Differential Equations

MAT244 Student Slides

Jason Siefken
Bernardo Galvão-Sousa

Exercise 1

You are observing starfish that made their way to a previously uninhabited tide-pool. You'd like to predict the year-on-year population of these starfish.

You start with a simple assumption

$$\#\text{new children per year} \sim \text{size of current population}$$

1.1 Come up with a mathematical model for the number of star fish in a given year. Your model should

- Define any notation (variables and parameters) you use
- Include at least one formula/equation
- Explain how your formula/equation relates to the starting assumption

Exercise 2

Let

$$\begin{aligned} &\text{(Birth Rate)} && K = 1.1 \text{ children per starfish per year} \\ &\text{(Initial Pop.)} && P_0 = 10 \text{ star fish} \end{aligned}$$

and define the model $\mathbf{M}_1$ to be the model for starfish population with these parameters.

2.1 Simulate the total number of starfish per year using Excel.

Exercise 3

Recall the model $\mathbf{M}_1$ (from the previous question).

Define the model $\mathbf{M}_1^*$ to be

$$P(t) = P_0 e^{0.742t}$$

3.1 Are $\mathbf{M}_1$ and $\mathbf{M}_1^*$ different models or the same?

3.2 Which of $\mathbf{M}_1$ or $\mathbf{M}_1^*$ is better?

3.3 List an advantage and a disadvantage for each of $\mathbf{M}_1$ and $\mathbf{M}_1^*$.

Exercise 4

In the model $\mathbf{M}_1$, we assumed the starfish had K children at one point during the year.

4.1 Create a model $\mathbf{M}_n$ where the starfish are assumed to have K/n children n times per year (at regular intervals).

4.2 Simulate the models $\mathbf{M}_1$, $\mathbf{M}_2$, $\mathbf{M}_3$ in Excel. Which grows fastest?

4.3 What happens to $\mathbf{M}_n$ as $n \to \infty$?

Exercise 5

Exploring $\mathbf{M}_n$

We can rewrite the assumptions of $\mathbf{M}_n$ as follows:

- At time t there are $P_n(t)$ starfish.
- $P_n(0) = 10$
- During the time interval $(t, t + 1/n)$ there will be (on average) K/n new children per starfish.

5.1 Write an expression for $P_n(t + 1/n)$ in terms of $P_n(t)$.

5.2 Write an expression for ΔP_n, the change in population from time t to $t + \Delta t$.

5.3 Write an expression for $\frac{\Delta P_n}{\Delta t}$.

5.4 Write down a *differential equation* relating $P'(t)$ to $P(t)$ where $P(t) = \lim_{n\to\infty} P_n(t)$.

Exercise 6

Recall the model $\mathbf{M}_1$ defined by

- $P_1(0) = 10$
- $P_1(t+1) = KP(t)$ for $t \geq 0$ years and $K = 1.1$.

Define the model $\mathbf{M}_\infty$ by

- $P(0) = 10$
- $P'(t) = kP(t)$.

6.1 If $k = K = 1.1$, does the model $\mathbf{M}_\infty$ produce the same population estimates as $\mathbf{M}_1$?

Exercise 7

Suppose that the estimates produced by $\mathbf{M}_1$ agree with the actual (measured) population of starfish.

Fill out the table indicating which models have which properties.

Model	Accuracy	Explanatory	(your favourite property)
$\mathbf{M}_1$			
$\mathbf{M}_1^*$			
$\mathbf{M}_\infty$			

Exercise 8

Recall the model $\mathbf{M}_1$ defined by

- $P_1(0) = 10$
- $P_1(t+1) = KP(t)$ for $t \geq 0$ years and $K = 1.1$.

Define the model $\mathbf{M}_\infty$ by

- $P(0) = 10$
- $P'(t) = kP(t)$.

8.1 Suppose that $\mathbf{M}_1$ accurately predicts the population. Can you find a value of k so that $\mathbf{M}_\infty$ accurately predicts the population?

Exercise 9

After more observations, scientists notice a seasonal effect on starfish. They propose a new model called **S**:

- $P(0) = 10$
- $P'(t) = k \cdot P(t) \cdot |\sin(2\pi t)|$

9.1 What can you tell about the population (without trying to compute it)?

9.2 Assuming $k = 1.1$, estimate the population after 10 years.

9.3 Assuming $k = 1.1$, estimate the population after 10.3 years.

Exercise 10

Consider the following argument for the population model **S** where $P'(t) = P(t) \cdot |\sin(2\pi t)|$ with $P(0) = 10$:

At $t = 0$, the change in population $\approx P'(0) = 0$, so

$$P(1) \approx P(0) + P'(0) \cdot 1 = P(0) = 10.$$

At $t = 1$, the change in population $\approx P'(1) = 0$, so

$$P(2) \approx P(1) + P'(1) \cdot 1 = P(0) = 10.$$

And so on.

So, the population of starfish remains constant.

10.1 Do you believe this argument? Can it be improved?

10.2 Simulate an improved version using a spreadsheet.

Exercise 11

(Simulating $\mathbf{M}_\infty$ with different Δs)

Time	Pop. ($\Delta = 0.1$)	Time	Pop. ($\Delta = 0.2$)
0.0	10	0.0	10
0.1	11.1	0.2	12.2
0.2	12.321	0.4	14.884
0.3	13.67631	0.6	18.15848
0.4	15.1807041	0.8	22.1533456

11.1 Compare $\Delta = 0.1$ and $\Delta = 0.2$. Which approximation grows faster?

11.2 Graph the population estimates for $\Delta = 0.1$ and $\Delta = 0.2$ on the same plot. What does the graph show?

11.3 What Δs give the largest estimate for the population at time t?

11.4 Is there a limit as $\Delta \to 0$?

Exercise 11

(Simulating $\mathbf{M}_\infty$ with different Δs)

11.1 Compare $\Delta = 0.1$ and $\Delta = 0.2$. Which approximation grows faster?

11.2 Graph the population estimates for $\Delta = 0.1$ and $\Delta = 0.2$ on the same plot. What does the graph show?

11.3 What Δs give the largest estimate for the population at time t?

11.4 Is there a limit as $\Delta \to 0$?

Consider the following models for starfish growth

M # new children per year $\sim$ current population

N # new children per year $\sim$ current population times resources available per individual

O # new children per year $\sim$ current population times the fraction of total resources remaining

12.1 Guess what the population vs. time curves look like for each model.

12.2 Create a differential equation for each model.

12.3 Simulate population vs. time curves for each model (but pick a common initial population).

Exercise 13

Recall the models

M # new children per year $\sim$ current population

N # new children per year $\sim$ current population times resources available per individual

O # new children per year $\sim$ current population times the fraction of total resources remaining

13.1 Determine which population grows fastest in the short term and which grows fastest in the long term.

13.2 Are some models more sensitive to your choice of Δ when simulating?

13.3 Are your simulations for each model consistently underestimates? Overestimates?

13.4 Compare your simulated results with your guesses from question 12.1. What did you guess correctly? Where were you off the mark?

Exercise 14

A simple model for population growth has the form

$$P'(t) = bP(t)$$

where b is the *birth rate*.

14.1 Create a better model for population that includes both births and deaths.

Exercise 15

Lotka-Volterra Predator-Prey models predict two populations, F (foxes) and R (rabbits), simultaneously. They take the form

$$F'(t) = (B_F - D_F) \cdot F(t)$$
$$R'(t) = (B_R - D_R) \cdot R(t)$$

where $B_?$ stands for births and $D_?$ stands for deaths.

We will assume:

- Foxes die at a constant rate.
- Foxes mate when food is plentiful.
- Rabbits mate at a constant rate.
- Foxes eat rabbits.

15.1 Speculate on when B_F, D_F, B_R, and D_R would be at their maximum(s)/minimum(s), given our assumptions.

15.2 Come up with appropriate formulas for B_F, B_R, D_F, and D_R.

Exercise 16

Suppose the population of F (foxes) and R (rabbits) evolves over time following the rule

$$F'(t) = (0.01 \cdot R(t) - 1.1) \cdot F(t)$$
$$R'(t) = (1.1 - 0.1 \cdot F(t)) \cdot R(t)$$

16.1 Simulate the population of foxes and rabbits with a spreadsheet.

16.2 Do the populations continue to grow/shrink forever? Are they cyclic?

16.3 Should the humps/valleys in the rabbit and fox populations be in phase? Out of phase?

Exercise 17

Open the spreadsheet

`https://uoft.me/foxes-and-rabbits`

which contains an Euler approximation for the Foxes and Rabbits population.

$$F'(t) = (0.01 \cdot R(t) - 1.1) \cdot F(t)$$
$$R'(t) = (1.1 - 0.1 \cdot F(t)) \cdot R(t)$$

17.1 Is the max population of the rabbits over/under estimated? Sometimes over, sometimes under?

17.2 What about the foxes?

17.3 What about the min populations?

Exercise 18

Open the spreadsheet

`https://uoft.me/foxes-and-rabbits`

which contains an Euler approximation for the Foxes and Rabbits population.

$$F'(t) = (0.01 \cdot R(t) - 1.1) \cdot F(t)$$
$$R'(t) = (1.1 - 0.1 \cdot F(t)) \cdot R(t)$$

Component Graph & Phase Plane. For a differential equation involving the functions F_1, F_2, $\ldots$, F_n, and the variable t, the ***component graphs*** are the n graphs of $(t, F_1(t))$, $(t, F_2(t))$, $\ldots$.
The ***phase plane*** or ***phase space*** associated with the differential equation is the n-dimensional space with axes corresponding to the values of F_1, F_2, $\ldots$, F_n.

18.1 Plot the Fox vs. Rabbit population in the *phase plane*.

18.2 Should your plot show a closed curve or a spiral?

18.3 What "direction" do points move along the curve as time increases? Justify by referring to the model.

18.4 What is easier to see from plots in the phase plane than from component graphs (the graphs of fox and rabbit population vs. time)?

Exercise 19

Open the spreadsheet

`https://uoft.me/foxes-and-rabbits`

which contains an Euler approximation for the Foxes and Rabbits population.

$$F'(t) = (0.01 \cdot R(t) - 1.1) \cdot F(t)$$
$$R'(t) = (1.1 - 0.1 \cdot F(t)) \cdot R(t)$$

> **Equilibrium Solution.** An *equilibrium solution* to a differential equation or system of differential equations is a solution that is constant in the independent variable(s).

19.1 By changing initial conditions, what is the "smallest" curve you can get in the phase plane? What happens at those initial conditions?

19.2 What should F' and R' be if F and R are *equilibrium solutions*?

19.3 How many equilibrium solutions are there for the fox-and-rabbit system? Justify your answer.

19.4 What do the equilibrium solutions look like in the phase plane? What about their component graphs?

Exercise 20

Recall the logistic model for starfish growth:

O # new children per year $\sim$ current population times the fraction of total resources remaining

which can be modeled with the equation

$$P'(t) = k \cdot P(t) \cdot \left(1 - \frac{R_i}{R} \cdot P(t)\right)$$

where

- $P(t)$ is the population at time t
- k is a constant of proportionality
- R is the total number of resources
- R_i is the resources that one starfish wants to consume

Use $k = 1.1$, $R = 1$, and $R_i = 0.1$ unless instructed otherwise.

20.1 What are the equilibrium solutions for model **O**?

20.2 What does a "phase plane" for model **O** look like? What do graphs of equilibrium solutions look like?

20.3 Classify the behaviour of solutions that lie *between* the equilibrium solutions. E.g., are they increasing, decreasing, oscillating?

Exercise 21

Classification of Equilibria. An equilibrium solution f is called

- *attracting* if locally solutions converge to f
- *repelling* if there is a fixed distance so that locally, solutions tend away from f by that fixed distance
- *stable* if there is a fixed distance so that locally, solutions stay within that fixed distance of f
- *unstable* if f is not stable

Classification of Equilibria (Formal). An equilibrium solution f is called

- *attracting at time t_0* if there exists $\varepsilon > 0$ such that for all solutions g satisfying $|g(t_0) - f(t_0)| < \varepsilon$, we have $\lim_{t\to\infty} f(t) = \lim_{t\to\infty} g(t)$.
- *repelling at time t_0* if there exists $\varepsilon > 0$ and $\delta > 0$ such that for all solutions g that satisfy $0 < |g(t_0) - f(t_0)| < \varepsilon$ there exists $T \in \mathbb{R}$ so that for all $t > T$ we have $|g(t) - f(t)| > \delta$
- *stable at time t_0* if for all $\varepsilon > 0$ there exists a $\delta > 0$ such that for all g satisfying $|g(t_0) - f(t_0)| < \delta$ we have $|g(t) - f(t)| < \varepsilon$ for all $t > t_0$.
- *unstable at time t_0* if f is not stable at time t_0

f is called attracting/repelling/stable/unstable if it has the corresponding property for all t.

Classification of Equilibria. An equilibrium solution f is called

- *attracting* if locally solutions converge to f
- *repelling* if there is a fixed distance so that locally, solutions tend away from f by that fixed distance
- *stable* if there is a fixed distance so that locally, solutions stay within that fixed distance of f
- *unstable* if f is not stable

Let

$$F'(t) = ?$$

be an unknown differential equation with equilibrium solution $f(t) = 1$.

21.1 Draw an example of what solutions might look like if f is *attracting*.

21.2 Draw an example of what solutions might look like if f is *repelling*.

21.3 Draw an example of what solutions might look like if f is *stable*.

21.4 Could f be stable but *not* attracting?

Exercise 22

Classification of Equilibria. An equilibrium solution f is called

- *attracting* if locally solutions converge to f
- *repelling* if there is a fixed distance so that locally, solutions tend away from f by that fixed distance
- *stable* if there is a fixed distance so that locally, solutions stay within that fixed distance of f
- *unstable* if f is not stable

Recall the starfish population model **O** given by

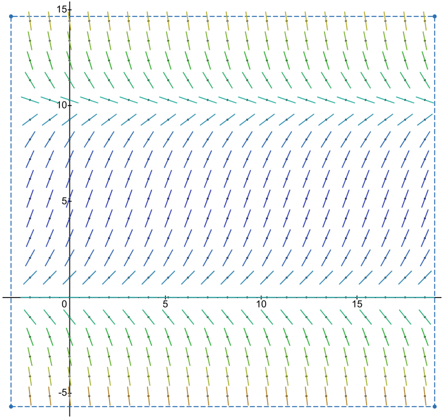
$$P'(t) = k \cdot P(t) \cdot \left(1 - \frac{R_i}{R} \cdot P(t)\right)$$

Use $k = 1.1$, $R = 1$, and $R_i = 0.1$ unless instructed otherwise.

22.1 Classify the equilibrium solutions for model **O** as attracting/repelling/stable/unstable/semi-stable.

22.2 Does changing k change the nature of the equilibrium solutions? How can you tell?

Exercise 23



A *slope field* is a plot of small segments of tangent lines to solutions of a differential equation at different initial conditions.

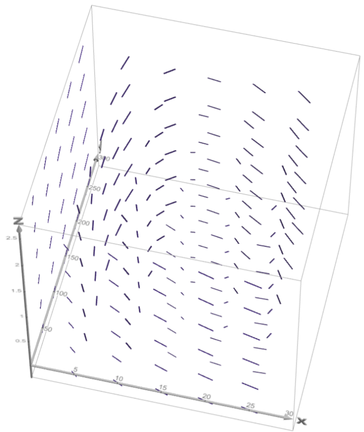
On the left is a slope field for model **O**, available at

`https://www.desmos.com/calculator/ghavqzqqjn`

23.1 If you were sketching the slope field for model **O** by hand, what line would you sketch (a segment of) at $(5,3)$? Write an equation for that line.

23.2 How can you recognize equilibrium solutions in a slope field?

23.3 Give qualitative descriptions of different solutions to the *differential equation* used in model **O** (i.e., use words to describe them). Do all of those solutions make sense in terms of *model **O***?



3d slope fields are possible, but hard to interpret.

On the left is a slope field for the Foxes–Rabbits model.

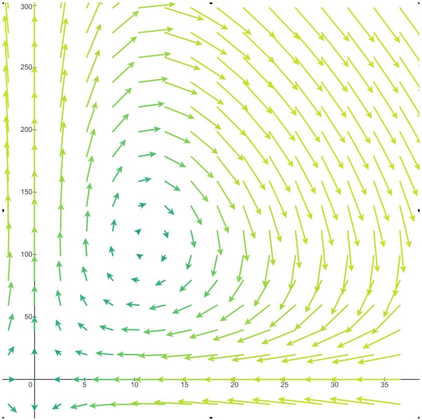
`https://www.desmos.com/3d/kvyztvmp0g`

24.1 What are the three dimensions in the plot?

24.2 What should the graph of an equilibrium solution look like?

24.3 What should the graph of a typical solution look like?

24.4 What are ways to simplify the picture so we can more easily analyze solutions?



Phase Portrait. A ***phase portrait*** or ***phase diagram*** is the plot of a vector field in phase space where each vector rooted at (x, y) is tangent to a solution curve passing through (x, y) and its length is given by the speed of a solution passing through (x, y).

On the left is a phase portrait for the Foxes–Rabbits model.

`https://www.desmos.com/calculator/vrk0q4espx`

25.1 What do the x and y axes correspond to?

25.2 Identify the equilibria in the phase portrait. What are the lengths of the vectors at those points?

25.3 Classify each equilibrium as stable/unstable.

25.4 Copy and paste data from your simulation spreadsheet into the Desmos plot. Does the resulting curve fit with the picture?

Exercise 26

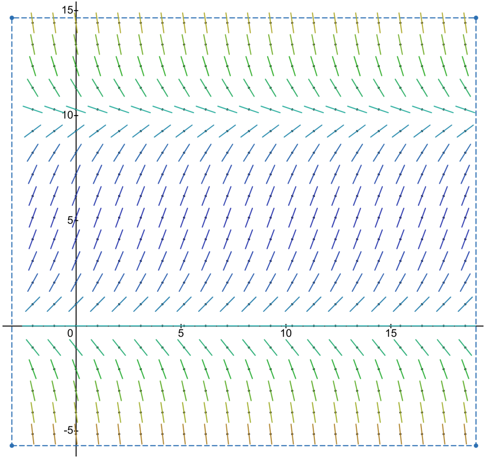
Sketch your own vector field where the corresponding system of differential equations:

26.1 Has an attracting equilibrium solution.

26.2 Has a repelling equilibrium solution.

26.3 Has no equilibrium solutions.

Exercise 27



Recall the slope field for model **O**.

27.1 What would a phase portrait for model **O** look like? Draw it.

27.2 Where are the arrows the longest? Shortest?

27.3 How could you tell from a 1d phase portrait whether an equilibrium solution is attracting/repelling/etc.?

Exercise 28

The following differential equation models the life cycle of a tree. In the model

- $H(t)$ = height (in meters) of tree trunk at time t
- $A(t)$ = surface area (in square meters) of all leaves at time t

$$\begin{aligned} H'(t) &= 0.3 \cdot A(t) - b \cdot H(t) \\ A'(t) &= -0.3 \cdot (H(t))^2 + A(t) \end{aligned}$$

and $0 \leq b \leq 2$

28.1 Modify

`https://www.desmos.com/calculator/vrk0q4espx`

to make a phase portrait for the tree model.

28.2 What do equilibrium solutions mean in terms of tree growth?

28.3 For $b = 1$ what are the equilibrium solution(s)?

Exercise 29

The following differential equation models the life cycle of a tree. In the model

- $H(t)$ = height (in meters) of tree trunk at time t
- $A(t)$ = surface area (in square meters) of all leaves at time t

$$H'(t) = 0.3 \cdot A(t) - b \cdot H(t)$$
$$A'(t) = -0.3 \cdot (H(t))^2 + A(t)$$

and $0 \leq b \leq 2$

29.1 Fix a value of b and use a spreadsheet to simulate some solutions with different initial conditions. Plot the results on your phase portrait from 28.1.

29.2 What will happen to a tree with $(H(0), A(0)) = (20, 10)$? Does this depend on b?

29.3 What will happen to a tree with $(H(0), A(0)) = (10, 10)$? Does this depend on b?

Exercise 30

The tree model

$$H'(t) = 0.3 \cdot A(t) - b \cdot H(t)$$
$$A'(t) = -0.3 \cdot (H(t))^2 + A(t)$$

was based on the premises

$P_{\text{height 1}}$ CO_2 is absorbed by the leaves and turned directly into trunk height.

$P_{\text{height 2}}$ The tree is in a swamp and constantly sinks at a speed proportional to its height.

$P_{\text{leaves 1}}$ Leaves grow proportionality to the energy available.

$P_{\text{energy 1}}$ The tree gains energy from the sun proportionally to the leaf area.

$P_{\text{energy 2}}$ The tree loses energy proportionally to the square of its height.

30.1 How are the premises expressed in the differential equations?

30.2 What does the parameter b represent (in the real world)?

30.3 Applying Euler's method to this system shows solutions that pass from the 1st to 4th quadrants of the phase plane. Is this realistic? Describe the life cycle of such a tree?

Exercise 31

Recall the tree model

$$H'(t) = 0.3 \cdot A(t) - b \cdot H(t)$$
$$A'(t) = -0.3 \cdot (H(t))^2 + A(t)$$

31.1 Find all equilibrium solutions for $0 \leq b \leq 2$.

31.2 For which b does a tree have the possibility of living forever? If the wind occasionally blew off a few random leaves, would that change your answer?

31.3 Find a value b_5 of b so that there is an equilibrium with $H = 5$.

Find a value b_{12} of b so that there is an equilibrium with $H = 12$.

31.4 Predict what happens to a tree near equilibrium in condition b_5 and a tree near equilibrium in condition b_{12}.

Exercise 32

Consider the system of differential equations

$$x'(t) = x(t)$$
$$y'(t) = 2y(t)$$

32.1 Make a phase portrait for the system.

`https://www.desmos.com/calculator/h3wtwjghv0`

32.2 What are the equilibrium solution(s) of the system?

32.3 Find a formula for $x(t)$ and $y(t)$ that satisfy the initial conditions $(x(0), y(0)) = (x_0, y_0)$.

32.4 Let $\vec{r}(t) = (x(t), y(t))$. Find a matrix A so that the differential equation can be equivalently expressed as

$$\vec{r}'(t) = A\vec{r}(t).$$

32.5 Write a solution to $\vec{r}' = A\vec{r}$ (where A is the matrix you came up with).

Exercise 33

Let A be an unknown matrix and suppose $\vec{p}$ and $\vec{q}$ are solutions to $\vec{r}' = A\vec{r}$.

33.1 Is $\vec{s}(t) = \vec{p}(t) + \vec{q}(t)$ a solution to $\vec{r}' = A\vec{r}$? Justify your answer.

33.2 Can you construct other solutions from $\vec{p}$ and $\vec{q}$? If yes, how so?

Exercise 34

Recall from MAT223:

Linearly Dependent & Independent (Algebraic).
The vectors $\vec{v}_1, \vec{v}_2, \dots, \vec{v}_n$ are ***linearly dependent*** if there is a non-trivial linear combination of $\vec{v}_1, \dots, \vec{v}_n$ that equals the zero vector. Otherwise they are linearly independent.

Define

$$\vec{p}(t) = \begin{bmatrix} e^t \\ 0 \end{bmatrix} \qquad \vec{q}(t) = \begin{bmatrix} 4e^t \\ 0 \end{bmatrix} \qquad \vec{h}(t) = \begin{bmatrix} 0 \\ e^{2t} \end{bmatrix} \qquad \vec{z}(t) = \begin{bmatrix} 0 \\ e^{3t} \end{bmatrix}.$$

34.1 Are $\vec{p}$ and $\vec{q}$ linearly independent or linearly dependent? Justify with the definition.

34.2 Are $\vec{p}$ and $\vec{h}$ linearly independent or linearly dependent? Justify with the definition.

34.3 Are $\vec{h}$ and $\vec{z}$ linearly independent or linearly dependent? Justify with the definition.

34.4 Is the set of three functions $\{\vec{p}, \vec{h}, \vec{z}\}$ linearly independent or linearly dependent? Justify with the definition.

Exercise 35

Recall

$$\vec{p}(t) = \begin{bmatrix} e^t \\ 0 \end{bmatrix} \qquad \vec{q}(t) = \begin{bmatrix} 4e^t \\ 0 \end{bmatrix} \qquad \vec{h}(t) = \begin{bmatrix} 0 \\ e^{2t} \end{bmatrix} \qquad \vec{z}(t) = \begin{bmatrix} 0 \\ e^{3t} \end{bmatrix}.$$

35.1 Describe $\operatorname{span}\{\vec{p}, \vec{h}\}$. What is its dimension? What is a basis for it?

35.2 Let S be the set of all solutions to $\vec{r}\,'(t) = \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix} \vec{r}(t)$. (You've seen this equation before.)

Is S a subspace? If so, what is its dimension?

35.3 Provided S is a subspace, give a basis for S.

Exercise 36

Consider the differential equation

$$y'(t) = 2 \cdot y(t).$$

36.1 Write a solution whose graph passes through the point $(t, y) = (0, 3)$.

36.2 Write a solution whose graph passes through the point $(t, y) = (0, y_0)$.

36.3 Write a solution whose graph passes through the point $(t, y) = (t_0, y_0)$.

36.4 Consider the following argument:

> For every point (t_0, y_0), there is a corresponding solution to $y'(t) = 2 \cdot y(t)$.
> Since $\{(t_0, y_0) : t_0, y_0 \in \mathbb{R}\}$ is two dimensional, this means the set of solutions to $y'(t) = 2 \cdot y(t)$ is two dimensional.

Do you agree? Explain.

Exercise 37

Theorem (Existence & Uniqueness 1). The system of differential equations represented by $\vec{r}\,'(t) = M\vec{r}(t) + \vec{p}$ (or the single differential equation $y' = ay + b$) has a unique solution passing through every initial condition. Further, the domain of every solution is $\mathbb{R}$.

Let S be the set of all solutions to $\vec{r}'(t) = \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix} \vec{r}(t)$.

37.1 Show that $\dim(S) \geq 2$ by finding at least two linearly independent solutions.

37.2 Let I be the set of all initial conditions. What is I?

37.3 Show that $\dim(S) \leq 3$ by applying the theorem to the set of initial conditions.

37.4 Can two points in I correspond to the same solution? Explain?

37.5 Find a subset $U \subseteq I$ so that every solution corresponds to a unique point in U.

37.6 Show that $\dim(S) \leq 2$.

37.7 Suppose M is an $n \times n$ matrix. Consider the differential equation $\vec{r}\,'(t) = M\vec{r}(t)$. If you have found n linearly independent solutions, can you determine the dimension of the set of all solutions? Explain.

Exercise 38

Consider the system

$$x'(t) = 2x(t)$$
$$y'(t) = 3y(t)$$

38.1 Rewrite the system in matrix form.

38.2 Classify the following as solutions or non-solutions to the system.

$$\vec{r}_1(t) = e^{2t} \qquad \vec{r}_2(t) = \begin{bmatrix} e^{2t} \\ 0 \end{bmatrix}$$

$$\vec{r}_3(t) = \begin{bmatrix} e^{2t} \\ 4e^{3t} \end{bmatrix} \qquad \vec{r}_4(t) = \begin{bmatrix} 4e^{3t} \\ e^{2t} \end{bmatrix}$$

$$\vec{r}_5(t) = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

38.3 State the definition of an eigenvector for the matrix M.

38.4 What should the definition of an *eigen solution* be for this system?

38.5 Which functions from 38.2 are eigen solutions?

38.6 Find an eigen solution $\vec{r}_6$ that is linearly independent from $\vec{r}_2$.

38.7 Let $S = \text{span}\{\vec{r}_2, \vec{r}_6\}$. Does S contain *all* solutions to the system? Justify your answer.

Recall the system

$$x'(t) = 2x(t)$$
$$y'(t) = 3y(t)$$

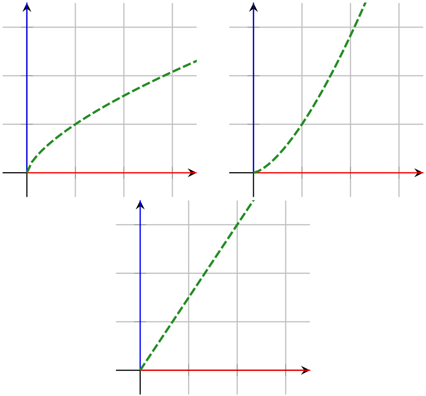
has eigen solutions $\vec{r}_2(t) = \begin{bmatrix} e^{2t} \\ 0 \end{bmatrix}$ and $\vec{r}_6(t) = \begin{bmatrix} 0 \\ e^{3t} \end{bmatrix}$.

39.1 Sketch $\vec{r}_2$ and $\vec{r}_6$ in the phase plane.

39.2 Use

`https://www.desmos.com/calculator/h3wtwjghv0`

to make a phase portrait for the system.

39.3 

In which phase plane above is the dashed (green) curve the graph of a solution to the system? Explain.

Exercise 40

Suppose A is a 2×2 matrix and $\vec{s}_1$ and $\vec{s}_2$ are eigen solutions to $\vec{r}' = A\vec{r}$ with eigenvalues 1 and -1, respectively.

40.1 Write possible formulas for $\vec{s}_1(t)$ and $\vec{s}_2(t)$.

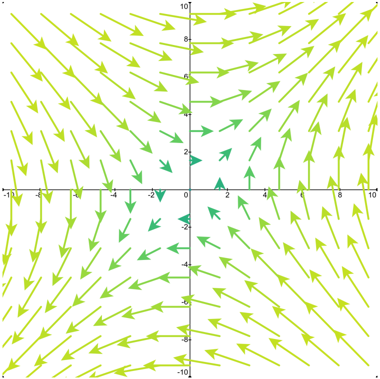
40.2 Sketch a phase plane with graphs of $\vec{s}_1$ and $\vec{s}_2$ on it.

40.3 Add a non-eigen solution to your sketch.

40.4 Sketch a possible phase portrait for $\vec{r}' = A\vec{r}$. Can you extend your phase portrait to all quadrants?

Exercise 41

Consider the following phase portrait for a system of the form $\vec{r}' = A\vec{r}$ for an unknown matrix A.



41.1 Can you identify any eigen solutions?

41.2 What are the eigenvalues of A? What are their sign(s)?

Exercise 42

Consider the differential equation $\vec{r}'(t) = M\vec{r}(t)$ where $M = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$.

42.1 Verify that $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$ and $\begin{bmatrix} 1 \\ -1 \end{bmatrix}$ are eigenvectors for M. What are the corresponding eigenvalues?

42.2 (a) Is $\vec{r}_1(t) = e^t \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ a solution to the differential equation? An eigen solution?

(b) Is $\vec{r}_2(t) = e^t \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ a solution to the differential equation? An eigen solution?

(c) Is $\vec{r}_3(t) = e^{2t} \begin{bmatrix} 1 \\ -1 \end{bmatrix}$ a solution to the differential equation? An eigen solution?

42.3 Find an eigen solution for the system corresponding to the eigenvalue -1. Write your answer in vector form.

42.4 Let $\vec{v}$ is an eigenvector for M with eigenvalue λ. Explain how to write down an eigen solution to $\vec{r}'(t) = M\vec{r}(t)$ with eigenvalue λ.

42.5 Let $\vec{v} \neq \vec{0}$ be a non-eigenvector for M. Could $\vec{r}(t) = e^{\lambda t}\vec{v}$ be a solution to $\vec{r}'(t) = M\vec{r}(t)$ for some λ? Explain.

Exercise 43

Recall the differential equation $\vec{r}\,'(t) = M\,\vec{r}(t)$ where $M = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$.

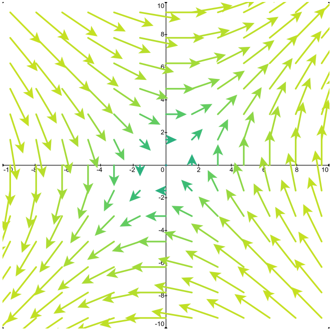
43.1 Write down a general solution to the differential equation.

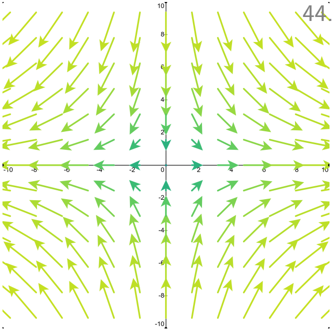
43.2 Write down a solution to the initial value problem $\vec{r}(0) = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix}$.

43.3 Are your answers to the first two parts the same? Do they contain the same information?

Exercise 44

The phase portrait for a differential equation arising from the matrix $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$ (left) and $\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$ (right) are shown.





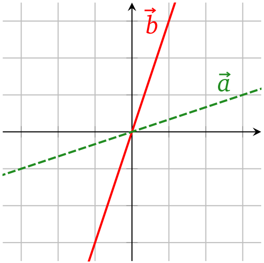
Both have eigenvalues ± 1, but they have different eigenvectors.

44.1 How are the phase portraits related to each other?

44.2 Suppose P is a 2×2 matrix with eigenvalues ± 1. In what ways could the phase portrait for $\vec{r}\,'(t) = P\,\vec{r}(t)$ look *different* from the above portraits? In what way(s) must it look the same?

Exercise 45

Consider the following phase plane with lines in the direction of $\vec{a}$ (dashed green) and $\vec{b}$ (red).



45.1 Sketch a phase portrait where the directions $\vec{a}$ and $\vec{b}$ correspond to eigen solutions with eigenvalues that are

	sign for $\vec{a}$	sign for $\vec{b}$
(1)	pos	pos
(2)	neg	neg
(3)	neg	pos
(4)	pos	neg
(5)	pos	zero

45.2 Classify the solution at the origin for situations (1)–(5) as stable or unstable.

45.3 Would any of your classifications in 45.2 change if the directions of $\vec{a}$ and $\vec{b}$ changed?

Exercise 46

You are examining a differential equation $\vec{r}'(t) = M\,\vec{r}(t)$ for an unknown 2×2 matrix M.

You would like to determine whether $\vec{r}(t) = \begin{bmatrix}0\\0\end{bmatrix}$ is stable/unstable/attracting/repelling.

46.1 Come up with a rule to determine the nature of the equilibrium solution $\vec{r}(t) = \begin{bmatrix}0\\0\end{bmatrix}$ based on the eigenvalues of M (provided there exists two linearly independent eigen solutions).

46.2 Consider the system of differential equations

$$\begin{aligned} x'(t) &= x(t) + 2\,y(t) \\ y'(t) &= 3\,x(t) - 4\,y(t) \end{aligned}$$

(a) Classify the stability of the equilibrium solution $(x(t), y(t)) = (0,0)$ using any method you want.

(b) Justify your answer analytically using eigenvalues.

Exercise 47

Consider the following model of Social Media Usage where

$$P(t) = \text{millions of social media posts at year } t$$
$$U(t) = \text{millions of social media users at year } t$$

($P1_P$) Ignoring all else, each year posts decay proportionally to the current number of posts with proportionality constant 1.

($P2_P$) Ignoring all else (independent of decay), posts grow by a constant amount of 2 million posts every year.

($P1_U$) Ignoring all else, social media users increase/decrease in proportion to the number of posts.

($P2_U$) Ignoring all else, social media users increase/decrease in proportion to the number of users.

($P3_U$) Ignoring all else, 1 million people stop using the platform every year.

A school intervention is described by the parameter $a \in [-1/2, 1]$:

- After the intervention, the proportionality constant for ($P1_U$) is $1 - a$.
- After the intervention, the proportionality constant for ($P2_U$) is a.

47.1 Model this situation using a system of differential equations. Explain which parts of your model correspond to which premise(s).

Exercise 48

The **SM** model of Social Media Usage is

$$\begin{aligned} P' &= -P + 2 \\ U' &= (1-a)P + aU - 1 \end{aligned}$$

where

$$\begin{aligned} P(t) &= \text{millions of social media posts at year } t \\ U(t) &= \text{millions of social media users at year } t \\ a &\in [-1/2, 1] \end{aligned}$$

48.1 What are the equilibrium solution(s)?

48.2 Make a phase portrait for the system.

`https://www.desmos.com/calculator/h3wtwjghv0`

48.3 Use phase portraits to conjecture: what do you think happens to the equilibrium solution(s) as a transitions from negative to positive? Justify with a computation.

Exercise 49

The **SM** model of Social Media Usage is

$$P' = -P + 2$$
$$U' = (1-a)P + aU - 1$$

where

$$P(t) = \text{millions of social media posts at year } t$$
$$U(t) = \text{millions of social media users at year } t$$
$$a \in [-1/2, 1]$$

49.1 Can you rewrite the system in matrix form? I.e., in the form $\vec{r}\,'(t) = M\vec{r}(t)$ for some matrix M where $\vec{r}(t) = \big(P(t), U(t)\big)$.

49.2 Define $\vec{s}(t) = \big(S_P(t), S_U(t)\big)$ to be the displacement from equilibrium in the **SM** model at time t (provided an equilibrium exists).

(a) Write $\vec{s}$ in terms of P and U.

(b) Find $\vec{s}\,'$ in terms of P and U.

(c) Find $\vec{s}\,'$ in terms of S_P and S_U.

(d) Can one of your differential equation for $\vec{s}$ be written in matrix form? Which one?

(e) Analytically classify the equilibrium solution for your differential equation for $\vec{s}$ when $a = -1/2$, $1/2$, and 1. (You may use a calculator for computing eigenvectors/values.)

Exercise 50

The **SM** model of Social Media Usage is

$$P' = -P + 2$$
$$U' = (1-a)P + aU - 1$$

where

$$P(t) = \text{millions of social media posts at year } t$$
$$U(t) = \text{millions of social media users at year } t$$
$$a \in [-1/2, 1]$$

Some politicians have been looking at the model. They made the following posts on social media:

1. *The model shows the number of posts will always be increasing. SAD!*
2. *I see the number of social media users always increases. That's not what we want!*
3. *It looks like social media is just a fad. Although users initially increase, they eventually settle down.*
4. *I have a dream! That one day there will be social media posts, but eventually there will be no social media users!*

50.1 For each social media post, make an educated guess about what initial conditions and what value(s) of a the politician was considering.

50.2 The school board wants to limit the number of social media users to fewer than 10 million. Make a recommendation about what value of a they should target.

Exercise 51

Consider the following **FD** model of Fleas and Dogs where

$$F(t) = \text{number of parasites (fleas) at year } t \text{ (in millions)}$$
$$D(t) = \text{number of hosts (dogs) at year } t \text{ (in thousands)}$$

($P1_F$) Ignoring all else, the number of parasites decays in proportion to its population (with constant 1).

($P2_F$) Ignoring all else, parasite numbers grow in proportion to the number of hosts (with constant 1).

($P1_D$) Ignoring all else, hosts numbers grow in proportion to their current number (with constant 1).

($P2_D$) Ignoring all else, host numbers decrease in proportion to the number of parasites (with constant 2).

($P1_c$) Anti-flea collars remove 2 million fleas per year.

($P1_c$) Constant dog breeding adds 1 thousand dogs per year.

51.1 Write a system of differential equations for the **FD** model.

51.2 Can you rewrite the system in matrix form $\vec{r}\,' = M\,\vec{r}$? What about in *affine* form $\vec{r}\,' = M\,\vec{r} + \vec{b}$?

51.3 Make a phase portrait for your mode.

51.4 What should solutions to the system look like in the phase plane? What are the equilibrium solution(s)?

Exercise 52

Recall the **FD** model of Fleas and Dogs where

$$F(t) = \text{number of parasites (fleas) at year } t \text{ (in millions)}$$

$$D(t) = \text{number of hosts (dogs) at year } t \text{ (in thousands)}$$

$$\vec{r}(t) = \begin{bmatrix} F(t) \\ D(t) \end{bmatrix}$$

and

$$\vec{r}\,'(t) = \begin{bmatrix} -1 & 1 \\ -2 & 1 \end{bmatrix} \vec{r}(t) + \begin{bmatrix} -2 \\ 1 \end{bmatrix}$$

Define $\vec{s}(t)$ to be the displacement of $\vec{r}(t)$ from equilibrium at time t.

52.1 Find a formula for $\vec{s}$ in terms of $\vec{r}$.

52.2 Can you find a matrix M so that $\vec{s}\,'(t) = M\,\vec{s}(t)$?

52.3 What are the eigen solutions for $\vec{s}\,' = M\,\vec{s}$?

Exercise 53

Recall the **FD** model of Fleas and Dogs where

$$F(t) = \text{number of parasites (fleas) at year } t \text{ (in millions)}$$
$$D(t) = \text{number of hosts (dogs) at year } t \text{ (in thousands)}$$

$$\vec{r}(t) = \begin{bmatrix} F(t) \\ D(t) \end{bmatrix} \qquad \vec{s}(t) = \vec{r}(t) - \begin{bmatrix} 3 \\ 5 \end{bmatrix}$$

and

$$\vec{s}\,'(t) = M\,\vec{s}(t) \qquad \text{where} \qquad M = \begin{bmatrix} -1 & 1 \\ -2 & 1 \end{bmatrix}.$$

This equation has eigen solutions

$$\vec{s}_1(t) = \begin{bmatrix} 1-i \\ 2 \end{bmatrix} e^{it}$$
$$\vec{s}_2(t) = \begin{bmatrix} 1+i \\ 2 \end{bmatrix} e^{-it}$$

53.1 Recall Euler's formula $e^{it} = \cos(t) + i\sin(t)$.

(a) Use Euler's formula to expand $\vec{s}_1 + \vec{s}_2$. Are there any imaginary numbers remaining?

(b) Use Euler's formula to expand $i(\vec{s}_1 - \vec{s}_2)$. Are there any imaginary numbers remaining?

53.2 Verify that your formulas for $\vec{s}_1 + \vec{s}_2$ and $i(\vec{s}_1 - \vec{s}_2)$ are solutions to $\vec{s}\,'(t) = M\,\vec{s}(t)$.

53.3 Can you give a third *real* solution to $\vec{s}\,'(t) = M\,\vec{s}(t)$?

Exercise 54

Recall the **FD** model of Fleas and Dogs where

$$F(t) = \text{number of parasites (fleas) at year } t \text{ (in millions)}$$
$$D(t) = \text{number of hosts (dogs) at year } t \text{ (in thousands)}$$

$$\vec{r}(t) = \begin{bmatrix} F(t) \\ D(t) \end{bmatrix} \qquad \vec{s}(t) = \vec{r}(t) - \begin{bmatrix} 3 \\ 5 \end{bmatrix}$$

and

$$\vec{s}\,'(t) = M\,\vec{s}(t) \qquad \text{where} \qquad M = \begin{bmatrix} -1 & 1 \\ -2 & 1 \end{bmatrix}.$$

54.1 What is the dimension of the space of solutions to $\vec{s}\,'(t) = M\,\vec{s}(t)$?

54.2 Give a basis for all solutions to $\vec{s}\,'(t) = M\,\vec{s}(t)$.

54.3 Find a solution satisfying $\vec{s}(0) = \begin{bmatrix} 1 \\ 3 \end{bmatrix}$.

54.4 Using what you know, find a general formula for $\vec{r}(t)$.

54.5 Find a formula for $\vec{r}(t)$ satisfying $\vec{r}(0) = \begin{bmatrix} 4 \\ 8 \end{bmatrix}$.

Exercise 55

Consider the differential equation

$$\vec{s}\,'(t) = M\vec{s}(t) \qquad \text{where} \qquad M = \begin{bmatrix} -1 & -4 \\ 2 & 3 \end{bmatrix}$$

55.1 Find eigen solutions for this differential equation (you may use a calculator/computer to assist).

55.2 Find a general *real* solution.

55.3 Make a phase portrait. What do sketches of your solutions look like in phase space?

Exercise 56

Recall the **FD** model of Fleas and Dogs where

$$F(t) = \text{number of parasites (fleas) at year } t \text{ (in millions)}$$

$$D(t) = \text{number of hosts (dogs) at year } t \text{ (in thousands)}$$

$$\vec{r}(t) = \begin{bmatrix} F(t) \\ D(t) \end{bmatrix} \qquad \vec{s}(t) = \vec{r}(t) - \begin{bmatrix} 3 \\ 5 \end{bmatrix}$$

and

$$\vec{s}\,'(t) = M\,\vec{s}(t) \qquad \text{where} \qquad M = \begin{bmatrix} -1 & 1 \\ -2 & 1 \end{bmatrix}.$$

Some research is being done on a shampoo for the dogs. It affects flea and dog reproduction:

(PS_F) Ignoring all else, the number of parasites decays in proportion to its population with constant $1+a$.

(PS_D) Ignoring all else, hosts numbers grow in proportion to their current number with constant $1-a$.

56.1 Modify the previous **FD** model to incorporate the effects of the shampoo.

56.2 Make a phase portrait for the **FD Shampoo** model.

56.3 Find the equilibrium solutions for the **FD Shampoo** model.

56.4 For each equilibrium solution determine its stability/instability/etc..

56.5 Analytically justify your conclusions about stability/instability/etc..

Exercise 57

Recall the tree model from Question 28:

- $H(t)$ = height (in meters) of tree trunk at time t
- $A(t)$ = surface area (in square meters) of all leaves at time t

$$H'(t) = 0.3 \cdot A(t) - b \cdot H(t)$$
$$A'(t) = -0.3 \cdot (H(t))^2 + A(t)$$

and $0 \leq b \leq 2$

A phase portrait for this model is available at

`https://www.desmos.com/calculator/tvjag852ja`

57.1 Find explicit formulas for equilibrium solutions of the tree model.

57.2 Visually classify the nature of each equilibrium solution as attracting/repelling/etc..

57.3 Can you rewrite the system in matrix/affine form? Why or why not?

Exercise 58

A simple logistic model for a population is

$$\frac{\mathrm{d}P}{\mathrm{d}t} = P(t) \cdot \left(1 - \frac{P(t)}{2}\right)$$

where $P(t)$ represents the population at time t.

We'd like to approximate $\mathrm{d}P/\mathrm{d}t$ when $P \approx 1/2$.

58.1 What is the value of $\mathrm{d}P/\mathrm{d}t$ when $P = 1/2$?

58.2 What is the approximate value of $\mathrm{d}P/\mathrm{d}t$ when $P = 1/2 + \Delta$ when Δ is small?

58.3 Write down a linear approximation $S(\Delta)$ that approximates $\mathrm{d}P/\mathrm{d}t$ when P is Δ away from $1/2$.

58.4 Let $A_{1/2}(t)$ be an *affine* approximation to $\mathrm{d}P/\mathrm{d}t$ that is is a good approximation when $P \approx 1/2$. Find a formula for $A_{1/2}(t)$ expressed in terms of $P(t)$.

58.5 Find additional affine approximations to $\mathrm{d}P/\mathrm{d}t$ centered at each equilibrium solution.

Exercise 59

Based on our calculations from last time, we have several different equations.

(Original)	$P' = P(1 - P/2)$	(`https://www.desmos.com/calculator/v1coz4shtw`)
$(A_{1/2})$	$P' \approx \frac{3}{8} + \frac{1}{2}(P - \frac{1}{2})$	(`https://www.desmos.com/calculator/zsb2apxhqs`)
(A_0)	$P' \approx P$	(`https://www.desmos.com/calculator/vw48bvqgrc`)
(A_2)	$P' \approx -(P - 2)$	(`https://www.desmos.com/calculator/i2utk6vnqh`)

59.1 What do you notice about the solutions sketched on the different slope fields (in Desmos)?

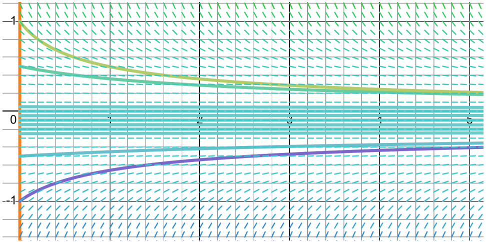
59.2 Does the nature of equilibrium solutions change when using an affine approximation?

Exercise 60

Consider the differential equation whose slope field is sketched below.

$$P'(t) = -P(t) \cdot (0.1 + P(t)) \cdot (0.2 + P(t)).$$

`https://www.desmos.com/calculator/ikp9rgo0kv`



60.1 Find all equilibrium solutions.

60.2 Use linear approximations to classify the equilibrium solutions as stable/unstable/etc..

To make a 1d affine approximation of a function f at the point E we have the formula

$$f(x) \approx f(E)+f'(E)(x-E).$$

To make a 2d approximation of a function $\vec{F}(x,y) = \big(F_1(x,y),F_2(x,y)\big)$ at the point $\vec{E}$, we have a similar formula

$$\vec{F}(x,y) \approx \vec{F}(\vec{E})+D_{\vec{F}}(\vec{E})\Big((x,y)-\vec{E}\Big)$$

where $D_{\vec{F}}(\vec{E})$ is the *total derivative* of $\vec{F}$ at $\vec{E}$, which can be expressed as the matrix

$$D_{\vec{F}}(\vec{E}) = \begin{bmatrix} \dfrac{\partial F_1}{\partial x} & \dfrac{\partial F_1}{\partial y} \\ \dfrac{\partial F_2}{\partial x} & \dfrac{\partial F_2}{\partial y} \end{bmatrix}$$

evaluated at $\vec{E}$.

Exercise 61

Recall our model from Question 28 for the life cycle of a tree where $H(t)$ was height, $A(t)$ was the leaves' surface area, and t was time:

$$H'(t) = 0.3 \cdot A(t) - b \cdot H(t)$$
$$A'(t) = -0.3 \cdot (H(t))^2 + A(t)$$

with $0 \leq b \leq 2$

We know the following:

- The equations cannot be written in matrix form.
- The equilibrium points are $(0,0)$ and $\left(\frac{100}{9}b, \frac{1000}{27}b^2\right)$.

We want to find an affine approximation to the system.

Define $\vec{F}(H,A) = (H',A')$

61.1 Find the matrix for $D_{\vec{F}}$, the total derivative of $\vec{F}$.

61.2 Create an affine approximation to $\vec{F}$ around $(0,0)$ and use this to write an approximation to the original system.

61.3 Create an affine approximation to $\vec{F}$ around $(\frac{100}{9}b, \frac{1000}{27}b^2)$ and use this to write an approximation to the original system.

61.4 Make a phase portrait for the original system and your approximation from part 3. How do they compare?

61.5 Analyze the nature of the equilibrium solution in part 3 using eigen techniques. Relate your analysis to the original system.

Exercise 61

Consider a spring with a mass attached to the end.

[XXX Diagram] |-www-[M]

Let

$$x(t) = \text{displacement of the right end of the spring from equilibrium at time } t$$

Recall from Physics the following laws:

(HL) Hooke's Law: For an elastic spring, force is proportional to displacement from equilibrium.

(NL) Newton's Second Law: Force is proportional to acceleration (the proportionality constant is called *mass*).

(ML) Laws of Motion: Velocity is the time derivative of displacement and acceleration is the time derivative of velocity.

61.1 Model $x(t)$ with a differential equation.