Programing fundamentals

- A program is a set of instructions for a computer to follow
- Programs are often used to manipulate data (in all type and formats you discussed last week)
- Simple to complex
  - the scripts you wrote last week (simple)
  - instructions to analyze relationships in census data and visualize them
  - a model of global climate

Programing fundamentals

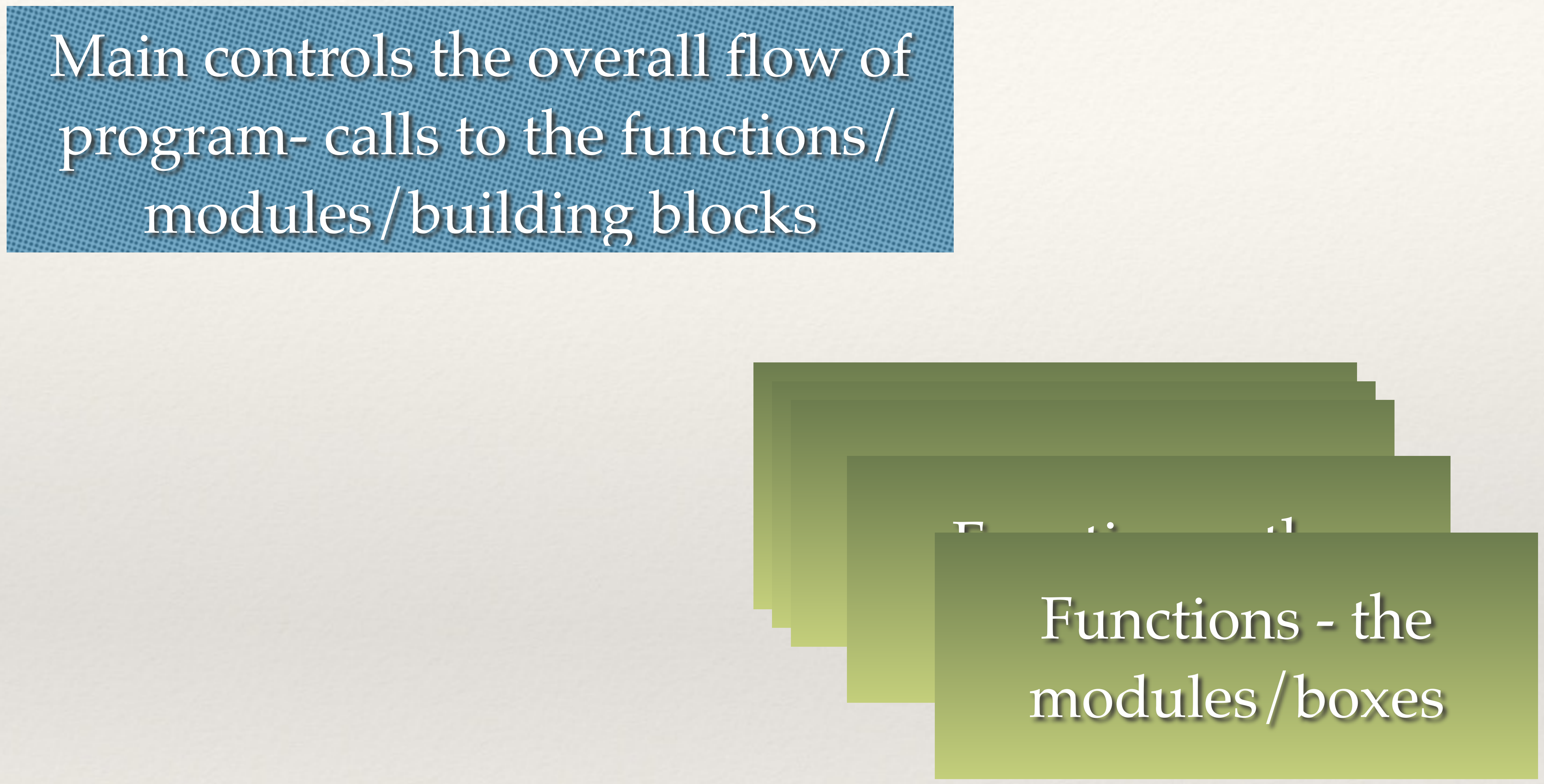
- Programs can be written in many different languages (all have their strengths and weakness)
- Languages expect instructions in a particular form (syntax) and then translate them to be readable by the computer
- Languages have evolved to make it help users write programs that are easy to understand, re-use, extend, test, run quickly, use lots of data…

Programing fundamentals

- Operations (=,+,-,…concatenate, copy)
- Data structures (simple variables, arrays, lists…)
- Control structures (if then, loops)
- Modules…

Concepts common to all languages through the syntax may be different

Modularity


Main controls the overall flow of program- calls to the functions/modules/building blocks

Functions - the modules/boxes

- A program is often multiple pieces put together
- These pieces or modules can be used multiple times

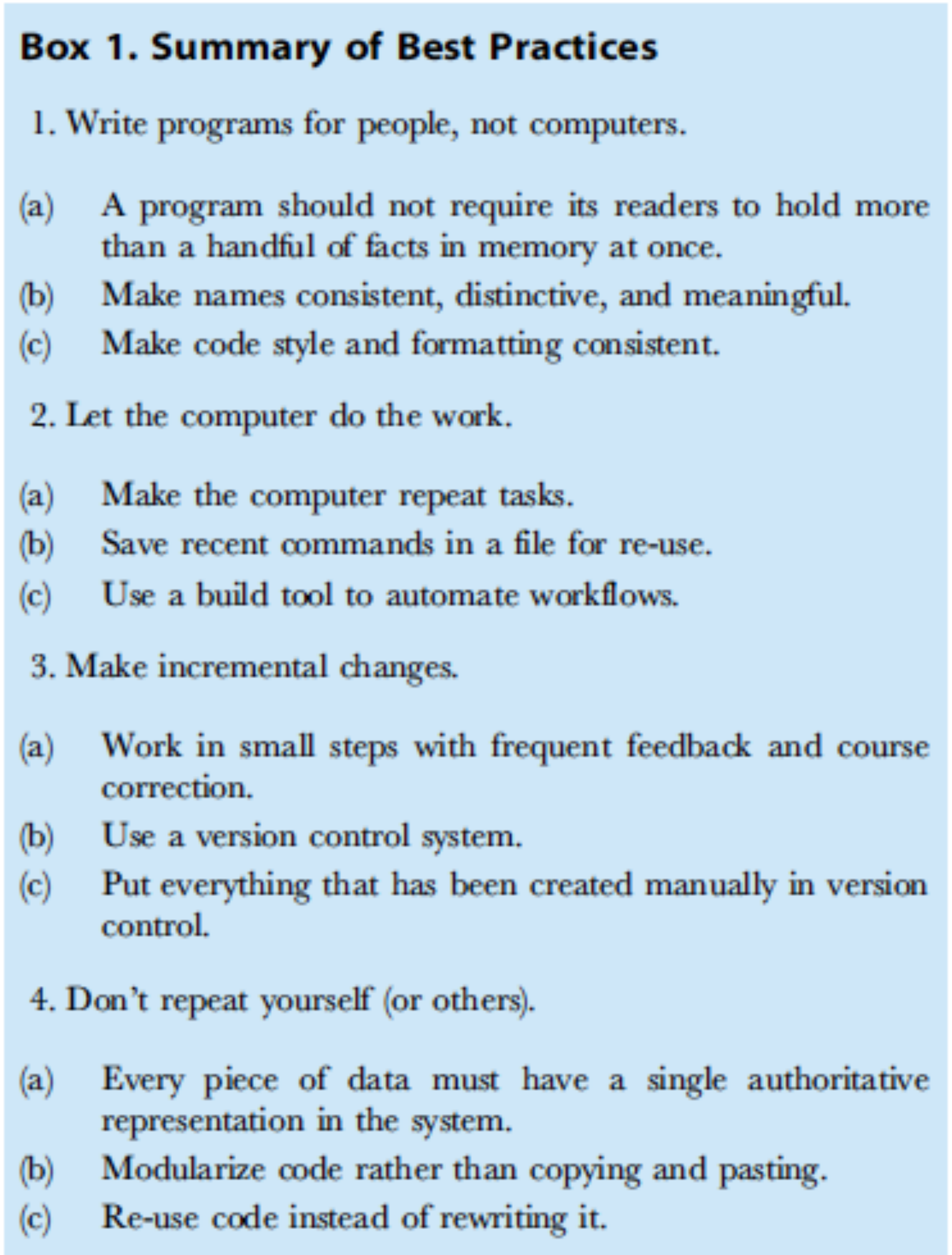
Programing fundamentals

- Modularity
  - breaking your instructions down into individual pieces
  - identifying instructions that can be reused
    - an ecosystem model might re-use instructions for calculating how a species grows
    - an accounting program might re-use instructions for computing net present value from interest rates
  - modules often become ‘black boxes’ which hides detail that might make understanding the program overly complex
  - most languages have lots of black boxes already written and most allow you to write your own

Best practices for software development

- Read: Wilson G, Aruliah DA, Brown CT, Chue Hong NP, Davis M, et al. (2014) Best Practices for Scientific Computing. PLoS Biol 12(1): e1001745. doi:10.1371/journal.pbio.1001745
- Blanton, B and Lenhardt, C 2014. A Scientist's Perspective on Sustainable Scientific Software. Journal of Open Research Software 2(1):e17, DOI: http://dx.doi.org/10.5334/jors.ba
- but also
- http://simpleprogrammer.com/2013/02/17/principles-are-timeless-best-practices-are-fads/

Programing fundamentals



Box 1. Summary of Best Practices

1. Write programs for people, not computers.

(a) A program should not require its readers to hold more than a handful of facts in memory at once.
(b) Make names consistent, distinctive, and meaningful.
(c) Make code style and formatting consistent.

2. Let the computer do the work.

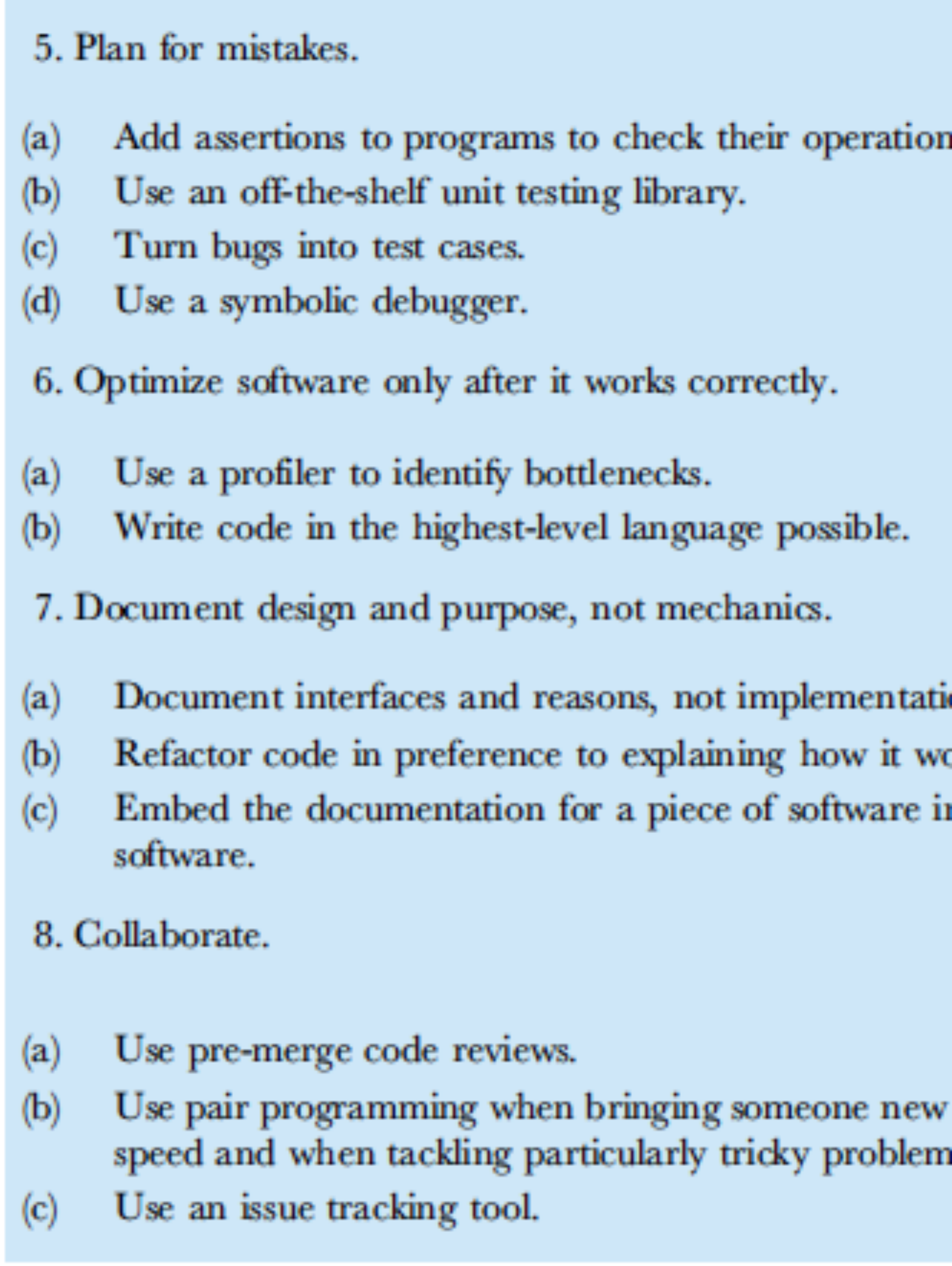
(a) Make the computer repeat tasks.
(b) Save recent commands in a file for re-use.
(c) Use a build tool to automate workflows.

3. Make incremental changes.

(a) Work in small steps with frequent feedback and course correction.
(b) Use a version control system.
(c) Put everything that has been created manually in version control.

4. Don't repeat yourself (or others).

(a) Every piece of data must have a single authoritative representation in the system.
(b) Modularize code rather than copying and pasting.
(c) Re-use code instead of rewriting it.



5. Plan for mistakes.

(a) Add assertions to programs to check their operation
(b) Use an off-the-shelf unit testing library.
(c) Turn bugs into test cases.
(d) Use a symbolic debugger.

6. Optimize software only after it works correctly.

(a) Use a profiler to identify bottlenecks.
(b) Write code in the highest-level language possible.

7. Document design and purpose, not mechanics.

(a) Document interfaces and reasons, not implementati
(b) Refactor code in preference to explaining how it wo
(c) Embed the documentation for a piece of software i software.

8. Collaborate.

(a) Use pre-merge code reviews.
(b) Use pair programming when bringing someone new speed and when tackling particularly tricky problem
(c) Use an issue tracking tool.

Best practices for model (software) development

- Common problems
    - Unreadable code (hard to understand, easy to forget how it works, hard to find errors, hard to expand)
    - Overly complex, disorganized code (hard to find errors; hard to modify-expand)
    - Insufficient testing (both during development and after)
    - Not tracking code changes (multiple versions, which is correct?)

Steps for building model

- We are going to use R; but the basic design of programs are similar across many programming languages
- Why R?
  - Free (and open source) software
  - Good (and getting better) visualization tools
  - Growing user community who make their R code available
    - (currently 2800+ user packages on CRAN R server)
  - Links with other tools and languages (GIS, Python, C, C++…)
  - Built in tools to deal with space and time
  - Lots of user support

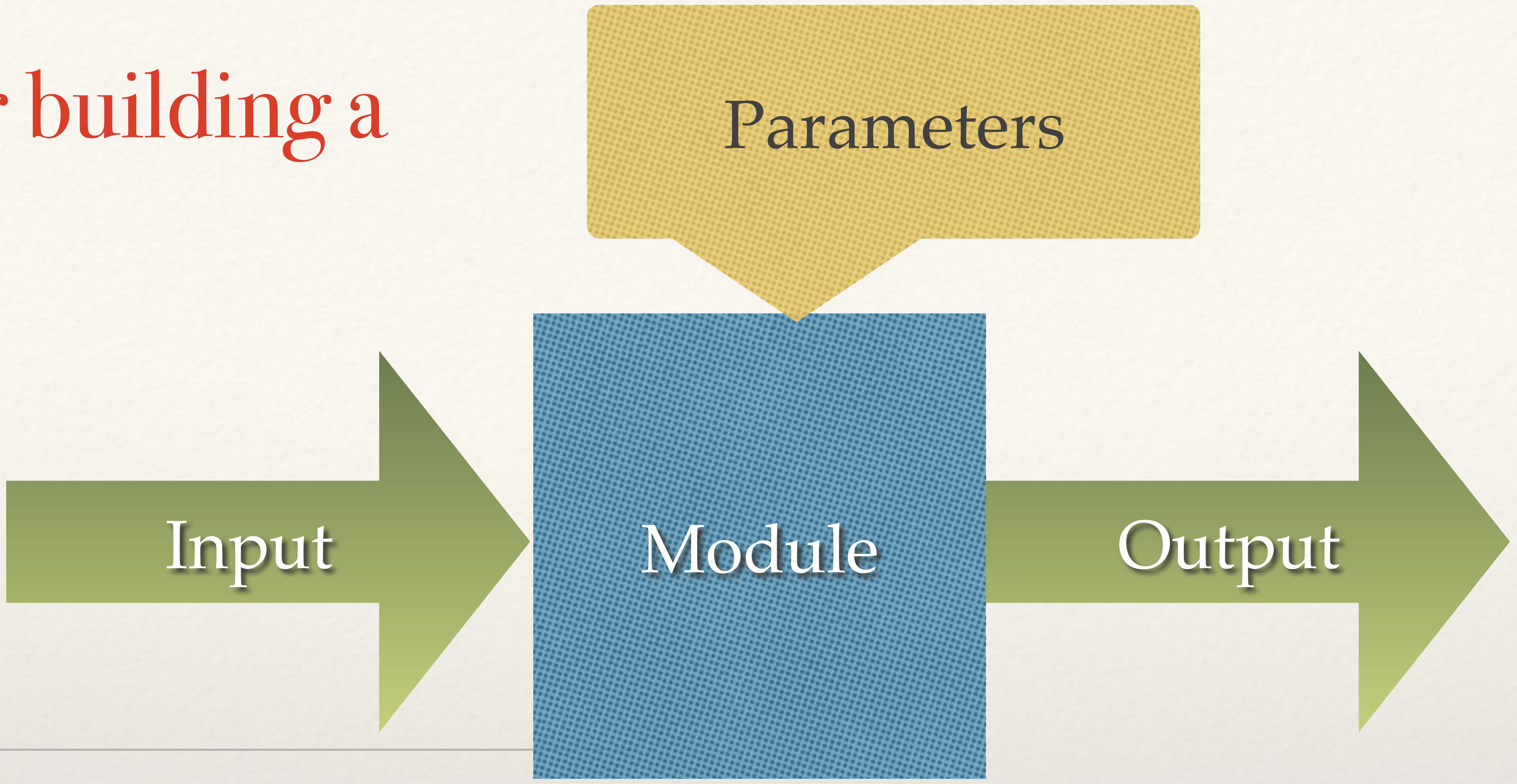
Steps for building model

- Why not R?
  - Not particularly computationally efficient (e.g slow for repetitive computations) ; hard to parallelize
  - Not the right tool for developing really complex models (you don’t develop GCMs in R!)

STEPS: Program Design

1. **Clearly define your goal as precisely as possible, what do you want your program to do**
    1. **inputs/parameters**
    2. **outputs**
2. Implement and document
3. Test
4. Refine

Steps for building a module



1. Design the program “conceptually” - “on paper” in words or figures
2. Translate into a step by step representation
3. Choose programming language
4. Define inputs (data type, units)
5. Define output (data type, units)
6. Define structure
7. Write program
8. Document the program
9. Test the program
10. Refine…

Best practices for model (software) development

- Let us change our traditional attitude to the construction of programs: Instead of imagining that our main task is to instruct a computer what to do, let us concentrate rather on explaining to humans what we want the computer to do. -- Donald E. Knuth, Literate Programming, 1984
- Developing readable (by PEOPLE) code and documenting what you are doing is essential
- "When was the last time you spent a pleasant evening in a comfortable chair, reading a good program?"— Bentley (1986)

Best practices for software development

- Automated tools (useful for more complex code development
- (note that GP's often create programs > 100 lines of code)
- Automated documentation
  - http://www.stack.nl/~dimitri/doxygen/
  - http://roxygen.org/roxygen2-manual.pdf
- Automated test case development
  - http://r-pkgs.had.co.nz/tests.html
- Automated code evolution tracking (Version Control)
  - https://github.com/

Designing Programs

- Inputs - sometimes separated into input data and parameters
  - input data = the "what" that is manipulated
  - parameters determine "how" the manipulation is done
  - "sort -n file.txt"
    - sort is the program - set of instructions - its a black box
    - input is file.txt
    - parameters is -n
    - output is a sorted version of file.txt
  - my iphone app for calculating car mileage
    - inputs are gallons and odometer readings at each fill up
    - graph of is miles/gallon over time
    - parameters control units (could be km/liter, output couple be presented as a graph or an average value)

Designing Programs

- What's in the box (the program itself) that gives you a relationship between outputs and inputs
  - the link between inputs and output
  - breaks this down into bite-sized steps or calls to other boxes)
  - think of programs as made up building blocks
  - the design of this set of sets should be easy to follow

Building Blocks

- Instructions inside the building blocks/box
  - Numeric data operators
    - *+,-,/,*, %*%*
  - Strings
    - substr, paste..
  - Math
    - sin, cos, exp, min, max…
    - these are themselves programs - boxes
  - R-reference card is useful!

Best practices for software development

- Structured practices that ensures
    - clear, readable code
    - modularity (organized “independent” building blocks)
    - testing as you go and after
    - code evolution is documented

Building Blocks

- Functions (or objects or subroutines)!
- The basic building blocks
- Functions can be written in all languages; in many languages (object-oriented) like C++, Python, functions are also objects
- Functions are the "box" of the model - the transfer function that takes inputs and returns outputs
- More complex models - made up of multiple functions; and nested functions (functions that call/user other functions)

Functions in R

- Format for a basic function in R

```
#' documentation that describes inputs, outputs and what the function does
FUNCTION NAME = function(inputs, parameters) {
body of the function (manipulation of inputs)
return(values to return)
}
```

In R, inputs and parameters are treated the same; but it is useful to think about them separately in designing the model - collectively they are sometimes referred to as arguments

ALWAYS USE Meaningful names for your function, its parameters and variables calculated within the function

A simple program: Example

- Input: Reservoir height and flow rate
- Output: Instantaneous power generation (W/s)
- Parameters: $K_{Efficiency}$, ϱ (density of water), g (acceleration due to gravity)

$P = \varrho * h * r * g * K_{Efficiency;}$

P is Power in watts, ϱ is the density of water (~1000 kg/m3), h is height in meters, r is flow rate in cubic meters per second, g is acceleration due to gravity of 9.8 m/s2, $K_{Efficiency}$ is a coefficient of efficiency ranging from 0 to 1.

Building Models

- Example (power_gen.R)

```
power_gen = function(height, flow, rho=1000, g=9.8, Keff=0.8) {

result = rho * height * flow * g * Keff
return(result)
}
```

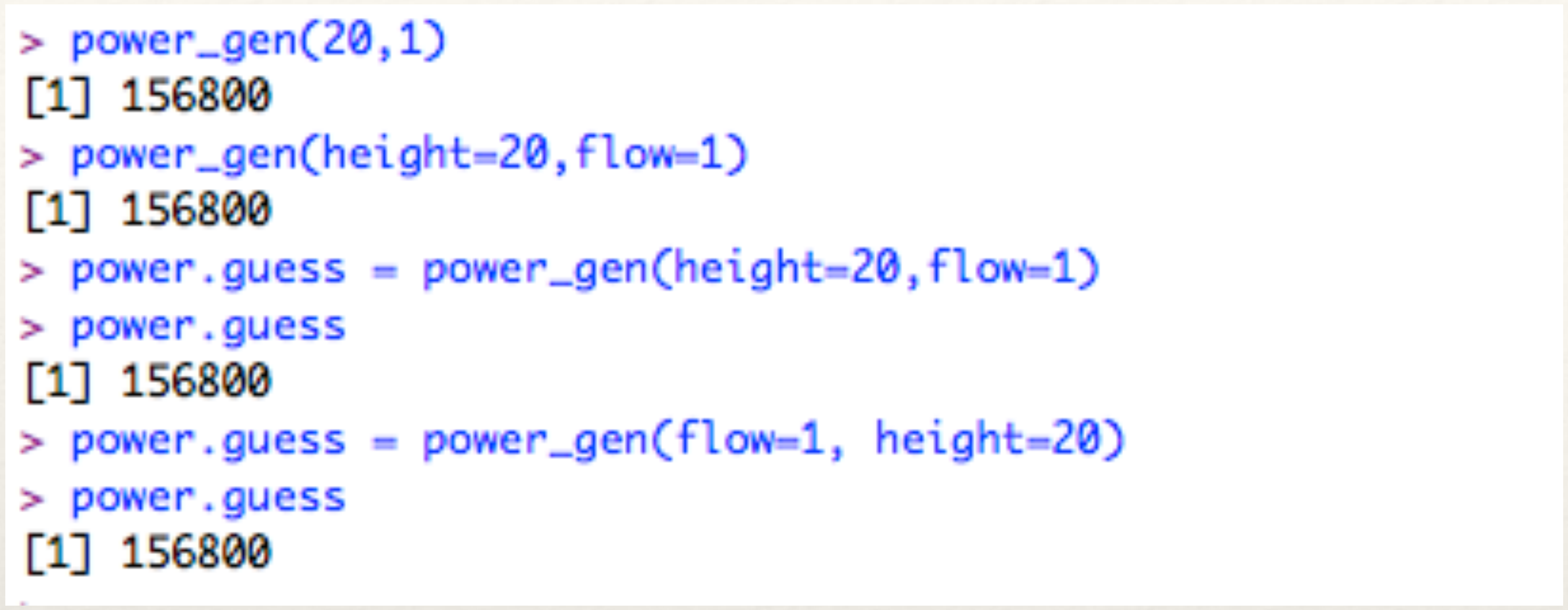
Building Models

- Inputs/parameters are height, flow, rho, g, and K
- For some (particularly parameters) we provide default values by assigning them a value (e.g Keff = 0.8), but we can overwrite these
- Body is the equations between { and }
- *return* tells R what the output is

```
power_gen = function(height, flow, rho=1000, g=9.8, Keff=0.8) {

result = rho * height * flow * g * Keff
return(result)
}
```

Building Models: Using the model



```
> power_gen(20,1)
[1] 156800
> power_gen(height=20,flow=1)
[1] 156800
> power.guess = power_gen(height=20,flow=1)
> power.guess
[1] 156800
> power.guess = power_gen(flow=1, height=20)
> power.guess
[1] 156800
```

Arguments to the function follow the order they are listed in your definition
Or you can specify which argument you are referring to when you call the program

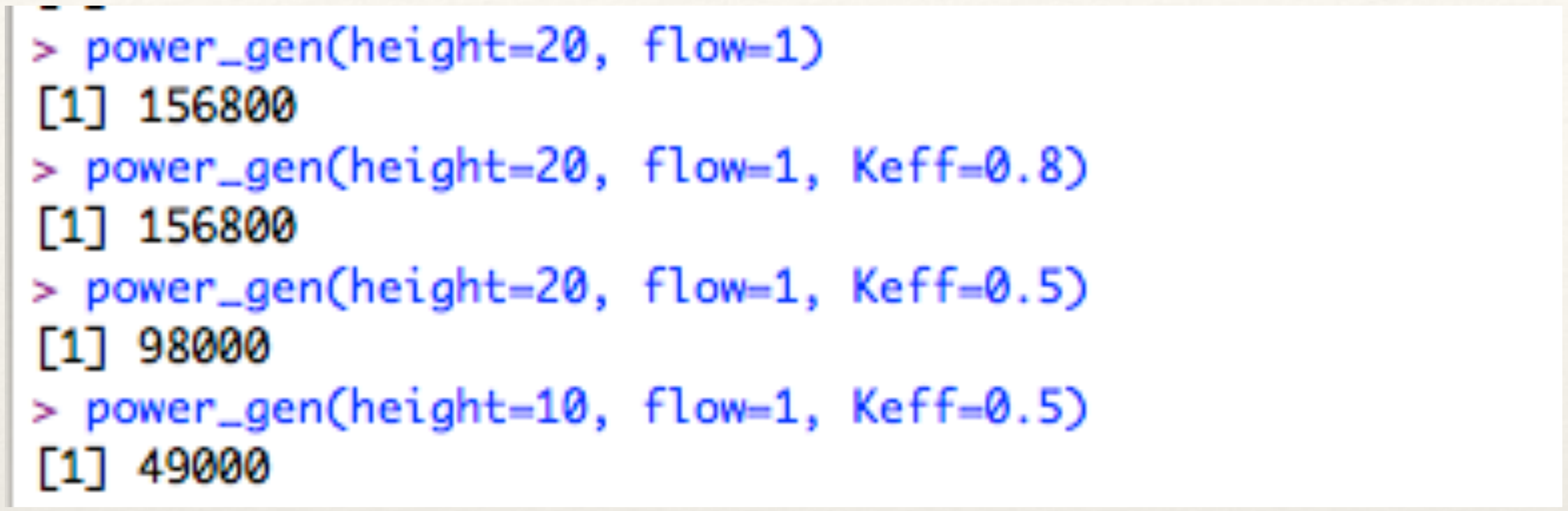
```
power_gen = function(height, flow, rho=1000, g=9.8, K=0.8) {

# calculate power
result = rho * height * flow * g * K
return(result)
}
```

Building Models

- Always write your function in a text editor and then copy into R
- By convention we name files with functions in them by the name of the function.R
    - so power_gen.R
- you can also have R read a text file by *source("power_gen.R")* - make sure you are in the right working directory
- Eventually we will want our function to be part of a package (a library of many functions) - to create a package you must use this convention (name.R)

Building Models: Using the model



```
> power_gen(height=20, flow=1)
[1] 156800
> power_gen(height=20, flow=1, Keff=0.8)
[1] 156800
> power_gen(height=20, flow=1, Keff=0.5)
[1] 98000
> power_gen(height=10, flow=1, Keff=0.5)
[1] 49000
```

Defaults take the value they were assigned in the definition, but can be overwritten

```
power_gen = function(height, flow, rho=1000, g=9.8, K=0.8) {

# calculate power
result = rho * height * flow * g * K
return(result)
}
```

Scoping

The scope of a variable in a program defines where it can be “seen”

Variables defined inside a function cannot be “seen” outside of that function

There are advantages to this - the interior of the building block does not ‘interfere’ with other parts of the program

```
> power_gen
function(height, flow, rho=1000, g=9.8, K=0.8) {

    # calculate power
    result = rho * height * flow * g * K
    return(result)
}
> result
Error: object 'result' not found
> K
Error: object 'K' not found
>
```

One of the equations used to compute automobile fuel efficiency is as follows this is the power required to keep a car moving at a given speed

$Pb = c_{rolling} * m *g*V + 1/2\ A*p_{air}*c_{drag}*V^3$

where $c_{rolling}$ and c_{drag} are rolling and aerodynamic resistive coefficients, typical values are 0.015 and 0.3, respectively.
V: is vehicle speed (assuming no headwind) in m/s (or mps)
m: is vehicle mass in kg
A is surface area of car (m2)
g: is acceleration due to gravity (9.8 m/s2)
p_{air} = density of air (1.2kg/m3)
Pb is power in Watts

Write a function to compute power, given a truck of m=31752 kg (parameters for a heavy truck) for a range of different highway speeds
plot power as a function of speed
how does the curve change for a lighter vehicle

Note that 1mph=0.477m/s

Simple Functions

```
power = function(cdrag=0.3, crolling=0.015,pair=1.2,g=9.8,V,m,A) {
P = crolling*m*g*V + 1/2*A*pair*cdrag*V**3
return(P)
}

v=seq(from=0, to=100, by=10)
plot(v, power(V=0.447*v, m=31752, A=25))
lines(v, power(V=0.447*v, m=61752, A=25))
```

Simple Functions

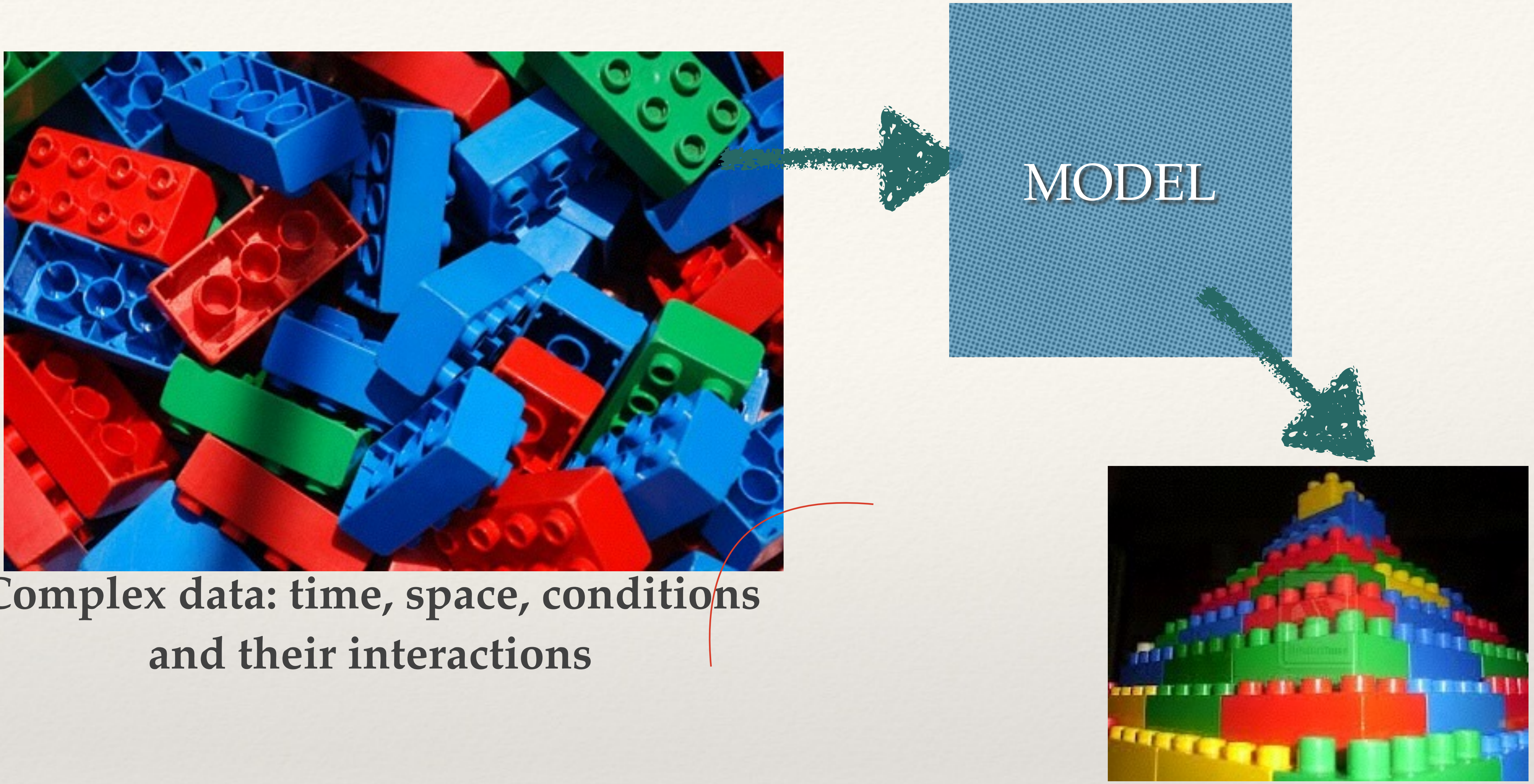
```
#' Power Required by Speed
#'
#' This function determines the power required to keep a vehicle moving
at
#' a given speed
#' @param cdrag coefficient due to drag default=0.3
#' @param crolling coefficient due to rolling/friction default=0.015
#' @param v vehicle speed (m/2)
#' @param m vehicle mass (kg)
#' @param A area of front of vehicle (m2)
#' @param g acceleration due to gravity (m/s) default=9.8
#' @param pair (kg/m3) default =1.2
#' @return power (W)

power = function(cdrag=0.3, crolling=0.015,pair=1.2,g=9.8,V,m,A) {
P = crolling*m*g*V + 1/2*A*pair*cdrag*V**3
return(P)
}

v=seq(from=0, to=100, by=10)
plot(v, power(V=0.447*v, m=31752, A=25))
lines(v, power(V=0.447*v, m=61752, A=25))
```

Key Programming concepts: Review of data types

- Understanding data types is important for designing your model I/O; specifying what the model will do
- Data types and data structures are necessary for creating more complex inputs and outputs
- All programming languages have sets of data types
  - single values: character, integer, real, logical/boolean (Y/N)
  - data structures: arrays, vectors, matrices,
    - in R core types; dataframes, lists, factors
    - in R defined types: spatial, date…



Complex data: time, space, conditions and their interactions

Building Programs

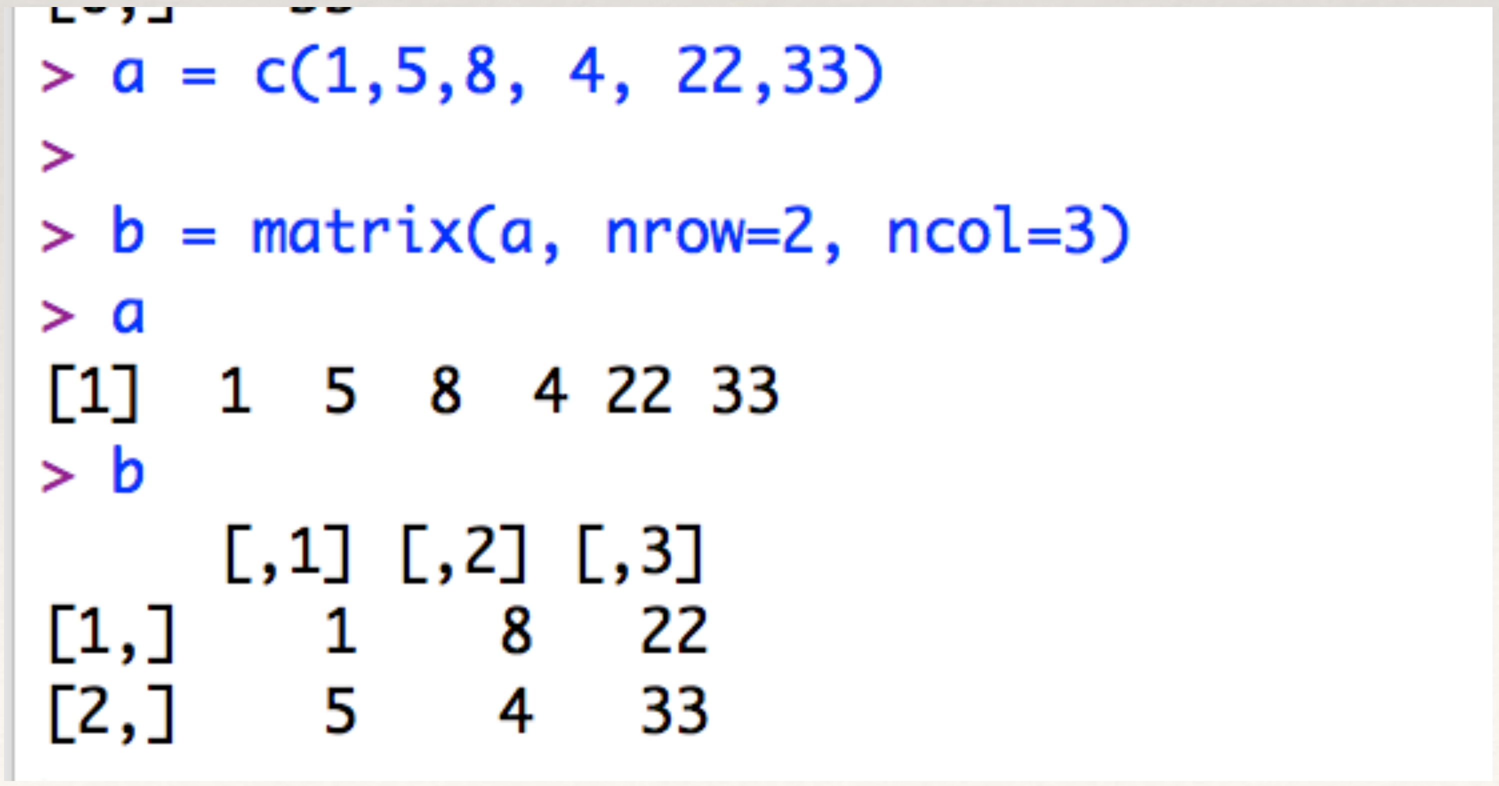
A core issue in modeling (both designing and using) are the **data structures**/formats used to hold data that is input and output from programs: In good programs, data structures support organization and program flow and readability

Key Programming concepts: Data types and structures

- Good data structures are:
  - as simple as possible
  - easy understand (readable names, and sub-names)
  - easy to manipulate (matrix operations, applying operations by category)
  - easy to visualize (graphs and other display)

Key Programming concepts: Review of data types

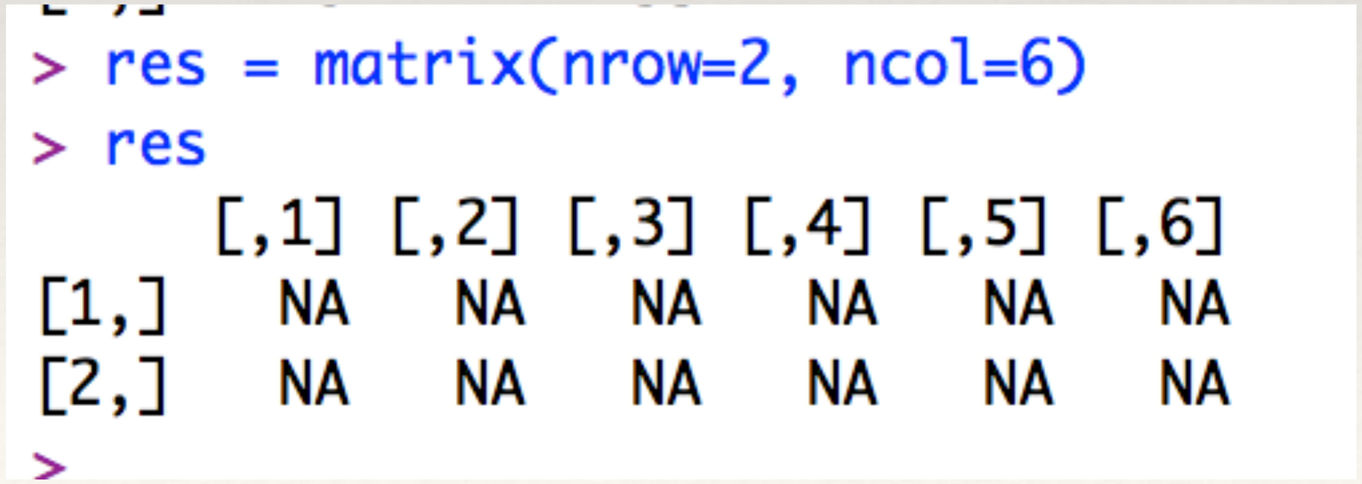
- Vectors - a 1-dimensional set of numbers
- a = c(1,5,8, 4, 22,33)
- Matrix - a 2-dimensional set of numbers (organized in rows and columns)
- b = matrix(a, nrow=2, ncol=3)



```
> a = c(1,5,8, 4, 22,33)
>
> b = matrix(a, nrow=2, ncol=3)
> a
[1]  1  5  8  4 22 33
> b
     [,1] [,2] [,3]
[1,]    1    8   22
[2,]    5    4   33
```

Key Programming concepts: Review of data types

- You can also define an "empty" matrix to fill values in later
- think of creating a data structure to store energy production in winter and summer for 6 different power plants)
- res = matrix(nrow=2, ncol=6)



```
> res = matrix(nrow=2, ncol=6)
> res
     [,1] [,2] [,3] [,4] [,5] [,6]
[1,]   NA   NA   NA   NA   NA   NA
[2,]   NA   NA   NA   NA   NA   NA
>
```

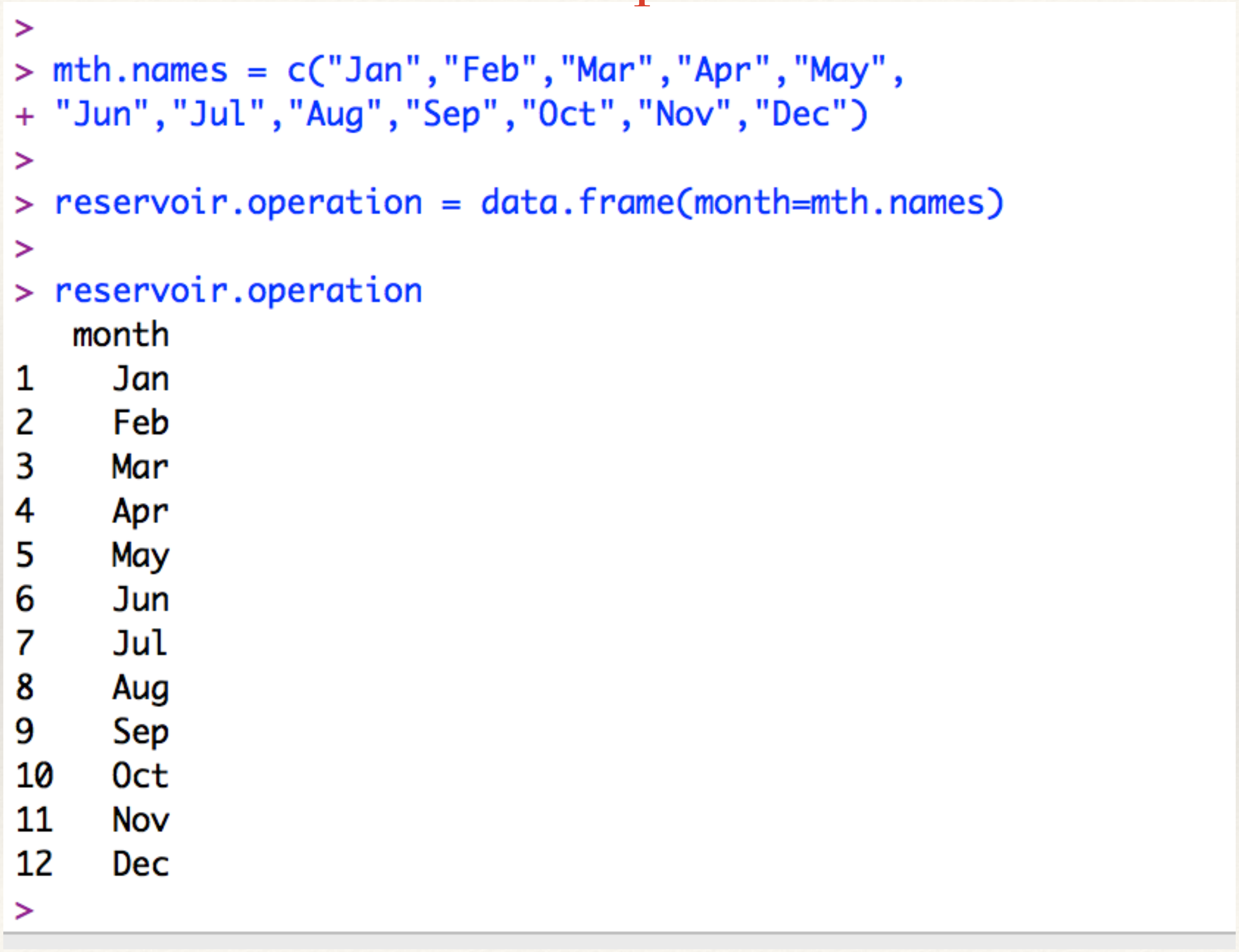
Key Programming concepts: Review of data types

- You can combine vectors into a matrix using
  - *cbind* by columns
  - *rbind* by rows

Key Programming concepts: Review of data types

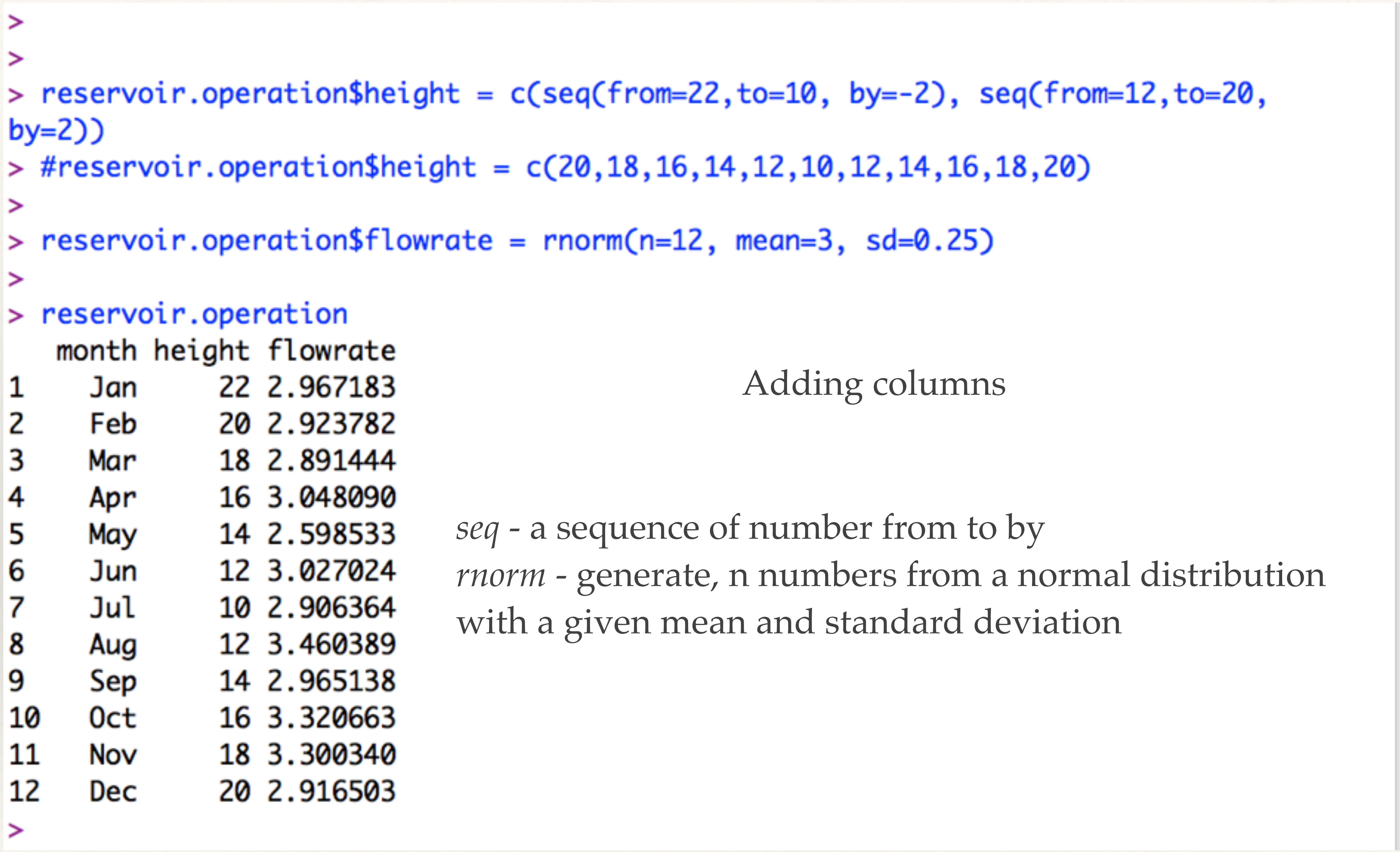
- A really useful data structure in R is a data frame
- Dataframe's are like matrices = they have rows and columns but they don't have to be numeric (although they can be)
- Useful if you have data that is of mixed type

Data Frame Creation Example



```
>
> mth.names = c("Jan","Feb","Mar","Apr","May",
+ "Jun","Jul","Aug","Sep","Oct","Nov","Dec")
>
> reservoir.operation = data.frame(month=mth.names)
>
> reservoir.operation
   month
1    Jan
2    Feb
3    Mar
4    Apr
5    May
6    Jun
7    Jul
8    Aug
9    Sep
10   Oct
11   Nov
12   Dec
>
```

Data Frame Creation Example



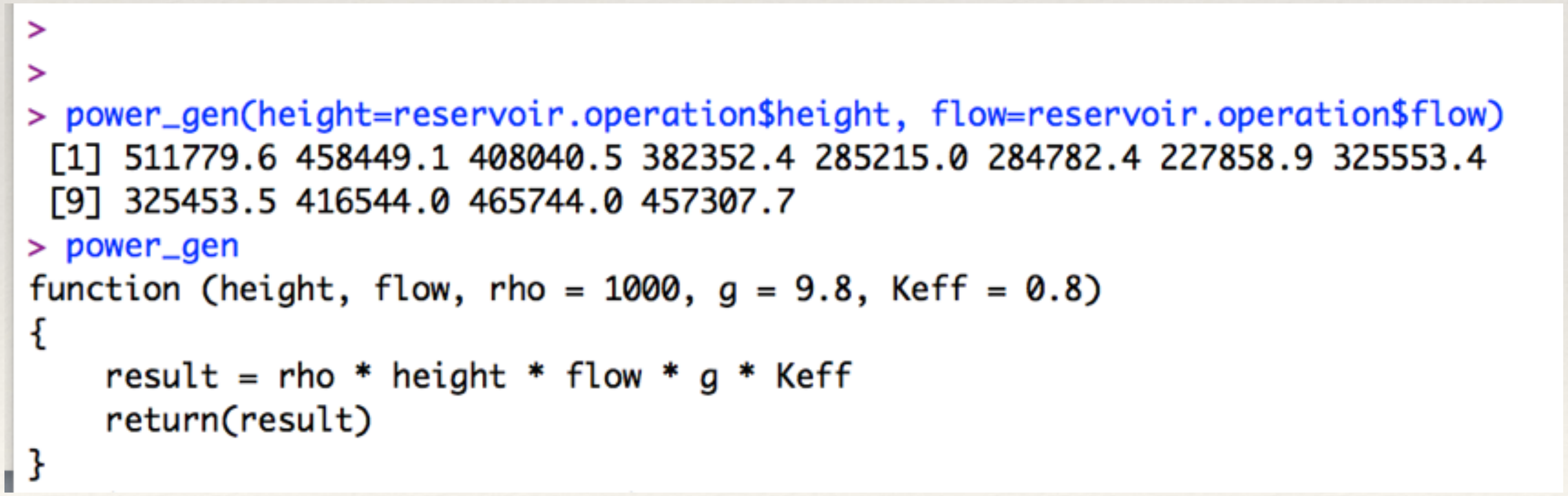
```
>
>
> reservoir.operation$height = c(seq(from=22,to=10, by=-2), seq(from=12,to=20,
by=2))
> #reservoir.operation$height = c(20,18,16,14,12,10,12,14,16,18,20)
>
> reservoir.operation$flowrate = rnorm(n=12, mean=3, sd=0.25)
>
> reservoir.operation
   month height flowrate
1    Jan     22 2.967183
2    Feb     20 2.923782
3    Mar     18 2.891444
4    Apr     16 3.048090
5    May     14 2.598533
6    Jun     12 3.027024
7    Jul     10 2.906364
8    Aug     12 3.460389
9    Sep     14 2.965138
10   Oct     16 3.320663
11   Nov     18 3.300340
12   Dec     20 2.916503
>
```

Adding columns

seq - a sequence of number from to by
rnorm - generate, n numbers from a normal distribution with a given mean and standard deviation

Key Programming concepts: Review of data types

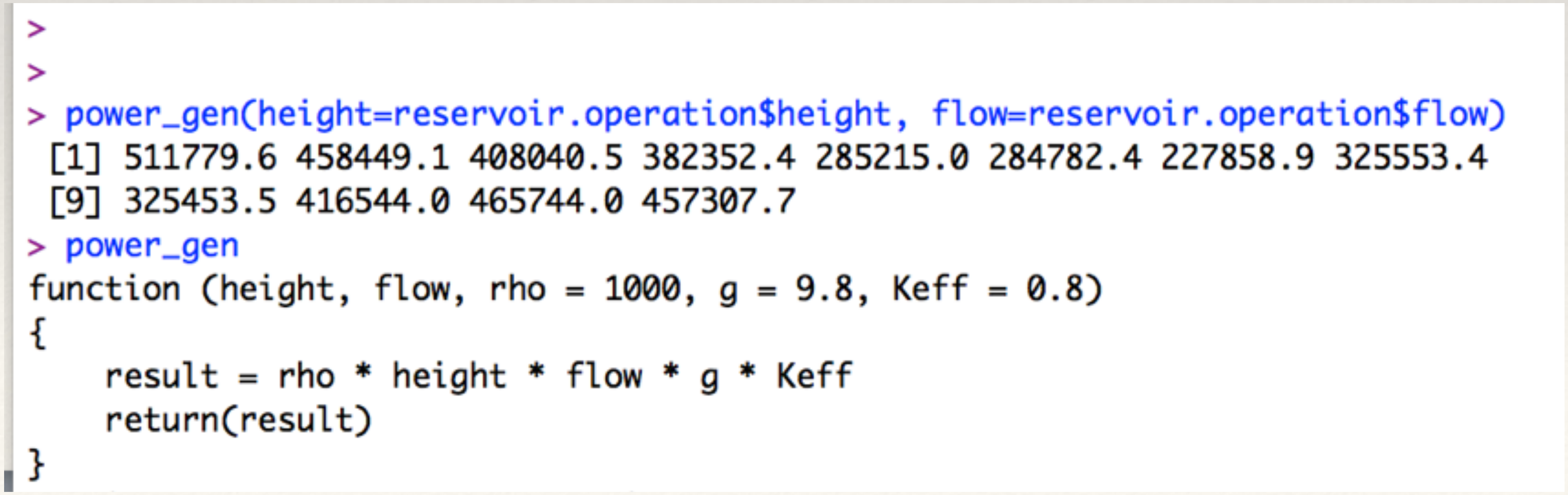
- Of course we can use matrices/data frames as inputs/output for our models
- Example using our **power_gen** model from earlier - using vectors instead of single values



```
>
>
> power_gen(height=reservoir.operation$height, flow=reservoir.operation$flow)
 [1] 511779.6 458449.1 408040.5 382352.4 285215.0 284782.4 227858.9 325553.4
 [9] 325453.5 416544.0 465744.0 457307.7
> power_gen
function (height, flow, rho = 1000, g = 9.8, Keff = 0.8)
{
    result = rho * height * flow * g * Keff
    return(result)
}
```

Key Programming concepts: Review of data types

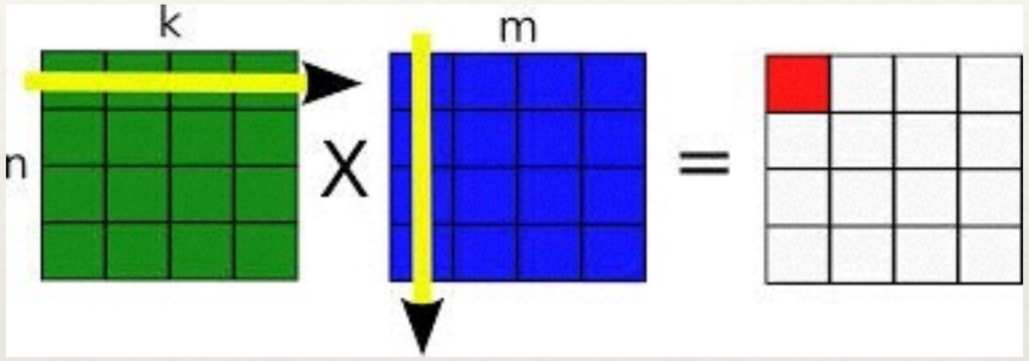
- Why does this work?
- Because height, flow columns are both from reservoir.operation (a data frame) so they are vectors of the SAME length
- So when you multiply height* flow, you multiply
    - height[1]*flow[1],,, and then height[2]*flow[2] etc



```
>
>
> power_gen(height=reservoir.operation$height, flow=reservoir.operation$flow)
 [1] 511779.6 458449.1 408040.5 382352.4 285215.0 284782.4 227858.9 325553.4
 [9] 325453.5 416544.0 465744.0 457307.7
> power_gen
function (height, flow, rho = 1000, g = 9.8, Keff = 0.8)
{
    result = rho * height * flow * g * Keff
    return(result)
}
```

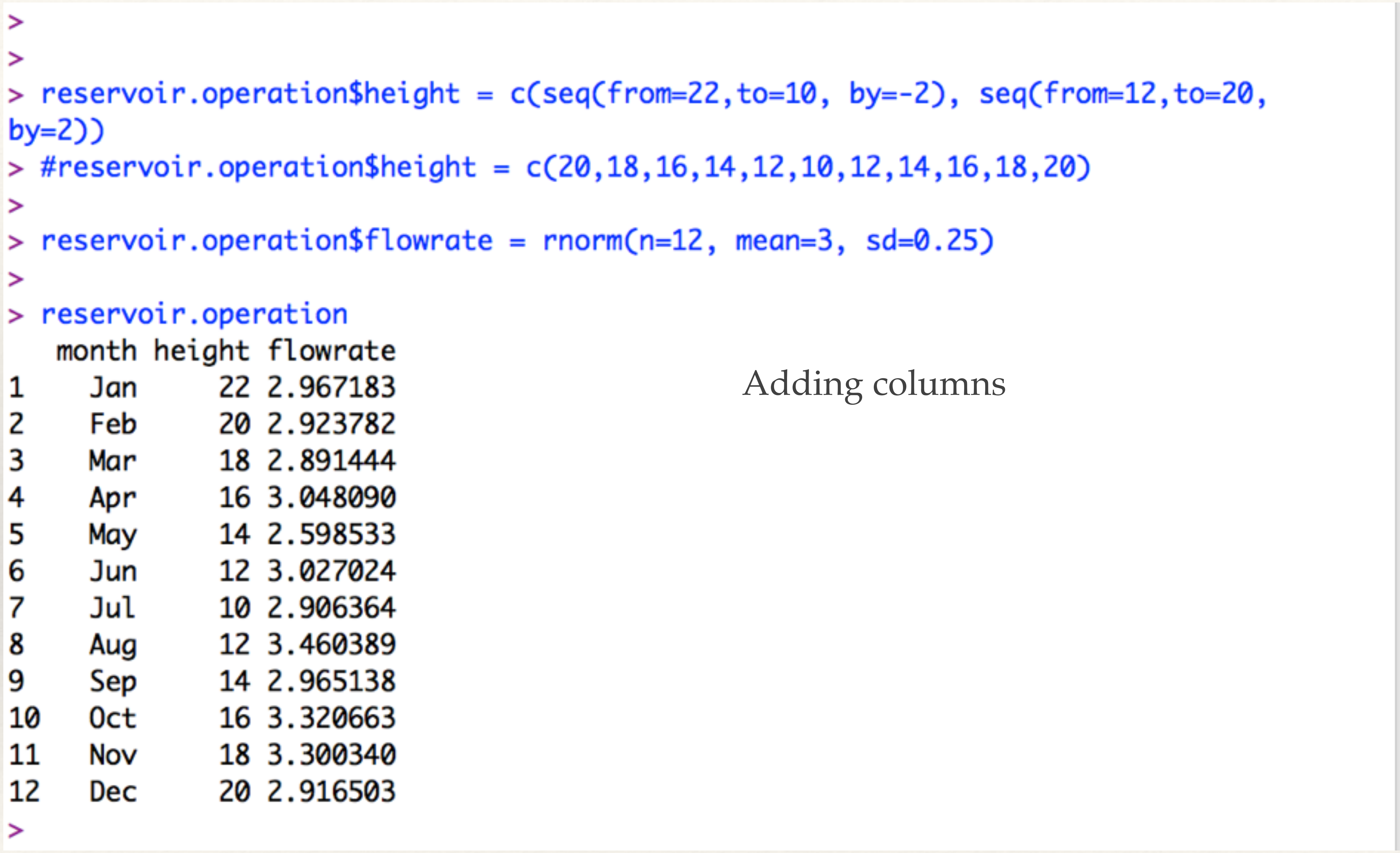
Key Programming concepts: Review of data types

- Matrix multiplication is different
- in R, this would be
  - k %*% m



- Matrix multiplication is often used within certain types of models…we will get to examples later

Data Frame Creation Example



```
>
>
> reservoir.operation$height = c(seq(from=22,to=10, by=-2), seq(from=12,to=20,
by=2))
> #reservoir.operation$height = c(20,18,16,14,12,10,12,14,16,18,20)
>
> reservoir.operation$flowrate = rnorm(n=12, mean=3, sd=0.25)
>
> reservoir.operation
   month height flowrate
1    Jan     22 2.967183
2    Feb     20 2.923782
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6    Jun     12 3.027024
7    Jul     10 2.906364
8    Aug     12 3.460389
9    Sep     14 2.965138
10   Oct     16 3.320663
11   Nov     18 3.300340
12   Dec     20 2.916503
>
```
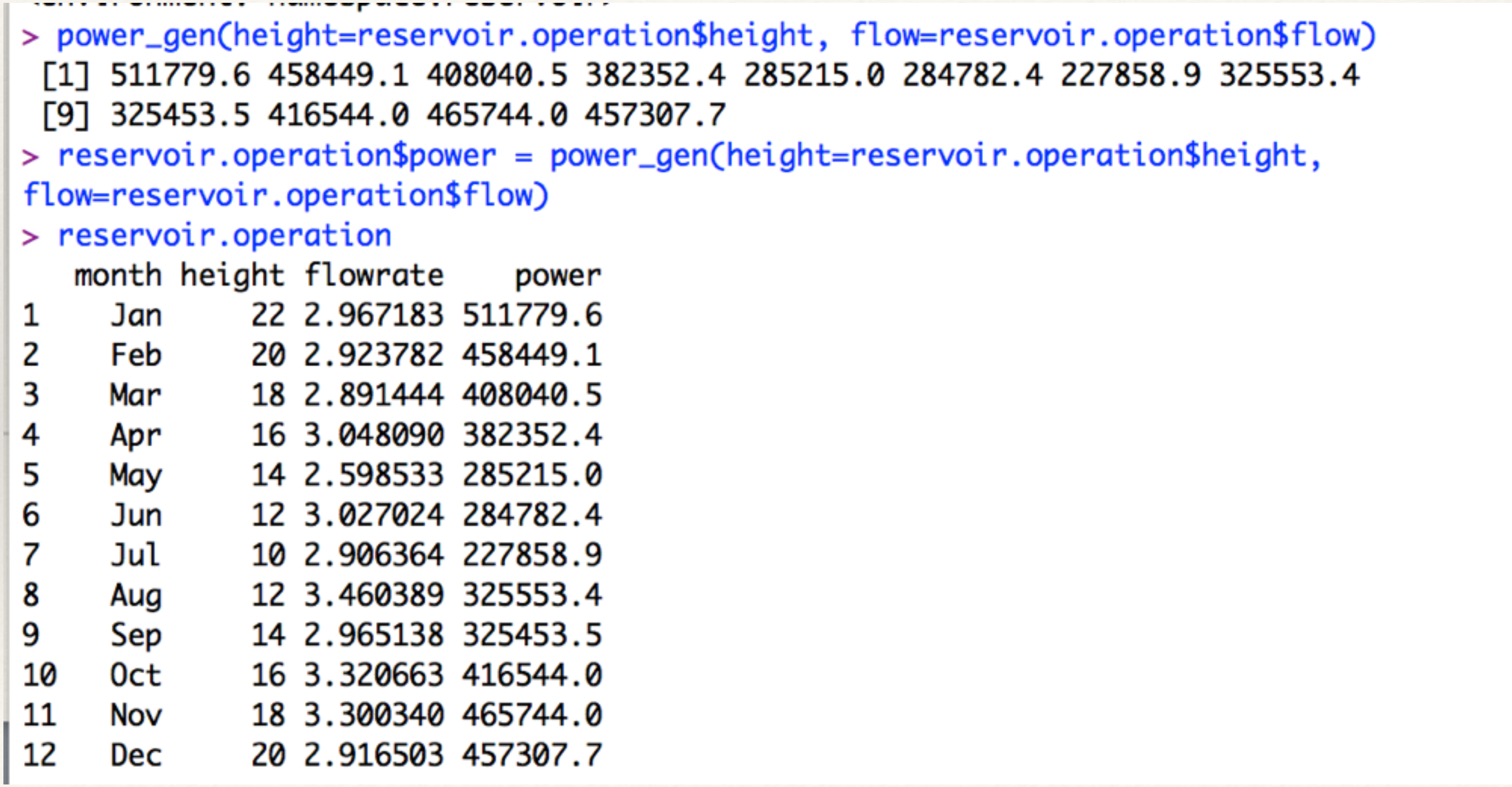

Adding columns

Key Programming concepts: Review of data types

- We can also use data frames (or matrices) to store results

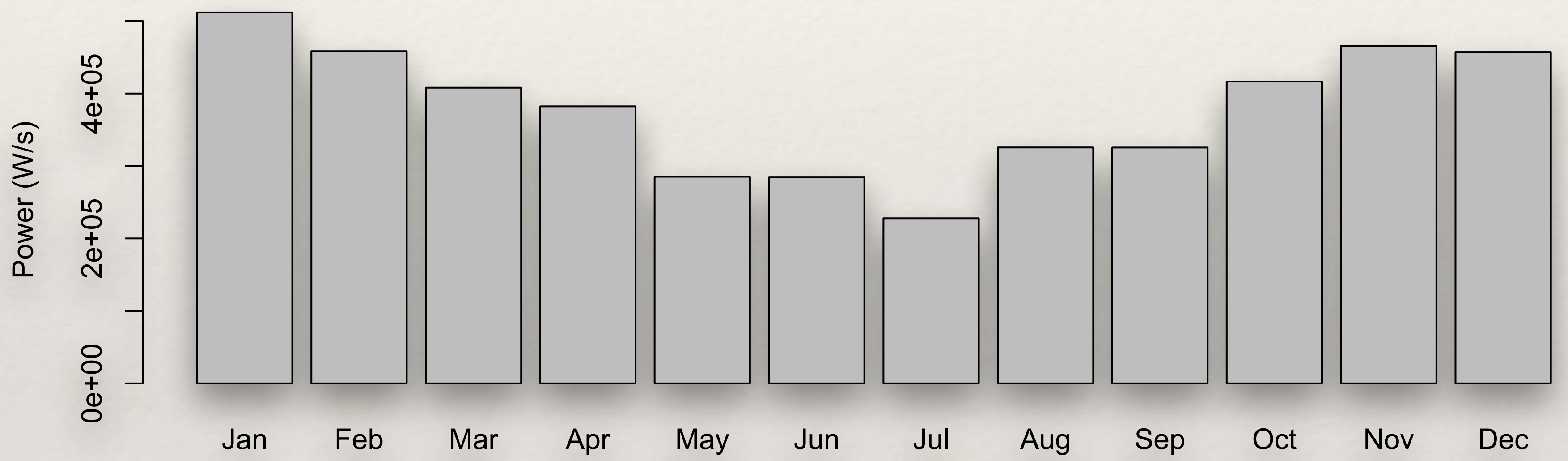


```
> power_gen(height=reservoir.operation$height, flow=reservoir.operation$flow)
 [1] 511779.6 458449.1 408040.5 382352.4 285215.0 284782.4 227858.9 325553.4
 [9] 325453.5 416544.0 465744.0 457307.7
> reservoir.operation$power = power_gen(height=reservoir.operation$height,
flow=reservoir.operation$flow)
> reservoir.operation
   month height flowrate    power
1    Jan     22 2.967183 511779.6
2    Feb     20 2.923782 458449.1
3    Mar     18 2.891444 408040.5
4    Apr     16 3.048090 382352.4
5    May     14 2.598533 285215.0
6    Jun     12 3.027024 284782.4
7    Jul     10 2.906364 227858.9
8    Aug     12 3.460389 325553.4
9    Sep     14 2.965138 325453.5
10   Oct     16 3.320663 416544.0
11   Nov     18 3.300340 465744.0
12   Dec     20 2.916503 457307.7
```

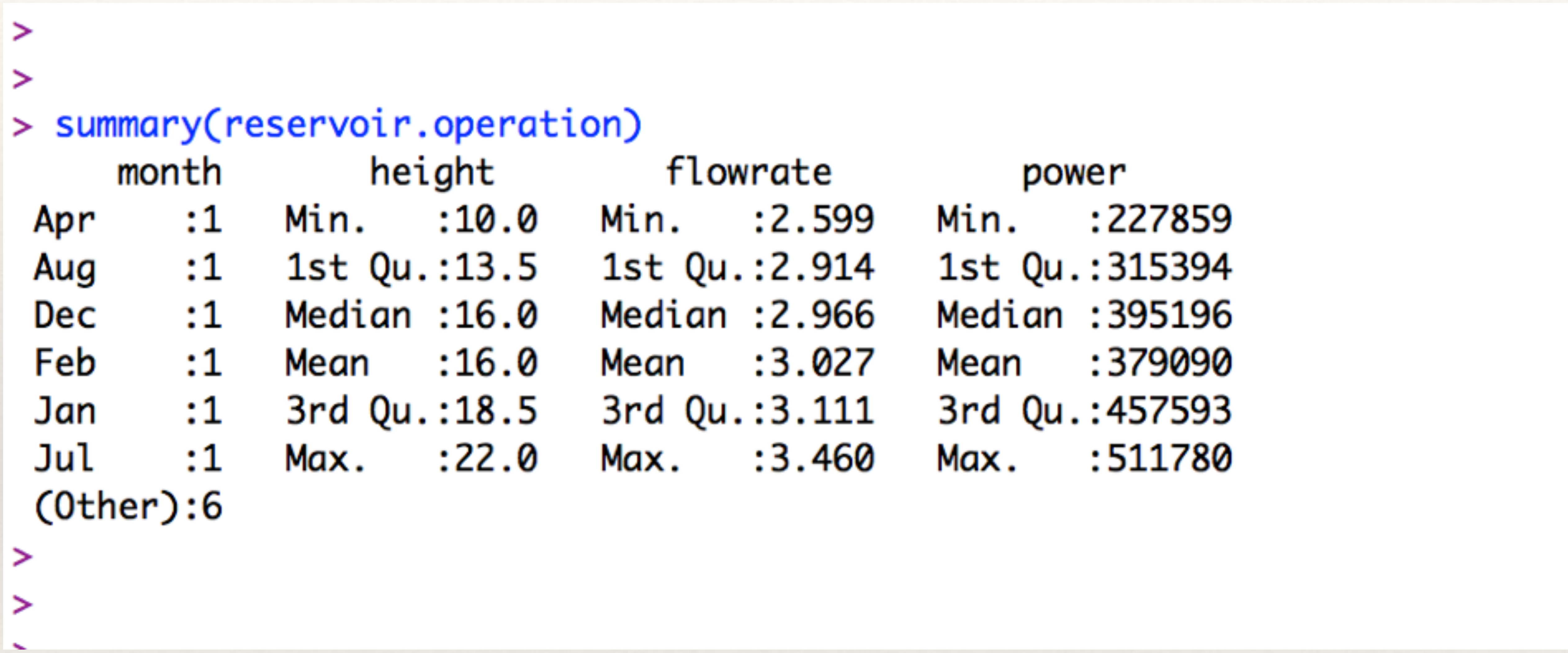
Key Programming concepts: Review of data types

- Some other useful commands
  - *with* - allows you to use the names of columns in the data frame directly
  - *summary* - summaries of columns (max, min, mean…)

```
>
> with(reservoir.operation, barplot(power, names=month, ylab="Power (W/s)"))
>
```



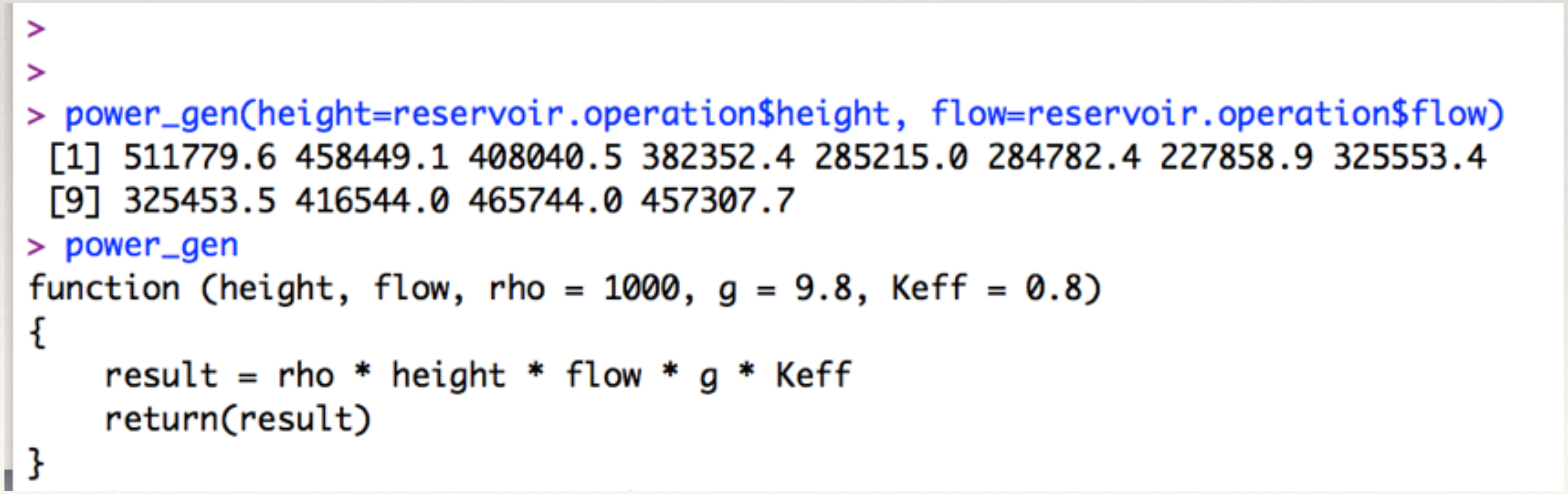
Summary



```
>
>
> summary(reservoir.operation)
     month         height         flowrate          power       
 Apr    :1   Min.   :10.0   Min.   :2.599   Min.   :227859  
 Aug    :1   1st Qu.:13.5   1st Qu.:2.914   1st Qu.:315394  
 Dec    :1   Median :16.0   Median :2.966   Median :395196  
 Feb    :1   Mean   :16.0   Mean   :3.027   Mean   :379090  
 Jan    :1   3rd Qu.:18.5   3rd Qu.:3.111   3rd Qu.:457593  
 Jul    :1   Max.   :22.0   Max.   :3.460   Max.   :511780  
 (Other):6                                                  
>
>
```

Key Programming concepts: Review of data types

- We can also use other functions and built in R functions (like *mean, lm, sum*) within our function
- Lets say we want to commute total annual power generated, given our inputs of average height and flow for each month?
    - what additional information would we need?



```
>
>
> power_gen(height=reservoir.operation$height, flow=reservoir.operation$flow)
 [1] 511779.6 458449.1 408040.5 382352.4 285215.0 284782.4 227858.9 325553.4
 [9] 325453.5 416544.0 465744.0 457307.7
> power_gen
function (height, flow, rho = 1000, g = 9.8, Keff = 0.8)
{
    result = rho * height * flow * g * Keff
    return(result)
}
```

```r
#' Total Power Generation
#'
#' This function computes total power generation from a reservoir given its
height and flow rate into turbines and number of days (and secs) within
those days that the turbines are in operation
#' @param rho Density of water (kg/m3) Default is 1000
#' @param g Acceleration due to gravity (m/sec2) Default is 9.8
#' @param Keff Turbine Efficiency (0-1) Default is 0.8
#' @param height height of water in reservoir (m)
#' @param flow flow rate (m3/sec)
#' @param number of days
#' @param secs in days Default is 86400
#' @author Naomi
#' @examples power_gen(20, 1, 10)
#' @return Power generation (MW)

power_gen_total = function(height, flow, days, secs=86400, rho=1000, g=9.8,
Keff=0.8) {

result = rho * height * flow * g * Keff
result = result * days * secs
total =  sum(result)/1e6

return(total)
}

>
> power_gen_total(reservoir.operation$height, reservoir.operation$flowrate,
days=30)
[1] 11702915
>
```

In Class example

- Expand your function that computes the power need to compute and return the total power given an input vector of different speeds and the time period over which those speeds are driven (we will ignore acceleration effect)

Key Programming concepts: Review of data types

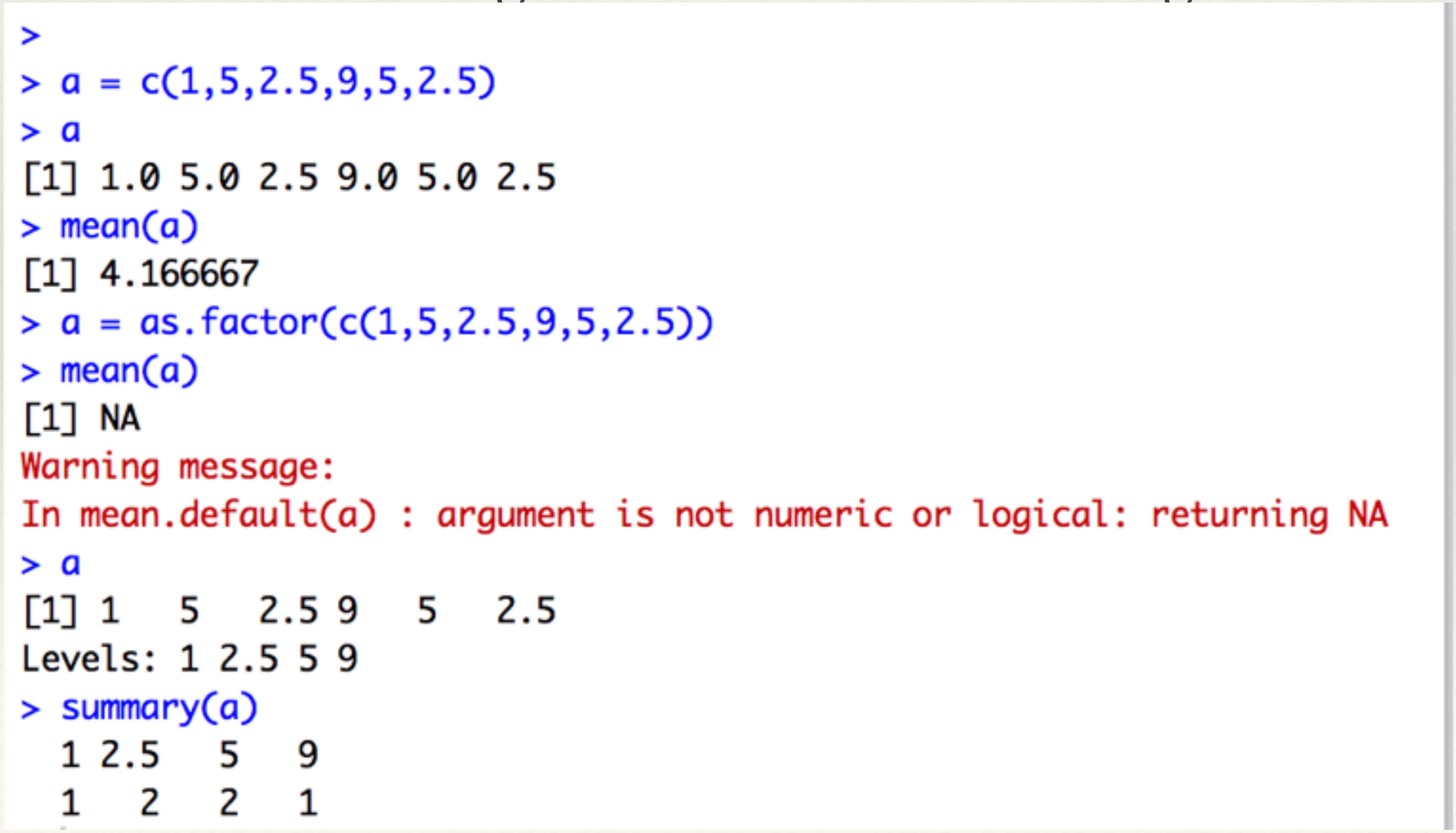
- **Arrays** are like matrices but can be multi-dimensional
- *dim* defines the dimensions of an array and gives the number of values in each dimension
- a matrix is a 2-dimensional array
- *test = array(dim=c(2,5)) - this has 2 rows and 5 columns*
- You can have N-dimensional arrays

Data Structures

- **vectors (c)**
- **matrices, arrays**
- **data frames**
- lists
- factors

Key Programming concepts: Review of data types

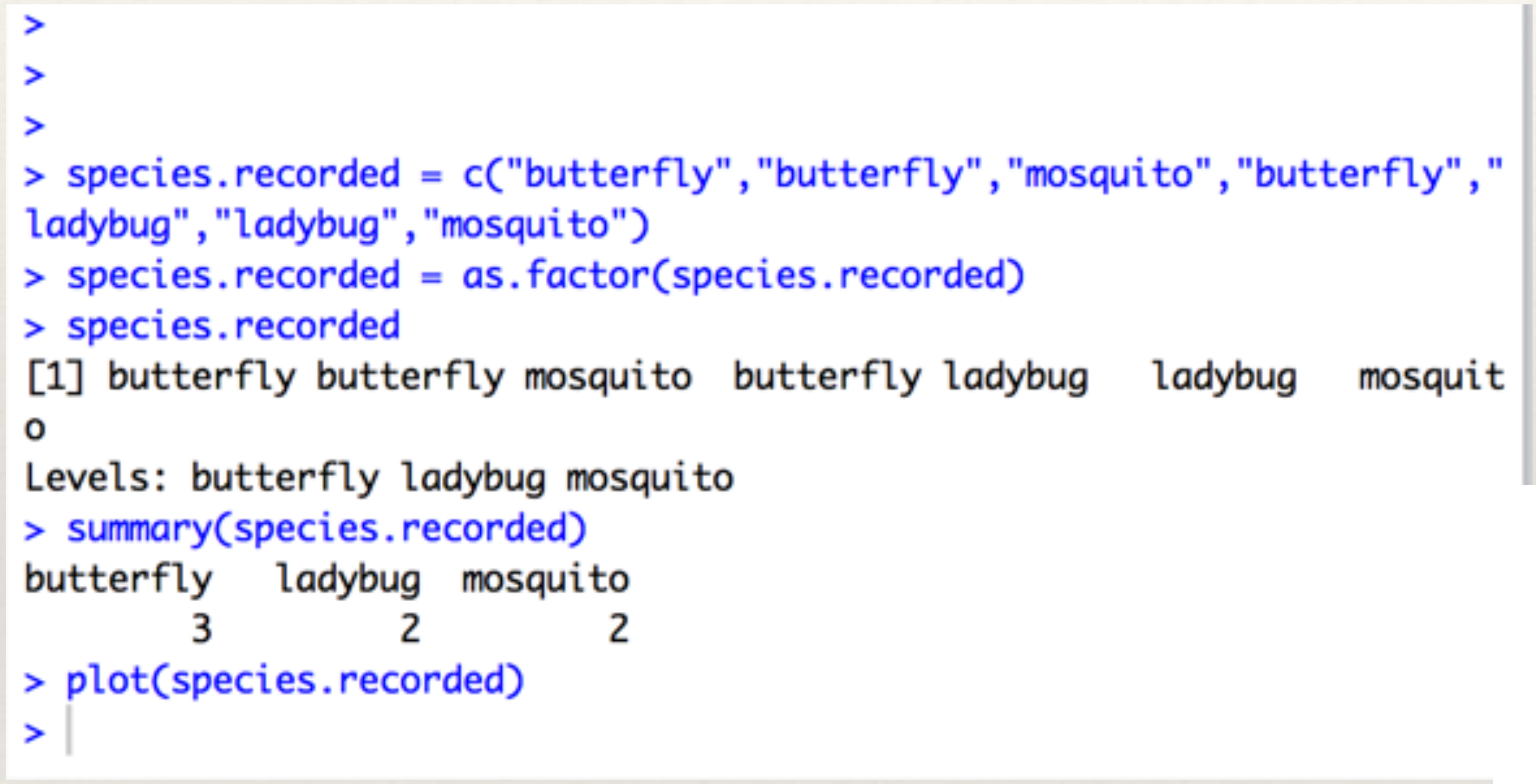
- Factors (a bit tricky, basically a vector of "things" that has different levels (classes); not really numeric - so you can't average them!)
- But can be useful for doing "calculations" with categories



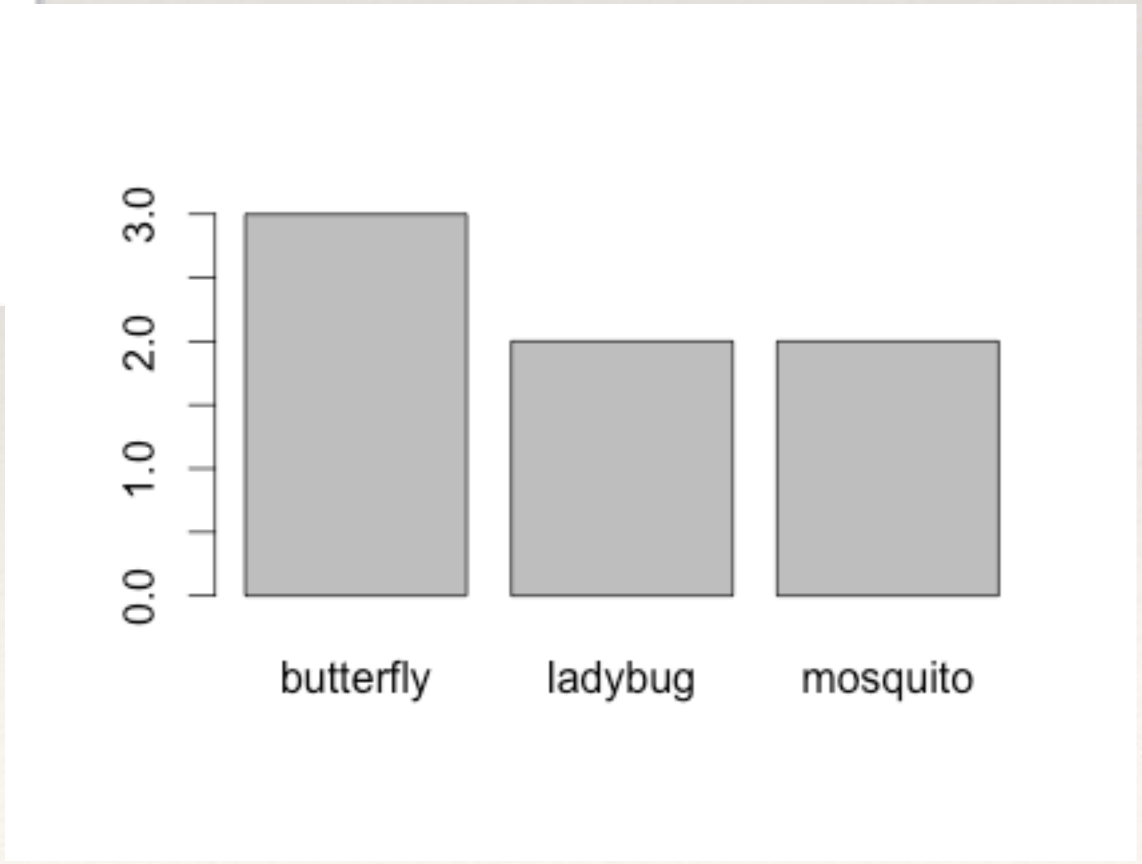
```
>
> a = c(1,5,2.5,9,5,2.5)
> a
[1] 1.0 5.0 2.5 9.0 5.0 2.5
> mean(a)
[1] 4.166667
> a = as.factor(c(1,5,2.5,9,5,2.5))
> mean(a)
[1] NA
Warning message:
In mean.default(a) : argument is not numeric or logical: returning NA
> a
[1] 1   5   2.5 9   5   2.5
Levels: 1 2.5 5 9
> summary(a)
  1 2.5   5   9
  1   2   2   1
```

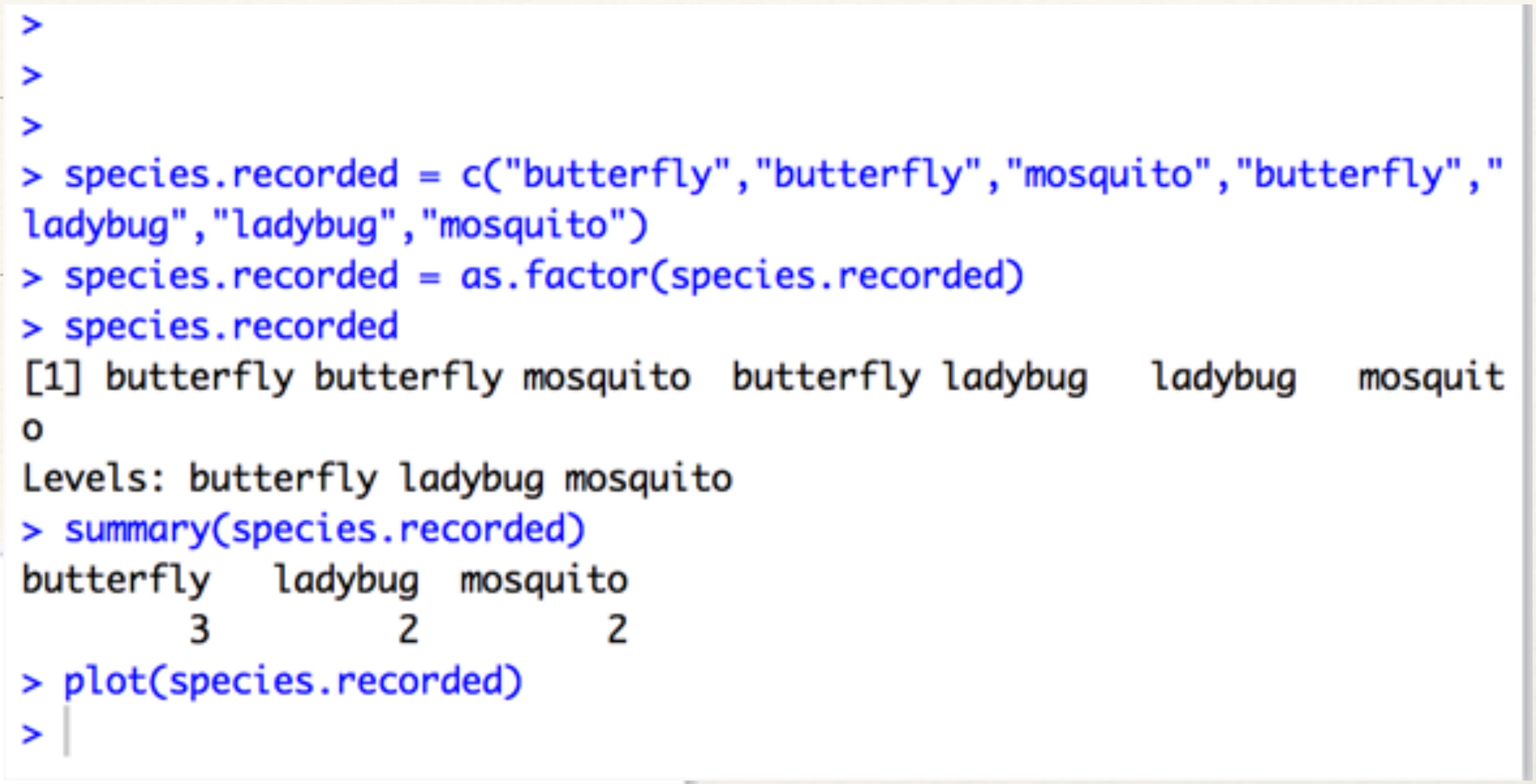
Key Programming concepts: Review of data types

- *summary* can be used with factors to get frequencies in each category (or “level”)

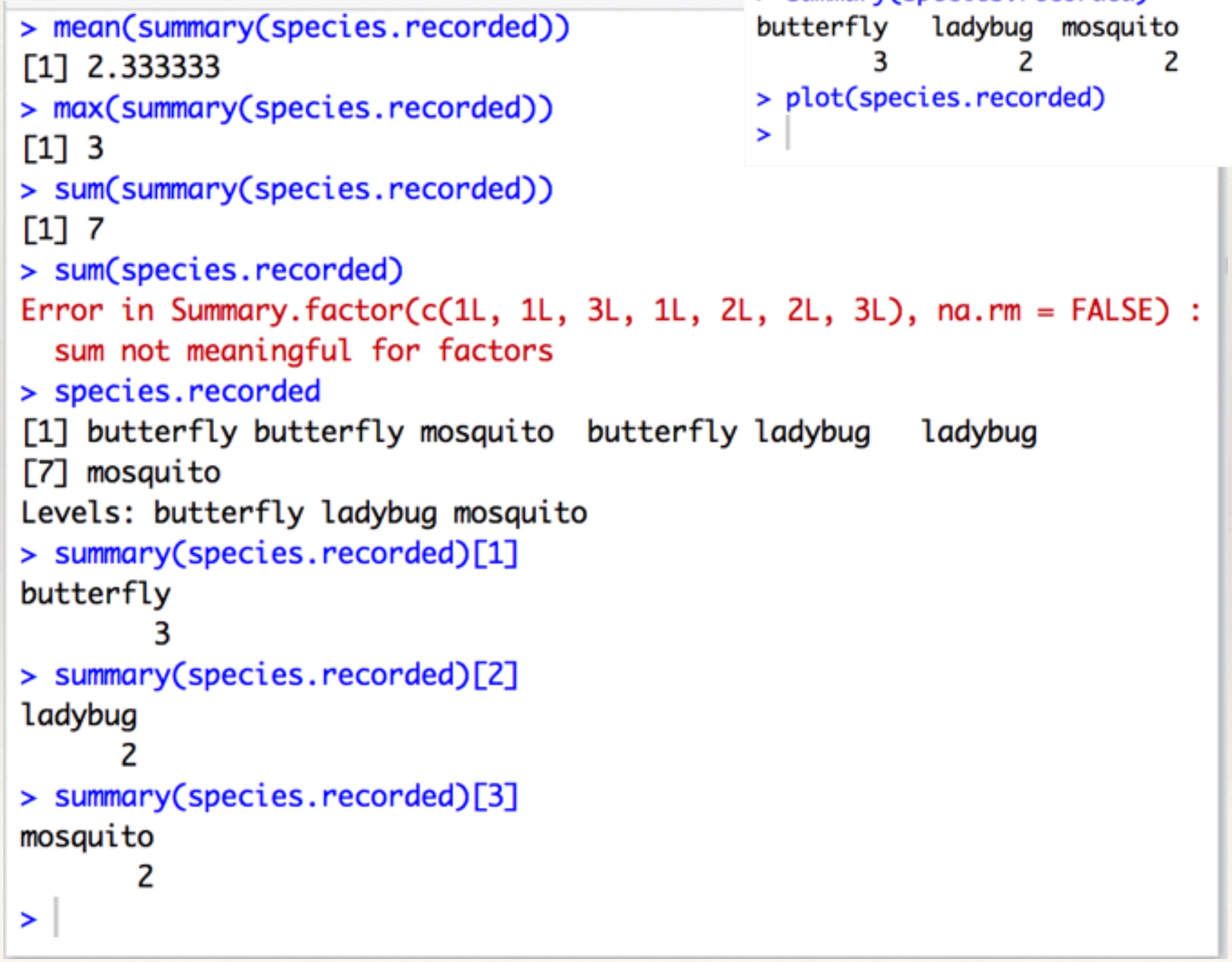


```
>
>
>
> species.recorded = c("butterfly","butterfly","mosquito","butterfly","
ladybug","ladybug","mosquito")
> species.recorded = as.factor(species.recorded)
> species.recorded
[1] butterfly butterfly mosquito  butterfly ladybug   ladybug   mosquit
o
Levels: butterfly ladybug mosquito
> summary(species.recorded)
butterfly   ladybug  mosquito 
        3         2         2 
> plot(species.recorded)
> 
```





```
>
>
>
> species.recorded = c("butterfly","butterfly","mosquito","butterfly","
ladybug","ladybug","mosquito")
> species.recorded = as.factor(species.recorded)
> species.recorded
[1] butterfly butterfly mosquito  butterfly ladybug   ladybug   mosquit
o
Levels: butterfly ladybug mosquito
> summary(species.recorded)
butterfly   ladybug  mosquito 
        3         2         2 
> plot(species.recorded)
> 
```



```
> mean(summary(species.recorded))
[1] 2.333333
> max(summary(species.recorded))
[1] 3
> sum(summary(species.recorded))
[1] 7
> sum(species.recorded)
Error in Summary.factor(c(1L, 1L, 3L, 1L, 2L, 2L, 3L), na.rm = FALSE) :
  sum not meaningful for factors
> species.recorded
[1] butterfly butterfly mosquito  butterfly ladybug   ladybug  
[7] mosquito 
Levels: butterfly ladybug mosquito
> summary(species.recorded)[1]
butterfly 
        3 
> summary(species.recorded)[2]
ladybug 
      2 
> summary(species.recorded)[3]
mosquito 
       2 
> 
```

You can "do things" (apply functions) to the summary (frequency of each "factor" level

Key Programming concepts: Review of data types

- A simple model that takes advantage of factors
- A model to compute an index of species diversity from a list of recorded species

$$D = \Sigma (n / N)^2$$

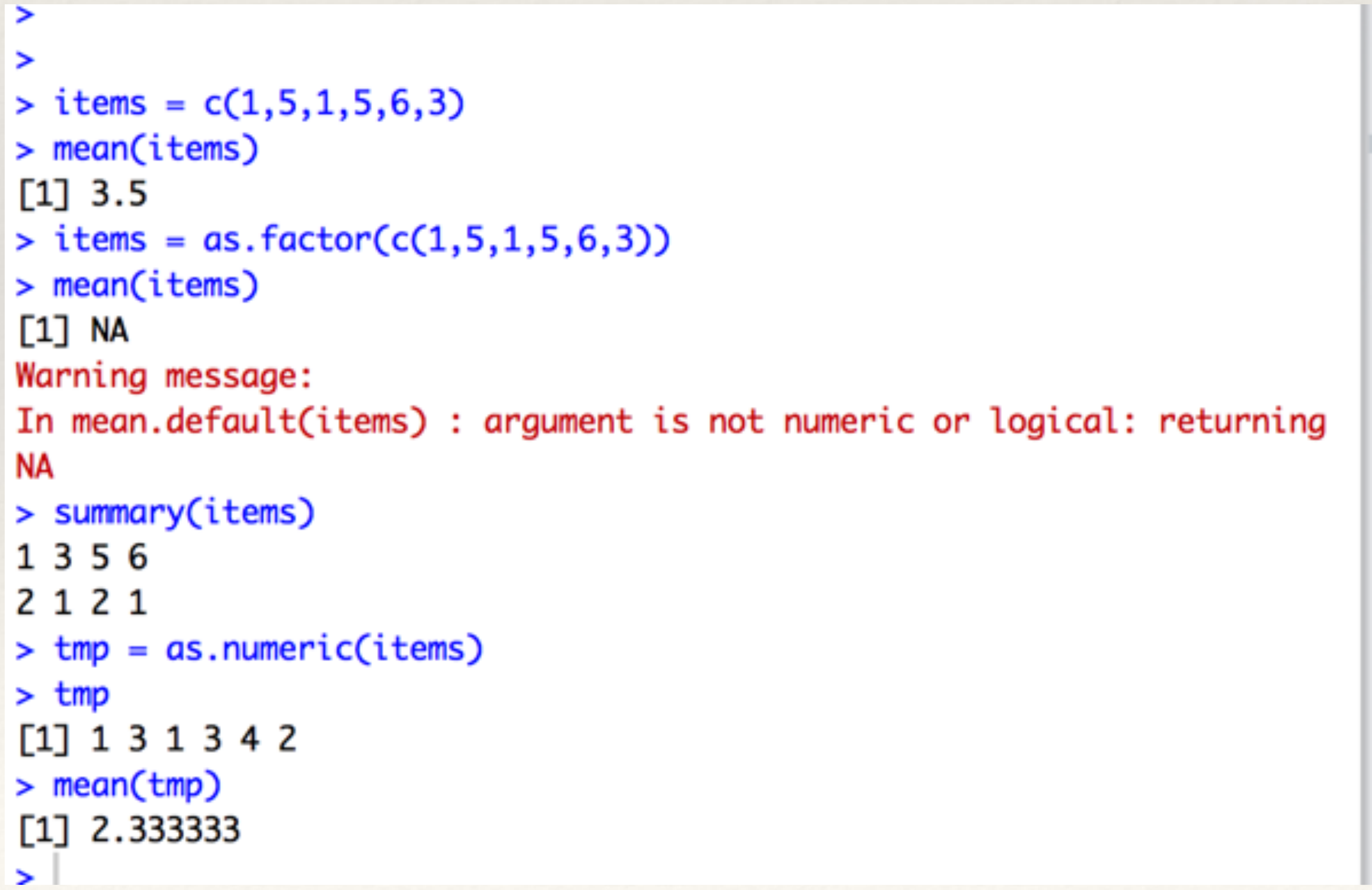
where n is the number of individuals in each species, and N is total number

Key Programming concepts: Review of data types

```
#' Simpson's Species Diversity Index
#'
#' Compute a species diversity index
#' @param species list of species (names, or code)
#' @return value of Species Diversity Index
#' @examples
#' compute_simpson_index(c(“butterfly","butterfly","mosquito","butterfly",
#′ ″ladybug","ladybug")))
#' @references
#' http://www.tiem.utk.edu/~gross/bioed/bealsmodules/simpsonDI.html

compute_simpson_index = function(species) {

species = as.factor(species)
tmp = (summary(species)/sum(summary(species))) ** 2
diversity = sum(tmp)
return(diversity)
}
```

Data Structures

- a bit more on factors; a list of numbers can also be a factor but then they are not treated as actual numbers - you could think of them as “codes” or addresses or..
- use *as.numeric* or *as.character* to go back to a regular vector from a factor



```
>
>
> items = c(1,5,1,5,6,3)
> mean(items)
[1] 3.5
> items = as.factor(c(1,5,1,5,6,3))
> mean(items)
[1] NA
Warning message:
In mean.default(items) : argument is not numeric or logical: returning
NA
> summary(items)
1 3 5 6
2 1 2 1
> tmp = as.numeric(items)
> tmp
[1] 1 3 1 3 4 2
> mean(tmp)
[1] 2.333333
>
```

Data Structures

- vector, (c)
- matrices, arrays
- data frames
- lists
- factors

Key Programming concepts: Review of data types

- Lists are the most “informal” data structures in R
- List are really useful for keeping track of and organizing groups of things that are not all the same
- A list could be a table where number of rows is different for each column
- A list can have numeric, character, factors all mixed together
- List are often used for returning more complex information from function (e.g. lm)

Key Programming concepts: Review of data types

- A simple list

```
> sale = list(2,"highquality","apple",4)
> sale
[[1]]
[1] 2

[[2]]
[1] "highquality"

[[3]]
[1] "apple"

[[4]]
[1] 4
```

Key Programming concepts: Review of data types

- A simple list: using names to identify elements

```
> sale = list(number=2, quality="high", what="apple", cost=4)
> sale
$number
[1] 2

$quality
[1] "high"

$what
[1] "apple"

$cost
[1] 4
```

```
>
> costs = c(20,40,22, 32, 5)
> quality = c("G","G","F","G","B")
> purchased = c(33,5,22,6,7)
>
> sales = data.frame(costs=costs, quality=quality, purchased=purchased)
>
>
> sales
  costs quality purchased
1    20       G        33
2    40       G         5
3    22       F        22
4    32       G         6
5     5       B         7
>
```

```
>costs = c(73,44)
>quality = c("G","G")
>purchased = c(100,22)

>sales2 = data.frame(costs=costs, quality=quality
purchased=purchased)
```

With lists we can combine sales data frames from two different places into a single data structure

Lists

```
>
> markets = list(site1=sales, site2=sales2)
> markets
$site1
  costs quality purchased
1    20       G        33
2    40       G         5
3    22       F        22
4    32       G         6
5     5       B         7

$site2
  costs quality purchased
1    73       G       100
2    44       G        22

> markets[[1]]$costs
[1] 20 40 22 32  5
>
> markets$site1$costs
[1] 20 40 22 32  5
>
```

Lists

```
>
>
> markets[[1]]
  costs quality purchased
1    20       G        33
2    40       G         5
3    22       F        22
4    32       G         6
5     5       B         7
>
> markets[[2]]
  costs quality purchased
1    73       G       100
2    44       G        22
>
> > markets[[1]][1,3]
[1] 33
>
```

***[[]]* is used to get elements from the list**

Key Programming concepts: Review of data types

- one of the most useful things to do with list is to use them to return multiple ‘items’ from a function

```
#' computes profit from  price for forest plot  and Mg/C in that plot
#' @param  price ($)
#' @param  carbon (MgC)
#' @return list with mean, min, and max prices
compute_carbonvalue = function(price, carbon) {

cost.per.carbon = price/carbon
a = mean(cost.per.carbon)
b = max(cost.per.carbon)
c = min(cost.per.carbon)

result = list(avg=a, min=c, max=b)
return(result)
}
```

Key Programming concepts: Review of data types

- example: returning lists from a function

```
>
> obs = data.frame(prices=c(23,44,60,4,2,33,59),
forestC=c(59,88,100,10,8,79,300))
> obs
  prices forestC
1     23      59
2     44      88
3     60     100
4      4      10
5      2       8
6     33      79
7     59     300
> forest.res = compute_carbonvalue(obs$prices, obs$forestC)
> forest.res
$avg
[1] 0.3934598

$min
[1] 0.1966667

$max
[1] 0.6

>
```

Key Programming concepts: Review of data types

- example: returning lists from a function

```
> obs=data.frame(prices=c(18,2,12,5), grassC=c(22,3,19,8))
> grass.res=compute_carbonvalue(obs$prices, obs$grassC)
> grass.res
$avg
[1] 0.6853569

$min
[1] 0.625

$max
[1] 0.8181818

>
```

Key Programming concepts: Review of data types

- Many functions that you use in R, return lists
- *names* (to see what is in a list)
- *attributes* (to see what is in a list)

```
> names(forest.res)
[1] "avg" "min" "max"
> attributes(forest.res)
$names
[1] "avg" "min" "max"
```

Key Programming concepts: Review of data types

- *lm* is an example of a function that returns a list

```
>
> res = lm(obs$prices~obs$forestC)
> names(res)
 [1] "coefficients"  "residuals"     "effects"
 [4] "rank"          "fitted.values" "assign"
 [7] "qr"            "df.residual"   "xlevels"
[10] "call"          "terms"         "model"
> res$coefficients
(Intercept) obs$forestC
 14.9789368   0.1865644
> res$model
  obs$prices obs$forestC
1         23          59
2         44          88
3         60         100
4          4          10
5          2           8
6         33          79
7         59         300
>
```

Key Programming concepts: Review of data types

- example: returning lists from a function

```
#' Describe diversity based on a list of species
#'
#' Compute a species diversity index
#' @param species list of species (names, or code)
#' @return list with the following items
#' \describe{
#' \item{num}{ Number of distinct species}
#' \item{simpson}{Value of simpson diversity index}
#' \item{dominant}{Name of the most frequently occuring species}
#' }
#' @examples
#'
compute_diversity(c("butterfly","butterfly","mosquito","butterfly","ladybug",
"ladybug")))
#' @references
#' http://www.tiem.utk.edu/~gross/bioed/bealsmodules/simpsonDI.html

compute_diversity = function(species) {

species = as.factor(species)
tmp = (summary(species)/sum(summary(species))) ** 2
diversity = sum(tmp)
nspecies = length(summary(species))
tmp = which.max(summary(species))
dominant = names(summary(species)[tmp])
return(list(num=nspecies, simpson=diversity, dominant=dominant))
}
```

Key Programming concepts: Review of data types

- to your function that computes power, also return
  - an array that contains both power for each input speed
  - total power

Key Programming concepts: Review of data typessd

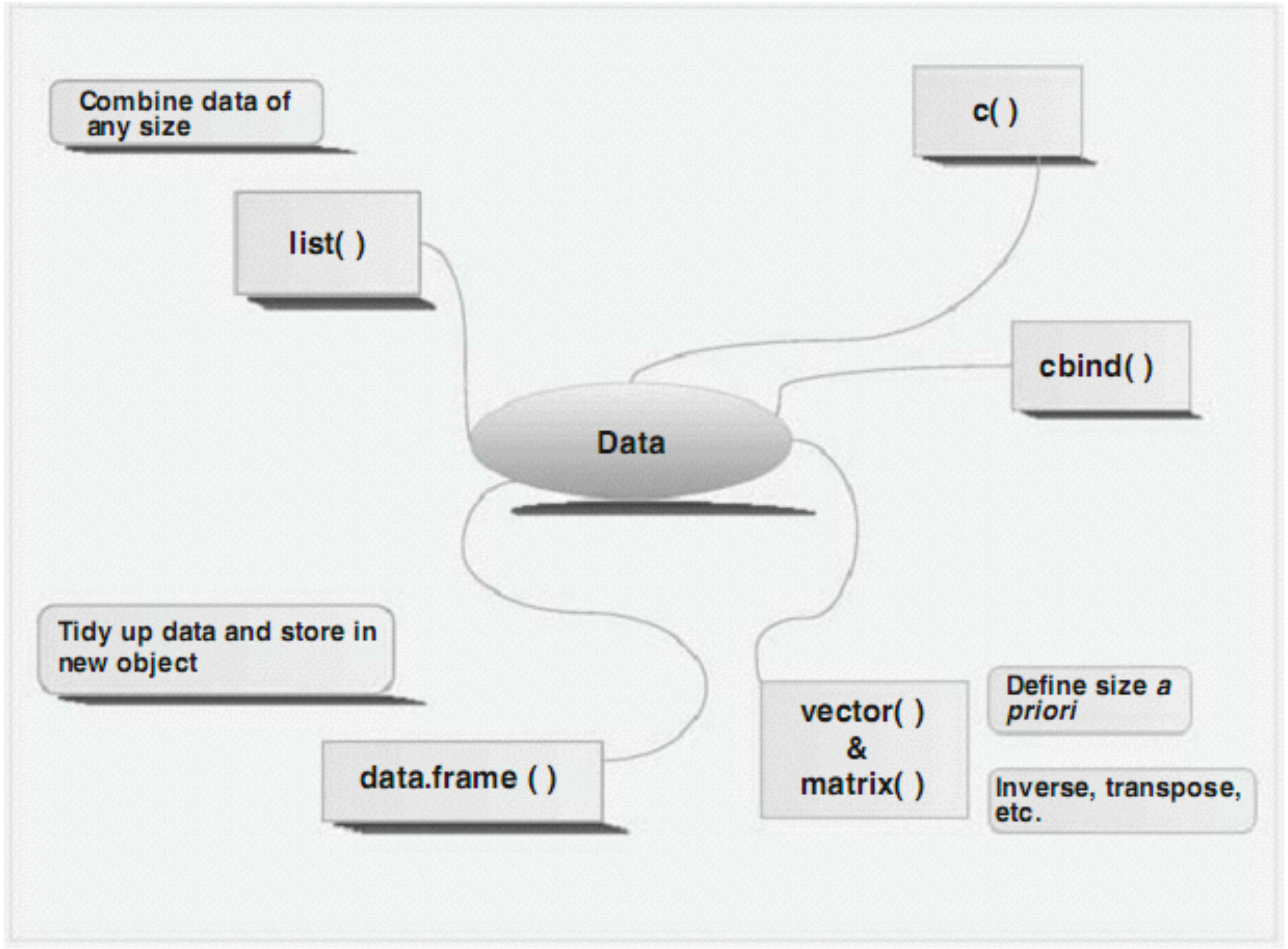
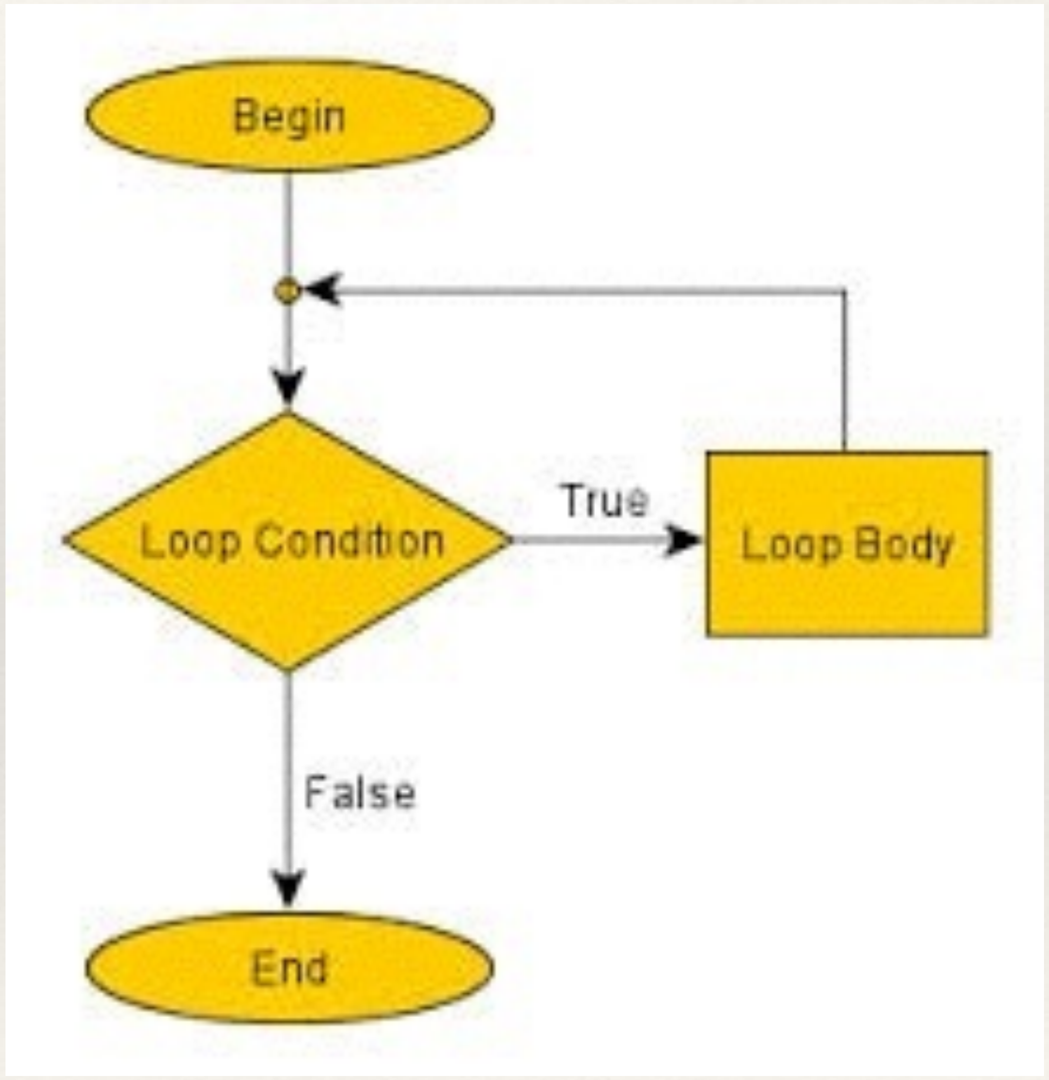


Fig. 2.1 Overview of various methods of storing data. The data stored by `cbind`, `matrix`, or `data.frame` assume that data in each row correspond to the same observation (sample, case)

http://www.simonqueenborough.com/R/basic/figure/data-types.png

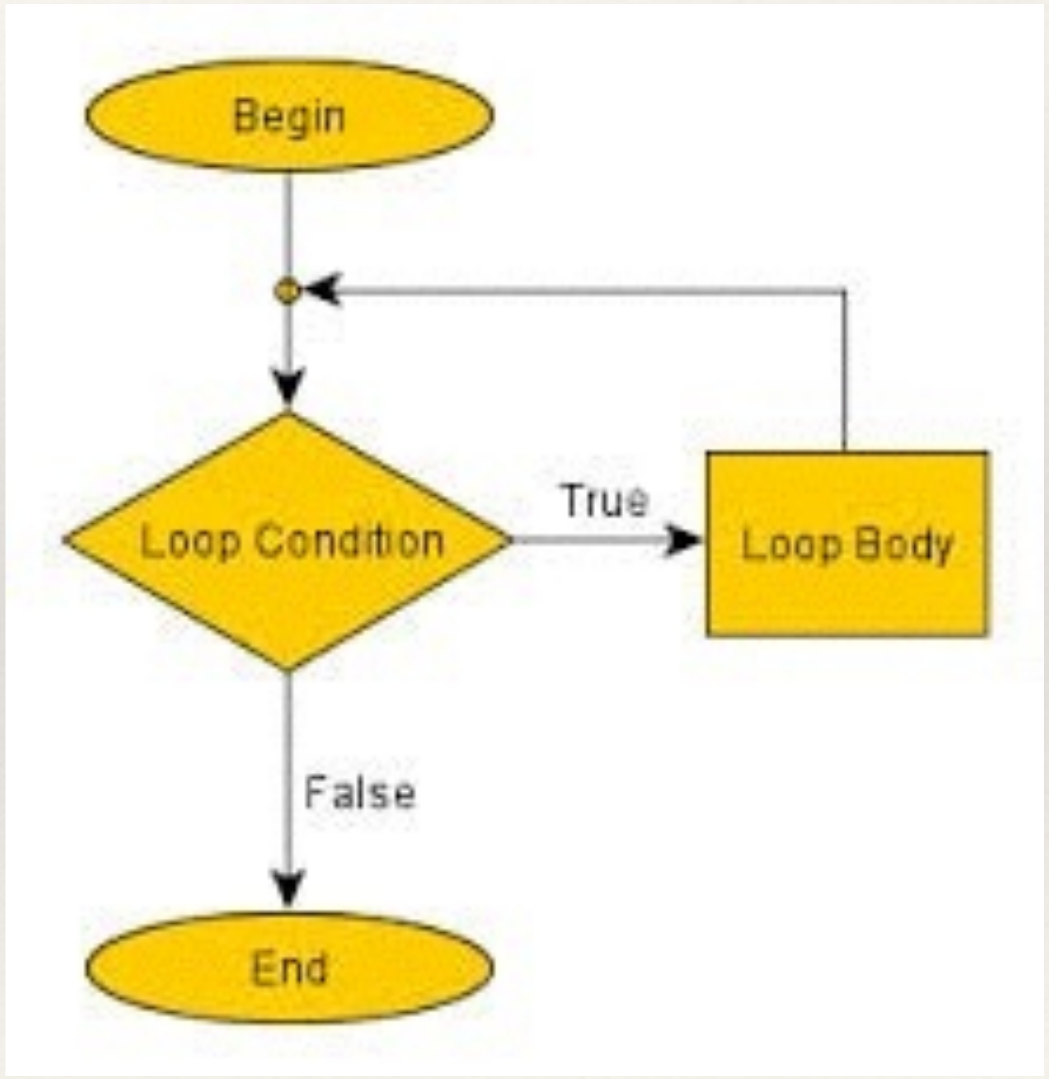
Key Programming concepts: Looping

- Loops are fundamental in all programming languages: and are frequently used in models



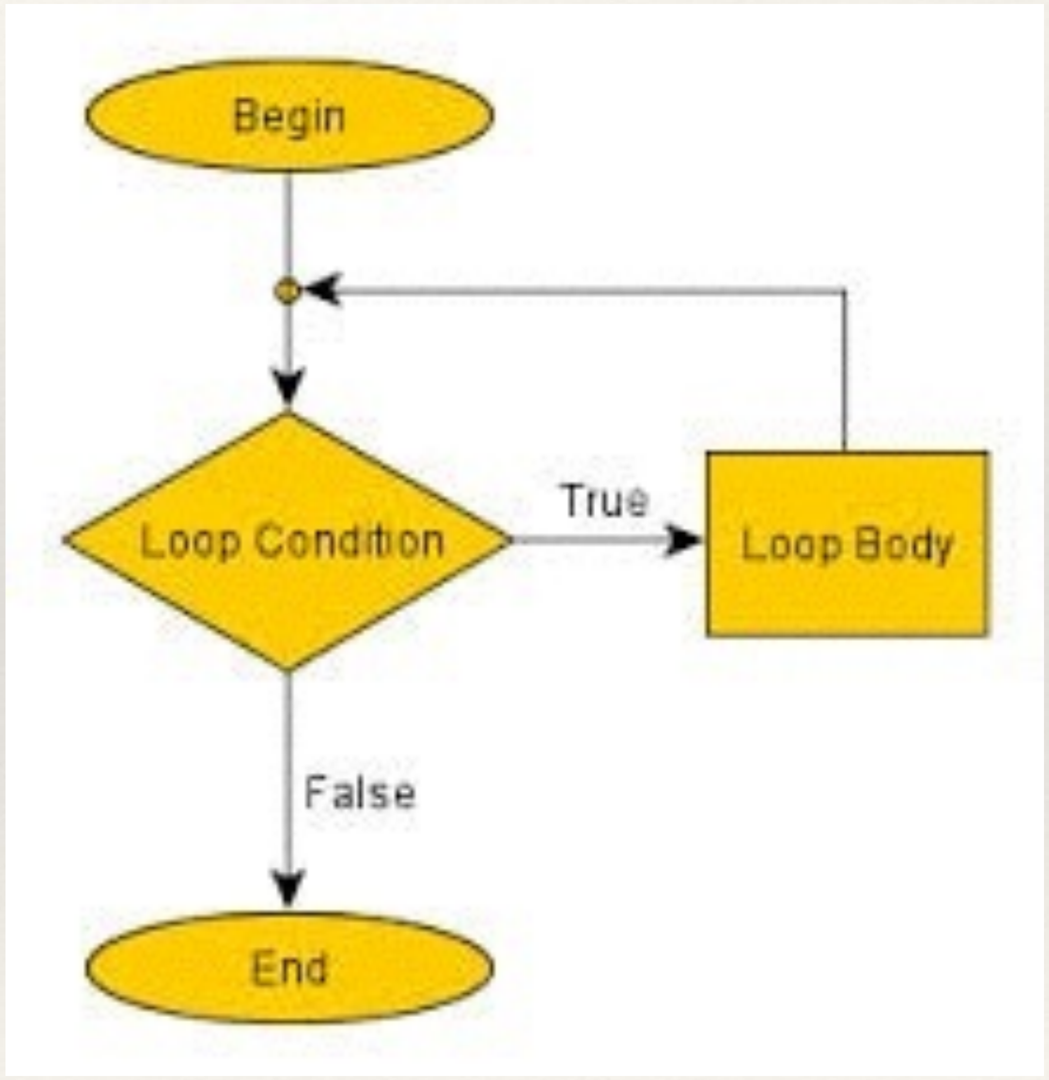
Key Programming concepts: Looping

- Two distinctive reasons for looping
- Apply the same equations (e.g for power generation) over a range of parameter values
- Evolve a variable through time (or space), when the variable's value at the next time step depends on the previous one (e.g growing a population)



Key Programming concepts: Looping

- All loops have this basic structure - repeat statements (loop body) until a condition is true



Key Programming concepts: Looping

- In R, the most commonly used loop is the ***For*** loop
- ***for (i in 1:n){ statements}***
- In “for” loops the i (or whatever variable you want to use as the counter, is automatically incremented each time the loop is gone through; and the looping ends when i (the counter) reaches n
- What is x? alpha? after this loop is run

```
>x=0
> for (alpha in 1:4) { x = x+alpha}
```

```
>
>
> x=0
> for (alpha in 1:4) { x = x+alpha}
>
>
> alpha
[1] 4
> x
[1] 10
```

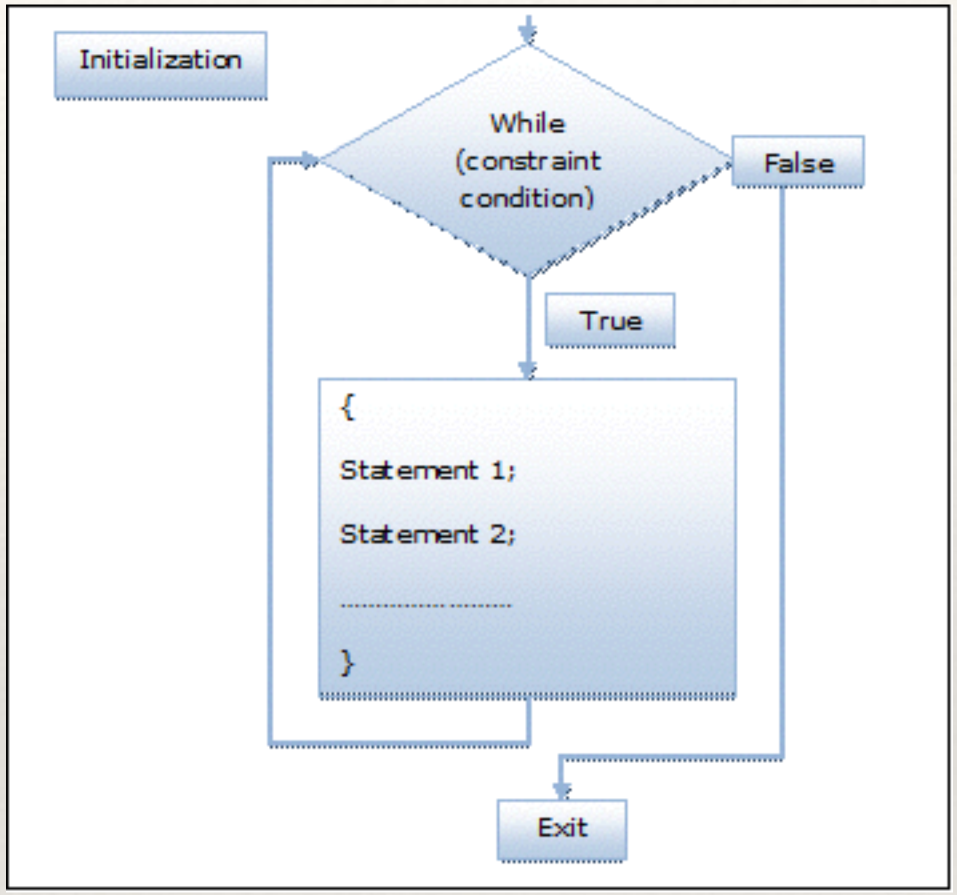
Key Programming concepts: Looping

- Loops can be “nested” - one loop inside the other
- For example, if we want to calculate NPV for a range of different interest rates and a range of damages that may be incurred 10 years in the future
    - using a function called compute_npv
- Steps
    - define inputs (interest rates, damages)
    - define a data structure to store results
    - define function/model (already available)
    - use looping to run model for all inputs and store in data structure

```
>
>
> damages = c(25,33,91,24)
> discount.rates = seq(from=0.01, to=0.04, by=0.005)
> yr=10
> npvs = as.data.frame(matrix(nrow=length(damages), ncol=length(discount.rates)))
> for (i in 1:length(damages)) {
+       for (j in 1:length(discount.rates)) {
+       npvs[i,j]= compute_npv(net=damages[i], dis=discount.rates[j],yr )
+       }
+ }
> npvs
        V1       V2       V3       V4       V5       V6       V7
1 22.63217 21.54168 20.50871 19.52996 18.60235 17.72297 16.88910
2 29.87447 28.43502 27.07149 25.77955 24.55510 23.39432 22.29362
3 82.38111 78.41172 74.65170 71.08905 67.71255 64.51161 61.47634
4 21.72689 20.68001 19.68836 18.74876 17.85825 17.01405 16.21354
> colnames(npvs)=discount.rates
> rownames(npvs)=damages
> npvs
       0.01    0.015     0.02    0.025     0.03    0.035     0.04
25 22.63217 21.54168 20.50871 19.52996 18.60235 17.72297 16.88910
33 29.87447 28.43502 27.07149 25.77955 24.55510 23.39432 22.29362
91 82.38111 78.41172 74.65170 71.08905 67.71255 64.51161 61.47634
24 21.72689 20.68001 19.68836 18.74876 17.85825 17.01405 16.21354
>
```

Key Programming concepts: Looping

- Another useful looping construct is the ***While*** loop
- keep looping until a condition is met
- Useful when you don't know what "n" in the for 1 in to "n" is
- often used in models where you are evolving
  - accumulate something until a threshold is reached (population, energy, biomass?



Key Programming concepts: Looping

- A simple *while* loop example

```
>
>
> alpha = 0
> x = 0
> while (alpha < 100) { alpha = alpha + x; x = x+1}
> x
[1] 15
> alpha
[1] 105
>
```

- alpha = (1+2+3+4+5+6+7+8+9+10+11+12+13+14) = 105

Key Programming concepts: Looping

- A more useful *while* loop example
- A question: if a metal toxin in a lake increases by 1% per year, how many years will it take for the metal level to be greater than 30 units, if toxin is current at 5 units
- there are other ways to do this, but a while loop would do it

why won’t this work?

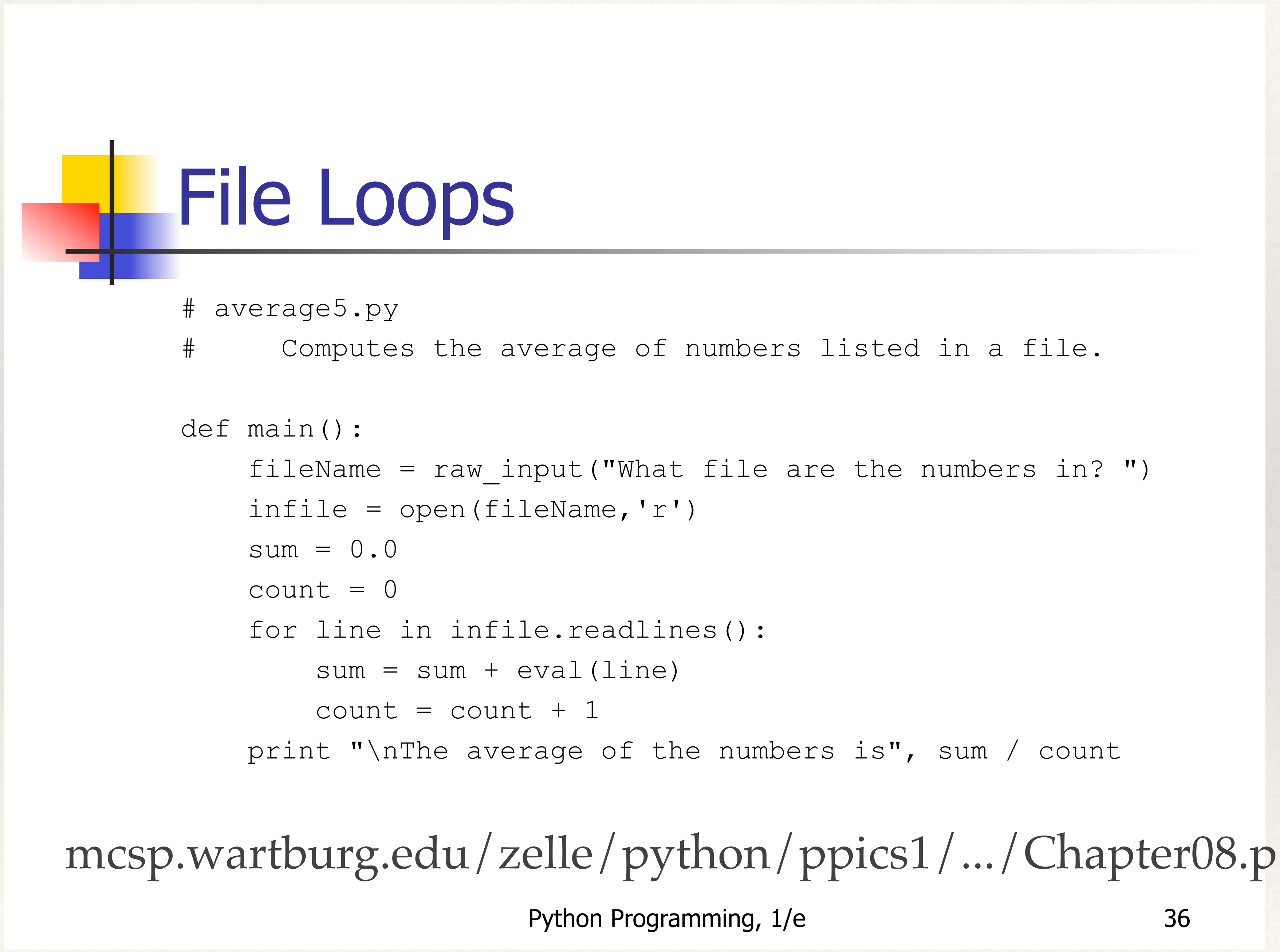
```
> >
> pollutant.level = 5
> while (pollutant.level < 30 ) {
+ pollutant.level = pollutant.level + 0.01* pollutant.level
+ yr = yr + 1
+ }
>
```

Key Programming concepts: Looping

```
> yr=1
> pollutant.level = 5
> while (pollutant.level < 30 ) {
+ pollutant.level = pollutant.level + 0.01* pollutant.level
+ yr = yr + 1
+ }
> > yr
[1] 182
> pollutant.level
[1] 30.2788
```

Key Programming concepts: Looping

- Most programming languages have For and while loops



File Loops

```
# average5.py
#     Computes the average of numbers listed in a file.

def main():
    fileName = raw_input("What file are the numbers in? ")
    infile = open(fileName,'r')
    sum = 0.0
    count = 0
    for line in infile.readlines():
        sum = sum + eval(line)
        count = count + 1
    print "\nThe average of the numbers is", sum / count
```

mcsp.wartburg.edu/zelle/python/ppics1/.../Chapter08.p

Key Programming concepts: Control Structures

- *if*(cond) expression

```
>
> a=4
> b=10
> if(a > b) win = "a"
> if(b > a) win = "b"
> win
[1] "b"
>
```

Conditions:
== equal
> greater than
>= greater than or equal to
< less than
<= less than or equal to
%in% is in a list of something

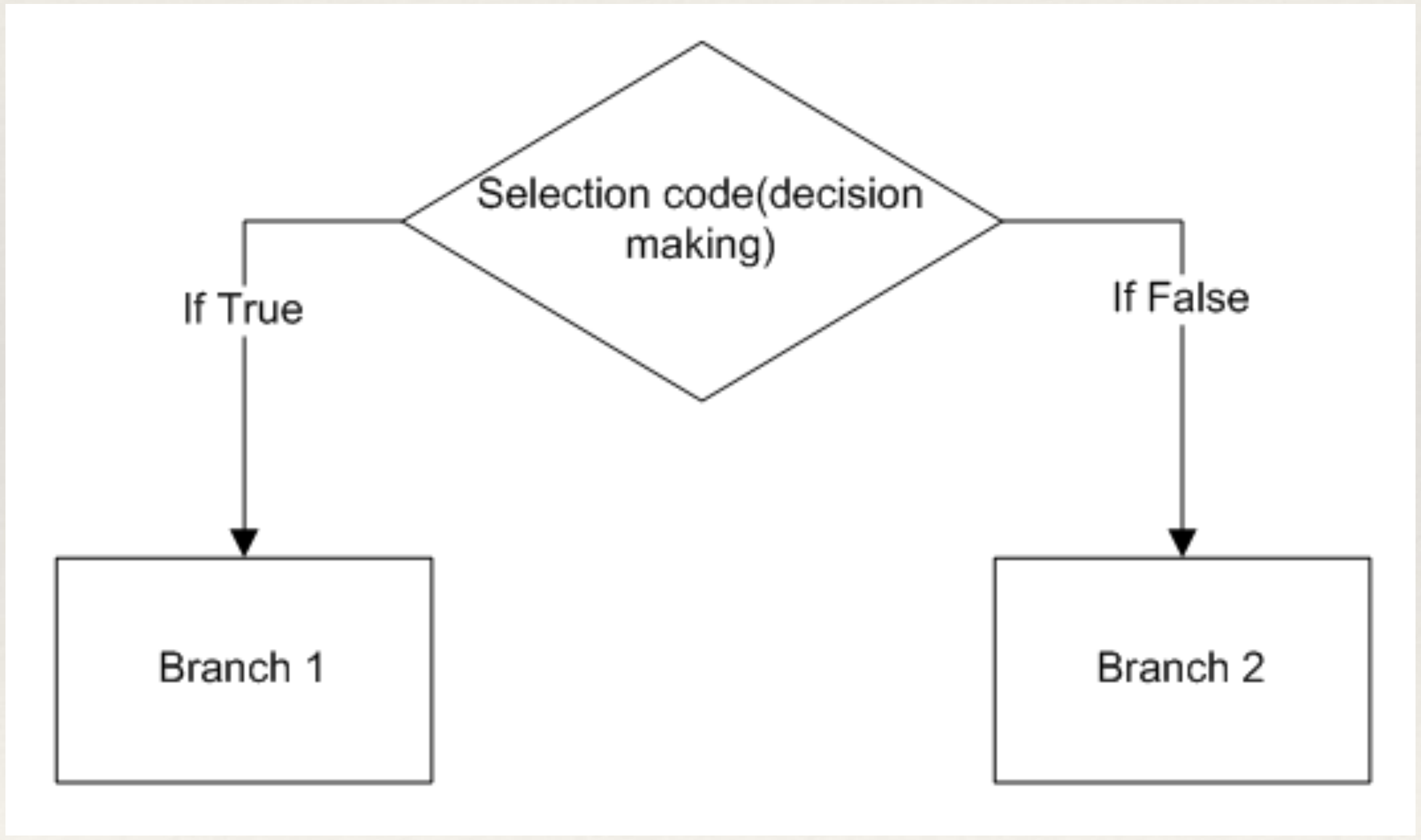
- *ifelse*(cond, true, false)

```
>
> win = ifelse(a > b, "a","b")
> win
[1] "b"
>
>
```

&& AND
| | OR
is.null()

Key Programming concepts: Looping

- Inside functions *if*(cond) {expression} *else* {expression}
- the expression can always have multiple statements using {}
- *If* can be useful for branching in your model



Key Programming concepts: Control Structures

```
#' compute annual yield
#'
#' Function to compute yeild of different fruits as a function of annual temperature and precipitation
#' @param T annual temperature (C)
#' @param P annual precipitation (mm)
#' @param ts slope on temperature
#' @param tp slope on precipitation
#' @param intercept  (kg)
#' @param irr  Y or  N (default N)
#' @return yield in kg


compute_yield = function(T, P, ts, tp, intercept, irr="N") {

if (irr=="N"){
yield = tp*P + ts*T + intercept
}
else {
yield = ts*T + intercept
}

return(yield)
}
```

```
>
> compute_yield(32,200, 0.2, 0.4, 500)
[1] 586.4
> compute_yield(32,200, 0.2, 0.4, 500, "N")
[1] 586.4
> compute_yield(32,200, 0.2, 0.4, 500, "Y")
[1] 506.4
```

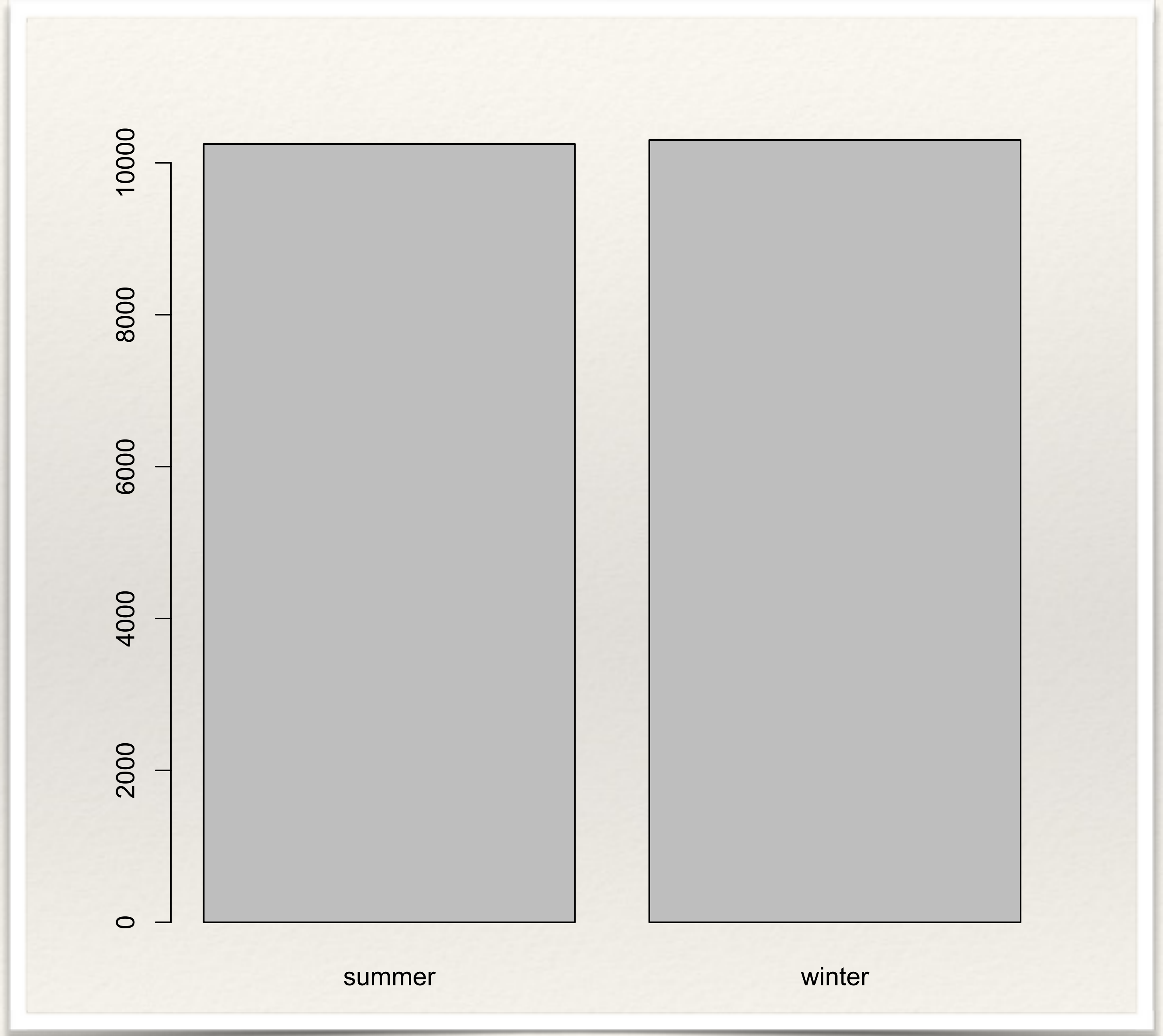
If can also be useful for creating classes of variables

Lets say we want to build a function that will compute mean spring, winter, summer, streamflow - from a dataset that looks something like this

```
> summary(streamflow)
      year          month             day               mm          
 Min.   :1953   Min.   : 1.000   Min.   : 1.00   Min.   : 0.08996  
 1st Qu.:1967   1st Qu.: 4.000   1st Qu.: 8.00   1st Qu.: 0.24290  
 Median :1981   Median : 7.000   Median :16.00   Median : 0.38685  
 Mean   :1981   Mean   : 6.542   Mean   :15.73   Mean   : 1.07800  
 3rd Qu.:1995   3rd Qu.:10.000   3rd Qu.:23.00   3rd Qu.: 0.98961  
 Max.   :2010   Max.   :12.000   Max.   :31.00   Max.   :71.97168  
> 
> head(streamflow)
  year month day        mm
1 1953    10   1 0.2608973
2 1953    10   2 0.2608973
```

```
>
>
> streamflow$season = ifelse(streamflow$month %in%
c(1,2,3,10,11,12),"winter","summer")
> head(streamflow)
  year month day        mm season
1 1953    10   1 0.2608973 winter
2 1953    10   2 0.2608973 winter
3 1953    10   3 0.2608973 winter
4 1953    10   4 0.2608973 winter
5 1953    10   5 0.2608973 winter
6 1953    10   6 0.2608973 winter
> plot(streamflow$season)
Error in plot.window(...) : need finite 'ylim' values
In addition: Warning messages:
1: In xy.coords(x, y, xlabel, ylabel, log) : NAs introduced by coercion
2: In min(x) : no non-missing arguments to min; returning Inf
3: In max(x) : no non-missing arguments to max; returning -Inf
> plot(as.factor(streamflow$season))
>
```

```
>

> plot(as.factor(streamflow$season))
>
```



```
#' @param str data frame with columns month and mm (mm is daily streamflow)
compute_seasonal_meanflow = function(str) {

str$season = ifelse( str$month %in% c(1,2,3,10,11,12),"winter","summer")

tmp = subset(str, str$season=="winter")
mean.winter = mean(tmp$mm)

tmp = subset(str, str$season=="summer")
mean.summer = mean(tmp$mm)
return(list(summer=mean.summer, winter=mean.winter))
}
```

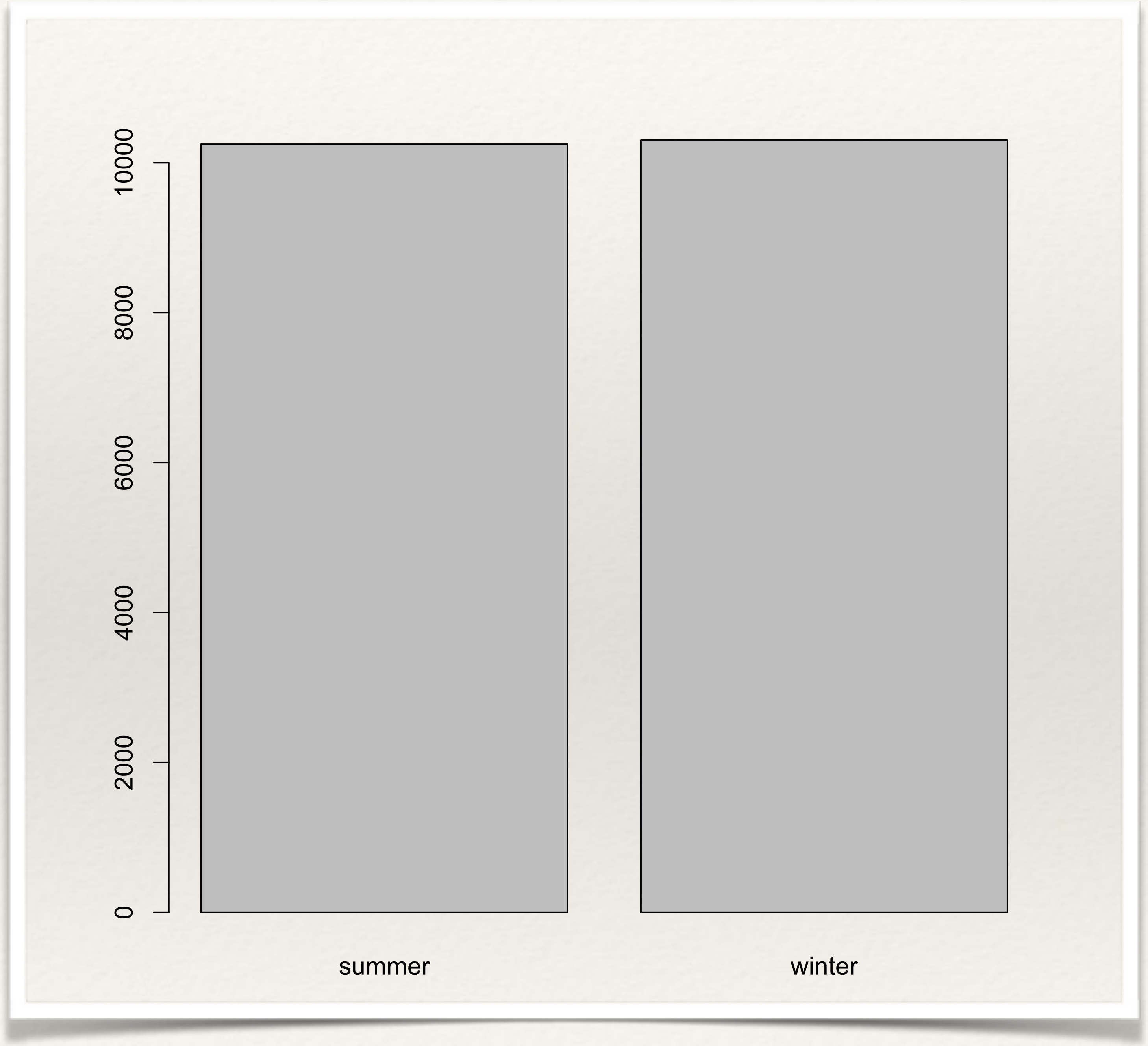
```
> compute_seasonal_meanflow(streamflow)
$summer
[1] 1.538304

$winter
[1] 0.6200728

>
```

Key Programming concepts: Control Structures

If can also be used to choose what you return from a function

```
compute_seasonal_flow = function(str,kind) {

str$season = ifelse( str$month %in% c(1,2,3,10,11,12),"winter","summer")

tmp = subset(str, str$season=="winter")
if(kind=="mean") winter= mean(tmp$mm)
if(kind=="max") winter= max(tmp$mm)
if(kind=="min") winter=min(tmp$mm)

tmp = subset(str, str$season=="summer")
if(kind=="mean") summer= mean(tmp$mm)
if(kind=="max") summer= max(tmp$mm)
if(kind=="min") summer=min(tmp$mm)


return(list(summer=summer, winter=winter))
}
```

```
>

> plot(as.factor(streamflow$season))
>
```



```r
#' @param str data frame with columns month and mm (mm is daily streamflow)
compute_seasonal_meanflow = function(str) {

str$season = ifelse( str$month %in% c(1,2,3,10,11,12),"winter","summer")

tmp = subset(str, str$season=="winter")
mean.winter = mean(tmp$mm)

tmp = subset(str, str$season=="summer")
mean.summer = mean(tmp$mm)
return(list(summer=mean.summer, winter=mean.winter))
}
```

```
> compute_seasonal_meanflow(streamflow)
$summer
[1] 1.538304

$winter
[1] 0.6200728

>
```

Key Programming concepts: Control Structures

If can also be used to choose what you return from a function

```
compute_seasonal_flow = function(str,kind) {

str$season = ifelse( str$month %in% c(1,2,3,10,11,12),"winter","summer")

tmp = subset(str, str$season=="winter")
if(kind=="mean") winter= mean(tmp$mm)
if(kind=="max") winter= max(tmp$mm)
if(kind=="min") winter=min(tmp$mm)

tmp = subset(str, str$season=="summer")
if(kind=="mean") summer= mean(tmp$mm)
if(kind=="max") summer= max(tmp$mm)
if(kind=="min") summer=min(tmp$mm)


return(list(summer=summer, winter=winter))
}
```

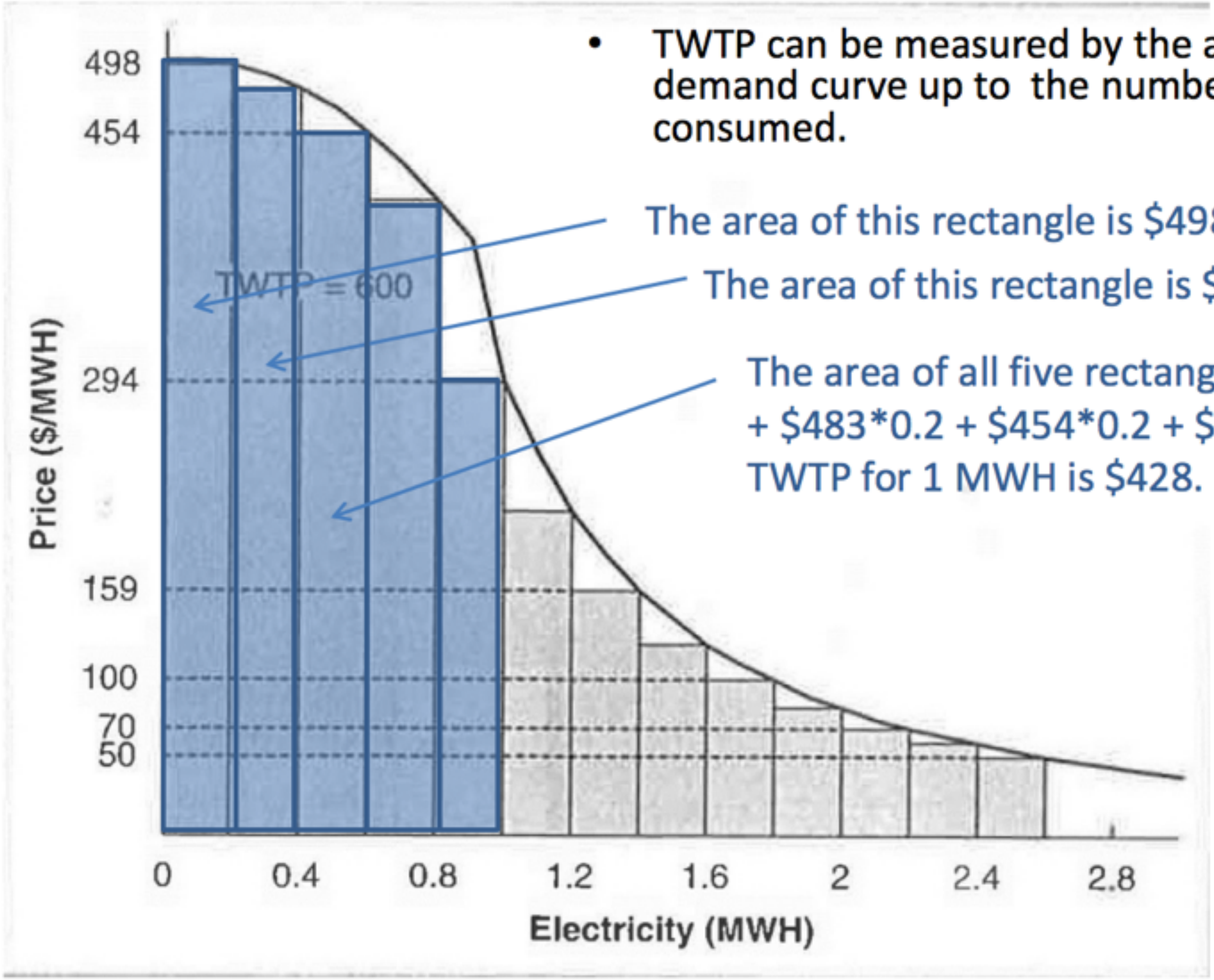
Key Programming concepts: Control Structures

If can also be used to choose what you return from a function

```
>
>
> compute_seasonal_flow(streamflow,"mean")
$summer
[1] 1.538304

$winter
[1] 0.6200728

> compute_seasonal_flow(streamflow,"max")
$summer
[1] 23.66069

$winter
[1] 71.97168
```

Measuring TWTP

- TWTP can be measured by the area under a demand curve up to the number of units consumed.



The area of this rectangle is $498*0.2

The area of this rectangle is $483*0.2

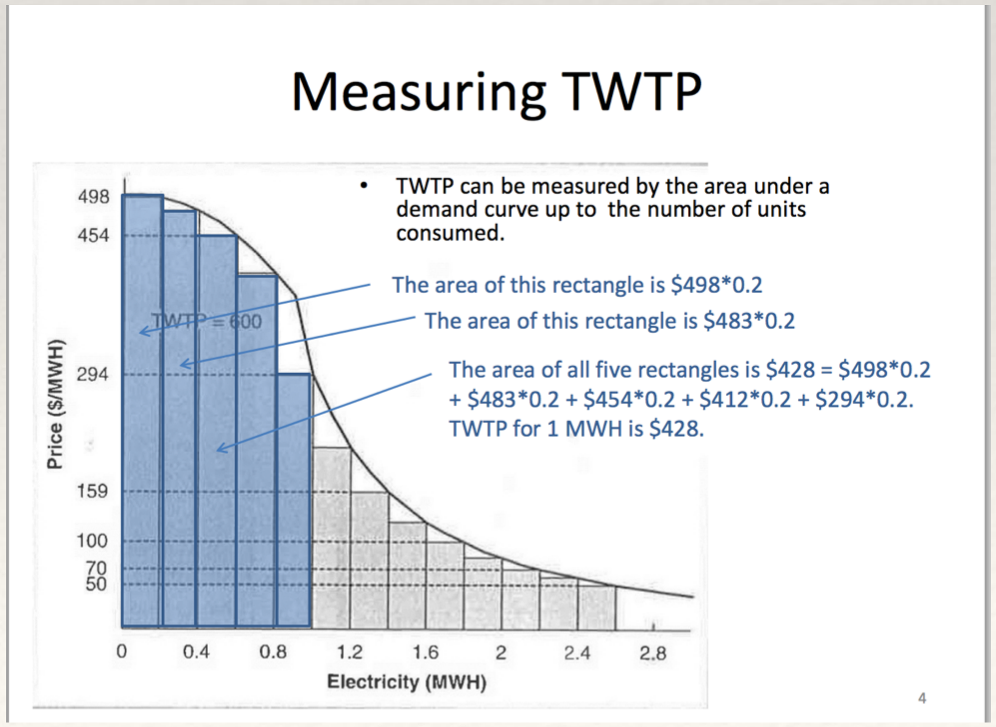
The area of all five rectangles is $428 = $498*0.2 + $483*0.2 + $454*0.2 + $412*0.2 + $294*0.2. TWTP for 1 MWH is $428.

Example

- Lets say our demand curve is as follows:
- Electricity = c(0.1, 0.2, 0.4, 0.5, 0.6) MW
- Marginal willingness to pay = c(300,250,200,50, 20) $/MW
- Write a function that takes as input a data frame with values for marginal willingness to pay for different electricity values and returns total willingness to pay for a given electricity requirement (in MW)
- Take as input to the function a data frame called curve that has two columns elect, mwtop (electricity and marginal willingness to pay), and the electricity requirement

Key Programming concepts: Control Structures

```
compute_TWP = function(curve, req) {


total = 0
i=1
prev.elect = 0
while (( curve$elect[i] <= req) && (i < length(curve$elect))) {
total = total + (curve$elect[i]-prev.elect)*curve$mwtop[i]
prev.elect = curve$elect[i]
i = i+1
}

return(total)
}
```



Measuring TWTP

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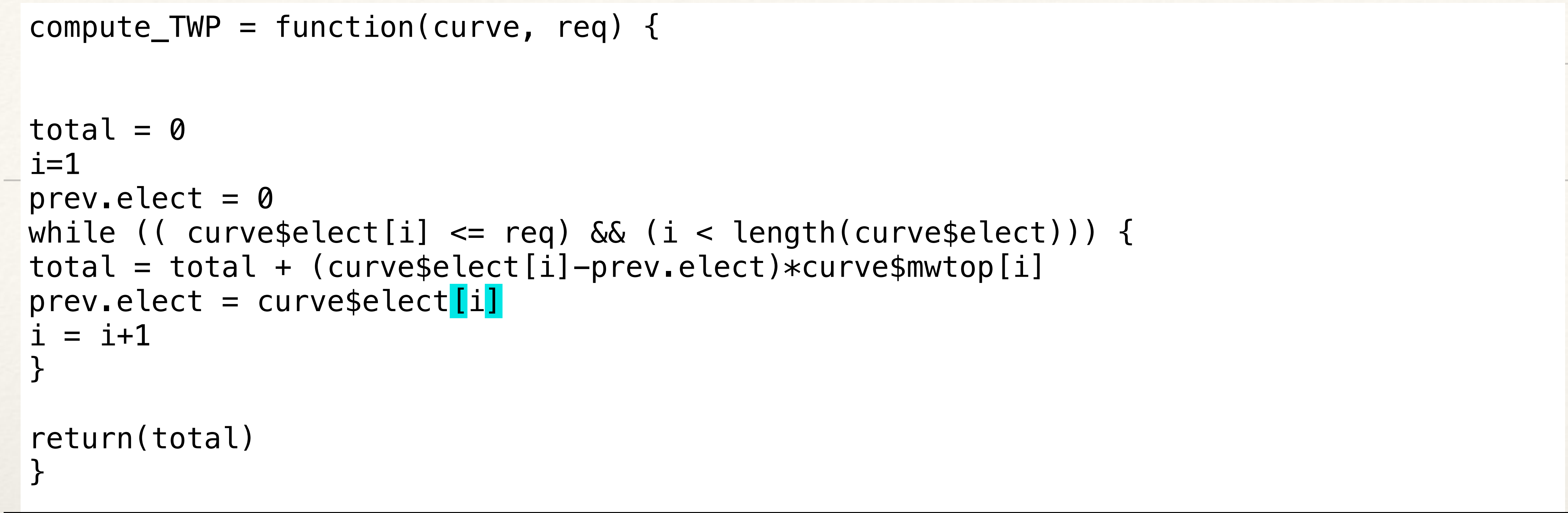


```r
compute_TWP = function(curve, req) {


total = 0
i=1
prev.elect = 0
while (( curve$elect[i] <= req) && (i < length(curve$elect))) {
total = total + (curve$elect[i]-prev.elect)*curve$mwtop[i]
prev.elect = curve$elect[i]
i = i+1
}

return(total)
}
```

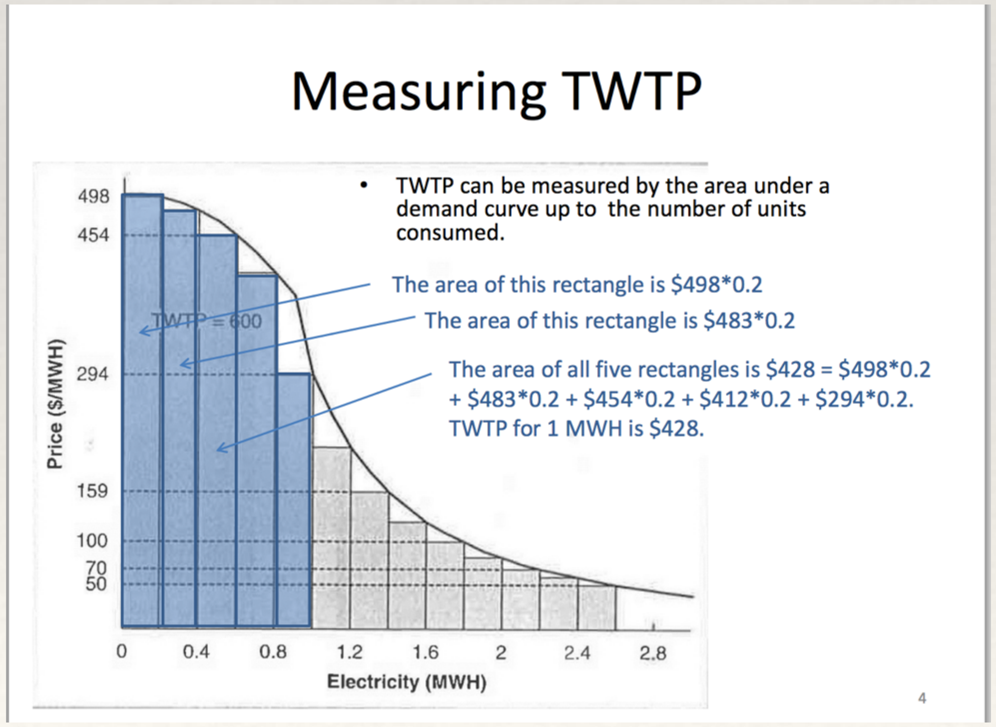
```
>
> example.curve = data.frame(elect = c(0.1,0.2,0.4,0.5,0.6), mwtop=c(300,250,200,50,20))
> example.curve
  elect mwtop
1   0.1   300
2   0.2   250
3   0.4   200
4   0.5    50
5   0.6    20
> compute_TWP(example.curve, req=0.2)
[1] 55
> (0.1*300)+(0.1*250)
[1] 55
>
```

```
compute_TWP = function(curve, req) {


total = 0
i=1
prev.elect = 0
while (( curve$elect[i] <= req) && (i < length(curve$elect))) {
total = total + (curve$elect[i]-prev.elect)*curve$mwtop[i]
prev.elect = curve$elect[i]
i = i+1
}

return(total)
}
```

```
> example.curve
  elect mwtop
1   0.1   300
2   0.2   250
3   0.4   200
4   0.5    50
5   0.6    20
> > compute_TWP(example.curve, req=0.7)
[1] 100
> compute_TWP(example.curve, req=0.6)
[1] 100
> compute_TWP(example.curve, req=0.9)
[1] 100
> compute_TWP(example.curve, req=0.3)
[1] 55
> compute_TWP(example.curve, req=0.4)
[1] 95
> >
```



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The area of this rectangle is $498*0.2

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Example

- If the user asks for an electricity requirement beyond what was described by the demand curve, return NA from the function
- How would you implement that

```
compute_TWP = function(curve, req) {


total = 0
i=1
prev.elect = 0
while (( curve$elect[i] <= req) && (i < length(curve$elect))) {
total = total + (curve$elect[i]-prev.elect)*curve$mwtop[i]
prev.elect = curve$elect[i]
i = i+1
}

return(total)
}
```

Example

```
compute_TWP = function(curve, req) {


highest.elect = max(curve$elect)
if (req <= highest.elect) {
total = 0
i=1
prev.elect = 0
while (( curve$elect[i] <= req) && (i < length(curve$elect))) {
total = total + (curve$elect[i]-prev.elect)*curve$mwtop[i]
prev.elect = curve$elect[i]
i = i+1
}
}
else { total="NA" }

return(total)
}
```

```
> example.curve
  elect mwtop
1   0.1   300
2   0.2   250
3   0.4   200
4   0.5    50
5   0.6    20


>
> compute_TWP(example.curve, req=0.4)
[1] 95
> compute_TWP(example.curve, req=0.9)
[1] "NA"
```

Assignment 2

In your group, write a simple function (that involves at least two data types and a control structure)

Enter this function in your organization's github space

Read/create some data to test your function

Also include that in github

Submit the link the repository