable
- Can plot all factors in a single plot
- An extension, **joint correspondence analysis**, gives a better account of inertia for each dimension

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Example: Titanic data



Plot of MCA for the Titanic data

All 4 variables represented in a single plot

Dim 1: Sex
Dim 2: Class & Age

Distance from origin = inertia $\sim 1/\text{category freq}$

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CA \rightarrow MCA: Indicator & Burt

Two ways to think about MCA:

Indicator matrix (dummy variables)

- A given categorical variable, q , can be represented by an indicator matrix $\mathbf{Z}(n \times J_q)$ of **dummy variables**, $z_{ij} = 1$ if case i is in category j
- Let $\mathbf{Z}_1, \mathbf{Z}_2, \dots, \mathbf{Z}_Q$ be the indicator matrices for Q variables
- MCA is then a simple CA applied to the partitioned matrix $\mathbf{Z} = [\mathbf{Z}_1, \mathbf{Z}_2, \dots, \mathbf{Z}_Q]$

Burt matrix

- The **Burt** matrix is the product of the indicator matrix \mathbf{Z} and its transpose

$$\mathbf{B} = \mathbf{Z}^T \mathbf{Z}$$

- MCA can be defined using the SVD of \mathbf{B} , giving category scores for all variables accounting for the largest proportion of all bivariate associations.

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Indicator matrix: Hair Eye color

- For the hair-eye data, the indicator matrix **Z** has n=592 rows (observations) and 4 + 4 = 8 columns (categories).
 - Shown below in frequency form: h1 — h4 indicators for hair color, e1—e4 for eye color
 - E.g., 1st row represents 68 observations with black hair and brown eyes

	Hair	Eye	Freq	h1	h2	h3	h4	e1	e2	e3	e4
1	Black	Brown	68	1	0	0	0	1	0	0	0
2	Brown	Brown	119	0	1	0	0	1	0	0	0
3	Red	Brown	26	0	0	1	0	1	0	0	0
4	Blond	Brown	7	0	0	0	1	1	0	0	0
5	Black	Blue	20	1	0	0	0	0	1	0	0
6	Brown	Blue	84	0	1	0	0	0	1	0	0
7	Red	Blue	17	0	0	1	0	0	1	0	0
8	Blond	Blue	94	0	0	0	1	0	1	0	0
...											

Expand this to case form to get **Z** (592 x 8)

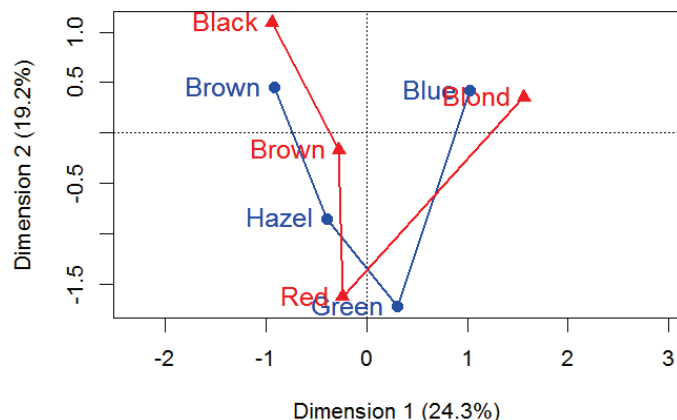
```
> Z <- expand.dft(haireye.df)[, -(1:2)]
> vnames <- c(levels(haireye.df$Hair), levels(haireye.df$Eye))
> colnames(Z) <- vnames
> dim(Z)
[1] 592 8
```

If the indicator matrix is partitioned as $\mathbf{Z} = [\mathbf{Z}_1; \mathbf{Z}_2]$, corresponding to the hair, eye categories, then the **contingency table** is given by $\mathbf{N} = \mathbf{Z}_1^T \mathbf{Z}_2$.

```
> Z1 <- as.matrix(Z[, 1:4])
> Z2 <- as.matrix(Z[, 5:8])
> (N <- t(Z1) %*% Z2)
      Brown Blue Hazel Green
Black   68   20   15    5
Brown  119   84   54   29
Red     26   17   14   14
Blond    7   94   10   16
```

- We can then use ordinary CA on the indicator matrix, **Z**
- Except for scaling, this is the same as the CA of **N**
- The inertia contributions differ, and this is handled better by MCA

```
Z.ca <- ca(Z)
res <- plot(Z.ca, what=c("none", "all")) # plus customization
```



The Burt matrix

For two categorical variables, the Burt matrix is

$$\mathbf{B} = \mathbf{Z}^T \mathbf{Z} = \begin{bmatrix} \mathbf{N}_1 & \mathbf{N} \\ \mathbf{N}^T & \mathbf{N}_2 \end{bmatrix}$$

- \mathbf{N}_1 and \mathbf{N}_2 are diagonal matrices containing the **marginal frequencies** of the two variables
- The contingency table, **N** appears in the off-diagonal block

A similar analysis to that of the indicator matrix **Z** is produced by:

```
Burt <- t(as.matrix(Z)) %*% as.matrix(Z)
rownames(Burt) <- colnames(Burt) <- vnames
Burt.ca <- ca(Burt)
plot(Burt.ca)
```

- Standard coords are the same
- Singular values of **B** are the squares of those of **Z**

Multivariate MCA

For Q categorical variables, the Burt matrix is

$$B = Z^T Z = \begin{bmatrix} N_1 & N_{[12]} & \cdots & N_{[1Q]} \\ N_{[21]} & N_2 & \cdots & N_{[2Q]} \\ \vdots & \vdots & \ddots & \vdots \\ N_{[Q1]} & N_{[Q2]} & \cdots & N_Q \end{bmatrix}$$

- The diagonal blocks N_i contain the one-way marginal frequencies
- The off-diagonal blocks $N_{[ij]}$ contain the bivariate contingency tables for each pair (i, j) of variables.
- Classical MCA can be defined as a SVD of the matrix B
- It produces scores for the categories of *all* variables accounting for the greatest proportion of the bivariate associations in off-diagonal blocks in a small number of dimensions.

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MCA properties

- The **inertia** contributed by a given variable increases with the number of response categories:
 - inertia (Z_q) = $J_q - 1$
- The **centroid** of the categories for each variable is at the **origin** of the display.
- For a given variable, the inertia contributed by a given category increases as the marginal frequency in that category decreases.
 - Low frequency points therefore appear **further** from the origin.
- The category points for a **binary** variable lie on a line through the origin.

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MCA example: pre- and extramarital sex

- PreSex data: the $2 \times 2 \times 2 \times 2$ table of gender, premarital sex, extramarital sex and marital status (divorced, still married)
- The function `mjca()` provides several scalings for the singular values
- Here I use `lambda="Burt"`

```
data("PreSex", package="vcd")
PreSex <- aperm(PreSex, 4:1) # order variables G, P, E, M
presex.mca <- mjca(PreSex, lambda="Burt")
summary(presex.mca, rows=FALSE, columns = FALSE)
```

Principal inertias (eigenvalues):

dim	value	%	cum%	scree plot
1	0.149930	53.6	53.6	*****
2	0.067201	24.0	77.6	*****
3	0.035396	12.6	90.2	***
4	0.027365	9.8	100.0	**

Total:	0.279892	100.0		

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MCA example: pre- and extramarital sex

```
vcdExtra::mcaplot(presex.mca,
  legend=TRUE, legend.pos = "bottomright")
```

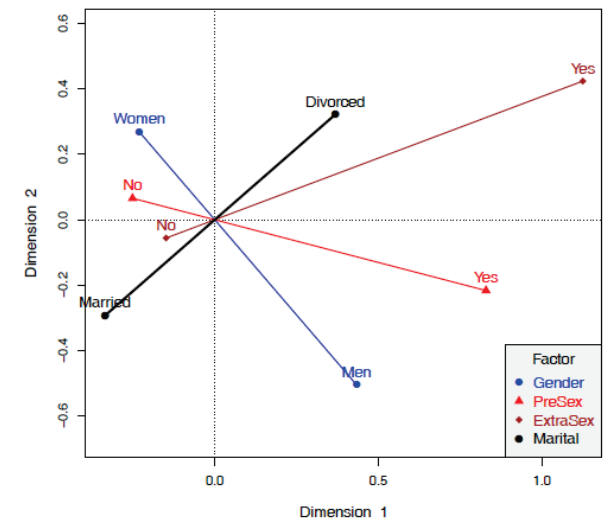
Accounts for 76% of total inertia

Women less likely to report pre- and/or extra-marital sex

Divorced associated with pre- and extra- sex

Gender \perp Marital

NB: This only analyzes **bivariate** associations, i.e., no 3-way associations



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Inertia in MCA

- In simple CA, total inertia = $\sum \lambda_i^2 = \chi^2/n$
- \implies sensible to consider % inertia for each dimension

Not so straight-forward in MCA:

- For a given indicator matrix, \mathbf{Z}_q , the inertia is $J_q - 1$
- For all variables, with $J = \sum J_q$ categories, the total inertia of $\mathbf{Z} = [\mathbf{Z}_1, \dots, \mathbf{Z}_Q]$ is the average of the inertias of the sub-tables

$$inertia(\mathbf{Z}) = \frac{1}{Q} \sum_q inertia(\mathbf{Z}_q) = \frac{1}{Q} \sum_q (J_q - 1) = \frac{J - Q}{Q}$$

- The average inertia per dimension is therefore $1/Q$
- \implies Interpret dimensions with inertia $> 1/Q$ (as in PCA: $\lambda > 1$)
- In analysis of the Burt matrix, average inertia is inflated by the diagonal blocks

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MCA example: Survival on the *Titanic*

Analyse the Titanic data using `ca::mcja()`

- The default inertia method is `lambda = "adjusted"`
- Other methods: "indicator", "Burt", "JCA"

```
data(Titanic)
titanic.mca <- mcja(Titanic)
summary(titanic.mca, columns = FALSE)
```

Principal inertias (eigenvalues):

dim	value	%	cum%	scree plot
1	0.067655	76.8	76.8	*****
2	0.005386	6.1	82.9	**
3	0.0000000	0.0	82.9	

Total: 0.088118

Using adjusted inertia, the 2D solution accounts for ~ 83% of total, bivariate association.

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Inertia in MCA: Details

Two solutions:

Adjusted inertia

- Ignores the diagonal blocks in the Burt matrix
- Calculates adjusted inertia as

$$(\lambda_i^*)^2 = \left[\frac{Q}{Q-1} (\lambda_i^Z - \frac{1}{Q}) \right]^2$$

- Express contributions of dimensions as $(\lambda_i^*)^2 / \sum (\lambda_i^*)^2$, with summation over only dimensions with $(\lambda_i^Z)^2 > 1/Q$.

Joint correspondence analysis

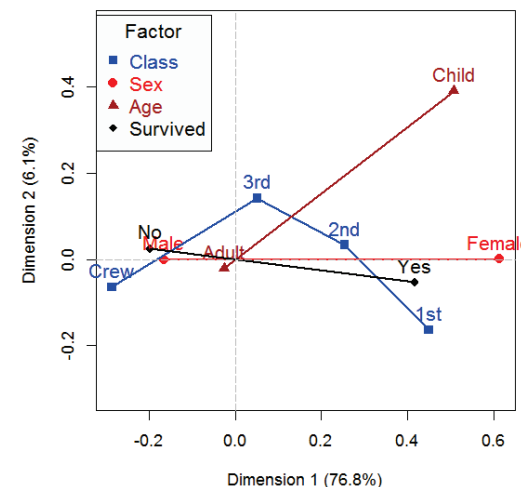
- Start with MCA analysis of the Burt matrix
- Replace diagonal blocks with values estimated from that solution
- Repeat until solution converges, improving the fit to off-diagonal blocks

NB: JCA solutions aren't nested. I generally use [adjusted inertia](#)

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Plot the solution with `vcdExtra::mcaplot()`

```
mcaplot(titanic.mca, legend=TRUE, legend.pos = "topleft")
```



Dim 1 perfectly aligned with Sex
Also strongly aligned w/ survival & class

Dim 2: reflects class & age

\rightarrow Survival associated with Female, 1st vs 3rd class, child

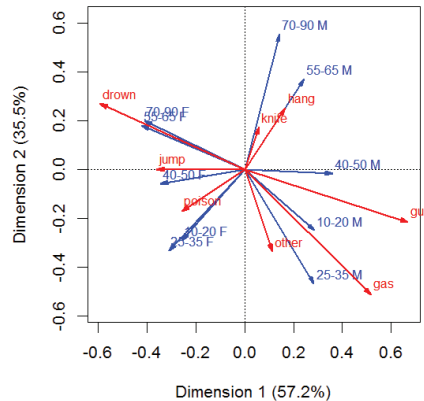
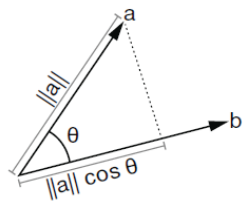
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Biplots for contingency tables

The biplot is a related visualization that also uses the SVD to give a low-rank (2D) approximation.

- In CA, the weighted χ^2 distances between row (column) points reflect the differences among row (column) profiles
- In the biplot, rows (columns) are represented by vectors from the origin, with an inner-product (projection) interpretation – row point a_i is fit by projection on col point b_j

$$Y \approx AB^T \iff y_{ij} \approx a_i^T b_j$$

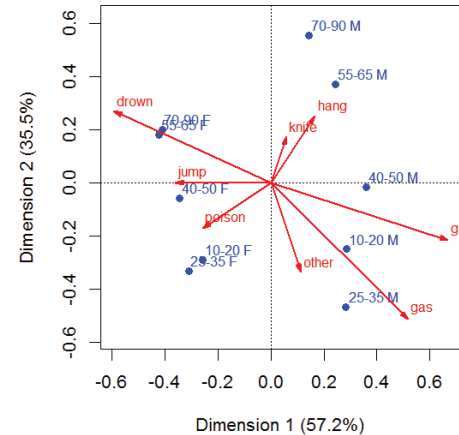


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Example: Suicide rates

There are different scalings for CA biplots. Here I use the 'contribution' biplot. I find the plot less messy to plot arrows for only rows or cols and imagine the projection

```
plot(suicide.ca, map="colgreen", arrows=c(FALSE, TRUE), lwd=2)
```



Associations between age-sex categories and suicide methods can be read as projections of the points on the vectors

Lengths of vectors for suicide reflect their contributions to this 2D plot

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Summary



- CA is an exploratory method designed to account for association (Pearson χ^2) in a small number of dimensions
 - Row and column scores provide an optimal scaling of the category levels
 - Plots of these can suggest an explanation for association
- CA uses the singular value decomposition to approximate the matrix of residuals from independence
- Standard and principal coordinates have different geometric properties, but are essentially re-scalings of each other
- Multi-way tables can be handled by:
 - Stacking approach—collapse some dimensions interactively to a 2-way table
 - Each way of stacking \rightarrow a loglinear model
 - MCA analyzes the full n -way table using an indicator matrix or the Burt matrix

Given a new 2-way table, my first thought is nearly always:

```
ca(mytable) |> plot()
```

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