Data Structures: Factors, Lists, Matrices, Arrays

Enrico Toffalini

Factors, Lists, Matrices, Arrays

As a data scientist, most of your tasks will probably require working with dataframes and vectors (see Part 1; remember that a dataframe is essentially a collection of vectors of different types)

However, other data structures that you will encounter are:

- **Factors**: store categorical data; factors are both a data type and a data structure
- **Lists**: collections of *objects of different types*, flexible and indexable
- **Matrices**: two-dimensional structures, essentially vectors organized into rows and columns, *all elements must be of the same type*
- **Arrays**: generalization of vectors and matrices to multi-dimensional data (e.g., 3D, 4D arrays), *all elements must be of the same type*

Factors

Factors are a special type of data used to represent **categorical data**. They may look similar to simple *character vectors*. In fact, they function differently:

- Internally, they consist of vectors of integers associated with "levels"
- Levels are unique categories, labelled for readability

```
df$TypeOfCourse
```

```
 [1] METHODOLOGY     METHODOLOGY     METHODOLOGY     PROGRAMMING
 [5] METHODOLOGY     METHODOLOGY     METHODOLOGY     METHODOLOGY
 [9] METHODOLOGY     SOFT SKILLS     PROGRAMMING     PROGRAMMING
[13] SOFT SKILLS     THEMATIC COURSE METHODOLOGY     METHODOLOGY
[17] METHODOLOGY     METHODOLOGY     METHODOLOGY     METHODOLOGY
[21] SOFT SKILLS     SOFT SKILLS     SOFT SKILLS     METHODOLOGY
[25] METHODOLOGY     SOFT SKILLS     THEMATIC COURSE PROGRAMMING
Levels: METHODOLOGY PROGRAMMING SOFT SKILLS THEMATIC COURSE
```

Note how the bottom row lists all existing levels

Factors

At any time, you can convert a vector (or a variable in a dataframe) into a factor using the `as.factor()` function

```
df$TypeOfCourse = as.factor(df$TypeOfCourse)
```

Internally, a factor is stored as **integer**, with associated **labels** for levels:

```
as.integer(df$TypeOfCourse)
```

```
 [1] 1 1 1 2 1 1 1 1 1 3 2 2 3 4 1 1 1 1 1 1 3 3 3 1 1 3 4 2
```

```
levels(df$TypeOfCourse)
```

```
[1] "METHODOLOGY"     "PROGRAMMING"     "SOFT SKILLS"     "THEMATIC COURSE"
```

Warning! Despite storing integers, factors are **not** numeric:

```
df$TypeOfCourse * 2
```

```
 [1] NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA NA
[26] NA NA NA
```

Factors

By default, **factors** in R are **non-ordered**, there is **no** hierarchy between their categories.

To create **ordered factors**, you can use the `as.ordered()` function.

```
as.ordered(df$TypeOfCourse)
```

```
 [1] METHODOLOGY     METHODOLOGY     METHODOLOGY     PROGRAMMING    
 [5] METHODOLOGY     METHODOLOGY     METHODOLOGY     METHODOLOGY    
 [9] METHODOLOGY     SOFT SKILLS     PROGRAMMING     PROGRAMMING    
[13] SOFT SKILLS     THEMATIC COURSE METHODOLOGY     METHODOLOGY    
[17] METHODOLOGY     METHODOLOGY     METHODOLOGY     METHODOLOGY    
[21] SOFT SKILLS     SOFT SKILLS     SOFT SKILLS     METHODOLOGY    
[25] METHODOLOGY     SOFT SKILLS     THEMATIC COURSE PROGRAMMING    
Levels: METHODOLOGY < PROGRAMMING < SOFT SKILLS < THEMATIC COURSE
```

Ordered factors include a hierarchical relationship between levels (e.g., `"low"` < `"medium"` < `"high"`; or a Likert scale like `"Strongly disagree"` < `"Disagree"` < `"Neutral"` < `"Agree"` < `"Strongly agree"`). Using ordered factors may be especially important for certain data analysis, e.g., *Structural Equation Modeling (SEM)* with ordinal data (e.g., using the `lavaan` package)

Factors

Why use factors?

In many cases, you might ignore and avoid them. However:

- Help **ensure consistency** when data is actually categorical
- Many *functions for statistical modeling* (e.g., `lm()`) **automatically treat characters as factors**, assigning dummy variables for each level; also tools like `ggplot2` for *visualization* use factors for grouping or labeling axes
- Ensure **efficient storage** of information as compared to characters, thanks to their internal structure
- **Ordered data**: see previous slide

Lists

Lists are flexible structure that contain **objects of different types and different lengths** (including other lists… potentially creating an infinite *Inception*…)

```
myChaos = list(TRUE, 0:5, df$Hours, letters[8:18], "PSICOSTAT")
myChaos
```

```
[[1]]
[1] TRUE

[[2]]
[1] 0 1 2 3 4 5

[[3]]
 [1] 10 15 20 10 15  5  5  5  5  5 10 10  5  5 10 10 15 20  5 15  5 10  5  5 10
[26] 15  5  5

[[4]]
 [1] "h" "i" "j" "k" "l" "m" "n" "o" "p" "q" "r"

[[5]]
```

Lists

You can access elements of a list with indexing using the double square brackets `[[]]`

```
myChaos[[3]]
```

```
 [1] 10 15 20 10 15  5  5  5  5  5 10 10  5  5 10 10 15 20  5 15  5 10  5  5 10
[26] 15  5  5
```

```
myChaos[[5]]
```

```
[1] "PSICOSTAT"
```

A convenient function for inspecting the structure of a list is `str()`:

```
str(myChaos)
```

```
List of 5
 $ : logi TRUE
 $ : int [1:6] 0 1 2 3 4 5
 $ : num [1:28] 10 15 20 10 15 5 5 5 5 5 ...
 $ : chr [1:11] "h" "i" "j" "k" ...
 $ : chr "PSICOSTAT"
```

Lists

If you **name** each element in the list, you can also access them using the `$` operator, just like a dataframe

```r
myLittleList = list(name = "Enrico",
                    sector = "m-psi/01",
                    hours = c(42,40,10,10),
                    school = c("psychology","amv","psychology","psychology"))
```

```r
myLittleList$sector
```

```
[1] "m-psi/01"
```

```r
myLittleList$hours
```

```
[1] 42 40 10 10
```

That's not surprising… a dataframe is actually a special kind of list! just two key constraints: 1) all elements are vectors of the same length; 2) vectors are named.

Lists

Why use lists?

- Provide **very flexible storage** (for example, in a complex Monte Carlo simulation you might want to store not just a single result from each iteration, but multiple objects, such as each simulated dataframe, or whole model outputs)
- **Common in R**: many functions (e.g., `lm()`) return their summaries and results as lists (even dataframes themselves are special cases of lists), so get familiar with them!
- Are used in many context for handling **nested data** (e.g., JSON-formatted data)

Lists

example with a power simulation

```
N = 30; b0 = 0; b1 = 0.3; sigma = 1

niter = 1000
results = list()

for(i in 1:niter){
  x = rnorm(N, 0, 1)
  y = b0 + b1*x + rnorm(N, 0, sigma)

  results[[i]] = lm(y ~ x)
}
```

This is an example of using a list in a power simulation. Typically, you store only one or a few values (e.g., p-values), but lists allow storing all fitted objects if needed.

Matrices

In R, a **matrix** is a **2-dimensional** structure that contains only elements **of the same type**. Essentially, it can be thought of as a 2D vector.

You can create a matrix easily using the `matrix()` function:

```
( myMat = matrix(1:28, nrow=4, ncol=7) )
```

```
     [,1] [,2] [,3] [,4] [,5] [,6] [,7]
[1,]    1    5    9   13   17   21   25
[2,]    2    6   10   14   18   22   26
[3,]    3    7   11   15   19   23   27
[4,]    4    8   12   16   20   24   28
```

```
( myMat = matrix(1:28, nrow=4, ncol=7, byrow=T) )
```

```
     [,1] [,2] [,3] [,4] [,5] [,6] [,7]
[1,]    1    2    3    4    5    6    7
[2,]    8    9   10   11   12   13   14
[3,]   15   16   17   18   19   20   21
[4,]   22   23   24   25   26   27   28
```

Matrices

Indexing in matrices is similar to dataframes, with indexes for row(s) and column(s), using `[ <row(s) index> , <column(s) index> ]`

```
myMat[2, 5] # access a single element
```

```
[1] 12
```

```
myMat[2:3, 5:7] # access ranges of elements
```

```
     [,1] [,2] [,3]
[1,]   12   13   14
[2,]   19   20   21
```

Like in vectors, you can perform **appropriate operations** on matrix data:

```
myMat^2 # element-wise squaring of all values
```

```
     [,1] [,2] [,3] [,4] [,5] [,6] [,7]
[1,]    1    4    9   16   25   36   49
[2,]   64   81  100  121  144  169  196
[3,]  225  256  289  324  361  400  441
[4,]  484  529  576  625  676  729  784
```

Matrices

Operator	What it does	Example
`t()`	Transposes a matrix	`t(matrix(1:6,2))`
`%*%`	Matrix multiplication	`matrix(1:8,2) %*% matrix(1:8,4)`
`*`	Element-wise matrix multiplication	`matrix(1:8,2) * matrix(1:8,2)`
`det()`	Determinant of a square matrix	`det(matrix(rnorm(16),4))`
`solve(A, b)`	Solves `A*x = b`	`solve(matrix(rnorm(16),4), rnorm(4))`

Matrices

Why use (know) matrices?

- **Mathematical operations**: matrices are fundamental for many tasks of linear algebra
- **Essential in modeling**: many statistical methods for statistical modeling and machine learning actually operate on matrices (even though this may remain hidden to you)
- **Computational efficiency**: much faster than dataframes for numeric computations

Arrays

Arrays are multi-dimensional structures in R, generalizing *vectors (1-dimensional)* and *matrices (2-dimensional)* to the ***n-dimensional*** case

It's easy to create an array using the **`array()`** function:

```
myArr = array(1:30, dim = c(3,5,2))
myArr
```

```
, , 1

     [,1] [,2] [,3] [,4] [,5]
[1,]    1    4    7   10   13
[2,]    2    5    8   11   14
[3,]    3    6    9   12   15

, , 2

     [,1] [,2] [,3] [,4] [,5]
[1,]   16   19   22   25   28
[2,]   17   20   23   26   29
[3,]   18   21   24   27   30
```

→ this is kind of a "cubic-structure" (3D structure): 3 rows, 5 columns, 2 slices

In a similar way, you could create hypercubes and so on (4D+)

Arrays

indexing

Indexing is exactly the same as with matrices but… with 3 (sets of) indices!

```r
myArr[1, 4, 2] # extract a single element
```

```
[1] 25
```

```r
myArr[1:2 , 1:2 , ] # extract subsets of elements
```

```
, , 1

     [,1] [,2]
[1,]    1    4
[2,]    2    5

, , 2

     [,1] [,2]
[1,]   16   19
[2,]   17   20
```

Arrays

Why use (know) arrays?

- Might be useful for storing, and manipulate efficiently structure of **multi-dimensional data**
- Generally used in advanced topics and *machine learning* like when working on **image/video processing** and **spatial data**
- Arrays in R are conceptually similar to **tensors** in Python (e.g., `NumPy`, `TensorFlow`), where they play a fundamental role in ***machine learning*** and ***deep learning***, as they allow researchers to manage large amounts of data with complex structures