Modeling Life

Theoretical Biology Group, Utrecht University

2025-04-24

Table of contents

Modeling life

Welcome to the course Modeling Life.

Part I

Course information

1 Quarto examples

1.1 Equations

Here's an equation:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = rN(1 - \frac{N}{K}) \tag{1.1}$$

And Equation **??** is a reference to the equation above.

1.2 References

See Knuth (1984) for additional discussion of literate programming.

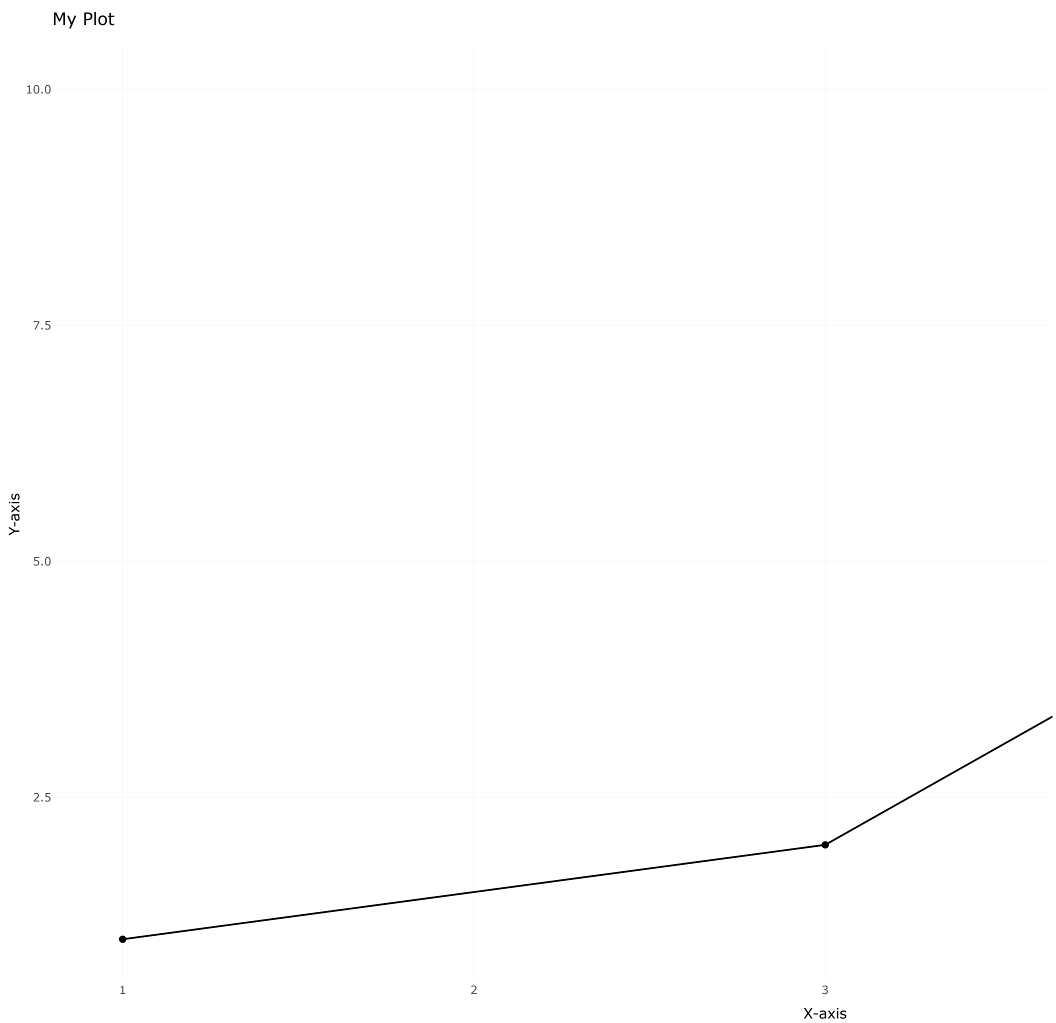
1.3 Syntax highlighting

Here's some python code:

```
import numpy as np
np.random.seed(42)
a = 1 + 2
b = a + 3
print("Hello")
```

1.4 Visualising data (R)

Here's an interactive plot generated with R:


My Plot
10.0
7.5
5.0
2.5
Y-axis
1
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1.5 A youtube clip:

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1.6 An 'iframe' to a different page (e.g. my simulations)

1.6.1 Mermaid

Diagrams (Mermaid syntax):

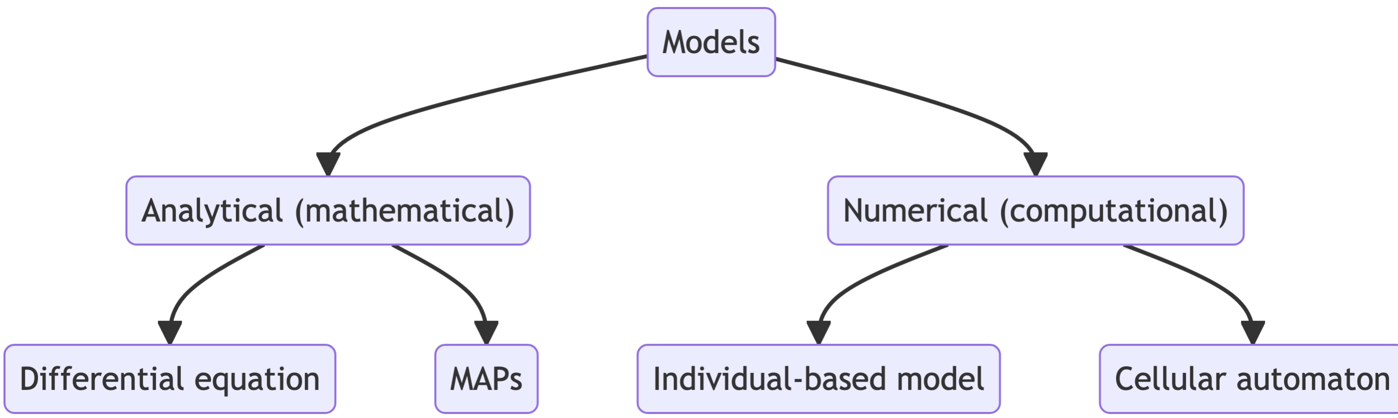

Figure 1.1: Types of models

Which can be referred to Figure **??**.

1.6.2 Callouts

Call-outs can organise information and highlight important points.

> **Note**
>
> Note that there are five types of callouts, including: `note`, `warning`, `important`, `tip`, and `caution`.

> **Tip with Title**
>
> This is an example of a callout with a title.

Expand To Learn About Collapse

This is an example of a 'folded' caution callout that can be expanded by the user. You can use `collapse="true"` to collapse it by default or `collapse="false"` to make a collapsible callout that is expanded by default.

Tip **??**: Cross-Referencing a Tip

Add an ID starting with `#tip-` to reference a tip.

See Tip **??**...

1.6.3 How to format questions/problem sets

Exercise 1.1 (Test 1)**.** The equation of any straight line, called a linear equation, can be written as:

$$y = mx + b \tag{1.2}$$

Refer to the equation like this Equation **??** or like Customlabel **??**.

a. Blabla?

b. Of blablabla?

1.6.4 Sharing data tables:

Show 5 entries Search:

	x1	x2	x3	x4	y1	y2	y3	y4
1	10	10	10	8	8.04	9.14	7.46	6.58
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4	9	9	9	8	8.81	8.77	7.11	8.84
5	11	11	11	8	8.33	9.26	7.81	8.47

Showing 1 to 5 of 11 entries Previous 1 2 3 Next

2 General course info

Our names, email addresses, an overview of the course content, learning goals, tips, grading, group formation, usage of Brightspace, materials they need, required attendencee, and feedback is welcome blabla.

3 Schedule

The schedule of the course and important deadlines are outlined below. The course is divided into blabla modules, each with its own set of topics and blabla. The schedule is subject to change, and any updates will be communicated in advance. Blabla.

(paste below is the schedule of Kwanti/BioMS as an example)

`file:////private/var/folders/22/dvqytf_15mqgwc9rn9l42y5w0000gn/T/RtmpyTgHQy/file7b6f4bc0af09/`

Show 10 entries Search:

Wk	Deel	Datum	Dag	Tijd	Activiteit	Content	Hfst
1	R en basiswiskunde	03/02/2025	Maandag	13:15 - 15:00	Hoorcollege	Introductie cursus + Introductie programmeren	1
1	R en basiswiskunde	03/02/2025	Maandag	15:15 - 17:00	Werkcollege	R installeren + Rstudio	1
1	R en basiswiskunde	04/02/2025	Dinsdag	9:00 - 10:45	Hoorcollege	Basis R	2
1	R en basiswiskunde	04/02/2025	Dinsdag	11:00 - 12:45	Werkcollege	Basis R	2
1	R en basiswiskunde	04/02/2025	Dinsdag	13.15 - 17:00	Zelfstudie	Inlezen wiskunde: inleiding, algebra, breuken, exponenten, logaritmen	3 t/m 6
1	R en basiswiskunde	06/02/2025	Donderdag	9:00 - 10:45	Hoorcollege	Inleiding, algebra, breuken, exponenten, logaritmen	3 t/m 6
1	R en basiswiskunde	06/02/2025	Donderdag	11:00 - 12:45	Werkcollege	Inleiding, algebra, breuken, exponenten, logaritmen	3 t/m 6
1	R en basiswiskunde	06/02/2025	Donderdag	13.15 - 17:00	Zelfstudie	Inlezen wiskunde: asymptoten, limieten, afgeleiden, schetsen	7 t/m 9
2	R en basiswiskunde	10/02/2025	Maandag	13:15 - 15:00	Hoorcollege	Asymptoten, limieten, afgeleiden, schetsen	7 t/m 9
2	R en basiswiskunde	10/02/2025	Maandag	15:15 - 17:00	Werkcollege	Asymptoten, limieten, afgeleiden, schetsen	7 t/m 9

Showing 1 to 10 of 72 entries

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Part II

I) Pattern formation

4 Pattern formation

4.1 Equations

Here's an equation:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = rN(1 - \frac{N}{K}) \tag{4.1}$$

And Equation **??** is a reference to the equation above.

4.2 References

See Knuth (1984) for additional discussion of literate programming.

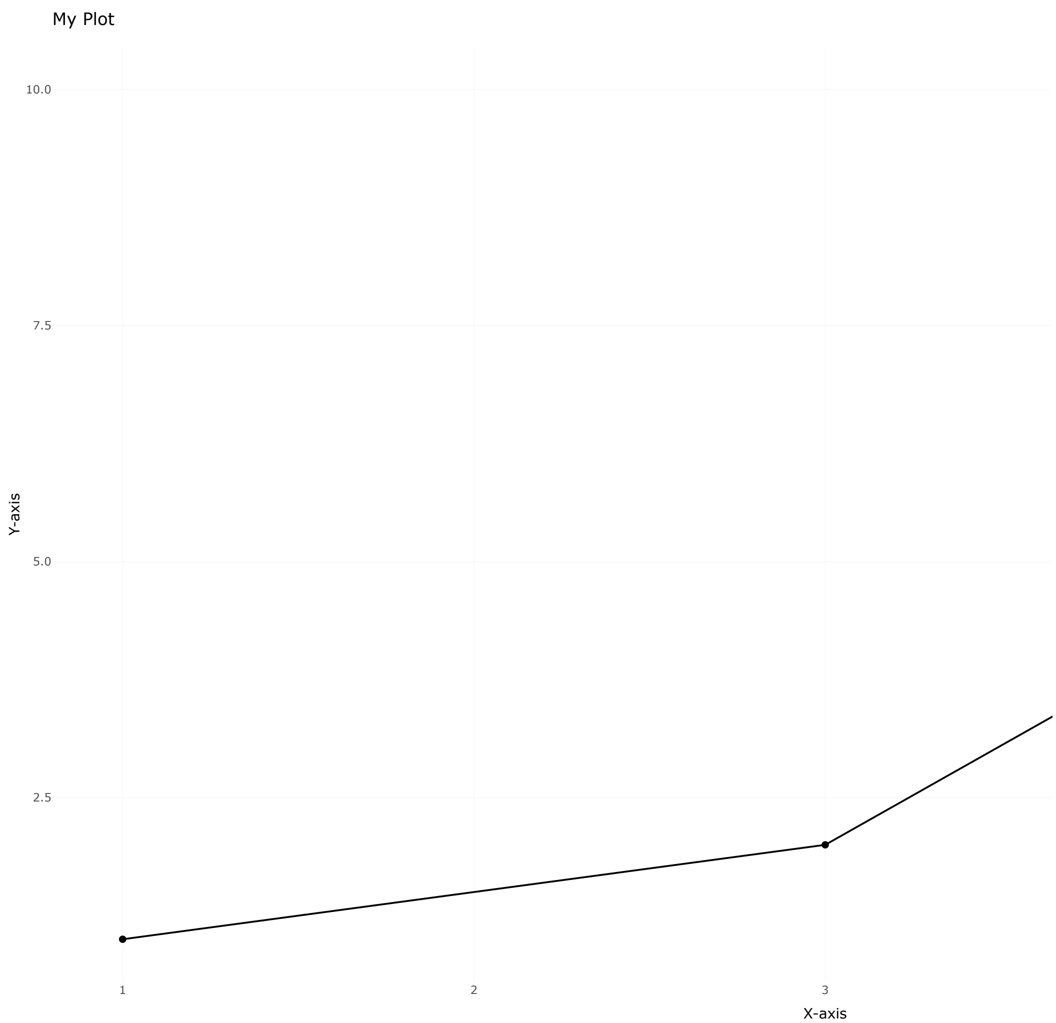
4.3 Syntax highlighting

Here's some python code:

```python
import numpy as np
np.random.seed(42)
a = 1 + 2
b = a + 3
print("Hello")
```

4.4 Visualising data (R)

Here's an interactive plot generated with R: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4.5 A youtube clip:

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4.6 An 'iframe' to a different page (e.g. my simulations)

4.6.1 Mermaid

Diagrams (Mermaid syntax):

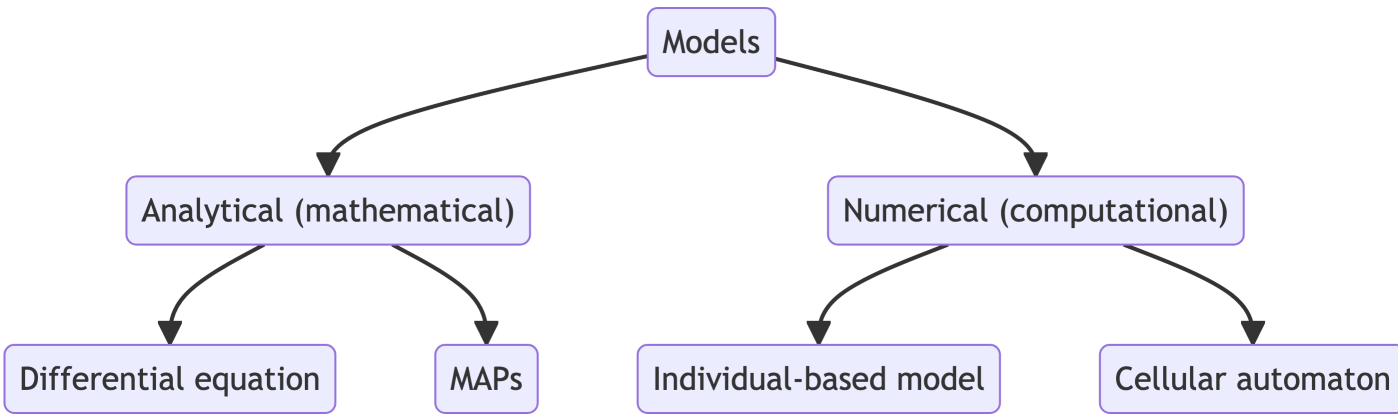

Figure 4.1: Types of models

Which can be referred to Figure **??**.

4.6.2 Callouts

Call-outs can organise information and highlight important points.

Note

Note that there are five types of callouts, including: `note`, `warning`, `important`, `tip`, and `caution`.

Tip with Title

This is an example of a callout with a title.

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Tip **??**: Cross-Referencing a Tip

Add an ID starting with `#tip-` to reference a tip.

See Tip **??**...

4.6.3 How to format questions/problem sets

Exercise 4.1 (Test 1)**.** The equation of any straight line, called a linear equation, can be written as:

$$y = mx + b \tag{4.2}$$

Refer to the equation like this Equation **??** or like Customlabel **??**.

a. Blabla?

b. Of blablabla?

4.6.4 Sharing data tables:

Show 5 entries Search:

	x1	x2	x3	x4	y1	y2	y3	y4
1	10	10	10	8	8.04	9.14	7.46	6.58
2	8	8	8	8	6.95	8.14	6.77	5.76
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5 Practical 1

5.1 Equations

Here's an equation:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = rN(1 - \frac{N}{K}) \tag{5.1}$$

And Equation **??** is a reference to the equation above.

5.2 References

See Knuth (1984) for additional discussion of literate programming.

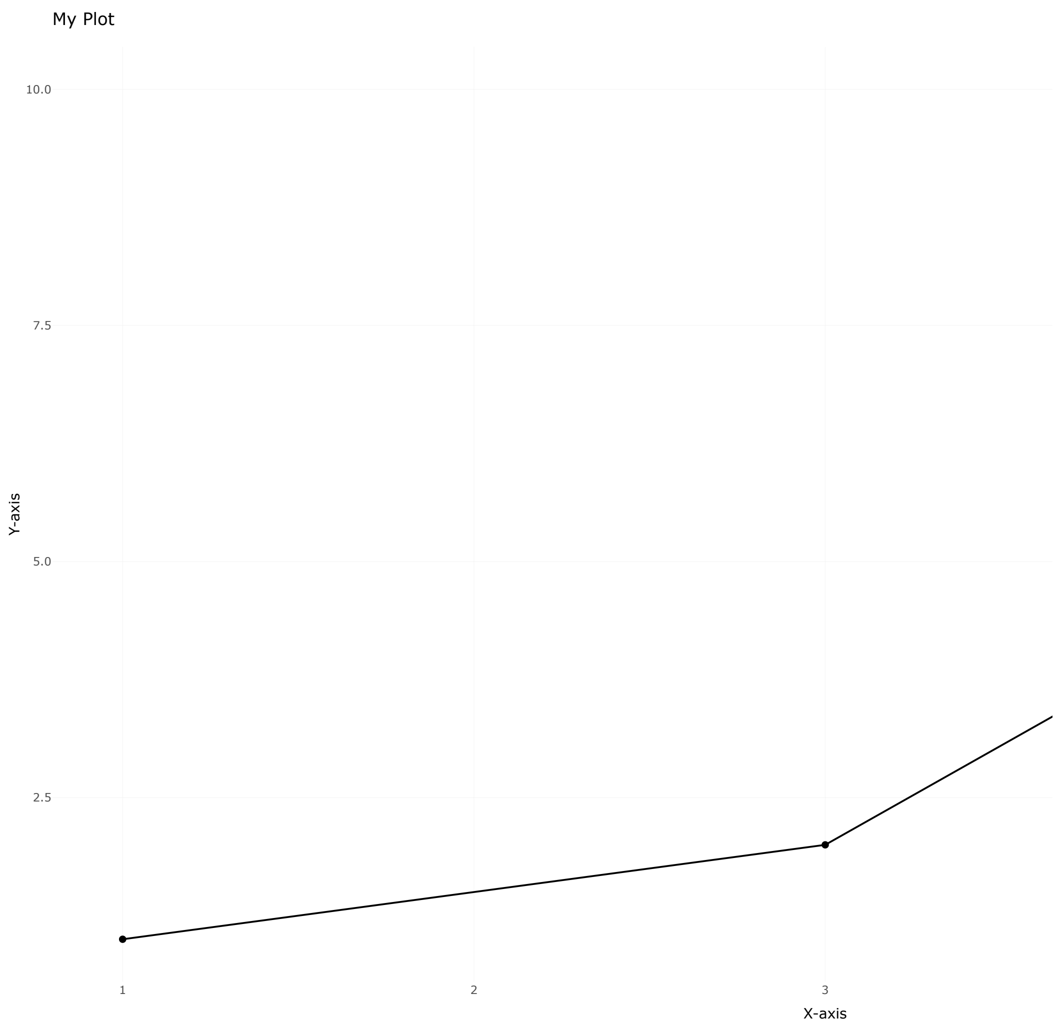
5.3 Syntax highlighting

Here's some python code:

```
import numpy as np
np.random.seed(42)
a = 1 + 2
b = a + 3
print("Hello")
```

5.4 Visualising data (R)

Here's an interactive plot generated with R: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Diagrams (Mermaid syntax):

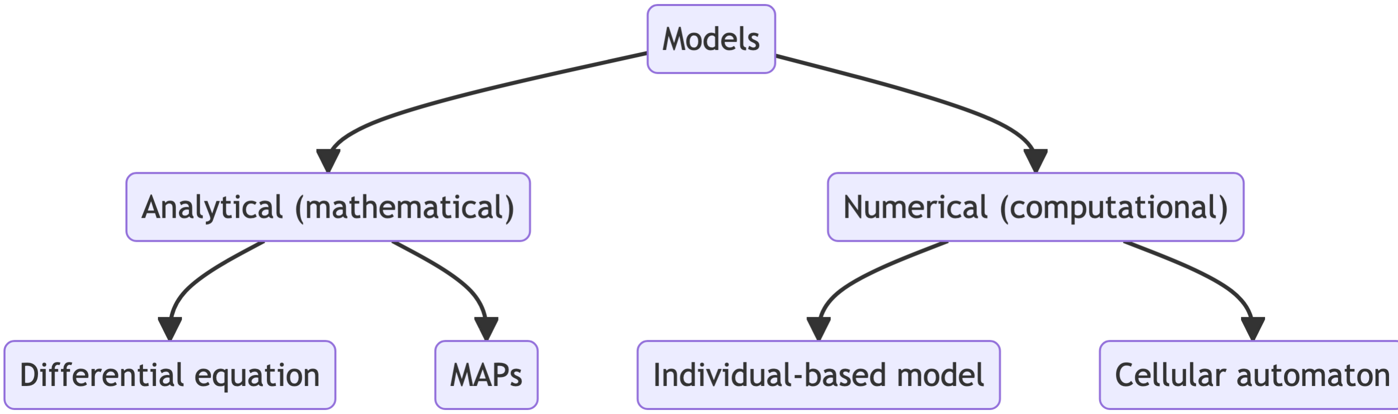

Figure 5.1: Types of models

Which can be referred to Figure **??**.

5.6.2 Callouts

Call-outs can organise information and highlight important points.

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Tip **??**: Cross-Referencing a Tip

Add an ID starting with `#tip-` to reference a tip.

See Tip **??**...

5.6.3 How to format questions/problem sets

Exercise 5.1 (Test 1)**.** The equation of any straight line, called a linear equation, can be written as:

$$y = mx + b \tag{5.2}$$

Refer to the equation like this Equation **??** or like Customlabel **??**.

a. Blabla?

b. Of blablabla?

5.6.4 Sharing data tables:

Show 5 entries Search:

	x1	x2	x3	x4	y1	y2	y3	y4
1	10	10	10	8	8.04	9.14	7.46	6.58
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6 Practical 2

6.1 Equations

Here's an equation:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = rN(1 - \frac{N}{K}) \tag{6.1}$$

And Equation **??** is a reference to the equation above.

6.2 References

See Knuth (1984) for additional discussion of literate programming.

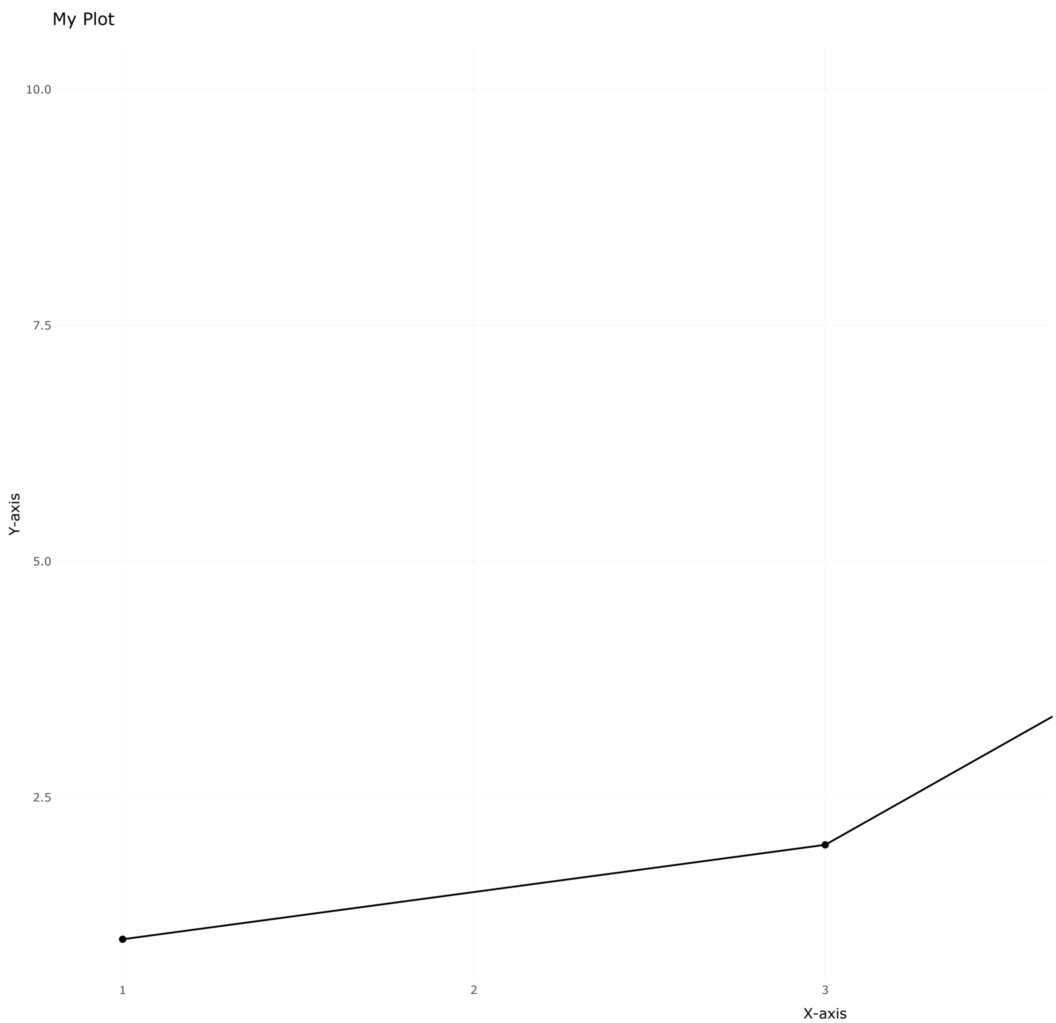
6.3 Syntax highlighting

Here's some python code:

```python
import numpy as np
np.random.seed(42)
a = 1 + 2
b = a + 3
print("Hello")
```

6.4 Visualising data (R)

Here's an interactive plot generated with R: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Diagrams (Mermaid syntax):

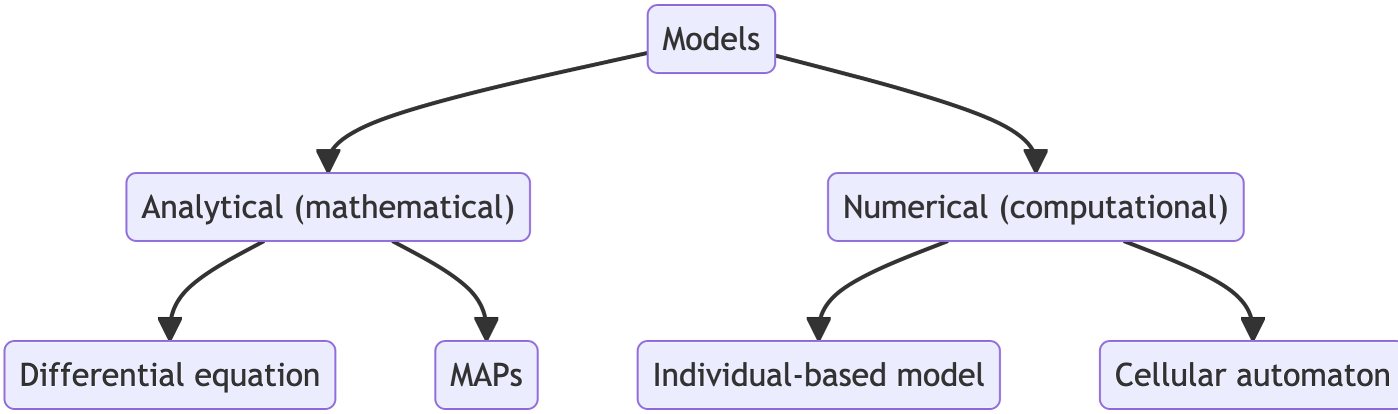

Figure 6.1: Types of models

Which can be referred to Figure **??**.

6.6.2 Callouts

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See Tip **??**...

6.6.3 How to format questions/problem sets

Exercise 6.1 (Test 1)**.** The equation of any straight line, called a linear equation, can be written as:

$$y = mx + b \tag{6.2}$$

Refer to the equation like this Equation **??** or like Customlabel **??**.

a. Blabla?

b. Of blablabla?

6.6.4 Sharing data tables:

Show 5 entries Search:

	x1	x2	x3	x4	y1	y2	y3	y4
1	10	10	10	8	8.04	9.14	7.46	6.58
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7 Practical 3

7.1 Equations

Here's an equation:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = rN(1 - \frac{N}{K}) \tag{7.1}$$

And Equation **??** is a reference to the equation above.

7.2 References

See Knuth (1984) for additional discussion of literate programming.

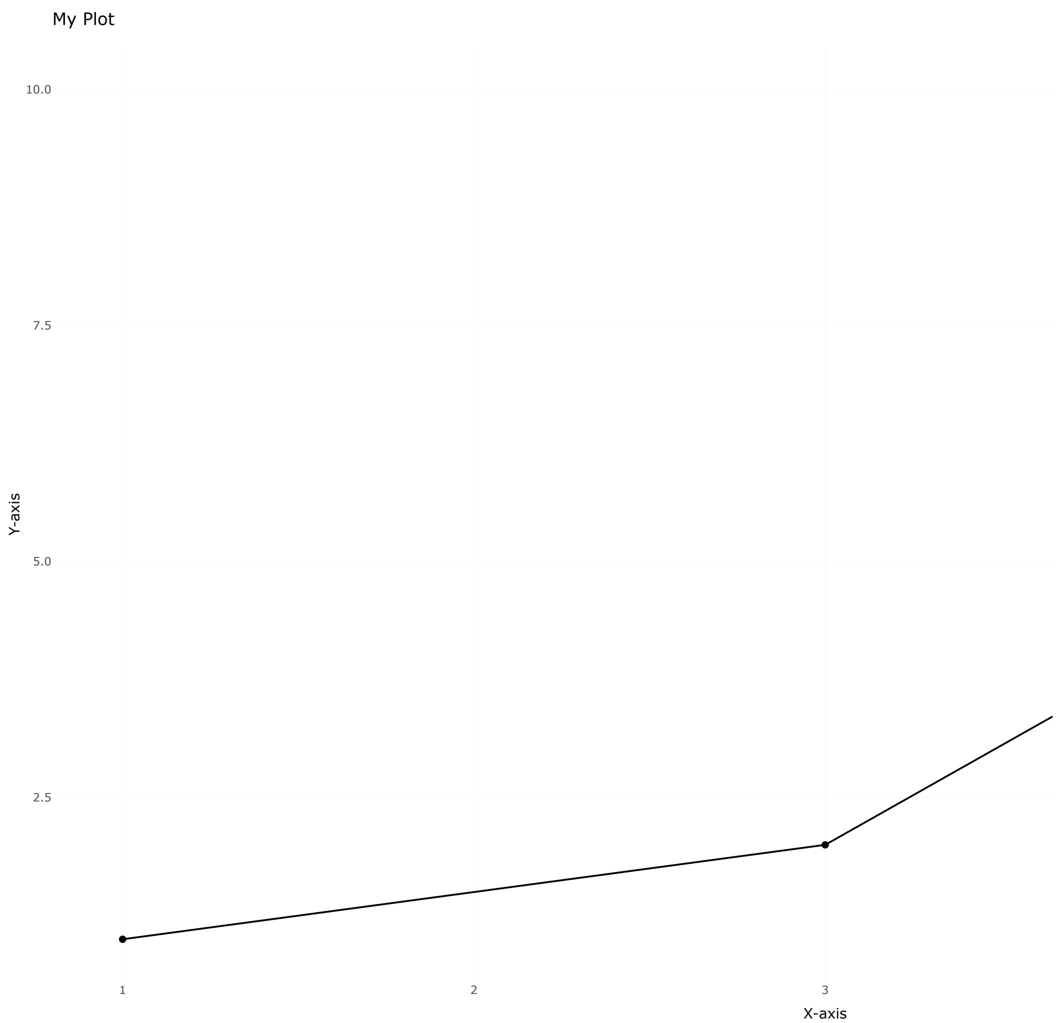
7.3 Syntax highlighting

Here's some python code:

```python
import numpy as np
np.random.seed(42)
a = 1 + 2
b = a + 3
print("Hello")
```

7.4 Visualising data (R)

Here's an interactive plot generated with R: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7.5 A youtube clip:

https://www.youtube.com/embed/wo9vZccmqwc

7.6 An 'iframe' to a different page (e.g. my simulations)

7.6.1 Mermaid

Diagrams (Mermaid syntax):

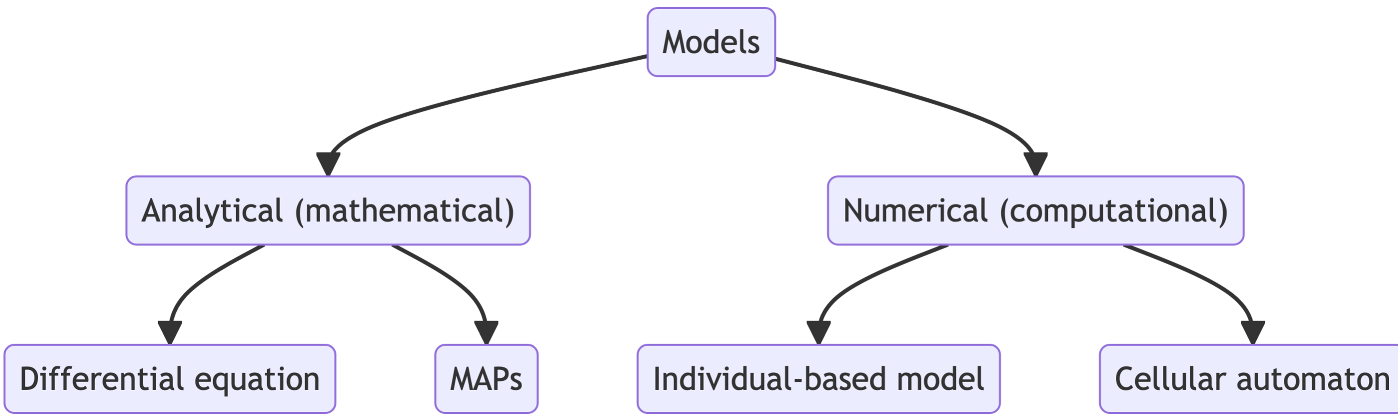

Figure 7.1: Types of models

Which can be referred to Figure **??**.

7.6.2 Callouts

Call-outs can organise information and highlight important points.

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Tip **??**: Cross-Referencing a Tip

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See Tip **??**...

7.6.3 How to format questions/problem sets

Exercise 7.1 (Test 1)**.** The equation of any straight line, called a linear equation, can be written as:

$$y = mx + b \tag{7.2}$$

Refer to the equation like this Equation **??** or like Customlabel **??**.

a. Blabla?

b. Of blablabla?

7.6.4 Sharing data tables:

Show 5 entries Search:

	x1	x2	x3	x4	y1	y2	y3	y4
1	10	10	10	8	8.04	9.14	7.46	6.58
2	8	8	8	8	6.95	8.14	6.77	5.76
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4	9	9	9	8	8.81	8.77	7.11	8.84
5	11	11	11	8	8.33	9.26	7.81	8.47

Showing 1 to 5 of 11 entries Previous 1 2 3 Next

Part III

II) Morphogenesis

8 What is morphogenesis?

8.1 Equations

Here's an equation:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = rN(1 - \frac{N}{K}) \tag{8.1}$$

And Equation **??** is a reference to the equation above.

8.2 References

See Knuth (1984) for additional discussion of literate programming.

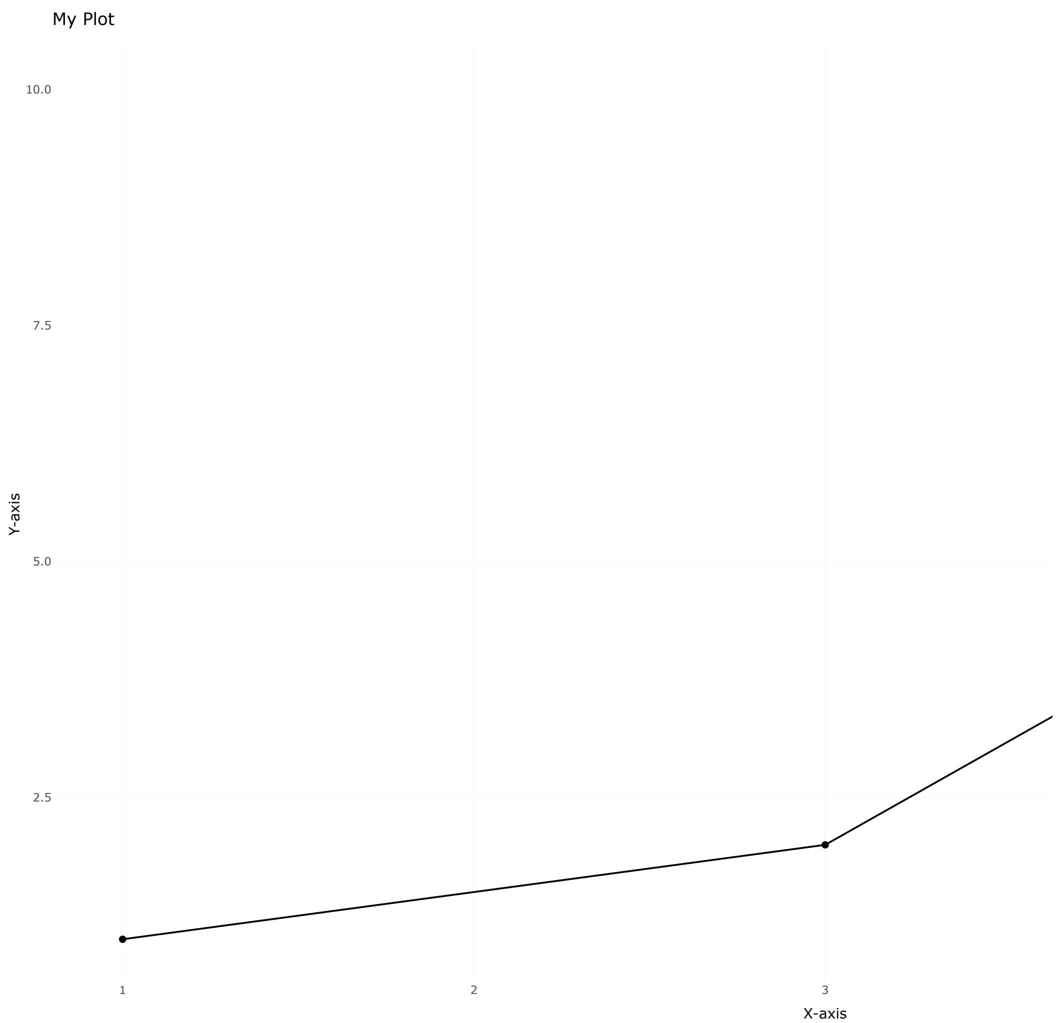
8.3 Syntax highlighting

Here's some python code:

```
import numpy as np
np.random.seed(42)
a = 1 + 2
b = a + 3
print("Hello")
```

8.4 Visualising data (R)

Here's an interactive plot generated with R: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https://www.youtube.com/embed/wo9vZccmqwc

8.6 An 'iframe' to a different page (e.g. my simulations)

8.6.1 Mermaid

Diagrams (Mermaid syntax):

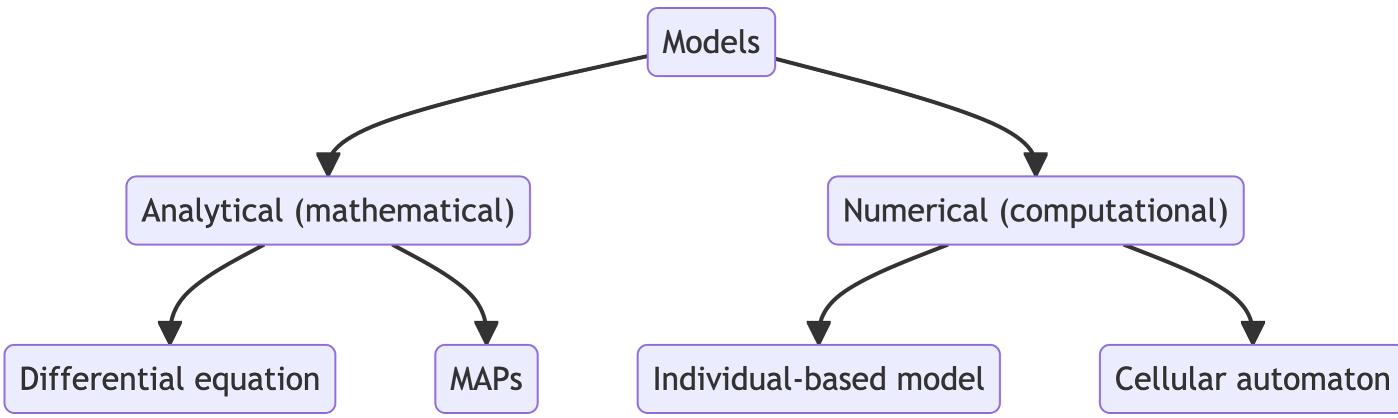

Figure 8.1: Types of models

Which can be referred to Figure **??**.

8.6.2 Callouts

Call-outs can organise information and highlight important points.

> **Note**
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Tip **??**: Cross-Referencing a Tip

Add an ID starting with `#tip-` to reference a tip.

See Tip **??**...

8.6.3 How to format questions/problem sets

Exercise 8.1 (Test 1)**.** The equation of any straight line, called a linear equation, can be written as:

$$y = mx + b \tag{8.2}$$

Refer to the equation like this Equation **??** or like Customlabel **??**.

a. Blabla?

b. Of blablabla?

8.6.4 Sharing data tables:

Show 5 entries Search:

	x1	x2	x3	x4	y1	y2	y3	y4
1	10	10	10	8	8.04	9.14	7.46	6.58
2	8	8	8	8	6.95	8.14	6.77	5.76
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5	11	11	11	8	8.33	9.26	7.81	8.47

Showing 1 to 5 of 11 entries Previous 1 2 3 Next

9 Practical 1

9.1 Equations

Here's an equation:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = rN(1 - \frac{N}{K}) \tag{9.1}$$

And Equation **??** is a reference to the equation above.

9.2 References

See Knuth (1984) for additional discussion of literate programming.

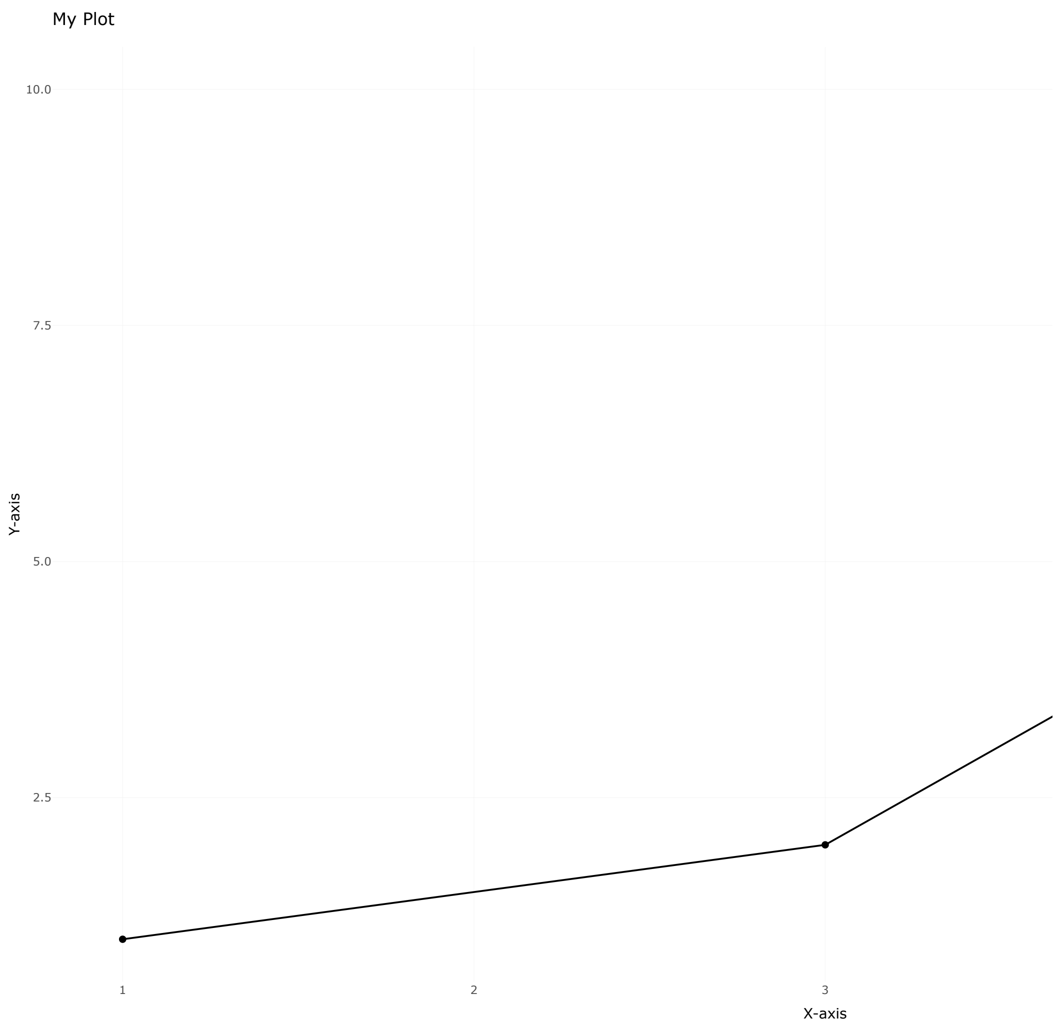
9.3 Syntax highlighting

Here's some python code:

```
import numpy as np
np.random.seed(42)
a = 1 + 2
b = a + 3
print("Hello")
```

9.4 Visualising data (R)

Here's an interactive plot generated with R: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9.6 An 'iframe' to a different page (e.g. my simulations)

9.6.1 Mermaid

Diagrams (Mermaid syntax):

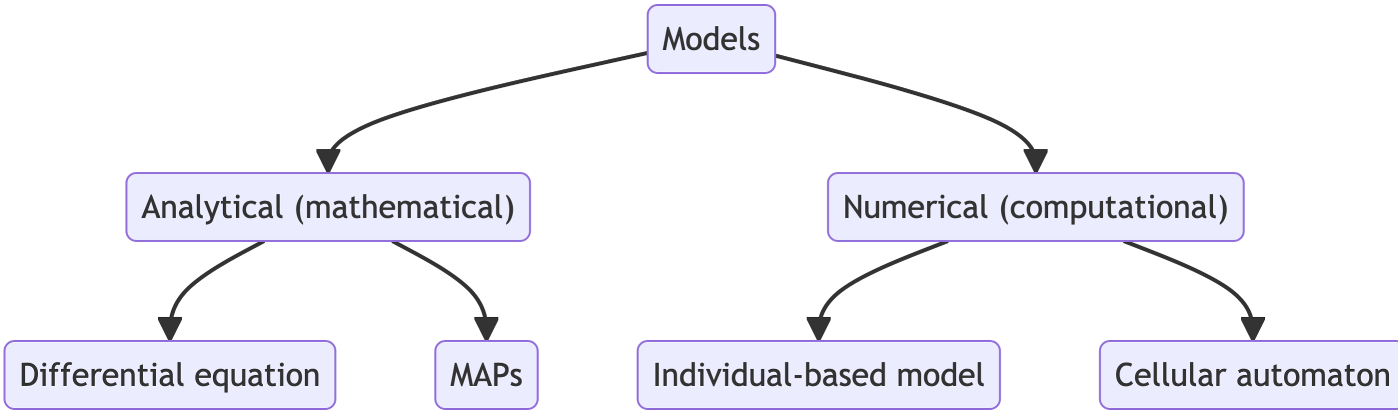

Figure 9.1: Types of models

Which can be referred to Figure **??**.

9.6.2 Callouts

Call-outs can organise information and highlight important points.

> Note
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> Tip with Title
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Tip **??**: Cross-Referencing a Tip

Add an ID starting with `#tip-` to reference a tip.

See Tip **??**...

9.6.3 How to format questions/problem sets

Exercise 9.1 (Test 1)**.** The equation of any straight line, called a linear equation, can be written as:

$$y = mx + b \tag{9.2}$$

Refer to the equation like this Equation **??** or like Customlabel **??**.

a. Blabla?

b. Of blablabla?

9.6.4 Sharing data tables:

Show 5 entries Search:

	x1	x2	x3	x4	y1	y2	y3	y4
1	10	10	10	8	8.04	9.14	7.46	6.58
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10 Practical 2

10.1 Equations

Here's an equation:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = rN(1 - \frac{N}{K}) \tag{10.1}$$

And Equation **??** is a reference to the equation above.

10.2 References

See Knuth (1984) for additional discussion of literate programming.

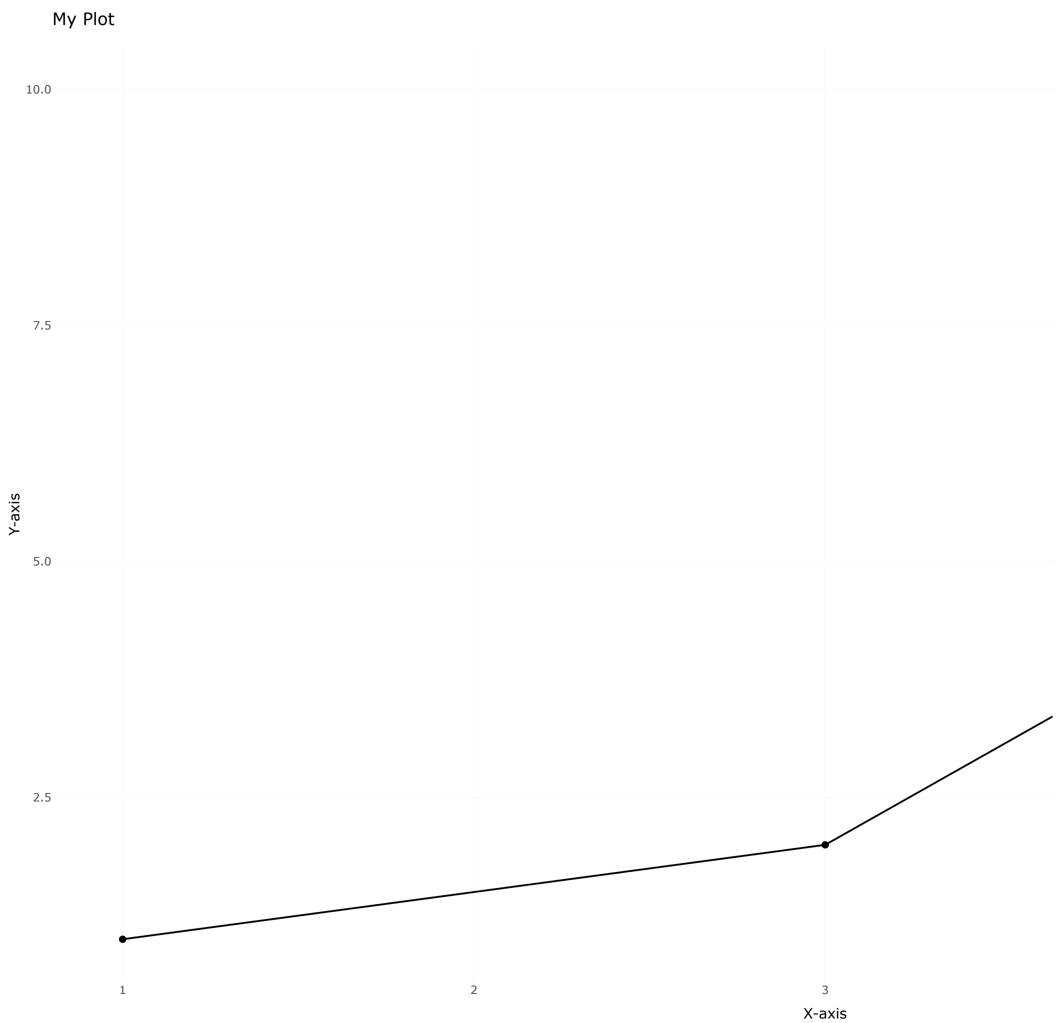
10.3 Syntax highlighting

Here's some python code:

```python
import numpy as np
np.random.seed(42)
a = 1 + 2
b = a + 3
print("Hello")
```

10.4 Visualising data (R)

Here's an interactive plot generated with R: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10.5 A youtube clip:

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10.6 An 'iframe' to a different page (e.g. my simulations)

10.6.1 Mermaid

Diagrams (Mermaid syntax):

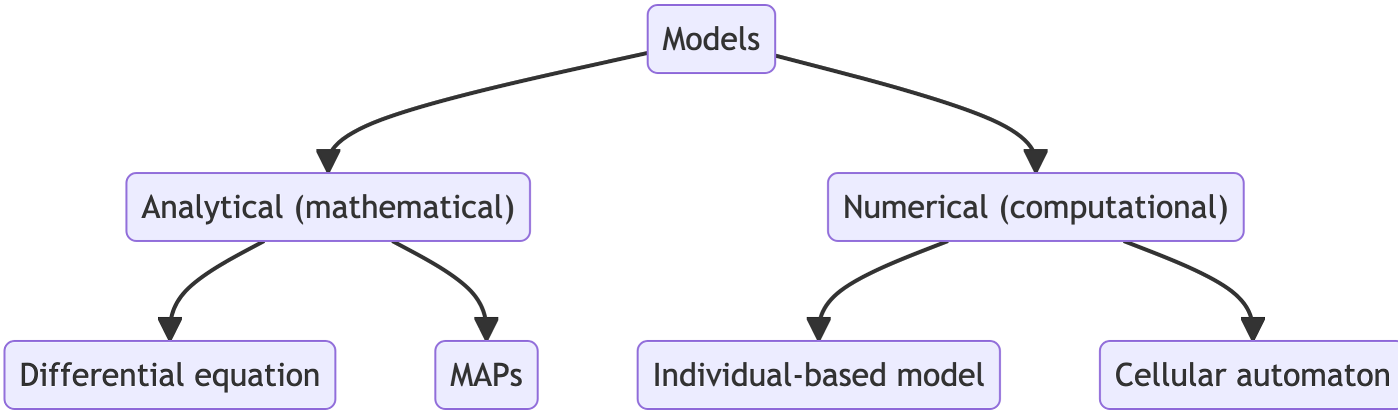


Figure 10.1: Types of models

Which can be referred to Figure **??**.

10.6.2 Callouts

Call-outs can organise information and highlight important points.

> **Note**
>
> Note that there are five types of callouts, including: `note`, `warning`, `important`, `tip`, and `caution`.

> **Tip with Title**
>
> This is an example of a callout with a title.

Expand To Learn About Collapse

This is an example of a 'folded' caution callout that can be expanded by the user. You can use `collapse="true"` to collapse it by default or `collapse="false"` to make a collapsible callout that is expanded by default.

Tip **??**: Cross-Referencing a Tip

Add an ID starting with `#tip-` to reference a tip.

See Tip **??**...

10.6.3 How to format questions/problem sets

Exercise 10.1 (Test 1)**.** The equation of any straight line, called a linear equation, can be written as:

$$y = mx + b \tag{10.2}$$

Refer to the equation like this Equation **??** or like Customlabel **??**.

a. Blabla?

b. Of blablabla?

10.6.4 Sharing data tables:

Show 5 entries Search:

	x1	x2	x3	x4	y1	y2	y3	y4
1	10	10	10	8	8.04	9.14	7.46	6.58
2	8	8	8	8	6.95	8.14	6.77	5.76
3	13	13	13	8	7.58	8.74	12.74	7.71
4	9	9	9	8	8.81	8.77	7.11	8.84
5	11	11	11	8	8.33	9.26	7.81	8.47

Showing 1 to 5 of 11 entries Previous 1 2 3 Next

Part IV

III) Cell differentiation

11 Differentiation introduction

11.1 Equations

Here's an equation:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = rN(1 - \frac{N}{K}) \tag{11.1}$$

And Equation **??** is a reference to the equation above.

11.2 References

See Knuth (1984) for additional discussion of literate programming.

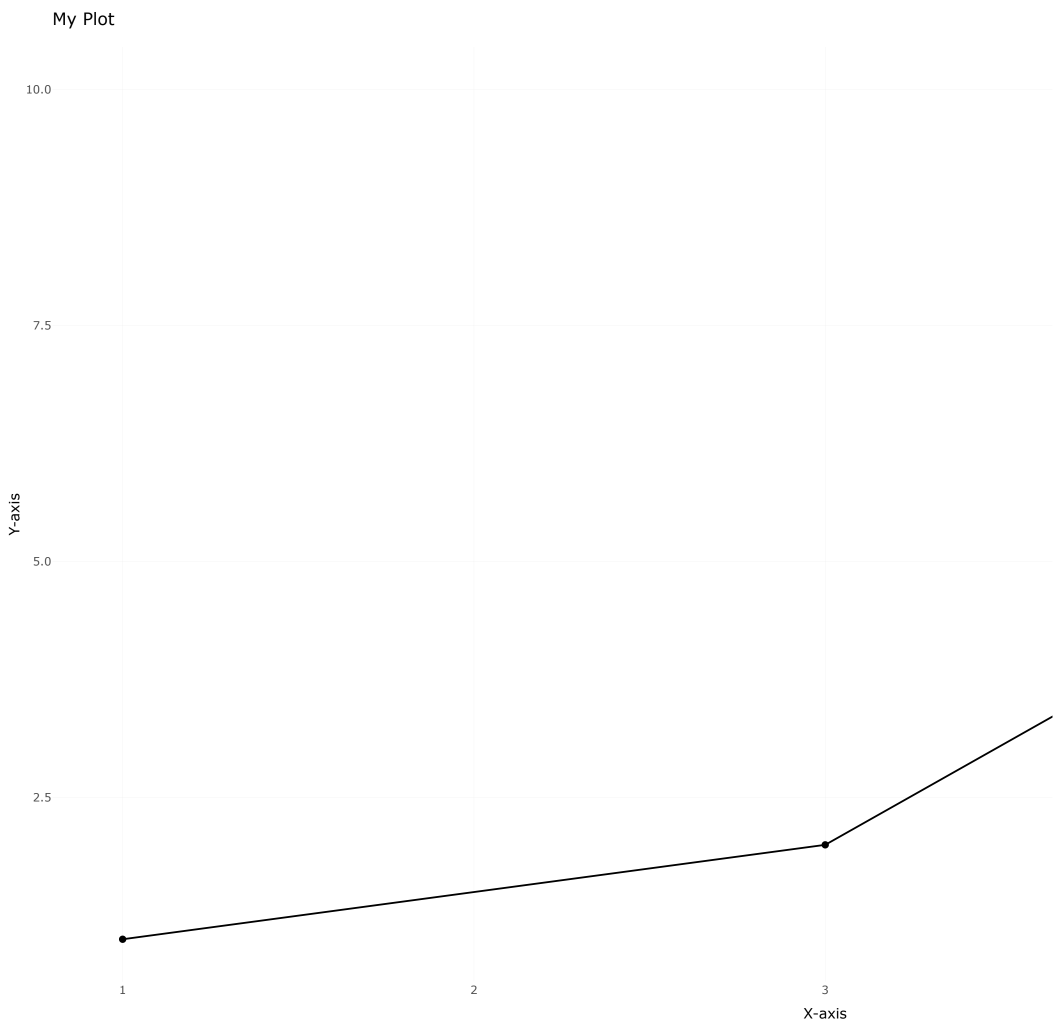
11.3 Syntax highlighting

Here's some python code:

```python
import numpy as np
np.random.seed(42)
a = 1 + 2
b = a + 3
print("Hello")
```

11.4 Visualising data (R)

Here's an interactive plot generated with R:


My Plot
10.0
7.5
5.0
2.5
Y-axis
1
2
3
X-axis

11.5 A youtube clip:

https://www.youtube.com/embed/wo9vZccmqwc

11.6 An 'iframe' to a different page (e.g. my simulations)

11.6.1 Mermaid

Diagrams (Mermaid syntax):

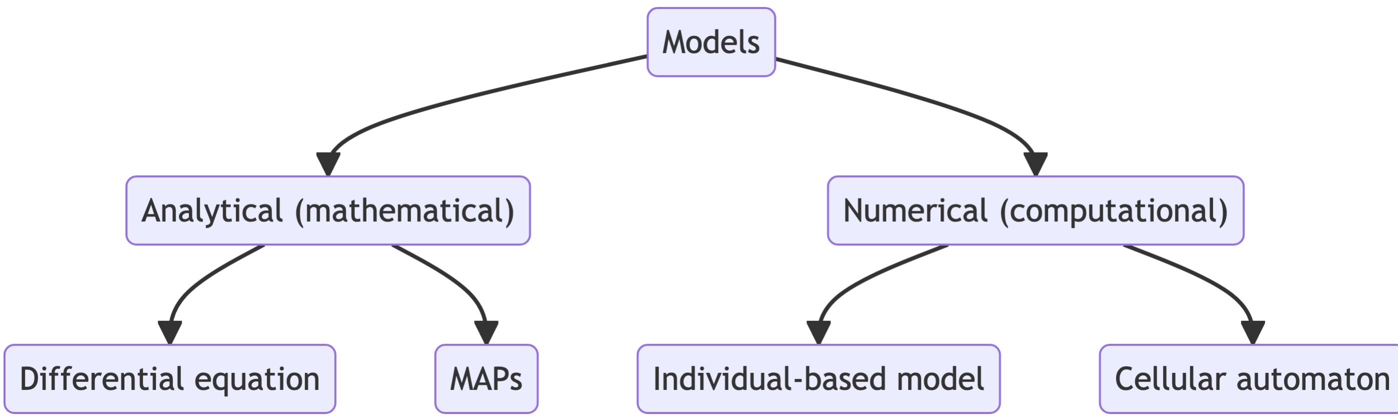


Figure 11.1: Types of models

Which can be referred to Figure **??**.

11.6.2 Callouts

Call-outs can organise information and highlight important points.

> **Note**
>
> Note that there are five types of callouts, including: `note`, `warning`, `important`, `tip`, and `caution`.

> **Tip with Title**
>
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Tip **??**: Cross-Referencing a Tip

Add an ID starting with `#tip-` to reference a tip.

See Tip **??**...

11.6.3 How to format questions/problem sets

Exercise 11.1 (Test 1)**.** The equation of any straight line, called a linear equation, can be written as:

$$y = mx + b \tag{11.2}$$

Refer to the equation like this Equation **??** or like Customlabel **??**.

a. Blabla?

b. Of blablabla?

11.6.4 Sharing data tables:

Show 5 entries Search:

	x1	x2	x3	x4	y1	y2	y3	y4
1	10	10	10	8	8.04	9.14	7.46	6.58
2	8	8	8	8	6.95	8.14	6.77	5.76
3	13	13	13	8	7.58	8.74	12.74	7.71
4	9	9	9	8	8.81	8.77	7.11	8.84
5	11	11	11	8	8.33	9.26	7.81	8.47

Showing 1 to 5 of 11 entries Previous 1 2 3 Next

12 Practical 1

12.1 Equations

Here's an equation:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = rN(1 - \frac{N}{K}) \tag{12.1}$$

And Equation **??** is a reference to the equation above.

12.2 References

See Knuth (1984) for additional discussion of literate programming.

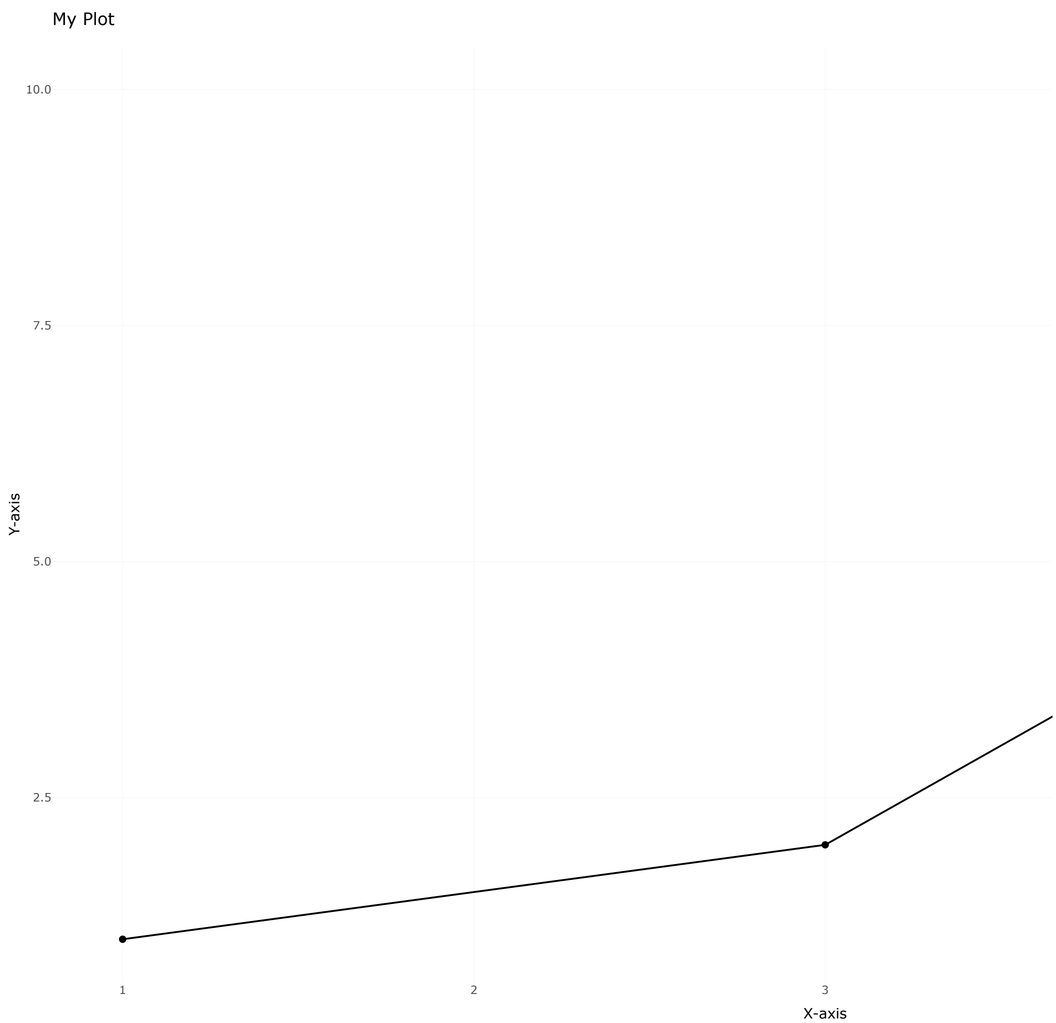
12.3 Syntax highlighting

Here's some python code:

```
import numpy as np
np.random.seed(42)
a = 1 + 2
b = a + 3
print("Hello")
```

12.4 Visualising data (R)

Here's an interactive plot generated with R:


My Plot
10.0
7.5
5.0
2.5
Y-axis
1
2
3
X-axis

12.5 A youtube clip:

https://www.youtube.com/embed/wo9vZccmqwc

12.6 An 'iframe' to a different page (e.g. my simulations)

12.6.1 Mermaid

Diagrams (Mermaid syntax):

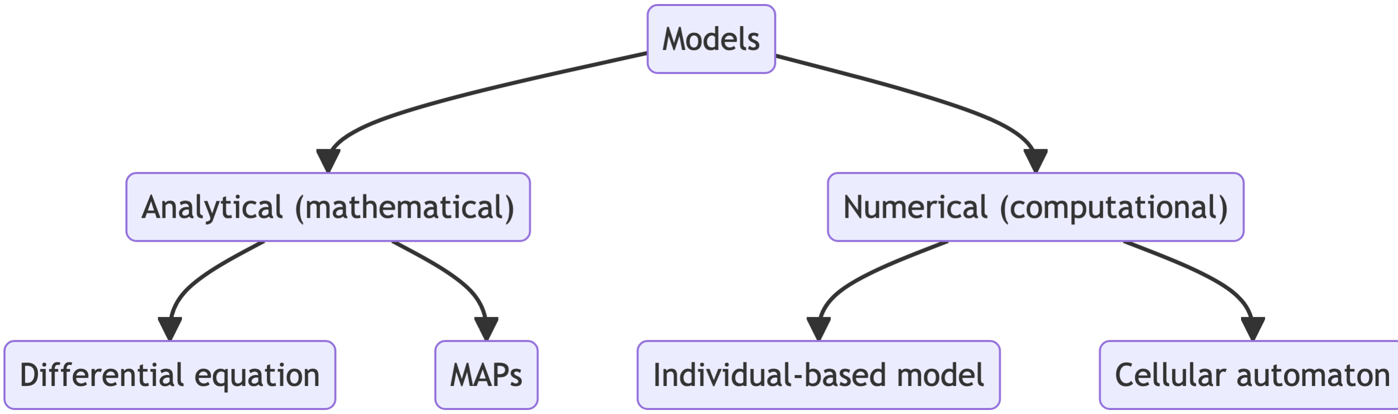


Figure 12.1: Types of models

Which can be referred to Figure **??**.

12.6.2 Callouts

Call-outs can organise information and highlight important points.

> **Note**
>
> Note that there are five types of callouts, including: `note`, `warning`, `important`, `tip`, and `caution`.

> **Tip with Title**
>
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Tip **??**: Cross-Referencing a Tip

Add an ID starting with `#tip-` to reference a tip.

See Tip **??**...

12.6.3 How to format questions/problem sets

Exercise 12.1 (Test 1)**.** The equation of any straight line, called a linear equation, can be written as:

$$y = mx + b \tag{12.2}$$

Refer to the equation like this Equation **??** or like Customlabel **??**.

a. Blabla?

b. Of blablabla?

12.6.4 Sharing data tables:

Show 5 entries Search:

	x1	x2	x3	x4	y1	y2	y3	y4
1	10	10	10	8	8.04	9.14	7.46	6.58
2	8	8	8	8	6.95	8.14	6.77	5.76
3	13	13	13	8	7.58	8.74	12.74	7.71
4	9	9	9	8	8.81	8.77	7.11	8.84
5	11	11	11	8	8.33	9.26	7.81	8.47

Showing 1 to 5 of 11 entries Previous 1 2 3 Next

13 Practical 2

13.1 Equations

Here's an equation:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = rN(1 - \frac{N}{K}) \tag{13.1}$$

And Equation **??** is a reference to the equation above.

13.2 References

See Knuth (1984) for additional discussion of literate programming.

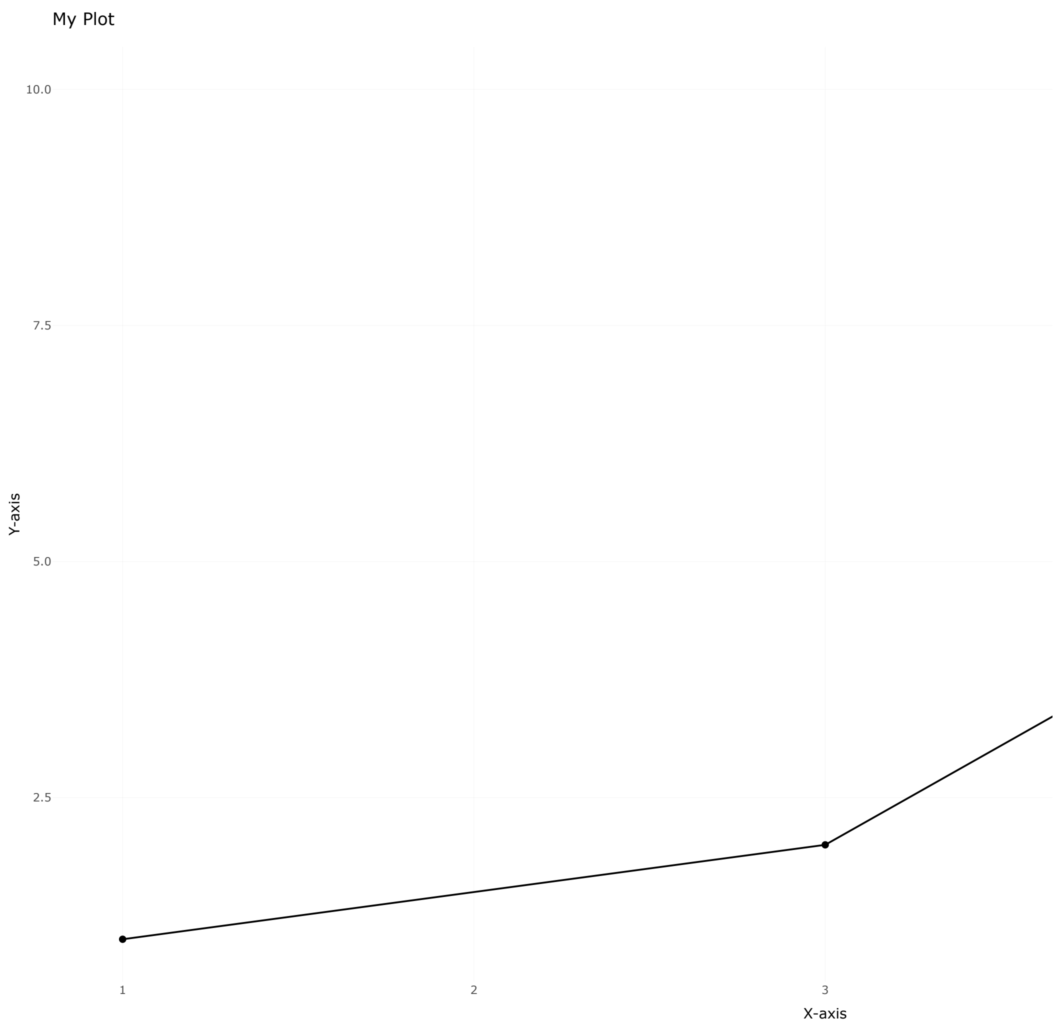
13.3 Syntax highlighting

Here's some python code:

```
import numpy as np
np.random.seed(42)
a = 1 + 2
b = a + 3
print("Hello")
```

13.4 Visualising data (R)

Here's an interactive plot generated with R:


My Plot
10.0
7.5
5.0
2.5
Y-axis
1
2
3
X-axis

13.5 A youtube clip:

https://www.youtube.com/embed/wo9vZccmqwc

13.6 An 'iframe' to a different page (e.g. my simulations)

13.6.1 Mermaid

Diagrams (Mermaid syntax):

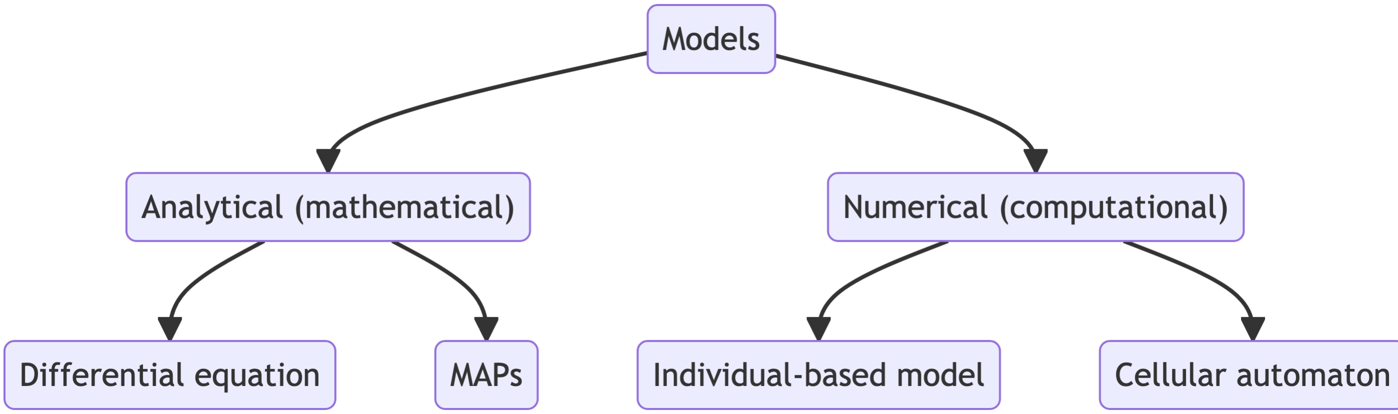


Figure 13.1: Types of models

Which can be referred to Figure **??**.

13.6.2 Callouts

Call-outs can organise information and highlight important points.

> **Note**
>
> Note that there are five types of callouts, including: `note`, `warning`, `important`, `tip`, and `caution`.

> **Tip with Title**
>
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Tip **??**: Cross-Referencing a Tip

Add an ID starting with `#tip-` to reference a tip.

See Tip **??**...

13.6.3 How to format questions/problem sets

Exercise 13.1 (Test 1)**.** The equation of any straight line, called a linear equation, can be written as:

$$y = mx + b \tag{13.2}$$

Refer to the equation like this Equation **??** or like Customlabel **??**.

a. Blabla?

b. Of blablabla?

13.6.4 Sharing data tables:

Show 5 entries Search:

	x1	x2	x3	x4	y1	y2	y3	y4
1	10	10	10	8	8.04	9.14	7.46	6.58
2	8	8	8	8	6.95	8.14	6.77	5.76
3	13	13	13	8	7.58	8.74	12.74	7.71
4	9	9	9	8	8.81	8.77	7.11	8.84
5	11	11	11	8	8.33	9.26	7.81	8.47

Showing 1 to 5 of 11 entries Previous 1 2 3 Next

Part V

IV) Evolution

14 Introduction to evolution

14.1 Evolution: Life's most clever algorithm

Evolution is the process by which populations change over generations through variation, inheritance, and differential survival. This idea, famously championed by Darwin and Wallace, explains the diversity of life on Earth. It describes how species adapt to their environments, how new species arise, and how complex traits evolve. Today, the concept of evolution has expanded beyond biology, it's recognised as a powerful algorithm that drives adaptation in systems ranging from bacteria (genes) to ideas (memes), from DNA (nucleotides) to computer code (bits).

In this part of the course, we'll bring these ingredients to life by writing our own simulations and watching evolution unfold on the screen. And while our digital creatures aren't made of flesh and blood, the evolutionary battles they fight, the strategies they discover, and the adaptations they evolve are as real, and often as surprising, as anything found in nature itself.

14.2 Three ingredients

As briefly mentioned above, we just need three ingredients to have evolution by means of natural selection:

- **variation** (differences between individuals),
- **inheritance** (the passing on of traits),
- **selection** (some variants performing better than others).

The last ingredient is self-evident. Evolution by means of natural selection requires selection. It is especially the first two that are a little more tricky to really understand, as they are not always as obvious as they seem.

14.3 Balancing change and stability

To evolve, a system needs enough variation – if everyone is the same, there's nothing for selection to act on. But this variation can't just be noise; it needs to be passed on. That means inheritance can't be perfect – there must be room for change, such as through mutations – but it also can't be too sloppy. If traits aren't reliably transmitted to the next generation, then even the best adaptations will vanish before they can take hold. Evolution lives in the sweet spot: not too rigid, not too chaotic, just enough memory and just enough change. To make this a little more tangible, let us make our very first simulation.

14.4 A simple evolutionary algorithm

One simple way to simulate evolution is with a Moran process, a classic model from population genetics. Imagine a population of 100 individuals, each with a single gene that determines its fitness. This gene can have all values from 0 to 1 (let's call this value ϕ). At each time step, one individual is chosen to reproduce with a probability proportional to ϕ, producing 1 offspring. This offspring inherits their parents gene (so the same ϕ), but with a probability μ, the value changes by a small amount (a mutation). The population size will now be 101, which could be interesting if we want to study population growth. However, in a Moran process we keep it simple: one random individual is removed by the new offspring, so the population size is constant while still allowing fitter individuals to spread over time.

Here's a minimal Python example:

```python
import numpy as np
import matplotlib.pyplot as plt

np.random.seed(5)

N = 100 # Population size
fitnesses = np.full(N, 0.05)
mu = 0.01
# Updated parameters
steps = 50000
avg_fitness = []

# Moran process with mutation (logging every 10 steps)
for step in range(steps):
    probs = fitnesses / fitnesses.sum()
    parent = np.random.choice(N, p=probs)
    dead = np.random.choice(N)
```

```python
    # Copy with mutation
    new_fit = fitnesses[parent]
    if np.random.rand() < mu:
        new_fit = np.clip(new_fit + np.random.normal(0, 0.05), 0, 1)

    fitnesses[dead] = new_fit

    # Save average fitness every 10 steps
    if step % 10 == 0:
        avg_fitness.append(fitnesses.mean())

# Plotting
plt.plot(np.arange(0, steps, 10), avg_fitness)
plt.xlabel("Step")
plt.ylabel("Average fitness")
plt.title("Evolution of Fitness in a Moran Process")
plt.grid(True)
plt.tight_layout()
plt.show()
```

Exercise 14.1 (Moran process simulation)**.** Study the Python code for the evolutionary algorithm given above. Answer the following questions:

a. How “well adapted” is the initial population?
b. How are mutations implemented in the code? Can you think of other ways?
c. Can the parent be replaced by its own offspring? Why/why not?
d. Investigate which value of μ works best if you want to achieve maximum fitness in the shortest amount of steps.

14.5 What this part of the course is about

The above simulation is fun, but not really… biologically relevant. While some simplifications are necessary to make models feasible, we will investigate a few evolutionary models that are somewhat more interesting. We will discuss how to model spatial structure and local competition, how genotypes (where mutations happen) get translated into phenotypes (where selection happens), and how the environment can change over time and lead to niche construction and interactions.

15 Practical 1

15.1 Sticking together

In this practical, you will practice building your own model of collective behaviour, based on the one you saw at the end of the lecture:

The example above is a implemented in Javascript, a programming language that is widely used for web development. It is easy to share with others, interactive, and surprisingly fast. But, it's not the most "professional" programming language. Plus, at this stage of the course there is no point in learning *yet another programming language*, as you are here to learn about modelling biology. So we will stick to Python.

First, let's discuss how we can let individuals walk around in space.

15.2 Steering

We can represent a moving individual in space as a point with a position and a velocity. The position is represented by two coordinates, x and y, and the velocity is represented by two components, v_x and v_y. All movement that this individual can do, will be a matter of repeatedly updating its position based on their velocity:

To model such a vector in python, we can simply define a base point with an x- and y-coordinate, and a velocity vector with an x- and y-component. The position of the individual can then be updated by adding the velocity to the position. Combining that with a function that draws an arrow in Python, we get the following code:

CODE FOR "moving vector in Python"

```
import numpy as np
import matplotlib.pyplot as plt

# Enable interactive mode for matplotlib
plt.ion()

# Setup figure and axis for plotting the arrow
fig, ax = plt.subplots(figsize=(8, 4))
ax.set_xlim(0, 600)  # x-axis limits
ax.set_ylim(0, 250)  # y-axis limits
ax.set_aspect('equal')  # Keep aspect ratio square
ax.set_facecolor('#f0f0f0')  # Background color
ax.set_title("A moving vector with an arrowhead")  # Title

# Initial position and velocity
x, y = 250.0, 180.0      # Position coordinates
vx, vy = 5.0, 10.5        # Velocity components


def draw_arrow(x, y, vx, vy):
    """
    Draws an arrow at position (x, y) with velocity (vx, vy).
    """
    ax.clear()
    ax.set_xlim(0, 600)
    ax.set_ylim(0, 250)
    ax.set_aspect('equal')
    ax.set_facecolor('#f0f0f0')
    ax.set_title("A moving vector with an arrowhead")

    # Normalize velocity for drawing the arrow

    dx = vx*5
    dy = vy*5

    # Arrow shaft
    end_x = x + dx
    end_y = y + dy

    # Arrowhead calculation
    angle = np.arctan2(dy, dx)
    angle_offset = np.pi / 7
    hx1_x = end_x - np.cos(angle - angle_offset)
    hx1_y = end_y - np.sin(angle - angle_offset)
    hx2_x = end_x - np.cos(angle + angle_offset)
    hx2_y = end_y - np.sin(angle + angle_offset)

    # Draw shaft
    ax.quiver(x, y, dx, dy, angles='xy', scale_units='xy', scale=1, color='#007acc', width=
    # Draw base point
    ax.plot(x, y, 'o', color='#333')

    # Labels
```

Exercise 15.1 (Playing with steering arrows)**.**

a.

b.

c.

15.3 Moving "cells"

[1]

[1]The code also contains a `Visualisation` class that uses the `matplotlib` library to draw the cells and their movement, which we have tuned to speed things up a bit. You do not need to understand this part of the code, but if you are interested feel free to check it out.

STARTING CODE FOR “moving cells”

15.4 Moving the target

a.
b.
c.

15.5 Reproduction

a.
b.
c.