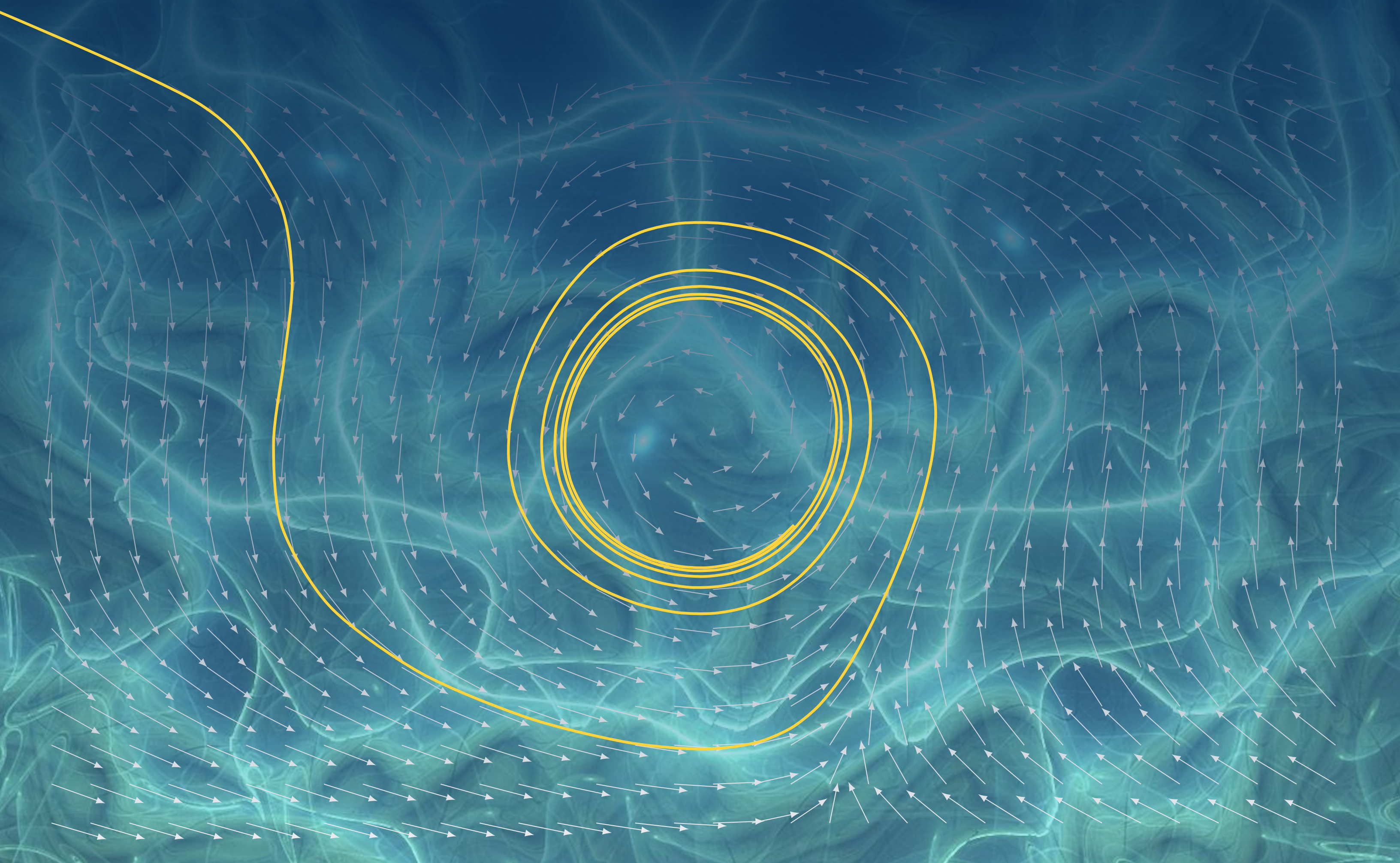
Differential Equations

MAT244 Workbook

2024/09/17 Edition



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Linear Algebra

About this Book

For the student

This book is your introductory guide to linear algebra. It is divided into *modules*, and each module is further divided into *exposition*, *practice problems*, and *core exercises*.

The *exposition* is easy to find—it's the text that starts each module and explains the big ideas of linear algebra. The *practice problems* immediately follow the exposition and are there so you can practice with concepts you've learned. Following the practice problems are the *core exercises*. The core exercises build up, through examples, the concepts discussed in the exposition.

To optimally learn from this text, you should:

- Start each module by reading through the *exposition* to get familiar with the main ideas and linear algebra terminology.
- Work through the *core exercises* to develop an understanding and intuition behind the main ideas and their subtleties.
- Re-read the *exposition* and identify which concepts each core exercise connects with.
- Work through the *practice problems*. These will serve as a check on whether you've understood the main ideas well enough to apply them.

The core exercises. Most (but not all) core exercises will be worked through during lecture time, and there is space for you to work provided after each of the core exercises. The point of the core exercises is to develop the main ideas of linear algebra by exploring examples. When working on core exercises, think "it's the journey that matters not the destination". The answers are not the point! If you're struggling, keep with it. The concepts you struggle with you remember well, and if you look up the answer, you're likely to forget just a few minutes later.

So many definitions. A big part of linear algebra is learning precise and technical language.[1] There are many terms and definitions you need to learn, and by far the best way to successfully learn these terms is to understand where they come from, why they're needed, and practice using them. That is, don't try to memorize definitions word for word. Instead memorize the idea and *reconstruct* the definition; go through the core exercises and identify which definitions appear where; and explain linear algebra to others using these technical terms.

Contributing to the book. Did you find an error? Do you have a better way to explain a linear algebra concept? Please, contribute to this book! This book is open-source, and we welcome contributions and improvements. To contribute to/fix part of this book, make a *Pull Request* or open an *Issue* at `https://github.com/siefkenj/IBLLinearAlgebra`. If you contribute, you'll get your name added to the contributor list.

For the instructor

This book is designed for a one-semester introductory linear algebra course course with a focus on geometry (MAT223 at the University of Toronto). It has not been designed for an "intro to proofs"-style course, but could be adapted for one.

Unlike a traditional textbook that is grouped into chapters and sections by subject, this book is grouped into modules. Each module contains exposition about a subject, practice problems (for students to work on by themselves), and core exercises (for students to work on with your guidance). Modules group related

[1] Beyond three dimensions, things get very confusing very quickly. Having precise definitions allows us to make arguments that rely on logic instead of intuition; and logic works in all dimensions.

concepts, but the modules have been designed to facilitate learning linear algebra rather than to serve as a reference. For example, information about change-of-basis is spread across several non-consecutive modules; each time change-of-basis is readdressed, more detail is added.

Using the book. This book has been designed for use in large active-learning classrooms driven by a *think, pair-share*/small-group-discussion format. Specifically, the *core exercises* (these are the problems which aren't labeled "Practice Problems" and for which space is provided to write answers) are designed for use during class time.

A typical class day looks like:

1. **Student pre-reading.** Before class, students will read through the relevant module.

2. **Introduction by instructor.** This may involve giving a definition, a broader context for the day's topics, or answering questions.

3. **Students work on problems.** Students work individually or in pairs/small groups on the prescribed core exercise. During this time the instructor moves around the room addressing questions that students may have and giving one-on-one coaching.

4. **Instructor intervention.** When most students have successfully solved the problem, the instructor refocuses the class by providing an explanation or soliciting explanations from students. This is also time for the instructor to ensure that everyone has understood the main point of the exercise (since it is sometimes easy to miss the point!).

   If students are having trouble, the instructor can give hints and additional guidance to ensure students' struggle is productive.

5. **Repeat step 3.**

Using this format, students are thinking (and happily so) most of the class. Further, after struggling with a question, students are especially primed to hear the insights of the instructor.

Conceptual lean. The *core exercises* are geared towards concepts instead of computation, though some core exercises focus on simple computation. They also have a geometric lean. Vectors are initially introduced with familiar coordinate notation, but eventually, coordinates are understood to be *representations* of vectors rather than "true" geometric vectors, and objects like the determinant are defined via oriented volumes rather than formulas involving matrix entries.

Specifically lacking are exercises focusing on the mechanical skills of row reduction and computing matrix inverses. Students must practice these skills, but they require little instructor intervention and so can be learned outside of lecture (which is why core exercises don't focus on these skills).

How to prepare. Running an active-learning classroom is less scripted than lecturing. The largest challenges are: (i) understanding where students are at, (ii) figuring out what to do given the current understanding of the students, and (iii) timing.

To prepare for a class day, you should:

1. **Strategize about learning objectives.** Figure out what the point of the day's lesson is and brain storm some examples that would illustrate that point.

2. **Work through the core exercises.**

3. **Reflect.** Reflect on how each core exercise addresses the day's goals. Compare with the examples you brainstormed and prepare follow-up questions that you can use in class to test for understanding.

4. **Schedule.** Write timestamps next to each core exercise indicating at what minute you hope to start each exercise. Give more time for the exercises that you judge as foundational, and be prepared to triage. It's appropriate to leave exercises or parts of exercises for homework, but change the order of exercises at your peril—they really do build on each other.

A typical 50 minute class is enough to get through 2–3 core exercises (depending on the difficulty), and class observations show that class time is split 50/50 between students working and instructor explanations.

Included in this text are tasks created by the Inquiry-Oriented Linear Algebra (IOLA) project. Details about these tasks can be found on their website `http://iola.math.vt.edu/`. Also included are some practice problems from Beezer's *A First Course in Linear Algebra* (marked with the symbol B next to the problem), and from Hefferon's *Linear Algebra* (marked with the symbol H next to the problem).

Contributing. You can report errors in the book or contribute to the book by filing an *Issue* or a *Pull Request* on the book's GitHub page: `https://github.com/siefkenj/IBLLinearAlgebra/`

Contributors

This book is a collaborative effort. The following people have contributed to its creation:

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Dedication

This book is dedicated to Dr. Bob Burton—friend and mentor.

"Sometimes you have to walk the mystical path with practical feet."

Contents

Modeling

In this module you will learn

- ??

Modeling

Suppose you are observing some *green* ants walking on the sidewalk. In the first minute you record 10 ants. In the second minute you record 20. In the third minute, you record 40 ants. This continues until there are too many ants for you to count.

Minute	#Green Ants
1	10
2	20
3	40
4	80
$\vdots$	$\vdots$

Since you lost count of the ants, you decide to use mathematics to try and figure out how many ants walked by on minutes 5, 6, ... You notice the pattern that

$$\text{Green ants per minute } n = 2^{n-1} \cdot 10.$$

Stupendous! Mathematics now predicts there were 160 ants during minute 5. But something else catches your eye. Across the sidewalk are *brown* ants. You count these ants every minute.

Minute	#Brown Ants
1	3
2	6
3	12
4	24
$\vdots$	$\vdots$

The pattern is slightly different. This time,

$$\text{Green ants per minute } n = 2^{n-1} \cdot 3.$$

Your friend, who was watching you the whole time, looks confused. "Why come up with two complicated equations when you can describe both types of ant at once?" they declare.

$$\begin{gathered}\#\text{Ants at minute } n \;=\; 2 \cdot (\#\text{Ants at minute } n-1)\\ \#\text{Green ants at minute } 1 = 10\\ \#\text{Brown ants at minute } 1 = 3\end{gathered}$$

Your friend has a point. Their model is elegant, but *your* model can predict how many ants pass by at minute 3.222! Though, your friend would probably complain that 46.654 is not a number of ants....

You and your friend have just come up with two different *mathematical models* for the number of ants that walk across the sidewalk. They happen to make similar predictions for each minute and each have their strengths and weakenesses. In this course, we will be focused on a particular type of mathematical model—one that uses *differential equations* at its core.

Types of Models

Mathematical Model. A ***mathematical model*** is a description of the world

1. created in the service of answering a question, and

> 2. where the complexity of the world has been abstracted away to numbers, quantities, and their relationships.[a]
>
> [a]Other mathematical objects are also allowed.

In the previous situation, the *question* you were trying to answer was "how many ants are there at a given minute?". We sidestepped difficult issues like, "Is an ant that is missing three legs still an ant?" by using the common-sense convention that "the number of ants is a whole number and one colored blob that moves under its own power corresponds to one ant"; thus, we could use single numbers to represent our quantity of interest (the ants).

You and your friend already came up with two types of models.

- An **analytic** model based on known functions.
- A **recursive** model where subsequent terms are based on previous terms and initial conditions.

If we define $A(n)$ to be the number of ants corssing the sidewalk at minute n, the *analytic* model presented for green ants is

$$A(n) = 2^{n-1} \cdot 10$$

and the *recursive* model presented is

$$\begin{aligned} A(1) &= 10 \\ A(n) &= 2 \cdot A(n-1). \end{aligned}$$

Each type of model has pros and cons. For example, the analytic model allows you to calculate the number of ants at any minute with few button presses on a calculator, whereas the recursive model is more difficult to calculate but makes it clear that the number of ants is doubling every minute.

Often times recursive models are easier to write down than analytic models,[2] but they maybe harder to analyze. A third type of model has similarities to both analytic and recursive models, and brings the power of calculus to modeling.

- A **differential-equations** model is a model based on a relationship between a function's derivative(s), its values, and initial conditions.

Differential-equations models are useful because derivatives correspond to rates of change—and things in the world are always changing. Let's try to come up with a differential equations model for the ants.

We'd like an equation relating $A(n)$, the number of ants at minute n, to $A'(n)$, the *instantaneous rate of change* of the number of ants at minute n. Making a table, we see

Minute	#Brown Ants	Change (from prev. minute)
1	3	?
2	6	3
3	12	6
4	24	12

or

Minute	#Brown Ants	Change (from next minute)
1	3	3
2	6	6
3	12	12
4	24	?

depending on whether we record the change from the previous minute or up to the subsequent minute. Neither table gives the *instantaneous* rate of change, but in both tables, the change is proportional to the number of ants. So, we can set up a model

$$A'(n) = kA(n)$$

where k is a constant of proportionality that we will try to determine later. We've just written down a *differential equation* with an undetermined parameter, k.

[2]In fact, in many real-world situations, an analytic model doesn't exist

Differential Equation. A ***differential equation*** is an equation relating a function to one or more of its derivatives.

We'd like to figure out what k is. One way to do so is to solve the differential equation and find the values of k so that our model correctly predicts the data. This is called *fitting* the model to data.

Fitting a Model. Given a model M with parameters $k_1, k_2, \ldots$ and data D, ***fitting the model M to the data D*** is the process of finding values for the parameters $k_1, k_2, \ldots$ so that M most accurately predicts the data D.

Note that, in general, fitting a model to data doesn't necessarily produce *unique* values for the unknown parameters, and a fitted model (especially when the data comes from real-world observations) usually doesn't reproduce the data exactly. However, in the case of these ants, we just might get lucky.

Solving Differential Equations

In general, *there is no algorithm for solving differential equations*. Fortunately, it is easy to check whether any particular function is a solution to a differential equation, since there *is* an algorithm to differentiate functions.[3] Because of this, *guess and check* will be our primary method for solving differential equations.

Example. Use educated guessing to solve $A'(n) = kA(n)$.

Since $A' \approx A$, we might start with a function that is equal to its own derivative. There is a famous one: e^n. Testing, we see

$$\frac{\mathrm{d}}{\mathrm{d}n} e^n = e^n = ke^n$$

if $k = 1$, but it doesn't work for other k's. Trying e^{kn} instead yields

$$\frac{\mathrm{d}}{\mathrm{d}n} e^{kn} = ke^{kn}$$

which holds for all k. Thus $A(n) = e^{kn}$ is *a* solution to $A'(n) = kA(n)$. However, there are other solutions, because

$$\frac{\mathrm{d}}{\mathrm{d}n} Ce^{kn} = C\left(ke^{kn}\right) = k\left(Ce^{kn}\right),$$

and so for every C, the function $A(n) = Ce^{kn}$ is a solution to $A'(n) = kA(n)$.

By guessing-and-checking, we have found an infinite number of solutions to $A'(n) = kA(n)$. It's now time to fit our model to the data.

Example. Find values of C and k so that $A(n) = Ce^{kn}$ best models brown ants.

Taking two rows from our brown ants table, we see

$$A(1) = Ce^k = 3$$
$$A(2) = Ce^{2k} = 6.$$

Since e^k can never be zero, from the first equation we get $C = 3/e^k$. Combining with the second equation we find

$$Ce^{2k} = \frac{3}{e^k} e^{2k} = 3e^k = 6$$

and so $e^k = 2$. In other words $k = \ln 2$. Plugging this back in, we find $C = 3/2$. Thus our fitted model is

$$A(n) = \frac{3}{2} e^{n \ln 2}.$$

Upon inspection, we can see that $\frac{3}{2} e^{n \ln 2} = 3 \cdot 2^{n-1}$, which is the analytic model that was first guessed for brown ants.

[3] More specifically, there is an algorithm to differentiate the *elementary* functions, those functions formed by compositions, sums, products, and quotients of polynomials, trig, exponentials, and logs.

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

2 Let

(Birth Rate) $K = 1.1$ children per starfish per year
(Initial Pop.) $P_0 = 10$ star fish

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.

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 $\mathbf{M}_1^*$.

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 $n \to \infty$?

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 $P(t) = \lim_{n\to\infty} P_n(t)$.

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 $\mathbf{M}_1$?

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)
$\mathbf{M}_1$			
$\mathbf{M}_1^*$			
$\mathbf{M}_\infty$			

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?

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.

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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.

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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 $\Delta \to 0$?

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

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

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

---

12 Consider the following models for starfish growth

M # new children per year ∼ current population

N # new children per year ∼ current population times resources available per individual

O # new children per year ∼ 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).

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13 Recall the models

M # new children per year ∼ current population

N # new children per year ∼ current population times resources available per individual

O # new children per year ∼ 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?

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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.

15 The *Lotka-Volterra Predator-Prey* models two populations, F (foxes) and R (rabbits), simultaneously. It takes 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.

15.1 Speculate on when would B_F, D_F, B_R, and D_R would be at their maximum(s)/minimum(s), given your knowledge about how foxes and rabbits might interact.

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

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?

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?

18 Open the spreadsheet

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Component Graph & Phase Plane

DEFINITION

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)?

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

DEF 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?

20 Recall the logistic model for starfish growth:

O # new children per year ∼ 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?

21 **Classification of Equilibria**

DEFINITION An equilibrium solution f is called

- ***attracting*** if solutions locally converge to f
- ***repelling*** if solutions locally diverge from f
- ***stable*** if solutions do not locally diverge from f
- ***unstable*** if solutions do not locally converge to f
- ***semi-stable*** if solutions locally converge to f from one side and locally diverge from f on another.

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?

22

Classification of Equilibria

DEFINITION

An equilibrium solution f is called

- ***attracting*** if solutions locally converge to f
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- ***unstable*** if solutions do not locally converge to f
- ***semi-stable*** if solutions locally converge to f from one side and locally diverge from f on another.

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

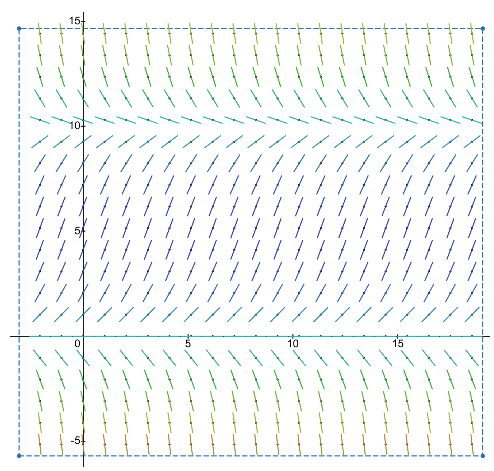
$$P'(t) = k \cdot P(t) \cdot \left(1 - \frac{R_i}{R} \cdot P(t)\right)$$

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?

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

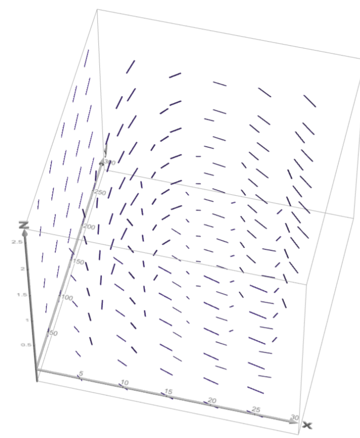
`https://www.desmos.com/calculator/ghavqzqqjn`

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 Describe different solutions to the *differential equation* using words. Do all of those solutions make sense in terms of *model* ***O***?

24



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/fsfbhvy2h9`

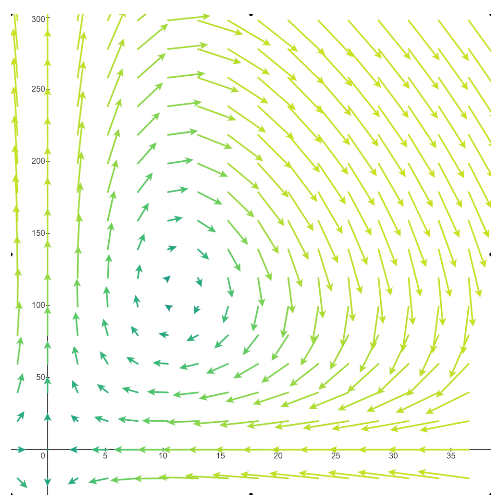
24.1 What are the three dimensions in the plot?

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?

25



Phase Portrait

DEF

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 Why is the vector at $(5, 100)$ longer than the vector at $(10, 100)$? Justify numerically.

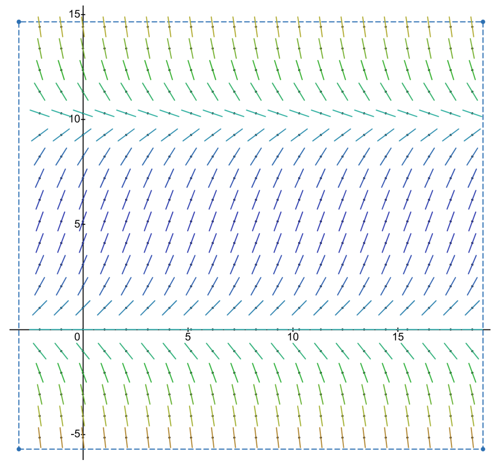
26 Sketch your own vector field where the corresponding system of differential equations:

26.1 Has an attracting equilibrium solution.

26.2 Has a repelling equilibrium solution.

26.3 Has no equilibrium solutions.

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.?

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

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

and $0 \leq b \leq 2$

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)?

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 $0 \le b \le 2$

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?

---

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 absorbs energy from the sun proportionality to the leaf area.

$P_{\text{energy 2}}$ It costs energy proportional to the square of the height for the tree to maintain its current size.

30.1 How are the premises expressed in the differential equations?

30.2 What does the parameter b represent?

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?

---

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 $0 \le b \le 2$.

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}.

---

32 Consider the system of differential equations

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

32.1 Make a phase portrait for the system.

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).

---

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?

---

34 Recall from MAT223:

Linearly Dependent & Independent (Algebraic)

DEF The vectors $\vec{v}_1, \vec{v}_2, \ldots, \vec{v}_n$ are ***linearly dependent*** if there is a non-trivial linear combination of $\vec{v}_1, \ldots, \vec{v}_n$ 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.

---

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 Intuitively, 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 $\vec{r}'(t) = \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix} \vec{r}(t)$. w (You've seen this equation before.) Intuitively, is S a subspace? If so, what is its dimension?

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

---

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.

37

THM For an ***autonomous*** ordinary differential equation (whose solutions are defined on all of $\mathbb{R}$), a solution that passes through (t_0, y_0) also passes through $(0, y_0^*)$ for some y_0^*.

(Uniqueness 1)

THM The differential equation $y'(t) = a \cdot y(t) + b$ has a unique solution passing through every point.

37.1 Explain why the *autonomous* condition is important for the first theorem.

37.2 Suppose that f and g are solutions to $y' = a \cdot y + b$. If the graph of f passes through $(0, 1)$ and the graph of g passes through $(1, 0)$, does the second theorem (Uniqueness 1) say that $f \neq g$? Explain.

37.3 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.

Apply the above theorems to decide if the argument is true or false.

38

THM For an ***autonomous*** ordinary differential equation (whose solutions are defined on all of $\mathbb{R}$), a solution that passes through (t_0, y_0) also passes through $(0, y_0^*)$ for some y_0^*.

(Uniqueness 1)

THM The differential equation $y'(t) = a \cdot y(t) + b$ has a unique solution passing through every point.

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

38.1 What is the dimension of S? Justify your answer.

39 Consider the system

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

39.1 Rewrite the system in matrix form.

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

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

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

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

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

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

39.5 Which functions from 39.2 are eigen solutions?

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

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

40 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 $\vec{r}_6(t) = \begin{bmatrix} 0 \\ e^{3t} \end{bmatrix}$.

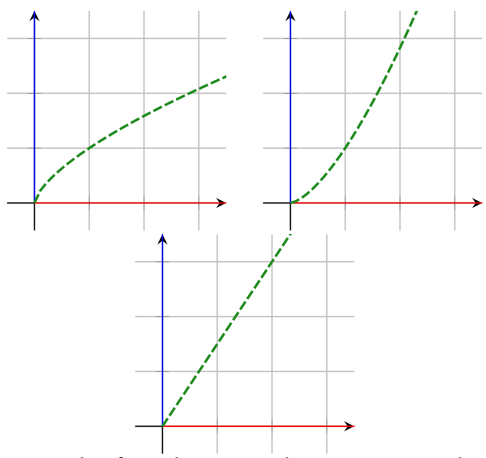
40.1 Sketch $\vec{r}_2$ and $\vec{r}_6$ in the phase plane.

40.2 Use

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

to make a phase portrait for the system.

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



---

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

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

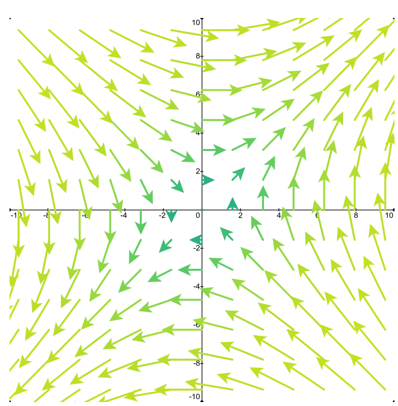
41.2 Sketch a phase plane with graphs of $\vec{s}_1$ and $\vec{s}_2$ on it.

41.3 Add a non-eigen solution to your sketch.

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

---

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



42.1 Can you identify any eigen solutions?

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

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

43.1 Find the eigenvectors and eigenvalues for M.

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

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

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

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

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

---

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

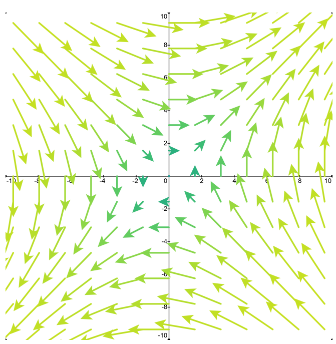
44.1 Write down a general solution to the differential equation.

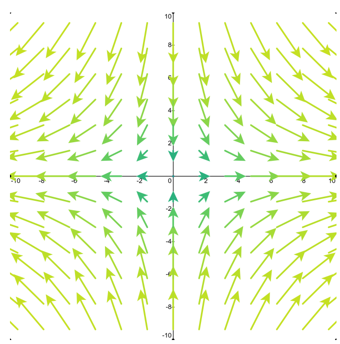
44.2 Write down a solution to the initial value problem $\vec{r}(0) = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix}$.

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

---

45 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.





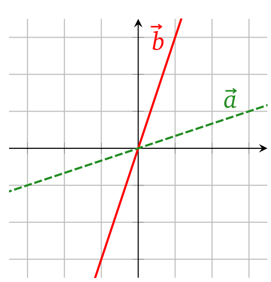
Both have eigenvalues ± 1, but they have different eigenvectors.

45.1 How are the phase portraits related to each other?

45.2 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?

---

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



46.1 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

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

46.3 Would any of your classifications in 46.2 change if the directions of $\vec{a}$ and $\vec{b}$ changed?

---

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

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

47.1 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.

47.2 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.

---

48 Consider the following model of Social Media Usage where

$$\begin{aligned} x(t) &= \text{number of social media posts at year } t \\ y(t) &= \text{number of social media users at year } t \end{aligned}$$

($P1_x$) Ignoring all else, each year posts decay proportionally to the current number of posts with proportionality constant 1.

($P2_x$) Ignoring all else, social media users increase/decrease in proportion to the number of posts.

($P1_y$) Ignoring all else (independent of decay), posts grow by a constant amount of 2 million posts every year.

($P2_y$) Ignoring all else, social media users increase/decrease in proportion to the number of users.

($P3_y$) 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 ($P1_y$) is $1 - a$.
- After the intervention, the proportionality constant for ($P2_y$) is a.

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

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

$$x' = -x + 2$$
$$y' = (1-a)x + ay - 1$$

where

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

49.1 What are the equilibrium solution(s)?

49.2 Make a phase portrait for the system.

49.3 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.

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

$$x' = -x + 2$$
$$y' = (1-a)x + ay - 1$$

where

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

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

50.2 Define $\vec{s}(t)$ to be the displacement from equilibrium in the **SM** model at time t.

(a) Write $\vec{s}$ in terms of x and y.

(b) Write a differential equation governing $\vec{s}$.

(c) Can your differential equation governing $\vec{s}$ be written in matrix form?

(d) 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.)

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

$$x' = -x + 2$$
$$y' = (1-a)x + ay - 1$$

where

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

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!*

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

51.2 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.

---

52 Consider the following **DF** model of Dogs and Fleas where

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

($P1_x$) Ignoring all else, the number of parasites decays in proportion to its population (with constant 1).

($P2_x$) Ignoring all else, parasite numbers grow in proportion to the number of hosts (with constant 1).

($P1_y$) Ignoring all else, hosts numbers grow in proportion to their current number (with constant 1).

($P2_y$) 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.

52.1 Write a system of differential equations for the **DF** model.

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

52.3 Make a phase portrait for your mode.

52.4 What should solutions to the system look like in the phase plane? What are the equilibrium solutions?

---

53 Recall the **DF** model of Dogs and Fleas where

$$x(t) = \text{number of parasites (fleas) at year } t \text{ (in millions)}$$
$$y(t) = \text{number of hosts (dogs) at year } t \text{ (in thousands)}$$
$$\vec{r}(t) = \begin{bmatrix} x(t) \\ y(t) \end{bmatrix}$$

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.

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

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

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

---

54 Recall the **DF** model of Dogs and Fleas where

$$x(t) = \text{number of parasites (fleas) at year } t \text{ (in millions)}$$
$$y(t) = \text{number of hosts (dogs) at year } t \text{ (in thousands)}$$
$$\vec{r}(t) = \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} \qquad \vec{s}(t) = \vec{r}(t) - \begin{bmatrix} 3 \\ 5 \end{bmatrix}$$

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

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

54.1 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 $\vec{s}_1 - \vec{s}_2$. Are there any imaginary numbers remaining?

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

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

---

55 Recall the **DF** model of Dogs and Fleas where

$$x(t) = \text{number of parasites (fleas) at year } t \text{ (in millions)}$$
$$y(t) = \text{number of hosts (dogs) at year } t \text{ (in thousands)}$$
$$\vec{r}(t) = \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} \qquad \vec{s}(t) = \vec{r}(t) - \begin{bmatrix} 3 \\ 5 \end{bmatrix}$$

and

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

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

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

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

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

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

---

56 Consider the differential equation

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

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

56.2 Find a general *real* solution.

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

---

57 Recall the **DF** model of Dogs and Fleas where

$$x(t) = \text{number of parasites (fleas) at year } t \text{ (in millions)}$$
$$y(t) = \text{number of hosts (dogs) at year } t \text{ (in thousands)}$$
$$\vec{r}(t) = \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} \qquad \vec{s}(t) = \vec{r}(t) - \begin{bmatrix} 3 \\ 5 \end{bmatrix}$$

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

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

57.1 Modify the previous **DF** model to incorporate the effects of the shampoo.

57.2 Make a phase portrait for the **DF Shampoo** model.

57.3 Find the equilibrium solutions for the **DF Shampoo** model.

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

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

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58 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`

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

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

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

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59 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 $P \approx 1/2$.

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

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

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

59.4 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 $P(t)$.

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

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60 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`)

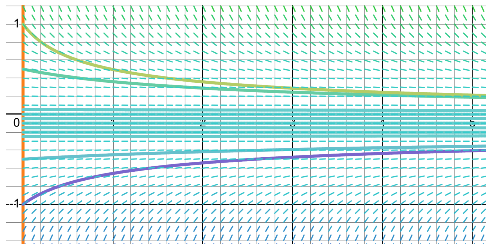
60.1 What do you notice about the solutions sketched on the different slope fields (in Desmos)?

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

61 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`



61.1 Find all equilibrium solutions.

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

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

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

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

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

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 $\vec{E}$.

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 $0 \le b \le 2$

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

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

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

62.3 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.

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

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

Indices

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