Teaching Portfolio

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1 Teaching Statement

"'Obvious' is the most dangerous word in mathematics"

Eric Temple Bell

Despite its antiquity and wide prevalence across other fields, mathematics can be one of the most polarizing subjects for students. In the past, I always found it a bit odd that the most common response I got when telling someone I'm a mathematics Ph.D. student was an unabashed "I always hated math". The more I've engaged with my students in recent years, however, I've realized that this crowd is often trying to say "I always disliked my mathematics *courses*" and not "I dislike mathematics *as a subject*". The silver lining in the latter is that it is significantly easier address; though there are many factors that shape a student's success. As a consequence, it is my duty as an educator to constantly strive to improve aspects of my teaching so that students not only feel less deterred from mathematics, but find a sense of comfort in my classroom.

As a personal anecdote, pursuing an academic career in mathematics was never something in my sights until quite late. Like most people, mathematics was simply a check-mark to fulfill a general education requirement — at least until my first linear algebra course. The instructor, we were told, was fairly fresh out of graduate school and this would be his first full-time position. While that may give the impression he did not have the capacity for teaching a long-time professor would have, the opposite could not have been more true: our instructor, Mr. Margraff, had an excitement and enthusiasm for mathematics that became increasingly more contagious the closer he was in proximity to a chalkboard. What would normally be rudimentary exercises in most other linear algebra courses became colorful segues into the delicate nature of spaces in higher dimensions. Any misunderstanding in a student's question was met with an appreciative reply, which he saw as an opportunity to better explain a topic that may have been glossed over. It was shortly after this course that I went to the college of science at my university to declare a math major; to no mystery, this is due to an instructor who believed his students finding beauty in a subject was the best possible outcome of a course.

Unfortunately, one's journey through their math education rarely gives the same warm and inclusive feeling that Mr. Margraff gave. Even within the literature, a student will begin to notice that more and more details become omitted, often replaced with an unsatisfactory 'the proof is trivial' in its stead; sometimes authors will be more straightforward about their limitations, and give the infamous 'proof is left as an exercise to the reader'. While I do believe that practice is necessary to improve mathematical understanding, it becomes quickly apparent that math education can be pitted against those who do not see the forest through the trees on first glance. As a consequence, I have made it a primary objective in teaching to foster the idea that no detail is too trivial to withhold, no question is too rudimentary to carefully answer, and no misunderstanding should be assumed the fault of the student.

In effort to cultivate students curiosity, I have spent countless hours over the past several years meeting with students outside of my normal TA schedule to ensure that they have a safe space to ask questions they may not feel comfortable asking in front of peers. This has not only led to me meeting with current students quite regularly, but students enrolled in my previous classes as well — topics I have covered have ranged anywhere from high-school polynomial division to graduate-level Galois theory to programming-based problems. When not engaging directly with students, I still find myself spending the remaining hours of the day thinking of ways to better approach topics for students (examples of such are given in §4); though it can be a challenge exploring new teaching styles, I feel that it has both made me a better instructor and provided my students with new perspectives on the topics they learn.

Ultimately, teaching mathematics has been one of the most rewarding experiences in my educational career. Somehow finding myself come full circle, I now hope to give my students the same enthusiasm for mathematics that my linear algebra instructor, Mr. Margraff did, many years ago. Though I cannot speak to whether every student has come out of my classes passionate about mathematics, at the very least I believe they walk away more confident in their mathematical abilities.

2 Diversity Statement

"Mathematics knows no races or geographic boundaries; for mathematics, the cultural world is one country."

David Hilbert

As an instructor, I believe that it is of the utmost importance to ensure that education is not just equally available to people of all races, genders, sexes, cultures, and beliefs, but *equitably* available. Specifically, it is vital to recognize that societal and socioeconomic disparities can, and have, lead to underrepresented students not getting same access to mathematics as their peers. Historically, mathematics has been dominated by institutions which disproportionately hire and cater to specific backgrounds, and the ripples of this imbalance are still felt today in mathematics departments across the world. Now more than ever, it is vital to foster a sense of belonging to underrepresented students to ensure that the knowledge and beauty of this subject does not become withheld from any group of people.

Among underrepresented groups, I believe that it is also absolutely necessary to ensure students with disabilities are given the means to participate and engage in mathematics at the same level as their peers. Just like any form of discrimination, ableism has no place in the academic setting — while this may seem like an obvious statement, there are still many indirect and passive forms of ableism which occur regularly in academia. This can include things like deflecting responsibility for accommodations to administrative departments, and refusing to incorporate accessible instructional resources into a curriculum. It becomes clear from both examples that, in order to ensure the success of these students, we as instructors must take a proactive role. To this end, I have spent a large portion of my collegiate education tutoring students with disabilities to not only help their academic careers, but inspire confidence in their strengths and abilities as well.

Lastly, I believe that it is important in today's political climate to address the importance of protecting the values and beliefs of all communities, and condemning any sort of censorship. The experiences of an individual or community should never be disregarded, and it is vital to ensure the voices of vulnerable communities are heard. Throughout my time as an instructor, I have been deeply committed to ensuring the opinions of every person in my classroom are valued, and no idea or trait is repressed.

3 Teaching History

Year	Quarter	Course	Instructor
	Winter		
2020	Spring		
	Summer		
	Fall	Math 34A — Calculus for Social Sciences	Daryl Cooper
	Winter	Math 6B — Vector Calculus II	Peter Garfield / Katy Craig
2021	Spring	Math 117 — Methods of Analysis	Katy Craig
	Summer	Math 4B — Differential Equations	Fabio Ricci
	Fall	Math 3B — Calculus with Applications II	Jea-Hyun Park
	Winter	Math 6B — Vector Calculus II	Zuhair Mullath
2022	Spring	Math 4B — Differential Equations	Gunhee Cho
	Summer		
	Fall	Math $4A$ — Linear Algebra	Peter Garfield
	Winter	Math 6A — Vector Calculus I	Marc Becker
2023	Spring	Math 3B — Calculus with Applications II	Peter Garfield
	Summer	Math 3B — Calculus with Applications II	Paige Hillen
	Fall	Math $6B$ — Vector Calculus II	Elie Abdo
	Winter	Math 8 — Transition to Higher Math	Wenchuan Tian
2024	Spring		
	Summer		
	Fall		

4 Sample Course Design

Though I have not yet had the opportunity to lead a course as instructor of record, I have been fortunate enough to exercise a good amount of freedom in several of my courses as a teaching assistant. This has ranged from designing my own quizzes to utilizing technology in unique ways in order to supplement students in their studies.

4.1 Sample Video Content / Visual Resources

Growing up as a visual learner, I found it especially helpful to approach topics in mathematics based on what was happening geometrically. Unfortunately, the resources available become increasingly scarce as topics become more and more complex. For example, there is a wide variety of visual resources to help a student in a first year calculus course (e.g. Khan Academy, Brilliant, Professor Leonard to name a few); however, a student taking their first real analysis math course may quickly find that textbooks are essentially the only means of independent study. Though I do believe that parsing textbooks is an increasingly important skill the further one delves into mathematics, that does not mean it needs to be the *only* resource.

I am incredibly grateful to Grant Sanderson, creator of the popular mathematics YouTube Channel 3Blue1Brown, for making the Python library which he uses for animations (Manim) free and open source to the public in order to better provide educators with the tools to make engaging visual content. During the course of Summer 2022, I spent a large portion of my free time re-learning the basics of Python and becoming familiar with the Manim library in order to supplement my teaching during the 2022-2023 school year.

4.1.1 Math 4B: Linear Equations

In Fall 2022 I had the chance to TA for Math 4A (Linear Algebra) at UCSB under Professor Peter Garfield; as with most TA rôles, this came with the task of planning weekly 50-minute instruction sections. I believed it would be beneficial to provide students a short visual recap of the topics covered in lectures.

Below is an examples of one of the videos I would show at the beginning of every section:







Since video (i.e. .MP4, .MOV) files are not able to be embedded in PDF files, I ask the reader to be generous in pretending the 3 frames provides an accurate approximation of the 40 second clip. However, anyone curious with how to render the scene in order to watch the full video is encouraged to use the code provided in Appendix A below.

4.1.2 Math 3B: Volume / Surfaces of Revolution

Fortunately, my efforts to provide a geometric intuition for topics at the beginning of each section found great success with my Math 4B students. Thus, it made sense to try to apply this strategy to future courses — for example, the following spring quarter I had the opportunity to once again TA for Professor Peter Garfield, now in the Math 3B (integral calculus). Though I mentioned visual resources for calculus courses are widely available online, I continued to spend several hours each week curating specifically tailored videos for the problems in the course.

As an example, around the fourth week of instruction we began covering volume and surfaces of revolution — the latter subject is something I truly believe benefits from visual demonstration. Thus, I would begin certain problems during section by showing the students a geometric representation of what they were about to solve.





As before, the interested reader may consult Appendix B to reference the source code which was used to generate the 1:28 minute video.

4.2 Sample Interactive Content

In addition to providing videos to help student who benefit from visual learning techniques, it is important to address other learning styles as well. In my opinion, one of the most difficult learning styles to address in mathematics is kinaesthetic learning; since the vast majority of mathematics is conceptual, a good bit of creativity is required in order to keep these students engaged. While it may not be perfect, one solution I have found useful is giving students access to tools they can use to tinker with equations and variables (similar to Desmos for more advanced topics).

One of the primary ways I have done this is through the mathematical coding software Mathematica, which allows me to create interactive graphs that can then be uploaded to the WolframAlpha cloud servers via an API call:

```
CloudDeploy[Manipulate[...]]
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This was particularly useful in my Winter 2021 vector calculus course (taught by Professor Katy Craig), since it provided a means for students to dynamically interact with partial differential equations (PDEs) and observe the behavior of solutions as certain variables grow. For example, around week 9 of quarter we began discussing the wave equationm which is a tricky concept fundamental

to the majority of quantum physics. In order to help with student's understanding, I gave a sample wave equation problem and uploaded the following interactive diagrams for students to utilize:





Unfortunately, it is significantly harder to provide the supplementary code used here in an appendix since Mathematica heavily utilizes the markdown language (which requires a handful of libraries to convert into IATEX).

4.3 Sample Quiz

ame:	
udent Number:	

Write all steps clearly in order to get any partial credit. No calculators, outside notes, or collaboration are allowed. By signing your name, you agree to adhere to and uphold the UCSB Academic Integrity statement.

Problem	Points	Score
1	5	
2	5	
3	5	
4	5	
Total	20	

Distribution of Marks

(1) [5 Points] Consider the "pinched plane" given by the equation $f(x,y) = \frac{x^2 - y^2}{x^2 + y^2}$. Using your geometric intuition based off the following picture, justify whether the limit $\lim_{(x,y)\to(0,0)} \frac{x^2 - y^2}{x^2 + y^2}$ exists.





(2) [5 Points] One of the most significant kinds of shapes to theoretical physicists is something known as 'Calabi-Yau Manifolds' — a slice of one can be given by the equation $xz^3 + 2y^2z^2 - yx^3 = 2$. Find what the tangent plane is at the point (x, y, z) = (0, 1, 1)

(3) [5 Points] Given $f(x, y) = e^{5-2x+3y}$, use the point $(x_0, y_0) = (4, 1)$ to (linearly) approximate the value of f(4.1, 0.9).

(4) [5 Points] Consider the function $g(v, w) = \langle ve^w, e^v - w, we^2 \rangle$. What is the Jacobian matrix for g?

5 Student Feedback

5.1 Course Evaluations

5.1.1 Evaluation 1

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5.1.2 Evaluation 2

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	Note that	the Campus and	Departmental Norms	for this Survey are	based ONLY on other ESCI	Online Courses.
ue to the	different	method of data	collection, these	Norms do not include	ESCI Surveys collected b	w the paper respo

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(3261) 2. Rate t	the clarity o	f the	TA's	expla	inatio	ons.						
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5.2 Student Emails / Additional Correspondence



6 Mentoring of Undergraduate Research

It was a pleasure to be a part of the UCSB Directed Reading Program (DRP) as a mentor to undergraduate mathematical research during the 2022-2023 school year. With a focus towards algebraic and complex geometry, I had the chance to work with a student on Hodge theory in the hope of covering the basics of Hodge theory and why it is important to geometers. We spent 14 weeks covering the following topics:

- (1) Smooth manifolds:
 - Topological spaces
 - Homeomorphisms and open charts
 - Differential forms and the (co)tangent bundle
 - Complex manifolds and complex structures
- (2) Cohomology on manifolds:
 - De Rham cohomology
 - Dolbeault cohomology
- (3) Basic Hodge Theory:
 - The Hodge diamond
 - Hodge structures
 - Correspondence between Hodge structures of weight 1 and tori

Following the 14 week instruction period, my student had the opportunity to create a poster based on the culmination of their research and present it to the UCSB mathematics faculty.

MANIFOLDS, COHOMOLOGIES, AND HODGE STRUCTURES Hespos Goodman University of California, Santa Barbara

COMPLEX MANIFOLDS

An n-dimensional **complex manifold** is a topological space that is locally isomorphic to \mathbb{C}^n . This means manifolds can take arbitrary, and often extremely complicated, forms on a global scale, but 'zooming in' allows us to study their local properties with relative seas. This construction is defined by an **atlas** of open sets $(U_i)_{i \in M}$ that cover our manifold, each with a **chart** ($_{\mathcal{C}}$) that that links it to C



In order for this construction to be useful. It must guarantee continuity of functions on the surface of our manifold. This is achieved through requiring that our drats (c_i) be holomorphic (analytic) diffeomorphisms, and requiring that, on the intersection, the composition $c_i^{-1} \circ c_j^{-1}$ is a smooth map.

TANGENT BUNDLES

Now that we know what the surface of a manifold looks like, we can begin talking about what happens along that surface. At any particular point *y* we define *T₂N*, the **tangent space** at that point. This space in generated by the tangent vectors (at *y*) of every curve on our manifold that passes through *y*. As usual, this is equivalent to using the partial derivatives of our chart with respect to the basis vectors in *V_i* at the preimage of our point,



The tangent space is specific to each individual point, because it relies on evaluating the partial derivative at the unique (restricted to I/i) preimage of p. In order to address the maniloid at large, we can define a **tangent** bundle (T/I) which is the set of all pairs of points (p), and vectors in that points tangent space. $TM = \{(p, \vec{v}) | p \in M, \vec{v} \in T_pM\}$

Naturally, there are a LOT of vectors in the tangent space of any particular point. The **(tangent) vector field** (ξ) provides us a method for selecting one of these vectors, given a particular point.

 $\xi:=M\mapsto TM$ $p \mapsto (p, \vec{v})$

For the purposes of integration, we want to remember which point each of these vectors comes from. This is why its essential for the vector field to map to the tangent bundle rather than a particular tangent space.

COTANGENT BUNDLES

Using our definitions of tangent spaces, bundles, and fields, we will define cotangent spaces, bundles, and fields. A covector (...)(also called a 0-form, or a linear functional) is a function that takes in a vector and outputs a scalar. $\omega := \vec{v} \mapsto z$

ally a **cotangent vector** is a covector who's domain is the tangent space (at a point), so we can be sure intakes tangent vectors. Applying what we know about tangent spaces, we can see that the **cotangent** e should be the space of all cotangent vectors.

$T_n^*M = \{\omega | \omega : T_pM \mapsto \mathbb{C}\}\$

COTANGENT BUNDLES (CONT.)

Here we use the notation for the dual of the tangent space since thats exactly what the cotangent space is it is the set of all maps(coxectors) from the tangent space to the under/ying field(C in our case). In light of this, we can define a basis for the cotangent space, with the conventional linear functional basis of a dual space

$$T_p^*M = \langle de_1^p, de_2^p, \cdots, de_{2n}^p \rangle, \quad de_i^p \left(\frac{\partial}{\partial e_j} \right|_p \right) = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$$

Similarly, the cotangent bundle is the set of all point-cotangent vector pairs $T^*M = \{(p, \omega) | p \in M, \omega \in T^*_*M\}$

 $\label{eq:alpha} e_{m} = (v, \omega) | p \in M, \ \omega \in t_p M \}$ Again, this is the dual of the tangent bundle Finally, a covector field is analogous to a vector field. It is a map that, given a point, provides a covector in the cotangent space of that point

$\alpha := M \mapsto T^*M$ $p \mapsto (p, \omega)$

When we require this map to be smooth, we realize this "covector field" as a section of the cotangent bundle, or a **differential one form**

DIFFERENTIAL 1-FORMS AND EXTERIOR DERIVATIVES

Differential 1-forms are functions that are nearly equivalent to covector fields, the main difference is that we allow them to intake a point AND a vector (i.e. a vector field), so their output becomes a point-scalar pair. Differential forms are written

$$\alpha(p, \vec{v}) = \left(p, \sum_{i=1}^{2n} f_i(p)de_i^p(\vec{v})\right) = \left(p, f_1(p)de_1^p(\vec{v}) + f_2(p)de_2^p(\vec{v}) + \dots + f_{2n}(p)de_{2n}^p(\vec{v})\right)$$

So, in the particular case where
$$\vec{v} = \frac{\partial}{\partial v_i}$$
 that we achieve

$$\alpha\left(p, \frac{\partial}{\partial e_i}\Big|_p\right) = 0 + \cdots + f_i(p)de_i^p\left(\frac{\partial}{\partial e_i}\Big|_p\right) + \cdots + 0 = (p, f_i(p))$$

Inspecting the second term, evaluation of α at a point allows us to "measure" the value of α in the $\frac{\partial c_{ij}}{\partial c_{ij}}$ direction. So, summing α along a curve is equivalent to integrating f_i with respect to c_i . More generally, evaluating along some vector field, ξ_i allows us to integrate along our entire manifold (with respect to ξ_i).

respect to $\chi_D^{(1)}$ Thus, 1-forms are the tools we use in every one dimensional integral. We can use the **exterior derivative** to achieve 2-forms, which allow us to integrate area, and eventually *m*-forms, which measure *m*-dimensional oriented density. The exterior derivative, *d*, asks us to differentiate each of our *f*, swith respect to each e_J^2 and to note that differentiation in the result.

$$d(\alpha) = \sum_{i=1}^{2n} \sum_{j=1}^{2n} \frac{\partial f_i}{\partial \alpha} de_i^p \wedge de_i^p$$

 $-\overset{(*)}{\longrightarrow} -\sum_{j=1}^{r} \sum_{i=1}^{r} \overline{\partial e_j}^m u_j^r \wedge de_i^n$ The wedge product (\() here is a complicated algebraic structure that explicitly outlines how to evaluate the vector part of our input.

COHOMOLOGIES

In order to better understand the properties of a certian manifold, it can be helpful to understand how differential forms of change as we differentiate them. A sequence of groups (and maps from one group to the next) is called exact if kerc $\delta_{i} = im \delta_{i-1}$



Inspecting the quotient group $^{ker(p_i)}/Im(\varphi_{i-1})$ allows us to measure how far a sequence is from being exact. This is the premise behind cohomology.

THE DOLBEAULT COHOMOLOGY

Since we are working with a complex manifold. We can chose a convenient basis to address our tangent and cotangent spaces $\langle z_1, \overline{z_1}, \cdots, z_n, \overline{z_n}, \rangle$

This choice of basis leads to a method for splitting the exterior derivative $d=\partial+\overline{\partial}$

Where ∂ takes the partial derivatives with respect to the complex basis (z_1, z_2, \cdots, z_n) , and $\overline{\partial}$ takes the partial derivatives with respect to the complex conjugate basis (z_1, z_2, \cdots, z_n) . Using these operators, we can construct a cohomology in two directions. Begining with $\Omega^{(0)}$ the space of 0-forms (covectors) we construct.

Note that $\partial \circ \overline{\partial} = \overline{\partial} \circ \partial$ and that $\Omega^{i,j} = \overline{\Omega^{j,i}}$. Inspecting i = 1, j = 0 reveals that $\Omega^{1,0}$ are the holomored 1-forms, and $\Omega^{0,1}$ are the antiholomorphic 1-forms, on our manifold.

THE HODGE DIAMOND

We now inspect the downward cohomology of the dobeault cohomology. We name the quotient groups that it creates $H^{i,j}(M) = ker(\overline{\partial}_{(i,j)}) / Im(\overline{\partial}_{(i,j-1)})$

We call the dimension of these groups the **hodge numbers**, $h^{ij} = |H^{ij}(M)|$. Then we arrange these into the Hodge diamond

The hodge diamond is ex-				
ceptionally useful in algebraic		$h^{0,0}$		
topology as a tool to classify				
manifolds. The row that each				
of these hodge numbers are in				
corresponds to the weight of	h0.0	ha/2.n/2	ha.0	
the represented group. This		<i>m</i> , ,		
weight is the order of the forms				
contained within the cosets				
that make up each individual				
$H^{i,j}(M)$.		$h^{n,n}$		

HODGE STRUCTURES

We call the direct sum of all cohomology groups of a particular weight(k), the hodge structure of weight k $H^k(M, \mathbb{C}) = \bigoplus_{i} H^{i,j}(M)$

In the case of hodge structures of weight 1 we know

 $H^1(M, \mathbb{C}) = H^{1,0}(M) \oplus H^{1,0}(M) = H^{1,0}(M) \oplus \overline{H^{1,0}(M)}$

So we conclude that $H^1(M,\mathbb{C})$ is of even dimension. This must also be true for the lattice subset $H^1(M,\mathbb{Z})\subset H^1(M,\mathbb{C})$. Thus we identify a torus

 $T = H^{0,1}(M) / H^1(M, \mathbb{Z})$

The map from a complex torus to the cohomology groups generated on that torus yields an inverse map and thus we establish a bijection between complex tori and hodge structrues of weight 1 $T \leftrightarrow H^1(M,\mathbb{C})$

ACKNOWLEDGEMENTS AND REFERENCES

Thank you to my mentor, Chris Dare, and the DRP committee for the opportunity to work on this

Voisin, C. (2002). Hodge Theory and Complex Algebraic Geometry, I. Cambridge, UK. Cambridge

7 Appendix A: Source Code for Linear Algebra Content

```
1 class SystemOfEquations(Scene):
2
      def construct(self):
3
4
          5
6
          # Title construction
          connecting_matrices_text = Text('Connecting Algebra to Geometry').shift(3*UP)
7
          ul=Underline(connecting_matrices_text)
8
9
          self.add(connecting_matrices_text, ul)
10
          self.play(Write(connecting_matrices_text), Create(ul))
          self.wait(2)
11
13
          # Intro text
          asked_to_solve = Text('Suppose we are\n asked to solve').scale(0.6).shift(2*
14
      UP + 5*LEFT)
          self.add(asked_to_solve)
15
          self.play(Write(asked_to_solve))
16
17
18
          # Linear equations
          matheqs = MathTex(r'3x + 2y &= 5 \\ 2x + y &= 1').shift(5*LEFT + 0.4*UP)
19
          self.add(matheqs)
20
          self.play(Write(matheqs))
21
22
          self.wait(2)
23
24
          # Arrow visualizing translation of linear equations to matrix
          arrow = Arrow(start=UP, end=DOWN, color=RED).scale(0.6).shift(5*LEFT + 0.8*
25
      DOWN)
          matheqs_matrix = MathTex(
26
27
             r'\begin{pmatrix} 3 & 2 \\ 2 & 1 \end{pmatrix}'
          ).shift(5*LEFT + 2*DOWN)
28
          self.play(Create(arrow))
29
          self.play(Uncreate(arrow), Write(matheqs_matrix))
30
          self.wait(2)
31
32
33
          34
35
          # Construct 2d-plane that vectors are going to sit on
36
37
          plane = NumberPlane(
             x_range = (-6, 6),
38
              y_range = (-6, 6),
39
40
              x_length=6, y_length=6,
              axis_config={"include_numbers": True},
41
42
          )
          self.add(plane)
43
          self.play(Create(plane))
44
45
46
          # Standard basis vectors for plane, colored in green in orange
47
          e1 = Vector([1, 0], color=GREEN, stroke_width=25).scale(0.5)
48
          e2 = Vector([0, 1], color=ORANGE, stroke_width=25).scale(0.5)
49
50
          self.add(e1,e2)
          self.play(Create(e1), Create(e2))
51
          self.wait(3)
52
53
54
55
          # Briefly color matrix red and enlarge it, giving the notion that we are
          # somehow clicking on or applying the matrix
56
          matheqs_matrix1 = MathTex(
57
58
              r'\begin{pmatrix} 3 & 2 \\ 2 & 1 \end{pmatrix}',
              color=RED
59
          ).shift(5*LEFT + 2*DOWN).scale(1.5)
60
61
          matheqs_matrix2 = MathTex(
              r'\begin{pmatrix} 3 & 2 \\ 2 & 1 \end{pmatrix}'
62
          ).shift(5*LEFT + 2*DOWN)
63
```

```
self.play(Transform(matheqs_matrix, matheqs_matrix1))
64
65
          self.play(Transform(matheqs_matrix, matheqs_matrix2))
66
          # Apply the actual transform to the plane
67
          self.play(ApplyMatrix([[3, 2], [2, 1]], plane),
68
                    ApplyMatrix([[3, 2], [2, 1]], e1),
69
70
                    ApplyMatrix([[3, 2], [2, 1]], e2))
          self.wait(3)
71
72
73
74
          75
      76
          # Move equations out of way
77
          matheqs_red = MathTex(r'3x + 2y &= 5 \\ 2x + y &= 1').shift(5*LEFT + 0.4*UP)
78
          matheqs_red[0][6].set_color(RED)
79
80
          matheqs_red[0][12].set_color(RED)
          self.play(Transform(matheqs, matheqs_red))
81
82
83
          # Represent the solution to our linear equations as a vector
84
          new_vect = Vector( [9, 1], color=RED).scale(0.5).shift(2*LEFT + 0.2*DOWN)
85
86
          self.add(new_vect)
          self.play(Create(new_vect))
87
88
          new_vect_label = new_vect.coordinate_label(color=RED)
89
          self.add(new_vect_label)
90
91
          self.play(Write(new_vect_label))
          self.wait(2)
92
93
94
          #
95
96
          same_as_asking_text = Tex(
              r"This is the same as asking\newline ''What vector $\begin{bmatrix}x \\ y
97
      \end{bmatrix}$ got\newline sent to $\begin{bmatrix} 5 \\ 1 \end{bmatrix}?''"
).scale(0.7).shift(4*RIGHT + 2*DOWN)
98
          self.add(same_as_asking_text)
99
100
          self.play(Write(same_as_asking_text))
          self.wait(7)
```

The above code can be run (after downloading Manim, see https://www.manim.community/) by running

1 manim -pqm SystemOfEquations

8 Appendix B: Source Code for Surface of Revolution

It is highly recommended to run this code with the

```
--disable_caching
```

option since several of the helper functions need to be optimized.

```
1 from manim.utils.color import Colors
2 import random
3
4 """
5 Helper function which generates a random color and translates it into a hexidecimal
      string
6
7 No input
8 returns: random string of the format #----- where the 6 characters following the #
     are hexidecimal
9 ....
10 def random_color_str():
      # generate random number between #000000 and #FFFFFF
11
12
      rand_color = hex(random.randrange(0, 2**24))
      13
      rc_str = "#" + str(rand_color[2:])
14
15
      # The string must be length 7 (i.e. 6 hexidecimal base numbers and one \# symbol)
16
      # However, random.randrange will occasionally generate a number too small
17
      while len(rc_str) < 7:</pre>
18
          rc_str = rc_str + "0"
19
20
21
      return rc_str
22
23
24 """
25 Helper function to generate an array of n=num_cyl VGroup objects each containing 2
      Surface objects:
      (1) Corresponding to the wall / side of a shell
26
      (1) Corresponding to a cap of the shell, so the surface of revolution does not
27
      appear hollow
28 which, once displayed, provide a 3D model of our surface of revolution
29
30 vars:
      function = a lambda function of a single input variable which represents the
31
      underlying f(x) that is being rotated
      axes = the ThreeDAxes object that the surfaces are to be added to
32
      x_{min} = a floating point number representing the lower bound on the interval in
33
      which the function is being rotated
      \mathtt{x\_max} = a floating point number representing the upper bound on the interval in
34
      which the function is being rotated
      num_cyl = the number of cylinders used to approximate
35
36
37
38 returns: an array of VGroup objects, each containing 2 surface objects corresponding
      to a wall and a cap of the same radius
39
40
41 WARNING: This function is massively inefficient and could use some aggressive
      optimization
  0.0.0
42
43 def create_washers_revolution(function, axes, x_min, x_max, num_cyl):
44
      assert x_min < x_max, "second input (x_min) should be smaller than third input (
45
      x_max)"
      assert int(num_cyl) == num_cyl and num_cyl > 0, "num_cyl must be a positive
46
      integer"
47
      # Calculate the width of each cylinder
48
      step_length = float(x_max - x_min) / num_cyl
49
```

```
# initialize the array we will return
50
51
       surfaces = []
52
53
       # Since there must be at least one cylinder, we inductively begin
54
       # creating our shells in the desired manner
55
56
       rc_str = random_color_str()
57
       initial_disk = Surface(
58
                lambda u, v: axes.c2p(
59
                    x_min, v*np.cos(u), v*np.sin(u)
60
                ),
61
                u_range=[0, 2*PI], # u represents theta
62
                v_range=[0, function(x_min)], # v represents our radius
checkerboard_colors=[rc_str, rc_str]
63
64
           )
65
66
67
       # Iteratively begin creating more shells
68
       for i in range(num_cyl):
69
70
           x_val = float(x_min) + i*step_length # increment x position
71
           f_val = function(x_val) # get corresponding function value at the point
72
73
           # We wish to group walls and caps which have the same radius / distance from
74
       the
75
            # center of revolution
           wall_and_cap = VGroup()
76
77
           wall = Surface(
78
                lambda u, v: axes.c2p(
79
                    v, f_val*np.cos(u), f_val*np.sin(u)
80
                ),
81
                u_range=[0, 2*PI], # u represents theta
82
                v_range=[x_val, x_val + step_length], # v represents the position along
83
       the x axis
84
                checkerboard_colors=[rc_str, rc_str]
           )
85
           cap = Surface(
86
                lambda u, v: axes.c2p(
87
                    x_val + step_length, v*np.cos(u), v*np.sin(u)
88
89
                ),
                u_range=[0, 2*PI],# u represents theta
90
                v_range=[0, f_val], # v now represents the radius
91
92
                checkerboard_colors=[rc_str, rc_str]
           )
93
           # Add surfaces to VGroup
94
           wall_and_cap.add(wall)
95
           wall_and_cap.add(cap)
96
97
            # Add VGroup to
98
           surfaces.append(wall_and_cap)
99
100
           rc_str = random_color_str()
101
102
       assert len(surfaces) > 0
104
105
       surfaces[0].add(initial_disk)
106
       return surfaces
108
109
110
112 class surface_of_rev_washer(ThreeDScene):
113
114
115 """
```

```
Helper function to write the title of the video within the first scene
116
117
       0.0.0
      def produce_title(self, title_str):
118
119
120
           title_text = Text(title_str, color='#5ad2d6')
          ul1 = Underline(title_text, color='#5ad2d6')
121
122
           self.add_fixed_in_frame_mobjects(title_text, ul1)
123
          self.play(Write(title_text))
124
          self.play(Create(ul1))
125
126
          self.wait(2)
           # Remove title for next scene
128
          self.play(Uncreate(title_text), Uncreate(ul1))
129
130
131
132
133
      def construct(self):
134
          135
          phi, theta, focal_distance, gamma, distance_to_origin = self.camera.
136
      get_value_trackers()
          axes = ThreeDAxes()
137
138
           self.produce_title('Surfaces of Revolution: Washer')
139
140
141
142
          self.play(Create(axes))
143
          self.wait(1)
144
145
          146
147
148
          # Begin to rotate camera
          self.play(phi.animate.increment_value(60*DEGREES),
149
                    theta.animate.increment_value(30*DEGREES))
150
151
          self.wait(1)
152
153
           graph = axes.plot(lambda x: (0.25*x**2 + 1), x_range=[0,4], color=YELLOW_A)
154
          area = axes.get_area(graph=graph, x_range=[0,4], color=YELLOW_E)
156
157
           self.play(Create(graph))
          self.wait(1)
158
159
          # highlight the area under graph
160
          self.play(Create(area))
161
          self.wait(1)
162
163
164
          # Begin to rotate the function 360 degrees around the axis of revolution
165
          self.play(
166
167
              Rotating(
                  VGroup(graph, area),
168
                  axis=RIGHT,
169
                  radians=2*PI,
170
                  about_point=axes.c2p(0,0,0)
171
172
              ),
              run_time=5,
173
              rate_func=linear
174
          )
175
176
177
178
           ############## SCENE 3: Construct the resulting surface of revolution
      ###########
179
          desired_surface = Surface(
180
          lambda u, v: axes.c2p(
181
```

```
v, (0.25*v**2 + 1)*np.cos(u), (0.25*v**2 + 1)*np.sin(u)
182
183
               ),
               u_range=[0, 2*PI],
184
               v_range=[0, 4],
185
               checkerboard_colors=[YELLOW, YELLOW_E]
186
           )
187
188
           # Add a disk to the top of hte cylinder to give the impression that
           # the shape is not hollow
189
           desired_surface_cap = Surface(
190
               lambda u, v: axes.c2p(
191
                   4, v*np.cos(u), v*np.sin(u)
192
               ),
193
               u_range=[0, 2*PI],
194
               v_range=[0, 5],
195
               checkerboard_colors=[YELLOW, YELLOW_E]
196
           )
197
198
199
           self.play(Create(desired_surface),
200
                     Create(desired_surface_cap),
201
                    run_time=3)
202
           self.wait(1)
203
204
205
           # Write text in scene
           what_is_volume_text = Text('What is the volume\n of this shape?').scale(0.6).
206
       shift(3*LEFT + 3*UP)
207
           self.add_fixed_in_frame_mobjects(what_is_volume_text)
           self.play(Write(what_is_volume_text),
208
                    run_time=2)
209
           self.wait(3)
210
211
           self.play(Uncreate(what_is_volume_text),
212
                     Uncreate(desired_surface),
213
214
                     Uncreate(desired_surface_cap))
215
           self.wait(1)
216
217
218
           219
       ##############
220
221
           use_familiar_shapes_text = Text('Idea: use familiar shapes\n like cylinders
       to approximate').scale(0.6).shift(4*LEFT + 3*UP)
           self.add_fixed_in_frame_mobjects(use_familiar_shapes_text)
222
           self.play(Write(use_familiar_shapes_text),
223
                     run_time=2)
224
225
           # Construct a rectangle of width 0.5 under the graph of our function
226
           line1 = Line(
227
228
                   start=axes.c2p(2, 0),
                   end=axes.c2p(2, graph.underlying_function(2)),
229
                   stroke_color=GREEN
230
231
               )
           self.play(Create(line1))
232
           line2 = Line(
233
                   start=axes.c2p(2.5, 0),
234
                   end=axes.c2p(2.5, graph.underlying_function(2)),
235
                   stroke_color=GREEN
236
237
               )
           line3 = Line(start=axes.c2p(2, graph.underlying_function(2)),
238
239
                         end=axes.c2p(2.5, graph.underlying_function(2)),
                         stroke_color=GREEN
240
                       )
241
242
           self.play(Create(line2), Create(line3))
           self.wait(1)
243
244
245
           # Begin to rotate the rectangle 360 degrees around the axis of revolution to
246
```

```
give
           # The impression of constructing a disk
247
248
            self.play(
                Rotating(
250
                    VGroup(line1, line2, line3),
                    axis=RIGHT,
251
                    radians=2*PI,
252
                    about_point=axes.c2p(0,0,0)
253
                ),
254
255
                run_time=2,
                rate_func=linear
256
           )
257
258
259
260
261
           # Fill in the area swept out by rotating the rectangle with an
262
263
           # actual cylinder. However, the cylinder should not appear hollow
            # So we must add a disk to the top and bottom to make it look filled
264
           # in
265
266
            cyl_cap1 = Surface(
                lambda u, v: axes.c2p(
267
268
                    2, v*np.cos(u), v*np.sin(u)
269
                ),
                u_range=[0, 2*PI],
270
271
                v_range=[0, 2],
                checkerboard_colors=[GREEN, YELLOW_E]
272
           )
273
274
            cyl_cap2 = Surface(
                lambda u, v: axes.c2p(
275
                   2.5, v*np.cos(u), v*np.sin(u)
276
                ),
277
                u_range=[0, 2*PI],
278
279
                v_range=[0, 2],
                checkerboard_colors=[GREEN, GREEN_E]
280
           )
281
            cyl_wall1 = Surface(
282
               lambda u, v: axes.c2p(
283
284
                    v, 2*np.cos(u), 2*np.sin(u)
                ),
285
                u_range=[0, 2*PI],
286
287
                v_range=[2, 2.5],
                checkerboard_colors=[GREEN, GREEN_E]
288
           )
289
290
            self.play(Create(cyl_cap1),
291
                      Create(cyl_cap2),
292
                      Create(cyl_wall1),
293
                     run_time=2)
294
295
            self.wait(1)
296
297
298
            # Provide formula for volume of this "solid"
299
           area_cyl_text = Text('Volume( cylinder ) =', t2c={'cylinder' : GREEN}).scale
300
       (0.6).shift(4.2*LEFT)
            self.add_fixed_in_frame_mobjects(area_cyl_text)
301
302
            self.play(Write(area_cyl_text))
303
            formula_cyl_tex = Tex(r'$\pi( \text{radius} )^2 \times \text{width}$').shift
304
       (4.8*LEFT+0.6*DOWN)
            self.add_fixed_in_frame_mobjects(formula_cyl_tex)
305
            self.play(Write(formula_cyl_tex))
306
307
            self.wait(2)
308
309
           the_radius_in_this_text = Text('The radius in this case is just\n the y-
310
       coordinate of y = f(x)').scale(0.6).shift(4.4*LEFT+3*DOWN)
```

```
self.add_fixed_in_frame_mobjects(the_radius_in_this_text)
311
312
            self.play(Write(the_radius_in_this_text))
            self.wait(1)
313
314
           formula_cyl_tex_new = Tex(r'$\pi( f(x) )^2 \times \text{width}$').shift(4.8*
315
       LEFT+0.6*DOWN)
316
            self.play(Uncreate(formula_cyl_tex))
            self.add_fixed_in_frame_mobjects(formula_cyl_tex_new)
317
           self.play(Write(formula_cyl_tex_new))
318
319
            # Clean up scene
320
            self.wait(2)
321
            self.play(Uncreate(the_radius_in_this_text), Uncreate(formula_cyl_tex_new),
322
       Uncreate(area_cyl_text))
323
            now_repeat_to_fill_in_text = Text('Now repeat until the shape is filled in').
324
       scale(0.6).shift(4*LEFT+3*DOWN)
325
            self.add_fixed_in_frame_mobjects(now_repeat_to_fill_in_text)
            self.play(Write(now_repeat_to_fill_in_text))
326
327
            self.wait(1)
328
329
           ############## SCENE 5: Use multiple shells to approximate volume
330
       #############
331
332
            # TODO: Replace the code below with call to create_washers_of_revolution
333
334
335
            # Create 6 shells to fill in the region from x_min to x_max
336
            cyl_wall2 = Surface(
337
                lambda u, v: axes.c2p(
338
                    v, 1.5625*np.cos(u), 1.5625*np.sin(u)
339
340
                ),
                u_range=[0, 2*PI],
341
                v_range=[1.5, 2],
342
                checkerboard_colors=[TEAL, TEAL_E]
343
           )
344
345
            cyl_cap6 = Surface(
346
                lambda u, v: axes.c2p(
347
348
                    3, v*np.cos(u), v*np.sin(u)
                ).
349
                u_range=[0, 2*PI],
350
351
                v_range=[0, 2.5625],
                checkerboard_colors = [BLUE, BLUE_E]
352
           )
353
            cyl_wall3 = Surface(
354
                lambda u, v: axes.c2p(
355
                    v, 2.5625*np.cos(u), 2.5625*np.sin(u)
356
357
                ).
                u_range=[0, 2*PI],
358
359
                v_range=[2.5, 3],
                checkerboard_colors = [BLUE, BLUE_E]
360
           )
361
            # Create first and second shell
362
           self.play(Create(cyl_wall2),
363
364
                      Create(cyl_cap6),
                      Create(cyl_wall3))
365
366
367
368
            cyl_wall4 = Surface(
369
370
               lambda u, v: axes.c2p(
                    v, 1.25*np.cos(u), 1.25*np.sin(u)
371
372
                ),
                u_range=[0, 2*PI],
373
                v_range=[1, 1.5],
374
```

```
29
```

```
checkerboard_colors=[MAROON, MAROON_E]
375
376
            )
377
            cyl_cap10 = Surface(
378
                lambda u, v: axes.c2p(
379
                   3.5, v*np.cos(u), v*np.sin(u)
380
381
                ),
                u_range=[0, 2*PI],
382
                v_range=[0, 3.25],
383
                checkerboard_colors=[PURPLE, PURPLE_E]
384
            )
385
            cyl_wall5 = Surface(
386
                lambda u, v: axes.c2p(
387
                    v, 3.25*np.cos(u), 3.25*np.sin(u)
388
                ),
380
                u_range=[0, 2*PI],
390
                v_range=[3, 3.5],
391
                checkerboard_colors=[PURPLE, PURPLE_E]
392
           )
393
            # Create third and fourth shell
394
395
            self.play(Create(cyl_wall4),
                      Create(cyl_cap10),
396
397
                       Create(cyl_wall5))
398
399
400
            cyl_wall6 = Surface(
401
                lambda u, v: axes.c2p(
402
                    v, 1.06*np.cos(u), 1.06*np.sin(u)
403
                ),
404
                u_range=[0, 2*PI],
405
                v_range=[0.5, 1],
406
                checkerboard_colors=[RED, RED_E]
407
408
            )
409
            cyl_cap14 = Surface(
410
411
                lambda u, v: axes.c2p(
                   4, v*np.cos(u), v*np.sin(u)
412
                ),
413
                u_range=[0, 2*PI],
414
                v_range=[0, 4.06],
415
                checkerboard_colors=[PINK, PURPLE_A]
416
417
            )
            cyl_wall7 = Surface(
418
419
                lambda u, v: axes.c2p(
                    v, 4.06*np.cos(u), 4.06*np.sin(u)
420
421
                ),
                u_range=[0, 2*PI],
422
                v_range=[3.5, 4],
423
424
                checkerboard_colors=[PINK, PURPLE_A]
            )
425
            # Create fifth and sixth shell
426
427
            self.play(Create(cyl_wall6),
                      Create(cyl_cap14),
428
                       Create(cyl_wall7))
429
430
            self.wait(2)
431
432
            self.play(Uncreate(now_repeat_to_fill_in_text))
433
434
435
            # Write down relevant equations
            total_volume_tex = Tex(r', \text{Volume}\approx $').scale(0.8).shift(4.5*LEFT)
436
            total_volume_formula_tex = Tex(r'$\sum_i \pi \times f(x_i)^2 \times \text{
437
       width}$').scale(0.8).shift(4.4*LEFT+DOWN)
            self.add_fixed_in_frame_mobjects(total_volume_tex, total_volume_formula_tex)
438
439
            self.play(Write(total_volume_tex),
                     Write(total_volume_formula_tex))
440
           self.wait(3)
441
```

442	
443	
444	# Clean up scene
445	<pre>self.play(Uncreate(cyl_wall1),</pre>
446	Uncreate(cyl_wall2),
447	Uncreate(cyl_wall3),
448	Uncreate(cyl_wall4),
449	Uncreate(cyl_wall5),
450	Uncreate(cyl_wall6),
451	Uncreate(cyl_wall7),
452	Uncreate(cyl_cap1),
453	Uncreate(cyl_cap2),
454	Uncreate(cyl_cap6),
455	Uncreate(cyl_cap10),
456	Uncreate(cyl_cap14))
457	
458	
459	########################## SCENE 6: Increase number of shells to closer approximate
	############
460	
461	<pre>this_approx_text = Tex(r'This approx. becomes more accurate as we take limit</pre>
	Width \$\to 0\$').scale(0.6).shift(3.4*DOWN)
462	self.add_fixed_in_frame_mobjects(this_approx_text)
463	<pre>self.play(Write(this_approx_text))</pre>
464	
465	self.wait(1)
466	
467	
468	# TODO: somehow speed up performance here
469	<pre>surfaces = create_washers_revolution(lambda x : (0.25*x**2 + 1), axes, 0, 4,</pre>
	16)
470	
471	for surface in surfaces:
472	<pre>self.play(Create(surface))</pre>
473	
474	<pre>self.wait(1)</pre>