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# CALCULUS

*Dynamic Mathematics*

*For AB*

*Fourth Edition*

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Chuck Garner, Ph.D.

Rockdale Magnet School for Science and Technology



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Conyers

# Calculus: Dynamic Mathematics

## For AB

Fourth Edition

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# Preface for the Fourth Edition

*I would like to throttle the man who wrote this book.*

— Hermann Weyl

To throw yet another calculus book into the marketplace is a laughable exercise indeed. Why bother? Aren't there plenty of good books from which one may learn calculus? So why another? The only reason one has for writing a new book on an old subject is that it must present some new viewpoint or some new reason for existence. Those reasons are embodied in one simple statement: This book presents calculus the way I think it should be taught to high school students.

I originally wrote this book because the existing calculus textbooks a) are too big to lug around in your hands or in your backpack, b) have too many exercises, c) try to do far too much to please hundreds of different needs, and d) those books that are directed towards high school are slaves to the Advanced Placement curriculum.

*"Advanced Placement" and "AP" are registered trademarks of the College Board, which is not associated or affiliated with the production of this book.*

Although this is the fourth edition, my goals for the book remain unchanged, and they still resonate today. This book is not the typical 1200-page calculus doorstop. That is because this book was written with *teaching* and *learning* in mind. Each section was written as if I was teaching in front of a class – nearly everything written is what I would say to my students, write on the board, or have them discuss. As such, there are no “supplemental” or “optional” sections: everything is taught and all is (hopefully!) learned.

Many calculus books are huge, not only for including unused content, but also for including vast numbers of unattempted problems. There are simply too many exercises for a student to complete in one year in most calculus textbooks. In this book, *every problem is attempted by every student*. Problems have been chosen carefully to be important, relevant, and worthwhile. As a result, there are not many problems at the end of a section. Should students need additional practice with mastering the skills of, say, the chain rule, such material is easily accessed elsewhere—in other books or on the internet—and as such I felt it was not worthwhile to include buckets of drill exercises.

Proofs are an important aspect of this book. The study of calculus begins the transition between computation-driven mathematics to proof-driven mathematics. Yet proofs are often neglected in the teaching of high school calculus. The book is some attempt at rectifying that situation. I have tried to present rigorous proofs without delving into

the higher analysis of the real numbers. Where rigor is not possible, or where such a proof would deliver more confusion than insight, I present an intuitive argument based on assumptions of certain properties of the real numbers. As the student progresses through the book, the rigor increases slightly. But in every case, the proofs are written in an accessible way in order to give high school students practice at thinking about proofs and reading proofs, as well as understanding the logic behind a statement of a theorem.

Most calculus books that are geared towards high school students are written with the goal of the student passing the AP exam. This is not an indictment of College Board's goals for calculus. Indeed, there is much that is good about the focus on understanding, justifications, and application. However, there is also much lacking: hyperbolic functions, real uses of Euler's method, other indeterminate cases for l'Hôpital's rule besides the  $0/0$  case, and trigonometric substitution, among others. Students learning nothing but the topics listed in the Course Description will do well on the Exam, but is the AP Exam the main reason a high school student should learn calculus? I don't think so. I believe that the student should learn calculus well in order *to learn calculus*, one of the most important intellectual endeavors of the human race, and *to apply calculus*, one of the most important tools in scientific application and prediction. The AP exam is extra; students who know calculus well will, of course, do well on the AP exam. This book does include every topic in the AP Calculus AB Course Description, for those teachers or students who wish to learn calculus for the AP exam.

Finally, I wish to reiterate that this book was written for one need and one need only: to present calculus to gifted high school students. There is no other motivation for this book: it is not intended for "liberal arts majors," for "future math teachers," or for "engineering majors." This book does not try to be all things to all instructors. It is simply a concise textbook for gifted high school students—students who may choose to become liberal arts majors, math teachers, or engineers.

**Organization.** Every topic in the AB course description is developed along with a few other topics to create a comprehensive single-year high school calculus course. The following is a chapter-by-chapter summary of the book.

**CHAPTER 1: RATE EQUATIONS.** This is the most crucial chapter of the book. Here, the students do number crunching to predict physical phenomena based on the rate at which the phenomena occur. They use Euler's method extensively before it is made formulaic. This sets up the students to understand how to work with and use rates to make predictions. Students also must make decisions about the validity of the data, determine constants used in exponential and logistic growth, and judge the validity of their predictions. Euler's method is used throughout the first volume as an investigative tool. In addition, problems in Section 1.4 set up the idea of Riemann sums and foreshadow the Fundamental Theorem of Calculus.

**CHAPTER 2: RATES AND DERIVATIVES.** After dwelling on the numerical and graphical, we introduce the algebraic as a way to make our predictive abilities more precise. Following this is a traditional approach to derivative rules, but with more of a focus on presenting proofs of major theorems, and less of a focus on the details of lim-

its. Applications of differentiation are deferred to Chapters 3 and 6, although the relationship between position, velocity, and acceleration is used throughout.

**CHAPTER 3: USING THE DERIVATIVE.** This chapter starts with the notion of the differential and then applies it to approximations, related rates, and implicit differentiation. The Mean Value Theorem continues the focus on proofs, and then we use derivatives to return to limits with l'Hôpital's Rule and limits involving infinity.

**CHAPTER 4: AREAS AND ANTIDERIVATIVES.** Like the arrangement in the first three chapters, we introduce the numerical and graphical first (Sections 1 through 3) before the algebraic (Sections 4 and 5). The sixth section of this short chapter wraps up the question of area computations.

**CHAPTER 5: THE INTEGRAL AS A FUNCTION.** The Fundamental Theorem of Calculus is stated and proved before students learn any antiderivative rules (other than basic reversal of differentiation) so that students don't get the impression that the Fundamental Theorem is just about antiderivatives. It is this chapter where the logarithmic function (in terms of an integral) and the exponential function (in terms of the inverse of the logarithm) are defined.

**CHAPTER 6: MODELING PHYSICAL PHENOMENA.** Here we find the traditional applications of single-variable calculus. Most books separate these applications so that they occur closer to the respective differentiation or integration chapters; I feel that the applications are more meaningful and relevant when presented after differentiation and integration have been introduced. Certainly, problems in position, velocity, and acceleration are more realistic when one has both derivatives and integrals at one's disposal, as are other problems from physics (Sections 6.4 and 6.5). The treatment of volume of solids of revolution is deliberately slow-paced to give students time to become familiar with these new methods.

**CHAPTER 7: DIFFERENTIAL EQUATIONS.** Here, we take another look at the situations in Chapter 1, but this time from the perspective of having built a huge toolbox of more precise techniques.

**APPENDICES.** The appendices are split into three sections. The first is a list of 40 *Challenge Problems*. They are difficult, and no answers are provided. The second section is a list of formulas. Also included is a blank unit circle diagram that students are encouraged to fill in. The third section is an essay concerning being successful in a mathematics class. It includes suggestions for studying, homework, asking questions in class, getting extra help, and preparing for a test.

**Problems and Exercises.** Most sections have at least one "Exercise" in the text. These exercises are designed to be completed by the student at that point in the lesson. They extend recent concepts, foreshadow upcoming ideas, or are for practicing new skills. I use these as classwork assignments, completed individually or in small groups.

One section common to each chapter is the section entitled "Preparation and Extension." The Preparation problems are designed to prepare students for a chapter test. The problems here are similar to test questions that I write and are a good measure of how well prepared the student is for the test. At the beginning of each Preparation section is a smattering of review problems as well. They are offered to help



students retain previously learned concepts. The Extension problems are meant to challenge the students by extending the concepts and skills learned in that chapter. Groups of three or four students work these problems together and they have a minimum of two weeks to complete them. Very often we forget that mathematics is a actually a group activity, and students should have opportunities to model real mathematical problem-solving as practiced by mathematicians.

*A teacher's guide and solutions manual for this new edition is available from my website, [drchuckgarner.com](http://drchuckgarner.com), as well as a student's solutions manual.*

**Changes from the Second Edition.** For the third edition, the entire text has been carefully revised. This includes the choice of problems. I retained the goals of the original edition while ensuring this text is suitable for the new AP Exam Course Description. What follows are the most notable changes.

A new section has been added to Chapter 1 concerning the rate equations for an epidemiological model. Using the standard S-I-R equations, we model the spread of measles. This section was included in the preliminary version of the book, used in 2009-2010. However, I removed it for publication because the technique used to solve the differential equations was beyond the scope of the book (it still is). Conversations with colleagues about the efficacy of using this material as a first-day activity in calculus class, led me to change my mind.

The old Chapter 2 is split into two chapters, Chapters 2 and 3. A great debt of gratitude goes to Mr. Bill “DM Ashura” Shillito, who convinced me that an approach using differentials makes so many things easier to explain. In seeing what differentials can do, I rewrote the implicit differentiation section and pulled the related rate problems from the old Chapter 5 (on applications), and included that in the new Chapter 3. Bill had a wonderful idea!

I also split the old Chapter 3 on integrals into two chapters, Chapters 4 and 5. I also introduce the integral chapter with a section on finite series so that problems concerning writing limits of Riemann sums as definite integrals, and vice versa, could be included. With the new focus on limits of Riemann sums, I felt it prudent to reinforce this by deriving the definite integrals of  $x^2$  and  $x^3$  using this technique. As a result, I no longer need Simpson's rule to do this, and it has been removed. A section on “properties of areas” is new: specific attention is given to finding the area between curves which was lacking in previous editions. I also reluctantly removed the section on hyperbolic functions in order to stream-line the book.

The sections on approximating polynomials and physics problems from the old Chapter 4 have been removed. I decided that the focus should be on linear approximations at this stage. The “free fall” part of the old physics section is retained; it is combined with the section on position, velocity, and acceleration.

Two sections from the old Chapter 6 on differential equations are removed: integration by partial fractions and logistic differential equations. As these topics are not part of the AB Course Description, many teachers using earlier editions of the book admitted that these sections were usually skipped anyway.

At the end of each chapter is a page titled “At the End of the Chapter, You Should Be Able To. . .”. This page acts as an outline of the topics and skills students should have by the close of each chapter. It is one thing to have a goal at the beginning of each section, or a summary

of each section at the end of the section. However, students need to develop the idea of a cumulative assessment, and they sometimes have trouble preparing for such an assessment. This new feature of the book should help students study for a test and to help focus their review on any deficits they may have.

All the problem sets have been revised, reordered, or re-written. There were review problems in each problem set, but these have been removed and gathered together at the beginning of each “Preparation and Extension” section.

**Changes from the Third Edition.** The fourth edition is different from the third in two major aspects: size and design.

When I published the first edition, it was printed on  $8\frac{1}{2} \times 11$ -inch paper. This allowed for a wide margin in which I could put many graphs and tables. However, it was just too big in length and width to be easily carried by my students. (It was not very dense at less than 300 pages.) The second edition and third editions were printed on  $6 \times 9$ -inch paper. This size did not allow for a wide margin, so the book was reformatted, and the page count rose to 440. Many students appreciated the smaller length and width – some could even carry it in a purse! However, I knew that I could decrease the page count if I went baack to a bigger size. Thus, I found a compromise at  $7 \times 10$ . This allowed for a wide margin (like the first edition) and gave a smaller page count (at just a little more than 300 pages).

The other significant change is color! I redrew every figure and added some new ones, using color throughout. I always envisioned the book printed in color, even with the first edition. However, color printing at the time was too costly. Luckily the costs of color printing have decreased enough that I think it is time to print the book I always saw in my head!

**History.** In 2002, inspired by a *Book of Exercises* written by calculus teacher Sergio Stadler at the Marist School in Atlanta, I wrote my own supplement to the calculus textbook my classes used that focused on AP-style questions and problems, as well as some extra topics not currently included in the AP curriculum. What I thought would be a small project blossomed into a 250-page *AP Calculus Problem Book*. About two-thirds of the problems were original, but I must confess that the best problems I stole from various sources. The *Problem Book* was self-published every school year which allowed me to make corrections and additions (or subtractions) easily. As the years went by, three unforeseen consequences arose from using the book.

First, I noticed that my students preferred the *Problem Book* to the regular textbook. They seemed more willing to do the problems and carry it around as opposed to the big textbook. This led to eventually dropping the published textbook altogether, and using the *Problem Book* as the sole “text.”

Second, I realized that I could put everything my students needed into one place. In future editions, I included the syllabus, labs, old tests, challenge problems, study tips, group projects, practice exams, and other items. This allowed the students to simply keep up with one book where everything was located instead of keeping up with multiple handouts. And, by including everything in one book I didn’t visit the

*Another difference is the multitude of “marginal notes.” These serve many purposes, some of which may even be related to calculus!*

*“Self-published” at that time meant that I made all the copies, collated them, and punched holes in the papers and ran the comb bindings through myself!*

copy machine throughout the school year to make all the handouts and worksheets.

The third consequence was a positive influence on how I teach. I began to include problems specifically designed to be worked in pairs or groups, so that more collaborative learning was taking place. It also allowed me the flexibility to assign homework problems on a class-by-class basis. I included group problem sets for those occasions when a substitute was necessary, so no day was ever wasted. These features exist in the present work—the “Exercises” are designed to be worked in class by pairs of students, and the “Extension Problems” are used as problem sets for groups of three or four students to tackle over a period of weeks.

But, students missed the examples of a textbook, and I grew complacent with teaching calculus the same way each year. So I started to wonder how best to shake things up. With the announcement that Georgia was moving to an integrated mathematics curriculum, I was charged with re-aligning the “calculus-and-beyond” classes at my school. That meant taking another look at the post-calculus courses: Multivariable Calculus, History of Mathematics, and Discrete Mathematics. The latter two changed little, and I still teach them both. Material from linear algebra and multivariable calculus were always approached together in a single year, and I wanted to include differential equations to a greater extent than in the past. So I took this opportunity to rethink my approach to calculus as a whole, and devised my own two-year calculus curriculum that would encompass everything required for students to do well on standardized tests, other single-variable calculus topics, as well as some differential equations, linear algebra, and multivariable calculus. Thankfully, my administration encouraged my ideas and was completely supportive.

*The content of Discrete Mathematics did not change but the name did. It was relaunched as “Advanced Finite Mathematics”. We also added a course in introductory operations research called “Mathematics of Industry and Government”.*

**Technicalities.** I began work on the book in June 2007. Besides creating something for my classes, I also approached this as an exercise in  $\LaTeX$ . I started using  $\LaTeX$  in late 2003, so I was familiar with the program and knew the possibilities. I started this book on a Windows machine using the fantastic MikTeX distribution with the  $\TeX$ nicCenter editor, but I soon migrated to a MacBook where I now use the wonderful MacTeX and the  $\TeX$ Shop editor.

*There was a learning curve with  $\LaTeX$ : the code for the Problem Book is quite rough!*

When I first learned how to draw figures in  $\LaTeX$ , I used the first package I found, which was  $\TeX$ draw.  $\TeX$ draw generates PostScript drawings and was suitable for the limited pictures I needed at the time. However, as this book progressed, I needed more than  $\TeX$ draw was capable of doing, and I wanted color. I needed another PostScript-output package. Hence, I started using the PSTricks bundle of packages. The resulting figures in this book are all PSTricks code.

CHUCK GARNER  
Conyers, Georgia  
June 2021

# Chapter 1

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## RATE EQUATIONS

HAVE YOU EVER HEARD SOMEONE—maybe you—say any of the following?

*“The population is growing more slowly.”*

*“The plane is landing smoothly.”*

*“The economy is picking up.”*

*“The tax rate is constant.”*

*“The unemployment rate is decreasing.”*

*“Stock prices have peaked.”*

What do these statements have in common? They are all describing **change**. What do these statements have to do with calculus? *Calculus is the mathematics of change.*

We begin our journey by discussing statements of this type. Each of the statements above describes a **rate of change**, a fundamental concept in mathematics and science. In this chapter we will investigate these rates through numerical and graphical analysis. Rates will usually be described by **rate equations**.

To be a bit more precise about it, rate equations are used to describe, predict, and model real-world phenomena, such as the population of Georgia, the growth of yeast bacteria, and the disposal of nuclear waste.

We will model these situations, introduce some useful mathematical tools for investigating these models, and test our predictions against real-world data. In later chapters, we will develop algebraic and analytical methods for investigating rate equations.

## 1.1 Water Flowing Into a Tank

*In the mathematics I can report no deficiency, except that it be that men do not sufficiently understand the excellent use of the pure mathematics, in that they do remedy and cure many defects in the wit and faculties intellectual. For if the wit be too dull, they sharpen it; if too wandering, they fix it; if too inherent in the sense, they abstract it. So that as tennis is a game of no use in itself, but of great use in respect that it maketh a quick eye and a body ready to put itself into all postures; so in the mathematics, that use which is collateral and intervenient is no less worthy than that which is principal and intended.*

— Roger Bacon

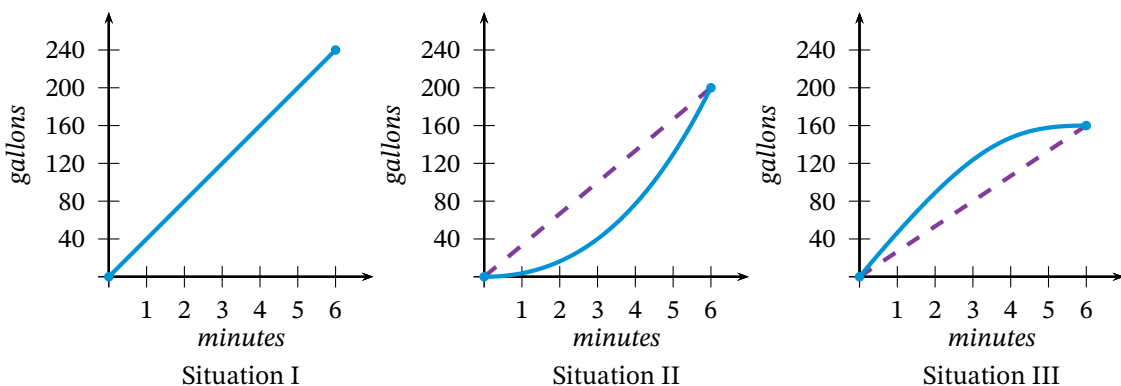
Before we begin with *rate equations*, we should begin simply with *rates*. Consider the three situations below, each with a graph plotting the time it takes to fill a tank with water, versus the volume of water in the tank.

*Situation I.* Water is flowing into a tank that is initially empty at a constant rate of 40 gallons per minute for 6 minutes. Since the rate is constant, we know that there must be  $6 \times 40 = 240$  gallons in the tank. The graph is therefore a line with endpoints  $(0, 0)$  and  $(6, 240)$ . The slope of the line is 40, the same as the rate. This gives us our first interpretation of a rate: **slope**.

*Situation II.* The tap, closed at the beginning, is gradually opened over 6 minutes, so that at 6 minutes the tank contains 200 gallons.

Here, the graph is concave up, meaning that the rate of water flow increases. The important question here is this: *What is the average rate of water flow over the 6-minute interval?* The answer is the slope of the line that connects the endpoints  $(0, 0)$  and  $(6, 200)$ . Thus, the **average rate of change** is  $\frac{200}{6} \approx 33.33$  gallons per minute.

*Situation III.* The tap, opened so that water flows at a rate of 40 gallons per minute, is gradually closed, so that at 6 minutes the tank contains 160 gallons. The graph is concave down, meaning that the rate of water flow decreases. The average rate of change is  $\frac{160}{6} \approx 26.667$  gallons per minute.



**Figure 1.1** – Three different situations for water flowing into a tank

The dashed lines in the graphs above connect the endpoints over which we compute the average rate of change. Such a line is called a **secant line**.

**Exercise 1.1.1** At time  $t = 0$ , water begins to flow from a tap into an empty tank at the rate of 40 gallons per minute. This flow rate is held constant for 2 minutes, then the tap is gradually closed until at  $t = 4$  the flow rate is 5 gallons per minute. This new rate is held constant for the final 2 minutes, so that at time  $t = 6$ , the tank contains 120 gallons.

- Draw a graph of the volume of water in the tank over the first 6 minutes.
- What is the average rate of flow over the interval from 2 to 4 minutes? Draw a secant line on your graph that conveys this information.
- If we wanted to put the entire 120 gallons into the tank at a constant rate, what would that constant rate be?
- Now suppose that a pump is started at  $t = 2$ , and, for the next 4 minutes, pumps water out of the tank at a constant rate of 15 gallons per minute. The graph you drew in part (a) now represents the total amount of water flowing into the tank at time  $t$ . On the same axes as your volume graph, draw the graph that represents the total amount of water pumped out at time  $t$ . How do you now interpret the *total* amount of water at time  $t$ ?
- What is the total amount of water in the tank at time  $t = 6$ ?
- On your graph from part (e), show how to find the point at which the water level in the tank is a maximum.
- What is the flow rate into the tank at the point found in part (f)?

Let us introduce some convenient mathematical shorthand for the rate of change. Take *Situation I* from the previous page. If we let  $V$  represent the volume of water in the tank, then the rate at which water flows into the tank will be denoted by  $V'$ . (The symbol  $'$  is a *prime mark* so that  $V'$  is read “ $V$  prime.”) For instance, in *Situation I*, we have  $V' = 40$ .

Notice that in *Situation II* and *Situation III*, the rate is not constant, and so  $V'$  cannot be expressed as easily as in *Situation I*. One of the questions that calculus helps us answer is that of finding and interpreting expressions for such nonconstant rates. In the next section, we will develop one such technique.

The material in this section and the exercise is adapted from Taylor (1992).

**Exercise 1.1.2** Referring to the tank in Exercise 1.1.1, suppose the pump does not operate, so that water is only flowing *into* the tank. Find:

- the exact time  $t = k$  for which the average flow rate into the tank over the first  $k$  minutes is 25;
- the exact time  $t = m$  for which the average flow rate into the tank over the interval from  $m$  minutes to 6 minutes is 15;
- a time interval from  $p$  to  $p + 4$  minutes over which the average flow rate is the same as the average flow rate over the entire 6 minutes.

## Problems for Section 1.1

- Illustrate the results in Exercise 1.1.2 using secant lines on the graph.
- Again referring to the tank in the exercise, now suppose that the pump does operate. If the pump continues past 6 minutes operating at 15 gallons per minute, and water continues past 6 minutes flowing in at 5 gallons per minute, then at what time will the tank be empty?
- A tank is being filled at a variable rate. The only thing known is that between 1 and 2 minutes, the

- average inflow rate is 18 gallons per minute, and the amount of water in the tank at 2 minutes is 42 gallons. What is your best estimate for the amount of water in the tank at 2.5 minutes?
- 4 A tank is being filled at a variable rate. The only thing known is that between 1 and 2 minutes, the average inflow rate is 18 gallons per minute, and the amount of water in the tank at 2 minutes is 36 gallons. What is your best estimate for the amount of water in the tank at 2.5 minutes?
  - 5 A tank has 20 gallons of water in it, then a tap is opened and water flows into the tank. From 0 to 3 seconds, the average flow rate is 6 gallons per second. From 3 to 5 seconds, the average flow rate is 15 gallons per second. How many gallons of water are there in the tank at 5 seconds?
  - 6 Suppose the equation of volume of water in a tank at time  $t$  for the first 10 seconds is given by  $V(t) = 0.3t^2$ . Find the average inflow rate over (a) the first 5 seconds; (b) seconds 2 to 5; (c) seconds 4 to 5; (d) seconds 4.5 to 5; (e) seconds 4.9 to 5. As the time interval gets shorter, to what value does the average inflow rate approach?
  - 7 Suppose the volume of water that is flowing out of a full tank is given by  $V(t) = 1024 - 0.25t^3$ . The time at which the tank is empty is when  $t = c$ . Find the value of  $c$ , then use it to find the average outflow rate over the interval from  $c - 1$  to  $c$  seconds.

## 1.2 Population Explosion

*In the company of friends, writers can discuss their books, economists the state of the economy, lawyers their latest cases, and businessmen their latest acquisitions, but mathematicians cannot discuss their mathematics at all. And the more profound their work, the less understandable it is.*

— Alfred Adler

*Thomas Malthus (1766-1834) was an English economist. His essay was titled "An Essay on the Principle of Population."*

Thomas Malthus wrote in an essay in 1798 that the growth of the human population is very different from that of the growth of the food supply. He concluded that the human population would grow so fast that famine would be a global epidemic. Malthus, in fact, referred to a rate equation in his essay that simply says that the rate of population growth is proportional to the population. (In simpler terms, this means that the greater the population, the faster the rate of growth.)

Let us consider his statement again with a bit of mathematical symbolism. We let  $P$  represent the population; that is, the number of people. Since the growth of that population is related to  $P$ , let us denote the rate of growth of that population by  $P'$ . Hence Malthus' rate equation becomes the proportion

$$P' = kP$$

where the real number  $k$  is called the **constant of proportionality**.

We will now use **Malthus' equation** to predict the population of the state of Georgia in the year 2030. Table 1.1 lists the population of the state of Georgia according to U. S. Census information for the years 1900 to 2010 in 10-year intervals.

The first obstacle we face is how to find the constant of proportionality. We cannot find it exactly, but we can approximate it using the data in the table. Notice that if we solve Malthus' equation for  $k$  we get

$$k = \frac{P'}{P}.$$

So we need only to divide values of  $P'$  by  $P$  to find  $k$ . But how do we find values of  $P'$ ? We use the average rate of change in the population over every 10-year interval. This means we treat the years as *single data*



Year	Population (millions)
1900	2.216
1910	2.609
1920	2.896
1930	2.909
1940	3.124
1950	3.445
1960	3.943
1970	4.590
1980	5.463
1990	6.478
2000	8.186
2010	9.688

**Table 1.1** – Population of the state of Georgia, rounded to the nearest thousand. Data from the U.S. Census Bureau, 2013. ([quickfacts.census.gov/qfd/states/13000.html](http://quickfacts.census.gov/qfd/states/13000.html)).

points, not as representing 10-year intervals. Thus, in the following computations, the years have been divided by 10 so they act as single data points. For instance, for the years 1900 to 1910, we have

$$P' \approx \frac{2.609 - 2.216}{191 - 190} = \frac{0.393}{1} = 0.393.$$

Therefore,

$$k = \frac{P'}{P} \approx \frac{0.393}{2.609} = 0.151.$$

Notice that we have rounded to the nearest thousandth which is appropriate for this estimation; however, more decimal places may be necessary in other computations. Also, we have not used the population figures in millions, but have treated the figures as if they were decimals. This will cause no problem, as long as we remember that *our predicted answers are in millions*. Most interestingly, we somewhat arbitrarily assumed  $P$  was the population in 1910 in the final calculation above. There is no mathematically valid reason to choose the 1910 population rather than the 1900 population. But we can offset this randomness by: finding the slope between the years 1910 and 1920; dividing again by the 1910 value; and taking the average of this with the previous result. This gives an approximate measure of the rate of change during the year 1910, rather than between 1900 and 1910, or between 1910 and 1920.

The slope between 1910 and 1920 is

$$P' \approx \frac{2.896 - 2.609}{192 - 191} = 0.287;$$

the  $k$ -value is

$$k = \frac{P'}{P} \approx \frac{0.287}{2.609} = 0.110.$$

Thus, the average of our two  $k$ -values at the year 1910 is

$$\frac{0.151 + 0.11}{2} = 0.1305.$$

*We have used four decimal places rather than the three we used before in order to better compare this  $k$ -value with later results.*

Mathematically, we have computed what is called the **symmetric difference** around the point (1910, 2.609). The symmetric difference is slope “around” a point, using  $x$ -values (the years in this case) that are spaced the same distance apart on either side of the point. Since the years are always 10 years apart, our “averaging” the two  $k$ -values is equivalent to finding the slope between the points (1900, 2.216) and (1920, 2.896), then dividing by the population at 1910 (again treating the years as single data points):

$$\frac{2.896 - 2.216}{192 - 190} = \frac{0.680}{2} = 0.340,$$

then

$$k \approx \frac{0.34}{2.609} = 0.1303.$$

**Exercise 1.2.1** What are the units of measure for  $P'$ ?

**Exercise 1.2.2** Create a table for the years 1910 to 2000 in 10-year intervals, and compute the approximate value of  $k$  for each year. Use the  $k$ -value of 0.1303 for the year 1910. Why should there be no entry for the year 2010?



**Exercise 1.2.3** Malthus' equation only admits one value of  $k$ . What is the best value we should adopt for our model? Justify your methods and reasons for deciding upon your value of  $k$ . Would the value  $k = 0.1316$  be appropriate? Can you determine what computations led to that value?

Let us assume  $k = 0.1316$ . Then Malthus' equation for the population of Georgia is  $P' = 0.1316P$ . This equation describes a rate of change; that is, this equation tells us how much to add ( $P'$ ) to the present value ( $P$  in 1900) to get the next value ( $P$  in 1910).

We have that the change in population is 0.1316 times the population. Hence, if the population in 1900 is 2.216 million, we can approximate the population in 1910 by computing

$$0.1316 \times 2.216 = 0.292$$

and then adding that to the population in 1900:

$$2.216 + 0.292 = 2.508 \text{ million.}$$

To approximate the population in 1920, we repeat the process, but this time using the population in 1910.

Note that the calculated population for 1910 does not agree with the given population in 1910. In fact, Table 1.2 gives the actual population and the population as determined by the model.

None of the estimated and actual numbers agree! But that's to be expected. After all, Malthus' equation is only a model of a real-world situation. This data is still useful, however, because one can readily approximate the answer to the original question: What will be the population of Georgia in the year 2030?

Notice that we cannot use the population in 2020 since we do not have that data available. Hence, we must approximate the population in 2020, and then use that approximation to estimate the population in 2030.

We compute:

$$(9.688 \times 0.1316) + 9.688 = 10.963 \text{ million in 2020, and} \quad (1.1)$$

$$(10.963 \times 0.1316) + 10.963 = 12.406 \text{ million in 2030.} \quad (1.2)$$

We pause briefly to clarify some rate concepts. Earlier, we used the symmetric difference to compute a rate of change *during* the year 1910. In effect, we have estimated the **instantaneous rate of change** of the population in 1910. The instantaneous rate of change is the concept described by a given rate equation.

For instance, if we are given the rate equation  $P' = 0.2P$ , where  $P$  is a population, then given any value of  $P$  we can compute the instantaneous rate of change *at that value of  $P$* . Notice that this is not an average rate of change, but the change *exactly* at the given value of  $P$ .

Hence, we can safely talk about the the change *at* a point, instead of the change *around* a point.

Year	Actual (millions)	Estimated (millions)
1910	2.609	2.508
1920	2.896	2.838
1930	2.909	3.211
1940	3.124	3.634
1950	3.445	4.112
1960	3.943	4.653
1970	4.590	5.265
1980	5.463	5.958
1990	6.478	6.742
2000	8.186	7.630
2010	9.688	8.634

**Table 1.2** – Actual and modeled population of Georgia.

## Problems for Section 1.2

- Notice that the population of Georgia rises dramatically in the second half of the 20th century. Let us compute a new value of  $k$  by averaging the five intermediate  $k$ -values in your table from 1960 to 2000. Use this new  $k$  to make a new prediction of the population of Georgia in 2030. Is this a better prediction than 12.239 million? How do you know?
- If the more recent data is more relevant, then the newest data should be the best! Compute the slope between the data points for the years 2000 and 2010, and let this be the value of  $P'$  so that the value of  $k$  can be found. Make another prediction of the population in 2030. Is this a better prediction? Justify your answer.
- The Government of the State of Georgia projects a population in Georgia of 12.189 million in 2020 and 14.688 million in 2030. Experiment with your calculator to determine a value of  $k$  that could arrive at these predictions.
- Is it possible to predict the population of Georgia in the year 2025? Either explain why it cannot be done, or give a method for doing so.
- Below is the population data for Gwinnett County, Georgia. Find an appropriate value of  $k$  for Malthus' equation that models the growth of Gwinnett County. Is the value of  $k$  for Gwinnett County larger or smaller than the value of  $k$  for the state of Georgia? What does this imply about the growth of Gwinnett County? Predict the population of Gwinnett County in the year 2030.
- Either by hand or with a calculator, plot the population data for Gwinnett County shown below. (You may want to convert the years to a more reasonable scale; for instance, 1940 to 0, 1950 to 1, etc.) What curve does the data resemble? Malthus' equation is more commonly referred to as the **exponential growth equation**—does this make sense based on the data?

POPULATION OF GWINNETT COUNTY

Year	Population (thousands)
1940	29.1
1950	32.3
1960	43.5
1970	72.3
1980	166.9
1990	352.9
2000	588.4
2010	805.3

## 1.3 Constrained Growth

*Our population and our use of the finite resources of planet Earth are growing exponentially, along with our technical ability to change the environment for good or ill.*

— Stephen Hawking

The equation in Section 1.2 is not the best model to use for population. As Malthus himself pointed out, the food supply will not support the growth of the human population. So what happens when the food supply runs out? The resources will not be able to support unlimited population growth, and the growth rate will slow to a crawl, or “level off.” A model to account for this type of **constrained growth** was first introduced by Pierre-Francois Verhulst (1804-1849), but it was not until Swedish biologist Tor Carlson used real data to develop a mathematical model in 1913 that constrained growth was taken seriously.

How can Malthus' equation be modified to produce a new constrained growth rate equation? Since the population  $P$  must level off, this implies that the rate of population growth  $P'$  must decrease towards zero. There must also be a maximum sustainable population; let us call this maximum sustainable population  $M$ . ( $M$  is also called the **carrying capacity** of the population.) The closer  $P$  is to  $M$ , the closer

the Chain Rules.

$$\begin{aligned} y &= x^2 \arctan(3x - 1) \\ \frac{dy}{dx} &= 2x \cdot \arctan(3x - 1) + x^2 \cdot \frac{3}{9x^2 - 6x + 2} \\ &= 2x \arctan(3x - 1) + \frac{3x^2}{9x^2 - 6x + 2}, \end{aligned}$$

where we have the 3 produced by the Chain Rule.  $\blacklozenge$

### Example 3.4.9

We find the derivative of  $y = 7 \operatorname{arcsec}(x^2)$ . We have

$$\begin{aligned} y &= 7 \operatorname{arcsec}(x^2) \\ \frac{dy}{dx} &= 7 \cdot \frac{1}{|x^2| \sqrt{(x^2)^2 - 1}} \cdot (2x) = \frac{14x}{|x^2| \sqrt{x^4 - 1}} = \frac{14}{|x| \sqrt{x^4 - 1}} \end{aligned}$$

as the derivative.  $\blacklozenge$

## Problems for Section 3.4

Evaluate each of the following expressions. Do not use a calculator. **16** Which of the following are undefined?

- 1**  $\sin^{-1}\left(-\frac{\sqrt{3}}{2}\right)$       **4**  $\tan(\sec^{-1}(2))$   
**2**  $\tan^{-1}(-\sqrt{3})$       **5**  $\sin(\arcsin(0.3))$   
**3**  $\sin(\arctan(1))$       **6**  $\arcsin(\sin(\pi))$   
**7**  $\arccos(\cos(-\frac{\pi}{4}))$

- $\arccos(1.5)$ ,     $\operatorname{arcsec}(1.5)$ ,     $\arctan(1.5)$ ,  
 $\operatorname{arcsec}(0.3)$ ,     $\arcsin(2.4)$ .

**17** This problem is an application of the Extreme Value Theorem.

- (a) Since  $y = \arcsin(x)$  is defined only on  $[-1, 1]$ , we can find the extrema by examining the graph. What are the extreme points?  
 (b) What are the extreme points of  $y = \operatorname{arcsec}(x)$ ? Are they local or global?  
 (c) What are the extreme points of  $y = \arctan(x)$ ?

Find the derivatives of the following functions.

- 8**  $y = \sec^{-1}(5x)$       **12**  $y = \tan^{-1}\left(\frac{3}{x}\right)$   
**9**  $y = \cos^{-1}(2x - 3)$       **13**  $y = \arccos\left(\frac{1}{x}\right)$   
**10**  $y = \arctan(2x - 3)$       **14**  $y = 2 \sin^{-1} \sqrt{1 - 2x^2}$   
**11**  $y = \operatorname{arcsec}(3x^2)$       **15**  $y = \arcsin(1 - x)$

**18** Find the derivative of  $y = 4 \arctan(x)$ . What is the equation of the tangent line when  $x = 1$ ?

## 3.5 More Value of Theorems

*Don't just read it; fight it! Ask your own questions, look for your own examples, discover your own proofs. Is the hypothesis necessary? Is the converse true? What happens in the classical special case? What about the degenerate cases? Where does the proof use the hypothesis?*

— Jacques Hadamard

We know that a function such as  $f(x) = 7$  has a derivative of zero. We begin this section with a Lemma concerning this fact.

**LEMMA 3.A** Let  $f(x)$  be differentiable on  $(a, b)$ . The function  $f(x)$  is constant on  $[a, b]$  if and only if  $f'(x) = 0$ .

*Proof.* Assume  $f(x)$  is constant on  $[a, b]$ . Then  $f(x) = r$  for all  $x$  in  $[a, b]$ , where  $r$  is some real number. Hence,

$$f'(x) = \lim_{\Delta x \rightarrow 0} \frac{f(x + \Delta x) - f(x)}{\Delta x} = \lim_{\Delta x \rightarrow 0} \frac{r - r}{\Delta x} = 0.$$

Next, assume  $f'(x) = 0$  on  $(a, b)$ . Then  $f$  is continuous on  $[a, b]$ , and we have

$$\begin{aligned} 0 &= \lim_{\Delta x \rightarrow 0} \frac{f(x + \Delta x) - f(x)}{\Delta x} \\ 0 &= \frac{f(x + \Delta x) - f(x)}{\Delta x} \\ 0 &= f(x + \Delta x) - f(x) \\ f(x) &= f(x + \Delta x). \end{aligned}$$

Since  $x$  is an arbitrary point in  $(a, b)$ , we have that all  $y$ -values are the same; hence,  $f$  must be constant on  $[a, b]$ . ■

**Exercise 3.5.1** Draw coordinate axes and pick any two points on your graph that have the same  $y$ -values and different  $x$ -values. Draw any differentiable function between your 2 points (make it as “curvy” as you wish, but make sure it meets the qualifications). Does your function have a horizontal tangent somewhere between your two points?

You may have difficulty drawing a differentiable function that doesn't have a horizontal tangent in the above exercise—simply because it is not possible to do so! The proof of the theorem below explains why.

*The proof is adapted from Apostol (1967).*

**THEOREM 3.B (Rolle's Theorem)** Let  $f(x)$  be differentiable on  $(a, b)$  and continuous on  $[a, b]$  where  $f(a) = f(b)$ . Then there is some point  $c$  in  $(a, b)$  such that  $f'(c) = 0$ .

*In a proof by contradiction, we assume the opposite of the conclusion and show that this leads to a contradiction of known facts. The result is that the opposite of the conclusion must be false, and so the conclusion must be true.*

*Proof.* We will use the method of proof by contradiction. Assume  $f'(x) \neq 0$  for every  $x$  in  $(a, b)$ .

By the Extreme Value Theorem,  $f$  has a global maximum  $M$  and a global minimum  $m$ . Fermat's Test indicates that neither extreme value can be given by an  $x$ -value within  $(a, b)$  or else  $f'$  is zero there; hence, both extrema occur at the endpoints of the interval. But since  $f(a) = f(b)$ , we have  $M = m$  and thus  $f$  is constant on  $(a, b)$ . By Lemma 3.A, this implies  $f'(x) = 0$  everywhere on  $(a, b)$ ; thus, we have a contradiction. Hence, there is at least one  $c$  in  $(a, b)$  such that  $f'(c) = 0$ . ■

**Example 3.5.2**

Consider the function  $f(x) = x^4 - 2x^2$  on the interval  $[-2, 2]$ . Since  $f(-2) = f(2) = 8$ , and  $f$  is differentiable and continuous, we may apply Rolle's Theorem. The theorem tells us that there is a point in the interval  $[-2, 2]$  where the derivative of  $f$  is zero. We now find that point.

Since  $f'(x) = 4x^3 - 4x = 4x(x^2 - 1)$  and we know that there is some point

where  $f' = 0$ , we set the derivative equal to zero and solve:  $4x(x^2 - 1) = 0$  gives solutions  $x = -1$ ,  $x = 0$ , and  $x = 1$ . All of these are in the interval  $[-2, 2]$  and so all of these points satisfy the conclusion of Rolle's Theorem.

(Note that Rolle's Theorem simply says that there is some point in the interval where the derivative is zero; there could be multiple points where the derivative is zero, as this example illustrates.) ♦

Over any interval, must it be true that the slope between the endpoints of the interval is equal to the derivative of a differentiable function within the interval? Surprisingly, this answer is yes, and it is due to the Mean Value Theorem.

The Mean Value Theorem is another one of those Big Important Theorems!

**THEOREM 3.C (The Mean Value Theorem)** Let  $f$  be a function continuous on  $[a, b]$  and differentiable on  $(a, b)$ . Then, for some  $c$  in  $(a, b)$ ,

$$\frac{f(b) - f(a)}{b - a} = f'(c)$$

provided  $b \neq a$ .

*Proof.* We note that the quantity

$$k = \frac{f(b) - f(a)}{b - a}$$

is constant since it depends only on the real constants  $a$  and  $b$ . We introduce the function  $P(x) = f(x) - kx$  on  $[a, b]$ , where  $k$  is defined above. Then we have

$$P(x) = f(x) - kx = f(x) - \frac{f(b) - f(a)}{b - a}x = \frac{f(x)[b - a] - x[f(b) - f(a)]}{b - a}$$

so that

$$P(a) = f(a) - ka = \frac{f(a)[b - a] - a[f(b) - f(a)]}{b - a} = \frac{bf(a) - af(b)}{b - a}$$

and

$$P(b) = f(b) - kb = \frac{f(b)[b - a] - b[f(b) - f(a)]}{b - a} = \frac{-af(b) + bf(a)}{b - a}$$

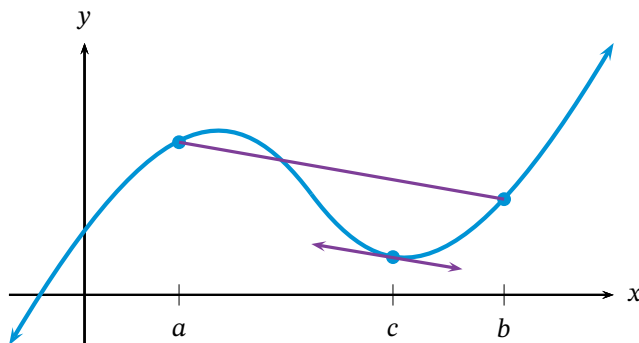
implying that  $P(a) = P(b)$ . Hence, we may apply Rolle's Theorem. Therefore, there exists a point  $c$  in  $(a, b)$  such that  $P'(c) = 0$ . We have

$$\begin{aligned} P'(c) &= f'(c) - k = 0 \\ f'(c) &= k \\ f'(c) &= \frac{f(b) - f(a)}{b - a} \end{aligned}$$

Some consider Rolle's Theorem as a special case of the MVT. But it isn't really: did you notice we needed Rolle to prove the MVT?

which proves the theorem. ■

This is called the Mean Value Theorem for a reason. Geometrically, we recognize the left side as the slope of the secant line between the points  $(a, f(a))$  and  $(b, f(b))$ . The theorem then says that the slope of the secant must be equal to the slope of the tangent to the curve at a point somewhere between  $x = a$  and  $x = b$ . See Figure 3.6.



**Figure 3.6** – Demonstrating the Mean Value Theorem. The secant line over  $[a, b]$  has the same slope as the tangent line at  $x = c$

This should make some intuitive sense: If you averaged 50 MPH on a trip in your car, then there would be *at least* one instant during your trip when your speed was *exactly* 50 MPH. In other words, the average rate of change is equal to the instantaneous rate of change at some point.

Notice that the Mean Value Theorem is another “existence theorem” – we know a point  $c$  exists, but we are given no method to find it. Fortunately, finding the value of  $c$  is not that difficult!

*Well, it depends on how complicated the derivative is. . .*

### Example 3.5.3

Let us find the appropriate value of  $c$  given by the Mean Value Theorem for the function  $f(x) = 4x^2 - x - 6$  on  $[1, 3]$ .

First, we compute the slope of the secant:

$$\frac{f(3) - f(1)}{3 - 1} = \frac{27 + 3}{2} = 15.$$

Next, we find that  $f'(x) = 8x - 1$ . Thus we take the secant slope (15), set it equal to the tangent slope ( $8x - 1$ ) and solve to get  $8x - 1 = 15$ , or  $x = 2$ . Thus, 2 is the value of  $c$  guaranteed to exist according to the Mean Value Theorem. ♦

**Exercise 3.5.4** Find the value of  $c$  guaranteed to exist by the Mean Value Theorem for the function  $f(x) = x + \cos(x)$  over the interval  $[0, \frac{\pi}{2}]$ .

**Exercise 3.5.5** Let  $a$  be a positive real number. Explain why the Mean Value Theorem cannot be used on the function  $g(x) = \sqrt[3]{x}$  over the interval  $[-a, a]$ .

The Mean Value Theorem may be expressed in a different form. Consider multiplying both sides of

$$\frac{f(b) - f(a)}{b - a} = f'(c)$$

by  $b - a$ . Then we may write

$$f(b) - f(a) = f'(c)(b - a).$$

Now add  $f(a)$  to both sides to get

$$f(b) = f(a) + f'(c)(b - a).$$

Since  $b - a$  is the change in  $x$ -values, and  $f'(c)$  is the slope, we have yet again an expression for a tangent line.

### Problems for Section 3.5

1 Explain why the Mean Value Theorem does not apply to the function  $y = |x|$  on any interval that includes zero.

In the following, verify the three conditions required by Rolle's Theorem and then find a suitable number  $c$  guaranteed to exist by Rolle's Theorem.

2  $f(x) = 2x^2 - 11x + 15$  on  $[\frac{5}{2}, 3]$

3  $g(x) = x^3 + 5x^2 - x - 5$  on  $[-5, -1]$

4  $p(x) = 4x^{4/3} - 6x^{1/3}$  on  $[0, 6]$

5  $k(x) = \frac{x^2 - 4}{x^2 + 4}$  on  $[-2, 2]$

In the following problems, verify the two conditions required by the Mean Value Theorem and then find a suitable number  $c$  guaranteed to exist by the Mean Value Theorem.

6  $f(x) = 4x^2 - x - 6$  on  $[0, 2]$

7  $g(x) = \frac{x - 1}{x + 2}$  on  $[0, 2]$

8  $p(x) = 3x^{2/3} - 2x$  on  $[0, 1]$

9  $k(x) = x^4 - 3x$  on  $[1, 3]$

10 The function

$$f(x) = \begin{cases} x & 0 \leq x < 1 \\ 0 & x = 1 \end{cases}$$

is zero at  $x = 0$  and  $x = 1$ , and differentiable on  $(0, 1)$ , but its derivative on  $(0, 1)$  is never zero. Doesn't this contradict Rolle's Theorem?

(Finney et al., 2001, p. 261)

11 Define a function  $f$  as follows:

$$f(x) = \begin{cases} \frac{3 - x^2}{2} & x \leq 1 \\ \frac{1}{x} & x \geq 1. \end{cases}$$

(a) Sketch the graph of  $f(x)$  in the interval  $[0, 2]$ .

(b) Show that  $f$  satisfies the conditions required by the Mean Value Theorem over the interval  $[0, 2]$ , and determine the values of  $c$  guaranteed to exist by the Mean Value Theorem.

(Apostol, 1967, p. 186)

12 A trucker was cited for speeding on a toll road with speed limit 70 MPH. He argued to the judge that he wasn't speeding. He handed in his ticket from a toll booth showing that in 3 hours he had covered 219 miles on the toll road. Determine whether the trucker was actually speeding.

13 Let  $f(x) = 1 - x^{2/3}$ . Show that  $f(1) = f(-1) = 0$ , but that  $f'(x) \neq 0$  in the interval  $[-1, 1]$ . Explain how this is possible, in view of Rolle's Theorem.

(Apostol, 1967, p. 186)

14 To save up for a car, you take a job working 10 hours a week at the library. For the first six weeks, the library pays you \$8 an hour. After that, you earn \$11.50 an hour. You put all the money you earn each week in a savings account. On the day you start work your savings account already holds \$200. Let  $S(t)$  be the function that describes the amount in your savings account  $t$  weeks after your library job begins.

(a) Find the values  $S(3)$ ,  $S(6)$ ,  $S(8)$ ,  $S'(3)$ ,  $S'(6)$ , and  $S'(8)$ , if possible, and describe their meaning in practical terms. If it is not possible to find one or more of these values, explain why.

(b) Write an equation for the function  $S(t)$ . Be sure that your equation correctly produces the values you calculated in part (a).

(c) Sketch a labeled graph of  $S(t)$ . By looking at the graph, determine whether  $S(t)$  is continuous and whether it is differentiable. Explain the practical significance of your answers.

(d) Show algebraically that  $S(t)$  is continuous but not differentiable.

(Taalman and Kohn, 2014, p. 186)

## 3.6 l'Hôpital's Rule

*A man is like a fraction whose numerator is what he is and whose denominator is what he thinks of himself. The larger the denominator, the smaller the fraction.*

— Leo Tolstoy

In the previous chapter, we discovered the values of the following

contained 25,000 gallons of oil, approximately how many more hours will elapse in the worst case before all the oil has spilled? In the best case? (Finney et al., 2001, p. 362)

- 5 Assume the following function  $f$  is a decreasing continuous function on the interval  $0 \leq x \leq 4$  and that the following is a table showing some function values.

$x$	0	1	1.5	3	4
$f(x)$	4	3	2	1.5	1

- (a) Use the trapezoid rule to approximate the area under  $f$ . (Be careful! The subintervals are not

all the same width!)

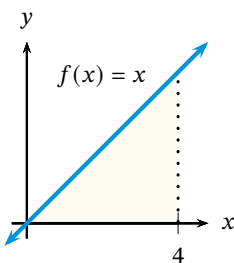
- (b) Is your answer to part (a) larger or smaller than the actual area under  $f$ ? How do you know?
- 6 Consider the area under  $y = 5$  over the interval  $-10 \leq x \leq 10$ .
- (a) Sketch the region and find the area using a basic geometry area formula.
- (b) Use the trapezoid rule on 5 equal subintervals and compare this with the answer from part (a). Does this result make sense? Why or why not?

## 4.4 Definite Integrals

*Success and failure have much in common that is good. Both mean you're trying.*

— Frank Tyger

As we have seen, Riemann sums provide an approximation to the area under a curve, and the smaller the subinterval width, the more rectangles are used, and the better our approximation becomes. In this section, we will explore this idea of using more and rectangles (on smaller and smaller subintervals) to determine exact areas under certain curves. To facilitate this, we need new symbolism to represent the exact area under  $f$ .



The exact area under a bounded function  $f(x)$  on the interval  $[a, b]$  is denoted by

$$\int_a^b f(x) dx.$$

The symbol  $\int_a^b$  is called the **definite integral** from  $a$  to  $b$ .

For example, using basic geometry, it is easy to determine the exact area under the function  $f(x) = x$  from 0 to 4. Since the area is that of a right triangle of base 4 and height 4, we see that the exact area must be  $\frac{1}{2}(4)(4) = 8$ . Hence, we say that the definite integral is equal to 8 or, in symbols,

$$\int_0^4 f(x) dx = \int_0^4 x dx = 8.$$

Previously, in Section 4.2, we spent some time discussing the fact that areas can be found under bounded functions. We clarify this discussion of exact areas (definite integrals) with an additional fact concerning such functions.



**THEOREM 4.F** Let  $f$  be an increasing bounded function on the interval  $[a, b]$ . Let  $A$  be any number that satisfies

$$\Delta x \sum_{k=0}^{n-1} f(x_k) < A < \Delta x \sum_{k=1}^n f(x_k)$$

for every integer  $n > 1$ . Then  $A = \int_a^b f dx$  as  $n \rightarrow \infty$ .

Note that there is a similar statement for decreasing bounded functions. As the argument is very similar, we will omit the proof for decreasing bounded functions.

*Proof.* The series above are nothing more than the definitions of LRS and RRS, respectively. We already know that these are approximations, so there must be some number  $A$  such that  $\text{LRS} < A < \text{RRS}$ . By the definition of a definite integral, we know that  $\int_a^b f dx$  satisfies the same inequalities as  $A$ . So we must prove that  $A$  is the definite integral. We begin by finding the difference between the left and right Riemann sums.

$$\begin{aligned} \text{RRS} - \text{LRS} &= \Delta x \sum_{k=1}^n f(x_k) - \Delta x \sum_{k=0}^{n-1} f(x_k) \\ &= \Delta x \left( \sum_{k=1}^n f(x_k) - \sum_{k=0}^{n-1} f(x_k) \right) \\ &= \Delta x \left( \sum_{k=1}^{n-1} f(x_k) + f(x_n) - \left[ f(x_0) + \sum_{k=1}^{n-1} f(x_k) \right] \right) \\ &= \Delta x \left( f(x_n) - f(x_0) + \sum_{k=1}^{n-1} f(x_k) - \sum_{k=1}^{n-1} f(x_k) \right) \\ &= \Delta x (f(x_n) - f(x_0)) \\ &= \frac{b-a}{n} (f(b) - f(a)) \end{aligned}$$

which we can write as

$$\text{RRS} - \text{LRS} = \frac{k}{n}$$

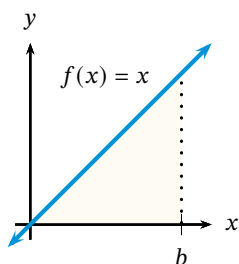
where  $k = (b-a)(f(b) - f(a))$  is constant since it only depends on constants  $a$  and  $b$ . Clearly, the difference between the left and right Riemann sums must be greater than the difference between  $A$  and the definite integral, since each of these is between the Riemann sums. Then

$$0 \leq \left| A - \int_a^b f dx \right| \leq \frac{k}{n}$$

for every  $n > 1$ . Letting  $n \rightarrow \infty$ , we see that  $\frac{k}{n} \rightarrow 0$ , so that this inequality approaches the equality  $A - \int_a^b f dx = 0$ , or  $A = \int_a^b f dx$ . ■

The preceding proof gives us an indication as to how to compute the definite integral. Let us re-do the previous example. This time, we want the area from 0 to any number  $b$ .

Again, using basic geometry, we may determine the exact area under the function  $f(x) = x$  from 0 to  $b$ . The area is that of a right



triangle of base  $b$  and height  $b$ , so the exact area must be  $\frac{1}{2}(b)(b) = \frac{1}{2}b^2$ . Hence,

$$\int_0^b f(x) dx = \int_0^b x dx = \frac{b^2}{2}.$$

But how can we determine the exact area under the standard parabola  $f(x) = x^2$  over the interval  $[0, b]$ ? For this, we rely on the previous theorem and the formulas for sum of powers of integers from Section 4.1. We will use a Riemann sum and find its limit as  $n \rightarrow \infty$ .

We wish to use  $n$  equal subintervals. Since the interval  $[0, b]$  has length  $b - 0 = b$ , each subinterval has length

$$\Delta x = \frac{b - 0}{n} = \frac{b}{n}.$$

Since the theorem guarantees that the answer is the same whether we use a left-hand or right-hand Riemann sum, we can choose whichever one we want; let us choose a right-hand sum. Hence, the  $x$ -coordinates we use are the right-hand endpoints of the subintervals  $[0, \Delta x]$ ,  $[\Delta x, 2\Delta x]$ ,  $[2\Delta x, 3\Delta x]$ , and so on, up to  $[(n-1)\Delta x, n\Delta x]$ . We can represent each right-hand endpoint as  $x_k = k\Delta x = kb/n$  for  $k = 1, 2, 3, \dots, n$ . Thus, we see that

$$\int_0^b x^2 dx = \lim_{n \rightarrow \infty} \sum_{k=1}^n x_k^2 \Delta x = \lim_{n \rightarrow \infty} \sum_{k=1}^n \left(\frac{kb}{n}\right)^2 \left(\frac{b}{n}\right).$$

Now we expand this sum, and take the limit.

$$\begin{aligned} \int_0^b x^2 dx &= \lim_{n \rightarrow \infty} \sum_{k=1}^n \left(\frac{kb}{n}\right)^2 \left(\frac{b}{n}\right) = \lim_{n \rightarrow \infty} \sum_{k=1}^n \left(\frac{k^2 b^2}{n^2} \cdot \frac{b}{n}\right) \\ &= \lim_{n \rightarrow \infty} \sum_{k=1}^n \left(\frac{k^2 b^3}{n^3}\right) = \lim_{n \rightarrow \infty} \frac{b^3}{n^3} \sum_{k=1}^n k^2 \\ &= \lim_{n \rightarrow \infty} \frac{b^3}{n^3} \left(\frac{n(n+1)(2n+1)}{6}\right) = \lim_{n \rightarrow \infty} \frac{b^3 (2n^3 + 3n^2 + n)}{6n^3} \\ &= \lim_{n \rightarrow \infty} \frac{b^3 \cdot 2n^3}{6n^3} = \frac{2b^3}{6} = \frac{b^3}{3}. \end{aligned}$$

Hence, we find that

$$\int_0^b x^2 dx = \frac{b^3}{3}.$$

**Exercise 4.4.1** Compute  $\int_0^4 x^2 dx$ .

We may use a similar procedure to find the area under  $f(x) = x^3$

over the interval  $[0, b]$ . We have

$$\begin{aligned} \int_0^b x^3 dx &= \lim_{n \rightarrow \infty} \sum_{k=1}^n \left( \frac{kb}{n} \right)^3 \left( \frac{b}{n} \right) = \lim_{n \rightarrow \infty} \sum_{k=1}^n \left( \frac{k^3 b^3}{n^3} \cdot \frac{b}{n} \right) \\ &= \lim_{n \rightarrow \infty} \sum_{k=1}^n \left( \frac{k^3 b^4}{n^4} \right) = \lim_{n \rightarrow \infty} \frac{b^4}{n^4} \sum_{k=1}^n k^3 \\ &= \lim_{n \rightarrow \infty} \frac{b^4}{n^4} \left( \frac{n(n+1)}{2} \right)^2 = \lim_{n \rightarrow \infty} \frac{b^4 (n^4 + 2n^3 + n^2)}{4n^4} \\ &= \lim_{n \rightarrow \infty} \frac{b^4 \cdot n^4}{4n^4} = \frac{b^4}{4}. \end{aligned}$$

If you are thinking that the area under  $x^4$  over  $[0, b]$  is  $b^5/5$ , you are correct!

By now, you should see a relationship between the function under which we want the area, and the area. As this applies to power functions, we will prove the the following theorem, which establishes the relationship.

**THEOREM 4.G** (Definite Integral of Power Functions) *If  $p$  is a positive integer and  $b > 0$ , then*

$$\int_0^b x^p dx = \frac{b^{p+1}}{p+1}.$$

*Proof.* We begin with the restatement of an algebraic fact for integer  $p \geq 1$ :

$$a^p - b^p = (a - b) \left( a^{p-1} + a^{p-2}b + a^{p-3}b^2 + \cdots + ab^{p-2} + b^{p-1} \right),$$

where there are exactly  $p$  terms in the rightmost parentheses. Let  $a = n+1$  and  $b = n$  in the identity above. Then, since  $a - b = n+1 - n = 1$ , we have, for any positive integer  $n \geq 1$ ,

$$\begin{aligned} (n+1)^{p+1} - n^{p+1} &= (n+1)^p + (n+1)^{p-1}n + \cdots + (n+1)n^{p-1} + n^p \\ &< (n+1)^p + (n+1)^{p-1}(n+1) + \cdots \\ &\quad + (n+1)(n+1)^{p-1} + (n+1)^p \\ &= (n+1)^p + (n+1)^p + \cdots + (n+1)^p + (n+1)^p \\ &= (p+1)(n+1)^p. \end{aligned}$$

Similarly, we find that  $(n+1)^{p+1} - n^{p+1} > (p+1)n^p$ . Hence,

$$n^p < \frac{(n+1)^{p+1} - n^{p+1}}{p+1} < (n+1)^p.$$

Now let  $n$  run from all integer values from 0 to some positive integer  $k$ , and add up each term on all sides of the inequality. We get

$$\begin{aligned} 0^p + 1^p + \cdots + k^p &< \frac{(k+1)^{p+1} - k^{p+1} + k^{p+1} - (k-1)^{p+1} + \cdots + 1^{p+1} - 0^{p+1}}{p+1} \\ &< 1^p + 2^p + \cdots + (k+1)^p \end{aligned}$$

which simplifies to

$$\sum_{n=1}^k n^p < \frac{(k+1)^{p+1}}{p+1} < \sum_{n=1}^{k+1} n^p.$$

Changing indicies slightly, we get the more useful form

$$\sum_{n=1}^{k-1} n^p < \frac{k^{p+1}}{p+1} < \sum_{n=1}^k n^p$$

which holds for every positive integer  $n \geq 1$  and every positive integer  $p \geq 1$ . Multiplication of these inequalities by  $b^{p+1}/k^{p+1}$  gives us

$$\frac{b}{k} \sum_{n=1}^{k-1} \left(\frac{nb}{k}\right)^p < \frac{b^{p+1}}{p+1} < \frac{b}{k} \sum_{n=1}^k \left(\frac{nb}{k}\right)^p.$$

Letting  $f(x) = x^p$ , and  $x_n = nb/k$  for  $n = 0, 1, 2, \dots, k$ , then these inequalities become

$$\frac{b}{k} \sum_{n=1}^{k-1} f(x_n) < \frac{b^{p+1}}{p+1} < \frac{b}{k} \sum_{n=1}^k f(x_n)$$

which are exactly the expressions for the left and right Riemann sums of  $x^p$  on the interval  $[0, b]$ . Since  $f(x) = x^p$  is increasing on this interval, we may apply Theorem 4.F. Thus,

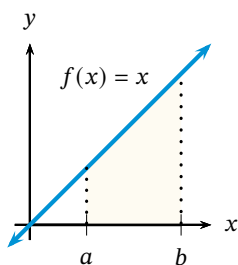
$$\int_0^b x^p dx = \frac{b^{p+1}}{p+1}. \quad \blacksquare$$

#### Example 4.4.2

With this Theorem, we may calculate the following:

$$\int_0^2 x^6 dx = \frac{2^7}{7} = \frac{128}{7}.$$

In this manner, we have easily found the exact area under the curve  $y = x^6$  on the interval  $[0, 2]$  to be  $\frac{128}{7}$ .  $\blacklozenge$



**Exercise 4.4.3** Compute  $\int_0^4 x^3 dx$ .

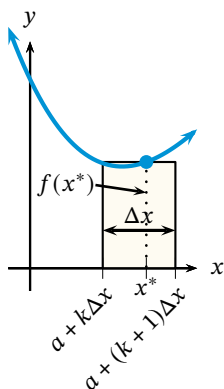
Finding the area over  $[0, b]$  is a step in the right direction, but we want to make this definite integral as general as possible. So next we find the area under  $f(x) = x$  over the interval  $[a, b]$ .

Again, using basic geometry, we may determine the exact area under the function  $f(x) = x$  from  $a$  to  $b$ . The area is that of a right triangle of base  $b$  and height  $b$ , with another right triangle of base  $a$  and height  $a$  cut off from it. The exact area must then be  $\frac{1}{2}b^2 - \frac{1}{2}a^2$ . Hence,

$$\int_a^b x dx = \frac{b^2}{2} - \frac{a^2}{2}.$$

**Exercise 4.4.4** Compute  $\int_3^5 x dx$ .

**Exercise 4.4.5** Conjecture the formula for  $\int_a^b x^p dx$ .



**Figure 4.8** – The  $k$ th rectangle in a Riemann sum. The height of the rectangle is determined by  $f(x^*)$ . The width of the rectangle is  $\Delta x = (b - a)/n$ , where  $n$  is the number of subintervals. The left-hand side of the rectangle is a distance of  $k\Delta x$  from the right endpoint  $a$  and the right-hand side is  $k\Delta x + \Delta x = (k + 1)\Delta x$  from  $a$ .

You may have been wondering about the significance of the differential  $dx$  in the expression for the definite integral. This can be thought of as arising from the definition of Riemann sums for the area between  $f$  and the  $x$ -axis.

Consider for instance the area under a function  $f(x)$  over the interval  $[a, b]$ . If we use rectangles to approximate the area, we must split the interval up into  $n$  subintervals. Thus the width of each one is  $(b - a)/n = \Delta x$ , and the height of each one is given by  $f(x^*)$ , where  $x^*$  may be the left endpoint, right endpoint, or midpoint of  $[a, b]$  (actually,  $x^*$  can be any point within the subinterval). Hence, the area of any rectangle is *height*  $\times$  *width*  $= f(x^*)\Delta x$ . By using more and more rectangles — that is, letting  $n \rightarrow \infty$ , which forces  $\Delta x \rightarrow 0$  — we arrive at infinitely many rectangles with height described by  $f(x)$  and with infinitely small widths now described by  $dx$  rather than  $\Delta x$ . Symbolically,

$$\lim_{n \rightarrow \infty} \sum_{k=1}^n f(x_k^*)\Delta x = \int_a^b f(x) dx.$$

Thus, as we pass to the infinite, the measurable quantity  $\Delta x$  becomes the infinitely small quantity  $dx$ .

#### Example 4.4.6

Let us make the relationship between Riemann sums and definite integrals more explicit. In this example, we will compute a definite integral using Riemann sums as the number of subintervals goes to infinity.

Suppose we wish to compute  $\int_1^5 3x^2 dx$ . By definition,

$$\int_1^5 3x^2 dx = \lim_{n \rightarrow \infty} \sum_{k=1}^n 3(x_k^*)^2 \Delta x.$$

Since we need  $n$  subintervals, we set  $\Delta x = (5 - 1)/n = 4/n$ . Choosing the right hand endpoint of each subinterval gives us

$$x_k^* = 1 + k\Delta x = 1 + \frac{4k}{n}$$

so that

$$3(x_k^*)^2 = 3 \left(1 + \frac{4k}{n}\right)^2 = 3 \left(1 + \frac{8k}{n} + \frac{16k^2}{n^2}\right) = 3 + \frac{24k}{n} + \frac{48k^2}{n^2}.$$

Now we are ready to evaluate the limit.

$$\begin{aligned} \int_1^5 3x^2 dx &= \lim_{n \rightarrow \infty} \sum_{k=1}^n 3(x_k^*)^2 \Delta x = \lim_{n \rightarrow \infty} \sum_{k=1}^n \left(3 + \frac{24k}{n} + \frac{48k^2}{n^2}\right) \left(\frac{4}{n}\right) \\ &= \lim_{n \rightarrow \infty} \left( \sum_{k=1}^n 3 + \frac{24}{n} \sum_{k=1}^n k + \frac{48}{n^2} \sum_{k=1}^n k^2 \right) \left(\frac{4}{n}\right) \\ &= \lim_{n \rightarrow \infty} \left( 3n + \frac{24}{n} \cdot \frac{n(n+1)}{2} + \frac{48}{n^2} \cdot \frac{n(n+1)(2n+1)}{6} \right) \left(\frac{4}{n}\right) \\ &= \lim_{n \rightarrow \infty} \left( 12 + \frac{48(n+1)}{n} + \frac{32(n+1)(2n+1)}{n^2} \right) \\ &= 12 + 48 + 64 = 124. \end{aligned}$$

This agrees with the answer obtained from using the Power Rule.  $\blacklozenge$

It is also important to know how to reverse the process. That is, given a Riemann sum, what is the definite integral the sum represents?

### Example 4.4.7

We will find the definite integral represented by the Riemann sum

$$\lim_{n \rightarrow \infty} \sum_{i=1}^n \left(2 + \frac{3i}{n}\right)^3 \frac{3}{n}.$$

Note that the fraction on the end,  $3/n$ , must be the width of each subinterval:  $\Delta x = 3/n$ . The interval over which we want the sum must then have a total width of 3. The expression  $2 + 3i/n$  must be the  $x$ -coordinate; hence,  $x_i^* = 2 + 3i/n$ . In terms of  $\Delta x$ , this is  $x_i^* = 2 + i\Delta x$ . This allows us to see that 2 must be the starting point of the definite integral. Since the width is 3, the definite integral must be from 2 to  $2 + 3 = 5$ . The summation can then be written in terms of  $x$ -coordinates, and this gives us our integral.

$$\lim_{n \rightarrow \infty} \sum_{i=1}^n \left(2 + \frac{3i}{n}\right)^3 \frac{3}{n} = \lim_{n \rightarrow \infty} \sum_{i=1}^n (x_i^*)^3 \Delta x = \int_2^5 x^3 dx. \quad \blacklozenge$$

We close this section by stating a useful property of definite integrals, the proof of which is left as a problem.

**THEOREM 4.H (The Linearity Property)** *Let  $f$  and  $g$  be bounded continuous functions on the interval  $[a, b]$ . Let  $k_1$  and  $k_2$  be real constants. Then*

$$\int_a^b [k_1 f(x) + k_2 g(x)] dx = k_1 \int_a^b f(x) dx + k_2 \int_a^b g(x) dx.$$

This is the property that allows us to find the area under any polynomial. Consider a polynomial such as  $f(x) = 3x^2 + 7x + 1$ . This linearity property says that we can find the area under  $f(x) = 3x^2 + 7x + 1$  by finding the area under each of  $x^2$ ,  $x$ , and 1. Then multiply the area under  $x^2$  by 3 and the area under  $x$  by 7. Finally, add the areas under  $3x^2$ ,  $7x$ , and 1 together.

The following example illustrates this idea. We will compute the area under a polynomial.

### Example 4.4.8

Since areas may be added or subtracted from other areas, we can compute

$$\begin{aligned} \int_0^2 (x^3 + 5x^2 - x) dx &= \int_0^2 x^3 dx + 5 \int_0^2 x^2 dx - \int_0^2 x dx \\ &= \frac{2^4}{4} + 5 \cdot \frac{2^3}{3} - \frac{2^2}{2} \\ &= 4 + 5 \cdot \frac{8}{3} - 2 = \frac{52}{3}. \end{aligned}$$

Hence, we have a method to find the area under any polynomial!  $\blacklozenge$

### Problems for Section 4.4

- 1 What is the area under the horizontal line  $y = 5$  over the interval  $[-2, 2]$ ? What is  $\int_{-2}^2 5 \, dx$ ? Make a conjecture concerning the value of  $\int_a^b C \, dx$  where  $C$  is any real constant.
- 2 Very often we use the *evaluation notation* to aid in computing definite integrals. For instance, writing " $x^2|_2^3$ " indicates that we should evaluate  $x^2$  at  $x = 3$  and at  $x = 2$ , then compute the difference:  $x^2|_2^3 = 3^2 - 2^2 = 5$ . Thus, we see that Theorem 4.G could be restated as

$$\int_0^b x^p \, dx = \left. \frac{x^{p+1}}{p+1} \right|_0^b = \frac{b^{p+1}}{p+1}.$$

In practice, we would then write

$$\int_1^2 x^5 \, dx = \left. \frac{x^6}{6} \right|_1^2 = \frac{2^6}{6} - \frac{1}{6} = \frac{21}{2}.$$

Use this notation to compute

$$\int_2^4 (3x^2 - x + 2) \, dx.$$

- 3 Evaluate the following.

- (a)  $\int_{-1}^5 (x+2) \, dx$       (c)  $\int_2^8 (x-1) \, dx$   
 (b)  $\int_1^7 x \, dx$       (d)  $\int_6^{12} (x-5) \, dx$   
 (e)  $\int_{1+k}^{7+k} (x-k) \, dx$  where  $k$  is constant  
 (f) What do you notice about the answers to the preceding problems? Why do you think this is? Explain your answer in terms of area.

Evaluate the following definite integrals. Remember to use the properties of definite integrals when possible.

- 4  $\int_{-1}^2 (x^2 + 4x - 1) \, dx$   
 5  $\int_2^4 (x-1)(x+2) \, dx$

6  $\int_{-3}^{-1} (3x^2 + 2x + 1) \, dx$

7  $\int_5^2 x \, dx$

8  $\int_{1/2}^{3/2} (4x - 6) \, dx$

9  $\int_0^1 (x^{10} - 8x^7 + 20) \, dx$

10  $\int_{-1}^1 (2x-1)(x+1) \, dx$

- 11 Use the limit definition (as shown in Example 4.4.6) to compute  $\int_3^7 2x \, dx$ .

Write each Riemann sum as a definite integral.

12  $\lim_{n \rightarrow \infty} \sum_{i=1}^n 6 \left( \frac{3i}{n} \right) \frac{3}{n}$

13  $\lim_{n \rightarrow \infty} \sum_{i=1}^n \left( \frac{3i}{n} \right)^3 \frac{3}{n}$

14  $\lim_{n \rightarrow \infty} \sum_{i=1}^n \left( \frac{3i}{n} \right) \left[ \left( \frac{3i}{n} \right) - 5 \right] \frac{3}{n}$

15  $\lim_{n \rightarrow \infty} \sum_{i=1}^n \left( 2 + \frac{3i}{n} \right)^4 \frac{3}{n}$

16  $\lim_{n \rightarrow \infty} \sum_{i=1}^n \left( \frac{3i}{n} \right)^3 \frac{3}{n}$

17  $\lim_{n \rightarrow \infty} \sum_{i=1}^n \frac{i^4}{n^5}$

18  $\lim_{n \rightarrow \infty} \sum_{i=1}^n \frac{n}{n^2 + i^2}$

19  $\lim_{n \rightarrow \infty} \sum_{i=1}^n \frac{i^3}{n^4}$

20  $\lim_{n \rightarrow \infty} \sum_{i=1}^n \frac{1}{n} \sqrt{\frac{i}{n}}$

21  $\lim_{n \rightarrow \infty} \sum_{i=1}^n \frac{80i}{n^2}$

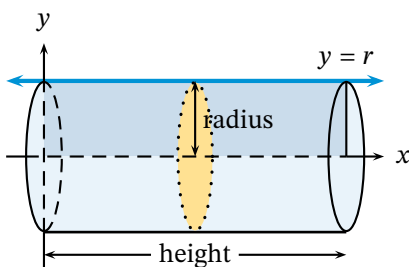
- 6 Let  $R$  be the region bounded by  $y = e^x$ ,  $y = 2$ , and  $x = 0$ . Find the volume of the solid whose base is bounded by the region  $R$  and the cross sections perpendicular to the  $x$ -axis are semicircles.
- 7 Let  $R$  be the region bounded by  $y = x^2$  and  $y = x$ . Find the volume of the solid whose base is bounded by the region  $R$  and the cross sections perpendicular to the  $x$ -axis are semicircles.
- 8 Let  $R$  be the region bounded by  $y = \frac{1}{16}x^2$  and  $y = 2$ . Find the volume of the solid whose base is bounded by the region  $R$  and the cross sections perpendicular to the  $x$ -axis are rectangles whose height is twice that of the side in the plane of the base.
- 9 Find the volume of the solid whose base is bounded by the curve  $y = 2\sqrt{\sin(x)}$ , the lines  $x = 0$ ,  $x = \pi$ , and  $y = 0$ , and the cross sections perpendicular to the  $x$ -axis are squares.

## 6.7 Disks and Washers, or Volume Part 2

*When we ask advice, we are usually looking for an accomplice.*

— Joseph-Louis Lagrange

In this section we consider solids formed by revolving a plane about an axis. We describe this procedure by establishing the known volume formula for a cylinder,  $V = \pi r^2 h$ .



**Figure 6.13** – A cylinder formed by revolving a rectangle about the  $x$ -axis.

Consider the region in the coordinate plane bounded by the line  $y = r$ , for constant  $r$ , and the  $x$ -axis over the interval  $[0, h]$ , for constant  $h$ . This region is a rectangle of dimensions  $r$  and  $h$ . But rather than treat this rectangle as a base for which we build cross sections, we will *revolve* the rectangle about the  $x$ -axis to form a solid. This creates circular cross sections of radius  $r$  with centers on the  $x$ -axis, as shown in Figure 6.13.

Since each cross section is a circle, we sum all the areas of all circles to find the volume over the entire length of the solid (the interval  $[0, h]$ ). Hence, using the same reasoning as in the previous section,

$$V = \int_0^h \pi r^2 dx = \pi r^2 x \Big|_0^h = \pi r^2 h.$$

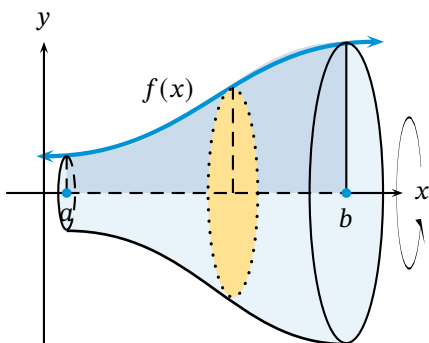
Consider what we have done. We took a curve  $f(x)$  (which in the case of the cylinder was simply  $f(x) = r$ ) which bounds a region with the  $x$ -axis over an interval  $[a, b]$  (which in the case of the cylinder was  $[0, h]$ ) and revolved the region around the  $x$ -axis, thereby creating a solid.

By revolving, we create circular cross sections whose radius is  $f(x)$  since this is the distance from the center to the edge of each cross section. So the area of each cross section is

$$A(x) = \pi [f(x)]^2.$$

Integrating (or summing) all the circular cross sections from  $x = a$  to  $x = b$ , we have

$$V = \int_a^b \pi [f(x)]^2 dx = \pi \int_a^b [f(x)]^2 dx.$$



**Figure 6.14** – The disk method in general.



Figure 6.14 shows a solid formed by revolving a region bounded by a general curve  $f(x)$  over the interval  $[a, b]$ . The figure also shows a typical circular cross section; note the radius of the cross section is determined by the function  $f(x)$ .

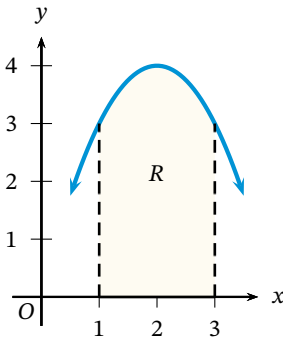
**Exercise 6.7.1** Establish the formula for the volume of a cone of radius  $r$  and height  $h$  using an appropriately situated region in the plane that is then revolved about the  $x$ -axis.

We clarify the method with the following definition.

Given a region  $R$  in the coordinate plane bounded by  $f(x)$  and the  $x$ -axis over the interval  $[a, b]$ , then the volume of the solid generated by revolving  $R$  about the  $x$ -axis is given by

$$V = \pi \int_a^b [f(x)]^2 dx.$$

This method is called the **disk method** of finding volume.



**Figure 6.15** – The region in Example 6.7.2.

### Example 6.7.2

Consider the region  $R$  in the plane bounded by the curve  $f(x) = 4x - x^2$  and the  $x$ -axis over the interval  $[1, 3]$ . This region is shown in Figure 6.15. Revolving this region about the  $x$ -axis generates a solid with circular cross sections (or, disks). Hence, the volume of the solid is

$$\begin{aligned} V &= \pi \int_1^3 [f(x)]^2 dx = \pi \int_1^3 (4x - x^2)^2 dx \\ &= \pi \int_1^3 (16x^2 - 8x^3 + x^4) dx = \pi \left( \frac{16}{3}x^3 - 2x^4 + \frac{1}{5}x^5 \right) \Big|_1^3 \\ &= \pi \left( 144 - 162 + \frac{243}{5} \right) - \pi \left( \frac{16}{3} - 2 + \frac{1}{5} \right) = \frac{406\pi}{15}. \end{aligned}$$

The calculator gives the approximate volume as 85.302.  $\blacklozenge$

### Example 6.7.3

Suppose the region  $R$  is bounded by the curve  $y = \exp(x) + 1$  and the  $x$ -axis over the interval  $[\ln(2), \ln(8)]$ . Revolving this region about the  $x$ -axis again produces a solid with circular cross sections. Thus, the volume of this solid is

$$\begin{aligned} V &= \pi \int_{\ln(2)}^{\ln(8)} [f(x)]^2 dx = \pi \int_{\ln(2)}^{\ln(8)} (e^x + 1)^2 dx \\ &= \pi \int_{\ln(2)}^{\ln(8)} (e^{2x} + 2e^x + 1) dx = \pi \left( \frac{1}{2}e^{2x} + 2e^x + x \right) \Big|_{\ln(2)}^{\ln(8)} \\ &= \pi \left( \frac{1}{2}e^{\ln(64)} + 2e^{\ln(8)} + \ln(8) - 2 - 4 - \ln(2) \right) = \pi(42 + \ln(4)) \end{aligned}$$

By the calculator, we have 136.302.  $\blacklozenge$

Suppose we change the axis of revolution to something other than the  $x$ -axis. This is what we do in the next example.

### Example 6.7.4

The region  $R$  is bounded by  $f(x) = \exp(x)$  and the line  $y = -1$  over  $[\ln(2), \ln(8)]$ .

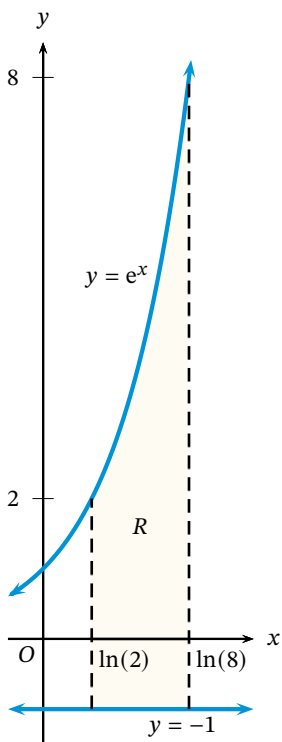


Figure 6.16 – The region in Example 6.7.4.

It is revolved around the line  $y = -1$ . How do we find the volume?

To calculate this volume, we recall that the lengths of the radii are needed. By revolving around the line  $y = -1$ , we are making the radii 1 unit longer than if we had revolved around the line  $y = 0$ . In Figure 6.17, we see the situation. Note that the radii are no longer simply defined by the curve  $y = e^x$ . They are now one unit longer: the radii are actually  $e^x + 1$ .

It is this “new” function we must integrate. The volume of this solid is given by

$$V = \pi \int_{\ln(2)}^{\ln(8)} (e^x + 1)^2 dx,$$

which is the same integral as in the previous example, so the volume is  $\pi(42 + \ln(4))$ . ♦

**Exercise 6.7.5** The region  $R$  is bounded by  $y = 10 - x^3$  and the line  $y = 2$  over the interval  $[1, 2]$ . Find the volume of the solid generated by revolving  $R$  about the line  $y = 2$ .

Notice that we have thus far always bounded our regions with a curve and a line, and the line has been the axis of revolution. What happens if the axis of revolution is not the line that bounds the region?

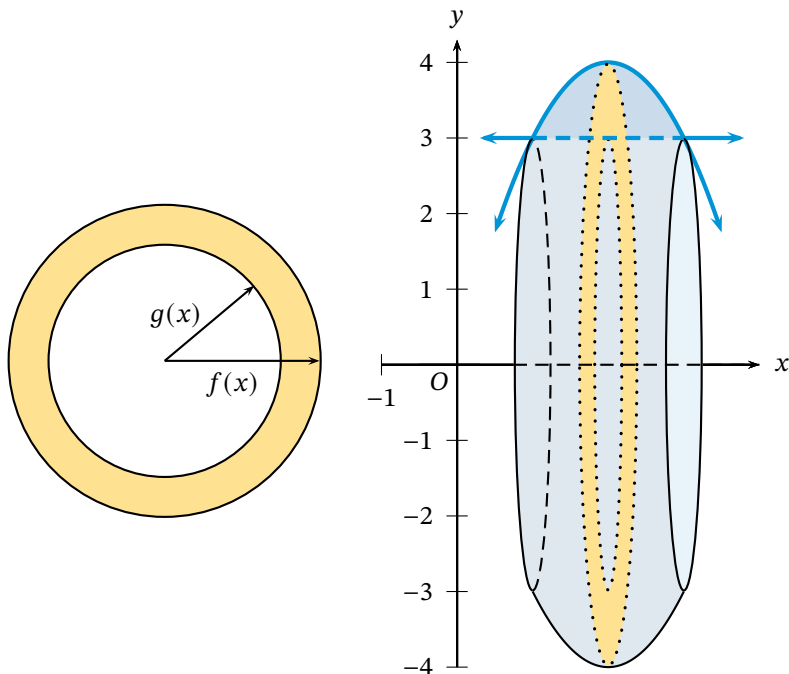


Figure 6.17 – The cross sections (left) and the resulting solid from Example 6.7.6 (right).

**Example 6.7.6**

The region  $R$  is bounded by  $f(x) = 4x - x^2$  and the line  $g(x) = 3$ . It is revolved about the  $x$ -axis. What is the volume of the resulting solid?

The solid created has a hole through the middle of it; in other words, it is a doughnut-like shape. The shape of the outer edge is determined by the parabola, while the shape of the “hole” is determined by the line. The solid is shown in Figure 6.17.

This causes us to consider the cross sections once more, because they are not disks this time. Due to the hole, each cross section, while still circular, has a circular hole in it. The cross sections are like rings (or like the washers one uses with bolts and screws) and can be seen in Figure 6.17. The area of the cross section is then the area of the larger circle minus the area of the inner circle (the hole). Note that the radii of the circles are given by the distance from the center to the outer and inner edges; these distances are given by the functions  $f$  and  $g$ . Hence, the area formula is

$$A(x) = \pi[f(x)]^2 - \pi[g(x)]^2 = \pi \left( [f(x)]^2 - [g(x)]^2 \right).$$

By integrating  $A(x)$  over the interval, we obtain the volume.

Back to the problem: Notice that we were not explicitly given an interval over which to integrate. However, we can find it. The interval is given by the  $x$ -coordinates of the intersection points of  $f$  and  $g$ . Setting  $f(x) = g(x)$  gives  $4x - x^2 = 3$  whose solutions are 1 and 3, from which we get an interval of  $[1, 3]$ .

Thus, using the washer method, we get a volume of

$$\begin{aligned} V &= \pi \int_1^3 \left( [f(x)]^2 - [g(x)]^2 \right) dx = \pi \int_1^3 \left( [4x - x^2]^2 - 3^2 \right) dx \\ &= \pi \int_1^3 \left( 16x^2 - 8x^3 + x^4 - 9 \right) dx = \pi \left( \frac{16}{3}x^3 - 2x^4 + \frac{1}{5}x^5 - 9x \right) \Big|_1^3 = \frac{136\pi}{15}, \end{aligned}$$

or 28.484. ♦

The method used in the previous example has a name.

Given a region  $R$  in the coordinate plane bounded above by  $f(x)$  and below by  $g(x)$  over the interval  $[a, b]$ , then the volume of the solid generated by revolving  $R$  about the  $x$ -axis is given by

$$V = \pi \int_a^b \left( [f(x)]^2 - [g(x)]^2 \right) dx.$$

This method is called the **washer method** of finding volume.

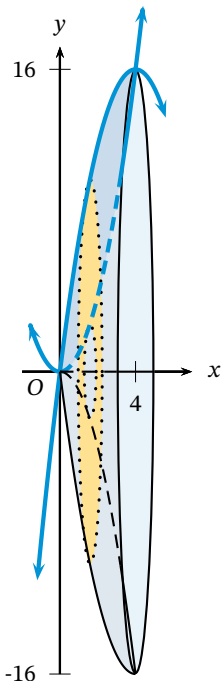
Next, we use this washer method again to find the volume of a solid of revolution.

### Example 6.7.7

The region  $R$  is bounded by  $f(x) = 8x - x^2$  and  $g(x) = x^2$ . Find the volume of the solid generated as  $R$  is revolved about the  $x$ -axis.

As in the previous example, we must find the intersection points so we know what interval we are to integrate over. Setting  $8x - x^2 = x^2$  gives  $x = 0$  and  $x = 4$ ; hence the interval is  $[0, 4]$ .

Note that the cross sections perpendicular to the axis of revolution (the  $x$ -axis in this case) are washers. This can be seen in Figure 6.18. Hence the



**Figure 6.18** – A solid formed by revolving a region bounded by two parabolas.

volume is given by

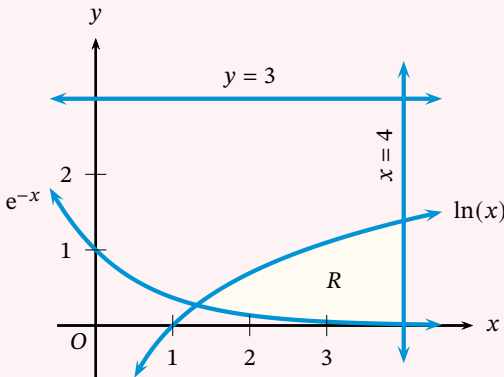
$$\begin{aligned}
 V &= \pi \int_0^4 \left( [8x - x^2]^2 - [x^2]^2 \right) dx \\
 &= \pi \int_0^4 (64x^2 - 16x^3 + x^4 - x^4) dx \\
 &= \pi \int_0^4 (64x^2 - 16x^3) dx \\
 &= \pi \left( \frac{64}{3}x^3 - 4x^4 \right) \Big|_0^4 = \frac{1024\pi}{3}
 \end{aligned}$$

or 1072.33. ♦

Finally, we see how a graphing calculator can help us.

**Example 6.7.8**

Suppose the region  $R$  is bounded by  $f(x) = \ln(x)$ ,  $g(x) = e^{-x}$ , and the line  $x = 4$ . Find the volume of the solid generated by revolving  $R$  about the line  $y = 3$ . (See the figure below.)



To calculate the volume, we must first determine the length of the radii. Since the region being revolved is not bounded by the axis of revolution, there will be a hole created in the solid, and therefore we must determine the length of the radii from the center to the inner and outer edges of the region. Hence, the length of the radius to the outer edge of the region is equal to the distance between the axis of revolution and the function. In this case, that is  $G(x) = 3 - e^{-x}$ . The distance from the axis of revolution to the inner function is  $F(x) = 3 - \ln(x)$ .

Next, we must find the interval. Using the calculator, we find the intersection point of  $Y1 = 3 - e^{-X}$  and  $Y2 = 3 - \ln(X)$  to be  $X = 1.309799586$ . Storing this as  $A$  so we may use it later (press  $X$   $STO$   $A$ ), we set up the volume integral.

This time, because the axis of revolution is *above* the region,  $G$  is the outer radius and  $F$  is the inner radius. Hence, we need to integrate  $G^2 - F^2$ . The volume integral is then

$$V = \pi \int_{1.309799586}^4 \left( [3 - e^{-x}]^2 - [3 - \ln(x)]^2 \right) dx.$$

Using the calculator, we enter  $\pi * \text{fnInt}((Y1)^2 - (Y2)^2, X, A, 4)$  where we have the functions entered in  $Y1$  and  $Y2$ , and  $A$  is the stored  $x$ -coordinate of the intersection point. The calculator gives the approximation 34.391. ♦

### Problems for Section 6.7

The region  $R$  is bounded by the given curves and/or lines. Find the volume of the solid generated by revolving  $R$  around the given axis. You may find graphing the curves on your calculator useful.

- 1  $y = \cos(x)$ ,  $y = \sin(x)$ ,  $x = 0$ ,  $x = \pi/4$ ; axis:  $x$ -axis
- 2  $y = 1/\sqrt{x}$ ,  $x = e$ ,  $x = e^3$ ,  $y = 0$ ; axis:  $x$ -axis
- 3  $y = 3 - x^2$ ,  $y = -1$ ; axis:  $y = -1$
- 4  $y = 16x - 4x^2$ ,  $y = 0$ ; axis:  $y = -20$
- 5  $y = (x + 3)^3$ ,  $y = 0$ ,  $x = 2$ ; axis:  $y = -1$
- 6 For the following problems, set up the required volume integral, then evaluate that integral on your calculator.
  - (a) The region  $R$  is bounded by the curve  $y = \sin x \cos x$  and the  $x$ -axis from  $x = 0$  to  $x = \frac{\pi}{2}$ . Find the volume of the solid generated by revolving  $R$  about the  $x$ -axis.

(b) The region  $R$  is bounded by the curve  $y = e^x$  and the lines  $y = 2$  and  $x = -1$ . Find the volume of the solid generated by revolving  $R$  about the line  $y = e$ .

(c) The region  $R$  is bounded by the curve  $16y^2 + 9x^2 = 144$  and the line  $4y = 3x + 12$  in Quadrant II. Find the volume of the solid generated by revolving  $R$  about the  $x$ -axis.

7 (Calculator) Let  $R$  be the region bounded by the graph of  $f(x) = e^{2x-x^2}$  and the graph of  $g(x) = \sec(x)$ .

- (a) Find the area of the region  $R$ .
- (b) The region  $R$  is revolved about the  $x$ -axis. Find the volume of the resulting solid.
- (c) The region  $R$  is revolved about the line  $y = 3$ . Find the volume of the resulting solid.
- (d) The region  $R$  is the base of a solid whose cross sections perpendicular to the  $x$ -axis are squares. Find the volume of this solid.

## 6.8 Cylindrical Shells, or Volume Part 3

*Anyone who cannot cope with mathematics is not fully human. At best he is a tolerable subhuman who has learned to wear shoes, bathe, and not make messes in the house.*

— Robert A. Heinlein

You may have noticed when we discussed disks and washers that we never revolved our region about any vertical axis. It is to this problem we now turn. Revolving a region around the  $y$ -axis can be done more efficiently with a method other than disks or washers. (That is not to say that it is impossible to use the disk and washer method. See problem 9 for instance.) To describe this new method we compute the volume of the solid generated by revolving around the  $y$ -axis the region bounded by  $f(x) = (x - 2)^2$  in the first quadrant.

Instead of creating circular cross sections as in the disk method, we consider this solid built of many hollow cylinders, each inside another. Figure 6.19 shows the region, the solid, and a few such “cylindrical shells.” Although we are not using a cross section method, we still compute volume by a sum; in this case, we sum all the cylindrical shells.

The thickness of each shell is infinitesimally small (as with the disks). As such, it is as if the shells consist only of the *surface* of a cylinder. The areas of the surfaces is what we sum. The area of each surface is simply that of a rectangle—a rectangle that has been wrapped in a circular fashion, but a rectangle nonetheless. The width of the rectangle is  $f(x)$ , and the length is the circumference of the cylindrical shell. This is  $2\pi x$  since  $x$  is the radius of each shell. Hence,

*The shell is just the outer portion of a cylinder without a top or bottom. You can think of a cylindrical shell as the label on a can of soup.*