

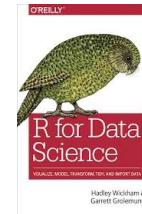
# System Dynamics Modelling using R

Prof. Jim Duggan,  
School of Computer Science  
National University of Ireland Galway.

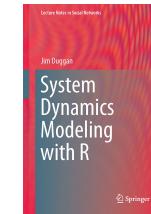
<https://github.com/JimDuggan/SDMR>

# Lecture Overview

- Introduction to R and the **tidyverse**
  - Visualisation - **ggplot2**
  - Transformation – **dplyr** and **purrr**
- Using R with System Dynamics, 3 Examples
  - deSolve
  - readsdr
  - Exploring sensitivity runs



<https://r4ds.had.co.nz>



<https://github.com/JimDuggan/SDMR>

## NOTES AND INSIGHTS

### **Input and output data analysis for system dynamics modelling using the tidyverse libraries of R**

Jim Duggan\* 

*Syst. Dyn. Rev.* **34**, 438–461 (2018)

## NOTES AND INSIGHTS

### **Using R libraries to facilitate sensitivity analysis and to calibrate system dynamics models**

Jim Duggan\* 

*Syst. Dyn. Rev.* **35**, 255–282 (2019)

# Jim Duggan



- Lecturer in:
  - Programming (R, MATLAB),
  - Modelling & Simulation
- Research interests:
  - System Dynamics
  - Data Science
  - Public Health Modelling
- Public Health Project Work
  - Infectious Disease Modelling (COVID-19)
  - PANDEM-2 Project
  - Contact Tracing (WHO)
  - Suicide Prevention (HSE, School of Psychology)

[Article](#) [Cited By \(6\)](#) [Tweetations \(14\)](#) [Metrics](#)

[Review](#)

Mobile Health Technology Interventions for Suicide Prevention: Systematic Review



Ruth Melia<sup>1,2</sup>, DClinPsych ; Kady Francis<sup>1</sup>, MSc ; Emma Hickey<sup>3</sup>, MSc ; John Bogue<sup>1</sup>, DClinPsych

Jim Duggan<sup>1</sup>, PhD ; Mary O'Sullivan<sup>1</sup>, MA ; Karen Young<sup>4</sup>, PhD

<sup>1</sup>School of Psychology, National University of Ireland Galway, Galway, Ireland

<sup>2</sup>Psychology Department, Health Service Executive Mid-West, Ennis, Ireland

<sup>3</sup>Psychology Department, Health Service Executive Mid-West, Limerick, Ireland

<sup>4</sup>Discipline of Information Technology, National University of Ireland Galway, Galway, Ireland

<sup>5</sup>Insight-Centre, Discipline of Information Technology, National University of Ireland Galway, Galway, Ireland

[Review](#) [Infodemiology and Infoveillance](#) [Infoveillance, Infodemiology, Digital Disease Surveillance, Infodemic Management](#)

[Article](#) [Cited By \(6\)](#) [Tweetations \(29\)](#) [Metrics](#)

[Review](#)

The Application of Internet-Based Sources for Public Health Surveillance (Infoveillance): Systematic Review

Joana M Barros<sup>1,2</sup>, MSc ; Jim Duggan<sup>2</sup>, PhD ; Dietrich Rebholz-Schuhmann<sup>3</sup>, PhD

<sup>1</sup>Insight Centre for Data Analytics, National University of Ireland Galway, Galway, Ireland

<sup>2</sup>School of Computer Science, National University of Ireland Galway, Galway, Ireland

<sup>3</sup>ZB MED - Information Centre for Life Sciences, University Cologne, Cologne, Germany

Epidemics 33 (2020) 100415



Contents lists available at [ScienceDirect](#)

Epidemics

journal homepage: [www.elsevier.com/locate/epidem](http://www.elsevier.com/locate/epidem)



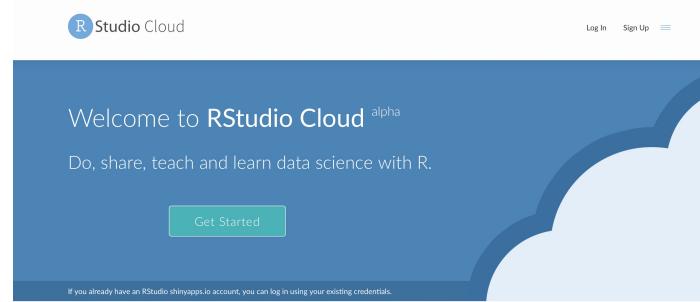
An evaluation of Hamiltonian Monte Carlo performance to calibrate age-structured compartmental SEIR models to incidence data

Jair Andrade<sup>1</sup>, Jim Duggan

Data Science Institute and School of Computer Science, National University of Ireland Galway, Ireland

# (1) R and the tidyverse

- R's *mission* is to enable the best and most thorough exploration of data possible (Chambers 2008).
- It is a dialect of the S language, developed at Bell Laboratories
- ACM noted that S “*will forever alter the way people analyze, visualize, and manipulate data*”



Welcome to RStudio Cloud alpha

Do, share, teach and learn data science with R.

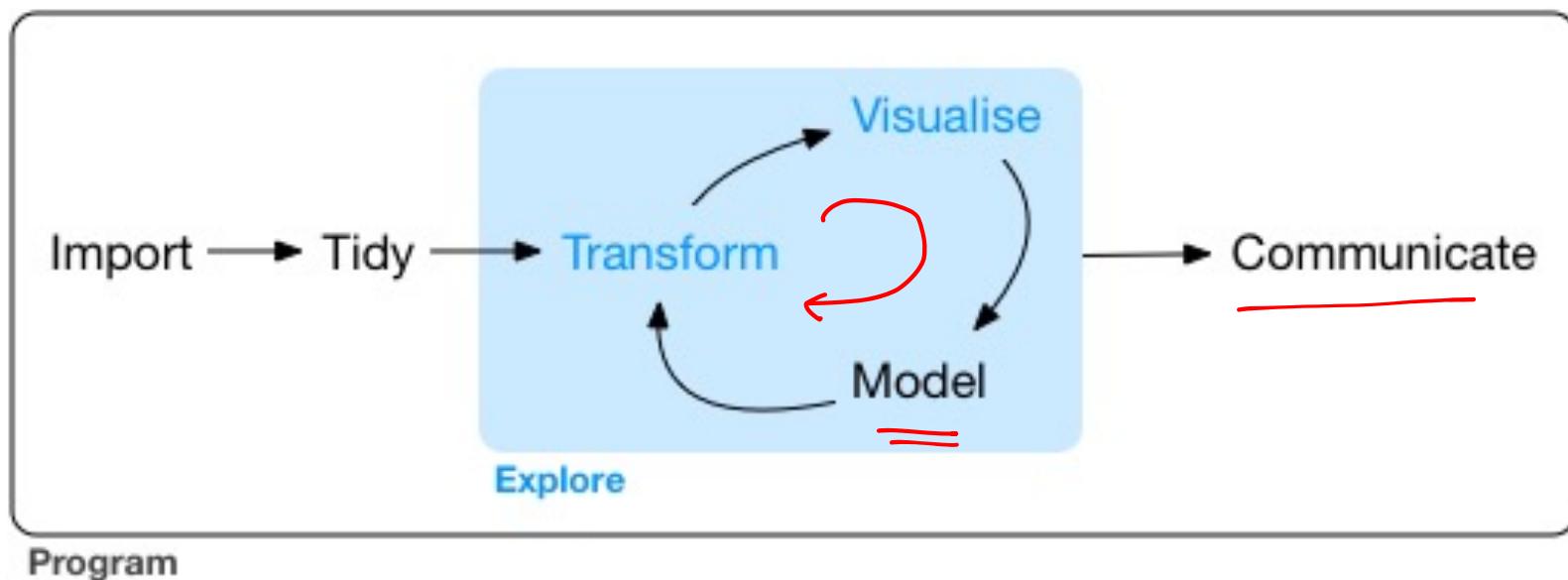
Get Started

If you already have an RStudio shinyapps.io account, you can log in using your existing credentials.

```
1 # We use this for processing the answer
2 # In programming, we "stand on the shoulders of giants"
3 library(stringi)
4
5 # This gets the input from the user.
6 # The result is stored in a variable
7 # Variables are important in programming!
8 name <- readline(prompt="Enter a name: ")
9
10 # We call a specially designed function to get the answer
11 # In R, we call functions all the time
12 # A function is a "mini-program"
13 ans <- stri_reverse(name)
14
15 # After all this work, we output the result
16 cat("The reverse of ", name, "is ===>", ans)
```

# Data Science Process and Workflow

“Data exploration is the art of looking at your data, rapidly generating hypotheses, quickly testing them, then repeating again and again and again.” (Wickham and Grolemund 2017).



# Data Frames/Tibbles – aimsir17

- The most common way of storing data in R
- A two-dimensional structure, with rows (observations) and columns (variables)

```
> observations
# A tibble: 219,000 x 12
  station year month day hour date          rain temp rhum
  <chr>   <dbl> <dbl> <int> <int> <dttm>     <dbl> <dbl> <dbl>
1 ATHENRY 2017    1     1     0 2017-01-01 00:00:00     0   5.2   89
2 ATHENRY 2017    1     1     1 2017-01-01 01:00:00     0   4.7   89
3 ATHENRY 2017    1     1     2 2017-01-01 02:00:00     0   4.2   90
4 ATHENRY 2017    1     1     3 2017-01-01 03:00:00     0.1  3.5   87
5 ATHENRY 2017    1     1     4 2017-01-01 04:00:00     0.1  3.2   89
6 ATHENRY 2017    1     1     5 2017-01-01 05:00:00     0   2.1   91
7 ATHENRY 2017    1     1     6 2017-01-01 06:00:00     0   2     89
8 ATHENRY 2017    1     1     7 2017-01-01 07:00:00     0   1.7   89
9 ATHENRY 2017    1     1     8 2017-01-01 08:00:00     0   1     91
10 ATHENRY 2017   1     1     9 2017-01-01 09:00:00     0   1.1   91
# ... with 218,990 more rows, and 3 more variables: msl <dbl>, wdsp <dbl>,
# wddir <dbl>
```

# Tidy Data - Overview

- The tidy data standard is designed to:
  - Facilitate initial exploration and analysis of data
  - Simplify the development of data analysis tools that work well together
- Rules
  - Each variable must have its own column
  - Each observation must have its own row
  - Each value must have its own cell

```
> observations
# A tibble: 219,000 x 12
  station year month   day hour date       rain    temp  rhum
  <chr>   <dbl> <dbl> <int> <int> <dttm>     <dbl> <dbl> <dbl>
1 ATHENRY 2017     1     1     0 2017-01-01 00:00:00     0    5.2   89
2 ATHENRY 2017     1     1     1 2017-01-01 01:00:00     0    4.7   89
3 ATHENRY 2017     1     1     2 2017-01-01 02:00:00     0    4.2   90
4 ATHENRY 2017     1     1     3 2017-01-01 03:00:00    0.1    3.5   87
5 ATHENRY 2017     1     1     4 2017-01-01 04:00:00    0.1    3.2   89
6 ATHENRY 2017     1     1     5 2017-01-01 05:00:00     0    2.1   91
7 ATHENRY 2017     1     1     6 2017-01-01 06:00:00     0    2     89
8 ATHENRY 2017     1     1     7 2017-01-01 07:00:00     0    1.7   89
9 ATHENRY 2017     1     1     8 2017-01-01 08:00:00     0    1     91
10 ATHENRY 2017    1     1     9 2017-01-01 09:00:00    0    1.1   91
# ... with 218,990 more rows, and 3 more variables: msl <dbl>, wdsp <dbl>,
# wddir <dbl>
```

In a tidy  
data set:



Each variable is saved  
in its own column

&



Each observation is  
saved in its own row

[https://rpubs.com/bradleyboehmke/data\\_wrangling](https://rpubs.com/bradleyboehmke/data_wrangling)

# Data Visualisation with **ggplot2**

“The simple graph has brought more information to the data analyst’s mind than any other device.” – John Tukey

```
> dt <- ggplot2::mpg  
>  
> dt  
# A tibble: 234 × 11  
   manufacturer     model    displ  year   cyl  trans  drv   cty   hwy   fl class  
   <chr>       <chr>    <dbl> <int> <int> <chr> <chr> <int> <int> <chr> <chr>  
 1 audi         a4      1.8  1999     4 auto(l5)   f    18    29   p compact  
 2 audi         a4      1.8  1999     4 manual(m5) f    21    29   p compact  
 3 audi         a4      2.0  2008     4 manual(m6) f    20    31   p compact  
 4 audi         a4      2.0  2008     4 auto(av)   f    21    30   p compact  
 5 audi         a4      2.8  1999     6 auto(l5)   f    16    26   p compact  
 6 audi         a4      2.8  1999     6 manual(m5) f    18    26   p compact  
 7 audi         a4      3.1  2008     6 auto(av)   f    18    27   p compact  
 8 audi a4 quattro 1.8  1999     4 manual(m5) 4    18    26   p compact  
 9 audi a4 quattro 1.8  1999     4 auto(l5)   4    16    25   p compact  
10 audi a4 quattro 2.0  2008     4 manual(m6) 4    20    28   p compact  
# ... with 224 more rows
```



# Fuel Economy Data Set (ggplot2::mpg)

This dataset contains a subset of the fuel economy data that the EPA makes available on <http://fueleconomy.gov>. It contains only models which had a new release every year between 1999 and 2008 - this was used as a proxy for the popularity of the car.

<b>manufacturer</b>	manufacturer	<b>drv</b>	f = front-wheel drive, r = rear wheel drive, 4 = 4wd
<b>model</b>	model name	<b>cty</b>	city miles per gallon
<b>displ</b>	engine displacement, in litres	<b>hwy</b>	highway miles per gallon
<b>year</b>	year of manufacture	<b>fl</b>	fuel type
<b>cyl</b>	number of cylinders	<b>class</b>	“type” of car
<b>trans</b>	type of transmission		

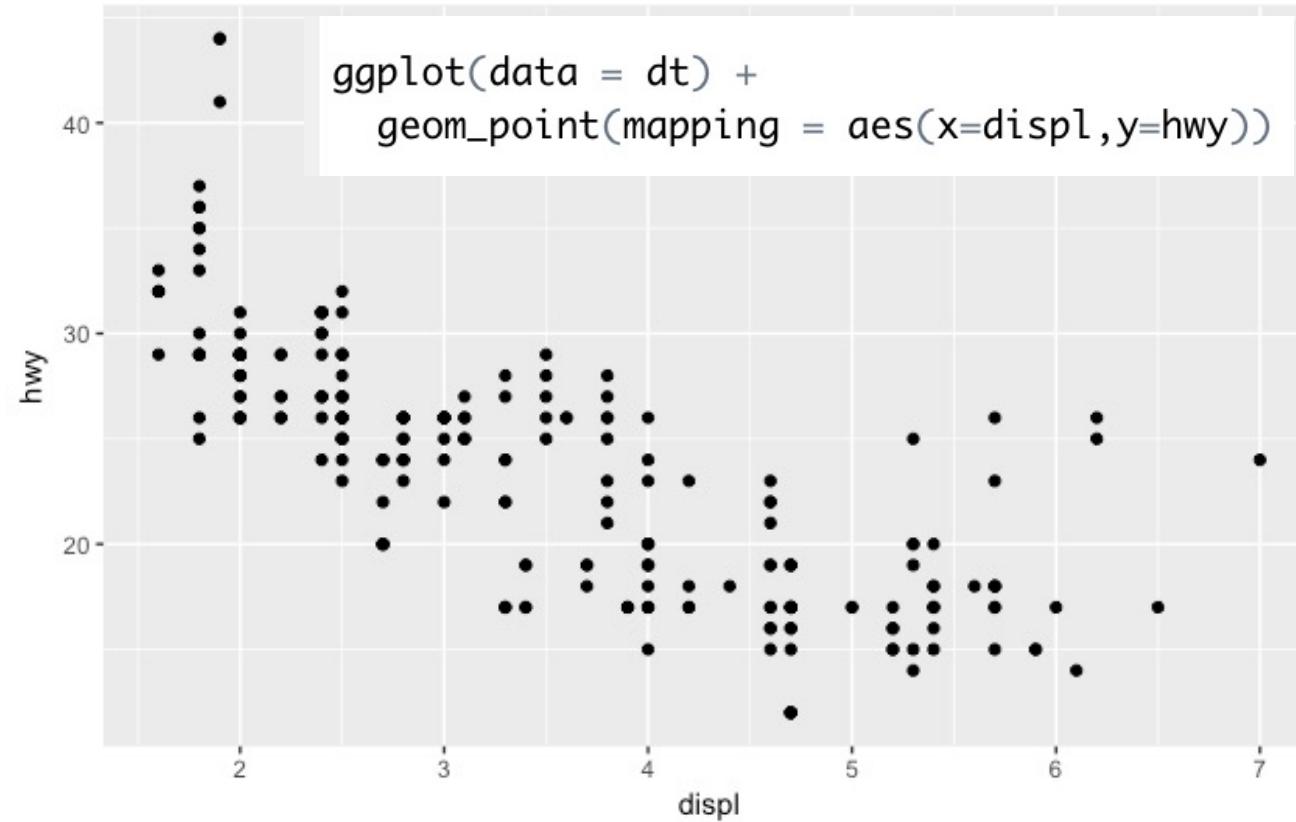
# Selecting data

```
> dt
# A tibble: 234 × 11
  manufacturer model displ year cyl trans drv cty hwy fl class
  <chr>     <chr> <dbl> <int> <int> <chr> <chr> <int> <int> <chr> <chr>
1 audi       a4    1.8  1999     4 auto(l5) f    18   29   p  compact
2 audi       a4    1.8  1999     4 manual(m5) f    21   29   p  compact
3 audi       a4    2.0  2008     4 manual(m6) f    20   31   p  compact
4 audi       a4    2.0  2008     4 auto(av)   f    21   30   p  compact
5 audi       a4    2.8  1999     6 auto(l5)  f    16   26   p  compact
```

- Among the variables are:
  - **displ**, a car's engine size in litres
  - **hwy**, a car's fuel efficiency on the highway in miles per gallon



# Creating a ggplot



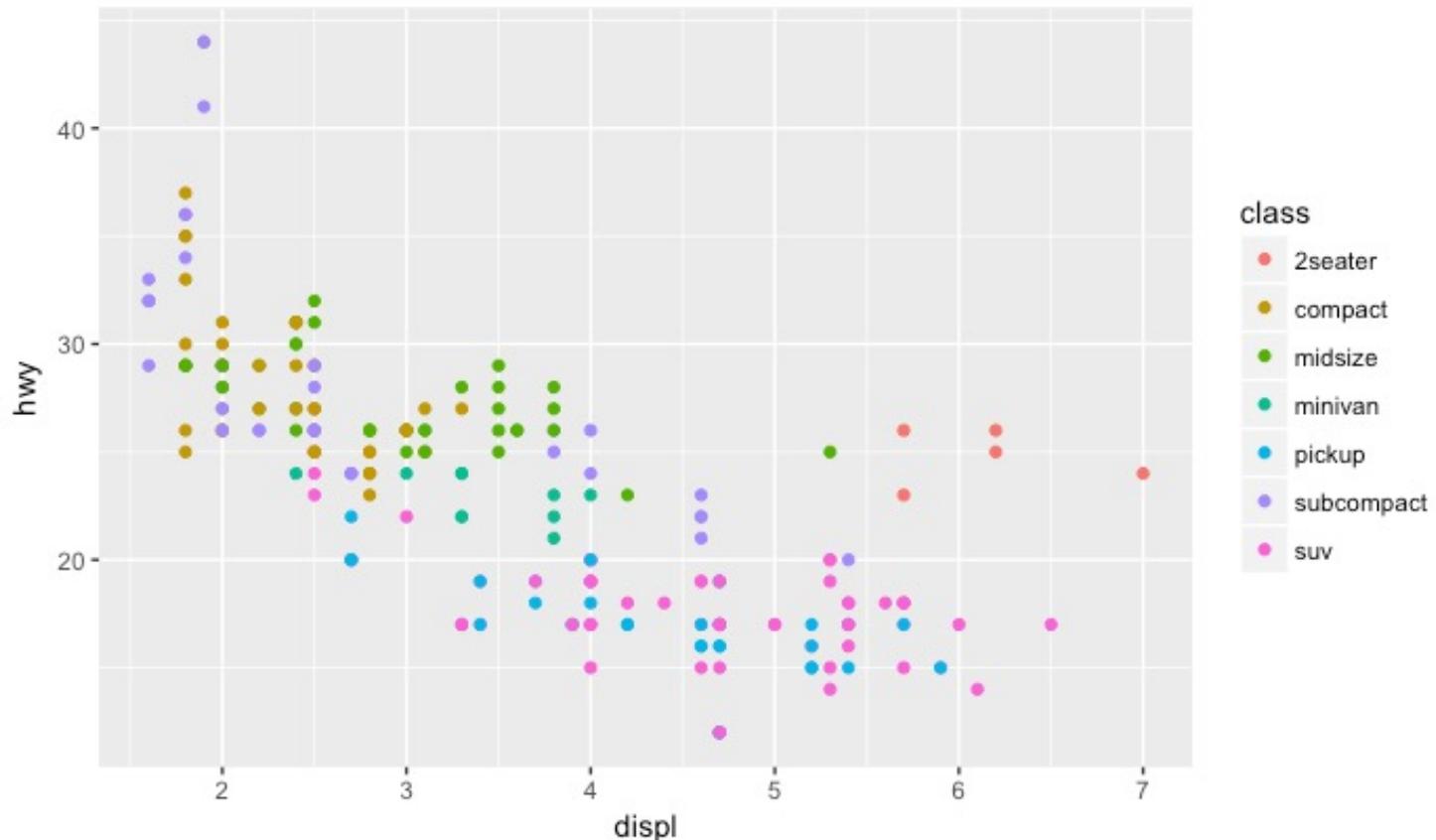
# Aesthetic Mappings

“The greatest value of a picture is when it forces us to notice what we never expected to see” – John Tukey

```
> unique(dt$class)
[1] "compact"      "midsize"      "suv"          "2seater"      "minivan"
[6] "pickup"       "subcompact"
```

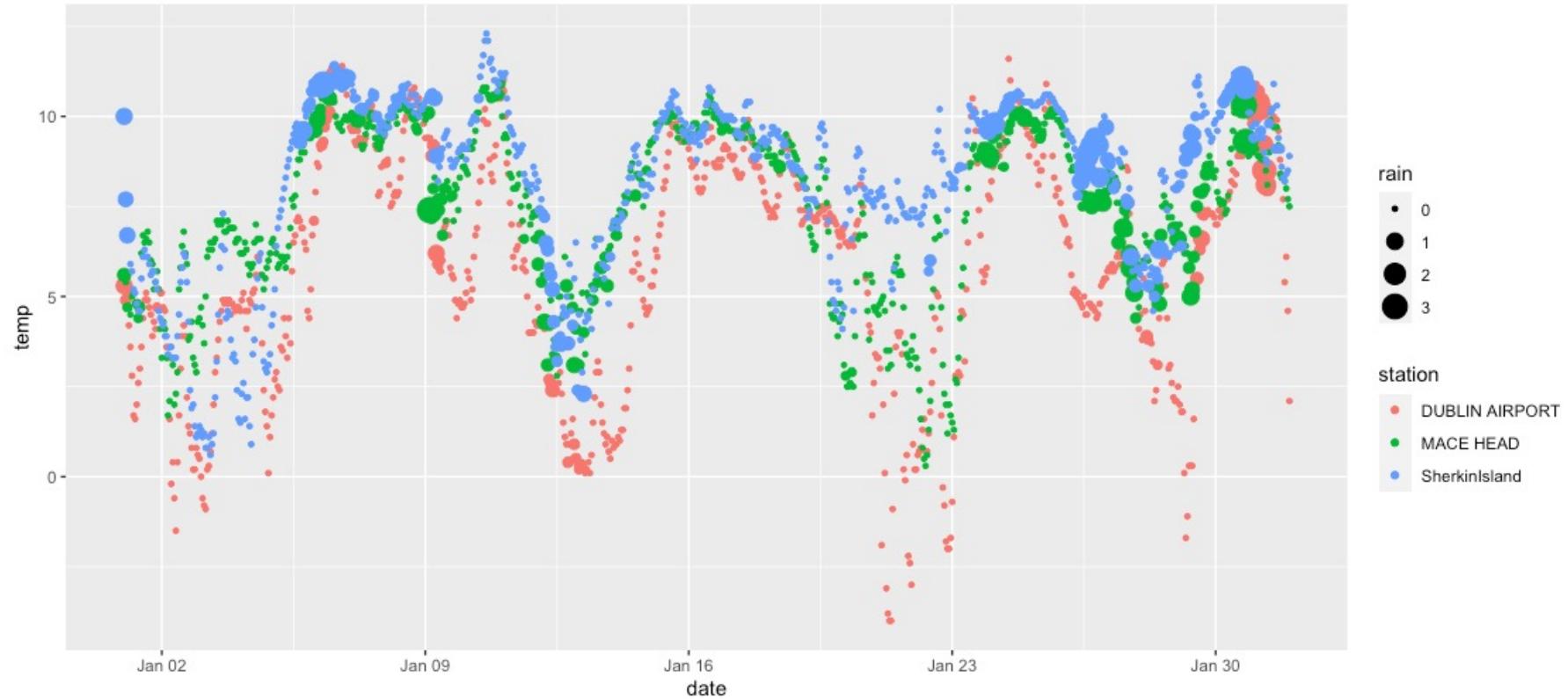
- A third variable can be added to a 2-D plot by mapping it to an aesthetic.
- An aesthetic is a visual property of the plot's objects.
- An aesthetic's *level* could be colour, size or shape.

```
ggplot(data = dt) +
  geom_point(mapping = aes(x=displ,y=hwy,colour=class))
```



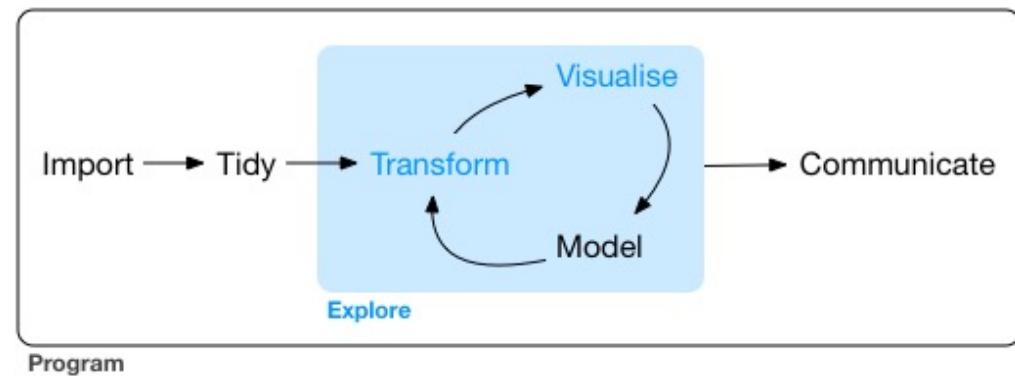
# Challenge

- Generate the following graph from aimsir17 (January)



# Data Transformation

- Visualisation is an important tool for insight generation, but it's rare that you get the data in exactly the right form you need (Wickham and Grolemund 2017)
  - Create new variables
  - Create summaries
  - Order data
- **dplyr** package is designed for data transformation



# dplyr Basics: 5 key functions

Function	Purpose
<b>filter()</b>	Pick observations by their values
<b>arrange()</b>	Reorder the rows
<b>select()</b>	Pick variables by their names
<b>mutate()</b>	<i>Create new variables with functions of existing variables</i>
<b>summarise()</b>	<i>Collapse many values down to a single summary</i>

- "A grammar of data manipulation" <https://dplyr.tidyverse.org>
- All verbs (functions) work similarly
  - The first argument is a data frame/tibble
  - The subsequent arguments decide what to do with the data frame/tibble
  - The result (data frame/tibble) supports chaining of steps – NOTE the “pipe operator” which we will cover later.

# 1. filter()

- First argument the name of the data frame
- Subsequent arguments are expressions that filter the data frame
- Subsequent arguments can be viewed as a succession of “and” statements
- Number of columns does not change
- Number of rows reduced (filtered)

```
> bel <- filter(observations, station=="BELMULLET")
> bel
# A tibble: 8,760 x 12
  station   year month   day hour date           rain
  <chr>     <dbl> <dbl> <int> <int> <dttm>      <dbl>
1 BELMUL... 2017     1     1     0 2017-01-01 00:00:00     0
2 BELMUL... 2017     1     1     1 2017-01-01 01:00:00     0.5
3 BELMUL... 2017     1     1     2 2017-01-01 02:00:00     0
4 BELMUL... 2017     1     1     3 2017-01-01 03:00:00     0.4
5 BELMUL... 2017     1     1     4 2017-01-01 04:00:00     0.6
6 BELMUL... 2017     1     1     5 2017-01-01 05:00:00     0.1
7 BELMUL... 2017     1     1     6 2017-01-01 06:00:00     0
8 BELMUL... 2017     1     1     7 2017-01-01 07:00:00     0
9 BELMUL... 2017     1     1     8 2017-01-01 08:00:00     0
10 BELMUL... 2017    1     1     9 2017-01-01 09:00:00     0
# ... with 8,750 more rows, and 5 more variables: temp <dbl>,
# . rhum <dbl>, msl <dbl>, wdsp <dbl>, wddir <dbl>
```

# Relational operators in R

Operators	Description
<	less than
<=	less than or equal to
>	greater than
>=	greater than or equal to
==	exactly equal to
!=	not equal to
!x	not x
x   y	x OR y
x & y	x AND y

```

> bel <- filter(observations,station=="BELMULLET")
> bel
# A tibble: 8,760 x 12
   station year month   day hour date          rain
   <chr>   <dbl> <dbl> <int> <int> <dttm>     <dbl>
 1 BELMUL... 2017     1     1     0 2017-01-01 00:00:00 0
 2 BELMUL... 2017     1     1     1 2017-01-01 01:00:00 0.5
 3 BELMUL... 2017     1     1     2 2017-01-01 02:00:00 0
 4 BELMUL... 2017     1     1     3 2017-01-01 03:00:00 0.4
 5 BELMUL... 2017     1     1     4 2017-01-01 04:00:00 0.6
 6 BELMUL... 2017     1     1     5 2017-01-01 05:00:00 0.1
 7 BELMUL... 2017     1     1     6 2017-01-01 06:00:00 0
 8 BELMUL... 2017     1     1     7 2017-01-01 07:00:00 0
 9 BELMUL... 2017     1     1     8 2017-01-01 08:00:00 0
10 BELMUL... 2017     1     1     9 2017-01-01 09:00:00 0
# ... with 8,750 more rows, and 5 more variables: temp <dbl>,
#   rhum <dbl>, msl <dbl>, wdsp <dbl>, wddir <dbl>

```

# Show rows for “MACE HEAD” in January

```
> mhj <- filter(observations,station=="MACE HEAD",month==1)
>
> mhj
# A tibble: 744 x 12
   station   year month   day hour date       rain  temp rhum   msl wdsp wddir
   <chr>     <dbl> <dbl> <int> <int> <dttm>    <dbl> <dbl> <dbl> <dbl> <dbl> <dbl>
 1 MACE HEAD 2017     1     1     0 2017-01-01 00:00:00  0.5   5.6   88 1023.    17   340
 2 MACE HEAD 2017     1     1     1 2017-01-01 01:00:00  0     5.4   84 1023.    17   340
 3 MACE HEAD 2017     1     1     2 2017-01-01 02:00:00  0.1   4.7   87 1023.    14   340
 4 MACE HEAD 2017     1     1     3 2017-01-01 03:00:00  0     4.7   81 1023.    15   350
 5 MACE HEAD 2017     1     1     4 2017-01-01 04:00:00  0     4.5   80 1024.    12   350
 6 MACE HEAD 2017     1     1     5 2017-01-01 05:00:00  0     5     71 1024    13   20
 7 MACE HEAD 2017     1     1     6 2017-01-01 06:00:00  0     5.1   66 1024.    13   30
 8 MACE HEAD 2017     1     1     7 2017-01-01 07:00:00  0     4.8   76 1026.    19   10
 9 MACE HEAD 2017     1     1     8 2017-01-01 08:00:00  0.1   4.8   78 1026.    16   360
10 MACE HEAD 2017     1     1     9 2017-01-01 09:00:00  0.1   4.4   82 1027.    15   10
# ... with 734 more rows
```

## 2. arrange()

- Changes the order of rows.
- Used for sorting values
- Takes a tibble and a set of column names to order by

```
> arrange(observations,temp)
# A tibble: 219,000 x 12
  station   year month   day hour date       rain   temp rhum   msl   wdsp wddir
  <chr>     <dbl> <dbl> <int> <int> <dttm>   <dbl> <dbl> <dbl> <dbl> <dbl> <dbl>
1 CASEMENT 2017    12     11     4 2017-12-11 04:00:00     0  -6.2  91  989.    5   250
2 GURTEEN   2017    12     11     3 2017-12-11 03:00:00     0  -6    94  989.    2   240
3 GURTEEN   2017    12     11     4 2017-12-11 04:00:00     0  -6    95  990.    1   240
4 GURTEEN   2017    12     11     1 2017-12-11 01:00:00     0  -5.9   92  988.    3   230
5 GURTEEN   2017    12     11     5 2017-12-11 05:00:00     0  -5.8   95  990.    1   260
6 GURTEEN   2017    12     11     0 2017-12-11 00:00:00     0  -5.7   94  988    2   280
7 CASEMENT  2017    12     11     2 2017-12-11 02:00:00     0  -5.6   92  988.    4   230
8 GURTEEN   2017    12     11     2 2017-12-11 02:00:00     0  -5.6   94  989.    3   230
9 MOORE PARK 2017    1     3     9 2017-01-03 09:00:00     0  -5.6   91  1033.   1   330
10 CASEMENT 2017    12     11     3 2017-12-11 03:00:00     0  -5.4   92  988.   4   250
# ... with 218,990 more rows
```



# In descending order - desc()

```
> arrange(observations,desc(temp))
```

```
# A tibble: 219,000 x 12
```

	station	year	month	day	hour	date	rain	temp	rhum	msl	wdsp	wddir
	<chr>	<dbl>	<dbl>	<int>	<int>	<dttm>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>
1	PHOENIX PARK	2017	6	21	13	2017-06-21 13:00:00	0.1	28.3	51	1010	NA	NA
2	PHOENIX PARK	2017	6	21	12	2017-06-21 12:00:00	0	27.5	54	1011.	NA	NA
3	PHOENIX PARK	2017	6	21	14	2017-06-21 14:00:00	0	27.5	49	1010.	NA	NA
4	PHOENIX PARK	2017	6	21	16	2017-06-21 16:00:00	0	26.8	61	1009.	NA	NA
5	CASEMENT	2017	6	21	12	2017-06-21 12:00:00	0	26.6	54	1011.	11	150
6	MOORE PARK	2017	6	19	16	2017-06-19 16:00:00	0	26.6	50	1018.	3	200
7	DUNSANY	2017	6	21	12	2017-06-21 12:00:00	0	26.5	55	1010.	8	150
8	PHOENIX PARK	2017	6	21	11	2017-06-21 11:00:00	0	26.5	56	1011.	NA	NA
9	PHOENIX PARK	2017	6	17	16	2017-06-17 16:00:00	0	26.4	42	1024.	NA	NA
10	PHOENIX PARK	2017	6	21	15	2017-06-21 15:00:00	0	26.4	61	1009.	NA	NA
# ... with 218,990 more rows												

### 3. select()

- It is not uncommon to get datasets with hundreds, or even thousands, of variables
- A challenge is to narrow down on the variables of you're interested in
- `select()` allows you to rapidly zoom in on a useful subset using operations based on the variable names
- Number of rows does not change

```
> new_obs <- select(observations, station, year, month, day, hour, temp)
> new_obs
# A tibble: 219,000 x 6
      station   year  month   day   hour   temp
      <chr>     <dbl> <dbl> <int> <int>   <dbl>
1 ATHENRY 2017     1     1     0     5.2
2 ATHENRY 2017     1     1     1     4.7
3 ATHENRY 2017     1     1     2     4.2
4 ATHENRY 2017     1     1     3     3.5
5 ATHENRY 2017     1     1     4     3.2
6 ATHENRY 2017     1     1     5     2.1
7 ATHENRY 2017     1     1     6     2
8 ATHENRY 2017     1     1     7     1.7
9 ATHENRY 2017     1     1     8     1
10 ATHENRY 2017    1     1     9     1.1
# ... with 218,990 more rows
```

# Useful options with select()

```
> select(observations, station:rain)
```

```
# A tibble: 219,000 x 7
```

```
  station year month day hour date      rain
  <chr>   <dbl> <dbl> <int> <int> <dttm> <dbl>
1 ATHENRY 2017     1     1     0 2017-01-01 00:00:00    0
2 ATHENRY 2017     1     1     1 2017-01-01 01:00:00    0
3 ATHENRY 2017     1     1     2 2017-01-01 02:00:00    0
4 ATHENRY 2017     1     1     3 2017-01-01 03:00:00    0.1
5 ATHENRY 2017     1     1     4 2017-01-01 04:00:00    0.1
6 ATHENRY 2017     1     1     5 2017-01-01 05:00:00    0
7 ATHENRY 2017     1     1     6 2017-01-01 06:00:00    0
8 ATHENRY 2017     1     1     7 2017-01-01 07:00:00    0
9 ATHENRY 2017     1     1     8 2017-01-01 08:00:00    0
10 ATHENRY 2017    1     1     9 2017-01-01 09:00:00    0
# ... with 218,990 more rows
```

```
> select(observations, -(station:rain))
```

```
# A tibble: 219,000 x 5
```

```
  temp rhum msl wdsp wddir
  <dbl> <dbl> <dbl> <dbl> <dbl>
1 5.2  89 1022.    8  320
2 4.7  89 1022     9  320
3 4.2  90 1022.    8  320
4 3.5  87 1022.    9  330
5 3.2  89 1023.    8  330
6 2.1  91 1023.    8  330
7 2    89 1024.    7  330
8 1.7  89 1024.    7  340
9 1    91 1025     7  330
10 1.1 91 1026.    8  330
# ... with 218,990 more rows
```

# Special functions with select()

## Special functions

As well as using existing functions like `:` and `c`, there are a number of special functions that only work inside `select`

- `starts_with(x, ignore.case = TRUE)`: names starts with `x`
- `ends_with(x, ignore.case = TRUE)`: names ends in `x`
- `contains(x, ignore.case = TRUE)`: selects all variables whose name contains `x`
- `matches(x, ignore.case = TRUE)`: selects all variables whose name matches the regular expression `x`
- `num_range("x", 1:5, width = 2)`: selects all variables (numerically) from `x01` to `x05`.
- `one_of("x", "y", "z")`: selects variables provided in a character vector.
- `everything()`: selects all variables.

## 4. mutate()

- It is often useful to add new columns that are functions of existing columns
- `mutate()` always adds new columns at the end of your data set.
- For example, convert the mph wind speed in observations to a new column, kph.
- Use a simplified observations tibble with day, month, station, wdsp as columns, and for “ROCHES POINT” on October 16<sup>th</sup>
- Assume 1 mi = 1.609344 km

# Example of mutate

```
library(aimsir17)
library(dplyr)

CM2K <- 1.609344

obs1 <- observations %>% select(day, month, station, wdsp) %>%
      filter(station=="ROCHES POINT", day==16,month==10)

obs1 <- mutate(obs1, wdsp_kph=wdsp*CM2K)

> obs1
# A tibble: 24 x 5
   day month station      wdsp  wdsp_kph
   <int> <dbl> <chr>     <dbl>     <dbl>
 1     16    10 ROCHES POINT     11     17.7
 2     16    10 ROCHES POINT     11     17.7
 3     16    10 ROCHES POINT     14     22.5
 4     16    10 ROCHES POINT     15     24.1
 5     16    10 ROCHES POINT     22     35.4
```

# Useful Creation Functions

- There are many functions for creating new variables that can be used with `mutate()`
- The key property is that the function **must be vectorised**:
  - It must take a vector of values as input, and,
  - Return a vector with the same number of values as output

Grouping	Examples
Arithmetic Operators	<code>+, -, *, /, ^</code>
Modular Arithmetic	<code>%/%</code> - Integer division <code>&amp;&amp;</code> - Remainder
Logical comparisons	<code>&lt;, &lt;=, &gt;, &gt;=, !=</code>
If-else Functions	<code>ifelse(), case_when()</code>

## 5. summarise()

- The last key verb is summarise()
- It collapses a data frame into a single row
- Not very useful unless paired with group\_by()
- Very useful to combine with the pipe operator

```
test <- filter(observations,  
                station=="MACE HEAD",  
                month==10)
```

## group\_by()

- Most data operations are useful done on groups defined by variables in the the dataset.
- The `group_by` function takes an existing `tbl` and converts it into a grouped `tbl` where operations are performed "by group".

```
> test_g <- group_by(test, day)
> test_g
# A tibble: 744 x 12
# Groups:   day [31]
  station  year month   day hour date           rain   temp
  <chr>    <dbl> <dbl> <int> <int> <dttm>       <dbl> <dbl>
1 MACE H... 2017     10     1     0 2017-10-01 00:00:00  1.2  11.7
2 MACE H... 2017     10     1     1 2017-10-01 01:00:00  1.9  11.3
```



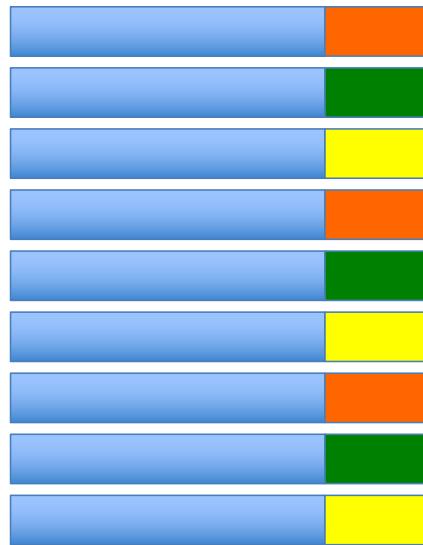
# Key idea

- This grouping can then be exploited by summarise

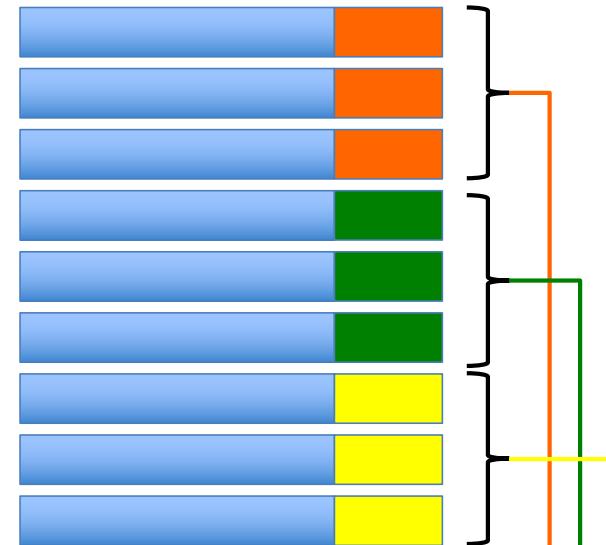
```
> summarise(test_g,TotalRainfall=sum(rain,na.rm=T))  
# A tibble: 31 x 2  
      day TotalRainfall  
   <int>      <dbl>  
 1     1        4.7  
 2     2        1.3  
 3     3        0.0  
 4     4        4.2  
 5     5        0.1  
 6     6        3.1  
 7     7        0.4  
 8     8        0.3  
 9     9        1.7  
10    10       1.6  
# ... with 21 more rows
```

# Overall idea...

Original data frame



Grouped data frame



`group_by()`

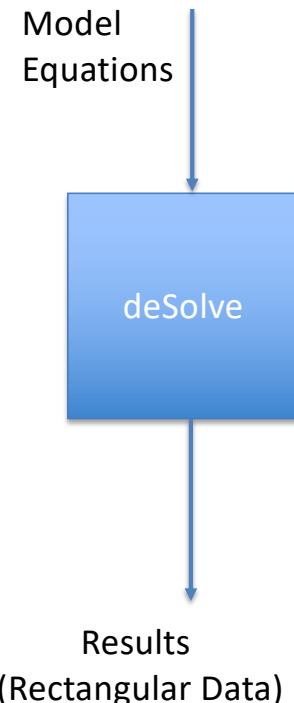
`summarise()`



# Useful Summary Functions

Grouping	Examples
<b>Measures of location</b>	mean(), median()
<b>Measures of spread</b>	sd(), IQR(), mad()
<b>Measures of rank</b>	min(), quantile(), max()
<b>Measures of position</b>	first(), nth(), last()
<b>Counts</b>	n(), n_distinct()
<b>Counts and proportions of logical values</b>	sum(x>0) when used with numeric functions, (T,F) converted to (1,0)

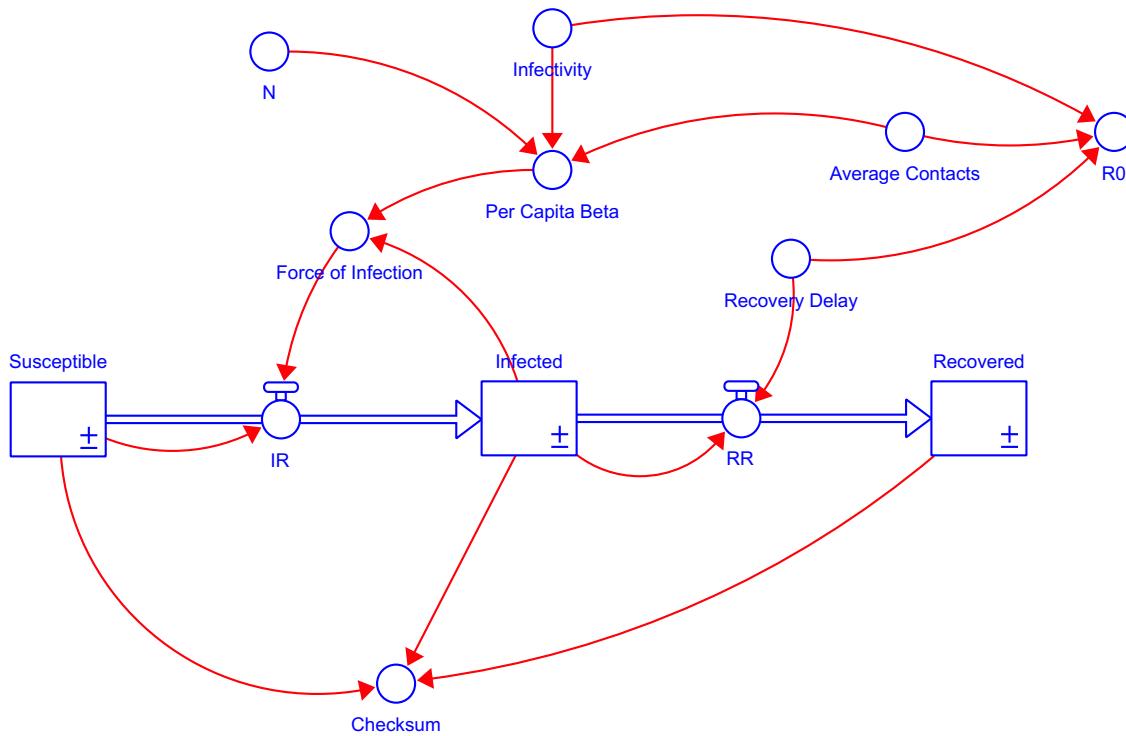
## (2.1) Using deSolve – model as a function



Argument	Description
y	The initial (state) values for the ODE system, a vector. If y has a name attribute, the names will be used to label the output matrix
times	Time sequence for which output is wanted; the first value of times must be the initial time
func	<ul style="list-style-type: none"><li>An R function that computes the values of the derivatives in the ODE system at time <math>t</math>. It must be defined as: <code>func &lt;- function(t, y, parms, ...)</code>, where <code>t</code> is the current time point in the integration and <code>y</code> is the current estimate of the variables in the ODE system.</li><li>If the initial value <code>y</code> has a names attribute, the names will be available inside <code>func</code>.</li><li><code>parms</code> is a vector or list of parameters; <code>...</code> (optional) are any other arguments passed to the function.</li><li>The return value of <code>func</code> should be a list, whose first element is a vector containing the derivatives of <code>y</code> with respect to time, and whose next elements are global values that are required at each point in <code>times</code>. The derivatives must be specified in the same order as the state variables <code>y</code>.</li></ul>
parms	Parameters passed to <code>func</code> .
method	Normally a string to indicate the integration method, for example, "euler", "rk4", "ode23", "ode45".
returns	A matrix of class <code>deSolve</code> with up to as many rows as elements in <code>times</code> and as many columns as elements in <code>y</code> plus the number of "global" values returned in the second element of the return from <code>func</code> , plus an additional column (the first) for the time value. This can be easily converted to a data frame object using the function <code>data.frame()</code>



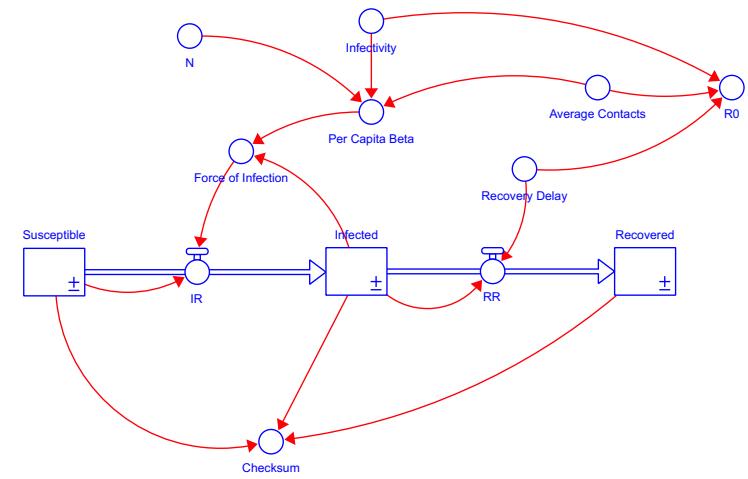
# Sample model



```

6 · sir_model <- function (time, stocks, auxs){
7 ·   with(as.list(c(stocks, auxs)), {
8     Per_Capita_Beta <- Average_Contacts * Infectivity/N
9     R0 <- Infectivity * Average_Contacts * Recovery_Delay
10    Checksum <- Susceptible + Infected + Recovered
11    Force_of_Infection <- Per_Capita_Beta * Infected
12
13    IR <- Susceptible * Force_of_Infection
14    RR <- Infected/Recovery_Delay
15
16    d_Susceptible_dt <- -IR
17    d_Infected_dt <- IR - RR
18    d_Recovered_dt <- RR
19
20    return(list(c(d_Susceptible_dt, d_Infected_dt, d_Recovered_dt),
21               RR = RR, Per_Capita_Beta = Per_Capita_Beta, R0 = R0,
22               Checksum = Checksum, Force_of_Infection = Force_of_Infection,
23               IR = IR, Recovery_Delay = Recovery_Delay, N = N,
24               Average_Contacts = Average_Contacts,
25               Infectivity = Infectivity))
26  })
27 }

```

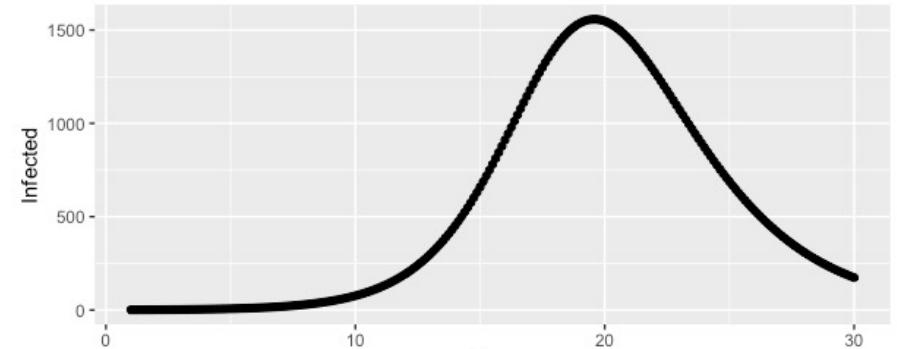


# Calling the model, and initial conditions

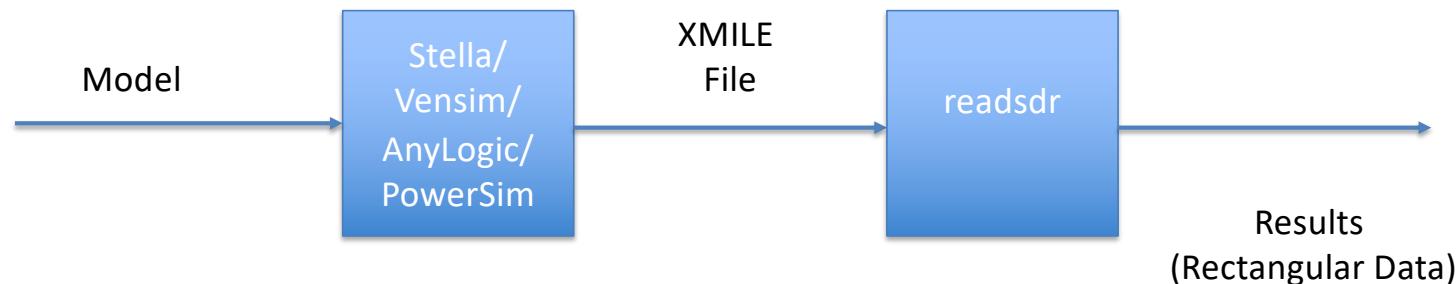
```
29 simtime <- seq(1,30,0.125)
30
31 stocks <- c(Susceptible=9999,
32             Infected=1,
33             Recovered=0)
34
35 params <- c(Recovery_Delay=2.0,
36             N = 10000,
37             Average_Contacts = 10.0,
38             Infectivity = 0.1)
39
40 results <- tibble(data.frame(ode(y      = stocks,
41                               times   = simtime,
42                               func    = sir_model,
43                               parms   = params,
44                               method  = "euler")))
```

```
> results
# A tibble: 233 x 15
   time Susceptible Infected Recovered RR Per_Capita_Beta R0 Checksum
   <dbl>     <dbl>     <dbl>     <dbl> <dbl>        <dbl> <dbl>     <dbl>
 1 1         9999     1       0       0.5     0.0001     2 10000
 2 1.12     9998.    1.06    0.0625  0.531    0.0001     2 10000
 3 1.25     9998.    1.13    0.129   0.564    0.0001     2 10000
 4 1.38     9998.    1.20    0.199   0.600    0.0001     2 10000.
 5 1.5       9998.    1.27    0.274   0.637    0.0001     2 10000.
 6 1.62     9998.    1.35    0.354   0.677    0.0001     2 10000.
 7 1.75     9998.    1.44    0.439   0.719    0.0001     2 10000
 8 1.88     9997.    1.53    0.529   0.764    0.0001     2 10000.
 9 2         9997.    1.62    0.624   0.812    0.0001     2 10000.
10 2.12     9997.    1.73    0.726   0.863    0.0001     2 10000.
# ... with 223 more rows, and 7 more variables: Force_of_Infection <dbl>,
#   IR <dbl>, Recovery_Delay <dbl>, N <dbl>, Average_Contacts <dbl>, Infectivity <dbl>,
#   INIT_Susceptible <dbl>
```

```
ggplot(results,aes(x=time,y=Infected))+
  geom_point() + geom_line()
```



## (2.2) Using readsdr package



### Package ‘readsdr’

January 8, 2021

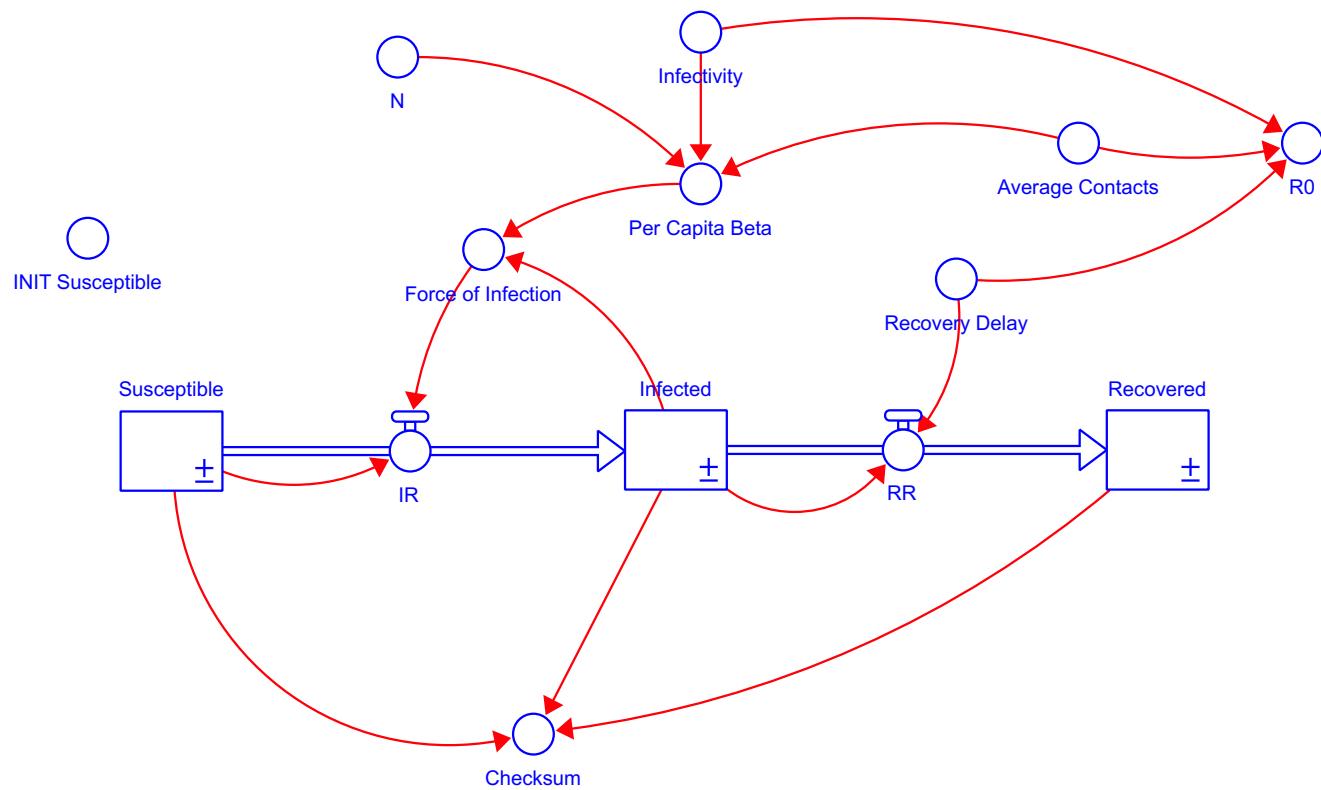
Type Package

Title Translate Models from System Dynamics Software into 'R'

Version 0.2.0

Description The goal of 'readsdr' is to bridge the design capabilities from specialised System Dynamics software with the powerful numerical tools offered by 'R' libraries. The package accomplishes this goal by parsing 'XMILE' files ('Vensim' and 'Stella') models into 'R' objects to construct networks (graph theory); 'ODE' functions for 'Stan'; and inputs to simulate via 'deSolve' as described in Duggan (2016) <[doi:10.1007/978-3-319-34043-2](https://doi.org/10.1007/978-3-319-34043-2)>.

# Model file



# Read in the Stella/XMILE file

```
3 library(readsdr)
4 library(deSolve)
5 library(dplyr)
6
7 filepath <- "workshops/03 Southampton 2021/Models/02 SIR deSolve/SIR.stmx"
8 mdl      <- read_xmile(filepath)
```

mdl	list [3]	List of length 3
description	list [4]	List of length 4
parameters	list [3]	List of length 3
levels	list [3]	List of length 3
variables	list [6]	List of length 6
constants	list [5]	List of length 5
deSolve_components	list [4]	List of length 4
stocks	double [3]	9999 1 0
consts	double [5]	2e+00 1e+04 1e+01 1e-01 1e+04
func	function	function(time, stocks, auxs) { ... }
sim_params	list [3]	List of length 3
graph_dfs	list [2]	List of length 2
nodes	list [9 x 3] (S3: data.frame)	A data.frame with 9 rows and 3 columns
edges	list [12 x 3] (S3: data.frame)	A data.frame with 12 rows and 3 columns

# deSolve\_components

⌚ deSolve_components	list [4]	List of length 4
⌚ stocks	double [3]	9999 1 0
Susceptible	double [1]	9999
Infected	double [1]	1
Recovered	double [1]	0
⌚ consts	double [5]	2e+00 1e+04 1e+01 1e-01 1e+04
Recovery_Delay	double [1]	2
N	double [1]	10000
Average_Contacts	double [1]	10
Infectivity	double [1]	0.1
INIT_Susceptible	double [1]	9999
⌚ func	function	function(time, stocks, auxs) { ... }
⌚ formals	pairlist [3]	Pairlist of length 3
⌚ body	language	with(as.list(c(stocks, auxs)), { RR <- Infected/Recovery_Delay Per_Capit ...
⌚ environment	environment [13]	<environment: 0x7fa02463ea8>
⌚ sim_params	list [3]	List of length 3
start	double [1]	1
stop	double [1]	30
dt	double [1]	0.125



# Running the model

```
simtime <- seq(mdl$deSolve_components$sim_params$start,
                 mdl$deSolve_components$sim_params$stop,
                 mdl$deSolve_components$sim_params$dt)

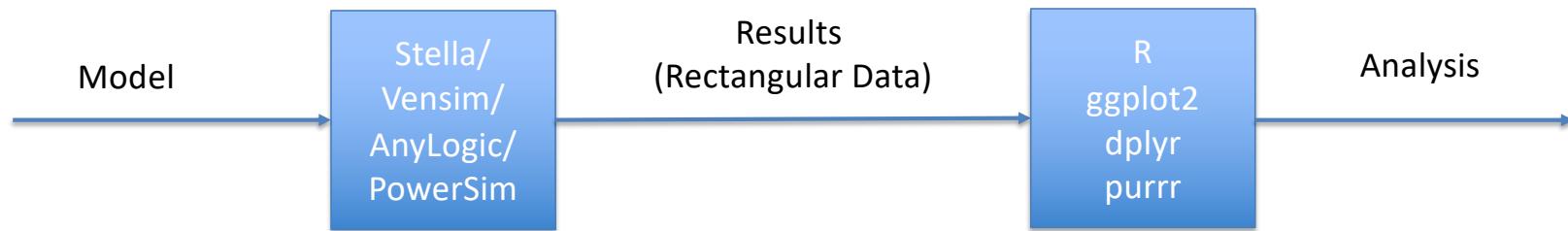
output_deSolve <- ode(y      = mdl$deSolve_components$stocks,
                      times   = simtime,
                      func    = mdl$deSolve_components$func,
                      parms   = mdl$deSolve_components$consts,
                      method  = "euler")

out <- data.frame(output_deSolve)
results <- tibble(out)

> results
# A tibble: 233 x 15
  time Susceptible Infected Recovered RR Per_Capita_Beta R0 Checksum
  <dbl>     <dbl>     <dbl>     <dbl> <dbl>     <dbl> <dbl>     <dbl>
1 1         9999     1       0       0.5     0.0001 2 10000
2 1.12     9998.    1.06    0.0625 0.531     0.0001 2 10000
3 1.25     9998.    1.13    0.129  0.564     0.0001 2 10000.
4 1.38     9998.    1.20    0.199  0.600     0.0001 2 10000.
5 1.5       9998.    1.27    0.274  0.637     0.0001 2 10000.
6 1.62     9998.    1.35    0.354  0.677     0.0001 2 10000.
7 1.75     9998.    1.44    0.439  0.719     0.0001 2 10000
8 1.88     9997.    1.53    0.529  0.764     0.0001 2 10000.
9 2         9997.    1.62    0.624  0.812     0.0001 2 10000.
10 2.12     9997.    1.73    0.726  0.863     0.0001 2 10000.
# ... with 223 more rows, and 7 more variables: Force_of_Infection <dbl>,
# Recovery_Delay <dbl>, N <dbl>, Average_Contacts <dbl>, Infectivity <dbl>,
# INIT_Susceptible <dbl>
```



## (2.3) Processing Sensitivity Results



- Extended SIR model (with vaccination)
- Use purrr libraries

# Introduction to purrr

[http://www.rebeccabarter.com/blog/2019-08-19\\_purrr/](http://www.rebeccabarter.com/blog/2019-08-19_purrr/)

- purrr is all about iteration.
- purrr introduces map functions (the tidyverse's answer to base R's apply functions, but more in line with functional programming practices) as well as some new functions for manipulating lists
- While the workhorse of dplyr is the data frame, the workhorse of purrr is the list.
  - A **vector** is a way of storing many individual elements (a single number or a single character or string) of the same type together in a single object,
  - A **data frame** is a way of storing many vectors of the same length but possibly of different types together in a single object
  - A **list** is a way of storing many objects of any type (e.g. data frames, plots, vectors) together in a single object

Apply functions with purrr :: CHEAT SHEET

Apply Functions

Work with Lists



# (1) Map functions – beyond apply

- A **map function** is one that applies the same action/function to every element of an object (e.g. each entry of a list or a vector, or each of the columns of a data frame)
  - The naming convention of the map functions are such that the type of the **output** is specified by the term that follows the underscore in the function name
  - Consistent with the way of the tidyverse, the **first argument** of each mapping function is always the **data object** that you want to map over, and the **second argument** is always the **function** that you want to iteratively apply to each element of the input object
- `map(.x, .f)` is the main mapping function and returns a list
  - `map_df(.x, .f)` returns a data frame
  - `map_dbl(.x, .f)` returns a numeric (double) vector
  - `map_chr(.x, .f)` returns a character vector
  - `map_lgl(.x, .f)` returns a logical vector

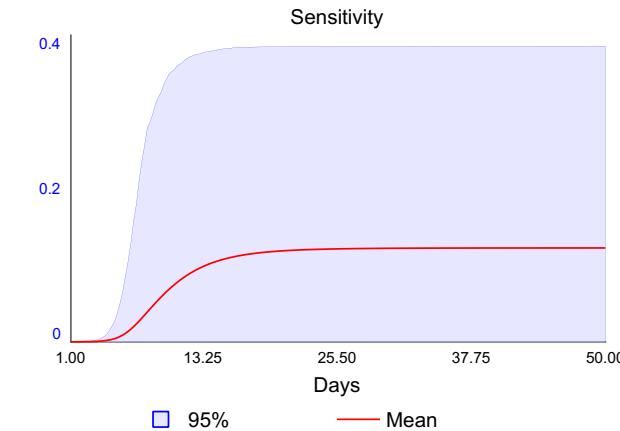
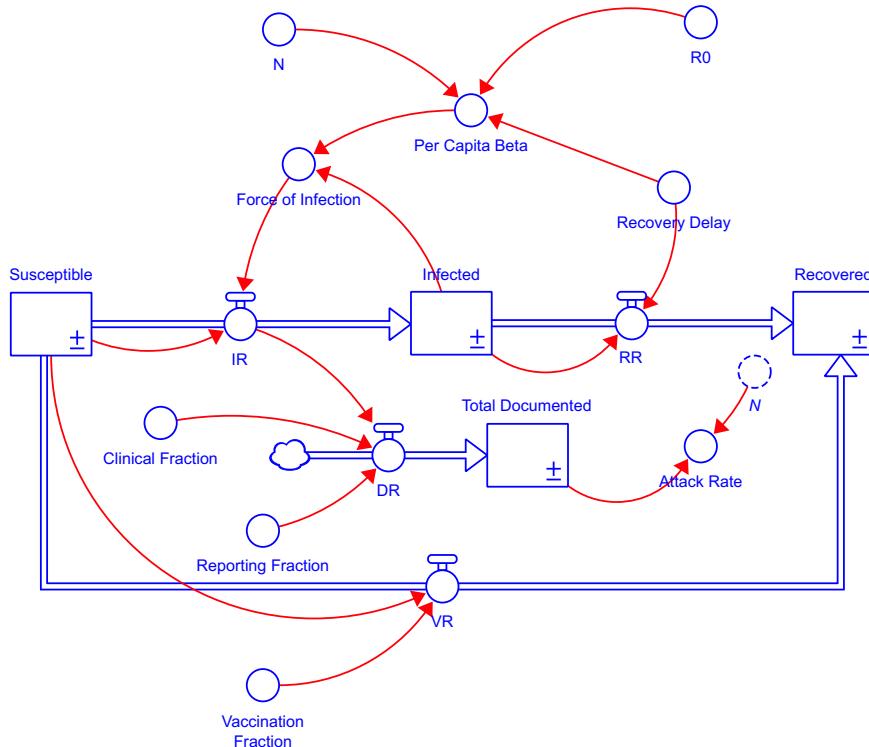


# The tilde-dot shorthand for functions in map

- To make the code more concise you can use the tilde-dot shorthand for anonymous functions (the functions that you create as arguments of other functions).
- `~` indicates that you have started an anonymous function, and the argument of the anonymous function can be referred to using `.x` (or simply `.`).
- Unlike normal function arguments that can be anything that you like, ***the tilde-dot function argument is always `.x`.***

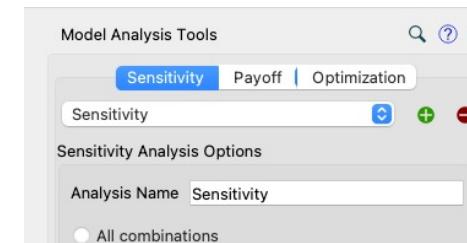
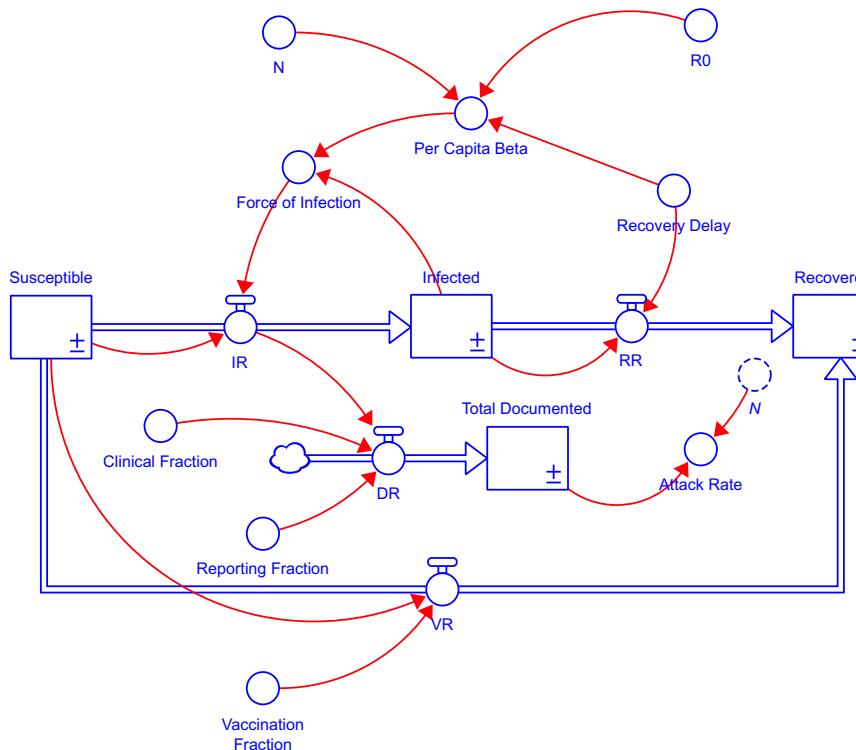
```
> map_dbl(c(1,4,7),~.x+10)
[1] 11 14 17
>
> map_dbl(c(1,4,7),~{.x+10})
[1] 11 14 17
>
> map_dbl(c(1,4,7),~.+10)
[1] 11 14 17
```

# Sample Model (Stella) and Output



Days	Run 1: Attack Rate	Run 2: Attack Rate	Run 3: Attack Rate	Run 4: Attack Rate	Run 5: Attack Rate
1	0	0	0	0	0
2	3.52017E-05	7.88358E-05	5.62767E-05	8.41314E-05	0.000100987
3	7.48378E-05	0.000223469	0.000151448	0.000261265	0.000337615
4	0.000116714	0.00046095	0.000311716	0.000614574	0.000848201
5	0.000158448	0.000813046	0.000580409	0.001282961	0.001865558
6	0.000197874	0.001288277	0.001028714	0.002482835	0.003740133
7	0.000233343	0.001876634	0.001772639	0.004525767	0.006932958
8	0.000263855	0.002549509	0.002999163	0.00781852	0.011946385
9	0.00028905	0.003265129	0.005004942	0.012824492	0.019168741
10	0.000309092	0.003977398	0.008249615	0.019964553	0.028656342
11	0.000324501	0.004644898	0.013419388	0.029454549	0.039960365
12	0.000335984	0.005237266	0.021478781	0.041127013	0.052151605
13	0.000344302	0.005737757	0.033651523	0.054343335	0.06409591
14	0.000350173	0.006142347	0.051220981	0.068098712	0.074829072

# Explore relationship between R<sub>0</sub>, VF for DR



# A tibble: 50 x 4,001

Days	Run 1: Attack Rate	Run 2: Attack Rate	Run 3: Attack Rate	Run 4: Attack Rate
1	0	0	0	0
2	3.52017E-05	7.88358E-05	5.62767E-05	0.000197874
3	7.48378E-05	0.000223469	0.000151448	0.000116714
4	0.000116714	0.00046095	0.000311716	0.000158448
5	0.000158448	0.000813046	0.000580409	0.000263855
6	0.000197874	0.001288277	0.001028714	0.00028905
7	0.000233343	0.001876634	0.001772639	0.0003265129
8	0.000263855	0.002549509	0.002999163	0.0003651523
9	0.00028905	0.003265129	0.005004942	0.006142347
10	0.000352	0.0009788	0.000563	0.001420981
11	0.000748	0.000223	0.000151	0.00197874
12	0.000117	0.000461	0.000312	0.000116714
13	0.000158	0.000813	0.000580	0.000263855
14	0.000198	0.00129	0.00103	0.00028905
15	0.000233	0.00188	0.00177	0.0003265129
16	0.000264	0.00255	0.00300	0.0003651523
17	0.000289	0.00327	0.00500	0.006142347
18	0.000309	0.00398	0.00825	0.01220981
19	0.000352	0.0009788	0.000563	0.001420981
20	0.000748	0.000223	0.000151	0.00197874
21	0.000117	0.000461	0.000312	0.000116714
22	0.000158	0.000813	0.000580	0.000263855
23	0.000198	0.00129	0.00103	0.00028905
24	0.000233	0.00188	0.00177	0.0003265129
25	0.000264	0.00255	0.00300	0.0003651523
26	0.000289	0.00327	0.00500	0.006142347
27	0.000309	0.00398	0.00825	0.01220981
28	0.000352	0.0009788	0.000563	0.001420981
29	0.000748	0.000223	0.000151	0.00197874
30	0.000117	0.000461	0.000312	0.000116714
31	0.000158	0.000813	0.000580	0.000263855
32	0.000198	0.00129	0.00103	0.00028905
33	0.000233	0.00188	0.00177	0.0003265129
34	0.000264	0.00255	0.00300	0.0003651523
35	0.000289	0.00327	0.00500	0.006142347
36	0.000309	0.00398	0.00825	0.01220981
37	0.000352	0.0009788	0.000563	0.001420981
38	0.000748	0.000223	0.000151	0.00197874
39	0.000117	0.000461	0.000312	0.000116714
40	0.000158	0.000813	0.000580	0.000263855
41	0.000198	0.00129	0.00103	0.00028905
42	0.000233	0.00188	0.00177	0.0003265129
43	0.000264	0.00255	0.00300	0.0003651523
44	0.000289	0.00327	0.00500	0.006142347
45	0.000309	0.00398	0.00825	0.01220981
46	0.000352	0.0009788	0.000563	0.001420981
47	0.000748	0.000223	0.000151	0.00197874
48	0.000117	0.000461	0.000312	0.000116714
49	0.000158	0.000813	0.000580	0.000263855
50	0.000198	0.00129	0.00103	0.00028905

R0 (Normal Distribution)  
Vaccination Fraction (Uniform Distribution)

# Data Input (Excel into a tibble)

Days	Run 1: Attack Rate	Run 2: Attack Rate	Run 3: Attack Rate	Ru
1	0	0	0	
2	3.52017E-05	7.88358E-05	5.62767E-05	
3	7.48378E-05	0.000223469	0.000151448	
4	0.000116714	0.00046095	0.000311716	
5	0.000158448	0.000813046	0.000580409	
6	0.000197874	0.001288277	0.001028714	
7	0.000233343	0.001876634	0.001772639	
8	0.000263855	0.002549509	0.002999163	
9	0.00028905	0.003265129	0.005004942	
10	0.000309092	0.003977398	0.008249615	
11	0.000324501	0.004644898	0.013419388	
12	0.000335984	0.005237266	0.021478781	
13	0.000344302	0.005737757	0.033651523	
14	0.000350173	0.006142347	0.051220981	

```
> res
# A tibble: 50 x 4,001
  Days `Run 1: Attack ... `Run 2: Attack ... `Run 3: Attack ...
  <dbl> <dbl> <dbl> <dbl>
1 1     0     0     0
2 2     0.000352 0.000788 0.000563
3 3     0.000748 0.000223 0.000151
4 4     0.000117 0.000461 0.000312
5 5     0.000158 0.000813 0.000580
6 6     0.000198 0.00129  0.00103 
7 7     0.000233 0.00188  0.00177 
8 8     0.000264 0.00255  0.00300 
9 9     0.000289 0.00327  0.00500 
10 10    0.000309 0.00398  0.00825 
# ... with 40 more rows, and 3,997 more variables: `Run 4: Attack
```



# Extract the 3 variables

```
12 v1_tib <- res %>% select(Days,contains("R0")) %>%
13   pivot_longer(names_to="Temp",values_to="R0",-Days) %>%
14   mutate(RunNumber=as.integer(str_extract(Temp,"\\d+"))) %>%
15   select(-Temp) %>%
16   select(RunNumber,Days,everything())
```

```
> v1_tib
# A tibble: 50,000 x 3
  RunNumber Days    R0
  <int>     <dbl> <dbl>
1       1     1  1.56
2       2     1  2.73
3       3     1  2.10
4       4     1  2.78
5       5     1  3.12
6       6     1  3.08
7       7     1  2.57
8       8     1  3.07
9       9     1  2.84
10      10    1  2.05
# ... with 49,990 more rows
```

```
> v2_tib
# A tibble: 50,000 x 3
  RunNumber Days    VF
  <int>     <dbl> <dbl>
1       1     1  0.0950
2       2     1  0.102
3       3     1  0.00398
4       4     1  0.0451
5       5     1  0.0637
6       6     1  0.0391
7       7     1  0.140
8       8     1  0.0827
9       9     1  0.110
10      10    1  0.134
# ... with 49,990 more rows
```

```
> v3_tib
# A tibble: 50,000 x 3
  RunNumber Days    DR
  <int>     <dbl> <dbl>
1       1     1  0.328
2       2     1  0.573
3       3     1  0.442
4       4     1  0.583
5       5     1  0.656
6       6     1  0.646
7       7     1  0.539
8       8     1  0.645
9       9     1  0.596
10      10    1  0.430
# ... with 49,990 more rows
```



# Join into a new table and nest

```
> sim <- v1_tib
> sim <- full_join(sim,v2_tib)
Joining, by = c("RunNumber", "Days")
> sim <- full_join(sim,v3_tib)
Joining, by = c("RunNumber", "Days")
> sim
# A tibble: 50,000 x 5
  RunNumber Days     R0      VF      DR
  <int> <dbl> <dbl>    <dbl>    <dbl>
1       1  1.56 0.0950  0.328
2       2  2.73 0.102   0.573
3       3  2.10 0.00398  0.442
4       4  2.78 0.0451   0.583
5       5  3.12 0.0632_  0.656
6       6  3.08 0.0391_  0.646
7       7  2.57 0.140   0.539
8       8  3.07 0.0827_  0.645
9       9  2.84 0.110   0.596
10      10  2.05 0.134   0.430
# ... with 49,990 more rows

> sim_nested <- sim %>%
+   group_by(RunNumber) %>%
+   nest()
>
>
> sim_nested
# A tibble: 1,000 x 2
# Groups:   RunNumber [1,000]
  RunNumber data
  <int> <list>
1       1 <tibble [50 x 4]>
2       2 <tibble [50 x 4]>
3       3 <tibble [50 x 4]>
4       4 <tibble [50 x 4]>
5       5 <tibble [50 x 4]>
6       6 <tibble [50 x 4]>
7       7 <tibble [50 x 4]>
8       8 <tibble [50 x 4]>
9       9 <tibble [50 x 4]>
10      10 <tibble [50 x 4]>
# ... with 990 more rows
```

# Get the results for each simulation

```
summ <- sim_nested %>%
  pull(data) %>%
  map_df(~{
    tibble(Max_DR=max(.\$DR),
      R0=first(.\$R0),
      VF=first(.\$VF))
  })
```

```
> summ
# A tibble: 1,000 x 3
  Max_DR     R0      VF
  <dbl>   <dbl>   <dbl>
1 0.422   1.56  0.0950
2 7.21    2.73  0.102 
3 346.    2.10  0.00398
4 137.    2.78  0.0451
5 122.    3.12  0.0637
6 305.    3.08  0.0391
7 2.09    2.57  0.140 
8 42.9    3.07  0.0827
9 7.55    2.84  0.110 
10 0.803   2.05  0.134
# ... with 990 more rows
```



# Merge Back into the original table.

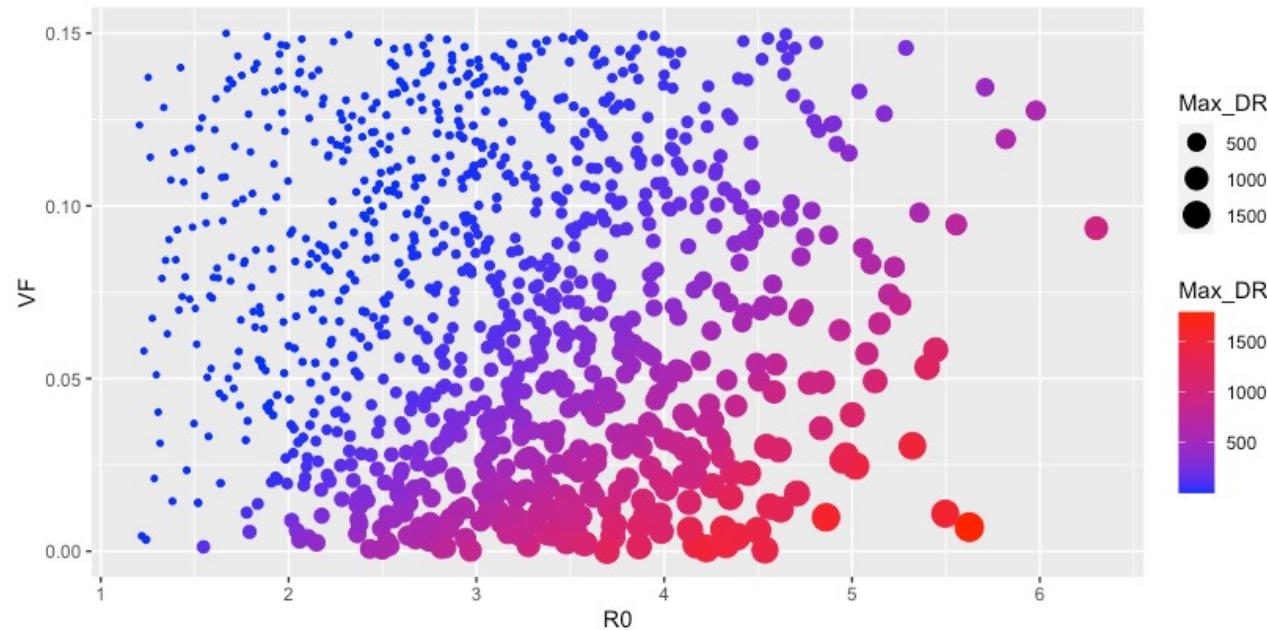
```
> sim_nested
# A tibble: 1,000 x 2
# Groups: RunNumber [1,000]
  RunNumber data
  <int> <list>
1 1 <tibble [50 x 4]>
2 2 <tibble [50 x 4]>
3 3 <tibble [50 x 4]>
4 4 <tibble [50 x 4]>
5 5 <tibble [50 x 4]>
6 6 <tibble [50 x 4]>
7 7 <tibble [50 x 4]>
8 8 <tibble [50 x 4]>
9 9 <tibble [50 x 4]>
10 10 <tibble [50 x 4]>
# ... with 990 more rows

> sim_nested <- bind_cols(sim_nested, summ)
>
> sim_nested
# A tibble: 1,000 x 5
# Groups: RunNumber [1,000]
  RunNumber data      Max_DR     R0      VF
  <int> <list>      <dbl>    <dbl>   <dbl>
1 1 <tibble [50 x 4]> 0.422 1.56 0.0950
2 2 <tibble [50 x 4]> 7.21  2.73 0.102 
3 3 <tibble [50 x 4]> 346.  2.10 0.00398
4 4 <tibble [50 x 4]> 137.  2.78 0.0451 
5 5 <tibble [50 x 4]> 122.  3.12 0.0637 
6 6 <tibble [50 x 4]> 305.  3.08 0.0391 
7 7 <tibble [50 x 4]> 2.09  2.57 0.140 
8 8 <tibble [50 x 4]> 42.9  3.07 0.0827 
9 9 <tibble [50 x 4]> 7.55  2.84 0.110 
10 10 <tibble [50 x 4]> 0.803 2.05 0.134
# ... with 990 more rows
```



# Plot the Exploratory Analysis

```
51 ggplot(sim_nested,aes(x=R0,y=VF,size=Max_DR,colour=Max_DR))+  
52   geom_point() +  
53   scale_color_gradient(low="blue", high="red")  
54
```



# Summary

- Introduction to R and the **tidyverse**
  - Visualisation - **ggplot2**
  - Transformation – **dplyr** and **purrr**
- Using R with System Dynamics, 3 Examples
  - **deSolve**
  - **readsdr**
  - Exploring sensitivity runs

