

# Level Three Calculus Worksheets



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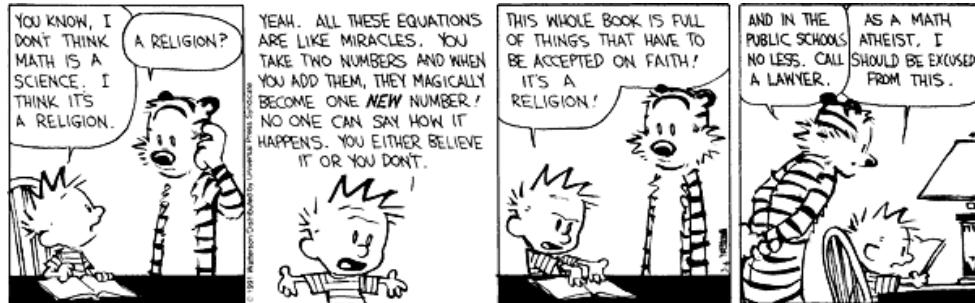
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## CHAPTER 1

### Preamble

## NCEA Level 3 Calculus (Differentiation)

### Prior Revision: Functions



### Introduction to the Notes

#### Mathematical Prerequisites

There are a number of things from Level 2 Mathematics that students should be comfortable with; generally, I assume in these notes a vague merit-level understanding of the core level 2 standards (by which I mean, the reader should be comfortable solving achieved level problems without guidance and have some idea how to approach more difficult problems):

- Level 2 Algebra: All material on quadratics (factorising, solving, discriminants), logs and exponents.
- Level 2 Calculus: Basic differentiation, geometric meaning of derivative (in particular, integration is *not* assumed)
- Level 2 Graphing: Recognising  $x$ -/ $y$ -shift of general functions, slope-intercept and point-slope form of linear equations, recognising period/frequency/amplitude/ $x$ -/ $y$ -shift from a trig function.
- Level 2 Trigonometry: Trig ratios, the Pythagorean theorem.
- Level 2 Simultaneous Equations: Solving linear and quadratic simultaneous equations.
- Level 2 Co-ordinate Geometry: Distances and linear equations.

Further into the notes, I also touch a bit on concepts covered in some of the other Level 3 standards, but not in so much detail that they need to be covered first:

- Level 3 Conics: Recognising forms from equations.
- Level 3 Algebra: Surds.
- Level 3 Trigonometry: Solving trig equations (including general solutions), reciprocal trig functions, use of trig identities (this latter mainly for E/S/OS-style integration problems).

In particular, no knowledge of complex algebra is assumed (or used) anywhere in the notes.

No knowledge from any L2 or L3 statistics standards is assumed.

#### A Note on Problem Difficulty

One of the main goals for these notes is that they should be useful for students at all levels, from A to OS. Accordingly, the problems each week range from simple (most students should be able to just write down an answer without thinking too hard) to extremely non-trivial (it took **me** a while to work the problem, and I

know this material quite well). If you can't do a problem, the best thing to do is to move on and come back to it — the problems don't always increase in difficulty. Of course, it is important to do a good number of problems **including some difficult ones**; you're not under exam conditions here and you're going to get an awful lot more out of a hard problem than an easy one!

I have marked the problems in the weekly worksheets (**not** the homework) with symbols relating vaguely to difficulty:

### A M E S O

However, these are for my own reference and should not be taken to be accurate with respect to actual examinations.

## A Note on the Textbook

Many problems are taken from a couple of places:

- Stewart's Calculus (the current trendy textbook)
- Anton's Calculus (the old trendy textbook)
- University of Canterbury MATH199 lecture notes and problem sets
- Old NCEA/Scholarship exams

Most textbooks cover all the relevant material in the first few chapters (the first five or so in Stewart).

## Homework

Every week has an associated homework sheet with a page of reading (five minutes or so) and a few questions (generally all pretty straightforward, but there is often a challenge question on there to keep you occupied).

I cannot emphasise enough how important it is to **do the homework**.

## How to Read Mathematics

*So we shall now explain how to read the book. The right way is to put it on your desk in the day, below your pillow at night, devoting yourself to the reading, and solving the exercises till you know it by heart. Unfortunately, I suspect the reader is looking for advice on how not to read, i.e. what to skip, and even better, how to read only some isolated highlights.*

- Saharon Shelah, ‘Classification Theory and the Number of Non-Isomorphic Models’

A major part of Level 3 Mathematics is preparation for university-level study in pure mathematics or the hard or soft sciences. As such, this year we begin to expose you to some ‘real mathematics’ — not just the watered-down calculation and computation you’ve been doing since intermediate, but a real journey of discovery through one of humanity’s great fields of human experience. I guarantee that at primary school you enjoyed this kind of mathematics — for example, consider the non-obvious fact that  $3 \times 5 = 5 \times 3$ . Next year you will learn that there are some objects which do not have this property (commutativity).

There are a lot of definitions and theorems, but they allow us to capture our intuition of mathematical objects, their behaviour, and their beauty in a more precise (and more correct) sense. It is important to read slowly and understand the symbolism as you go, as every piece strengthens the whole (like a single flute in a symphony).

**Recommended reading for the interested:** Paul Lockhart’s ‘A Mathematician’s Lament’.

## Welcome to Calculus

### What is Calculus?

Calculus is the study of:

- Continuous change.
- Slope, area, and volume.
- Functions and relationships.

It has applications in:

- Physics and chemistry.
- Probability theory.
- Population theory.
- Economics (I am assured).

In pure mathematics, calculus can be seen as the computational side of a pretty subject called **real analysis**.

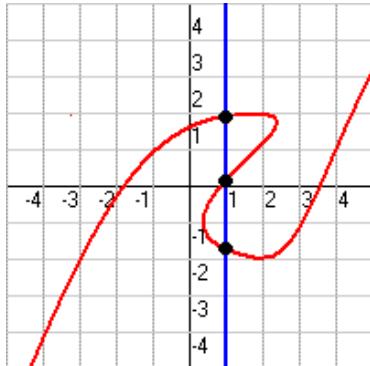
### Revision of Functions

The most fundamental concept in calculus is that of a *function*.

**Definition** (Function). A function is a something which takes a set of things (for example, the real numbers  $\mathbb{R}$ ) and assigns to each one exactly one thing (which could be the same or different).

**Example.** The map which takes a number  $x$  and spits out  $x^2$  is a function — for every input, there is exactly one output. If we *graph* this function, we plot its input on the  $x$ -axis and its output on the  $y$ -axis and obtain a parabola.

**Example.** The curve graphed below is *not* a function, since for some inputs (like 1) it has more than one output. We can check this by drawing vertical lines along the function, like that pictured: if a graph is a function, no vertical line can ever cross the curve more than once (this is the *vertical-line test*).

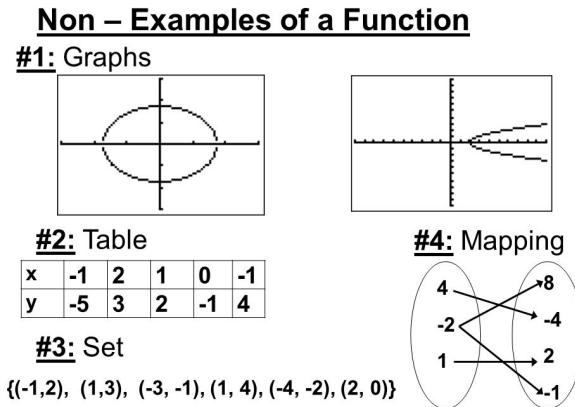


**Example.** The map  $f : x \mapsto \sin x$  is a function. We could also define it by ‘the function  $f$  such that  $f(x) = \sin x$ ’. This function  $f$  can only produce numbers between 1 and  $-1$ ; we say that its *range* is the interval from  $-1$  to  $1$ .

**Example.** The map  $\iota : x \mapsto x$  is a function, called the *identity function*.

**Example.** The map  $\ln x$  is a function, but it is only defined when  $x > 0$ : we say that its *domain* is the positive real numbers.

**Example.** Some more non-examples:



## Questions

1. Which of the following are functions?
  - (a)  $E(x) = 2^x$
  - (b)  $\phi : x \mapsto \frac{2}{x}$
  - (c) The thing which maps every person to their youngest sibling.
  - (d) The thing which sends every person to their youngest sibling that isn't themself.
  - (e)  $x \mapsto \lfloor x \rfloor$  (the floor map).
  - (f) The relation that sends every person to their age.
2. I will define two functions,  $\varphi$  and  $\vartheta$ , as follows:
 
$$\varphi(x) = 2x - 7, \quad \vartheta(\zeta) = \frac{1}{7}(14\zeta - 49).$$

Explain why these functions are equal.
3. If  $f(x) = x^2 + x$ , find:
  - (a)  $f(1)$
  - (b)  $f(y)$
  - (c)  $f(x + h)$
4. Find the distance between  $(-3, 4)$  and  $(2, 1)$ .
5. Three sides of a triangle have lengths 8, 15, and 17.
  - (a) Show that the triangle is right-angled.
  - (b) Find the other two angles.
6. Factorise and solve  $x^2 - 3x + 2 = 0$ .
7. How many **lines** are there through the point  $(2, 3)$  and the origin? Give the equations of all such lines.
8. Find the slope of the line  $4x + 3y + 2 = 0$ .

9. Find the solution to the following linear system:

$$\begin{aligned}2x + y &= 7 \\3x - y &= 8\end{aligned}$$

10. How many (real) solutions does  $x^2 + 4x + 1$  have?
11. Draw  $\sin(x)$ ,  $\cos(x)$ ,  $\tan(x)$ ,  $\exp(x)$ , and  $\ln(x)$ .
12. How many solutions does  $\cos(3\pi x + 1) = 2$  have?
13. How many solutions does  $\sin(3x) = \frac{1}{3}$  have?

CHAPTER 2

**Differentiation**

## NCEA Level 3 Calculus (Differentiation)

### 1. The Derivative

What is the derivative?

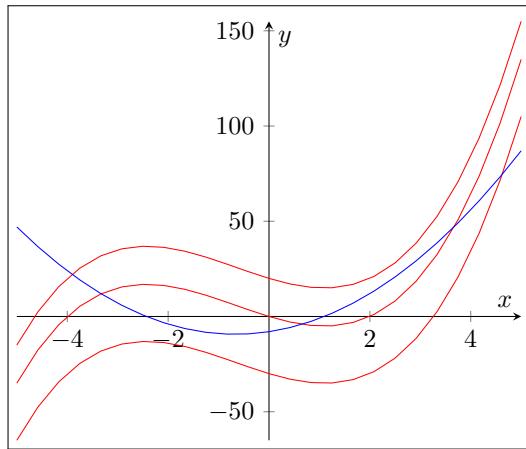
- A way to find the slope of another function.
- A function giving a rate of change.
- A way to find maxima and minima of a function.

Essentially, the value of the derivative of a function at a point is the gradient/slope/rate of change of that function at that point.

**Example.** Consider a function defined by  $y = 2x + 1$ . At every point, the slope of the graph of this function is 2; so the value of the derivative of this function is 2 at every point.

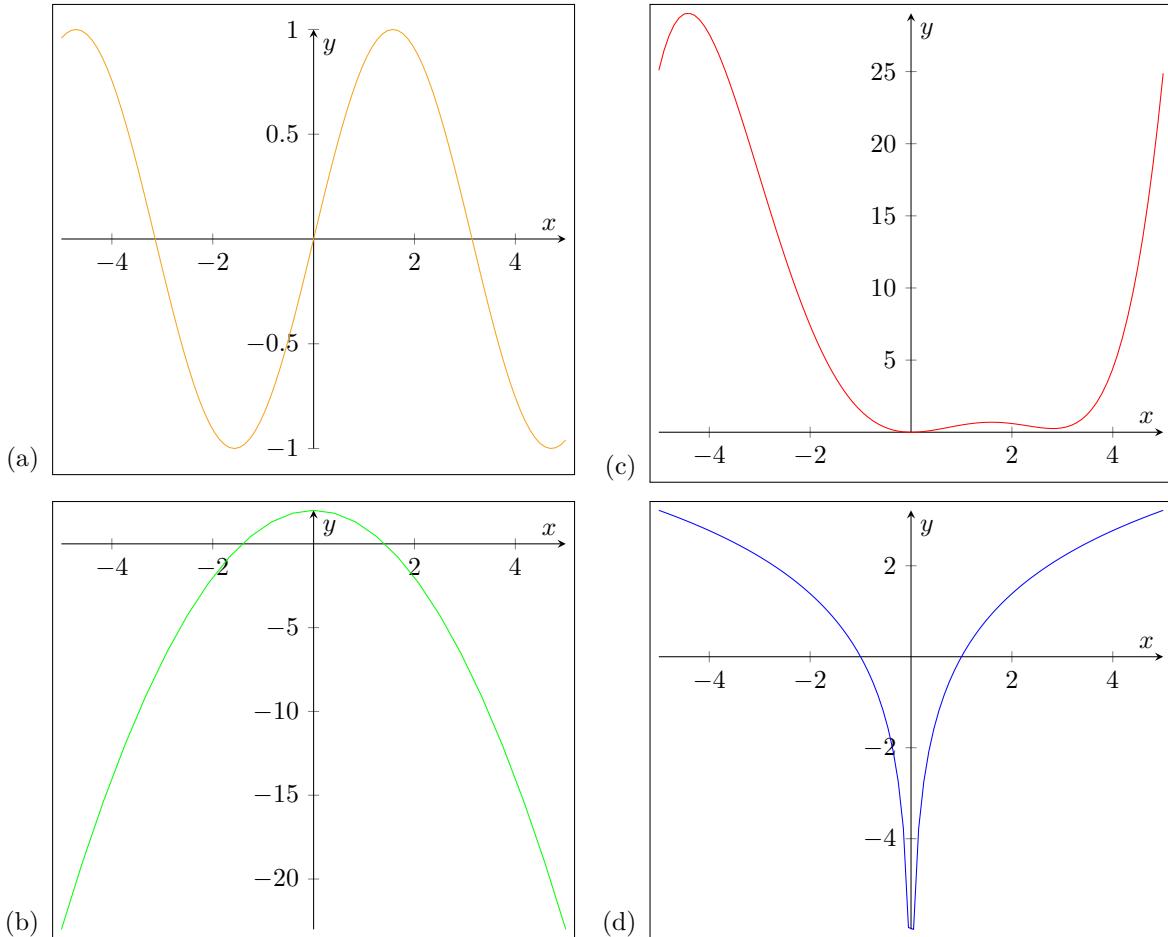
**Example.** The speed of a particle at any time is the rate of change of the displacement of the particle at that time; this can also be viewed as the slope of the displacement-time graph of the particle. Hence the speed of the particle is the derivative of the displacement.

**Example.** In the diagram, the derivative of the red functions is shown as the blue function. Note that the derivative of the function depends only upon the shape, not the  $y$ -shift. Also, see that the derivative is positive as the function increases and is negative when the function is decreasing. The derivative is zero exactly where the function is ‘flat’.



## Questions

1. A Why does the derivative not depend on the  $y$ -shift of a function?
2. A Draw the derivative of each graphed function.



3. A Consider each of these functions in turn. Where is the derivative of each (i) negative, (ii) positive, (iii) zero, and (iv) undefined?
  - (a)  $x \mapsto x^2$
  - (b)  $x \mapsto \sin x$
  - (c)  $x \mapsto \tan x$
4. A Describe the derivative of the function  $x \mapsto \tan^{-1} x$ .
5. M Consider the function  $f : t \mapsto \text{floor}(t)$ . Where is  $f$  differentiable? (Define  $\text{floor}(t)$  to be the greatest integer less than or equal to  $t$ .)
6. M When a hot water tap is turned on, the temperature  $T$  of the water depends on how long the water has been running.
  - (a) Sketch a possible graph of  $T$  as a function of the time  $t$  that the tap has been running.

- (b) Describe how the rate of change of  $T$  w.r.t.  $t$  varies as  $t$  increases.
- (c) Sketch a graph of the derivative of  $T$  w.r.t.  $t$ .
7. **M** The rate of change of a population at a time  $t$  is directly proportional to the population  $P(t)$  at that time, such that  $\frac{dP}{dt} = P$ . Draw a graph of the population over time if  $P(0) \approx 1000$ .
8. **M** Consider a continuous function  $f : \mathbb{R} \rightarrow \mathbb{R}$  which has  $n$  roots (all of multiplicity one) in some interval  $I$ . How many roots must its derivative have in  $I$ ?
9. **M** If a function is periodic, with a period of  $T$ , what can you say about its derivative?
10. **M** Consider an ellipse,  $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$ . This is not a function: since both  $(0, b)$  and  $(0, -b)$  are members of the function, it fails the vertical line test. However, it would be nice to reason about its rate of change *as if it were* a function. Describe the slope of the ellipse as a particle traces the curve in an anticlockwise direction at a constant rate.
11. **M** The number of bacteria after  $t$  hours in a controlled laboratory experiment is  $n = f(t)$ .
- (a) What is the meaning of the derivative  $f'(5)$ ? What are its units?
- (b) Suppose that there is an unlimited amount of space and nutrients. Which would you expect to be larger,  $f'(5)$  or  $f'(10)$ ? If the supply of nutrients is limited does your answer change?

## NCEA Level 3 Calculus (Differentiation)

### 1. The Derivative (Homework)

#### Reading

*From Calculus Made Easy, by Silvanus P. Thompson and revised by Martin Gardner*

Considering how many fools can calculate, it is surprising that it should be thought a difficult or a tedious task for any other fool to learn how to master the same tricks.

Some calculus-tricks are quite easy. Some are enormously difficult. The fools who write the text-books of advanced mathematics — and they are mostly clever fools — seldom take the time to show you how easy the easy calculations are. On the contrary, they seem to desire to impress you with their tremendous cleverness by going about it in the most difficult way.

Being myself a remarkably stupid fellow, I have had to unteach myself the difficulties, and now beg to present to my fellow fool the parts that are not hard. Master these thoroughly, and the rest will follow. What one fool can do, another can.

The preliminary terror, which chokes off most high school students from even attempting to learn how to calculate, can be abolished once and for all by simply stating what is the meaning — in common-sense terms — of the two principal symbols that are used in calculating.

These dreadful symbols are:

(1)  $d$ , which merely means "a little bit of".

Thus  $dx$  means a little bit of  $x$ ; or  $du$  means a little bit of  $u$ . Ordinary mathematicians think it more polite to say "an element of", instead of "a little bit of". Just as you please. But you will find that these little bits (or elements) may be considered to be infinitesimally small.

(2)  $\int$ , which is merely a long  $S$ , and may be called (if you like) "the sum of".

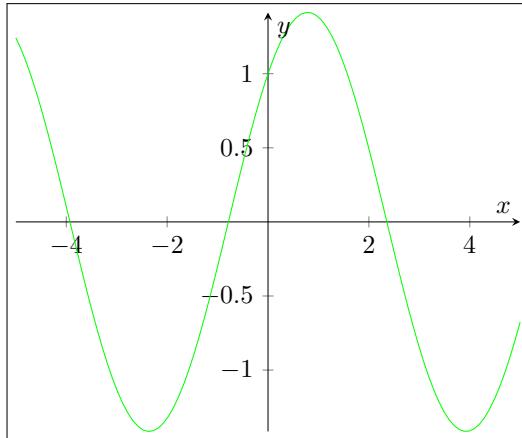
Thus  $\int dx$  means the sum of all the little bits of  $x$ ; or  $\int dt$  means the sum of all the little bits of  $t$ . Ordinary mathematicians call this symbol "the integral of". Now any fool can see that if  $x$  is considered to be made up of a lot of little bits, each of which is called  $dx$ , if you add them all up together you get the sum of all the  $dx$ 's (which is simply the same thing as the whole of  $x$ ). The word "integral" simply means "the whole". If you think of the duration of time for one hour, you may (if you like) think of it cut up into 3600 little bits called seconds. The whole of the 3600 little bits added up together make one hour.

When you see an expression that begins with this terrifying symbol, you will henceforth know that it is put there merely to give you instructions that you are now to perform the operation (if you can) of totalling up all the little bits that are indicated by the symbols that follow.

That's all.

**Questions**

1. Given that the following graph is the derivative of a function passing through  $(0, 0)$ , draw the original function.



2. (a) At a maxima or minima, what value  $m$  does the derivative of a function take? Explain this geometrically.  
(b) Show, by example (i.e. draw a graph), that there exist functions such that they have a derivative equal to  $m$  at a point but not a minimum or maximum at that point.

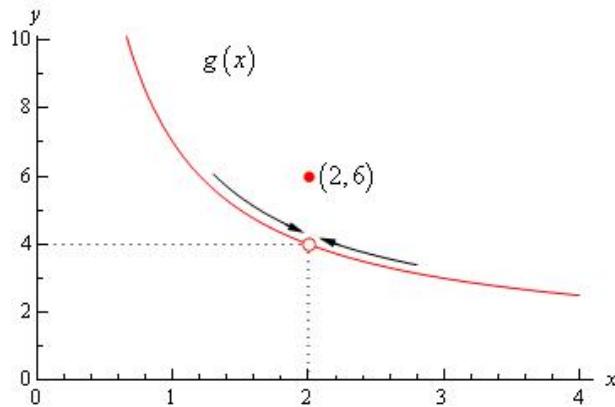
## NCEA Level 3 Calculus (Differentiation)

### 2. Limits

How can we define the derivative in such a way that we can calculate with it? Recall that the *average gradient* (or average slope) of a function  $f$  over the interval  $a \leq x \leq b$  is defined to be  $m = \frac{\Delta y}{\Delta x} = \frac{f(b)-f(a)}{b-a}$ . We wish to find the gradient at a single point; in order to do this, we will slowly move point  $b$  towards point  $a$ , letting  $\Delta x$  get closer and closer to zero. However, we cannot actually let  $\Delta x = 0$  — and so we can only ever find an *approximation* to the instantaneous gradient!

Before moving on with the definition of the derivative, let's explore this idea of assigning values to a function by seeing what it looks like really close to the point we're interested in. We call this operation the *limit*.

Consider the following function:



Although the *value* of the function at 2 is 6, the *limit*  $\lim_{x \rightarrow 2} g(x) = 4$  because when taking a limit we don't care what the function does at the point — only what it looks like it should do! Essentially, the limit of a function at a point is a property of the area around the point **and not a property of the point itself**.

**Example.** Here are a few algebraic examples:

- $\lim_{x \rightarrow 0} \frac{x}{x} = 1$  since as  $x$  gets closer and closer to 0,  $\frac{x}{x} = 1$ .
- $\lim_{x \rightarrow 3} \frac{(x-2)(x-3)}{x-3} = 1$  since as  $x$  gets closer and closer to 3, the fraction gets arbitrarily close to 1.
- $\lim_{x \rightarrow 0} \frac{1}{x}$  does not exist, since if we approach 0 from the left the function becomes arbitrarily negative and if we approach 0 from the right the function becomes arbitrarily positive — we do not approach the same value on both sides.
- $\lim_{x \rightarrow \infty} \frac{1}{x} = 0$  since as  $x$  becomes arbitrarily large,  $\frac{1}{x}$  becomes arbitrarily small.
- $\lim_{x \rightarrow 0} \sqrt{x}$  does not exist, since  $\sqrt{x}$  is undefined for  $x < 0$ .

Now, let's revisit the derivative. We will define the derivative of a function  $f$  at a point  $a$  as the value of the limit

$$\lim_{h \rightarrow 0} \frac{f(a+h) - f(a)}{h},$$

which is equivalent to the definition above (see exercises).

**Example.** We will find the derivative of  $f(x) = x^3$  at the point  $x$  using the definition.

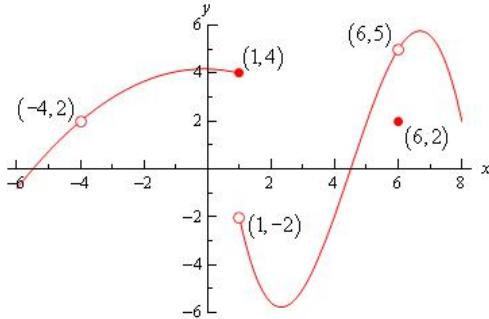
$$\begin{aligned} f'(x) &= \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h} \\ &= \lim_{h \rightarrow 0} \frac{(x+h)^3 - x^3}{h} \\ &= \lim_{h \rightarrow 0} \frac{x^3 + 3x^2h + 3xh^2 + h^3 - x^3}{h} \\ &= \lim_{h \rightarrow 0} \frac{3x^2h + 3xh^2 + h^3}{h} \\ &= \lim_{h \rightarrow 0} 3x^2 + 3xh + h^2 \\ &= 3x^2. \end{aligned}$$

## Questions

1. A Guess the value of the following limit by evaluating it at  $x \in \{\pm 1, \pm 0.5, \pm 0.2, \pm 0.1, \pm 0.05, \pm 0.01\}$ :

$$\lim_{x \rightarrow 0} \frac{\sin x}{x + \tan x}$$

2. A Consider the function  $f$  graphed below.



- (a) For each of the following expressions, either give the value or explain why the expression is undefined.
- $f(-4)$
  - $\lim_{x \rightarrow -4} f(x)$
  - $f(1)$
  - $\lim_{x \rightarrow 1} f(x)$
- (b) Explain why the limit  $\lim_{x \rightarrow 6} f(x)$  is not equal to  $f(6)$ .
- (c) At which points is  $f$ :
- Discontinuous?
  - Non-differentiable?

3. M Evaluate the limit or explain why it does not exist:

- |  |  |
|--|--|
| (a) $\lim_{x \rightarrow 2} \frac{x^2+x-6}{x-2}$               | (i) $\lim_{x \rightarrow 0} \tan x$  |
| (b) $\lim_{x \rightarrow 0} \frac{1}{x^3}$                     | (j) $\lim_{x \rightarrow 0} \csc x$  |
| (c) $\lim_{x \rightarrow 9} \frac{1}{x^3}$                     | (k) $\lim_{x \rightarrow a} C$ , where $a$ and $C$ are constants.                |
| (d) $\lim_{h \rightarrow 0} \frac{(2+h)^3 - 8}{h}$             | (l) $\lim_{x \rightarrow -\infty} \tan^{-1} x$                                   |
| (e) $\lim_{x \rightarrow 4} \frac{x^2 + 5x + 4}{x^2 + 3x - 4}$ | (m) $\lim_{y \rightarrow 0} \lim_{x \rightarrow 0} \frac{(x+y)(x-y)}{x^2 - y^2}$ |
| (f) $\lim_{x \rightarrow \frac{\pi}{2}} \sin x$                | (n) $\lim_{x \rightarrow \infty} 1/x$ .  |
| (g) $\lim_{x \rightarrow \infty} \sin x$                       | (o) $\lim_{x \rightarrow \infty} \frac{2x}{x^2 + 1}$ .                           |
| (h) $\lim_{x \rightarrow \frac{\pi}{2}} \tan x$                | (p) $\lim_{x \rightarrow \infty} \frac{x+2}{x-3}$ .                              |

4. M Consider the function  $\varphi$  defined by

$$\varphi(x) = 1/\frac{1}{x-x}.$$

Explain why neither  $\varphi(\alpha)$  nor  $\lim_{x \rightarrow \alpha} \varphi(x)$  exists for any real  $\alpha$ .

5. M Find the derivative of  $x^2 + x$  from first principles.
6. E Find the derivative of  $\sin x$  from first principles, given that  $\lim_{x \rightarrow 0} \frac{\sin x}{x} = 1$  and  $\lim_{x \rightarrow 0} \frac{1 - \cos x}{x} = 0$ .
7. E Show that  $f(x) = |x - 6|$  is not differentiable at  $x = 6$ . Find a formula for  $f'$ .
8. E Show that  $\lim_{x \rightarrow a} \frac{f(x) - f(a)}{x - a}$  and  $\lim_{h \rightarrow 0} \frac{f(a+h) - f(a)}{h}$  are equivalent definitions for the derivative at the point  $a$  of some function  $f$ .
9. E If  $\lim_{x \rightarrow a} [f(x) + g(x)] = 2$  and  $\lim_{x \rightarrow a} [f(x) - g(x)] = 1$ , find  $\lim_{x \rightarrow a} f(x)g(x)$ .
10. S Consider the following limit (you may assume that it exists):

$$L = \lim_{n \rightarrow \infty} \sum_{i=0}^n \frac{9}{10^i}$$

- (a) Write  $L = 0.9 + 0.09 + \dots$ , and make a conjecture about the value of  $L$ .
- (b) Prove or disprove your conjecture from (a). [*Hint: you may wish to consider the following working.*]

$$\left(1 - \frac{1}{10}\right)L = 9 \left(1 - \frac{1}{10}\right) \left(\frac{1}{10} + \frac{1}{100} + \dots\right)$$

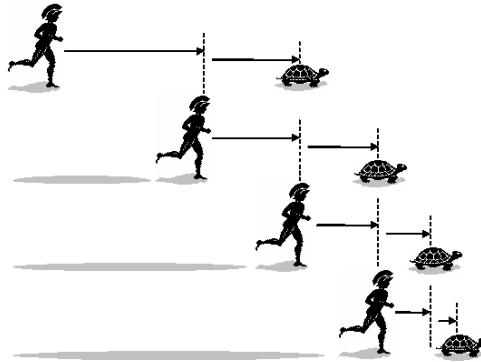
- (c) In general, consider the sum  $S_n = \sum_{i=1}^n ar^i$  for some real constants  $a$  and  $r$ . Prove that

$$\lim_{n \rightarrow \infty} S_n = \frac{a(1 - r^n)}{1 - r}.$$

[*Hint: use the same trick as in (b).*] Is there any restriction on  $r$  for this limit to exist?

11. S Zeno was a Greek philosopher active in the 5th century BCE. He presented a list of ‘paradoxes’, or apparent contradictions, including the following (adapted from Wikipedia):

- Suppose Achilles is in a foot race with a tortoise. Achilles runs much faster than the tortoise, but the latter has a head start. By the time Achilles reaches the location that the tortoise started, the tortoise will have moved a small amount further on; similarly, by the time Achilles reaches the new location of the tortoise, it will have moved an even smaller distance further on; and by this reasoning it follows that Achilles can never overtake the tortoise.



- Suppose Homer wishes to walk to the end of a path. Before he can get there, he must get halfway there. Before he can get halfway there, he must get a quarter of the way there. Before traveling a quarter, he must travel one-eighth; before an eighth, one-sixteenth; and so on. So Homer cannot walk to the end of the path.
- For motion to occur, an object must change the position which it occupies. Consider an example of an arrow in flight. In any one (duration-less) instant of time, the arrow is neither moving to where it is, nor to where it is not. It cannot move to where it is not, because no time elapses for it to move there; it cannot move to where it is, because it is already there. In other words, at every instant of time there is no motion occurring. If everything is motionless at every instant, and time is entirely composed of instants, then motion is impossible.

Use your knowledge of limits to explain these apparent contradictions.

## NCEA Level 3 Calculus (Differentiation)

### 2. Limits (Homework)

#### Reading

You may be wondering why we bother introducing the concept of limits: after all, we are simply replacing one handwavy picture-based definition (that of the derivative) with another! I will give the answer in two parts:

1. Limits are a more general and hence more useful concept; and
2. It is much easier to formally define a limit than a derivative.

#### Limits are more general

The obvious use of limit notation this year is to ‘plug gaps’ in functions; however, we can also (as you have seen) take limits of things towards infinity. This allows us to formalise things like infinite sums: we define the value of an infinite sum to be a special kind of limit.

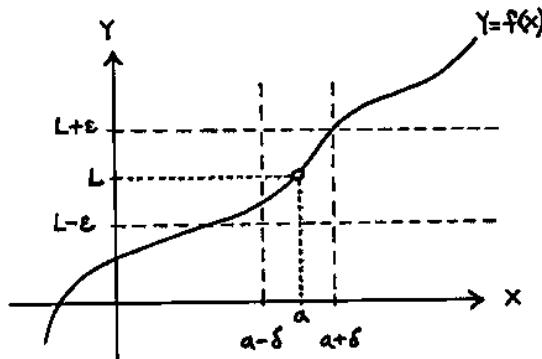
Limiting situations come up surprisingly often in physics and chemistry as well, if we want to look at the behaviour of a system in the long term: say the concentration of a particular compound in solution can be modelled by  $C(t) = \frac{k}{t^2}$ ; then, if we wait a long time (i.e. let  $t \rightarrow \infty$ ), we predict that the concentration becomes negligible.

#### It is easier to formally define a limit

Suppose that we have some function  $f$  such that

$$\lim_{x \rightarrow a} f(x) = L.$$

All we are saying here is (intuitively) that we can make the value of  $f$  as close as we like to being  $L$ , by taking  $x$  to be sufficiently close to  $a$ . I will not state the formal definition here (it is easy enough to find), except to state that it is a little stricter than this intuitive statement suggests (i.e. for all  $x \neq a$  within the interval  $(a - \delta, a + \delta)$  we must have  $f(x)$  be within  $(L - \varepsilon, L + \varepsilon)$ ).



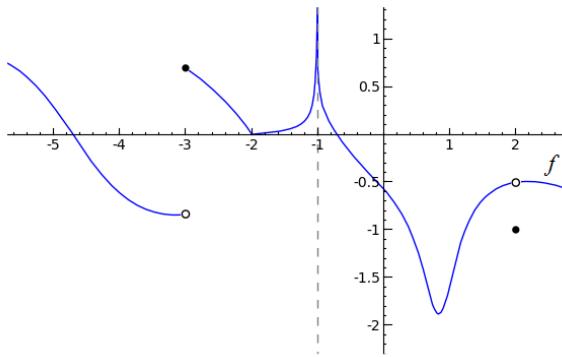
## Questions

Derivatives and limits allow us to classify functions and their behaviour. Consider the following:

### Properties of Functions

- A function is **increasing** if its derivative is positive.
- A function is **decreasing** if its derivative is negative.
- A function is **concave down** if its derivative is decreasing.
- A function is **concave up** if its derivative is increasing.
- A function  $f$  is **continuous** at a point  $a$  if  $\lim_{x \rightarrow a} f(x) = f(a)$ .

1. Describe all the function properties given above geometrically, and give an example of each.
2. Consider the function graphed below.



- (a) Find  $\lim_{x \rightarrow -2} f(x)$  and  $\lim_{x \rightarrow 2} f(x)$ .
- (b) Does  $\lim_{x \rightarrow -3} f(x)$  exist? Why/why not?
- (c) Does  $\lim_{x \rightarrow 0} f(x)$  exist? Why/why not?
- (d) On what intervals is  $f(x)$  continuous?
- (e) At what points is  $f(x)$  not differentiable?
3. On an axis, sketch a graph of some function  $f$  that has the following features:
  - Is continuous for  $0 < x < 5$  and  $5 < x < 9$  and is discontinuous when  $x = 5$
  - Is concave down ( $f''(x) < 0$ ) for  $0 < x < 5$
  - Has  $f'(x) = 0$  at  $(3, 8)$
  - Has  $\lim_{x \rightarrow 5} f(x) = 6$ .
  - Is not differentiable at  $(7, 3)$ .

## NCEA Level 3 Calculus (Differentiation)

### 3. Derivatives of Common Functions

Now that we understand the purpose and form of the derivative, we can begin to calculate the derivatives of some common functions. We list them here without proving them; all the proofs are reasonably short and can be found in the calculus notes.

Function	Derivative
$x^n$	$nx^{n-1}$
$e^x$	$e^x$
$\ln x $	$\frac{1}{x}$
$\sin x$	$\cos x$
$\cos x$	$-\sin x$
$\tan x$	$\sec^2 x$
$\csc x$	$-\csc x \cot x$
$\sec x$	$\sec x \tan x$
$\cot x$	$-\csc^2 x$

Today, we also introduce several rules for finding the derivative of a more complicated function in terms of the derivatives of component functions. Let  $f$  and  $g$  be functions, and let  $\lambda$  be a real constant. Then:

$$\begin{aligned} (\lambda)' &= 0 \\ (\lambda f)' &= \lambda f' \\ (f + g)' &= f' + g'. \end{aligned}$$

In particular, the derivative is *linear*: that is, for functions  $f, g$  and real constants  $\alpha, \beta$  we have  $(\alpha f + \beta g)' = \alpha f' + \beta g'$  (formally, the derivative is a linear transformation from the vector space of differentiable functions to the vector space of real-valued functions).

Note that the obvious product rule,  $(fg)' = f'g'$  does **not** hold. We will discuss this further soon, although it should be noted that Leibniz initially believed this rule to be true! A counterexample is outlined in the exercises for you to work out.

## Questions

1. A Find the derivatives of  $3x^3$ ,  $2x^2$ , and  $6x^5$ . Conclude that  $(fg)' \neq f'g'$  in general.
2. A Find the derivatives of the following functions with respect to  $t$ :
  - (a)  $y = 2t^3 + 3t^2$
  - (b)  $y = \sqrt{t}$
  - (c)  $y = (2t+1)(t-4)$
  - (d)  $g(t) = 4 \sec t + 9 \tan t$
  - (e)  $h(t) = \sqrt[5]{t} + 2 \csc t - \ln t^3$
  - (f)  $\phi'(t) = \csc x + 12x^{1273} + 9$
  - (g)  $y = 2017t^{2016} + (t+2)^2$
  - (h)  $y = 940 \sin t + \frac{1}{2}e^{t+2}$
3. A Where is the function  $x \mapsto x^3 - 2x^2 - x + 1$  increasing?
4. A Find the slope of the tangent line to  $y = e^x - \sin x$  at  $x = 2\pi$ .
5. A Find the slope of the tangent line to  $y = x + \tan x$  at  $(\pi, \pi)$ .
6. A Compute the derivative of  $\ln x^2$ .
7. A Differentiate  $\tan x \cot x \sin x$ .
8. A True or false: if  $f(x)$  is a cubic polynomial, then  $f'(x)$  is a quadratic polynomial.
9. A Suppose the derivative of a function is  $\frac{dy}{dx} = 3x^2 - x - 4$ . What could the original function be?
10. M Find the 64th derivative of  $\sin x$ .
11. M Find the  $n$ th derivative of  $x^n$ .
12. M If  $y = 2 \sin 3x \cos 2x$ , find  $\frac{dy}{dx}$ . (Hint: use an identity to rewrite this as a sum of functions)
13. M For which values of  $x$  does the graph of  $f(x) = x + 2 \sin x$  have a horizontal tangent?
14. E Show that  $y = 6x^3 + 5x - 3$  has no tangent line with a slope of 4.
15. E Find real values of  $\alpha$  and  $\beta$  such that, if  $y = \alpha \sin x + \beta \cos x$ , then  $y'' + y' - 2y = \sin x$ .
16. E Consider a 12 m long ladder leaning against a wall such that the top of the ladder makes an angle  $\theta$  with the wall. If this angle  $\theta$  is varied, the distance  $D$  between the bottom of the ladder and the wall also changes. If  $\theta = \pi/3$ , what is the rate of change of  $D$  with respect to  $\theta$ ?
17. E Prove that the function  $\varphi$  given by
 
$$\varphi(x) = x^{101} + x^{51} + x + 1$$
 has no extreme values.
18. (a) A The area of a circle of radius  $r$  is  $A = \pi r^2$ . Find  $\frac{dA}{dr}$ . What do you notice?
  - (b) M Explain part (a) geometrically.
  - (c) E The volume of a sphere is given by  $V = \frac{4}{3}\pi r^3$ . Find an expression for the surface area.
19. E Calculate  $\frac{dy}{dx}$  if  $y = \log_{10} x$ .

## NCEA Level 3 Calculus (Differentiation)

### 3. Derivatives of Common Functions (Homework)

#### Reading

Mathematics is fantastic. It is a subject where we do not have to take anyone's word or opinion. The truth is not determined by a higher authority who says 'because I say so', or because they saw it in a dream, the pixies at the bottom of their garden told them, or it came from some ancient mystical tradition. The truth is determined and justified with a mathematical proof.

A proof is an explanation of why a statement is true. More properly it is a convincing explanation of why the statement is true. By convincing I mean that it is convincing to a mathematician. (What that means is an important philosophical point which I am not going to get into; my interest is more in practical matters.)

Statements are usually proved by starting with some obvious statements, and proceeding by using small logical steps and applying definitions, axioms and previously established statements until the required statement results.

The mathematician's concept of proof is different to everyday usage. In everyday usage or in court for instance, proof is evidence that something is likely to be true. Mathematicians require more than this. We like to be 100% confident that a statement has been proved. We do not like to be 'almost certain'.

Having said that, how confident can we be that a theorem has been proved? Millions have seen a proof of Pythagoras' Theorem; we can be certain it is true. Proofs of newer results, however, may contain mistakes. I know from my own experience that some proofs given in books and research journals are in fact wrong.

From *How to Think Like a Mathematician*, by Kevin Houston.

**Theorem.** Suppose  $f$  and  $g$  are functions which are differentiable at some point  $x$ , and suppose that  $\lambda$  is a real constant. Then:

1.  $(\lambda)'(x) = 0$ ,
2.  $(f + g)'(x) = f'(x) + g'(x)$ , and
3.  $(\lambda f)'(x) = \lambda f'(x)$ .

*Proof.* We prove these using the properties of the limits.

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

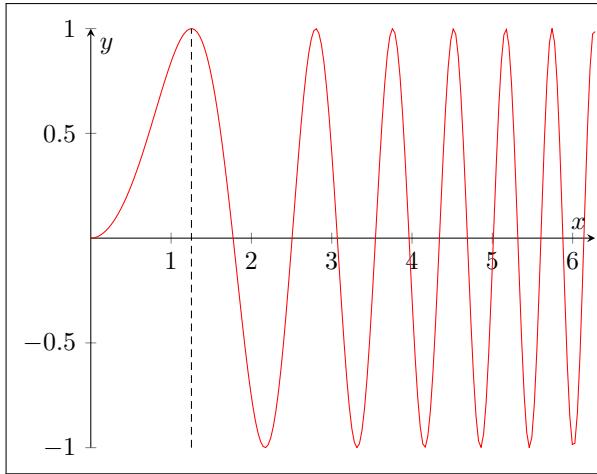
□

**Questions**

1. Differentiate with respect to  $x$ :
  - (a)  $x^2 + \ln x$
  - (b)  $tx^t$
  - (c)  $\sin x - \cos x$
  - (d)  $\sqrt[5]{x^4}$
2. Explain why you cannot use the power rule to find the derivative of  $x^x$ .
3. Find the  $n$ th derivative of  $\frac{1}{x^n}$ .
4. (More difficult!) Suppose a population grows exponentially with time, such that after  $t$  years the population  $P = P_0 + 10^t$ .
  - (a) Given that the derivative of  $e^{cx}$  is  $ce^{cx}$  when  $c$  is constant, find the rate of change of the population at  $t = 100$ .
  - (b) Explain why this population model is unrealistic.

## NCEA Level 3 Calculus (Differentiation)

### 4. The Chain Rule



Consider the function  $x \mapsto \sin(x^2)$ . This function is made up of two functions, applied one after the other:

$$x \xrightarrow{f} x^2 \xrightarrow{g} \sin(x^2).$$

We often denote this *function composition* as  $g \circ f$  (note that we evaluate from the right, so  $(g \circ f)(x) = g(f(x))$ ).

Obviously the derivative of  $\sin(x^2)$  is not just  $\cos(2x)$ , since the former has a stationary point at  $x = \sqrt{\frac{\pi}{2}}$  but  $\cos(\sqrt{2\pi}) \neq 0$ . This shows us that, in general, the derivative of a function composition is not simply the composition of the derivatives.

In fact, it turns out that the derivative of  $f \circ g$  is  $g'(f' \circ g)$ ; in other words,

$$\frac{d}{dx} f(g(x)) = g'(x)f'(g(x)).$$

This is known as the *chain rule*, since we are "chaining" together functions.

**Example.** The correct derivative of  $\sin(x^2)$  is  $2x \cos(x^2)$ .

**Example.** If  $f(r) = \sqrt{r^2 - 3}$ , then  $f'(r) = 2r^{\frac{1}{2}}(r^2 - 3)^{-\frac{1}{2}} = \frac{r}{\sqrt{r^2 - 3}}$ .

**Example.** If  $g(x) = \sin((\sin^7 x^7 + 1)^7)$ , then we compute:

$$\begin{aligned} g(x) &= \sin \left( \left[ (\sin x^7)^7 + 1 \right]^7 \right) \\ g'(x) &= 7x^6 \cdot \cos x^7 \cdot 7 \left( \sin x^7 \right)^6 \cdot 7 \left[ (\sin x^7)^7 + 1 \right] \cdot \cos \left( \left[ (\sin x^7)^7 + 1 \right]^7 \right) \end{aligned}$$

This result can probably be simplified, however the point is to evaluate the derivative chain from inside to outside in a systematic fashion.

**Example.** One of the main uses of the chain rule is in related rates problems. For example, consider a disc of radius  $r$ . The area of this disc is given by  $A = \pi r^2$ , and so  $\frac{dA}{dr} = 2\pi r$ . But what if  $r$  is itself changing with respect to time, say at a rate of  $3 \text{ m s}^{-1}$ ? Then  $\frac{dA}{dt} = \frac{dr}{dt}(2\pi r) = 6\pi r = 6\pi(r_0 + 3t)$  (where  $r_0$  is the radius at  $t = 0$ ).

## Questions

1.  A Identify the inner and outer functions, but do not attempt to differentiate.
  - (a)  $\sqrt{\sin x}$
  - (b)  $\sin \cos \tan x$
  - (c)  $(2x + 3)^{17}$
  - (d)  $97(x + 2)^2$
  - (e)  $\ln \sin x$
  - (f)  $\frac{1}{\sqrt{23x - x^2}}$
2.  A Differentiate with respect to  $t$ :
  - (a)  $(2t + 3)^{3000}$
  - (b)  $\sin \ln t$
  - (c)  $\sqrt{t^3 + 10t^2 + 3}$
  - (d)  $\csc e^t$
  - (e)  $\sin^3 t + 14 \ln(3t)$
  - (f)  $\sin \sin \sin t$
  - (g)  $\cot(t + \sec t)$
  - (h)  $\sin^2((t + \sin t)^2)$
  - (i)  $\ln \sqrt{t + 9}$
  - (j)  $\sqrt{t} + \frac{1}{\sqrt[3]{t^4}}$
  - (k)  $e^{\sec(t^2)}$
  - (l)  $\sin \sqrt{t + \tan t}$
3.  A The derivative of a function is  $2 \cos 2x$ . What could the original function be?
4.  M Differentiate  $y = \sin^2 x + \cos^2 x$ , and hence prove that  $\sin^2 x + \cos^2 x = 1$ .
5.  A Suppose that the displacement of a particle on a vibrating spring is given by  $x(t) = 5 + \frac{1}{8} \sin(5\pi t)$ , where  $x$  is measured in centimetres and  $t$  in seconds.
  - (a) Find the velocity of the particle at time  $t$ .
  - (b) At which times is the particle momentarily stationary?
6. The volume of a spherical balloon at a time  $t$  is given by  $V(t)$ , and its radius is given by  $r(t)$ .
  - (a)  A What do the derivatives  $\frac{dV}{dt}$  and  $\frac{dV}{dr}$  represent?
  - (b)  M The volume of a sphere of radius  $r$  is  $V_{\text{sphere}} = \frac{4}{3}\pi r^3$ . Find  $\frac{dV}{dt}$  in terms of  $\frac{dr}{dt}$ .
7.  M If  $F(x) = f(3f(4f(x)))$ , where  $f(0) = 0$  and  $f'(0) = 2$ , find  $F'(0)$ .
8.  A Suppose  $f(x) = g(x + g(a))$  for some differentiable function  $g$  and constant  $a$ . Find  $f'(x)$ .

9. The depth of water at the end of a jetty in a harbour varies with time due to the tides. The depth of the water is given by the formula

$$W = 4.5 - 1.2 \cos \frac{\pi t}{6}$$

where  $W$  is the water depth in metres, and  $t$  is the time in hours after midnight.

- (a) A What is the rate of change of water depth 5 hours after midnight?
  - (b) M When is the first time after  $t = 0$  that the tide changes direction?
  - (c) E At that time, is the water changing from rising to falling or from falling to rising?
10. Consider the function  $\psi$  given by

$$\psi(t) = \frac{e^t + e^{-t}}{2}$$

- (a) A Compute  $\psi'$ .
  - (b) M Find  $\psi^{(2017)}$  (the 2017th derivative of  $\psi$ ).
  - (c) A Show that  $\psi$  satisfies the differential equation  $\frac{d}{dt}(\psi + \psi') = \psi + \psi'$ .
11. The force  $F$  (in newtons) acting at an angle  $\theta$  with the horizontal that is needed to drag a mass of  $W$  kilograms along a horizontal surface at a constant velocity is given by

$$F = \frac{\mu W}{\cos \theta + \mu \sin \theta}$$

where  $\mu$  is the coefficient of static friction (a constant).

- (a) A If  $W = 200$  kg and  $\mu = 0.2$ , find  $\frac{dF}{d\theta}$  when  $\theta = \frac{\pi}{6}$  rad.
  - (b) M Suppose now that  $\theta$  is a function of time, so that  $\frac{d\theta}{dt} = 0.5$  rad/s. Find  $\frac{dF}{dt}$ .
12. E Prove that

$$\frac{d}{dx} |x| = \frac{x}{|x|}.$$

[Hint: Write  $|x| = \sqrt{x^2}$ .]

## NCEA Level 3 Calculus (Differentiation)

### 4. The Chain Rule (Homework)

#### Reading

Suppose we have the function  $y = \sin(x^2)$  which we saw in the tutorial. Consider what happens if we let  $x$  change by a small amount, to  $x + dx$ . Then  $y$  will change to  $y + dy$ , and we have

$$y + dy = \sin((x + dx)^2) = \sin(x^2 + 2x dx + dx^2).$$

Let's let  $dx$  become really small; so  $dx^2$  becomes even smaller. In fact, we will take  $dx$  to be so small that  $dx^2 \rightarrow 0$ . Then we can basically ignore it, and continue computing:

$$\sin(x^2 + 2x dx + dx^2) = \sin(x^2 + 2x dx) = \sin(x^2) \cos(2x dx) + \cos(x^2) \sin(2x dx).$$

Now, when  $t$  is small,  $\sin(t) \approx t$ . Similarly,  $\cos(t) \approx 1$ . Since  $dx$  is small, we apply these approximations:

$$\sin(x^2) \cos(2x dx) + \cos(x^2) \sin(2x dx) = \sin(x^2) + 2x dx \cos(x^2).$$

But recall that this is equal to  $y + dy$ ; so

$$\begin{aligned} y + dy &= \sin(x^2) + 2x dx \cos(x^2) \\ dy &= 2x dx \cos(x^2) \\ \frac{dy}{dx} &= 2x \cos(x^2). \end{aligned}$$

Note that this computation is most definitely **not rigorous** — we don't justify why we can ignore  $dx^2$  but not  $dx$ , and we don't define what it even means to be "small enough to ignore"! However, it does at least suggest that, intuitively, the chain rule does what we expect it to do.

This calculation can be made rigorous if we define infinitesimals and rules for calculating with them, and this branch of mathematics is known as non-standard analysis. However, for the remainder of this year we will continue to base our discussions of calculus on limits and inequalities because they are easier to make rigorous, despite the initial barriers to intuition.

#### Questions

1. If  $y = \sqrt{\cot x} - \sqrt{\cot a}$  (where  $a$  is constant), find  $\frac{dy}{dx}$ .
2. (a) Show that if  $y = f(g(h(x)))$  then  $\frac{dy}{dx} = h'(x) \cdot g'(h(x)) \cdot f'(g(h(x)))$ .  
 (b) Calculate the derivative of  $y = \sin \cos \sin \cos \sin x^5$ .
3. We will prove the double angle formula for cosine from the double angle formula for sine. Suppose  $f(\theta) = \cos 2\theta$ , and  $g(\theta) = 1 - 2 \sin^2 \theta$ .
  - (a) Show that  $f' = g'$ . (You may assume that  $\sin 2\theta = 2 \sin \theta \cos \theta$ .)
  - (b) Verify that  $f$  and  $g$  agree at  $\theta = 0$ , and conclude that  $f = g$ .

## NCEA Level 3 Calculus (Differentiation)

### 5. The Product and Quotient Rules

Two weeks ago we saw that the derivative of a product is not simply the product of the derivatives; for example, take  $(x)(x)$ . If we differentiate each term and multiply, we obtain 1; however, the derivative of  $x^2$  is (of course)  $2x$ .

Suppose  $f$  and  $g$  are functions; then the *real* product rule is

$$(fg)' = gf' + fg'.$$

**Example.** Consider  $y = 2t \sin t$ . Then  $\frac{dy}{dt} = 2 \sin t + 2t \cos t$ .

We can also write a rule for the derivative of a quotient of functions. You will be asked to prove it as an exercise, using the product rule.

$$\left(\frac{f}{g}\right)' = \frac{gf' - fg'}{g^2}$$

**Example.** Consider  $f(s) = \sqrt{\frac{s^2+1}{s^2+4}}$ . Then

$$\begin{aligned} f'(s) &= \frac{d}{ds} \left[ \frac{s^2+1}{s^2+4} \right] \cdot \frac{1}{2\sqrt{\frac{s^2+1}{s^2+4}}} \\ &= \frac{(s^2+4)(2s) - (s^2+1)(2s)}{(s^2+4)^2} \cdot \frac{\sqrt{s^2+4}}{2\sqrt{s^2+1}} \\ &= \frac{6s}{(s^2+4)^{\frac{3}{2}}(s^2+1)^{\frac{1}{2}}} \end{aligned}$$

## Questions

1. **A** In each case, find  $\frac{dy}{dt}$ .
- (a)  $y = (3 + 2t^2)^4$
  - (b)  $y = \frac{t^3}{\ln t}$
  - (c)  $y = t\sqrt{t}$
  - (d)  $y = 2t \sin t - (t^2 - 2) \cos t$
  - (e)  $y = \frac{t}{\sqrt{a^2 - t^2}}$  (*a* constant)
  - (f)  $y = \frac{1}{8}t^8(1 - t^2)^{-4}$
  - (g)  $y = e^t \ln t$
  - (h)  $y = \log \left[ 1 + \frac{t^2 + 3t + 17}{t^{17}} \right]$
  - (i)  $y = \sin [e^{\tan t} \ln \tan t]$
  - (j)  $y = \frac{3t - 2}{\sqrt{2t+1}}$
  - (k)  $y = \frac{\sec 2t}{1 + \tan 2t}$
  - (l)  $y = \frac{(t-1)(t-4)}{(t-2)(t-3)}$
  - (m)  $y = t \sin^2(\cos \sqrt{\sin \pi t})$
  - (n)  $y = \sqrt[5]{t \tan t}$
  - (o)  $y = \frac{(t + \lambda)^4}{t^4 + \lambda^4}$
2. **A** If  $f(x) = e^{-x}$ , find  $f(0) + xf'(0)$ .
3. **M** Suppose  $f$  and  $g$  are functions ( $g$  not the zero function). Write  $\frac{f}{g} = fg^{-1}$  and prove the quotient rule from the product rule.
4. **M** Show that if  $f$ ,  $g$ , and  $h$  are functions then  $(fgh)' = f'gh + fg'h + fgh'$ .
5. **E** Suppose  $f(x) = f(-x)$  for all  $x$  in the domain of  $f$ . Prove that  $f'(x) = f'(-x)$  for all  $x$  in the domain of  $f'(x)$ .
6. **E** Consider the function defined by  $f(x) = x^x$ .
- (a) Rewrite  $f$  in the form  $f(x) = e^{x \ln x}$ , and hence find  $f'(x)$ .
  - (b) Find  $\frac{dy}{dt}$  if  $y = (t^2 + 3)^{(t^2 + 3)}$ .
7. **E** A circle that closely fits points on a local section of a curve can be drawn for any continuous curve. The radius of curvature of the curve is defined as the radius of the approximating circle, which changes as we move around the curve.
- $$\text{radius of curvature} = \frac{\left[ 1 + \left( \frac{dy}{dx} \right)^2 \right]^{\frac{3}{2}}}{\left| \frac{d^2y}{dx^2} \right|}$$
- Find the radius of curvature of the curve  $y = e^{-x} \sin x$  at the point  $(0, 0)$ .
8. **M** Show that  $y = xe^{-x}$  satisfies the differential equation  $xy' = (1 - x)y$ .
9. **M** If  $y = \ln \frac{1+\sqrt{\sin x}}{1-\sqrt{\sin x}}$ , find  $y''$ .
10. **M** Find the equation of the tangent line to the graph of  $y = \ln \cos \frac{x-1}{x}$  at the point  $(1, 0)$ .
11. **M** Show that  $y = (1 + x + \ln x)^{-1}$  satisfies the differential equation  $xy' = y(y \ln x - 1)$ .
12. **E** Find the angle at which  $y = x^2 \ln[(x - 2)^2]$  cuts the  $x$ -axis at the point  $(0, 0)$ .
13. **M** When  $x = 0$ , is the curve  $y = (x + 20)^2(2x^2 - 3)^6 - \ln \sin(x - \frac{\pi}{2})$  concave up or concave down?
14. **M** If  $y = \frac{e^x}{\sin x}$ , show that  $\frac{dy}{dx} = y(1 - \cot x)$ .

## NCEA Level 3 Calculus (Differentiation)

### 5. The Product and Quotient Rules (Homework)

#### Reading

Even next year, when you will be expected to know the derivative rules, it is not necessary to remember the quotient rule because it is just a special case of the product rule. However, here is a little rhyme:

*If it's the quotient rule you wish to know,  
It's low-de-high less high-de-low.  
Then draw the line and down below,  
Denominator squared will go.\**

#### Questions

1. Find the derivatives:

- (a)  $\frac{dy}{dx}$  if  $y = \sin x \ln x$ .
- (b)  $\frac{dy}{dx}$  if  $y = x \sec kx$  ( $k$  constant).
- (c)  $\frac{df}{d\theta}$  if  $f(\theta) = \frac{\cos \pi\theta}{\sin \pi\theta + \cos \pi\theta}$ .
- (d)  $\frac{dy}{dt}$  if  $y = \cos^4(\sin^3 t)$ .

2. The force  $F$  acting on a body with mass  $m$  and velocity  $v$  is the rate of change of momentum,  $F = \frac{d}{dt}[mv]$ . If  $m$  is constant, this becomes  $F = ma$ , where  $a = \frac{dv}{dt}$  is the acceleration of the body. However, due to relativistic effects, the mass of a particle varies with  $v$  as

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}},$$

where  $m_0$  is the rest mass of the body and  $c$  is the speed of light. Show that

$$F = \frac{m_0 a}{\left(1 - \frac{v^2}{c^2}\right)^{\frac{3}{2}}}.$$

3. Recall that if  $\theta$  is given in degrees, then  $\frac{\pi\theta}{180}$  is the equivalent angle in radians. Find the derivative of  $\sin \theta$  if  $\theta$  is given in degrees.

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\*Quoted in *Mathematical Apocrypha* by Steven G. Krantz (p.36).

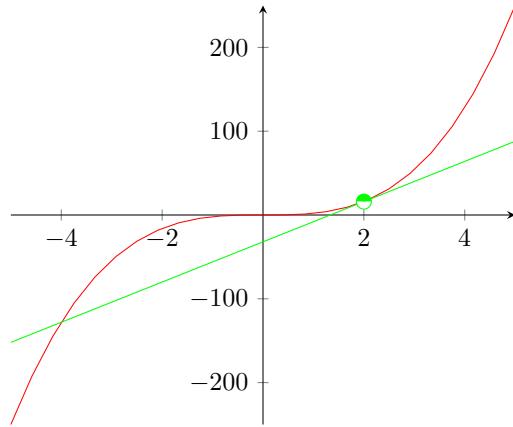
## NCEA Level 3 Calculus (Differentiation)

### 6. Tangent and Normal Lines

Last year, we defined the tangent line of a function at a point to be the unique line passing through that point such that the line has the same slope as the function at that point. More formally, if we have some function  $f$  which is differentiable at a point  $(x_0, y_0)$  then the tangent line to the function at that point is

$$(y - y_0) = f'(x_0)(x - x_0).$$

**Example.** Consider  $f : x \mapsto 2x^3$ . Then  $f' : x \mapsto 6x^2$ , and the tangent line to the function at  $(2, 16)$  is  $(y - 16) = 24(x - 2)$ , or in slope-intercept form  $y = 24x - 32$ .

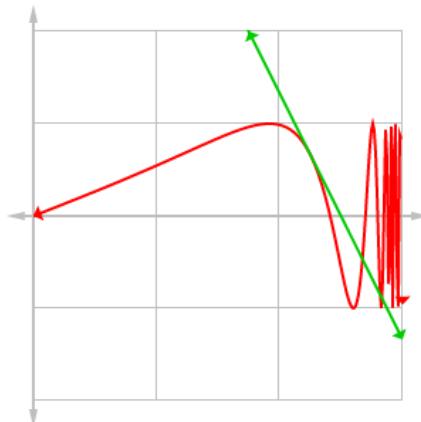


The tangent line of a function at a point is the best linear approximation to the function at that point.

We further defined the normal line of a function at a point to be the unique line passing through the point at right angles to the tangent line. If the gradient of the tangent line is  $m$ , then the gradient of the normal line is  $m^\perp = -\frac{1}{m}$ .

**Example.** The slope of the normal line of the function  $f$  defined above at the given point is  $-\frac{1}{24}$ .

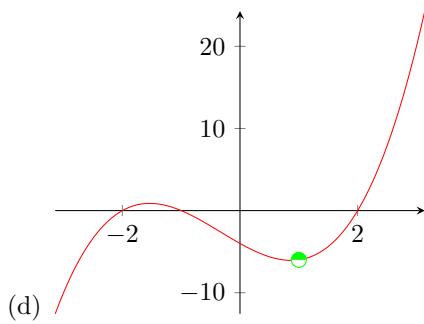
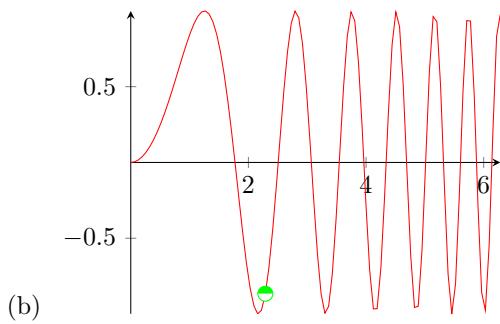
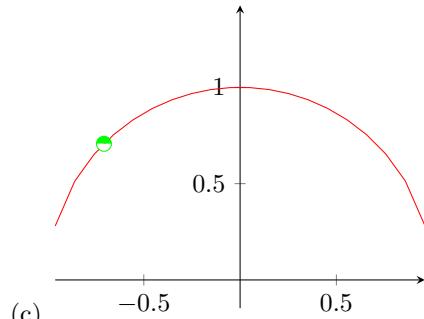
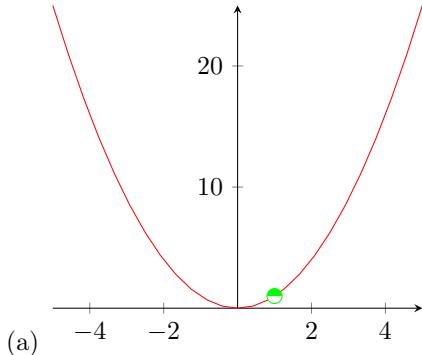
**Example.** Consider the function  $y = \sin \tan x$ . The derivative of this function is  $y' = \sec^2 x \cos \tan x$ ; at the point  $P(\frac{3\pi}{8}, 0.6649)$ , the slope is  $-5.1$ .



The tangent line at  $P$  is  $y = \sin(\sqrt{2} + 1) + \cos(\sqrt{2} + 1)((\sqrt{2} + 1)^2 + 1)(x - \frac{3\pi}{8})$ , or (approximately)  $y = -5.1(x - 1.178) + 0.6649$ .

## Questions

1. A Draw the tangent and normal lines to each function at the indicated points.



2. A When is the tangent line a good approximation to a function?

3. M Find the tangent and normal lines to the following functions at the given points.

- (a)  $x \mapsto \sin x$  at  $(0, 0)$
- (b)  $x \mapsto \sin x$  at  $(\pi, 0)$
- (c)  $x \mapsto e^x$  at  $(0, 1)$
- (d)  $x \mapsto \sec x$  at  $(0, 0)$
- (e)  $x \mapsto x^2$  at  $(1, 1)$
- (f)  $x \mapsto \sqrt{x}$  at  $(1, 1)$
- (g)  $x \mapsto (x^4 - 3x^2 + 5)^3$  at  $(0, 125)$
- (h)  $x \mapsto \cos \tan x$  at  $(\pi, 1)$
- (i)  $x \mapsto (x + \frac{1}{x^2})^{\sqrt{7}}$  at  $(1, 2^{\sqrt{7}})$ .

4. S Consider the surface  $S : (x, y) \mapsto z = x^2 + 2 \sin(y^2 + 1) + 2$ .

- (a) Differentiate  $S$  with respect to  $x$ , and find the tangent line in the  $x$  direction at  $(0, 0)$ .
- (b) Differentiate  $S$  with respect to  $y$ , and find the tangent line in the  $y$  direction at  $(0, 0)$ .
- (c) Hence describe the tangent *plane* of the surface  $S$  at  $(0, 0)$ .

5. M Find the equation of the tangent line to  $y = x + \tan x$  at  $(\pi, \pi)$ .

6. M Find an equation for the normal line to the curve  $y = \frac{1}{\sqrt{x^2 - x}}$  at  $(2, \frac{1}{\sqrt{2}})$ .

7. Consider the curve  $y = \tan(2 \sin x)$ .
- Show that  $\frac{dy}{dx} = 2 \cos x \sec^2(2 \sin x)$ .
  - Find the equation of:
    - The tangent to the curve at  $(\pi, 0)$
    - The normal to the curve at  $(0, 0)$
8. Find the best linear approximation to  $y = 3x^3 + 2x + 4$  around  $x = 2$ .
9. Find the point(s) on the graph of the function  $y = x^2$  such that the slope of the normal to the curve at that point is  $m^\perp = -1$ .
10. The tangents to the curve  $y = \frac{1}{4}(x - 2)^2$  at points  $P$  and  $Q(6, 4)$  are perpendicular. What is the  $x$ -ordinate of  $P$ ?
11. Consider the function  $y = \sin x$ .
- Find the best linear approximation to this function around  $(0, 0)$ .
  - Find the percentage error of this approximation to 1dp when  $x = \pi$ .
  - At what point on the curve ( $x \geq 0$ ) does the percentage error of the approximation rise above 100%?
12. Consider the quartic polynomial  $p(x) = 2x^4 - 4x^3 - 23x^2 + 84x - 61$ .
- Find the best linear approximation to  $p$  around the point  $(2, 15)$ .
  - Find the unique quadratic polynomial  $q(x)$  such that  $q(2) = p(2)$ ,  $q'(2) = p'(2)$ , and  $q''(2) = p''(2)$ . This is the best quadratic approximation to  $p$  at the point  $(2, 15)$ .
  - Show that the best quadratic approximation to a function  $f$  at the point  $(x_0, y_0)$  is given by

$$T_2(x) = f(x_0) + f'(x_0)(x - x_0) + \frac{1}{2}f''(x_0)(x - x_0)^2.$$

**NCEA Level 3 Calculus (Differentiation)****6. Tangent and Normal Lines (Homework)****Reading****Go and watch...**<https://www.youtube.com/watch?v=6sNeE-mMYB8>**Questions**

1. Write a definition for the normal line to a curve  $f$  at a point  $(x_0, y_0)$ .
2. Find the best linear approximation to the curve  $y = \sqrt{\cos(x + \pi)} + \sin x - e^{2(\tan x)^2}$  at the point  $(\pi, 0)$ .
3. Find a function such that the normal line to the function at  $(1, 0)$  has the equation  $y = 3x - 3$ .
4. Find a linear approximation to the curve  $y = \sqrt[3]{1 + 3x}$  around  $x = 0$ , and determine an approximate value for  $\sqrt[3]{1.03}$ .

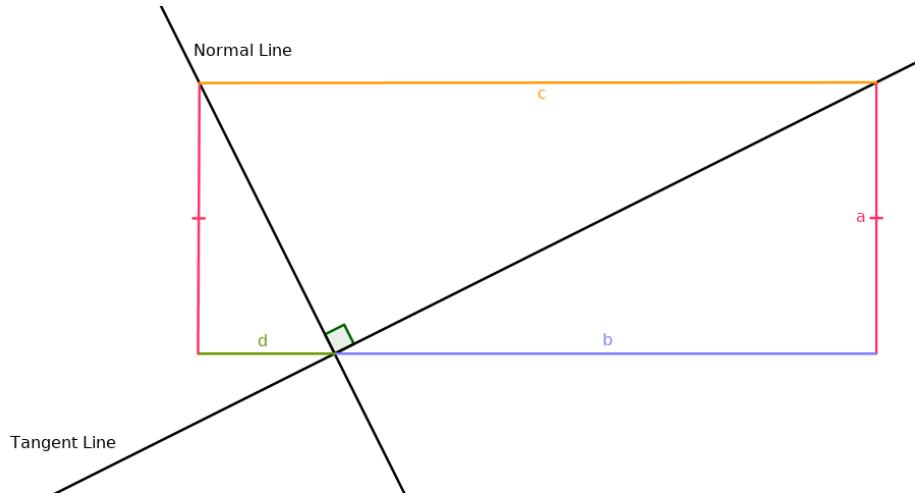


FIGURE 1. Diagram showing the various triangles used.

**Theorem.** *If a tangent line has slope  $m$ , then the normal line to it has slope  $-1/m$ .*

*Proof.* Consider the line shown in figure 1, and let  $m = \frac{a}{b}$  be the slope of the tangent line. So the length of the hypotenuse of the  $ab$  triangle is  $\sqrt{a^2 + b^2}$ . But  $c = d + b$ . Hence the length of the hypotenuse of the  $ad$  triangle can be found in two ways:

$$\sqrt{(d+b)^2 - (\sqrt{a^2 + b^2})^2} = \sqrt{a^2 + d^2}.$$

Since all the lengths are positive, we have

$$d^2 + 2db + b^2 - a^2 - b^2 = a^2 + d^2$$

and therefore

$$db = a^2 \Rightarrow \frac{d}{a} = \frac{a}{b} = m$$

So the slope of the normal line is simply  $-\frac{a}{d} = -\frac{1}{m}$ . □

## NCEA Level 3 Calculus (Differentiation)

### 7. Higher Derivatives and the Geometry of a Function

Back in the homework on limits, I gave you the following definitions:

#### Properties of Functions

- A function is **increasing** if its derivative is positive.
- A function is **decreasing** if its derivative is negative.
- A function is **concave down** if its derivative is decreasing.
- A function is **concave up** if its derivative is increasing.
- A function  $f$  is **continuous** at a point  $a$  if  $\lim_{x \rightarrow a} f(x) = f(a)$ .

**Example.** The function  $x \mapsto x^2$  is concave up everywhere.

**Example.** The function  $x \mapsto \sin x$  is concave down when  $(2n)\pi < x < (2n+1)\pi$ , and concave up when  $(2n+1)\pi < x < (2n+2)\pi$  (for all integers  $n$ ). Draw a diagram to see this.

We can tell if a function is increasing (getting larger) or decreasing (getting smaller) around a point by looking at the derivative at that point. However, in order to look for concavity we must look at the derivative of the derivative (the second derivative). If a function is concave up (curving up), the second derivative is positive; if a function is concave down at a point, then the second derivative is negative.

A point where a function changes from concave up to concave down (or vice versa) is known as an **inflection point**.

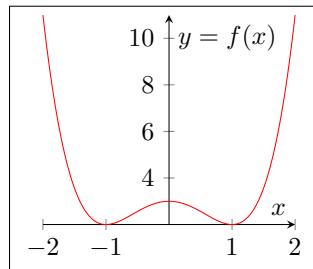
**Example.** The function  $x \mapsto x^3$  has an inflection point at  $(0,0)$ ; to the left of this point, the function is concave down (the second derivative is negative) and to the right the function is concave up (the second derivative is positive).

We call the value of the first derivative the *slope* or *gradient* of the function at a point; similarly, the second derivative measures how "curvy" a function is and we call its value the *concavity* of a function at a point.

Unfortunately, there is no nice method for checking for continuity involving the derivatives. At this level, however, it should be fairly obvious at which points a function is discontinuous.

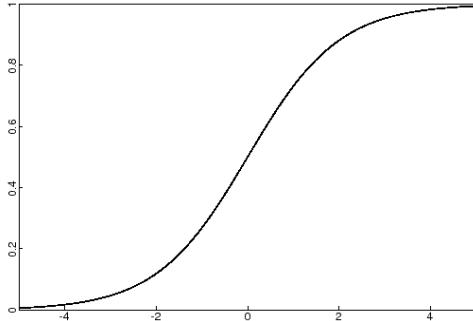
**Example. Question.** Consider the function defined by  $f(x) = x^4 - 2x^2 + 3$ . (a) Find the intervals on which  $f$  is increasing or decreasing. (b) Find the intervals of concavity and the inflection points.

**Solution.** We have  $f'(x) = 4x^3 - 4x$ . This function is zero at  $x \in \{-1, 0, 1\}$ , and so (since the function is a positive cubic)  $f$  will be decreasing when  $x < -1$ , increasing when  $-1 < x < 0$ , decreasing when  $0 < x < 1$ , and increasing when  $x > 1$ . We also have  $f''(x) = 12x^2 - 4$  and so  $f''(x) = 0$  when  $x = \pm\frac{1}{\sqrt{3}}$ . Hence the function is concave up when  $x < -\frac{1}{\sqrt{3}}$ , concave down when  $|x| < \frac{1}{\sqrt{3}}$ , and concave up when  $x > \frac{1}{\sqrt{3}}$ . The inflection points will be  $x = \pm\frac{1}{\sqrt{3}}$ .



## Questions

1.  A Find the second derivative of the following functions.
  - (a)  $y = x^2 + x$
  - (b)  $f(x) = \sin x$
  - (c)  $g(x) = \cot(3x^2 + 5)$
  - (d)  $y = \frac{\sin mx}{x}$
  - (e)  $y = 4\sin^2 x$
  - (f)  $y = \tan^2(\sin \theta)$
  - (g)  $y = \tan \sqrt{1-x}$
2.  A Find the concavity of the function  $y = \frac{x^2-1}{x^2+1}$  at  $(0, -1)$ .
3.  M Find the intervals on which the following functions are increasing or decreasing, and find their intervals of concavity.
  - (a)  $y = x^2 + 1$
  - (b)  $y = 2x^3 + 3x^2 - 36x$
  - (c)  $G(x) = x - 4\sqrt{x}$
4.  A The following function is known as the *logistic curve* and is used for population modelling. Find the intervals of concavity, and label any inflection points.



5.  M Sketch a function satisfying the given criteria.
  - (a) i. Vertical asymptote at  $x = 0$ ,
  - ii.  $f'(x) > 0$  if  $x < -2$ ,
  - iii.  $f'(x) < 0$  if  $x > -2$  ( $x \neq 0$ ),
  - iv.  $f''(x) < 0$  if  $x < 0$ ,  $f''(x) > 0$  if  $x > 0$ .
  - (b) i.  $f'(0) = f'(2) = f'(4) = 0$ ,
  - ii.  $f'(x) > 0$  if  $x < 0$  or  $2 < x < 4$ ,
  - iii.  $f'(x) < 0$  if  $0 < x < 2$  or  $x > 4$ ,
  - iv.  $f''(x) > 0$  if  $1 < x < 3$ ,
  - v.  $f''(x) < 0$  if  $x < 1$  or  $x > 3$ .

6. **S** Scholarship 2010: Recall that the points of inflection of a curve are places where the second derivative changes sign. These are typically, **but not always**, points at which the second derivative is zero.

Consider the curve  $y = \sqrt[3]{x}e^{-x^2}$ .

Write the second derivative in the form  $\frac{d^2y}{dx^2} = (ax^4 + bx^2 + x)e^{-x^2}x^{-5/3}$ , and hence find the  $x$ -ordinates of the points of inflection of the curve.

7. **S** Scholarship 2004: (You may wish to remind yourself how to perform long division of polynomials.) Consider the function

$$y = \frac{x^2}{1+x^2},$$

where  $-1 \leq x \leq 1$ . The gradient at the point  $x = 1$  is  $\frac{1}{2}$ .

Hence show that there is a point with  $\frac{1}{4} \leq x \leq \frac{1}{2}$  where the gradient is also  $\frac{1}{2}$ .

## NCEA Level 3 Calculus (Differentiation)

### 7. Higher Derivatives and the Geometry of a Function (Homework)

#### Reading



The German polymath Gottfried Wilhelm Leibniz occupies a grand place in the history of philosophy. He was, along with René Descartes and Baruch Spinoza, one of the three great 17th Century rationalists, and his work anticipated modern logic and analytic philosophy. Like many great thinkers before and after him, Leibniz was a child prodigy and a contributor in many different fields of endeavour.

But, between his work on philosophy and logic and his day job as a politician and representative of the royal house of Hanover, Leibniz still found time to work on mathematics. He was perhaps the first to explicitly employ the mathematical notion of a function to denote geometric concepts derived from a curve, and he developed a system of infinitesimal calculus, independently of his contemporary Sir Isaac Newton. He also revived the ancient method of solving equations using matrices, invented a practical calculating machine and pioneered the use of the binary system.

Like Newton, Leibniz was a member of the Royal Society in London, and was almost certainly aware of Newton's work on calculus. During the 1670s (slightly later than Newton's early work), Leibniz developed a very similar theory of calculus, apparently completely independently. Within the short period of about two months he had developed a complete theory of differential calculus and integral calculus (see the section on Newton for a brief description and explanation of the development of calculus).

Unlike Newton, however, he was more than happy to publish his work, and so Europe first heard about calculus from Leibniz in 1684, and not from Newton (who published nothing on the subject until 1693). When the Royal Society was asked to adjudicate between the rival claims of the two men over the development of the theory of calculus, they gave credit for the first discovery to Newton, and credit for the first publication to Leibniz. However, the Royal Society, by then under the rather biased presidency of Newton himself, later also accused Leibniz of plagiarism, a slur from which Leibniz never really recovered.

Ironically, it was Leibniz's mathematics that eventually triumphed, and his notation and his way of writing calculus, not Newton's more clumsy notation, is the one still used in mathematics today.

In addition to calculus, Leibniz re-discovered a method of arranging linear equations into an array, now called a matrix, which could then be manipulated to find a solution. A similar method had been pioneered by Chinese mathematicians almost two millennia earlier, but had long fallen into disuse. Leibniz paved the way for later work on matrices and linear algebra by Carl Friedrich Gauss. He also introduced notions of self-similarity and the principle of continuity which foreshadowed an area of mathematics which would come to be called topology.

From [http://www.storyofmathematics.com/17th\\_leibniz.html](http://www.storyofmathematics.com/17th_leibniz.html).

## Questions

1. Explain the geometric meaning of the second derivative.
2. Find the second derivative of the following functions.
  - (a)  $f(x) = x^5 - 5x + 3$
  - (b)  $f(x) = \frac{x^2}{x-1}$
  - (c)  $f(x) = \sqrt{x} - \sqrt[4]{x}$
3. Sketch a function satisfying the given criteria.
  - (a) (hint: your result should be an odd function)
    - i.  $f'(1) = f'(-1) = 0$ ,
    - ii.  $f'(x) < 0$  if  $|x| < 1$ ,
    - iii.  $f'(x) > 0$  if  $1 < |x| < 2$ ,
    - iv.  $f'(x) = -1$  if  $|x| > 2$ .
  - (b) i.  $f'(x) < 0$ ,  
ii.  $f''(x) < 0$ .

## NCEA Level 3 Calculus (Differentiation)

### 8. Optimisation

Recall from Level 2 that a *local maximum* of a function  $f$  is some point  $(x, f(x))$  such that, for a sufficiently small interval  $I$  around  $x$ , for all  $y \in I$   $f(y) \leq f(x)$ ; a *local minimum* is defined in a similar way (see exercises).

**Example.** The function  $x \mapsto x^2$  has a local minimum at  $(0, 0)$ .

**Example.** The function  $x \mapsto 2x^3 + 15x^2 + 36x + 2$  has a local maximum at  $(-3, -25)$  and a local minimum at  $(-2, -26)$ .

**Example.** The function  $x \mapsto \sin x$  has a local maximum at  $(2n\pi + \frac{\pi}{2}, 1)$  for every  $n \in \mathbb{Z}$ , and a local minimum at  $(2n\pi - \frac{\pi}{2}, 1)$  for every  $n \in \mathbb{Z}$ .

Local extrema are also sometimes called *relative extrema*.

It is possible to prove that if  $f$  is defined around some value  $x$ , if  $f$  has a relative extremum at  $(x, f(x))$ , and if  $f'$  is defined at  $x$ , then  $f'(x) = 0$  (Theorem 1.10 in the notes). Because of this, we define a *critical point* of a function  $f$  to be some value  $x$  such that either  $f'(x) = 0$ , or  $f'(x)$  is undefined. In the first case, we also call the value a *stationary point*.

**All local extrema occur at critical points, but not all critical points occur at extrema.**

**Example.** The function  $x \mapsto 2x^3 + 15x^2 + 36x + 2$  above has critical points  $x = -2$  and  $x = -3$ . Both of these are local extrema.

**Example.** The function  $x \mapsto x^3$  above has a critical point at  $x = 0$ , but does not have a local extrema there.

**Example.** The function  $x \mapsto \frac{1}{x}$  does not have a critical point at  $x = 0$ , because it is not defined there.

We can use the first derivative to classify extrema as either maxima or minima.

#### The First Derivative Test

1. Determine all critical points of  $f$ .
2. Determine the sign of  $f'(x)$  to the left and right of each critical point  $x_0$ :
  - If  $f'(x)$  changes from positive to negative as we move from left to right across  $x_0$ , then  $f(x)$  has a local maximum at  $x_0$ .
  - If  $f'(x)$  changes from negative to positive as we move from left to right across  $x_0$ , then  $f(x)$  has a local minimum at  $x_0$ .
  - If  $f'(x)$  does not change sign across  $x_0$ , then  $f(x)$  does not have a relative extremum at  $x_0$  (e.g.  $y = x^3$ ).

Recall last week's material; using the second derivative, we can come up with a second test:

#### The Second Derivative Test

1. Compute  $f'(x)$  and  $f''(x)$ .
2. Find all the stationary points of  $f$  by finding all the points  $x_0$  such that  $f'(x_0) = 0$ .
3. Determine the sign of  $f''(x)$  for each stationary point  $x_0$ :
  - If  $f''(x_0) < 0$ , then  $f(x)$  has a relative maximum at  $x_0$ .
  - If  $f''(x_0) > 0$ , then  $f(x)$  has a relative minimum at  $x_0$ .
  - If  $f''(x_0) = 0$ , then  $f(x)$  could have a relative maximum, a relative minimum, or neither.

**Example.** Find and classify the critical points of  $y = x^3 - 3x^2 + 6$ .

*Solution.* We have  $\frac{dy}{dx} = 3x^2 - 6x$  and  $\frac{d^2y}{dx^2} = 6x - 6$ . Hence the critical points are  $x = 0$  and  $x = 2$ . At the former point,  $\frac{d^2y}{dx^2} < 0$ , and so the point is a maximum; at the latter point,  $\frac{d^2y}{dx^2} > 0$  and so the point is a minimum.

**Example.** Find two numbers whose difference is 100 and whose product is a minimum.

*Solution.* Let the two numbers be  $x$  and  $x + 100$ . We wish to minimise  $y = x(x + 100)$ ; clearly  $y' = 2x + 100$ , and so  $x = 50$  is a critical point. To the left of  $x = 50$ , the derivative is negative; to the right, the derivative is positive. Hence  $x = 50$  is indeed a minimum. The two required numbers are therefore 50 and 150.

**Example.** Find and classify the critical points of  $y = (x - 1)^2 + \ln x$ .

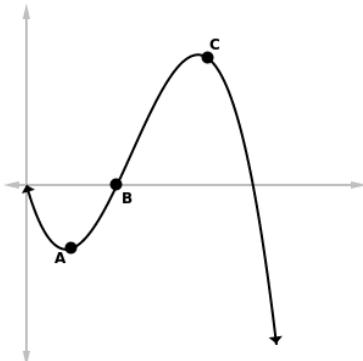
*Solution.* The derivative is  $y' = 2x - 2 + \frac{1}{x}$ . We therefore have one critical point at  $x = 0$  (where  $y'$  is undefined); this is an asymptote. Setting  $y' = 0$ , we have  $0 = 2x - 2 + \frac{1}{x} = 2x^2 - 2x + 1$  which has no real roots. Hence  $x = 0$  is the only critical point, and the curve has no local extrema.

**Example.** A rectangular plot of land is to be fenced using two varieties of fence. Two opposite sides will use fences selling for \$3 per metre, while the other two sides will use cheaper fence selling for \$2 per metre. Given that the total budget is \$1200, what is the greatest area of land which can be fenced?

*Solution.* Let  $x$  be the length of one of the expensive sides; then the length of one of the cheaper sides is  $\frac{1}{2}(1200 - 3x)$ , and the total area is  $A = \frac{1}{2}x(1200 - 3x) = \frac{1}{2}(1200x - 3x^2)$ . Hence  $\frac{dA}{dx} = 600 - 3x$ . We wish to find the maximum area, so set  $\frac{dA}{dx} = 0$ ; hence  $3x = 600$  and  $x = 200$ . Note that the second derivative is always negative, so this stationary point must be a maximum as required. The length of the other side will be  $\frac{1}{2}(1200 - 600) = 300$ , and so the maximum area is  $300 \times 200 = 60000$  square metres.

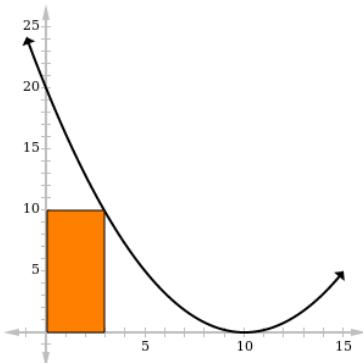
## Questions

1.  A Write down a definition of a local minimum similar to that given for a maximum.
2.  A Show that  $f(x) = x^4$  has  $f''(0) = 0$  but not a point of inflection at  $x = 0$  (in fact, it has a minimum at that point).
3.  A Describe the advantages and disadvantages of the first and second derivative tests for local extrema.
4.  M Describe the local extrema, concavity, and points of inflection of the function  $f(x) = x^4 - 4x^3$ .
5.  A Consider the following graph:



Find the signs of  $\frac{dy}{dx}$  and  $\frac{d^2y}{dx^2}$  at the three points  $A$ ,  $B$ , and  $C$ .

6.  M Find all the local extrema of the following curves in the given intervals, and classify them as maxima, minima, or neither.
  - (a)  $f(x) = \sin x - \cos x$  on the interval  $0 < x < \pi$
  - (b)  $g(x) = x^3 - x^2 + x - 1$  on the interval  $-\infty < x < \infty$
7.  M The sum of two positive numbers  $x$  and  $y$  is 16. Find the smallest possible value for  $S = x^2 + y^2$ .
8.  M A box with an open top is to be constructed from a square piece of cardboard with a side length of 3 m by cutting out a square from each of the four corners and bending up the sides. Find the dimensions of the resultant box of maximum volume.
9.  M Find the dimensions of a rectangle with area  $1000 \text{ m}^2$  such that the perimeter is minimised.
10.  E A large orange rectangle is to be drawn with one corner sitting on the origin and the opposite corner lying on the curve  $y = 0.2(x - 10)^2$ . What is the maximum possible area of the rectangle?



11. **M** A window consisting of a rectangle topped with a semicircle is to have a fixed perimeter  $p$ . Find the radius of the semicircle in terms of  $p$  if the total area is to be maximised.
12. **E** A thin wire of length  $L$  is cut in two and the resulting lengths are bent to make a square and an equilateral triangle. Where should the wire be cut to make the total area of the shapes (a) a maximum and (b) a minimum?
13. **E** Find the point on the line  $y = 2x + 3$  closest to the origin.
14. **E** Find the point on the curve  $y = \sqrt{x}$  closest to  $(3, 0)$ .
15. **M** The rate in which photosynthesis takes place for a species of phytoplankton is modeled by the function

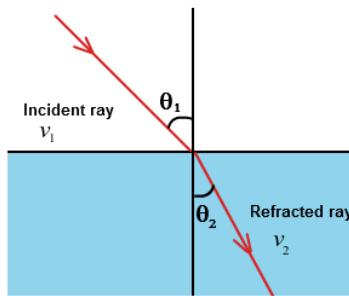
$$P = \frac{100I}{I^2 + I + 4}$$

For which light intensity  $I$  is  $P$  a maximum?

16. **E** By finding the  $x$ - and  $y$ -intercepts, the asymptotes, the critical points, the intervals of increase and decrease, the intervals of concavity, and any other important points, sketch the following functions (199):
- (a)  $f(x) = \frac{x^2}{4-x^2}$
- (b)  $f(x) = \frac{4x}{x^2+1}$  [Hint: consider what happens to  $f(x)$  as  $x \rightarrow \pm\infty$ .]
- (c)  $f(x) = \frac{x^2-4x+5}{x-2} = x - 2 + \frac{1}{x-2}$  [Hint: consider what happens to  $f(x) - (x - 2)$  as  $x \rightarrow \pm\infty$ .]
17. **E** A cone with height  $h$  is inscribed in a larger cone of height  $H$  such that the vertex of the small cone is at the centre of the base of the larger cone. Show that the maximum volume of the smaller cone occurs when  $h = \frac{1}{3}H$ .
18. **E** Let  $v_1$  be the velocity of light in air and  $v_2$  be the velocity of light in water. A ray of light will travel from a point  $A$  in the air to a point  $B$  in the water by a path  $ACB$  that minimises the time taken. Show that

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2}$$

where  $\theta_1$  is the angle of incidence and  $\theta_2$  is the angle of refraction.



19. **E** Show that the polynomial  $p(x) = 10x^3 + x^2 + x - 34$  has exactly one real zero.
20. **E** A rain gutter is to be constructed from a metal sheet of width 30 cm by bending up one third of the sheet on each side by an angle  $\theta$ . What angle should be chosen in order to obtain the maximum possible volume?
21. **E** A steel pipe is carried around a right-angled corner from a hallway 3 m wide into a hallway 2 m wide. What is the length of the longest pipe that can be carried horizontally around the corner? [Hint: this is actually a minimisation problem, despite the wording.]

22. E Find and classify the critical points of  $h(x) = x^4 + x^3 + cx^2$ .
23. S Show that  $\frac{x^2+1}{x} \geq 2$ ; hence (or otherwise) show that  $\frac{(x^2+1)(y^2+1)(z^2+1)}{xyz} \geq 8$ .
24. S Scholarship 2013: Prince Ruperts drops are made by dropping molten glass into cold water. A mathematical model for a drop as a volume of revolution uses  $y = \sqrt{\phi(e^{-x} - e^{-2x})}$  for  $x \geq 0$ , where  $\phi$  is the golden ratio  $\phi = \frac{1+\sqrt{5}}{2}$ .
- (a) Where is the modelled drop widest, and how wide is it there?
- (b) The drop changes shape at a point  $B$ , where the concavity of the function is zero. Use

$$\frac{d^2y}{dx^2} = \sqrt{\phi} \frac{e^{2x} - 6e^x + 4}{y^2 e^{4x}}$$

to find the exact  $x$ -ordinate of  $B$ .

## NCEA Level 3 Calculus (Differentiation)

### 8. Optimisation (Homework)

#### Reading

Our students are not fencing in farm fields, cutting wires and folding them, or designing windows, so they are often uninspired by the optimization problems we give them. They seem like something that "someone, somewhere" might use, but the examples feel distant.

**What are good examples of constrained optimization problems (perhaps not simple!) that today's students might actually encounter in their lives?**

#### Bad Optimization Problems

I thought that Jack M made an interesting comment about this question:

There aren't any. There may be situations where it's possible to apply optimization to solve a problem you've encountered, but in none of these cases is it honestly worth the effort of solving the problem analytically. I optimize path lengths every day when I walk across the grass on my way to classes, but I'm not going to get out a notebook and calculate an optimal route just to save myself twelve seconds of walking every morning. Mathematics beyond basic arithmetic is simply not useful in ordinary life. But I'm not sure if that's exactly what you mean. — JackM

To some extent, I agree with this comment. With few exceptions, mathematics beyond basic arithmetic is simply not useful in everyday life. Students know this, and you'll have trouble convincing them otherwise.

Because of this, I've always found "everyday"-style calculus problems a little artificial. Consider the following problem from Stewart's Calculus: Concepts and Contexts.

A fence 8 ft tall runs parallel to a tall building at a distance of 4 ft from the building. What is the length of the shortest ladder that will reach from the ground over the fence to the wall of the building?

The proper response to this question is: who cares? Is there any reason to calculate this length precisely? Why would anyone ever use calculus to compute this? If you have an actual building and an actual ladder, you could just try it and see if the ladder fits. If you don't have a specific ladder in mind (e.g. you are buying a ladder), the thing to do would be to draw the situation on paper and then use a ruler to estimate the minimum length. Of course, it's neat that you can use calculus to solve this problem precisely, but this is more of a curiosity than a legitimate application.

Chris specifically mentions the farmer fence problem, the wire-cutting problem, and the Norman window problem as not relevant to the students' lives. I agree—none of these problems are relevant. But it's not because the students aren't farmers, or wire-cutters, or architects. Even in a class full of future farmers, the fence problem would still be bad, because farmers don't use calculus to plan their fences. Good Optimization Problems

What calculus is useful for is science, economics, engineering, industrial operations, finance, and so forth. That is, it's useful for all the things that make our society run. Most students who take calculus at a university are planning to go into one of these fields, so calculus will be relevant in their lives—specifically in their future studies and in their professions.

Here's something that's closer to a real-life optimization problem:

When a critically damped RLC circuit is connected to a voltage source, the current  $I$  in the circuit varies with time according to the equation

$$I = \left( \frac{V}{L} \right) t e^{-Rt/(2L)}$$

where  $V$  is the applied voltage,  $L$  is the inductance, and  $R$  is the resistance (all of which are constant).

Suppose an RLC circuit with a resistance of  $30.0\ \Omega$  and an inductance of  $0.400\text{ H}$  is attached to a  $12.0\text{ V}$  voltage source. Find the maximum current that will occur in the circuit.

This is at least close to something that a physics or engineering student might actually come across in their future studies. It's real in a way that the farmer fence problem isn't, and even students who don't plan to study physics can sense that this is a legitimate application. (By the way, if you have good students, you might even ask them to come up with a formula for the maximum current, without giving them specific numbers for  $V$ ,  $L$  and  $R$ . This has the advantage that it can't simply be solved using a graphing calculator.)

Of course, this isn't actually a constrained optimization problem — it's just an optimization problem. I'm not actually aware of any place in science that simple constrained optimization problems arise, although there are examples from economics (maximizing utility), finance (optimal portfolios), and industrial design (e.g. shape of a can type problems). When I cover constrained optimization in calculus, I usually stick to industrial-type problems (best cans, best shipping crates/boxes, best pipeline across a river, etc.), but that's probably just because I don't know enough about economics or finance to make up problems that involve them.

Finally, I should mention that I've never found the optimization portion of Calculus I particularly compelling. It's good to introduce the idea of optimization, but setting the derivative equal to zero isn't actually a very useful optimization technique by itself. It only really works for simple formulas—for anything complicated it just replaces one essentially numerical problem (finding the maximum of a function) with another (finding roots of a function). I agree that it should be covered, but it's far from the most important application of calculus.

From <https://matheducators.stackexchange.com/questions/1550>.

## Questions

1. What is the minimum vertical distance between the parabolae  $y = x^2 + 1$  and  $y = x - x^2$ ?
2. Show that  $3x + 2 \cos x + 5 = 0$  has exactly one real root by showing that it is increasing everywhere and crosses the  $x$ -axis somewhere between two values of  $x$ .
3. Find the area of the largest rectangle that can be inscribed in the ellipse  $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$ .
4. **Scholarship practice:**  $ABCD$  is a square piece of paper with sides of length 1 m. A quarter-circle is drawn from  $B$  to  $D$  with centre  $A$ . The piece of paper is folded along  $EF$ , with  $E$  on  $AB$  and  $F$  on  $AD$ , so that  $A$  falls on the quarter-circle. Determine the maximum and minimum areas that the triangle  $AEF$  can have. (Hint: you may want to introduce a coordinate system)

## NCEA Level 3 Calculus (Differentiation)

### 9. Related Rates

We can use the chain rule to relate rates of change together — for example, the area of a circle is given by  $A = \pi r^2$  and so the rate of change of area with respect to radius  $\frac{dA}{dr} = 2\pi r$ ; but if  $r$  varies with respect to time then we can find the rate of change of the area with respect to time using the chain rule.

A useful mnemonic is

$$\frac{dx}{dy} \cdot \frac{dy}{dz} = \frac{dx}{dz}$$

although one must remember that derivatives are **not** fractions!

**Example.** A ladder 5 m long rests against a vertical wall. If the bottom of the ladder slides away from the wall at a rate of  $1 \text{ m s}^{-1}$ , how fast is the top of the ladder sliding down the wall when the bottom of the ladder is 3 m from the wall?

*Solution.* Let  $x$  be the distance of the bottom of the ladder from the wall, and let  $y$  be the height of the top of the ladder up the wall. We have  $\frac{dx}{dt} = 1$  and  $x = 3$ ; we also know that  $y = \sqrt{25 - x^2}$ , so:

$$\begin{aligned}\frac{dy}{dt} &= \frac{dy}{dx} \cdot \frac{dx}{dt} = -\frac{x}{\sqrt{25 - x^2}} \cdot 1 \\ \left. \frac{dy}{dt} \right|_{x=3} &= -\frac{3}{\sqrt{25 - 9}} = -\frac{3}{4}.\end{aligned}$$

Hence the ladder is sliding down the wall at a rate of  $-0.75 \text{ m s}^{-1}$ .

### Questions

For each of the following situations: (a) identify the quantities given in the problem; (b) identify the unknown; (c) draw a diagram; (d) write an equation relating the given quantities to an equation; (e) solve the problem.

1. **M** Each side of a square is increasing at a rate of  $6 \text{ cm s}^{-1}$ . At what rate is the area of the square increasing when the area of the square is  $16 \text{ cm}^2$ ?
2. **M** Gas is being forced into a spherical balloon at a rate of  $400 \text{ cm}^3 \text{ min}^{-1}$ . How fast is the radius of the balloon increasing when the radius is 5 cm?
3. **M** If a snowball melts so that its surface area decreases at a rate of  $1 \text{ cm}^2 \text{ min}^{-1}$ . find the rate at which the diameter decreases when the diameter is 10 cm.
4. **M** If  $W = 4H^3S$  where  $H = 3S^2 - 5$ , find  $\frac{dW}{dS}$  in terms of  $H$  and  $S$ .
5. **M** If  $x^2 + y^2 + z^2 = 9$ ,  $\frac{dx}{dt} = 5$ , and  $\frac{dy}{dt} = 4$ , find  $\frac{dz}{dt}$  when  $(x, y, z) = (2, 2, 1)$ .
6. **E** The demand for an article varies inversely as the  $\frac{5}{2}$  power of the selling price (i.e. if  $x$  is the number of articles sold and  $p$  is the price then  $x = p^{-5/2}$ ). If the manufacture cost of one article is \$1, determine the selling price which will produce the greatest profit.
7. **E** A particle moves along the curve  $y = 2 \sin(\pi x/2)$ . As the particle moves through the point  $(1/3, 1)$ , its  $x$ -ordinate increases at a rate of  $\sqrt{10} \text{ cm s}^{-1}$ . How fast is the distance from the particle to the origin changing at this instant?
8. **M** Gravel is dumped from a conveyor belt at a rate of  $3 \text{ m}^3 \text{ min}^{-1}$ , and forms a pile in the shape of a cone with equal height and base diameter. How fast is the height of the cone increasing when the pile is 3 m tall?

9. **M** The top of a ladder slides down a vertical wall at a rate of  $0.15 \text{ m s}^{-1}$ . At the moment when the bottom of the ladder is 3 m from the bottom of the wall, it slides away from the wall at a rate of  $0.2 \text{ m s}^{-1}$ . Find the length of the ladder.
10. **M** Two sides of a triangle have lengths 2 m and 3 m. The angle between these sides is increasing at a rate of  $4^\circ \text{ s}^{-1}$ . How fast is the length of the third side changing when it is of length 4 m?
11. **E** A particle is moving along a hyperbola  $xy = 8$ . As it reaches the point  $(4, 2)$ , the  $y$ -ordinate is decreasing at a rate of 3 units per second. How fast is the  $x$ -ordinate of the particle changing at that instant?
12. **E** The minute hand on a watch is 8 mm long and the second hand is 4 mm long. How fast is the distance between the tips of the hands changing at 1 o'clock?
13. **S** Scholarship 2015: A tank contains 200 litres of brine (solution of salt in water). Initially, the concentration is 0.5 kg of salt per litre. Brine containing 0.8 kg of salt per litre runs into the tank at a rate of 6 litres per minute. The mixture is kept thoroughly mixed and is running out at the same rate. Find out how long it takes for the amount of salt in the tank to be 130 kg.

**NCEA Level 3 Calculus (Differentiation)****9. Related Rates (Homework)****Reading****Problem-Solving Strategy**

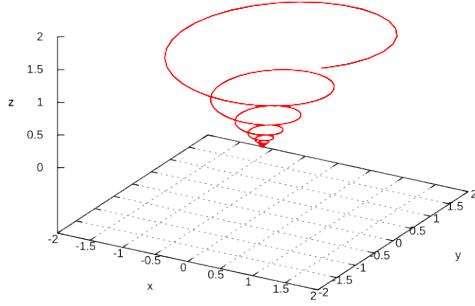
1. Read the problem carefully.
2. Identify the quantities given in the problem.
3. Identify the unknown quantity.
4. Draw a diagram and assign symbols to all quantities.
5. Write an equation relative the various quantities together (if necessary, using substitution to eliminate unwanted variables).
6. Use the chain rule to differentiate and solve for the unknown.

**Questions**

1. If  $V$  is the volume of a cube with edge length  $x$  and the cube expands as time passes, find  $\frac{dV}{dt}$  in terms of  $\frac{dx}{dt}$ .
2. A water tank has the shape of an inverted circular cone with base radius 2 m and height 4 m. If water is being pumped into the tank at a rate of  $2 \text{ m}^3 \text{ min}^{-1}$ , find the rate at which the water level is rising when the water is 3 m deep.
3. A boat is pulled into a dock by a rope attached to the bow of the boat and passing through a pulley on the dock that is 1 m higher than the bow of the boat. If the rope is pulled in at a rate of  $1 \text{ m s}^{-1}$ , how fast is the boat approaching the dock when it is 8 m from the dock?

## NCEA Level 3 Calculus (Differentiation)

### 10. Parametric Functions



Some curves cannot be described simply with a function; for example, the above track of a particle is too complicated to analyse using any of the techniques which we have studied so far. One strategy which does work is to split the  $x$ ,  $y$ , and  $z$  components apart and study them separately. For example, we can *parameterise* the above curve as:

$$\begin{aligned}x(t) &= e^{-t} \cos(10t) \\y(t) &= e^{-t} \sin(10t) \\z(t) &= e^{-t}.\end{aligned}$$

For a simpler example, consider the unit circle  $x^2 + y^2 = 1$ . By recalling the definitions of the trigonometric functions, we can parameterise the circle as  $(x, y) = (\cos \theta, \sin \theta)$  for  $0 \leq \theta < 2\pi$ . Then  $\frac{dy}{dt} = -\sin \theta = -y$  and  $\frac{dx}{dt} = \cos \theta = x$ , so by the chain rule  $\frac{dy}{dx} = \frac{dy}{dt} \cdot \frac{dt}{dx} = -\frac{x}{y}$  — a much simpler calculation than taking the derivative of the square root required by working directly with the circle formula.

In general, we have

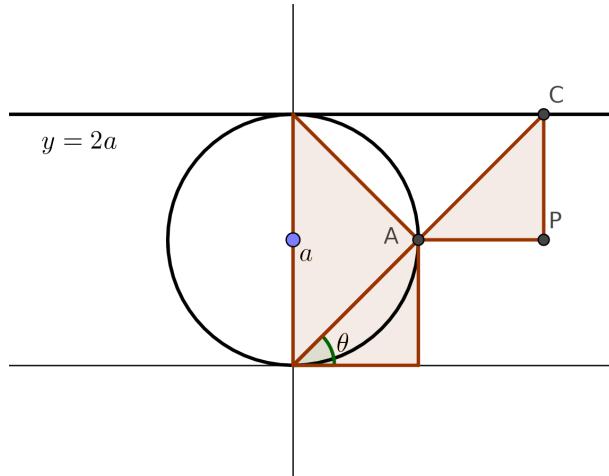
$$d\frac{dy}{dx} = \frac{dy}{dt} \cdot \frac{dt}{dx}$$

In order to find the second derivative, we replace  $y$  with  $\frac{dy}{dx}$ :

$$\frac{d^2y}{dx^2} = \frac{d\frac{dy}{dx}}{dx} = \left( \frac{d}{dt} \frac{dy}{dx} \right) \cdot \frac{dt}{dx}.$$

## Questions

1. **M** In each case find  $\frac{dy}{dx}$ .
    - (a)  $x = t \sin t$ ,  $y = t^2 + t$
    - (b)  $x = 2 \sec \theta$ ,  $y = 3 \tan \theta$
    - (c)  $x = \cos \theta$ ,  $y = \cos 3\theta$
    - (d)  $x = e^{\sin \theta}$ ,  $y = e^{\cos \theta}$
  2. **A** Find the equation of the chord joining the two points  $t = 2$  and  $t = 4$  on the curve  $(x, y) = (2t - 3, t^3 + 6)$ .
  3. **M** Determine the point(s) of intersection of the curves  $\gamma$  and  $\delta$ :
- $$\gamma : t \mapsto (t^2 - 2, t - 1)$$
- $$\delta : t \mapsto (t, 2/t)$$
4. (a) **M** If  $y = 2t$  and  $x = 4t^2$  define a curve, what is the gradient  $\frac{dy}{dx}$  in terms of  $t$ ?
  - (b) **E** Show that this curve is a parabola.
  5. **M** A curve has parametric equations  $x = t^2 + 1$  and  $y = t^3 + 2$ . Find  $\frac{dy}{dx}$  and  $\frac{d^2y}{dx^2}$ .
  6. **M** Find the equation of the tangent to the curve  $t \mapsto (2x^2 + 1, t^3 - 1)$  at  $t = 2$ .
  7. **E** If  $t \mapsto (x, y)$  is a parametric curve, find an expression for  $\frac{d^3y}{dx^3}$  analogous to that found for the second derivative.
  8. **S** A curve, called a *witch of Maria Agnesi*, consists of all possible positions of the point  $P$  in the diagram below. Show that the curve is given by  $(x, y) = (2a \cot \theta, 2a \sin^2 \theta)$  and find the derivative  $\frac{dy}{dx}$ .



9. A particle moves through space over time; the position of the particle at time  $t$  is given by  $(3 \sin t, 2 \cos t)$  ( $0 \leq t < 2\pi$ ).
  - (a) **A** What is the component of the acceleration of the particle in the  $x$  direction at  $t = \pi/4$ ?
  - (b) **A** At what times is the particle stationary in the  $x$  direction?
  - (c) **M** Is the particle ever momentarily totally stationary?

10. E Find the rightmost point on the curve  $x = t - t^6$ ,  $y = e^t$ .
11. E For which values of  $t$  is the curve  $x = \cos 2t$ ,  $y = 3 \cos t$  concave up?
12. S Show that the curve  $\gamma : t \mapsto (\cos t, \sin t \cos t)$  has two tangents at  $(0,0)$  and find their equations.
13. S Scholarship 2000: The piriform is the curve defined by the equation  $16y^2 = x^3(8 - x)$  where  $x \geq 0$ .

(a) Show that

$$\begin{cases} x = 4(1 + \sin \theta) \\ y = 4(1 + \sin \theta) \cos \theta. \end{cases}$$

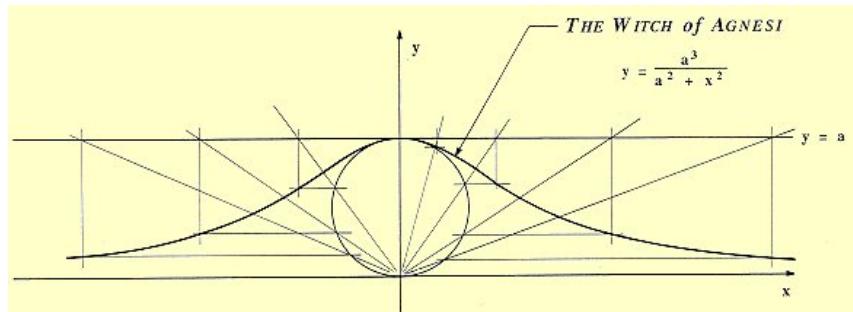
are parametric equations for the piriform.

(b) Find  $\frac{dy}{dx}$  in terms of  $\theta$ , and show that  $\theta = \frac{\pi}{6}$  is a stationary point of the curve.

## NCEA Level 3 Calculus (Differentiation)

### 10. Parametric Functions (Homework)

#### Reading



Maria Gaetana Agnesi (1718 - 1799) was an Italian mathematician and philosopher, considered to be the first woman in the Western world to have achieved a reputation in mathematics.

Agnesi was the eldest child of a wealthy silk merchant who provided her with the best tutors available. She was an extremely precocious child who mastered Latin, Greek, Hebrew, and several modern languages at an early age, and her father liked to host gatherings where she could display her knowledge. *Propositiones philosophicae* ("Propositions of Philosophy"), a series of essays on natural philosophy and history based on her discussions before such gatherings, was published in 1738.

Agnesi's best-known work, *Instituzioni analitiche ad uso della gioventù italiana* (1748; "Analytical Institutions for the Use of Italian Youth"), in two huge volumes, provided a remarkably comprehensive and systematic treatment of algebra and analysis, including such relatively new developments as integral and differential calculus. In this text is found a discussion of the Agnesi curve, a cubic curve known in Italian as *versiera*, which was confused with *versicra* ("witch") and translated into English as the "Witch of Agnesi." The French Academy of Sciences, in its review of the *Instituzioni*, stated that: "We regard it as the most complete and best made treatise." Pope Benedict XIV was similarly impressed and appointed Agnesi professor of mathematics at the University of Bologna in 1750.

However, Agnesi had turned increasingly to religion and never journeyed to Bologna. After the death of her

father in 1752, she devoted herself almost exclusively to charitable work and religious studies. She established various hospices and died in one of the poorhouses that she had once directed.

From <https://www.britannica.com/biography/Maria-Gaetana-Agnesi>.

## Questions

1. In each case find  $\frac{dy}{dx}$  and  $\frac{d^2y}{dx^2}$ .
  - (a)  $x = t^4 - 2t^3 + 2t^2$ ,  $y = t^3 - t$
  - (b)  $x = \cos t + 2 \cos 2t$ ,  $y = \sin t + 2 \sin 2t$
2. Find an equation for the tangent to the curve  $x = 1 + \sqrt{t}$ ,  $y = e^{t^2}$  at the point  $(2, e)$  by substituting one function into the other to eliminate the parameter.
3. (a) Use graphing software (e.g. <http://graphfree.com/>), change ‘plot type’ to ‘parametric’) to graph the curve  $x = 4(\cos t)^3$ ,  $y = 4(\sin t)^3$ . This curve is called an *astroid* (as opposed to an asteroid).
  - (b) Use calculus to find the slope of the tangent to the astroid in terms of  $t$ .
  - (c) Use calculus to find the locations of the cusps (points).

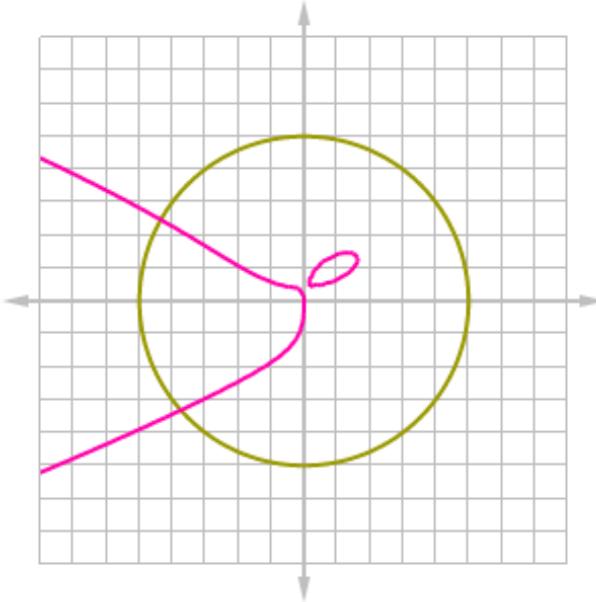
## NCEA Level 3 Calculus (Differentiation)

### 11. Implicit Differentiation

This week we continue the study of more interesting curves which we began last week. Consider the curves

$$x^2 + y^2 = 25 \text{ and } x^3 + y^4 = 5xy - 2x$$

graphed here:



We can solve for the first  $y$ , as  $y = \pm\sqrt{25 - x^2}$ ; however, the second is much harder to solve and so we cannot find its derivative using the techniques we have studied so far. These equations are examples of *implicit functions* of  $x$ . Note that neither is a ‘real’ function since they both fail the vertical-line test.

The key observation here is that **differentiation is an operation**, similar to addition. Just like we can add 3 to both sides of the true equation  $2 + 4 = 6$  to obtain another true equation  $2 + 3 + 4 = 3 + 6$ , we can differentiate both sides of an equation to obtain another true equation. The only catch is that we must remember that  $y$  is a function of  $x$  and so we must employ the chain rule.

**Example.** If  $x^2 + y^2 = 25$ , by differentiating both sides with respect to  $x$  we obtain  $2x + \frac{dy}{dx}2y = 0$  and therefore we have  $\frac{dy}{dx} = -\frac{x}{y}$ . Note that this depends on both  $x$  and  $y$  which makes sense: at  $x = 0$ , for example, we have two gradients (both of which are zero).

**Example.** If  $x^3 + y^4 = 5xy - 2x$ , then by differentiating both sides with respect to  $x$  we obtain  $3x^2 + \frac{dy}{dx}4y^3 = 5y + 5x\frac{dy}{dx} - 2$  (being careful to use the product and chain rules in differentiating). Hence we have that the derivative is:

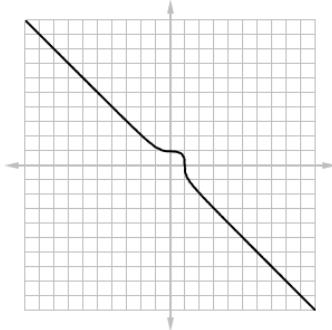
$$\frac{dy}{dx} = \frac{5y - 3x^2 - 2}{4y^3 - 5x}$$

Be careful to always specify which is the variable which you are differentiating with respect to.

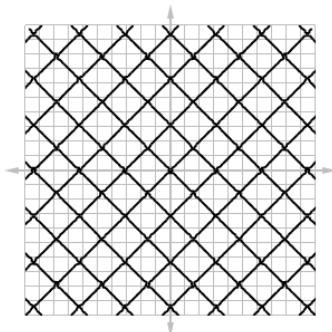
**Questions**

1.  In each case, look at the cool pictures and find  $y'$ :

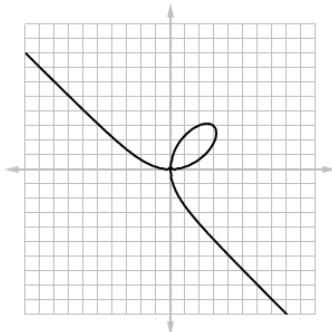
(a)  $x^3 + y^3 = 1$



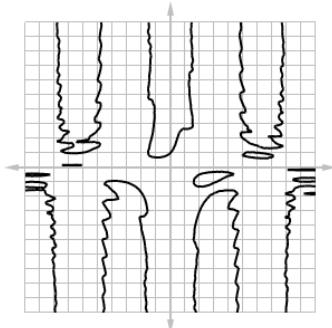
(b)  $\sin^2 y + \cos^2 x = 1$



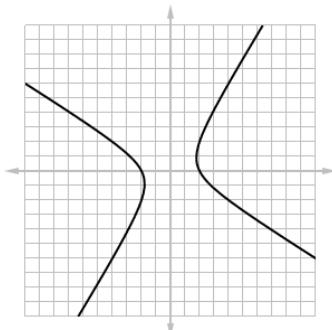
(c)  $x^3 + y^3 = 6xy$  (the folium of Descartes)



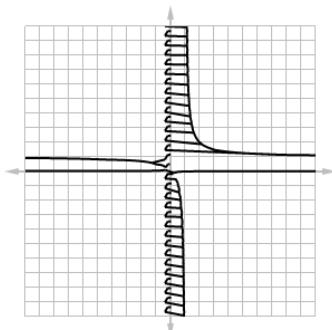
(d)  $y \cos x = 1 + \sin(xy)$



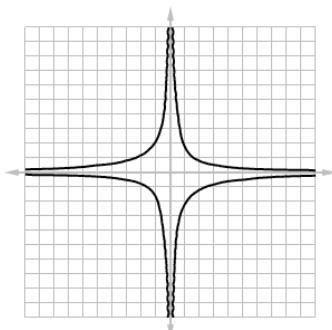
(e)  $x^2 + xy - y^2 = 4$



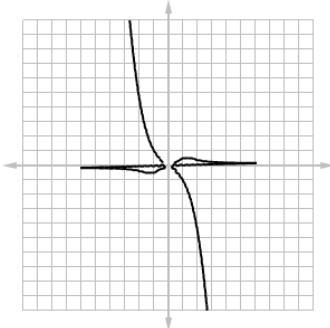
(f)  $\frac{1}{x} + \frac{1}{y} = 1$



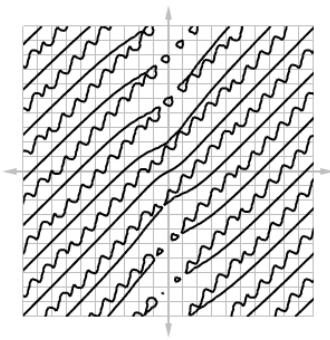
(g)  $x^2y^2 + x \sin y = 4$



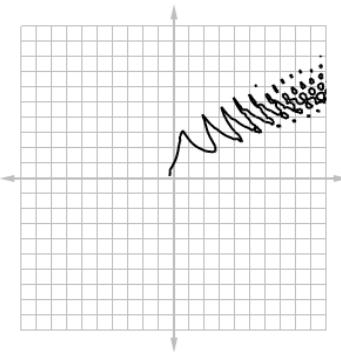
(h)  $x^4y^2 - x^3y + 2xy^3 = 0$



(i)  $\tan(x - y) = \frac{y}{1+x^2}$

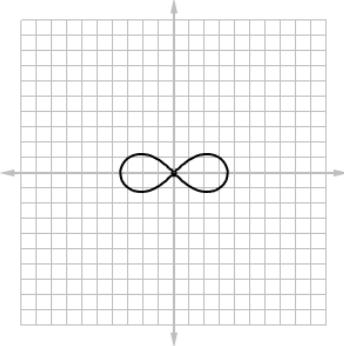


2. M Consider the circle  $x^2 + y^2 = 1$ . Find the equation of the tangent to the curve at  $(\sqrt{2}, \sqrt{2})$ .
3. S The ellipse  $x^2 + 3y^2 = 36$  has two tangent lines passing through the point  $(12, 3)$ . Find both. *This question is similar to one from the 2015 Scholarship paper.*
4. M Find  $x'$  and  $y'$  if  $\ln(y) = \sin(xy) + \frac{x}{y}$ .

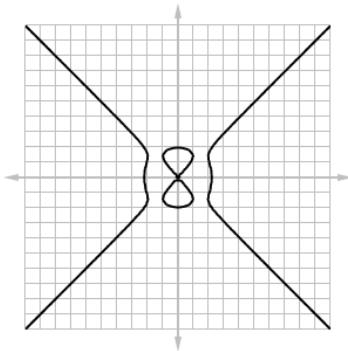


5. M Find  $y''$  if  $x^4 + y^4 = 16$ .
6. M If  $x^2 + xy + y^3 = 1$ , find the value of  $y'''$  at the point where  $x = 1$ .

7. **M** Find a tangent line to the curve  $2(x^2 + y^2)^2 = 25(x^2 - y^2)$  at the point  $(3, 1)$ . This curve is known as a lemniscate.



8. **M** Find a tangent line to the curve  $y^2(y^2 - 4) = x^2(x^2 - 5)$  at the point  $(0, -2)$ . This curve is known as a devil's curve.



9. Consider the ellipse  $x^2 - xy + y^2 = 3$ .
- A** Find the points where the ellipse crosses the  $x$ -axis.
  - M** Show that the tangent lines of the curve at these points are parallel.
  - E** Find the maximum and minimum points of the curve.
10. **E** Consider a circle  $C$  that is tangent to  $3x + 4y - 12 = 0$  at  $(0, 3)$  and contains  $(2, -1)$ . Set up equations that would determine the centre  $(h, k)$  and radius  $r$  of  $C$ .
11. **S** The Bessel function of order 0,  $y = J(x)$ , satisfies the differential equation

$$xy'' + y' + xy = 2$$

for all values of  $x$ . The value of the function at 0 is  $J(0) = 1$ .

- Find  $J'(0)$ .
  - Use implicit differentiation to find  $J''(0)$ .
12. **S** Consider the following family of curves, known as Durer's shell curves:

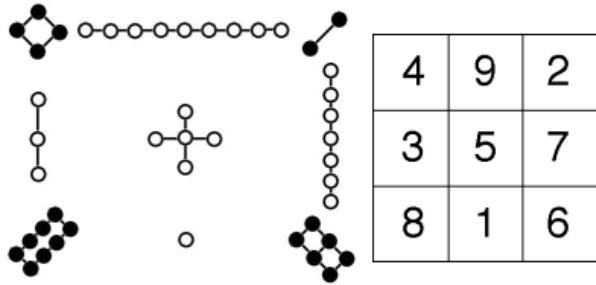
$$(x^2 + xy + ax - b^2)^2 = (b^2 - x^2)(x - y + a)^2.$$

- For which value(s) of  $b$  does the curve become a straight line?
- Suppose that we restrict  $a = \frac{b}{2}$ . Find all non-differentiable points on the curve.

## NCEA Level 3 Calculus (Differentiation)

### 11. Implicit Differentiation (Homework)

#### Reading



Even as mathematical developments in the ancient Greek world were beginning to falter during the final centuries BCE, the burgeoning trade empire of China was leading Chinese mathematics to ever greater heights.

The simple but efficient ancient Chinese numbering system, which dates back to at least the 2nd millennium BCE, used small bamboo rods arranged to represent the numbers 1 to 9, which were then placed in columns representing units, tens, hundreds, thousands, etc. It was therefore a decimal place value system, very similar to the one we use today - indeed it was the first such number system, adopted by the Chinese over a thousand years before it was adopted in the West - and it made even quite complex calculations very quick and easy.

Written numbers, however, employed the slightly less efficient system of using a different symbol for tens, hundreds, thousands, etc. This was largely because there was no concept or symbol of zero, and it had the effect of limiting the usefulness of the written number in Chinese.

The use of the abacus is often thought of as a Chinese idea, although some type of abacus was in use in Mesopotamia, Egypt and Greece, probably much earlier than in China (the first Chinese abacus, or "suanpan", we know of dates to about the 2nd Century BCE).

There was a pervasive fascination with numbers and mathematical patterns in ancient China, and different numbers were believed to have cosmic significance. In particular, magic squares - squares of numbers where each row, column and diagonal added up to the same total - were regarded as having great spiritual and religious significance.

The Lo Shu Square, an order three square where each row, column and diagonal adds up to 15, is perhaps the earliest of these, dating back to around 650 BCE (the legend of Emperor Yu's discovery of the the square on the back of a turtle is set as taking place in about 2800 BCE). But soon, bigger magic squares were being constructed, with even greater magical and mathematical powers, culminating in the elaborate magic squares, circles and triangles of Yang Hui in the 13th Century (Yang Hui also produced a triangular representation of binomial coefficients identical to the later Pascals' Triangle, and was perhaps the first to use decimal fractions in the modern form).

But the main thrust of Chinese mathematics developed in response to the empire's growing need for mathematically competent administrators. A textbook called "Jiuzhang Suanshu" or "Nine Chapters on the Mathematical Art" (written over a period of time from about 200 BCE onwards, probably by a variety of authors) became an important tool in the education of such a civil service, covering hundreds of problems in practical areas such as trade, taxation, engineering and the payment of wages.

It was particularly important as a guide to how to solve equations - the deduction of an unknown number

from other known information - using a sophisticated matrix-based method which did not appear in the West until Carl Friedrich Gauss re-discovered it at the beginning of the 19th Century (and which is now known as Gaussian elimination).

Among the greatest mathematicians of ancient China was Liu Hui, who produced a detailed commentary on the “Nine Chapters” in 263 CE, was one of the first mathematicians known to leave roots unevaluated, giving more exact results instead of approximations. By an approximation using a regular polygon with 192 sides, he also formulated an algorithm which calculated the value of  $\pi$  as 3.14159 (correct to five decimal places), as well as developing a very early forms of both integral and differential calculus.

The Chinese went on to solve far more complex equations using far larger numbers than those outlined in the “Nine Chapters”, though. They also started to pursue more abstract mathematical problems (although usually couched in rather artificial practical terms), including what has become known as the Chinese Remainder Theorem. This uses the remainders after dividing an unknown number by a succession of smaller numbers, such as 3, 5 and 7, in order to calculate the smallest value of the unknown number. A technique for solving such problems, initially posed by Sun Tzu in the 3rd Century CE and considered one of the jewels of mathematics, was being used to measure planetary movements by Chinese astronomers in the 6th Century AD, and even today it has practical uses, such as in Internet cryptography.

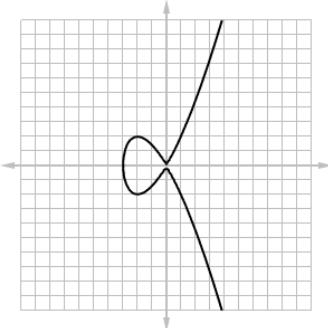
By the 13th Century, the Golden Age of Chinese mathematics, there were over 30 prestigious mathematics schools scattered across China. Perhaps the most brilliant Chinese mathematician of this time was Qin Jiushao, a rather violent and corrupt imperial administrator and warrior, who explored solutions to quadratic and even cubic equations using a method of repeated approximations very similar to that later devised in the West by Sir Isaac Newton in the 17th Century. Qin even extended his technique to solve (albeit approximately) equations involving numbers up to the power of ten, extraordinarily complex mathematics for its time.

*From <http://www.storyofmathematics.com/chinese.html>.*

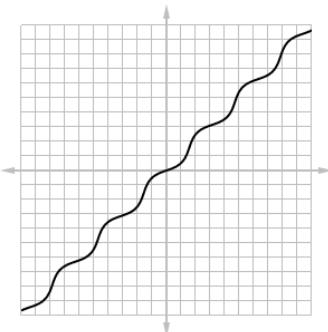
## Questions

1. Find  $y'$  in each case:

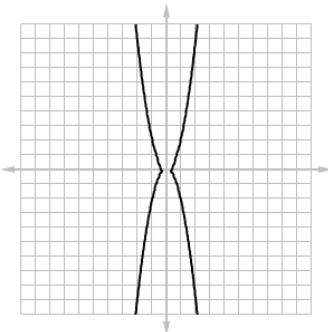
(a)  $y^2 = x^3 + 3x^2$  (Tschirnhausen cubic)



(b)  $\sin(x+y) = 2x - 2y$



(c)  $y^2 = 5x^4 - x^2$  (kampyle of Eudoxus)



2. Find the equation of the normal line to the curve  $x^2 + 2xy - y^2 + x = 2$  at the point  $(1, 2)$ .

3. Show that the sum of the  $x$  and  $y$  intercepts of any tangent line to the curve  $\sqrt{x} + \sqrt{y} = \sqrt{c}$  is just  $c$ .

## NCEA Level 3 Calculus (Differentiation)

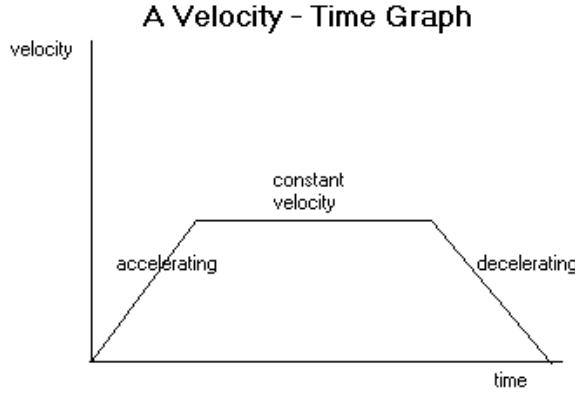
### 12. Kinematics

**This is an easy week, especially if you are doing physics (or did level 2 physics). Take a well-earned break!** Calculus was independently developed by Sir Isaac Newton to describe motion in physics. This use is known as *kinematics* (from the Greek *kinein*, ‘to move’). Suppose a particle moves from position  $x_0$  to position  $x_1$  over a time  $\Delta t$ . We call the ratio

$$\frac{x_1 - x_0}{\Delta t}$$

the *average velocity* of the particle; if we let  $x_1 \rightarrow x_2$  (or let  $t \rightarrow 0$ ), we obtain the derivative  $\frac{dx}{dt} = v$ , the *instantaneous velocity* of the particle at the point  $x$  (usually just abbreviated to *velocity*).

Similarly, the rate of change of velocity is called *acceleration*. We have  $a = \frac{dv}{dt} = \frac{d^2x}{dt^2}$ . (Out of interest, the third derivative of displacement is known as *jerk*, and the fourth is *jounce*.)



The distance travelled is area under graph.  
The acceleration and deceleration can be found by  
finding the gradient of the lines.

If we draw a velocity-time graph, like that above, the area under the graph gives us the distance travelled by the object during a time interval; this means that in some sense finding area is inverse to finding slope. Intuitively, this is a bit weird — the way to think about it is that if we increase the area under the velocity curve by a little bit, then the distance we move in that time also increases proportionally. On the other hand, if we move a certain distance then we increase the area under the velocity curve because we have a non-zero velocity.

Algebraically, we have  $\text{rate} = \frac{\text{change in quantity}}{\text{time}}$  and so  $\text{change in quantity} = \text{rate} \times \text{time}$ . In calculus, we are interested in finding the total change in a quantity over a longer period of time than just a single instant, by adding up infinitely many instantaneous rates.

We will explore this idea in more detail in a couple of weeks when we start talking about *integration*.

We can derive the following *kinematic equations* if acceleration is kept constant over a time period  $t$ :

$$\begin{aligned} v_f &= v_i + a\Delta t \\ \Delta x &= v_i \Delta t + \frac{1}{2} a \Delta t^2 \\ v_f^2 &= v_i^2 + 2a\Delta x \\ \Delta x &= \frac{v_f + v_i}{2} \Delta t \end{aligned}$$

These can all be found from the definitions of acceleration and velocity, and by taking areas and slopes of graphs (if we remember that the velocity graph must be made up of straight lines since the acceleration is constant). The equations are not examinable in the L3 calculus exam. We mainly look at them for context.

## Questions

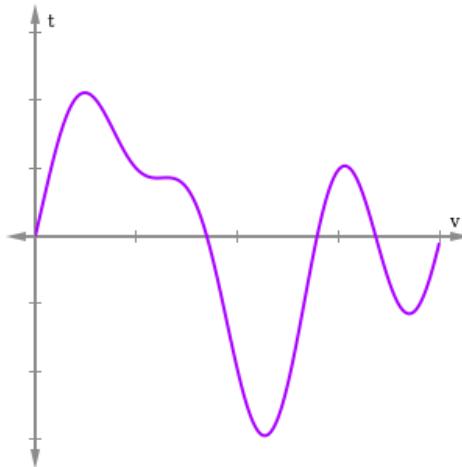
All distances are given in m, and all times in s, unless otherwise stated.

1.  A Describe the relationship between velocity and displacement.
2.  A particle moves from  $x = 2\text{ m}$  to  $x = 3\text{ m}$  over a time 3 s. What is its average velocity over that time?
3.  A particle moves from  $(3, 4)$  to  $(12, -3)$  over a time 10 s. If the displacements are measured in metres, what is the magnitude of its average velocity during that period?
4.  An object  $A$  has a positive acceleration  $a$ , and a second object  $B$  has a negative acceleration  $-a$ . Both are moving in the same direction. Which of the following is **not** true?
  - (a) Object  $B$  is slowing down compared to object  $A$ .
  - (b) Object  $B$  has a lower velocity than object  $A$ .
  - (c) At some point, object  $B$  will reach a velocity of zero and then start moving in the opposite direction.
  - (d) If object  $B$  is behind object  $A$ , the two will never cross paths.
5.  Suppose a particle has a velocity of  $34\text{ m s}^{-1}$ . How long does it take for the particle to travel 150 m?
6. The velocity  $v$  of an object  $t$  seconds after it moves from the origin is given by

$$v(t) = 3t^2 - 6t - 24.$$

- (a)  A Write down the formulae for the acceleration of the particle after  $t$  seconds.
- (b)  A Work out the initial velocity and acceleration.
- (c)  A When is the object at rest momentarily?
- (d)  M When is the object travelling at minimum speed?
- (e)  M When did the object return to the origin?
7.  A well-wrapped food parcel is dropped from an aeroplane flying at a height of 500 m above the ground. The constant acceleration due to gravity is  $-9.81\text{ m s}^{-2}$ . Air resistance is negligible.
  - (a) How long does it take for the food parcel to hit the ground?
  - (b) How fast is the food parcel moving when it hits the ground?
8.  A racing car travelling at  $210\text{ km h}^{-1}$  skids for a distance of 150 m after its brakes are applied. The brakes provide a constant deceleration.
  - (a) What is the deceleration in  $\text{m s}^{-2}$ ?
  - (b) How long does it take for the car to stop?

9. M The following is a graph of the instantaneous velocity of an object moving in one dimension over time.



- (a) Draw the acceleration of the object over time.  
(b) Draw the position of the object over time, if it was originally located at  $x = 0$ .
10. E The displacement of an object moving in a straight line on either side of a fixed origin is given by

$$s(t) = 2t^3 - 12t^2 + 18t + 3.$$

Find the minimum velocity of the object. Prove that it is a minimum. Which position is it at at that time?

11. M Derive the kinematic equations by looking at the velocity graph of an object with constant acceleration.

## NCEA Level 3 Calculus (Differentiation)

### 12. Kinematics (Homework)

#### Reading

This is an easy week, especially if you are doing physics (or did level 2 physics). Take a well-earned break!

**Go and watch...**

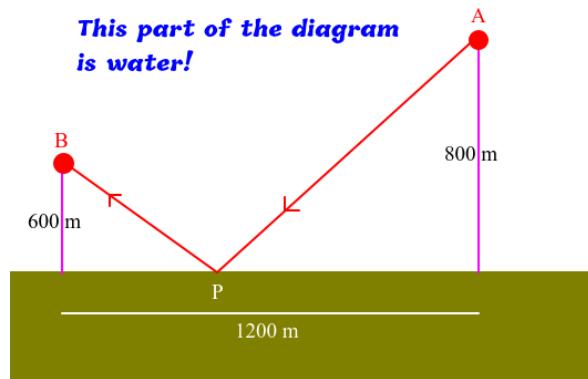
<https://www.youtube.com/watch?v=fIaupXkpB00>

#### Questions

All distances are given in m, and all times in s, unless otherwise stated.

1. A distress flare is fired vertically into the air from a boat at sea. The height in metres of the flare  $t$  seconds after firing is given by  

$$h = 122.5t - 4.9t^2.$$
  - (a) What is the initial velocity of the flare?
  - (b) At the peak of its flight, what is the vertical velocity of the flare?
  - (c) What is the maximum height reached by the flare?
2. Part of the course for an ocean swim runs from bouy  $A$  to bouy  $B$ . Swimmers must come ashore on the at some point  $P$  along a long straight beach on the way. Bouy  $A$  is 800 m away from the beach, and bouy  $B$  is 600 m away from the beach. What is the least distance that a swimmer must swim? (Hint: minimise  $PA + PB$ .)



## NCEA Level 3 Calculus (Differentiation)

### 13. Inverse Functions

A function is one-to-one (or injective) if  $f(x) = f(y)$  implies that  $x = y$  (i.e. two different inputs can never give the same output/the function passes the horizontal-line test).

**Definition.** Let  $f$  be a function that is one-to-one. Then the **inverse** of  $f$  is the (unique) function  $f^{-1}$  such that

$$f(x) = y \iff f^{-1}(y) = x.$$

In other words,  $f(f^{-1}(y)) = y$  and  $f^{-1}(f(x)) = x$ .

**Example.** Here are some functions with their inverses:

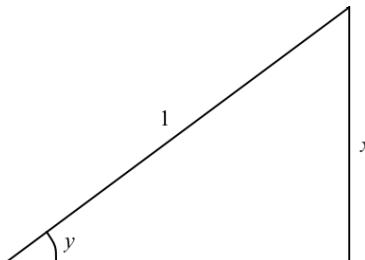
Function	Inverse	Notes
$e^x$	$\ln x$	Note that $\ln x$ is defined only when $x > 0$ since $e^x > 0$ for all real $x$ .
$\sin x$	$\sin^{-1} x$	Note that $\sin^{-1} x$ is only defined when $-\pi < x \leq \pi$ since otherwise $\sin x$ is not one-to-one.
$\cos x$	$\cos^{-1} x$	Note that $\cos^{-1} x$ is only defined when $-\pi < x \leq \pi$ since otherwise $\cos x$ is not one-to-one.
$\tan x$	$\tan^{-1} x$	Note that $\tan^{-1} x$ is defined for all $x$ (why?), and so $\tan^{-1} x \neq \frac{\sin^{-1} x}{\cos^{-1} x}$ .
$x^2$	$\sqrt{x}$	When $x$ is positive.

The graph of the inverse of a function is the reflection of the graph of the original function around the line  $x = y$  (essentially, we swap the  $x$  and  $y$  axes).

Let us now find the derivative of  $y = \sin^{-1} x$ .

$$\begin{aligned} y &= \sin^{-1} x \\ \sin y &= x \\ \frac{dy}{dx} \cos y &= 1 \\ \frac{dy}{dx} &= \frac{1}{\cos y} = \frac{1}{\cos \sin^{-1} x} \\ &= \frac{1}{\sqrt{1-x^2}}. \end{aligned}$$

The identity  $\cos \sin^{-1} x = \sqrt{1-x^2}$  comes from the following triangle:



**Theorem** (Inverse Trigonometric Derivatives). *The following table gives the derivatives of inverses of the three primary trigonometric functions and their reciprocals.*

Function	Derivative	Function	Derivative
$\sin^{-1} x$	$\frac{1}{\sqrt{1-x^2}}$	$\csc^{-1} x$	$-\frac{1}{x\sqrt{x^2-1}}$
$\cos^{-1} x$	$-\frac{1}{\sqrt{1-x^2}}$	$\sec^{-1} x$	$\frac{1}{x\sqrt{x^2-1}}$
$\tan^{-1} x$	$\frac{1}{1+x^2}$	$\cot^{-1} x$	$-\frac{1}{x^2+1}$

## Questions

1. **M** Prove or disprove the statement that  $f : x \mapsto x^2 + x + 1$  is one-to-one (where  $x$  is real).
2. **M** Prove or disprove the statement that  $f : x \mapsto 2^x$  is one-to-one (where  $x$  is a positive real).
3. **M** Determine whether the following functions have inverses on the given interval:
  - (a)  $x \mapsto x^3$  (on  $\mathbb{R}$ )
  - (b)  $y \mapsto y^4$  (on  $\mathbb{R}$ )
  - (c)  $y \mapsto y^4$  (for  $y \geq 0$ )
  - (d)  $y \mapsto y^4$  (for  $y > 0$ )
  - (e)  $\theta \mapsto \cos^{-1} \theta$  (on  $\mathbb{R}$ )
  - (f)  $\theta \mapsto \cos^{-1} \theta$  (for  $-1 \leq \theta \leq 1$ )
4. **A** True or false:
  - (a)  $\cos^{-1} x = \frac{1}{\cos x}$
  - (b) If  $x > 0$  then  $(\ln x)^6 = 6 \ln x$
  - (c)  $\tan^{-1}(-1) = \frac{3\pi}{4}$  (think about which arm of  $\tan x$  we're talking about)
  - (d) The inverse of  $y = e^{3x}$  is  $y = \frac{1}{3} \ln y$ .
5. **A** Find  $y'$  if:
  - (a)  $y = \sin^{-1} 2x$
  - (b)  $x = \sin^2 y$
  - (c)  $y = x + \tan^{-1} y$
  - (d)  $y = \ln \sin x - \frac{1}{2} \sin^2 x$
  - (e)  $y = 24 \arctan x + \arcsin \sqrt{x}$
  - (f)  $y = \sqrt{\sec^{-1} 2x}$
6. **E** Find the local extrema, areas of concavity, and inflection points of the following functions; hence sketch their graphs.
  - (a)  $y = e^x \sin x$  for  $-\pi < x < \pi$
  - (b)  $y = x + \ln(x^2 + 1)$
  - (c)  $y = \sin^{-1}(1/x)$
7. **S** Prove the derivatives of  $\cos^{-1}$  and  $\tan^{-1}$  using a similar method to that for  $\sin^{-1} x$ .
8. **S** Scholarship 2012: Consider the equation  $x^n = \tan(ny)$ , where  $n$  is a constant. Find an expression for  $\frac{dy}{dx}$  in terms of  $x$ .

**NCEA Level 3 Calculus (Differentiation)****13. Inverse Functions (Homework)****Reading**

<https://blogs.scientificamerican.com/roots-of-unity/dont-fall-for-babylonian-trigonometry-hype/>

**Questions**

1. Find the derivatives with respect to  $x$ :

(a)  $y = \tan^{-1}(x^2)$   
(b)  $\tan f(x) = x$   
(c)  $g(x) = \arctan(\arcsin \sqrt{x})$

2. Show that

$$\frac{d}{dx} \left( \frac{1}{2} \tan^{-1} x + \frac{1}{4} \ln \frac{(x+1)^2}{x^2+1} \right) = \frac{1}{(1+x)(1+x^2)}$$

3. Prove that  $\frac{d}{dx} \cot^{-1} x = -\frac{1}{x^2+1}$ .

## NCEA Level 3 Calculus (Differentiation)

### 14. Differentiation Revision

Halfway there! Let's do a bit of revision.

#### Questions

1.  A True or False:

- (a) If a function  $f$  is continuous around a point, then it is differentiable at that point.
- (b) If a function  $f$  is differentiable around a point, then it is continuous at that point.
- (c) If  $f$  and  $g$  are differentiable, then  $\frac{d}{dx}[f(x) + g(x)] = f'(x) + g'(x)$ .
- (d) If  $f$  and  $g$  are differentiable, then  $\frac{d}{dx}[f(x)g(x)] = f'(x)g'(x)$ .
- (e)  $\frac{d}{dx}(x+3)^2 = 2(x+3)$ .
- (f)  $\frac{d}{dx}(x^2+3)^2 = 2(x^2+3)$ .
- (g)  $\frac{d}{dx} \tan^2 x = \frac{d}{dx} \sec^2 x$ .
- (h)  $\frac{d^2y}{dx^2} = \left(\frac{dy}{dx}\right)^2$ .
- (i) If  $A = \pi r^2$ , then  $dA/\pi = 0$ .

2.  A Find  $\frac{dy}{dt}$  in each case.

- |                                    |   |
|------------------------------------|---|
| (a) $y = t^2 + 3t$                 | (f) $y = \sin 2t$                               |
| (b) $y = \frac{4-t}{3+t}$          | (g) $y = \sin^2 t$                              |
| (c) $y = (t^4 - 3t^2 + 5)^2$       | (h) $y = \sin t^2$                              |
| (d) $y = (t+1)^{2017}$             | (i) $y = \cos \tan t$                           |
| (e) $y = \frac{3t+4t^2}{\sqrt{t}}$ | (j) $y = (27t+3)^{2017}(t^2 - \sqrt{t})^{2020}$ |
|                                    | (k) $y = (t + \frac{1}{t^2})^{\sqrt{7}}$        |

3.  M Find the equation of the tangent line to the curve  $\sqrt{1+4\sin x}$  at the point  $(0, 1)$ .

4.  A Find  $y''$  in each case:

- (a)  $y = 3x^3 + 2x + \sqrt{2x} + \frac{1}{x^2}$
- (b)  $y = e^{2x}$
- (c)  $y = \sqrt{4t+1}$
- (d)  $y = 4\sin^2 x$

5.  M Find the  $n$ th derivative of  $e^{2x}$  (where  $n$  is a natural (counting) number).

6.  E The height of a projectile after  $t$  seconds can be modelled by  $h = 3t(t-10)$ . At what time is the height of the projectile at a maximum? Use the second-derivative test to prove that you have found a maximum.

7. **M** Find  $f'(x)$  if:

- (a)  $f(x) = \frac{1}{3} \ln \left| \frac{x-1}{x+2} \right| + 3$
- (b)  $f(x) = 2 \ln \left| \frac{x-2}{x} \right| + \frac{2}{x} + 7$

8. **M** In each case, find  $y'$  in terms of  $x$  and  $y$ :

- (a)  $x^2 + y^2 = 4$
- (b)  $x^2 + 4xy + y^2 = 13$
- (c)  $xy^4 + x^2y = x + 3y$
- (d)  $x^2 \cos y + \sin 2y = xy$

9. **M** By differentiating the double-angle formula for cosine,

$$\cos 2x = \cos^2 x - \sin^2 x,$$

obtain the double-angle formula for the sine function.

10. **M** Find  $f'$  in terms of  $g'$  if  $f(x) = x^2 g(x)$ .

11. **M** The volume of a cube is increasing at a rate of  $10 \text{ cm}^3 \text{ min}^{-1}$ . How fast is the surface area increasing when the length of an edge is 30 cm?

12. **M** The volume of a right circular cone is  $V = \frac{1}{3}\pi r^2 h$ .

- (a) Find the rate of change of volume with respect to height if the radius is constant.
- (b) Find the rate of change of volume with respect to radius if the height is constant.

13. **M** A particle moves along a horizontal line such that its coordinate at time  $t$  is  $x = \sqrt{b^2 + c^2 t^2}$  ( $t \geq 0$ ), where  $b$  and  $c$  are positive constants. Find its velocity and acceleration functions.

14. **M** From first principles, show that:

- (a)  $\frac{d}{dx} x^2 = 2x$
- (b)  $\frac{d}{dx} [2x^3 + 2x] = 6x^2 + 2$

15. **E** Find the derivative of  $f(x) = \frac{4}{\sqrt{1-x}}$  from first principles.

16. **E** Each limit represents the derivative of a function  $f$  at a point  $a$ . Identify each function and point.

- (a)  $\lim_{h \rightarrow 0} \frac{\cos(\pi+h)+1}{h}$
- (b)  $\lim_{t \rightarrow 1} \frac{t^4+t-2}{t-1}$

17. **M** Find the best linear approximation to  $f(x) = \sqrt{25 - x^2}$  near  $x = 3$ .

18. **M** A balloon is rising at a constant speed of  $2 \text{ m s}^{-1}$ . A girl is cycling along a straight road at a speed of  $5 \text{ m s}^{-1}$ . When she passes under the balloon, it is 15 m above her. How fast is the distance between the person and the balloon increasing 3 seconds later?

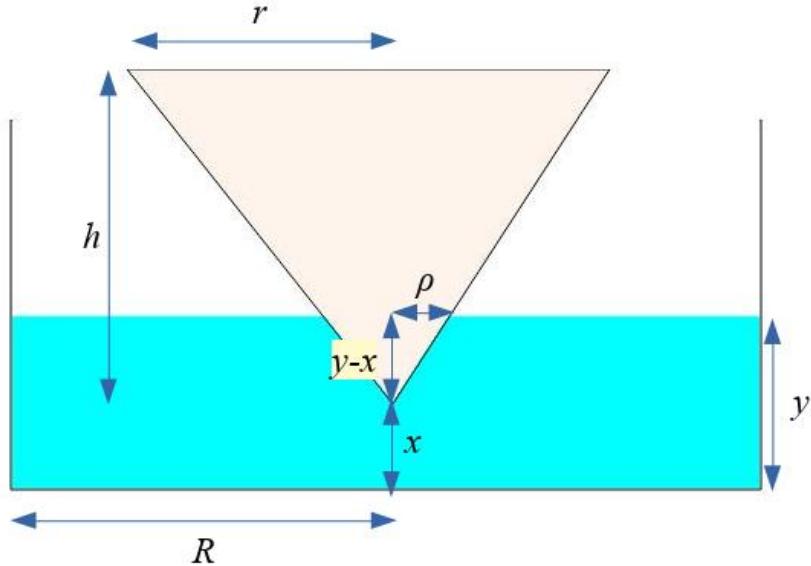
19. **E** On a straight shoreline there is a tree and exactly opposite it, 100 m away in the sea, stands a lighthouse. A strong and thin spotlight on its top revolves at the rate of one revolution per 4 seconds, its light creating a running light spot on the shore. You stand on the shore 100 m from the tree. How fast does this spot move when it goes past you?

20. **M** Find  $\frac{dy}{dx}$  in terms of  $t$  for the following parametrically-defined curves.

- (a)  $t \mapsto (1 + e^{2t}, e^t)$
- (b)  $x = \tan t, y = \sec 2t$
- (c)  $x = \frac{t^2 - 10}{t^2 + 1}, y = tx$
21. E Find the lowest point on the curve  $\gamma : t \mapsto (t^3 - 3t, t^2 + t + 1)$ . Prove you have found a minimum.
22. M Find the acceleration of a particle at time  $t$  if its displacement from the origin at time  $t$  is  $-t^6 + 5t^4 + \sin t$ .
23. E A piece of wire 10 m long is cut into two pieces; one is bent into a square and the other into a circle. Where should the wire be cut to ensure the total area of the enclosed shapes is (a) a minimum and (b) a maximum?
24. M A cone is made by cutting a sector out of a circle of paper of radius  $R$  and gluing together the edges of the cut. Find the maximum possible volume of the cone.
25. E Find the dimensions of the rectangle of largest area that can be inscribed in a circle of radius  $r$ .
26. E At which points does the ‘bouncing wagon’ curve  $2y^3 + y^2 - y^5 = x^4 - 2x^3 + x^2$  have horizontal tangents?
27. E Salt forms a cone as it falls from a conveyor belt. The slant of the cone forms an angle of  $30^\circ$  with the horizontal. The belt delivers salt at a rate of  $2\text{ m}^3$  per minute. When the radius of the cone is ten metres, what is the rate of increase of the slant height (measured along the surface of the cone)?
28. S Suppose we take a circle of radius  $r$ , and inscribe within it a triangle such that each corner of the triangle is located on the circle. What is the maximum possible area of the triangle?
29. E Take derivatives of the following functions with respect to  $x$ :
- (a)  $f(x) = 2^x$
- (b)  $g(x) = \log_{\log x} x$
30. S Scholarship 2017: For  $y = x^{(x^x)}$ , find  $\frac{dy}{dx}$  when  $x = 2$ .
31. S Scholarship 2015 (adapted): A car is driving along a road shaped like a parabola at night. The parabola has a vertex at the origin, and the car starts at a point 100 m west and 100 m north of the origin.
- (a) Write an equation modelling the road as a parabola.
- (b) Find the general equation for the tangent line to the parabola at some point  $(x_0, y_0)$ , and substitute into it the parabola equation to obtain an equation only in  $x$ ,  $x_0$ , and  $y_0$ .
- (c) Suppose there is a statue of the Roman emperor Augustus located 100 m east and 50 m north of the origin. Write the equation for the tangent line of the parabola passing through the statue (so that it only depends on a value  $x$  on the parabola).
- (d) Hence find the single point  $(x, y)$  on the road where the headlights of the car illuminate the statue.
32. O (Difficult) Find the two points on the curve  $y = x^4 - 2x^2 - x$  that have a common tangent line.
33. S (Difficult) A cone of radius  $r$  centimetres and height  $h$  centimetres is lowered point first at a rate of  $1\text{ cm}^2$  into a cylinder of radius  $R$  centimetres that is partially filled with water. How fast is the water level rising at the instant that the cone is fully submerged?

## WORKED SOLUTION FOR PROBLEM:

(Difficult) A cone of radius  $r$  centimetres and height  $h$  centimetres is lowered point first at a rate of  $1 \text{ cm}^2$  into a cylinder of radius  $R$  centimetres that is partially filled with water. How fast is the water level rising at the instant that the cone is fully submerged?



Let  $V$  be the volume of water in the tank, which we know to be constant. We are given that  $\frac{dx}{dt} = -1$ . Using trigonometry, we find  $\rho = \frac{r}{h}(y - x)$  so we have

$$\begin{aligned} V &= x\pi R^2 + (y - x)\pi R^2 - \frac{1}{3}\pi\rho^2(y - x) \\ &= \pi R^2 y - \frac{1}{3}\pi \frac{r^2}{h^2}(y - x)^3 \end{aligned}$$

Hence  $\frac{dV}{dx} = \pi R^2 - \frac{\pi r^2}{h^2}(y - x)^2(1 - \frac{dx}{dy})$ ; but  $V$  is constant, so any derivative of  $V$  is zero and

$$0 = \pi R^2 - \frac{\pi r^2}{h^2}(y - x)^2(1 - \frac{dx}{dy}).$$

When the cone is exactly submerged,  $y - x = h$ . So  $0 = R^2 - r^2(1 - \frac{dx}{dy})$  and  $\frac{dx}{dy} = \frac{r^2 - R^2}{r^2}$ ; hence

$$\frac{dy}{dt} = \frac{dx}{dt} \frac{dy}{dx} = -1 \times \frac{r^2}{r^2 - R^2} = \frac{r^2}{R^2 - r^2}.$$

## NCEA Level 3 Calculus (Differentiation)

### 14. Differentiation Revision (Homework)

#### Reading

Go and watch...

<https://www.youtube.com/watch?v=i5bH-EwTLAU>

#### Questions

1. Find  $f'$  in each case:
  - (a)  $f(x) = 3x^{2017} + \frac{1}{x^{19}} + \sqrt[2017]{x+2}$
  - (b)  $f(h) = \pi r^2 h$
  - (c)  $f(\theta) = \frac{\mu mg}{\mu \sin \theta + \cos \theta}$
  - (d)  $f(g) = \frac{\sin g}{g^2 + \ln g}$
  - (e)  $3x \cdot f(x) + [f(x)]^2 = \frac{x}{3+f(x)}$
2. A kite 50 m above the ground moves horizontally at a speed of  $2 \text{ m s}^{-1}$ . At what rate is the angle between the string and the horizontal decreasing when 100 m of string has been let out?
3. A cone-shaped paper drinking cup is to be made to hold  $27 \text{ cm}^3$  of water (or other liquid beverage). Find the height and radius of the cup that will use the smallest amount of paper.
4. Find the closest point on the hyperbola  $x^2 - 2x - y^2 = 2$  to the following points. You may find it useful to complete the square and parameterise the hyperbola (it's easier than dealing with solving the hyperbola equation for  $x$  or  $y$ ).
  - (a) (2, 1).
  - (b) (3, 1).

## CHAPTER 3

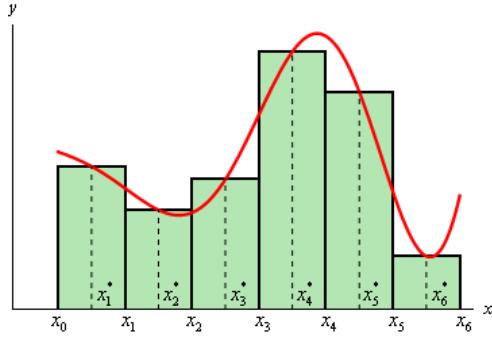
# Integration

## NCEA Level 3 Calculus (Integration)

### 15. Approximating Areas

We now move from finding rates of change of curves to finding areas under curves. Just as for differentiation, we begin by finding finite approximations to area.

#### Approximating area using rectangles



We start with the simplest and most naive approximation: using a bunch of rectangles under the curve. Suppose we wish to find the area under the curve  $y = f(x)$  between the two lines  $x = a$  and  $x = b$  by splitting it up into  $n$  rectangles of width  $\Delta x$ . If we pick a value  $x_i^*$  inside each rectangle, as shown in the diagram, the approximate area is

$$f(x_1^*)\Delta x + \cdots + f(x_n^*)\Delta x = \sum_{i=1}^n f(x_i^*)\Delta x.$$

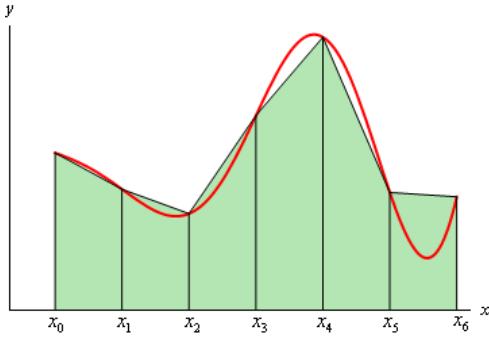
Usually, we pick each  $x_i^*$  to be either the left-hand or right-hand edge of each rectangle. Note that we also have  $\Delta x = \frac{b-a}{n}$  and so our left-hand approximation becomes

$$L_n = \frac{b-a}{n} [f(x_0) + \cdots + f(x_{n-1})]$$

and the right-hand approximation is

$$R_n = \frac{b-a}{n} [f(x_1) + \cdots + f(x_n)].$$

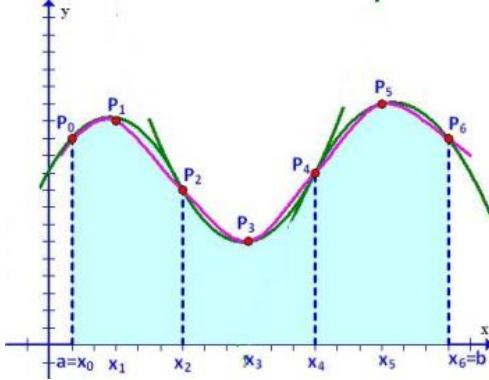
#### Approximating area using trapezoids



A more useful approximation is found when we inscribe trapezoids into the curve. This can be done by taking the average of the left-hand and right-hand rectangle approximations (recall that the area of a trapezoid is the average of the area of two rectangles). When we do this, we obtain

$$T_n = \frac{b-a}{2n} \left( f(x_0) + f(x_n) + 2 [f(x_2) + \cdots + f(x_{n-1})] \right).$$

### Approximating area using parabolae



An even better approximation (for smooth functions) is formed when we use parabolae to estimate the area. The resulting formula is called *Simpson's rule*. Note that  $n$  must be even to use Simpson's rule.

$$S_n = \frac{b-a}{3n} \left( f(x_0) + f(x_n) + 4 [f(x_1) + f(x_3) + \cdots + f(x_{n-1})] + 2 [f(x_2) + \cdots + f(x_{n-2})] \right).$$

### The Definite Integral

It is obvious that all three methods of approximating area above will approach the ‘real’ area of the curve as  $n \rightarrow \infty$ . We call the true area under a curve  $y = f(x)$  from  $x = a$  to  $x = b$  the *definite integral* of the curve from  $a$  to  $b$ , and we notate it as

$$\lim_{n \rightarrow \infty} R_n = \lim_{n \rightarrow \infty} L_n = \lim_{n \rightarrow \infty} T_n = \lim_{n \rightarrow \infty} S_n = \int_a^b f(x) dx.$$

The large  $\int$  is an elongated ‘S’, which stands for **sum** — we are summing all of the little areas from  $a$  to  $b$ . Note the similarity to the notation above: we replace  $\sum$  with  $\int$ ,  $x_i^*$  with  $x$ , and  $\Delta x$  with  $dx$ .

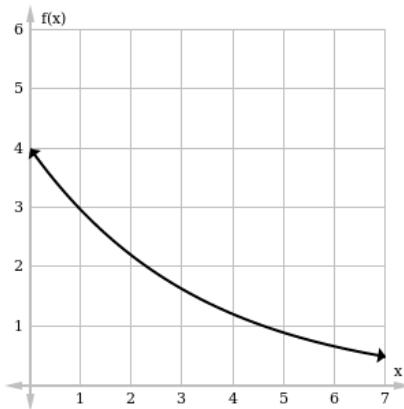
The  $dx$  is **not a number**; it is merely a piece of notation which tells us which variable we are taking area with respect to. For example,  $\int_a^b x^2 + y^3 dx \neq \int_a^b x^2 + y^3 dy$ . At this stage in time, you can think of the notation as a pair of fancy brackets: the  $\int_{z_0}^{z_1}$  corresponds to  $($ , and the  $dz$  corresponds to  $)$ . It makes no sense to have one without the other (or, for that matter, to have  $\int$  without the bounds).

## Questions

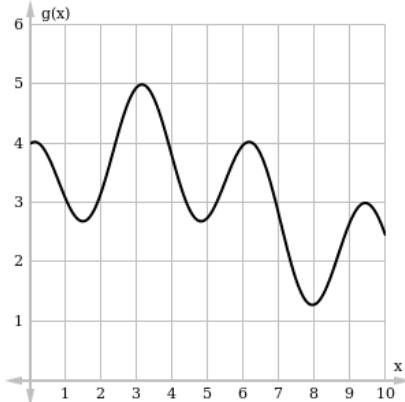
1.  A Estimate the area under the graph of  $f(x) = \cos x$  from  $x = 0$  to  $x = \frac{\pi}{2}$  using four approximating rectangles and right endpoints. Sketch the graph and the rectangles. Is your estimate an overestimate or an underestimate?
2.  A Estimate the area under the graph of  $f(x) = \sqrt{x}$  from  $x = 0$  to  $x = 4$  using four approximating rectangles and left endpoints. Sketch the graph and the rectangles. Is your estimate an overestimate or an underestimate?
3.  A Using the trapezoidal rule with  $n = 4$ , estimate the area under the graph of  $f(x) = 1 + x^2$  from  $x = -1$  to  $x = 2$ . Repeat with  $n = 8$ . Compare the two results.
4.  A Use Simpson's rule with  $n = 10$  to estimate the area under the graph of  $y = e^{x^2}$  from  $x = 0$  to  $x = 1$ .
5.  A Use both the trapezoidal rule and Simpson's rule (both with  $n = 10$ ) to compute the area under the graph of  $y = \sqrt{ze^{-z}}$  from  $z = 0$  to  $z = 1$ .
6.  A Using four rectangles, find the approximate area under the graph of  $f(x)$  from  $x = 1$  to  $x = 5$  given the following table.

$x$	$f(x)$	$x$	$f(x)$
1.0	2.4	3.5	4.0
1.5	2.9	4.0	4.1
2.0	3.3	4.5	3.9
2.5	3.6	5.0	3.5
3.0	3.8		

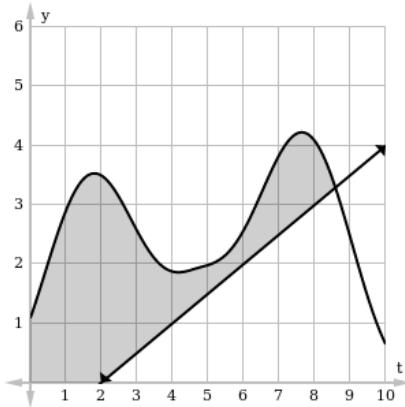
7.  M Find the area of a circle of radius 4 using Simpson's rule with  $n = 4$ . What is the percentage error of the estimate?
8.  A Approximate the area under  $y = f(x)$  from  $x = 0$  to  $x = 6$  using Simpson's rule.



9. A Approximate the area under  $y = f(x)$  from  $x = 0$  to  $x = 10$  using the trapezoidal rule.



10. M Approximate the shaded area using the trapezoidal rule.



11. M Show that  $T_n = \frac{1}{2}(L_n + R_n)$ .

12. A (Lifted straight from a Level 2 worksheet.)

- Draw the line  $y = 2t + 1$  and use geometry to find the area under this line, above the  $t$ -axis, and between the vertical lines  $t = 1$  and  $t = 3$  (i.e. find  $\int_1^3 2t + 1 dt$  using geometry).
- If  $x > 1$ , let  $A(x)$  be the area of the region that lies under the line  $y = 2t + 1$  between  $t = 1$  and  $t = x$ . Sketch this region and use geometry to find an expression for  $A(x)$  (i.e. find  $A(x) = \int_1^x 2t + 1 dt$  using geometry).
- Find  $A'(x)$ . What do you notice?

## NCEA Level 3 Calculus (Integration)

### 15. Approximating Areas (Homework)

#### Reading

*Engineering is like dancing; you don't learn it in a darkened lecture hall watching slides: you learn it by getting out on the dance floor and having your toes stepped on.* - Professor Jack Alford (1920–2006). The same can be said for doing definite integrals.

To really appreciate this book, one dedicated to the arcane art of calculating definite integrals, it is necessary (although perhaps it is not sufficient) that you be the sort of person who finds the following question fascinating, one right up there in a fierce battle with a hot cup of coffee and a sugar donut for first place on the list of sinful pleasures: without actually calculating  $x$ , show that if  $x + \frac{1}{x} = 1$  then it follows that  $x^7 + \frac{1}{x^7} = 1$ .

Okay, I know what many (but, I hope, not *you*) are thinking at being confronted with a question like this: of what Earthly significance could such a problem possibly have? Well, none as far as I know, but its fascination (or not) for you provides (I think) excellent psychological insight into whether or not you should spend time and/or good money on this book. If the problem leaves someone confused, puzzled, or indifferent (maybe all three) then my advice to them would be to put this book down and to look instead for a good mystery novel, the latest Lincoln biography (there seems to be a new one every year — what could possibly be left unsaid?), or perhaps a vegetarian cookbook.

*But*, if your pen is already out and scrawled pages of calculations are beginning to pile-up on your desk, then by gosh you *are* just the sort of person for whom I wrote this book. More specifically, I've written with three distinct types of readers in mind: (1) physics/engineering/math students in their undergraduate years; (2) professors looking for interesting lecture material; and (3) nonacademic professionals looking for a 'good technical read.'

There are two possible concerns associated with calculating definite integrals that we should address with no delay. First, do *real* mathematicians actually do that sort of thing? Isn't mere *computation* the dirty business (best done out of sight, in the shadows of back-alleys so as not to irreparably damage the young minds of impressionable youths) of grease-covered engineers with leaky pens in their shirts, or of geeky physicists in rumpled pants and chalk dust on their noses? Isn't it in the deep, clear ocean of analytical proofs and theorems where we find *real* mathematicians, swimming like powerful, sleek seals? As an engineer, myself, I find that attitude just a bit elitist, and so I am pleased to point to the pleasure in computation that many of the great mathematicians enjoyed, from Newton to the present day.

Let me give you two examples of that. First, the reputation of the greatest English mathematician of the first half of the twentieth century, G.H. Hardy (1877–1947), partially rests on his phenomenal skill at doing definite integrals. (Hardy appears in numerous places in this book.) And second, the hero of this book (Riemann) is best known today for (besides his integral) his formulation of the greatest unsolved problem in mathematics, about which I'll tell you lots more at the end of the book. But after his death, when his private notes on that very problem were studied, it was found that imbedded in all the deep theoretical stuff was a calculation of  $\sqrt{2}$ . To 38 decimal places!

The other concern I occasionally hear strikes me as just plain crazy; the complaint that there is no end to definite integrals. (This should, instead, be a cause for joy.) You can fiddle with integrands, and with upper and lower limits, in an uncountable infinity of ways, goes the grumbling, so what's the point of calculating definite integrals since you can't possibly do them all? I hope writing this concern out in words is sufficient to make clear its ludicrous nature. We can never do all possible definite integrals, so why bother doing any? Well, what's next—you can't possibly add together all possible pairs of the real numbers, so why bother learning to add? Like I said—that's nuts!

What makes doing the specific integrals in this book of value aren't the specific answers we'll obtain, but

rather the tricks (excuse me, the methods) we'll use in obtaining those answers; methods you may be able to use in evaluating the integrals you will encounter in the future in your own work. Many of the integrals I'll show you do have important uses in mathematical physics and engineering, but others are included just because they look, at first sight, to be so damn tough that it's a real kick to see how they simply crumble away when attacked with *the right trick*.

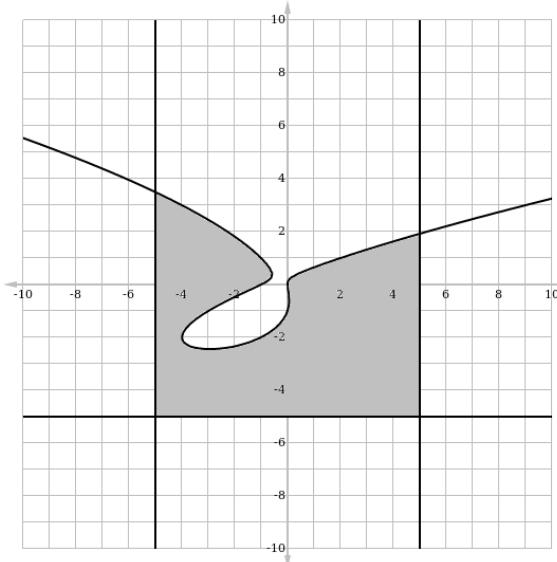
From *Inside Interesting Integrals*, by Paul J. Nahin.

## Questions

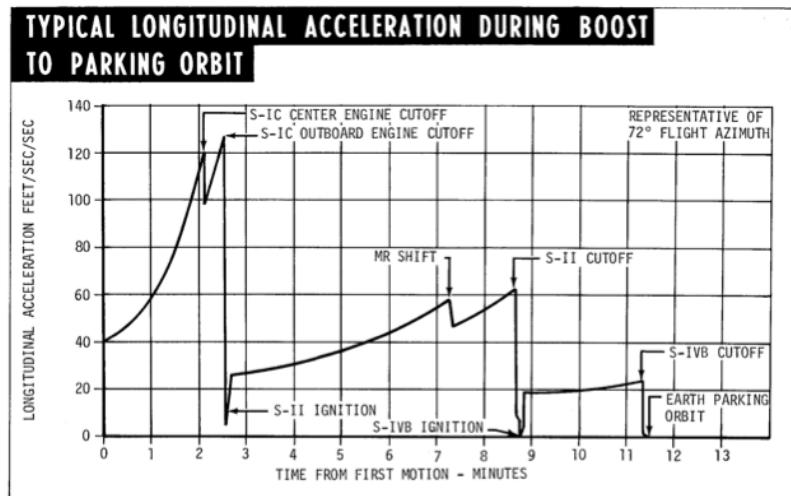
1. Using the following table of values, estimate  $\int_0^{1.6} g(x) dx$ .

$x$	$g(x)$	$x$	$g(x)$
0.0	12.1	1.0	12.2
0.2	11.6	1.2	12.6
0.4	11.3	1.4	13.0
0.6	11.1	1.6	13.2
0.8	11.7		

2. Estimate the shaded area.



3. The following graph shows the acceleration of a rocket from launch until it reaches orbit. Given that the initial velocity of the rocket was  $0 \text{ ft s}^{-1}$ , find the final velocity of the rocket.



## NCEA Level 3 Calculus (Integration)

### 16. Anti-differentiation

A few weeks ago when we looked at kinematics, I hinted that finding area was in some way the inverse to finding slope. In last week's questions, the curtain was pulled back a little further when we calculated an area function for a variable endpoint, took the derivative, and got the original function back. Next week, all will be revealed; but first, we need to do a little bit more work. This week, we're going to look at *anti-differentiation*: finding the original function given its derivative.

**Example.** One antiderivative of  $y' = 3x^2 + 4$  is  $x^3 + 4x$ . Another is  $x^3 + 4x + 1$ . A third is  $x^3 + 4x + 7$ . Obviously every function of the form  $y = x^3 + 4x + C$  for some constant  $C$  will differentiate to the given  $y'$ , so we must remember always to make this clear.

We also call antiderivatives **indefinite integrals**, and in this notation the above example is

$$\int 3x^2 + 4 \, dx = x^3 + 4x + C.$$

**Example.** The most general antiderivative of  $\sin x$  is  $-\cos x + C$ .

**Example.** The most general antiderivative of  $\tan x$  is  $-\ln|\cos x| + C$ .

**Example.**  $\int \frac{1}{x+3} \, dx = \ln|x+3| + C$ .

**Example.**  $\int \tan^2 \theta \, d\theta = \int \sec^2 \theta - 1 \, d\theta = \tan \theta - \theta + C$ .

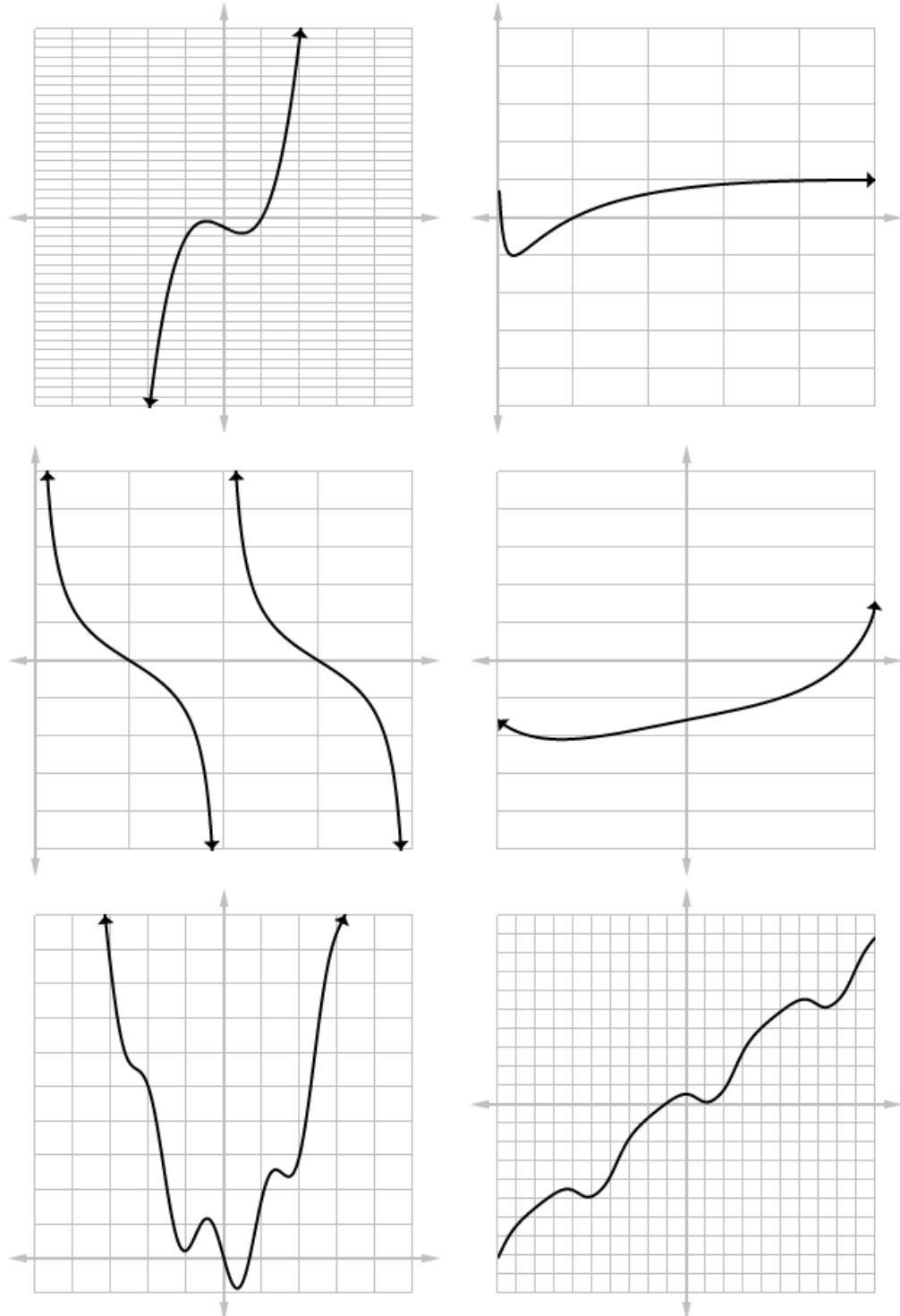
**Example.**  $\int \frac{2x}{x^2+1} \, dx = \ln|x^2+1| + C$ .

**Example.**  $\int K e^{Kx} \, dx = e^{Kx} + C$  for all constants  $K$ .

### Questions

1. A In each case, find the most general antiderivative.
  - (a)  $f(x) = 2x$
  - (b)  $f(x) = x^{-3}$
  - (c)  $f(x) = 0$
  - (d)  $f(x) = \sec^2(x) + \sqrt{x}$
  - (e)  $f(x) = x\sqrt{x}$
  - (f)  $f(t) = \sin t - \cos t$
2. A Verify the above examples by differentiation.
3. A Show that  $\int 3x^2 + 4x + 5 + 2e^{2x} \, dx = x^3 + 2x^2 + 5x + e^{2x} + C$ .
4. A Find  $y'$  when  $y = 3 + \sin(2x + 4)$  and hence find  $\int 2 \cos(2x + 4) \, dx$ .
5. A If  $\frac{dy}{dt} = 1.5\sqrt{t}$  and  $y(4) = 10$ , find  $y(t)$  exactly.
6. M Find  $f$  if  $f''(x) = 12x^2 + 6x - 4$ ,  $f(0) = 4$ ,  $f(1) = 1$ .
7. A The velocity of a particle is given by  $v(t) = 2t + 1$ . Find its position at  $t = 4$  if its position at  $t = 0$  is  $x = 0$ .
8. M The acceleration of a particle is given by  $a(t) = 10 \sin t + 3 \cos t$ . At  $t = 0$ , its position is  $x = 0$ ; at  $t = 2\pi$ , its position is  $x = 12$ . Find its position at  $t = \frac{\pi}{2}$ .
9. A Find all functions  $g$  such that  $g'(x) = 4 \sin x + \frac{2x^5 - \sqrt{x}}{x}$ .

10.  For each function, sketch an antiderivative passing through  $(0, 0)$ :



## NCEA Level 3 Calculus (Integration)

### 16. Anti-differentiation (Homework)

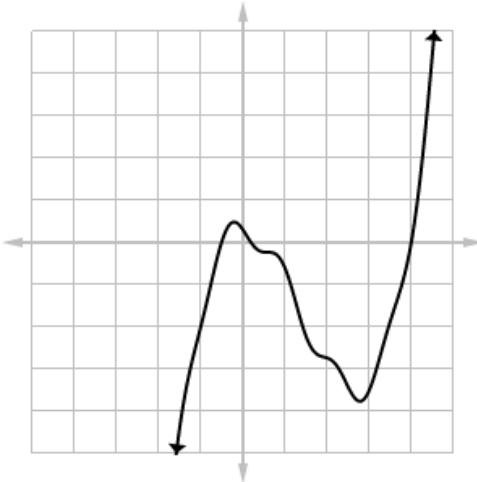
#### Reading

Go and watch...

<https://www.youtube.com/watch?v=7dcDuVyzb8Y>

#### Questions

1. Find the most general antiderivative.
  - (a)  $f(x) = x - 3$
  - (b)  $f(x) = (x + 1)(x + 2)$
  - (c)  $f(\theta) = 6\theta^2 - 7 \sec^2 \theta$
  - (d)  $g(h) = \pi^2$
  - (e)  $f(x) = x^{3.7} + \sqrt{x} + 7x^{\sqrt{7}-1}$
2. Given that the graph of  $\varphi$  passes through the point  $(1, 6)$  and that the slope of its tangent line at  $(x, \varphi(x))$  is  $2x + 1$ , find  $\varphi(2)$ .
3. This is the second derivative of  $g$ . Find  $g$  given that  $g'(0) = 0$  and  $g(0) = 1$ .



## NCEA Level 3 Calculus (Integration)

### 17. The Fundamental Theorem of Calculus

**Theorem** (First Fundamental Theorem)

Suppose  $f$  is a continuous function, and suppose  $F$  is any antiderivative of  $f$  (so  $F' = f$ ). Then:

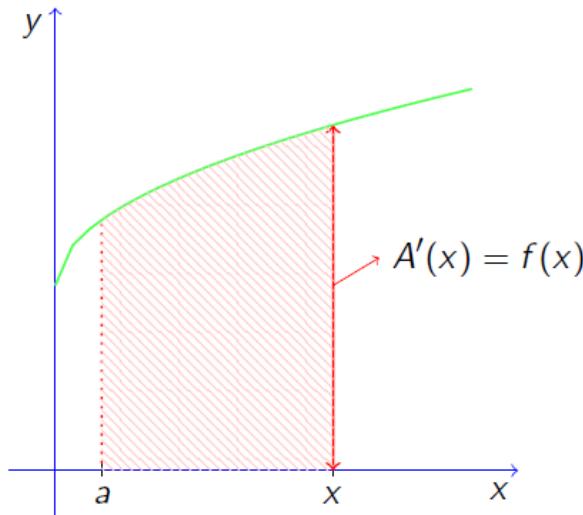
$$\int_a^b f(x) dx = F(b) - F(a) = F(x) \Big|_a^b$$

In other words, the definite integral of a function can be found by evaluating the indefinite integrals at the endpoints.

**Theorem** (Second Fundamental Theorem)

Suppose  $f$  is a continuous function. Then:

$$\frac{d}{dx} \int_a^x f(t) dt = f(x)$$



The rate of change of the area under a curve is simply the height of the curve.

We also have the following theorem:

**Theorem.** Suppose  $f, g$  are functions and  $\lambda$  is a real constant. Then:

1.  $\lambda \int_a^b f(x) dx = \int_a^b \lambda f(x) dx.$
2.  $\int_a^b f(x) dx + \int_a^b g(x) dx = \int_a^b f(x) + g(x) dx.$
3.  $\int_a^a f(x) dx = 0.$
4.  $\int_a^b f(x) dx + \int_b^c f(x) dx = \int_a^c f(x) dx.$

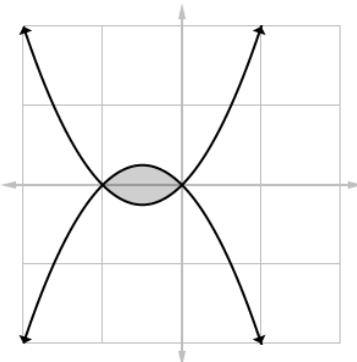
Note that the areas below a curve are assigned **NEGATIVE AREA**.

**Example.** Note that the definite integral  $\int_0^\pi \cos(x) dx$  is equal to 0; this is because the (negative) area under the  $x$ -axis exactly cancels the (positive) area above the  $x$ -axis. (Draw a picture.)

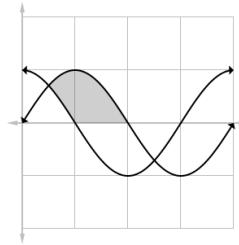
## Questions

1. A Compute the following definite integrals.
    - (a)  $\int_0^1 dx$
    - (b)  $\int_{-1}^1 e^x dx$
    - (c)  $\int_3^4 x^2 + 3x - 1 dx$
    - (d)  $\int_0^1 x^n dx$  for integer values of  $n$ .
  2. A Find the area underneath the given curves between the given bounds:
    - (a)  $y = 6x^2 + 4x + 9$  between  $x = 0$  and  $x = 4$
    - (b)  $y = \sin x$  between  $x = 0$  and  $x = \pi$
    - (c)  $y = \sin x$  between  $x = -\pi$  and  $x = \pi$
    - (d)  $y = \cos x$  between  $x = -\pi$  and  $x = \pi$
    - (e)  $y = \frac{1}{x}$  between  $x = 1$  and  $x = 2$
  3. A Find all the problems in the following working.
- $$\int_1^{-1} \frac{dx}{x} = \ln|-1| - \ln|1| = 0$$
4. A Show that  $\int \ln x dx = x \ln x - x + C$ .
  5. M Let  $f$  be a function such that for all  $x$ ,  $f(-x) = -f(x)$ . Such a function is called *odd*. Show that for all  $a$ ,
- $$\int_{-a}^a f(x) dx = 0.$$
- What does this mean geometrically?
6. M Let  $f$  be an odd function with period 2 such that  $\int_0^1 f(x) dx = k$ . Compute:
    - (a)  $\int_{-1}^1 f(x) dx$
    - (b)  $\int_0^{-1} f(x) dx$
  7. A Let  $f$  be a function such that for all  $x$ ,  $f(-x) = f(x)$ . Such a function is called *even*. Show that for all  $a$ ,
- $$\int_{-a}^a f(x) dx = 2 \int_0^a f(x) dx.$$
- What does this mean geometrically?
8. M If  $\int_{-2}^1 f(x) dx = 2$  and  $\int_1^3 f(x) dx = -6$ , what is the value of  $\int_{-2}^3 f(x) dx$ ?

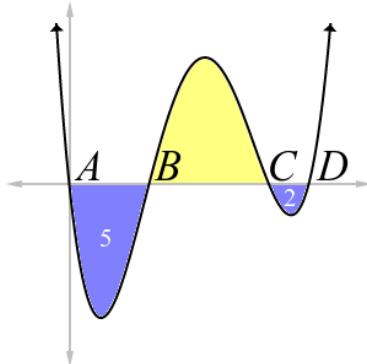
9. **M** Find the area between the curves  $y = x^2 + x$  and  $y = -x^2 - x$  shaded here.



10. **M** Find the area between the two curves  $y = 1 + x^2$  and  $y = 3 + x$ .
11. **M** Find the area of the region bounded by  $f(x) = 4$ ,  $g(x) = \frac{e^x}{5}$ , and  $x = 0$ .
12. **M** What is the area of the region between the graphs of  $f(x) = 2x^2 + 5x$  and  $g(x) = -x^2 - 6x + 4$  from  $x = -4$  to  $x = 0$ ?
13. **E** Find the area bounded by the curves  $y = \sin x$  and  $y = \cos x$  and the  $x$ -axis graphed here.



14. **A** Consider the function  $f$  graphed below; the total **unsigned** area between the curve and the  $x$ -axis is 10 square units. Find  $\int_A^D f(x) dx$ .



15. **M**
- Sketch the graph of  $y = |\sin x|$ .
  - Compute  $\int_0^{\pi/2} y dx$  using the FTC.
  - Hence, without doing any anti-differentiation, compute  $\int_0^{2\pi} y dx$ .

16. M Define  $F(x)$  by

$$F(x) = \int_{\frac{\pi}{4}}^x \cos(2t) dt.$$

- (a) Use the Second Fundamental Theorem of Calculus to find  $F'(x)$ .
- (b) Verify part (a) by integration and differentiation.

17. M Compute  $\frac{d}{dx} \int_2^x t^t dt$ .

**NCEA Level 3 Calculus (Integration)****17. The Fundamental Theorem of Calculus (Homework)****Reading**

This is an explanation with visualisations of why the FTC is true (but is not a proof); it follows the same kind of reasoning that I use in the calculus notes: <https://www.youtube.com/watch?v=FnJqaIESC2s>.

**Questions**

1. Evaluate

$$\int_0^{\frac{\pi}{4}} \sec^2 \theta \, d\theta$$

2. If  $\int_1^3 f(x) \, dx = 7$  and  $\int_2^3 f(x) \, dx = -3$ , what is the value of  $\int_1^2 f(x) \, dx$ ?

3. Find the area enclosed between the graphs of  $3y = x^2$  and  $y = 2x$ .

## NCEA Level 3 Calculus (Integration)

### 18. Substitution

Recall that the *chain rule* is:

$$\frac{d}{dx}[f(g(x))] = f'(g(x))g'(x)$$

Since integration is (in some sense) the inverse of differentiation, we can write:

$$\int f'(g(x))g'(x) dx = f(g(x)) + C.$$

For a mnemonic, we can let  $u = g(x)$ . Then  $du = g'(x) dx^*$ , and then (by substitution) we have

$$\int f'(g(x))g'(x) dx = \int f'(u) du = f(u) + C = f(g(x)) + C.$$

**Example.** Suppose we wish to find  $\int \sin x \cos x dx$ . Then let  $u = \sin x$ , so  $du = \cos x dx$  and

$$\int \sin x \cos x dx = \int u du = \frac{1}{2}u^2 + C = \frac{1}{2}\sin^2 x + C.$$

In this case, we also could have used a trigonometric identity.

**Example.** Suppose we wish to find  $\int xe^{x^2} dx$ . We can let  $u = x^2$ , and then  $du = 2x dx \Rightarrow dx = \frac{du}{2x}$ . Hence:

$$\int xe^{x^2} dx = \int \frac{1}{2}e^u du = \frac{1}{2}e^u + C = \frac{1}{2}e^{x^2} + C.$$

**Example.** Suppose we wish to find  $\int \frac{4}{x}(\ln x)^3 dx$ . We let  $u = \ln x$ , and then  $du = \frac{dx}{x}$ . Hence:

$$\int \frac{4}{x}(\ln x)^3 dx = 4 \int u^3 du = u^4 + C = (\ln u)^4 + C.$$

### Questions

1. A Find the following indefinite integrals:

- (a)  $\int \sin 2x dx$
- (b)  $\int (4x - 44)^{2019} dx$
- (c)  $\int 4x\sqrt{x^2 + 3} dx$
- (d)  $\int (3t - 4)^2 dx$
- (e)  $\int \frac{x}{x^2+1} dx$
- (f)  $\int \frac{2}{4x+3} dx$
- (g)  $\int e^{2x+1} dx$
- (h)  $\int \sec 4x \tan 4x dx$
- (i)  $\int 2 \cos x + \sin 2x dx$
- (j)  $\int -2x \csc^2(3x^2) dx$
- (k)  $\int \frac{3}{x^3} - \frac{4}{x+1} dx$

\*this is not rigorous, but it ‘works’

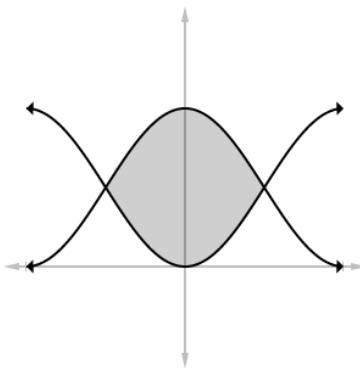
- (l)  $\int e^{x/2} + \frac{2}{x} dx$   
 (m)  $\int x^2 \sec^2 x^3 + 9 dx$   
 (n)  $\int -\csc(\tan x) \cot(\tan x) \sec^2 x dx$   
 (o)  $\int \frac{\cos x - \sin x}{\cos x + \sin x} dx$   
 (p)  $\int \frac{2017}{x \ln x} dx$

2. M By using the substitution  $x = \sin \theta$ , find

$$\int \frac{1}{\sqrt{1-x^2}} dx.$$

3. M Compute the following definite integrals:

- (a)  $\int_0^1 xe^{-x^2} dx$   
 (b)  $\int_{-\pi/3}^{\pi/3} x^4 \sin x dx$  (hint: no substitution is required)  
 (c)  $\int_0^1 \cos(\pi t/2) dt$   
 (d)  $\int_0^1 (3t-1)^{50} dt$   
 (e)  $\int_0^1 \sqrt[3]{1+7x} dx$   
 (f)  $\int_0^1 \frac{dx}{1+\sqrt{x}} dx$   
 (g)  $\int_{-1}^2 x(x-1)^3 dx$   
 (h)  $\int_0^3 x\sqrt{1+x^2} dx$
4. M Find the area enclosed by the curve  $y = 4 \sin 3x \cos x$  and the  $x$ -axis from  $x = 0$  to  $x = \frac{\pi}{3}$ .  
 5. E Find  $k$  such that  $\int_0^k e^{2x} dx = 40$ .  
 6. E Calculate the area enclosed by the curve  $y = \frac{3x-2}{x+4}$  and the lines  $y = 0$ ,  $x = 1$ , and  $x = 5$ .  
 7. E Find the area between the curves  $y = \sin^2 kx$  and  $y = \cos^2 kx$  shaded below.



8. M Find  $\int \tan \theta d\theta$  and  $\int \cot \theta d\theta$ .

9. A Complete the following working:

$$\begin{aligned}\int \sec x \, dx &= \int \sec x \frac{\sec x + \tan x}{\sec x + \tan x} \, dx \\ &= \int \frac{\dots}{\sec x + \tan x} \, dx\end{aligned}$$

Let  $u = \dots$

$$\begin{aligned}&= \int \frac{1}{\dots} \, du \\ &= \dots\end{aligned}$$

10. M Show that

$$\int x^4 \sin x \, dx = 4x(x^2 - 6x) \sin x - (x^4 - 12x^2 + 24) \cos x + C.$$

11. M If  $y = x\sqrt{\sin x^3 + \cos x^3}$ , find  $\pi \int_0^1 y^2 \, dx$ .

12. M The velocity of a particle at time  $t$  is given by  $v = \frac{\cos(\sqrt{2t+1})}{\sqrt{2t+1}}$ . What is the position of the particle at time  $t = 5$ , given that  $x(0.5) = 0$ ?

13. S Evaluate  $I = \int_0^{\pi/2} \frac{\sqrt{\sin x}}{\sqrt{\sin x + \sqrt{\cos x}}} \, dx$  [Hint: use the substitution  $x = \frac{\pi}{2} - u$  and add the result to the original integral.]

14. S Scholarship 1999:

- (a) Evaluate  $\int \cos^5 x \, dx$  using the substitution  $t = \sin x$ .

- (b) i. If  $f(x) = \cos^5 x$ , what are  $f(0)$ ,  $f'(0)$ , and  $f''(0)$ ?

- ii. Hence evaluate  $a$ ,  $b$ , and  $c$  in the approximation  $\cos^5 x \approx a + bx + cx^2$ .

- iii. Use this to give an approximation for  $\int \cos^5 x \, dx$ .

- (c) Evaluate  $\int_0^{0.6} \cos^5 x \, dx$  to three significant figures, using:

- i. The exact integration in (a).

- ii. The expression in (b)(iii).

- iii. Simpson's rule.

## NCEA Level 3 Calculus (Integration)

### 18. Substitution (Homework)

#### Reading

Historically, when Leibniz conceived of the notation,  $\frac{dy}{dx}$  was supposed to be a quotient: it was the quotient of the “infinitesimal change in  $y$  produced by the change in  $x$ ” divided by the “infinitesimal change in  $x$ ”. However, the formulation of calculus with infinitesimals in the usual setting of the real numbers leads to a lot of problems. For one thing, infinitesimals can’t exist in the usual setting of real numbers! Because the real numbers satisfy an important property, called the Archimedean Property: given any positive real number  $\varepsilon > 0$ , no matter how small, and given any positive real number  $N > 0$ , no matter how big, there exists a natural number  $n$  such that  $n\varepsilon > N$ . But an “infinitesimal”  $\xi$  is supposed to be so small that no matter how many times you add it to itself, it never gets to 1, contradicting the Archimedean Property. Other problems: Leibniz defined the tangent to the graph of  $y = f(x)$  at  $x = a$  by saying “Take the point  $(a, f(a))$ ; then add an infinitesimal amount to  $a$ ,  $a + dx$ , and take the point  $(a + dx, f(a + dx))$ , and draw the line through those two points.” But if they are two different points on the graph, then it’s not a tangent, and if it’s just one point, then you can’t define the line because you just have one point. That’s just two of the problems with infinitesimals. (See below where it says “However...”, though.) So Calculus was essentially rewritten from the ground up in the following 200 years to avoid these problems, and you are seeing the results of that rewriting. Because of that rewriting, the derivative is no longer a quotient, now it’s a limit:

$$\lim_{h \rightarrow 0} \frac{f(x + h) - f(x)}{h}$$

And because we cannot express this limit-of-a-quotient as a-quotient-of-the-limits (both numerator and denominator go to zero), then the derivative is not a quotient. However, Leibniz’ notation is very suggestive and very useful; even though derivatives are not really quotients, in many ways they behave as if they were quotients. So we have the Chain Rule:

$$\frac{dy}{dx} = \frac{dy}{du} \frac{du}{dx}$$

which looks very natural if you think of the derivatives as “fractions”. You have the Inverse Function theorem, which tells you that

$$\frac{dx}{dy} = 1 / \frac{dy}{dx}$$

which is again almost “obvious” if you think of the derivatives as fractions. So, because the notation is so nice and so suggestive, we keep the notation even though the notation no longer represents an actual quotient, it now represents a single limit. In fact, Leibniz’ notation is so good, so superior to the prime notation and to Newton’s notation, that England fell behind all of Europe for centuries in mathematics and science because, due to the fight between Newton’s and Leibniz’ camp over who had invented Calculus and who stole it from whom (consensus is that they each discovered it independently), England’s scientific establishment decided to ignore what was being done in Europe with Leibniz’ notation, stuck to Newton’s, and got stuck in the mud in large part because of it. So, even though we write  $\frac{dy}{dx}$  as if it were a fraction, and many computations look like we are working with it like a fraction, it isn’t really a fraction (it just plays one on television). However... There is a way of getting around the logical difficulties with infinitesimals; this is called nonstandard analysis. It’s pretty difficult to explain how one sets it up, but you can think of it as creating two classes of real numbers: the ones you are familiar with, that satisfy things like the Archimedean Property, the Supremum Property, and so on, and then you add another, separate class of real numbers that includes infinitesimals and a bunch of other things. If you do that, then you can, if you are careful, define derivatives exactly like Leibniz, in terms of infinitesimals and actual quotients; if you do that, then all the rules of Calculus that make use of  $\frac{dy}{dx}$  as if it were a fraction are justified because, in that setting, it is a fraction. Still, one has to be careful because you have to keep infinitesimals and regular real numbers separate and not let them get confused, or you can run into some serious problems.

From <https://math.stackexchange.com/questions/21199/is-frac-dy-dx-not-a-ratio>.

## Questions

1. Calculate the following indefinite integrals:
  - (a)  $\int -\csc 3x \cot 3x \, dx$
  - (b)  $\int -x \sec^2 3x^2 \, dx$
  - (c)  $\int \frac{\sqrt{x}+3x-2}{x} \, dx$
  - (d)  $\int \sin^3 x \cos^2 x \, dx$  (hint: use  $\sin^2 x = 1 - \cos^2 x$  to rewrite the integrand)
2. Find the area enclosed between the curve  $y = 2 \sin 5x \cos 3x$  and the  $x$ -axis from  $x = 0$  to  $x = \frac{\pi}{6}$ .
3. Recall that  $\frac{d}{dx} \tan^{-1} x = \frac{1}{1+x^2}$ . Find  $\int \frac{x}{1+x^4} \, dx$ .

## NCEA Level 3 Calculus (Integration)

### 19. Differential Equations

Suppose  $\frac{dy}{dx} = f(x)g(y)$ . It would be nice if we could find  $y$  in terms of  $x$  only. This is in fact possible, using substitution:

$$\begin{aligned}\frac{dy}{dx} &= f(x)g(y) \\ \Rightarrow \frac{1}{g(y)} \frac{dy}{dx} &= f(x) \\ \Rightarrow \int \frac{1}{g(y)} \frac{dy}{dx} dx &= \int f(x) dx.\end{aligned}$$

Now, let  $G(y)$  be an antiderivative of  $\frac{1}{g(y)}$  (with respect to  $y$ ). By the chain rule, then,

$$\frac{d}{dx} G(y) = \frac{1}{g(y)} \frac{dy}{dx}$$

and so

$$\int \frac{1}{g(y)} \frac{dy}{dx} dx = G(y) = \int \frac{1}{g(y)} dy.$$

Hence we have

$$\int \frac{1}{g(y)} dy = \int f(x) dx$$

This way of solving *differential equations* is called *separation of variables*.

**Example.** Suppose we know that  $y \frac{dy}{dx} = e^x$ . Then we can separate the variables:

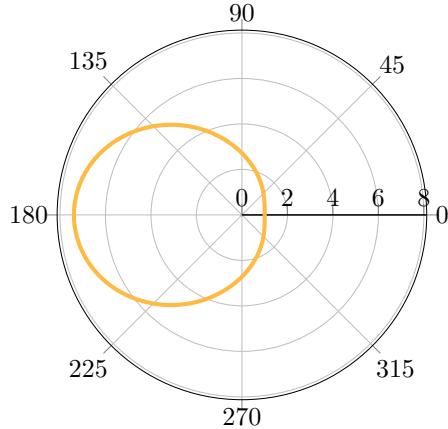
$$\begin{aligned}\int y dy &= \int e^x dx \\ \Rightarrow \frac{1}{2}y^2 &= e^x + C \\ \Rightarrow y^2 &= 2e^x + C.\end{aligned}$$

If we know that the curve passes through  $(0, 0)$ , then  $0 = 2e^0 + C$  and  $C = -2$ , so  $y^2 = 2e^x - 2$ .

To check our answer, let us now use implicit differentiation to differentiate this curve. We have  $2y \frac{dy}{dx} = 2e^x$  and  $y \frac{dy}{dx} = e^x$  as expected so our solution is correct.

**Example.** Suppose that  $r(\theta)$  is implicitly defined by  $\frac{dr}{d\theta} = r \sin \theta$  with the condition  $r(\pi) = e$ . Graph  $r(\theta)$ .

Separating variables, we have  $\int \frac{dr}{r} = \int \sin \theta d\theta$ ; so  $\ln|r| = -\cos \theta + C$  and therefore  $r = Ke^{-\cos \theta}$  for some constant  $K$ . But  $e = Ke^{-\cos \pi} = Ke^0 = K$ ; so  $r(\theta) = ee^{-\cos \theta} = e^{1-\cos \theta}$ . Graphing this:



## Questions

1. M Find  $y$  in terms of  $x$  in each case, if each curve passes through  $(1, 1)$ :
  - (a)  $\frac{dy}{dx} = yx$
  - (b)  $\frac{dy}{dx} + x = yx$
  - (c)  $\frac{dy}{dx} + y = yx$
  - (d)  $\sqrt{y}\frac{dy}{dx} = \frac{1}{x}$
  - (e)  $\frac{dy}{dx} = (x + 2)^2$
  - (f)  $\frac{dy}{dx} = \frac{y^2+1}{2y}e^x$
  - (g)  $\frac{dy}{dx} = x \cos^2 y$
  - (h)  $\frac{dy}{dx} = \sin x \tan y$
  - (i)  $2y\frac{dy}{dx} = x^3 + 2x + 1$
  - (j)  $\sin y\frac{dy}{dx} = 3x$
  - (k)  $\frac{dy}{dx} = \frac{x(e^{x^2}+2)}{6y^2}$
2. E
  - (a) Show that one antiderivative of  $f(x) = x \sin x \, dx$  is  $F(x) = \sin x - x \cos x$ .
  - (b) Find  $y(\pi)$  if  $y(0) = \pi$  and
$$\frac{dy}{d\theta} = \theta y \sin \theta.$$
3. E Newton's law of cooling states that the rate of heat loss of a body is directly proportional to the difference in the temperatures between the body and its surroundings; in other words, if the temperature of the body at time  $t$  is  $T$  and the ambient temperature is  $T_\infty$  then  $\frac{dT}{dt} = -k(T - T_\infty)$  (where  $k$  is some constant.)
  - (a) A loaf of bread is taken from the oven at a temperature of  $400^\circ\text{C}$  and is set down on a bench in an area with an ambient temperature of  $20^\circ\text{C}$ . It is found that it takes ten minutes for the loaf to cool to half its initial temperature. How many minutes will it take for the loaf to cool to  $30^\circ\text{C}$ ?
  - (b) A detective is called to the scene of a crime where a dead body has just been found. She arrives on the scene at 10:23 pm and begins her investigation. Immediately, the temperature of the body is taken and is found to be  $24^\circ\text{C}$ . The detective checks the programmable thermostat and finds that the room has been kept at a constant  $20^\circ\text{C}$  for the past 3 days.

After evidence from the crime scene is collected, the temperature of the body is taken once more and found to be  $22^\circ\text{C}$ . This last temperature reading was taken exactly one hour after the first one. Assuming that the victim's body temperature was normal ( $37.5^\circ\text{C}$ ) prior to death, at what time did the victim die?
4. E We will apply calculus concepts to chemical rates of reaction.
  - (a) A *first-order reaction* is one whose rate depends linearly on the concentration of one reactant  $A$ ; in other words,  $-\frac{d[A]}{dt} = k[A]$ .

One example of a first-order reaction is the decomposition of hydrogen peroxide:

$$2 \text{H}_2\text{O}_2(\text{aq}) \longrightarrow 2 \text{H}_2\text{O} + \text{O}_2(\text{g})$$

What percentage of hydrogen peroxide will have decomposed after 600 seconds, if the reaction constant is  $k = 6.40 \times 10^{-5} \text{ s}^{-1}$ ?

- (b) If a reaction depends linearly on the concentrations of two reactants,  $A$  and  $B$  (as in  $\text{A} + \text{B} \longrightarrow \text{C}$ ) then the rate of reaction is given by

$$-\frac{d[A]}{dt} = -\frac{d[B]}{dt} = \frac{d[C]}{dt} = k[A][B].$$

If we consider the reaction  $\text{NO}_2 + \text{CO} \longrightarrow \text{CO}_2 + \text{NO}$ , the rate is experimentally found to be *second-order* in the reactant  $\text{NO}_2$  and independent of the concentration of carbon monoxide. It follows that the rate of reaction is

$$\frac{d[\text{NO}_2]}{dt} = -k[\text{NO}_2]^2$$

where  $k$  is some constant.

Initially, the concentration of  $\text{NO}_2$  is  $2.0 \text{ mol L}^{-1}$ ; after ten minutes, the concentration has decreased to  $1.0 \text{ mol L}^{-1}$ . How long will it take for the concentration to become  $0.5 \text{ mol L}^{-1}$ ?

5. M It is known that the motion of a particle is described by the differential equation

$$v = \frac{4 \sin(2t)}{x}.$$

Initially, the particle is two metres away from the origin in the positive  $x$ -direction. Find the particle's position after ten seconds.

6. M Suppose that  $y'(x) = e^{x+2y}$ , and  $y(0) = 0$ . Find  $y(x)$  explicitly.

7. M Recall from physics that **simple harmonic motion** occurs when the force  $F$  on an object is proportional to (and opposite in direction to) its displacement  $x$  from some zero point ( $F = -kx$ ). Recall also that Newton's second law tells us that the acceleration felt by an object of mass  $m$  is given by  $\frac{d^2x}{dt^2} = \frac{F}{m}$ . We wish to find a formula for  $x$ , the displacement of the object, at time  $t$ . We have:

$$\frac{d^2x}{dt^2} = -\frac{kx}{m}$$

Show that  $x = A \cos(\sqrt{k/m} \cdot t)$  is a solution of the given differential equation.

8. S Consider the general wave equation,  $y = A \sin(kx - \omega t)$  (where  $A$ ,  $k$ , and  $\omega$  are constant). We write  $\frac{\partial y}{\partial x}$  for the derivative of  $y$  with respect to  $x$  holding  $t$  constant, and  $\frac{\partial y}{\partial t}$  for the derivative of  $y$  with respect to  $t$  keeping  $x$  constant.

Show that  $\frac{\partial^2 y}{\partial t^2} = c^2 \frac{\partial^2 y}{\partial x^2}$  for some constant  $c$ .

9. S Physics: Write down a differential equation modelling the charge on the capacitor in an RC circuit over time. Solve the equation.

10. S Scholarship 2000: The piriform is the curve defined by the equation  $16y^2 = x^3(8 - x)$  where  $x \geq 0$ . By solving the differential equation

$$\frac{dy}{dx} = \frac{x^2(6 - x)}{8y}$$

( $y = 0$  when  $x = 0$ ), show the piriform is the solution.

11. S Scholarship 2015: Determine all differentiable equations of the form  $y = f(x)$  which have the properties:

$$f'(x) = (f(x))^3 \text{ and } f(0) = 2$$

## NCEA Level 3 Calculus (Integration)

### 19. Differential Equations (Homework)

#### Reading

So far, we have looked at equations where the unknown is either a number or a point in  $n$ -dimensional space (that is, a sequence of  $n$  numbers). In order to generate these equations, we took various combinations of the basic arithmetical operations and applied them to our unknowns.

Here, for comparison, are two well-known differential equations, the first “ordinary” and the second “partial”:

$$\frac{d^2x}{dt^2} + k^2x = 0,$$

$$\frac{\partial T}{\partial t} = \kappa \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right).$$

The first is the equation for simple harmonic motion, which has the general solution  $x(t) = A \sin kt + B \cos kt$ ; the second is the heat equation which describes the way that the distribution of heat in a physical medium changes with time.

For many reasons, differential equations represent a jump in sophistication. One is that the unknowns are *functions*, which are much more complicated objects than numbers or  $n$ -dimensional points. (For example, the first equation above asks what function  $x$  of  $t$  has the property that if you differentiate it twice then you get  $-k^2$  times the original function.) A second is that the basic operations one performs on functions include differentiation and integration, which are considerably less “basic” than addition and multiplication. A third is that differential equations which can be solved in “closed form,” that is, by means of a formula for the unknown function  $f$ , are the exception rather than the rule, even when the equations are natural and important.

*From ‘The Princeton Companion to Mathematics’, I.4 §1.5*

#### Questions

1. Solve the following equations for  $y(t)$ :
  - (a)  $e^{y-t} \frac{dy}{dt} = 1$
  - (b)  $\frac{dy}{dt} = ty^2$
  - (c)  $\frac{dy}{dt} = \frac{1}{\sec^2 y}$
  - (d)  $\frac{dy}{dt} = -\frac{t}{\sec t \sin y}$  (*Hint: first show that  $\frac{d}{dx}[\cos x - x \sin x] = -x \cos x$* )
2. A copper ball with temperature 100 °C is dropped into a basin of water with constant temperature 30 °C. After 3 minutes the temperature of the ball has decreased to 70 °C. When will it reach a temperature of 31 °C?
3. Consider a tank of water. The rate of flow of water into the tank is a constant  $3 \text{ L s}^{-1}$ ; the flow out is directly proportional to the volume of water in the tank. Initially, the volume of water in the tank is 100 L; if the volume were to increase to  $120 \text{ L s}^{-1}$ , the rate of water flowing out would exactly balance the rate of water flowing in.
  - (a) Form a differential equation and find the volume of water after ten minutes.
  - (b) Does the outward rate of flow ever become greater than the incoming rate of flow?

## NCEA Level 3 Calculus (Integration)

### 20. Partial Fractions

**This is a Scholarship topic! The algebraic computations required can get quite messy.**

**Definition** (Rational Function). A **rational function** is a function  $f$  which can be written in the form

$$f(x) = \frac{p(x)}{q(x)}$$

for suitable polynomials  $p$  and  $q$  (where  $q \neq 0$ ).

We can already integrate some rational functions; in particular, those of the form  $f(x) = p'(x)/p(x)$ :

$$\int \frac{p'(x)}{p(x)} dx = \ln|p(x)|.$$

This week we will learn a technique that, in theory, allows us to integrate *all* rational functions. To understand the idea, note that we can easily integrate all functions of the form

$$f(x) = \frac{A}{(ax + b)^n}$$

for real constants  $A$ ,  $a$ ,  $b$ , and  $n$ .

Our task is simply to ‘deconstruct’ arbitrary fractions into this form.

**Example.**

$$\frac{2}{x-4} + \frac{3}{x+1} = \frac{5x-10}{x^2-3x-4}$$

so

$$\int \frac{5x-10}{x^2-3x-4} dx = \int \frac{2}{x-4} + \frac{3}{x+1} dx = 2 \ln|x-4| + 2 \ln|x+1|.$$

In effect, the technique of partial fractions is the reverse of this: we *decompose* the more complex rational function into two or more functions which are easier to integrate.

Let  $f(x) = \frac{p(x)}{q(x)}$ . Then we have four cases

1.  $q(x)$  is the product of distinct linear factors.
2.  $q(x)$  is the product of linear factors, some of which are repeated.
3.  $q(x)$  is the product of distinct factors, some of which are irreducible quadratics.
4.  $q(x)$  contains a repeated irreducible quadratic factor.

**The degree of  $p$  must be less than the degree of  $q$ , so you may need to use long division before applying the technique of partial fractions.**

We consider only the first two cases here. See Stewart §7.4 for the others.

### Type I: Distinct linear factors

Suppose that  $q(x) = (\alpha_1x + \beta_1) + \cdots + (\alpha_nx + \beta_n)$ . Then the partial fraction decomposition is of the form

$$\sum_{i=1}^n \frac{A_i}{\alpha_i x + \beta_i}.$$

**Example.**

$$\frac{11x - 2}{6x^2 + x - 1} = \frac{11x - 2}{(2x + 1)(3x - 1)} = \frac{A}{2x + 1} + \frac{B}{3x - 1}.$$

So  $11x - 2 = A(3x - 1) + B(2x + 1)$ . Let  $x = 1/3$ , so  $B = \frac{11/3 - 2}{2/3 + 1} = 1$ ; then let  $x = -1/2$ , so  $A = \frac{11/2 + 2}{3/2 + 1} = 3$ .

Hence

$$\int \frac{11x - 2}{6x^2 + x - 1} dx = \int \frac{3}{2x + 1} + \frac{1}{3x - 1} dx = \frac{3}{2} \ln|2x + 1| + \frac{1}{2} \ln|3x - 1| + C.$$

### Type II: Repeated linear factors

Suppose some factor  $(\alpha_i x + \beta_i)^r$  appears in the factorisation of  $Q(x)$ . Then the partial fraction decomposition will include

$$\sum_{j=1}^r \frac{A_{i_j}}{(\alpha_i x + \beta_i)^j}.$$

**Example.** Consider  $\int \frac{2x+4}{x^3-2x^2} dx$ . We wish to find a partial fraction expansion:

$$\begin{aligned} \frac{A}{x} + \frac{B}{x^2} + \frac{C}{x-2} &= \frac{2x+4}{x^3-2x^2} \iff 2x+4 = Ax(x-2) + B(x-2) + Cx^2 \\ &\iff 2x+4 = (A+C)x^2 + (B-2A)x - 2B \end{aligned}$$

Matching coefficients, we find  $B = -2$ ,  $A = -2$ , and  $C = 2$ . Then:

$$\begin{aligned} \int \frac{2x+4}{x^3-2x^2} dx &= \int \frac{-2}{x} + \frac{-2}{x^2} + \frac{2}{x-2} dx \\ &= -2 \ln|x| + \frac{2}{x} + 2 \ln|x-2| + C \\ &= 2 \ln \left| \frac{x-2}{x} \right| + \frac{2}{x} + C. \end{aligned}$$

## Questions

1. S Find  $\int \frac{A}{(ax+b)^n} dx$  if  $A$ ,  $a$ ,  $b$ , and  $n$  are real constants.

2. S Evaluate, using partial fractions:

(a)  $\int \frac{3x-1}{(x-3)(x+4)} dx$

(b)  $\int \frac{1}{x^2 - 3x - 4} dx$

(c)  $\int \frac{1}{x^2 - 6x - 7} dx$

(d)  $\int \frac{11x+17}{2x^2+7x-4} dx$

(e)  $\int \frac{5x-10}{x^2-3x-4} dx$

(f)  $\int \frac{x+7}{x^2-x-6} dx$

(g)  $\int \frac{1}{x^2+5x+6} dx$

(h)  $\int \frac{2x^2+3}{x(x-1)^2} dx$

3. Some more interesting problems:

(a) S Rewrite in the form  $\frac{A}{x-1} + \frac{B}{(x-1)^2} + \frac{C}{x+1}$  and integrate:

$$\int \frac{4x}{x^3 - x^2 - x + 1} dx.$$

(b) S Use the obvious substitution and divide through:

$$\int \frac{\sqrt{x+1}}{x} dx.$$

4. S Use appropriate substitutions to evaluate:

(a)  $\int \frac{\cos \theta}{\sin^2 \theta + 4 \sin \theta - 5} d\theta$

(b)  $\int \frac{e^{3x}}{e^{2x} + 4} dt$

(c)  $\int \frac{5 + 2 \ln x}{x(1 + \ln x)^2} dx$

5. E Don't use a sledgehammer to kill a fly, and compute the following:
- $\int \frac{x^2(5x^2 + 4x - 3)}{x^5 + x^4 - x^3 + 1} dx$
  - $\int \frac{x^2 + 1}{x(x^2 + 3)} dx$
6. O We have already computed  $\int \sec x dx$  via a bit of a trick, but we could also use partial fractions.
- Show that  $\sec x = \frac{\cos x}{1 - \sin^2 x}$ .
  - Hence, or otherwise, compute  $\int \sec x dx$ .
7. S Solve the following differential equation for  $y(x)$ :
- $$\frac{dy}{dx} = \frac{y^2 - a^4}{x^2 - a^2}$$
8. S Scholarship 2008:
- $\frac{A}{x} + \frac{B}{P-x} = \frac{1}{x(P-x)}$  where  $x$  is a variable and  $P$  is a constant. Find  $A$  and  $B$  in terms of  $P$ .
  - When a rumour about a teacher is started at a school of size  $P$  students, it spreads at a rate (in students per day) that is proportional to the product of the number of students who know the rumour,  $N$ , and those who do not. Find an expression for the number of students  $N$  who know the rumour after  $t$  days.
  - For a particular rumour about a teacher, 0.5% of students know the rumour initially. The principal will need to act to stop the rumour once more than half the school's students know it. When  $\frac{1}{5}$  of the students know the rumour, the number who know the rumour is increasing at a rate of  $0.08P$  students per day. How long will it be before the principal must act?
9. O Scholarship 2015: The rate of spread of a rumour at a particular school is proportional to both the number of students who know a rumour,  $S$ , and the number of students who do not. If  $N$  is the total number of students in the school, then  $\frac{dS}{dt} = kS(N - S)$ . Initially, two students knew the rumour. Show that the number of students who know the rumour at time  $t$  is  $S(t) = \frac{N}{1 + \frac{1}{2}e^{-kNt}(N - 2)}$ .
10. O Recall that  $\frac{d}{dx} \tan^{-1} x = \frac{1}{x^2 + 1}$ .
- Find a partial expansion of the given rational function as follows:

$$\frac{x^2 + x - 2}{3x^3 - x^2 + 3x - 1} = \frac{A}{3x - 1} + \frac{Bx + C}{x^2 + 1}$$

- (b) Hence (or otherwise) compute:

$$\int_{\pi/4}^{\pi/3} \frac{x^2 + x - 2}{3x^3 - x^2 + 3x - 1} dx.$$

11. S (Revenge of the limits.) Compute the following series. [Hint: this sheet is on partial fractions.]

$$\lim_{N \rightarrow \infty} \sum_{n=1}^N \left( \frac{1}{n(n+1)} \right)$$

## NCEA Level 3 Calculus (Integration)

### 20. Partial Fractions (Homework)

#### Reading

Perhaps I can best describe my journey of doing mathematics in terms of a journey through a dark unexplored mansion. You enter the first room of the mansion and it's completely dark. You stumble around bumping into the furniture, but eventually you learn where each piece of furniture is. Finally after six months or so, you find the light switch, you turn it on, and suddenly it's all illuminated. You can see exactly where you were. Then you move into the next room and spend another six months in the dark. So each of these breakthroughs, while sometimes they're momentary, sometimes over a period of a day or two, they are the culmination of — and couldn't exist without — the many months of stumbling around in the dark that precede them.

*From an interview by Nova of Andrew Wiles*

**Note:** For the interested, a proof that one can always expand a rational function into partial fractions is outlined as exercise 11.1.13 in Artin (p. 441).

#### Questions

1. The *logistic equation* is used when modelling populations:

$$\frac{dP}{dt} = rP(1 - P)$$

- (a) Find  $P(t)$  explicitly.
- (b) Examine the behaviour of the population as  $t \rightarrow \infty$ . Graph the function.
- (c) Examine the behaviour of the population over time if you vary  $r$  (check  $r = 0$ , and  $r < 0$  for example).
- (d) Do you think the logistic equation is a good model? Why/why not?

2. In the following, let  $t = \tan \frac{x}{2}$  (where  $|x| < \pi$ ).

- (a) Show that:

$$\cos\left(\frac{x}{2}\right) = \frac{1}{\sqrt{1+t^2}} \quad \text{and} \quad \sin\left(\frac{x}{2}\right) = \frac{t}{\sqrt{1+t^2}}$$

- (b) Show that:

$$\cos x = \frac{1-t^2}{1+t^2} \quad \text{and} \quad \sin x = \frac{2t}{1+t^2}$$

- (c) Show that:

$$\frac{dx}{dt} = \frac{2}{1+t^2}$$

- (d) Use the substitution  $t$  to evaluate:

- i.  $\int (1 - \cos x)^{-1} dx$
- ii.  $\int (3 \sin x - 4 \cos x)^{-1} dx$

## NCEA Level 3 Calculus (Integration)

### 21. Integration by Parts

The substitution rule is the inverse of the chain rule; similarly, there is an inverse of the product rule.

$$\begin{aligned} \frac{d}{dx} [f(x)g(x)] &= f'(x)g(x) + f(x)g'(x) \\ \Leftrightarrow \int f'(x)g(x) + f(x)g'(x) dx &= f(x)g(x) \\ \Leftrightarrow \int f(x)g'(x) dx &= f(x)g(x) - \int f'(x)g(x) dx \end{aligned}$$

Mnemonically,

$$\int u dv = uv - \int v du.$$

**Example.** Consider  $\int x \sin x dx$ , which does not yield to any obvious change of variable. Let  $u = x$ , and let  $dv = \sin x dx$ . So  $du = dx$ , and  $v = -\cos x$ . Hence:

$$\int x \sin x dx = -x \cos x + \int \cos x dx = -x \cos x + \sin x + C,$$

where  $C$  is an arbitrary constant. Check that  $(-x \cos x + \sin x)' = x \sin x$ .

The aim is to end up with an easier integral than the one that was started with. A good choice for  $u$  is usually (in descending order of usefulness):

1. Logarithms
2. Powers of  $x$
3. Exponentials
4. Trig functions

### Questions

1. S Compute the following indefinite integrals.

- (a)  $\int xe^x dx$
- (b)  $\int x^2 e^{2x} dx$
- (c)  $\int \ln x dx$
- (d)  $\int p^5 \ln p dp$
- (e)  $\int t^3 e^{-t^2} dt$
- (f)  $\int \sin \ln y dy$
- (g)  $\int x \tan^2 x dx$

2. S Prove that

$$\int \cos^n x dx = \frac{1}{n} \sin x \cos^{(n-1)} x + \frac{n-1}{n} \int \cos^{(n-2)} x dx$$

3. S If  $I_n = \int_0^n x^n e^x dx$ , write down an explicit general formula for  $I_n$ .

4. S Evaluate  $\int (\ln x)^2 dx$ .
5. S Compute  $\int_0^\lambda t e^{-\lambda t} dt$ .
6. S Suppose that  $f(1) = 2$ ,  $f(4) = 7$ ,  $f'(1) = 5$ , and  $f'(4) = 3$ . Evaluate  $\int_1^4 x f''(x) dx$ .
7. S A particle moving in one dimension has a velocity function  $v(t) = t^2 e^{-t}$  (where  $t$  is in seconds). What is its displacement from its starting position after three minutes?
8. S Find the area bounded by  $y = x^2 \ln x$  and  $y = 4 \ln x$
9. Scholarship 2012:
- E Find  $\frac{d}{dx}[x \cos x]$  and use this result to find  $\int x \sin x dx$ .
  - S Hence find the value of  $\int_0^{n\pi} x \sin x dx$  for integer values of  $n$ .
10. O Scholarship 2016:
- A function  $f(x)$ , where  $x$  is a real number, is defined implicitly by the formula

$$f(x) = x - \int_0^{\pi/2} f(x) \sin(x) dx.$$

Find the explicit expression for  $f(x)$  in simplest form.

- (b) A curve passing through the point  $(1, 1)$  has the property that at each point  $(x, y)$  on the curve, the gradient of the curve is  $x - 2y$ ; that is,  $\frac{dy}{dx} = x - 2y$ .
- Show that  $\frac{d}{dx} e^{2x} y = x e^{2x}$ .
  - Hence, or otherwise, find the equation of the curve.
11. S It is well known that

$$\int_{-\infty}^{\infty} e^{-x^2} dx = \sqrt{\pi}.$$

Using this result, show that

$$\int_{-\infty}^{\infty} x^2 e^{-x^2} dx = \frac{\sqrt{\pi}}{2}.$$

12. O Find  $I = \int e^x \cos x dx$ .
13. S Recall that  $\frac{d}{dx} \tan^{-1} x = \frac{1}{1+x^2}$ . Find  $\int \tan^{-1} x dx$ .

**NCEA Level 3 Calculus (Integration)****21. Integration by Parts (Homework)****Reading****Go and watch...**<https://www.youtube.com/watch?v=-reFBJ4R9iA>**Questions**

1. Compute the following indefinite integrals.

(a)  $\int x \cos 5x \, dx$

(b)  $\int \cos x \ln \sin x \, dx$

(c)  $\int \cos \sqrt{x} \, dx$

2. Evaluate:

(a)  $\int_{\pi/2}^{\sqrt{\pi}} \theta^3 \cos(\theta^2) \, d\theta$

(b)  $\int_0^1 (x^2 + 1)e^{-x} \, dx$

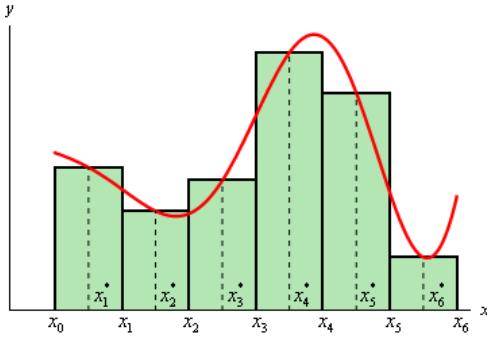
3. (a) Prove that  $\int (\ln x)^n \, dx = x(\ln x)^n - \int (\ln x)^{(n-1)} \, dx$ .

- (b) Find  $\int (\ln x)^3 \, dx$ .

## NCEA Level 3 Calculus (Integration)

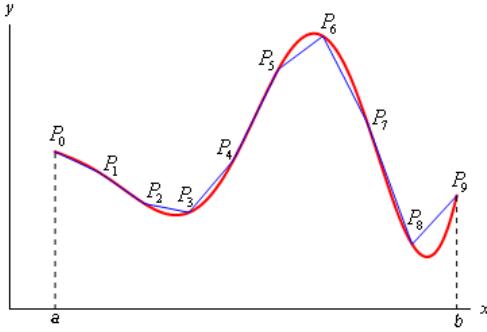
### 22. Lengths, Volumes, and Areas

Recall that the definite integral is simply a way of calculating the area bounded by a curve. We defined it to be an infinite sum of areas under the curve that individually tended to zero.



Today we will investigate finding volumes, curve lengths, and areas of surfaces by integration.

#### Curve Lengths



Suppose we have a function  $f$  and we wish to find the length *measured along the curve* between two points  $a$  and  $b$ . Split the interval into pieces of length  $\Delta x$ ; then the arc length over each subdivision is approximated by  $\sqrt{\Delta x^2 + (f'(x_i^*)\Delta x)^2}$  where  $x_i$  is a point inside the subdivision. We therefore have the sum over the whole interval  $(a, b)$  (where the total number of subdivisions is  $n$ ):

$$\sum_{i=0}^n \sqrt{\Delta x^2 + (f'(x_i^*)\Delta x)^2} = \sum_{i=0}^n \sqrt{1 + (f'(x_i^*))^2} \Delta x.$$

But if we let  $n \rightarrow \infty$ , this is exactly the following integral:

$$R = \int_a^b \sqrt{1 + (f'(x))^2} dx.$$

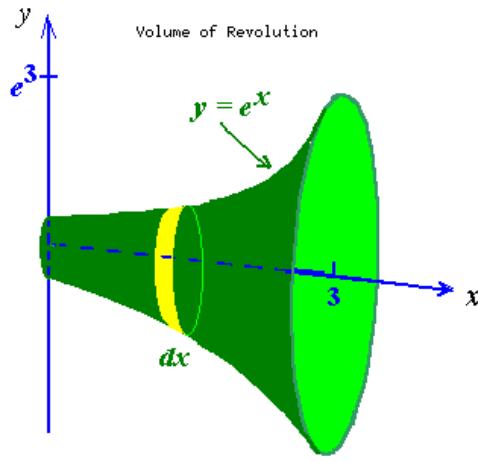
**Example.** We wish to find the length along the curve  $y = \ln \cos x$  along the interval  $(0, \pi/3)$ . We have the

following integral (noting that  $y' = -\frac{\sin x}{\cos x} = -\tan x$ ):

$$R = \int_0^{\pi/3} \sqrt{1 + \tan^2 x} dx = \int_0^{\pi/3} \sec x dx = \int_0^{\pi/3} \frac{\sec^2 x + \sec x \tan x}{\sec x + \tan x} dx = \int_1^{2+\sqrt{3}} \frac{1}{u} du = \ln(2 + \sqrt{3}) \approx 1.3170.$$

The integral of sec is tricky; it can also be done by partial fractions (multiply top and bottom of  $1/\cos x$  by  $\cos x$  and substitute  $u = \sin x$ ).

## Volumes of Revolution



We can carry out the same procedure to find a volume of revolution; the volume of each small disc can be approximated with  $\pi[f(x_i^*)]^2 \Delta x$ , and so we have

$$\begin{aligned} V &= \lim_{n \rightarrow \infty} \sum_{i=0}^n \pi[f(x_i^*)]^2 \Delta x \\ &= \int_a^b \pi[f(x)]^2 dx. \end{aligned}$$

## Surface Areas of Revolution

We can model the surface area of revolution of a curve is similarly found by modelling the volume as a disc of radius  $f(x_i^*)$  and length  $\sqrt{1 + (f'(x_i^*))^2} \Delta x$ :

$$\begin{aligned} A &= \lim_{n \rightarrow \infty} \sum_{i=0}^n 2\pi f(x_i^*) \sqrt{1 + (f'(x_i^*))^2} \Delta x \\ &= \int_a^b 2\pi f(x) \sqrt{1 + (f'(x))^2} dx. \end{aligned}$$

## Questions

1. **M** Determine the length of:
  - (a)  $x = \frac{2}{3}(y-1)^{3/2}$  between  $1 \leq y \leq 4$ .
  - (b)  $y = \ln \sec x$  between  $0 \leq x \leq \frac{\pi}{4}$ .
2. **M** The arc of the parabola  $y = x^2$  from  $(1, 1)$  to  $(2, 4)$  is rotated about the  $y$ -axis. Find the area of the resulting surface.
3. **E**
  - (a) Suppose  $f$  is a function of  $x$ , and that you know that the graph  $y = f(x)$  is a straight line. Furthermore, assume that  $f(0) = 0$  and  $f(h) = r$  where  $h$  and  $r$  are constants. Find a formula for  $f$ , and draw its graph.
  - (b) Find a formula for the volume enclosed by rotating the graph  $y = f(x)$  around the  $x$ -axis between the origin ( $x = 0$ ) and  $x = h$ . Sketch a diagram showing the volume.
4. **E** The cartesian equation for a circle of radius  $r$  is  $y^2 = r^2 - x^2$ . Compute the volume of revolution of the circle from  $x = -r$  to  $x = r$ , and hence write down the formula for the volume of a sphere of radius  $r$ .
5. **M** Find the volume of the solid obtained by rotating the region bounded by the given curves around the  $x$ -axis. Sketch the region and the solid.
  - (a) 
$$\begin{cases} y = 2 - \frac{1}{2}x \\ y = 0 \\ x = 1 \\ x = 2 \end{cases}$$
  - (b) 
$$\begin{cases} y = x - x^2 \\ y = 0 \end{cases}$$
  - (c) 
$$\begin{cases} y = \sqrt{25 - x^2} \\ y = 0 \\ x = 2 \\ x = 4 \end{cases}$$

6. **E** Find the volume of rotation of the region bounded by  $y = \sin x$  and  $y = \cos x$  around the line  $y = -1$ , where  $0 \leq x \leq \pi/4$ .

7. **M** The ellipse

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \quad \text{where } a > b$$

is rotated around the  $x$ -axis to form an ellipsoid. Find the surface area of the ellipsoid.

8. **M** Use Simpson's rule with  $n = 8$  to estimate the volume of the solid resulting when the region enclosed by the curves

$$\begin{cases} y = \sin^8 x \\ y = 2x/\pi \\ x = 0 \\ x = \pi/2 \end{cases}$$

is revolved around the  $x$ -axis.

9. S A vase is created by rotating the curve

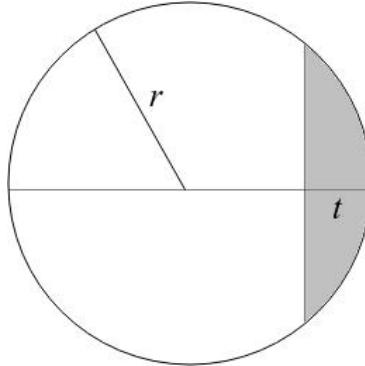
$$x = \frac{1}{200}y^3 - \frac{1}{10}y^2 + \frac{3}{2}y + \frac{5}{3}$$

for  $0 \leq y \leq 20$  ( $y$  is in centimetres).

- (a) Find a function  $V(\alpha)$  for the volume of water in the vase if it is filled up to  $y = \alpha$ .
- (b) Water flows into the vase at a rate of  $10 \text{ cm}^3 \text{ min}^{-1}$ ; water flows out at a rate directly proportional to the square root of the volume in the vase at time  $t$ .
  - i. The initial volume of water in the vase at time  $t = 0$  is  $3 \text{ cm}^3$ . Find the initial height of the water.
  - ii. After three minutes, the volume of water in the vase is  $3.6 \text{ cm}^3$ . Will the vase ever fill completely? If so, how long does it take?
- 10. E Use integration to find the volume of a cylinder by taking slices along the cylinder's axis.
- 11. E Use integration to find the volume of a cone by taking slices along the cone's axis.
- 12. S Compute the integral

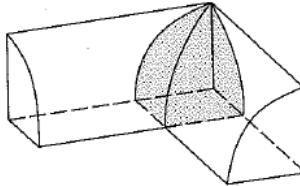
$$\int_{r-t}^t \sqrt{r^2 - x^2} \, dx$$

and hence write down an expression for the slice of width  $t$  of a circle of radius  $r$  (figure).



- 13. S The base of a solid  $S$  is a circle of radius  $r$ . Cross-sections perpendicular to the base are squares. What is the volume of  $S$ ?
  - 14. S A cathedral dome is designed with three semicircular supports of radius  $r$  such that each horizontal cross-section is a regular hexagon. Show that the volume of the dome is  $r^3\sqrt{3}$ .
  - 15. E The integral
- $$V = \int_0^3 2\pi x^5 \, dx$$
- represents the volume of a solid. Describe the solid.
- 16. O Consider a cylindrical hole of length  $h$  drilled through the centre of a sphere. Find the volume  $V(h)$  of the remaining solid. Hint: you should find that  $V$  is independent of the size of the sphere.
- Page 4

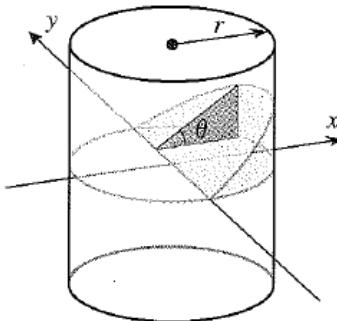
17. **O** Two identical right circular cylinders of radius  $r$  have axes that intersect at right angles. Find the volume of the intersection region (known as the *Steinmetz solid*). Hint: an interesting portion of the intersection is shown in the figure.\*



18. **S** Use an integral to estimate the value of the sum

$$\sum_{n=0}^{1000000} \sqrt{n}.$$

19. **O** A wedge is cut from a right circular cylinder of radius  $r$  by two planes, one perpendicular to the axis of the cylinder and one at an angle  $\theta$  with the first (as in the figure†). Find the volume of the wedge by slicing perpendicular to the  $y$ -axis.



20. **S** Scholarship 2000: The piriform is the curve defined by the equation  $16y^2 = x^3(8 - x)$  where  $x \geq 0$ . Find the volume of revolution obtained by rotating the piriform around the  $x$ -axis.

21. **O** Scholarship 2012: Stewie Griffin is a character from the television programme *Family Guy*. His head can be considered as a volume of revolution, turning a curve on an axis passing through his ears. Different volumes are obtained, depending on the shape of the rotated curve.

Assuming the head has width  $2w$  and height  $2h$ , find the **ratio** of the volume obtained using a parabolic curve to the volume obtained using a semi-elliptical curve.

22. **S** Scholarship 2013: Prince Rupert's drops are made by dropping molten glass into cold water. A mathematical model for a drop as a volume of revolution uses  $y = \sqrt{\phi(e^{-x} - e^{-2x})}$  for  $x \geq 0$ , where  $\phi$  is the golden ratio  $\phi = \frac{1+\sqrt{5}}{2}$ .

(a) Show that the volume of the drop between  $x = 0$  and  $x = \ln(p)$  is  $V = \frac{\pi\phi}{2} \left(\frac{p-1}{p}\right)^2$ .

(b) Hence or otherwise, explain why the volume of the drop is never more than some upper limit  $V_L$ , no matter how long its tail.

23. **S** Scholarship 2015: Find the area of the surface of revolution obtained when the graph of  $f(x) = x^3 + \frac{1}{12x}$ , from  $x = 1$  to  $x = 3$ , is revolved  $360^\circ$  around the  $x$ -axis.

\* Figure from Anton, Early Trans. 10th Ed., p 431.

† Ibid.

## NCEA Level 3 Calculus (Integration)

### 22. Lengths, Volumes, and Areas (Homework)

#### Reading



Leonhard Euler, (born April 15, 1707, Basel, Switzerland — died September 18, 1783, St. Petersburg, Russia), Swiss mathematician and physicist, one of the founders of pure mathematics. He not only made decisive and formative contributions to the subjects of geometry, calculus, mechanics, and number theory but also developed methods for solving problems in observational astronomy and demonstrated useful applications of mathematics in technology and public affairs.

Euler's mathematical ability earned him the esteem of Johann Bernoulli, one of the first mathematicians in Europe at that time, and of his sons Daniel and Nicolas. In 1727 he moved to St. Petersburg, where he became an associate of the St. Petersburg Academy of Sciences and in 1733 succeeded Daniel Bernoulli to the chair of mathematics. By means of his numerous books and memoirs that he submitted to the academy, Euler carried integral calculus to a higher degree of perfection, developed the theory of trigonometric and logarithmic functions, reduced analytical operations to a greater simplicity, and threw new light on nearly all parts of pure mathematics. Overtaxing himself, Euler in 1735 lost the sight of one eye. Then, invited by Frederick the Great in 1741, he became a member of the Berlin Academy, where for 25 years he produced a steady stream of publications, many of which he contributed to the St. Petersburg Academy, which granted him a pension.

In 1748, in his *Introductio in analysin infinitorum*, he developed the concept of function in mathematical analysis, through which variables are related to each other and in which he advanced the use of infinitesimals and infinite quantities. He did for modern analytic geometry and trigonometry what the Elements of Euclid had done for ancient geometry, and the resulting tendency to render mathematics and physics in arithmetical terms has continued ever since. He is known for familiar results in elementary geometry—for example, the Euler line through the orthocentre (the intersection of the altitudes in a triangle), the circumcentre (the centre of the circumscribed circle of a triangle), and the barycentre (the “centre of gravity,” or centroid) of a triangle. He was responsible for treating trigonometric functions—i.e., the relationship of an angle to two sides of a triangle—as numerical ratios rather than as lengths of geometric lines and for relating them, through the so-called Euler identity ( $e^{i\theta} = \text{cis } \theta$ ), with complex numbers. He discovered the imaginary logarithms of negative numbers and showed that each complex number has an infinite number of logarithms.

Euler's textbooks in calculus, *Institutiones calculi differentialis* in 1755 and *Institutiones calculi integralis* in 1768–70, have served as prototypes to the present because they contain formulas of differentiation and numerous methods of indefinite integration, many of which he invented himself, for determining the work done by a force and for solving geometric problems, and he made advances in the theory of linear differential equations, which are useful in solving problems in physics. Thus, he enriched mathematics with substantial new concepts and techniques. He introduced many current notations, such as  $\sum$  for the sum; the symbol  $e$  for the base of natural logarithms; the notation  $f(x)$  for a function; and the notation  $i^2 = -1$ . He also popularized the use of the symbol  $\pi$  (devised by British mathematician William Jones) for the ratio of circumference to diameter in a circle.

After Frederick the Great became less cordial toward him, Euler in 1766 accepted the invitation of Catherine II to return to Russia. Soon after his arrival at St. Petersburg, a cataract formed in his remaining good eye, and he spent the last years of his life in total blindness. Despite this tragedy, his productivity continued undiminished, sustained by an uncommon memory and a remarkable facility in mental computations. His interests were broad, and his *Lettres à une princesse d'Allemagne* in 1768-72 were an admirably clear exposition of the basic principles of mechanics, optics, acoustics, and physical astronomy. Not a classroom teacher, Euler nevertheless had a more pervasive pedagogical influence than any modern mathematician. He had few disciples, but he helped to establish mathematical education in Russia.

Euler devoted considerable attention to developing a more perfect theory of lunar motion, which was particularly troublesome, since it involved the so-called three-body problem—the interactions of Sun, Moon, and Earth. (The problem is still unsolved.) His partial solution, published in 1753, assisted the British Admiralty in calculating lunar tables, of importance then in attempting to determine longitude at sea. One of the feats of his blind years was to perform all the elaborate calculations in his head for his second theory of lunar motion in 1772. Throughout his life Euler was much absorbed by problems dealing with the theory of numbers which treats the properties and relationships of integers. In this his greatest discovery, in 1783, was the law of quadratic reciprocity, which has become an essential part of modern number theory.

In his effort to replace synthetic methods by analytic ones, Euler was succeeded by J.-L. Lagrange. But, where Euler had delighted in special concrete cases, Lagrange sought for abstract generality, and, while Euler incautiously manipulated divergent series, Lagrange attempted to establish infinite processes upon a sound basis. Thus it is that Euler and Lagrange together are regarded as the greatest mathematicians of the 18th century, but Euler never excelled either in productivity or in the skillful and imaginative use of algorithmic devices (i.e., computational procedures) for solving problems.

*Edited from <https://www.britannica.com/biography/Leonhard-Euler>.*

## Questions

1. Find the volume of revolution around the  $x$ -axis of the hyperbola  $y = \frac{1}{x}$  from  $x = 1$  to  $x = 2$ .
2. Find the area of the surface created by rotating the curve  $y = \sin x$  around the  $x$ -axis ( $0 \leq x \leq \pi$ ). What is the radius of the circle with the same area?
3. Write down a formula for the volume of a square-based pyramid with base side length  $L$  and height  $H$ .
4. Scholarship 2017: The length  $S$  of a curve expressed in polar coordinates is given by

$$S = \int_{\theta_1}^{\theta_2} \sqrt{r^2 + \left(\frac{dr}{d\theta}\right)^2} d\theta.$$

Find the length of the entire curve  $r = a(1 - \cos \theta)$  in terms of the constant  $a$ .

[Note: you may wish to graph the curve first.]

## NCEA Level 3 Calculus (Integration)

### 23. Trigonometric Substitution

Consider the integral

$$\int_0^1 x^3 \sqrt{1-x^2} dx.$$

There is no obvious easy substitution to simplify this integral and integration by parts could work but will require a lot of work with no guaranteed payoff. However, recall that  $\sqrt{1-\sin^2 \theta} = \cos \theta$ ; this identity suggests that we could perhaps substitute  $x = \sin \theta$  in order to obtain  $dx = \cos \theta d\theta$  and so

$$\begin{aligned} \int_0^1 x^3 \sqrt{1-x^2} dx &= \int_0^{\frac{\pi}{2}} \sin^3 \theta \cos^2 \theta d\theta \\ &= \int_0^{\frac{\pi}{2}} \sin \theta (1 - \cos^2 \theta) \cos \theta d\theta \\ &= \int_0^{\frac{\pi}{2}} (\cos^2 \theta - \cos^4 \theta) \sin \theta d\theta \end{aligned}$$

Now, letting  $u = \cos \theta$  we obtain

$$\begin{aligned} \int_0^{\frac{\pi}{2}} (\cos^2 \theta - \cos^4 \theta) \sin \theta d\theta &= - \int_1^0 u^2 - u^4 du \\ &= \frac{1}{3}u^3 - \frac{1}{5}u^5 \Big|_{u=0}^1 \\ &= \frac{1}{3} - \frac{1}{5} = \frac{2}{15}. \end{aligned}$$

Here is a table of trig substitutions:

Integrand	Substitution	Identity
$\sqrt{a^2 - x^2}$	$x = a \sin \theta$	$1 - \sin^2 \theta = \cos^2 \theta$
$\sqrt{a^2 + x^2}$	$x = a \tan \theta$	$1 + \tan^2 \theta = \sec^2 \theta$
$\sqrt{x^2 - a^2}$	$x = a \sec \theta$	$\sec^2 \theta - 1 = \tan^2 \theta$

**Example.** Consider  $I = \int \frac{dx}{\sqrt{9+x^2}}$ . Let  $x = 3 \tan \theta$  so  $dx = 3 \sec^2 \theta d\theta$  and:

$$\begin{aligned} I &= \int \frac{3 \sec^2 \theta}{3 \sqrt{1 + \tan^2 \theta}} d\theta = \int \sec \theta d\theta \\ &= \ln(\sec \theta + \tan \theta) + C = \ln(\sec \tan^{-1}(x/3) + x/3) + C \\ &= \ln \left( \sqrt{\left(\frac{x}{3}\right)^2 + 1} + \frac{x}{3} \right) + C. \end{aligned}$$

## Questions

1. S Find the following integrals:

$$\begin{aligned}(a) \quad & \int \frac{x^2-9}{x^3} dx \\(b) \quad & \int \frac{dx}{\sqrt{x^2+a^2}} \\(c) \quad & \int_0^3 x^2(9-x^2) dx \\(d) \quad & \int_0^1 x\sqrt{1-x^4} dx \\(e) \quad & \int_{\sqrt{2}}^2 \frac{dx}{t^3\sqrt{t^2-1}} \\(f) \quad & \int \frac{\sqrt{25x^2-4}}{x} dx\end{aligned}$$

2. S Use the integral  $2 \int_r^{-r} \sqrt{r^2 - x^2} dx$  to find the area of a circle of radius  $r$ .
3. S Scholarship 2005: Find, in terms of  $r$ , the area between the ellipse  $x^2 + 16(y-r)^2 = r^2$  and the circle  $x^2 + y^2 = r^2$ . You may use the substitution  $x = r \sin u$  to find the integral  $\int \sqrt{r^2 - x^2} dx$ .

4. S By integrating, verify that

$$\int_0^x \sqrt{a^2 - t^2} dt = \frac{1}{2} a^2 \sin^{-1} \left( \frac{x}{a} \right) + \frac{1}{2} x \sqrt{a^2 - x^2}.$$

5. S A charged rod of length  $L$  produces a electric field at the point  $(a, b)$  given by

$$E(a, b) = \int_{-a}^{L-a} \frac{\lambda b}{4\pi\varepsilon_0(x^2 + b^2)^{3/2}} dx.$$

Evaluate this integral to find an explicit expression for  $E(a, b)$ .

6. O One of these integrations should be done by partial fractions and one by trig substitution. Do them both.

$$\int \frac{dx}{(4x^2+9)^2} \quad \int \frac{x^3}{x^2+x-6} dx$$

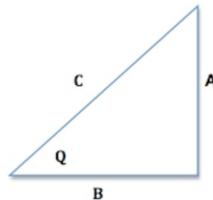
7. S Check this working (the substitution  $x = 3 \sin \theta$  is used). Find any mistakes.

$$\begin{aligned}I &= \int \frac{\sqrt{9-x^2}}{x^2} dx = \int \frac{\cos^2 \theta}{\sin^2 \theta} d\theta \\&= \int \frac{1-\sin^2 \theta}{\sin^2 \theta} d\theta = \int \csc^2 \theta - 1 d\theta \\&= -\cot \theta - \theta = -\cot(\sin^{-1}(x/3)) - \sin(x/3) \\&= \frac{\sqrt{9-x^2}}{x} - \sin(x/3).\end{aligned}$$

8. S A water storage tank has the shape of a cylinder with diameter 10 m. It is mounted so that the circular cross-sections are vertical. If the depth of the water is 7 m, what percentage of the total capacity is being used?

9. S When writing this worksheet I went on the internet and found this. Find the mistake(s), and do the integral.

$$\int \frac{7}{x^2\sqrt{36-25x^2}} dx$$



For trigonometric substitution to solve the above integral, fill in the blanks below using the picture of the triangle given.

side A =  $5x$

side B =  $6$

side C =  $\sqrt{36-25x^2}$

$\frac{5x}{6} = \tan(Q)$

$\frac{5}{6} dx = \frac{1}{\cos(Q)^2} dQ$

$\frac{\sqrt{36-25x^2}}{6} = \frac{1}{\cos(Q)}$

Incorrect. Tries 1/8 [Previous Tries](#)

## NCEA Level 3 Calculus (Integration)

### 23. Trigonometric Substitution (Homework)

#### Reading

The movement of humanity, arising as it does from innumerable arbitrary human wills, is continuous.

To understand the laws of this continuous movement is the aim of history...

Only by taking infinitesimally small units for observation (the differential of history, that is, the individual tendencies of men) and attaining to the art of integrating them (that is, finding the sum of these infinitesimals) can we hope to arrive at the laws of history.

From *War and Peace*, by Leo Tolstoy.

Extra reading:

[http://teachers.dadeschools.net/akoski/downloads/Reading\\_Journals/Essays/tolstoy\\_integration.pdf](http://teachers.dadeschools.net/akoski/downloads/Reading_Journals/Essays/tolstoy_integration.pdf)  
(*Tolstoy's Integration Metaphor*, S. Ahearn, 2004.)

#### Questions

Compute the following integrals. Some may not require trig substitution.

1.  $\int \frac{dx}{\sqrt{x^2 + 4}}$

2.  $\int \frac{x^6}{\sqrt{1 - x^{14}}} dx$

3.  $\int \sqrt{9 - x^2} dx$

4.  $\int x \sqrt{25x^2 - 4} dx$

5.  $\int \sqrt{4 - 9z^2} dz$

6.  $\int_0^{1/6} \frac{x^5}{(36x^2 + 1)^{3/2}} dx$

7.  $\int \frac{\ln x}{x^5} dx$

8.  $\int_1^2 \frac{5t - 2}{2t^2 - t - 1} dt$

## NCEA Level 3 Calculus (Integration)

### 24. Formal Definitions of $\exp$ and $\ln$

Today we will write down formal definitions of the natural exponential and logarithm functions.

#### The Natural Logarithm

We can integrate  $x^3$ ,  $x^2$ ,  $x^{-2017}$ , and  $x^0$  easily using the reverse power rule (respectively, they become  $x^4/4$ ,  $x^3/3$ ,  $-x^{-2016}/2016$ , and 0). However, we cannot integrate  $x^{-1}$ :

$$\int x^{-1} dx = \frac{1}{-1+1} x^{-1+1} = \frac{1}{0} x^0 = ???$$

But we know that the indefinite integral of  $x^{-1}$  must exist, since there is obviously a finite area beneath the curve  $y = x^{-1}$  over (for example) the interval  $[1, 2]$ . We therefore make the following **definition**:

$$\ln x := \int_1^x \frac{1}{t} dt.$$

**How does one pronounce ‘ $\ln$ ’?** log.

We can prove the log rules using this definition; as a sampler, we prove that  $\ln x + \ln y = \ln xy$ :

$$\begin{aligned} \ln x + \ln y &= \int_1^x \frac{1}{t} dt + \int_1^y \frac{1}{t} dt \\ &= \int_1^x \frac{1}{t} dt + \int_x^{xy} \frac{1}{u/x} \frac{1}{x} du \quad (u = tx) \\ &= \int_1^x \frac{1}{t} dt + \int_x^{xy} \frac{1}{u} du \\ &= \int_1^x \frac{1}{t} dt + \int_x^{xy} \frac{1}{t} dt \\ &= \int_1^{xy} \frac{1}{t} dt \\ &= \ln xy. \end{aligned}$$

## The Exponential Function

We define the exponential function to be the function implicitly defined by  $\exp(x) = y \iff \ln(y) = x$ . Consider the following (where  $y = \exp(x)$ ):

$$\frac{dy}{dx} = \frac{1}{\frac{dx}{dy}} = \frac{1}{1/y} = y$$

So  $\frac{d}{dx} \exp(x) = \exp(x)$ .

We can also write  $\exp(x) \equiv e^x$ .

Note that  $e$  is the unique number such that  $\ln(e) = 1$ :

$$\ln(e) = \ln(e^1) = \ln(\exp(1)) = 1.$$

## Questions

1. S Prove the following:
  - (a)  $\ln 1 = 0$
  - (b)  $\ln x > 0$  for all  $x > 1$ .
  - (c)  $\ln x < 0$  for all  $0 < x < 1$ .
  - (d)  $a \ln x = \ln(x^a)$  (Remember, multiplication is just repeated addition.)
  - (e)  $\ln x - \ln y = \ln(x/y)$
  - (f)  $e^{x+y} = e^x e^y$
  - (g)  $e^{x-y} = e^x / e^y$
  - (h)  $e^0 = 1$
  - (i)  $(e^x)^y = e^{xy}$

**NCEA Level 3 Calculus (Integration)****24. Formal Definitions of exp and ln (Homework)****Reading****Go and watch...**<https://www.youtube.com/watch?v=N-7tcTlrers>**Question**

Show that  $\int \frac{1}{\text{cabin}} d(\text{cabin}) = \text{houseboat}$ .

## NCEA Level 3 Calculus (Integration)

### 25. Integration Revision

#### Questions

1. A True or false:

- (a)  $\int_a^b \frac{dy}{dx} dx = y(b) - y(a)$
- (b)  $\int_0^1 f(x) dx + \int_0^1 g(x) dx = \int_0^1 f(x) + g(x) dx$
- (c)  $\int_0^2 f(x) dx + \int_0^1 f(x) dx = \int_1^2 f(x) dx$
- (d)  $\int \sin(x) dx \int \cos(x) dx = \int \sin(x) \cos(x) dx$
- (e)  $\int \frac{1}{u} du = \int \frac{1}{x} dx$
- (f) A definite integral always represents the area under a curve.
- (g) If  $u = 2x$  then  $\int \sqrt{2x} dx = \int \sqrt{u} du$ .
- (h) The indefinite integral of  $\ln x$  is just  $\ln x$ .

2. A Compute the following indefinite integrals:

- (a)  $\int \sin x dx$
- (b)  $\int \sec 3x \tan 3x dx$
- (c)  $\int \frac{2x^4 - x^2}{x^3} dx$
- (d)  $\int \sin x \cos x dx$
- (e)  $\int \sin^2 x dx$
- (f)  $\int \frac{1}{2u} du$
- (g)  $\int \frac{2x + \sec^2 x}{2\sqrt{x^2 + \tan x}} dx$
- (h)  $\int \frac{t^4 - 1}{t - 1} dt$
- (i)  $\int \frac{t^{2017} + \sqrt{t^{2017}} + \sqrt[3]{t^{2017}}}{2017\sqrt{t^2}} dt$
- (j)  $\int \sec \theta d\theta$  (hint: multiply through by  $\frac{\sec x + \tan x}{\sec x + \tan x}$ )
- (k)  $\int \sec x \tan x + \sec^2 x \tan x dx$

3. A Compute the definite integrals:

- (a)  $\int_0^1 x^2 dx$
- (b)  $\int_0^{\pi/2} \tan(x/2) dx$
- (c)  $\int_0^4 x^3 + x^2 + \sqrt{x} dx$
- (d)  $\int_1^e \frac{1}{t} dt$
- 4. M Suppose  $f'(x) + \frac{f(x)}{x} = 0$ , and  $f(1) = 1$ . Find  $f(x)$  explicitly.
- 5. M If  $\int_A^B f(x) dx = 3$  and  $\int_A^C f(x) dx = 4$ , find  $\int_B^C f(x) dx$ .

6. **M** A function  $\phi$ , whose graph passes through the origin, is such that the slope of  $\phi$  at any given point  $x$  is exactly  $2\phi(x)$ . Find  $\phi$  exactly.
7. **E** Find  $A$  such that  $\int_0^A \sin x \, dx$  is maximised.
8. **E** Find  $B$  such that  $\int_B^{B^2} x^2 - 4x - 4 \, dx$  is maximised.
9. **M** Find the area of the region bounded by  $y = 1 + x^2$ ,  $y = -1 - x^2$ ,  $x = 1$ , and  $x = -1$ .
10. **M** Use integration to find the area enclosed between the curve  $y = e^{2x} - \frac{1}{e^{3x}}$  and the lines  $y = 0$ ,  $x = 0$ , and  $x = 1.2$ .
11. **M** A function  $f$  is *even* if  $f(-x) = f(x)$  for all  $x$  in its domain.
- What geometric property does the graph of an even function have?
  - Suppose  $f$  is an even function with  $\int_0^7 f(x) \, dx = 20$ . Find:
    - $\int_{-7}^7 f(x) \, dx$
    - $\int_0^7 3f(x) + 2 \, dx$
12. **M** A function  $y$  is implicitly defined in terms of  $x$  in each case; find  $y(x)$  explicitly.
- $\frac{dy}{dx} = xy^2$ ,  $y(1) = 0$ .
  - $\frac{dy}{dx} = \frac{\cos x}{3y}$ ,  $y(\pi/6) = 1$ .
13. **M** Use integration to find the area enclosed between  $y = 1 - 0.2x^4$  and  $y = 0.4x^4$ .
14. **E** Mr Leibniz has a container of oil and places it in the garage. Unfortunately, he puts the container on top of a sharp nail and it begins to leak. The rate of decrease of the volume of oil in the container is given by the differential equation  $\frac{dV}{dt} = -kVt$ , where  $V$  is the remaining volume of oil remaining after  $t$  hours have passed. The volume of oil in the container when it was placed in the garage was 3000 mL; after twenty hours have passed, the volume remaining is 2400 mL. How much (if any) oil will remain in the container after 96 hours have passed?
15. **M** An object has acceleration (in one dimension)  $a(t) = 0.2t + 0.3\sqrt{t}$  for  $0 \leq t \leq 10$ . At  $t = 4$ , the velocity of the object is  $5 \text{ m s}^{-1}$ . How far has the object travelled after nine seconds?
16. **S** The formula for integration by parts is  $\int f(x)g'(x) \, dx = f(x)g(x) - \int f'(x)g(x) \, dx$ .
- Find  $\int \ln x \, dx$  explicitly.
  - Hence, or otherwise, find  $\int_1^2 4x \ln x \, dx$ .
17. (a) i. **E** Show that  $\frac{3}{x+1} - \frac{4}{x-2} = \frac{-x-10}{x^2-x-2}$ .
- ii. **E** Hence, or otherwise, compute  $\int_0^1 \frac{-x-10}{x^2-x-2} \, dx$ .
- (b) **S** Find  $\beta$  such that  $\int_\beta^{2\beta} \frac{1}{x^2+5x+6} \, dx = 1$ .
18. **A** Use the trapezium rule to approximate the value of  $\int_1^4 x^x \, dx$ . This function cannot be integrated in terms of elementary functions.
19. **M** The indefinite integral  $\int e^{-x^2} \, dx$  cannot be integrated in terms of elementary functions, but it can be shown that the definite integral  $\int_{-\infty}^{\infty} e^{-x^2} \, dx$  has the value  $\sqrt{\pi}$ . Most of the curve lies within the bounds  $-2 \leq x \leq 2$ . Use Simpson's rule to approximate the value of  $\int_{-2}^2 e^{-x^2}$ , and compare this with the expected value.

20. **M** Consider the function implicitly defined by  $y(x) = x + \int_0^{\sqrt{2}} y(u) du$ . If the graph of the function includes the point  $(0, 1)$ , find  $y(x)$  explicitly.
21. **E** An object is at  $4^\circ$  in a refrigerator. It is removed and placed on a shelf with an ambient temperature of  $20^\circ$ . After two minutes, the object has warmed to  $5^\circ$ . How long will it take for the object to reach  $10^\circ$ ? [Use Newton's law of cooling.]
22. **E** A property owner assumes that the rate of increase of the value of his property at any time is proportional to the value,  $\$V$ , of the property at that time.
- Write the differential equation that expresses this statement.
  - The property was valued at \$365 000 in May 2012, and at \$382 000 in November 2013. Solve the differential equation from (a) to find the price that the owner paid for the property in May 2007 when he purchased the property, given his assumption is accurate.
23. **M** Find  $x$  such that  $\int_1^x \frac{\ln u}{u} du = 1$ .
24. **E** The formula for surface area of the volume of revolution of  $y = f(x)$  is  $2\pi \int_a^b f(x) \sqrt{f'(x) + 1} dx$ . Find the area of the surface obtained by rotating about the  $x$ -axis the part of the curve  $x = \frac{1}{4}y^2 - \frac{1}{2}\ln y$  that lies between  $y = 1$  and  $y = e$ .
25. **E** The base of a solid is the region bounded by the parabolae  $y = x^2$  and  $y = 2 - x^2$ . Find the volume of the solid, if cross-sections perpendicular to the  $x$ -axis are squares with one side lying along the base.
26. **S** Find the volume of the ellipsoid  $\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$ .
27. **O** Scholarship 2016: Consider  $I_n = \int_0^{\pi/2} \frac{\sin 2nx}{\sin x} dx$ , where  $n \geq 0$ . Show that  $I_n - I_{n-1} = \frac{2(-1)^{n-1}}{2n-1}$ .
28. **S** Scholarship 2010: A flower pattern is constructed by using a sinusoidal function  $r(\theta)$  to define the distance from the origin to the curve at a radial angle  $\theta$ . The  $x$  and  $y$  coordinates of a point on the curve are given by the following equations, where  $0 \leq b \leq a$  and  $n$  is a positive integer (the number of petals).

$$r(\theta) = a + b \sin(n\theta)$$

$$x(\theta) = r(\theta) \cos(\theta)$$

$$y(\theta) = r(\theta) \sin(\theta)$$

- (a) The area inside such a function is given by

$$A = \frac{1}{2} \int_0^{2\pi} (r(\theta))^2 d\theta$$

when  $r(\theta) \geq 0$ .

Show that the area of a flower pattern is  $\pi(a^2 + \frac{1}{2}b^2)$ .

- (b) A lemon squeezer with base radius  $a_0$  and height  $H$  is made to the following specifications.

At a height  $h$  (where  $0 \leq h \leq H$ ) the cross-section is a flower pattern with

$$a(h) = \frac{H-h}{H}a_0 \text{ and } b(h) = \frac{h}{H}a_0.$$

Use integration with respect to  $h$  to show that the volume of a lemon squeezer is exactly 5% greater than the volume of a cone with the same base and height.

29. **O** Evaluate the following:

$$\frac{d^2}{dx^2} \int_0^x \left( \int_0^{\sin t} \sqrt{1+u^4} du \right) dt$$

[Hint: no integration is required. Use the FTC and the (differentiation) chain rule.]

## NCEA Level 3 Calculus (Integration)

### 25. Integration Revision (Homework)

#### Reading

Go and watch...

[https://www.youtube.com/watch?v=iGI\\_LLb3rgg](https://www.youtube.com/watch?v=iGI_LLb3rgg)

#### Questions

1. Compute the following integrals.
  - (a)  $\int_1^2 \sin x \, dx$
  - (b)  $\int \frac{u^2+1}{u^3+3u} \, du$
  - (c)  $\int_0^{\pi/6} \tan x \, dx$
2. Suppose  $y'(x) = \frac{3x^2+4x-4}{2y(x)-4}$  and  $y(1) = 3$ . Compute the possible values of  $y$  when  $x$  is 2.
3. Let  $\omega(a, x) = \int_0^x \frac{a^3}{t^2+a^2} \, dt$ .
  - (a) Find  $\omega(a, x)$  explicitly in terms of  $a$  and  $x$ . You may wish to use the substitution  $t = a \tan \theta$ .
  - (b) Compute  $\omega(2, 2)$  exactly.
  - (c) Find  $x$  such that  $\omega(\sqrt{3}, x) = \pi$ .
4. Scholarship 2016: Compute the following integral, giving your answer in exact form.

$$\int_{-\pi/2}^{\pi/2} (\sin^5 x + \cos^5 x) \, dx$$

## NCEA Level 3 Calculus (Integration)

### 26. More Interesting Problems

These problems do not just concern integration.

#### Questions

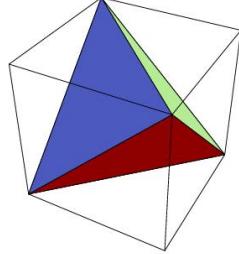
1. E Find the equation of the line through the point  $(3, 5)$  which cuts off the least area from the first quadrant.
2. E The area of a square is increasing at a constant rate of  $k \text{ m}^2$  per second. A tetrahedron (equilateral triangular pyramid), has a side length that is the same as that of the square at each instant. The initial volume of the tetrahedron was  $1 \text{ m}^3$ . In terms of  $k$ , what is the volume of the tetrahedron three seconds after that?
3. S Scholarship 2017: The hyperbolic functions  $\sinh x$  and  $\cosh x$  are defined as follows:

$$\sinh x = \frac{1}{2}(e^x - e^{-x}) \quad (1)$$

$$\cosh x = \frac{1}{2}(e^x + e^{-x}). \quad (2)$$

Show that  $\frac{d}{dx} \sinh^{-1} x = \frac{1}{\sqrt{x^2+1}}$ .

4. S Consider the tetrahedron inscribed inside a cube, as in the figure.



The volume  $V$  of the cube at any instant  $t$  is increasing at a rate proportional to the value of  $V$  at that instant. The initial volume of the cube at  $t = 0$  was 8 cubic units. What is the volume of the tetrahedron at time  $t = 20$ ?

5. S If  $x \sin \pi x = \int_0^{x^2} f(t) dt$ , where  $f$  is continuous, find  $f(4)$ . [Hint: you need not perform any integration.]
6. S If  $f$  and  $g$  are differentiable functions with  $f(0) = g(0) = 0$  and  $g'(0) \neq 0$ , show that

$$\lim_{x \rightarrow 0} \frac{f(x)}{g(x)} = \frac{f'(0)}{g'(0)}.$$

Hence, or otherwise, evaluate

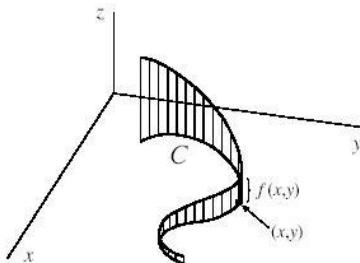
$$\lim_{x \rightarrow 0} \frac{\sin(a + 2x) - 2 \sin(a + x) + \sin a}{x^2}.$$

7. (a) S Consider the differential equation

$$\frac{d^2\Phi}{dt^2} + 5 \frac{d\Phi}{dt} + 6\Phi(t) = 0.$$

Let  $f$  and  $g$  be the functions defined by  $f(x) = e^{-2x}$  and  $g(x) = e^{-3x}$ .

- i. Show that all linear combinations of  $f$  and  $g$  are solutions to the differential equation.
- ii. Find the (unique) solution passing through  $(0, 1)$  and  $(1, 1)$ .
- (b) O More generally, consider the differential equation  $a \frac{d^2y}{dx^2} + b \frac{dy}{dx} + cy = 0$ . Let the zeroes of the quadratic polynomial  $p(D) = aD^2 + bD + c$  be  $\alpha$  and  $\beta$ . Show that all the linear combinations of  $e^{\alpha x}$  and  $e^{\beta x}$  are solutions to the differential equation.
8. S Compute the following definite integral. [Hint: begin with a substitution.]
- $$\int_0^{\pi/6} \sqrt{\tan \theta} d\theta$$
9. (a) E Consider the two functions  $p(x) = 3x^5 - 5x^3 + 2x$  and  $q(x) = 3x^5$ . Show that their ratio approaches 1 as  $x \rightarrow \infty$ .
- (b) S Let  $p(x)$  and  $q(x) \neq 0$  be polynomials. Recall that the degree of a polynomial is the highest  $n$  such that  $x^n$  has a non-zero coefficient. Compute the limit
- $$\lim_{x \rightarrow \infty} \frac{p(x)}{q(x)}$$
- if:
- i. the degree of  $p(x)$  is less than that of  $q(x)$ .
  - ii. the degree of  $p(x)$  is greater than that of  $q(x)$ .
10. S A definite integral calculates the area between a curve and straight line, the  $x$ -axis. In a similar way, it is possible to use integration to calculate the area above a curved line and below a surface  $z = f(x, y)$ , like that in the figure.



If the curve  $C$  is defined parametrically, that is  $C(t) = (x(t), y(t))$ , then the integral along the line can be calculated with the formula

$$\int_a^b f(x(t), y(t)) \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt.$$

Compute the line integral of the function  $f(x, y) = 2 + x^2y$  around the upper half of the unit circle.

11. S The **sine integral** function is defined by

$$\text{Si}(x) = \begin{cases} \int_0^x \frac{\sin t}{t} dt, & \text{for } x \neq 0; \\ 1, & \text{for } x = 0. \end{cases}$$

- (a) Recall that  $\int_a^b f'(t) dt = f(b) - f(a)$ . Use this to show that  $\frac{d}{dx} \int_0^x f'(t) dt = f'(x)$ .

- (b) Find the  $x$ -coordinate of the first local maximum of  $S_i$  to the right of the origin. Carefully prove that you have found a maximum.
- (c) Use the result in (a) to find an expression for the integral

$$\frac{d}{dx} \int_{g(x)}^{h(x)} f(t) dt,$$

where  $f$  is continuous and  $g$  and  $h$  are differentiable.

12. E Minimise the function  $f(x) = b \log_b N$  with respect to  $b$ , and show that the result is independent of the constant  $N$ .\*
13. S We can calculate **improper integrals** (those where the bounds are infinite) as follows:

$$\int_a^{\infty} f(x) dx = \lim_{b \rightarrow \infty} \int_a^b f(x) dx.$$

Decide whether each of the integrals given below exists. If so, calculate its value; if not, explain why.

(a)  $\int_1^{\infty} \frac{1}{x} dx$

(b)  $\int_1^{\infty} \frac{1}{x^2} dx$

(c)  $\int_1^{\infty} \sin x dx$

14. (a) S Show that  $F(x) = \tan^{-1} x$  is an anti-derivative of  $f(x) = \frac{1}{1+x^2}$  in the following ways:
- Differentiate  $F(x)$  and simplify to give  $f(x)$ .
  - Use the substitution  $x = \tan \theta$  to integrate  $f(x)$  and simplify to give  $F(x)$ .
- (b) O Recall that  $22/7$  is often given as a rough approximation to  $\pi$ . Consider the integral

$$I = \int_0^1 \frac{x^4(1-x)^4}{1+x^2} dx,$$

and hence show that  $22/7 > \pi$ .†

15. S Consider the operator  $\mathcal{L}$  defined by

$$\mathcal{L}f(x) = \frac{d}{dx} \ln [f(e^x)].$$

- Show that  $\mathcal{L}x^n = n$  and that  $\mathcal{L}[u(x)]^n = n\mathcal{L}u(x)$ .
  - Find an expression for  $\mathcal{L}[u(x)v(x)]$  and  $\mathcal{L}[u(x)/v(x)]$ .
  - Find an expression for  $\mathcal{L}[u(x) + v(x)]$ .
  - For which  $y$  is  $\mathcal{L}y = y$ ?
16. S Compute the following indefinite integrals:

(a)  $\int \frac{\sin \frac{1}{x}}{x^2} dx$

(b)  $\int \frac{\ln x \cos x - \frac{\sin x}{x}}{(\ln x)^2} dx$

\* Dudley, *Mathematical Cranks*, p.52.

† Nahin, *Inside Interesting Integrals*, pp.23-4.

CHAPTER 4

**Exams and Assignments**

## NCEA Level 3 Calculus Exam Advice

Now is the time when I pass on my exam-taking wisdom in bullet-point list form.

- Don't cram the night before the exam. Get a good night's sleep and have a proper meal for breakfast.
- Prepare your exam bag the night before. Know the earthquake procedures and have an emergency pack.
- Stay calm and be confident.
- If you forget how numbers work, try counting your fingers and work upwards from there. (Quality advice from a former Scholarship candidate.)
- Draw a diagram if one isn't given.
- Don't study by reading examples, study by doing problems.
- Read through all the questions before attempting any of them.
- Have a problem-solving strategy.
- Begin by working out the part of the standard the question is asking about.
- Show all your work.
- Never leave a problem blank.
- If you're stuck, move on and do another question.
- Write sentences, not symbols. Use correct spelling, grammar, and punctuation??!
- **If the question gives you a hint, there's probably a reason for that!**

Scholarship exams especially are a competition between you and the examiner. They want to impress you with the difficulty of the questions that they throw at you, **but you can meet that challenge**. There is nothing that they can chuck your way that cannot be done with level three material (because they're not allowed to), and so the way to get through a scholarship question is usually to work methodically.

Remember that mathematics is difficult, and that it took hundreds of years for humanity to discover the concepts and techniques which you will apply in the three hours of an NZQA external examination.



## Study Skills for Mathematics

(From the University of Cambridge)

[Examinations are] designed to test your knowledge of the courses you have attended rather than your ability to jump through mathematical hoops. Nevertheless, strategy matters. Extreme marks (either high or low) are available in mathematics examinations, which means that playing the cards you hold to best advantage is of vital importance.

Here are some thoughts; you've heard them all before, but that does not make them any less worth saying. The examinations may be some way off, but you will find that good examination technique can be acquired over the course of the year by making suitable preparations and developing good habits. (For example, the first two points assume that your year's work is in good order.)

- For revision, work through examples while reading the relevant section of your notes (just reading is not enough).
- For last minute preparation, look through your supervision work to remind yourself how to do questions.
- In the examination, above all, stay cool — if it is hard for you, it is probably hard for everyone.
- Don't rush into a question — read the whole paper carefully and start with the question you feel most confident about.
- Analyse exactly what you are being asked to do; try to understand the hints (explicit and implicit); remember to distinguish between terms such as explain/prove/define/etc.
- Remember that different parts of a question are often linked (it is usually obvious from the notation and choice of variables).\*
- Set out your answer legibly and logically (don't scribble down the first thought that comes into your head) — this not only helps you to avoid silly mistakes but also signals to the examiner that you know what you are doing (which can be effective even if you haven't the foggiest idea what you are doing).
- If you get stuck, state in words what you are trying to do and move on (at E-level, you don't get credit for merely stating intentions, but university examiners are generally grateful for any sign of intelligent life).

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\* This is less relevant for modern NCEA examinations (even the last 2-3 Scholarship exams).

## NCEA Level 3 Calculus Integration Assignment

1. Compute the indefinite integrals.

(a) (2 points)  $\int x \cdot \cos(x^2) \cdot \sin(\sin x^2) dx$

(b) (2 points)  $\int \pi t \csc^2(2t^2) dt$

(c) (2 points)  $\int \frac{\sqrt{j} + 3j^5 + 3j^6 + 3j^7 + 2}{2j^7} dj$

(d) (2 points)  $\int \frac{\ln t^2}{t} dt$

**Solution:**

(a) Let  $u = \sin x^2$ . Then  $du = 2x \cos x^2 dx$  and our integral becomes  $\int \frac{1}{2} \sin u du = -\frac{1}{2} \cos u + C = -\frac{1}{2} \cos \sin x^2 + C$ . This could also be done by two substitutions,  $u = x^2$  and then  $v = \sin u$ .

(b) Let  $u = 2t^2$ . Then  $du = 4t dt$  and our integral becomes  $\int \frac{\pi}{4} \csc^2(u) du = -\frac{\pi}{4} \cot u + C = -\frac{\pi}{4} \cot(2x^2) + C$ .

(c) We simplify to find that our integral becomes  $\frac{1}{2} \int j^{-6.5} + 3j^{-2} + 3j^{-1} + 3 + 2j^{-7} dj = \frac{1}{2} \left( -\frac{j^{-5.5}}{5.5} - 3j^{-1} + 3 \ln|j| + 3j - \frac{1j^{-6}}{3} \right) + C = \frac{1}{2} \left( -\frac{1}{5.5\sqrt{j^{11}}} - \frac{3}{j} + 3 \ln|j| + 3j - \frac{1}{3j^6} \right) + C$ .

(d) First note that  $\ln t^2 = 2 \ln t$ . Then let  $u = \ln t$  so  $du = \frac{1}{t} dt$  and the integral becomes  $\int 2u du = u^2 + C = (\ln t)^2 + C$ .

2. We will prove the identity  $1 + \tan^2 x = \sec^2$ .

(a) (1 point) Calculate  $\frac{d}{dx} \sec^2 x$ .

(b) (4 points) Using the substitution  $u = \tan x$ , integrate your answer to part (a). Conclude that  $\sec^2 x = \tan^2 x + C$  for some constant  $C$ .

(c) (2 points) Find the value of  $C$  and conclude the identity above.

**Solution:**

(a) Using the chain rule the required derivative is  $2 \sec x \cdot \sec x \tan x = 2 \sec^2 x \tan x$ .

(b) We find  $\int 2 \sec^2 x \tan x dx$ . Let  $u = \tan x$ . Then  $du = \sec^2 x$ , and our integral becomes  $\int 2u du = u^2 + C = \tan^2 x + C$ . But from (a) we have  $\int 2 \sec^2 x \tan x = \sec^2 x + C'$ . Hence  $\tan^2 x + C = \sec^2 x + C'$  and the two differ only by a constant.

**(c)** The identity must hold for all  $x$ , and so we set  $x = 0$ . Then  $\sec^2 0 = \tan^2 0 + C$  and  $C = 1$ . Hence we have  $\sec^2 x = \tan^2 x + 1$  as expected.

3. (2 points) Find the area bounded by the curve  $y = 3x^2 + x - 2$  and the  $x$ -axis.

**Solution:** The curve can be factored as  $y = (3x - 2)(x + 1)$  and so the  $x$ -intercepts are  $x = -1$  and  $x = \frac{2}{3}$ . We must therefore find  $\int_{-1}^{2/3} 3x^2 + x - 2 \, dx = x^3 + 0.5x^2 - 2x \Big|_{-1}^{2/3} = -\frac{125}{54} \approx -2.315$ .

4. (2 points) If  $\int_{-1}^2 3f(x) \, dx = 9$  and  $\int_{-1}^3 f(x) \, dx = 1$ , find  $\int_2^3 f(x) \, dx$ .

**Solution:**  $\int_2^3 f(x) \, dx = \int_{-1}^3 f(x) \, dx - \frac{1}{3} \int_{-1}^2 3f(x) \, dx = 1 - 3 = -2$ .

5. (a) (3 points) Compute  $\int_0^R 2\pi r \, dr$ . Interpret your answer (you may wish to draw a diagram).  
(b) (2 points) Find the volume of a sphere of radius  $R$  by integration; the surface area of a sphere of radius  $r$  is given by  $SA = 4\pi r^2$ .

**Solution:**

**(a)**  $\int_0^R 2\pi r \, dr = \pi r^2 \Big|_0^R = \pi R^2$ , which is the area of a circle of radius  $R$ . This makes sense as we are summing up all the circumferences of circles radiating out from the centre of our larger circle: we expect to get the full area.

**(b)** Same reasoning:  $\int_0^R 4\pi r^2 \, dr = 4/3\pi r^3 \Big|_0^R = 4/3\pi R^3$ .

6. (5 points) Find  $y(\sqrt{\pi/2})$  if  $y(0) = 0$  and

$$\frac{dy}{dx} = x \sin(x^2) \cot y.$$

**Solution:** Separating variables, we have  $\int \tan y \, dy = \int x \sin x^2 \, dx$ . The RHS is simply  $-\frac{1}{2} \cos x^2 + C$  (substitute  $x^2$  out), and we can rewrite the LHS as  $\tan y = \frac{\sin y}{\cos y}$  so (using the substitution  $\cos y$ ); hence overall we have got  $-\ln|\cos y| = -\frac{1}{2} \cos x^2 + C$ . But  $y(0) = 0$  so  $-\ln 1 = -\frac{1}{2} + C$  and  $\ln 1 = 0$  so  $C = 0.5$  and  $|\cos y| = e^{\frac{1}{2} \cos x^2 - \frac{1}{2}}$ . At  $x = \sqrt{\pi/2}$ , the RHS becomes  $e^{-0.5}$  and so  $\cos y = \pm e^{-0.5}$ ; therefore we have two solutions for  $y$ :  $y = \cos^{-1}(\pm e^{-0.5})$ .



## Level Three Calculus Differentiation

There are three questions, worth a total of 28 marks.

Attempt ALL questions, showing all working.

Read questions carefully before attempting them.

Marks are available for partial answers.

The amount of time expected to be spent per question may not necessarily correlate "nicely" to the number of marks.

Diagrams may be used to support answers.

Candidates who do not provide diagrams for some questions may be disadvantaged.

Some marks are given for clarity and neatness of solutions or proofs.

**Time Allowed:** One Hour

**Achieved:** 10 marks

**Merit:** 17 marks

**Excellence:** 24 marks

Question:	1	2	3	Total
Points:	8	10	10	28
Score:				

**Available Grades:** *Not Achieved    Achieved    Merit    Excellence*

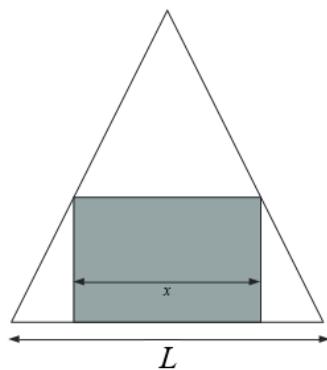
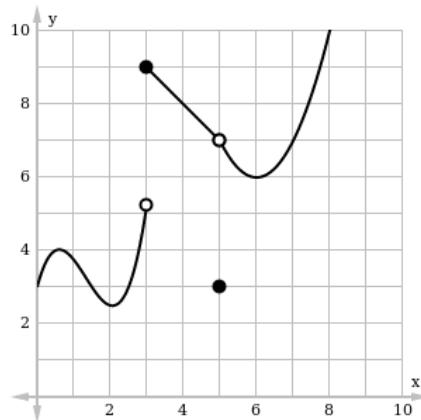


Figure 1: A triangle with an inscribed rectangle.

Figure 2: The graph of  $y = g(x)$ .**Question 1**

- (a) Differentiate

$$y = x^2 + x + 1 + \frac{1}{x} + \frac{1}{x^2}. \quad (1)$$

- (b) A stone is dropped into a lake. The resulting circular ripple spreads at a constant speed of
- $0.5 \text{ m s}^{-1}$
- . Find the rate of change of the area of the ripple after 10 seconds.
- (3)

- (c) Consider an equilateral triangle with side length
- $L$
- . Find the maximum area of a rectangle sitting on the lowest edge of the triangle (as shown in figure 1).
- You need not prove that you have found a maximum.*
- (4)

**Question 2**

- (a) Suppose
- $f$
- is a function defined by

$$f(x) = \cos(2x) + e^{x/2}.$$

- i. Find
- $f'(x)$
- and
- $f''(x)$
- .
- (2)

- ii. Determine the nature of the critical point of
- $f$
- at
- $(0, 0)$
- .
- (1)

- (b) Consider the function
- $g$
- shown in figure 2.
- (1)

- i. Find
- $g(3)$
- .
- (1)

- ii. Explain why
- $\lim_{x \rightarrow 3} g(x)$
- does not exist.
- (2)

- iii. Find the value of
- $\lim_{x \rightarrow 5} g(x)$
- .
- (1)

- (c) From first principles, prove that
- (3)

$$\frac{d}{dt}(x^2 - 5x) = 2x - 5.$$

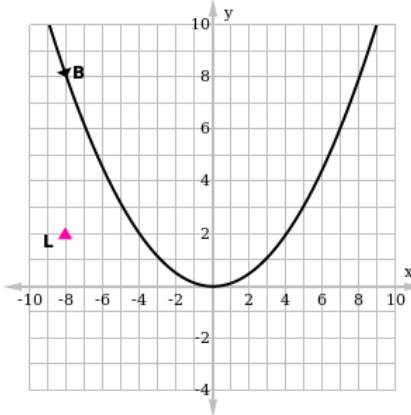


Figure 3: The trajectory of a boat.

**Question 3**

- (a) Find
- $\frac{dx}{dt}$
- if

$$x = \frac{\sec t}{1 + \tan t}. \quad (2)$$

- (b) A boat follows a parabolic trajectory determined by the parametric equations

$$\begin{aligned} y(t) &= 2t^2 \\ x(t) &= 4t \end{aligned}$$

and shown in figure 3.

- i. Find
- $\frac{dy}{dx}$
- in terms of
- $x$
- only.
- (2)

- ii. For which value of
- $t$
- is the distance between the lighthouse
- $L$
- at
- $(-8, 2)$
- and the boat
- $B$
- at a minimum? You need not prove that the value which you find is a minimum.
- (4)

- (c) Show that if

$$y = \frac{1}{m} \sec^2(m \ln \theta) \quad (2)$$

(where  $m$  is a constant) then the rate of change of  $y$  with respect to  $\theta$  when  $\theta = 1$  is 0.

# Solutions to L3 Calculus Differentiation Exam 1

Alexander Elzenaar

3 September 2017

## Question One

### Part (a)

$$\frac{dy}{dx} = 2x + 1 - \frac{1}{x^2} - \frac{2}{x^3}$$

(1 mark)

### Part (b)

We have  $\frac{dr}{dt} = 0.5$ . Since  $A = \pi r^2$ , we can write  $\frac{dA}{dt} = \frac{dr}{dt} \times 2\pi r = \pi r$ . After 10 seconds, the radius will be 5 metres and so  $\left. \frac{dA}{dt} \right|_{t=10} = 5\pi$ . (3 marks)

### Part (c)

Noting that an equilateral triangle has angles of  $\frac{\pi}{3}$ , the height of the rectangle must be  $\frac{L-x}{2} \tan \frac{\pi}{3} = \frac{\sqrt{3}}{2}(L-x)$ . Hence the area of the rectangle is

$$A = \frac{\sqrt{3}}{2}(L-x)x = \frac{\sqrt{3}}{2}(Lx - x^2)$$

and, taking the derivative,

$$A' = \frac{L\sqrt{3}}{2} - x\sqrt{3}$$

The area will be maximised when  $A' = 0$ , which is exactly when  $x = L/2$ . (4 marks)

## Question Two

### Part (a)

(i)

$$\begin{aligned} f'(x) &= -2 \sin(2x) + \frac{1}{2}e^{x/2} \\ f''(x) &= -4 \cos(2x) + \frac{1}{4}e^{x/2} \end{aligned}$$

(2 marks)

(ii) We have  $f''(0) = -4 + \frac{1}{4} < 0$ , so the function is concave down and the point is a minimum. (1 mark)

### Part (b)

(i)  $g(3) = 9$  (1 mark)

(ii) The function approaches a value near  $y = 5.5$  on the left, but a value near  $y = 9$  from the right. Hence the left and right limits are different, and the limit of the function at  $x = 3$  does not exist. (2 marks)

(iii)  $\lim_{x \rightarrow 5} = 7$  (1 mark)

### Part (c)

$$\begin{aligned}\frac{d}{dt}(x^2 - 5x) &= \lim_{h \rightarrow 0} \frac{[(x+h)^2 - 5(x+h)] - (x^2 - 5x)}{h} \\ &= \lim_{h \rightarrow 0} \frac{x^2 + 2xh + h^2 - 5x - 5h - x^2 + 5x}{h} \\ &= \lim_{h \rightarrow 0} \frac{2xh + h^2 - 5h}{h} \\ &= \lim_{h \rightarrow 0} 2x - 5 + h \\ &= 2x - 5.\end{aligned}$$

(3 marks)

## Question Three

### Part (a)

$$\begin{aligned}\frac{dx}{dt} &= \frac{(1 + \tan t)(\sec t)' - (\sec t)(1 + \tan t)'}{(1 + \tan t)^2} \\ &= \frac{(1 + \tan t)(\sec t \tan t) - (\sec t)(\sec^2 t)}{1 + 2 \tan t + \tan^2 t} \\ &= \frac{\sec t \tan t + \sec t \tan^2 t - \sec^3 t}{1 + 2 \tan t + \tan^2 t}\end{aligned}$$

(2 marks)

### Part (b)

(i) We have  $y'(t) = 4t$  and  $x'(t) = 4$ . Hence  $\frac{dy}{dx} = t = \frac{x}{4}$ . (2 marks)

(ii) Suppose that  $B = (x, y)$ . Then the distance we wish to minimise is

$$D = \sqrt{(x+8)^2 + (y-2)^2} = \sqrt{(4t+8)^2 + (2t^2-2)^2} = \sqrt{4t^4 + 8t^2 + 64t + 68}$$

Then we can take the derivative and set it to zero:

$$\begin{aligned}\frac{dD}{dt} &= \frac{1}{2(4t^4 + 8t^2 + 64t + 68)} \times 16t^3 + 16t + 64 \\ 0 &= 16t^3 + 16t + 64 \\ &= t^3 + t + 4 \\ t &\approx -1.3788.\end{aligned}$$

(4 marks)

**Part (c)**

Taking the derivative:

$$\begin{aligned}y &= \frac{1}{m} [\sec(m \ln \theta)]^2 \\ \frac{dy}{d\theta} &= \frac{1}{m} \cdot 2 \cdot \sec(m \ln \theta) \cdot \sec(m \ln \theta) \tan(m \ln \theta) \cdot \frac{m}{\theta} \\ &= \frac{2}{\theta} \cdot \sec^2(m \ln \theta) \cdot \tan(m \ln \theta).\end{aligned}$$

Plugging in  $\theta = 1$ , we have  $\frac{2}{1} \cdot \sec^2(m \ln 1) \cdot \tan(m \ln 1) = 2 \cdot 1 \cdot 0 = 0$ . (2 marks)



## Level Three Calculus Differentiation

There are three questions, worth a total of 30 marks.

Attempt ALL questions, showing all working.

Read questions carefully before attempting them.

Marks are available for partial answers.

The amount of time expected to be spent per question may not necessarily correlate "nicely" to the number of marks.

Diagrams may be used to support answers.

Candidates who do not provide diagrams for some questions may be disadvantaged.

Some marks are given for clarity and neatness of solutions or proofs.

**Time Allowed:** One Hour

**Achieved:** 11 marks

**Merit:** 19 marks

**Excellence:** 27 marks

Question:	1	2	3	Total
Points:	10	10	10	30
Score:				

**Available Grades:** *Not Achieved    Achieved    Merit    Excellence*

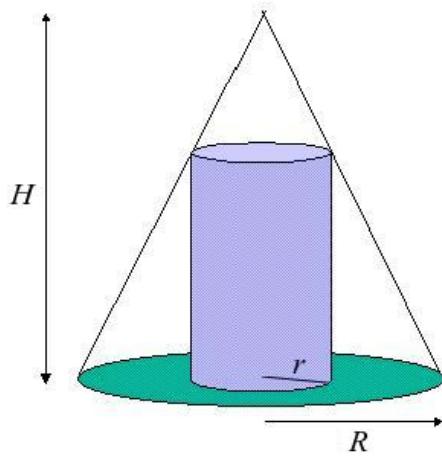


Figure 1: A cylinder inscribed in a cone.

**Question 1**

- (a) Find  $\frac{dD}{dt}$  and  $\frac{dD}{dx}$  if  $D = A \sin(kx - \omega t + \phi_0)$ . (2)  
 (b) Find the rate of change of  $y$  with respect to  $x$  at the point  $(0, \frac{\pi}{4})$  if (3)

$$\tan y = e^x$$

- (c) Consider a cylinder of radius  $r$  within a right-angled circular cone of radius  $R$  and height  $H$  (see figure 1). Show that the volume of the cylinder is maximised when  $r = \frac{2}{3}R$ . *Show any derivatives you require, and carefully justify that the volume is a maximum.* (5)

**Question 2**

- (a) Compute the derivatives of the following functions.
- $y = \frac{e^{-x} + \sin x}{x}$  (2)
  - $y = \sqrt{x} \left( x^2 + 5x + \frac{1}{x} \right)$  (1)
- (b) i. Write down the expression for the derivative of  $x^3$  from first principles. *You need not evaluate the limit.* (1)  
 ii. Hence, or otherwise, compute the following limit: (2)

$$\lim_{h \rightarrow 0} \frac{(2+h)^3 - 8}{h}$$

- (c) Find the interval(s) on which the function  $f$  defined below is concave up. (4)

$$f(x) = \frac{x^5}{20} - \frac{2x^3}{3} + 16x + 9$$

**Question 3**

- (a) Show that the rate of change of  $g$  with respect to  $t$  at  $t = 2$  is  $\frac{3\pi}{2}$  if (2)

$$g(t) = \sin(\pi\sqrt{3t^2 + 4}).$$

- (b) Find the equation to the normal line of the curve  $y = x^4 - 3x^3 - 2x^2 + 2x - 1$  at the point  $(0, -1)$ . (3)

- (c) Sand is being poured into a hole at a rate of  $\frac{dS}{dt} = 3t + 4$ , and the depth of the hole is given by  $h = 12 - \sqrt{S}$ . Find  $\frac{dh}{dt}$  in terms of  $t$  and  $S$ , and show that  $h$  has no maxima or minima at any time after  $t = 0$ . (2)

- (d) Show that  $y = 2x^3 - 18x^2 + 90x + 3$  has no tangent line with a slope of 3. (3)

## Solutions to L3 Calculus Differentiation Exam 2

Alexander Elzenaar

4 September 2017

## Question One

### Part (a)

$$\frac{dD}{dt} = -\omega A \cos(kx - \omega t + \phi_0)$$

$$\frac{dD}{dx} = kA \cos(kx - \omega t + \phi_0)$$

(2 marks)

### Part (b)

$$\tan y = e^x$$

$$\frac{dy}{dx} \sec^2 y = e^x$$

$$\frac{dy}{dx} = e^x \cos^2 y$$

So at  $(0, \frac{\pi}{4})$  we have  $\frac{dy}{dx} = e^0 \cos^2 \frac{\pi}{4} = \frac{1}{2}$ . (3 marks)

### Part (c)

We have that the angle of the slope of the cone with the base is  $\tan^{-1} \frac{H}{R}$  and so the height of the cylinder at radius  $r$  is  $h = (R - r)\frac{H}{R} = H(1 - \frac{r}{R})$ . The volume of the cylinder is  $V = \pi r^2 h = \pi r^2 H(1 - \frac{r}{R}) = H\pi r^2 - \frac{H\pi}{R} r^3$ . Taking the derivative,  $\frac{dV}{dr} = 2H\pi r - \frac{3H\pi}{R} r^2$ ; setting to zero,  $2H\pi r = \frac{3H\pi}{R} r^2$  and so (since  $r \neq 0$ )  $r = \frac{2R}{3}$ .

We also have  $\frac{d^2V}{dr^2} = 2H\pi - \frac{6H\pi}{R} r$ , so at our found radius  $\frac{d^2V}{dr^2} = 2H\pi - 4H\pi < 0$  and so the function is concave down at that point — we have indeed found a maximum.

(5 marks)

## Question Two

### Part (a)

(i)

$$\frac{dy}{dx} = -\frac{e^{-x}}{x^2} - \frac{e^{-x}}{x} - \frac{\sin x}{x^2} + \frac{\cos x}{x}.$$

(2 mark)

(ii)

$$\frac{dy}{dx} = \frac{5}{2}x^{3/2} + \frac{15}{2}x^{1/2} - \frac{1}{2}x^{-3/2}.$$

(1 mark)

**Part (b)**

(i)

$$\frac{d}{dx}x^3 = \lim_{h \rightarrow 0} \frac{(x+h)^3 - x^3}{h}$$

(1 mark)

(ii) Noticing that we are just finding the value of the derivative of  $x^3$  at  $x = 2$ , we evaluate  $3x^2$  at 2 and obtain 12 as the value of the limit. Alternatively, one could expand the brackets and evaluate the limit algebraically. (2 marks)

**Part (c)**

$$\begin{aligned} f'(x) &= \frac{x^4}{4} - 2x^2 + 16 \\ f''(x) &= x^3 - 4x = x(x^2 - 4) = (x-2)x(x+2) \end{aligned}$$

Since  $f''(x)$  is a positive conic, it is negative on the intervals  $x < -2$  and  $0 < x < 2$  and positive on the intervals  $-2 < x < 0$  and  $x > 2$ . Hence the function  $f$  is concave up on the latter two intervals. (4 marks)

**Question Three****Part (a)**

$$g'(t) = 6t \cdot \frac{\pi}{2\sqrt{3t^2 + 4}} \cdot \cos(\pi\sqrt{3t^2 + 4}).$$

We therefore have  $g'(2) = 12 \cdot \frac{\pi}{2\sqrt{16}} \cdot \cos(\pi\sqrt{16}) = 12 \cdot \frac{\pi}{8} \cdot 1 = \frac{3\pi}{2}$ . (2 marks)

**Part (b)**

$$\frac{dy}{dx} = 4x^3 - 9x^2 - 4x + 2$$

Therefore at the point  $(0, -1)$  the gradient is  $m = 2$  and the normal line will have a slope of  $-\frac{1}{2}$ . Hence the equation of the normal is  $(y + 1) = -\frac{1}{2}x$ , or  $y = -\frac{1}{2}x - 1$ . (3 marks)

**Part (c)**

We have  $\frac{dh}{dt} = \frac{dS}{dt} \cdot \left(-\frac{1}{\sqrt{S}}\right) = -\frac{3t+4}{\sqrt{S}}$ . This is zero exactly when  $3t+4 = 0$ , which is when  $t = -\frac{4}{3} < 0$ . (2 marks)

**Part (d)**

$$\frac{dy}{dx} = 6x^2 - 36x + 90$$

Suppose  $\frac{dy}{dx} = 4$ . Then  $6x^2 - 36x + 86 = 0$ . But  $36^2 - 4 \times 6 \times 86 < 0$ , so the gradient of the curve is never 4. (3 marks)



## Level Three Calculus Differentiation

There are three questions, worth a total of 24 marks.

Attempt ALL questions, showing all working.

Read questions carefully before attempting them.

Marks are available for partial answers.

The amount of time expected to be spent per question may not necessarily correlate “nicely” to the number of marks.

Diagrams may be used to support answers.

Candidates who do not provide diagrams for some questions may be disadvantaged.

Some marks are given for clarity and neatness of solutions or proofs.

**Time Allowed:** One Hour

**Achieved:** 11 marks

**Merit:** 19 marks

**Excellence:** 27 marks

Question:	1	2	3	Total
Points:	8	8	8	24
Score:				

**Available Grades:** *Not Achieved    Achieved    Merit    Excellence*

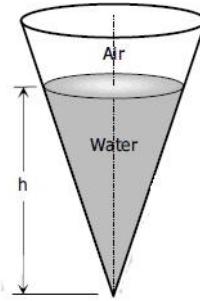


Figure 1: The leaky tank.

**Question 1**

- (a) For i. and ii., find the derivatives of the given functions with respect to
- $x$
- .

i.  $f(x) = e^{-\sqrt{x}}$  (1)

ii.  $g(x) = \frac{2\sqrt[3]{x+1}}{\ln x}$  (1)

- (b) The path through space of a particle can be modelled by the following 2D parametric equation.

$$x(t) = \sin(2t)$$

$$y(t) = \sin(t + \sin(2t))$$

- i. Calculate the velocity of the particle as it passes through the origin at
- $t = 0$
- . Give your answer in the form
- $(v_x(t), v_y(t))$
- , where
- $v_x(t)$
- and
- $v_y(t)$
- are the
- $x$
- and
- $y$
- components of the velocity respectively. (3)

- ii. Write down an expression for
- $\frac{dy}{dx}$
- , and explain its geometric interpretation. (3)

**Question 2**

- (a) Find the equation of the tangent line to the curve (3)

$$y^5 + 4x^2y - x^3 + 2x^3y - 1 = 0$$

at the point  $(-5, 1)$ . Write your answer in the form  $y = mx + c$ .

- (b) Amanda is dreaming that water is leaking out of a tank shaped like an upside-down cone, as in figure 1. The radius of the base of the cone is
- $R = 2$
- m, and the height of the cone is
- $H = 5$
- m.

- i. Water is leaking out of the tank at a constant rate of
- $0.2 \text{ m}^3$
- per second. What is the rate-of-change of the depth of the water at the instant that the depth of the water is
- $h = 3$
- m? (3)

- ii. Amanda notices that the tank has less water in it than she would prefer, and dreams that she begins to pump water back in at a constant rate
- without plugging the original leak**
- . When the height of the water is
- $h = 2$
- m, the water level is rising at a rate of
- $0.1 \text{ m s}^{-1}$
- . Find the rate at which water is being pumped back in. (2)

**Question 3**

- (a) Let
- $\varphi(x) = \sqrt{x}$
- . Explain why the limit
- $\lim_{x \rightarrow 0} \varphi(x)$
- does not exist, even though
- $\varphi(x)$
- has a value at
- $x = 0$
- . (2)

- (b) Recall that an isosceles triangle is a triangle with two equal sides. Find the side-lengths of the isosceles triangle of greatest area with perimeter
- $P$
- . (3)

- (c) Peter Pan is opening a lemonade stand in Taumarunui. Each lemon costs \$5, but only half a lemon is needed for each glass; there is also an initial fixed cost of \$5 for the glasses, sugar, and other equipment. After conducting a survey, Peter finds that if he sells the lemonade at a price
- $c$
- per glass, the expected demand is
- $D = 30e^{-c/2}$
- . What price should he sell a glass for in order to maximise his profit? (3)

# Solutions to L3 Calculus Differentiation Exam 3

Alexander Elzenaar

16 November 2017

## Question One

### Part (a)

i.  $f'(x) = -\frac{1}{2\sqrt{x}}e^{-\sqrt{x}}$  (or accept in form with indices) (1 mark)

ii.  $g'(x) = \frac{\frac{2}{3}\ln x(x+1)^{-2/3} - \frac{2}{x}(x+1)^{1/3}}{\ln^2 x}$  (or simplified) (1 mark)

### Part (b)

i.  $v_x(t) = 2\cos 2t, v_y(t) = (1 + 2\cos 2t)\cos(t + \sin 2t)$  so

$$v(t) = (2\cos 2t, (1 + 2\cos 2t)\cos(t + \sin 2t))$$

(3 marks)

ii.

$$\frac{dy}{dx} = \frac{(1 + 2\cos 2t)\cos(t + \sin 2t)}{2\cos 2t}$$

This derivative represents the instantaneous change in the  $y$ -ordinate of the particle as its  $x$ -ordinate varies. (3 marks)

## Question Two

### Part (a)

First, we have  $\frac{dy}{dx} 5y^4 + 8xy + 4x^2 \frac{dy}{dx} - 3x^2 + 6x^2y + 2x^3 \frac{dy}{dx} = 0$ , so it follows that

$$\frac{dy}{dx} = -\frac{8xy + 3x^2 + 6x^2y}{5y^4 + 4x^2 + 2x^3}$$

and at the given point the tangent line has slope  $m = \frac{37}{29}$ . Hence the tangent line is described by

$$(y - 1) = \frac{37}{29}(x + 5) \Rightarrow y = \frac{37}{29}x + \frac{214}{19}.$$

(3 marks)

### Part (b)

i. We have  $\frac{dV}{dt} = -0.2$ . Then  $\frac{R}{r} = \frac{H}{h}$  so  $r = \frac{Rh}{H}$  and  $V(h) = \frac{\pi}{3}r^2h = \frac{R^2\pi}{3H^2}h^3$ . Hence  $\frac{dV}{dh} = \frac{R^2\pi}{H^2}h^2$ ,  $\frac{dh}{dt} = -\frac{0.2H^2}{R^2h^2\pi}$ , so at  $h = 3$  the depth of water is decreasing at a rate of  $0.0442 \text{ m s}^{-1}$ . (3 marks)

ii. Let the rate of pumping be  $k$ . We now have  $\frac{dV}{dt} = k - 0.2$ , so  $\frac{dh}{dt} = \frac{H^2(k-0.2)}{R^2h^2\pi}$  and at  $h = 2$ ,  $0.1 = 0.4974(k - 0.2)$  and  $k = 0.40 \text{ m}^3 \text{ s}^{-1}$ . (2 marks)

## Question Three

### Part (a)

Since  $\varphi(x)$  is undefined for all  $x < 0$ , we cannot take the limit  $\lim_{x \rightarrow 0} \varphi(x)$  as the function cannot tend to a single value from both sides. (2 marks)

### Part (b)

Let the three sides of the triangle be  $x$ ,  $\frac{1}{2}(P - x)$ , and  $\frac{1}{2}(P - x)$ . Then the height of the triangle is given by

$$h = \sqrt{\left(\frac{P-x}{2}\right)^2 - \left(\frac{x}{2}\right)^2} = \frac{1}{2}\sqrt{P^2 - 2Px}$$

and the area is

$$A = \frac{1}{2}xh = \frac{1}{4}\sqrt{P^2x^2 - 2Px^3}.$$

We wish to maximise this, so we take the derivative:

$$\frac{dA}{dx} = \frac{P^2x - 3Px^2}{4\sqrt{P^2x^2 - 2Px^3}}.$$

Setting to zero, we have  $P^2 - 3Px = 0$  and so  $x = \frac{P}{3}$ ; so the triangle needs to be equilateral.

### Part (c)

Profit  $P$  is income minus costs. Total income is  $Dc$ , total cost is  $5 + \frac{5D}{2}$ , so:

$$P = D\left(c - \frac{5}{2}\right) - 5 = 30\left(c - \frac{5}{2}\right)e^{-c/2} - 5$$

Taking the derivative,  $\frac{dP}{dc} = 30e^{-c/2} - 15\left(c - \frac{5}{2}\right)e^{-c/2}$ . Hence  $30 = 15\left(c - \frac{5}{2}\right)$  and  $c = \$4.50$ . (3 marks)



## Level Three Calculus Integration

There are three questions, worth a total of 36 marks.

Attempt ALL questions, showing all working.

Read questions carefully before attempting them.

Marks are available for partial answers.

The amount of time expected to be spent per question may not necessarily correlate “nicely” to the number of marks.

Diagrams may be used to support answers.

Candidates who do not provide diagrams for some questions may be disadvantaged.

Some marks are given for clarity and neatness of solutions or proofs.

**Time Allowed:** One Hour

**Achieved:** 13 marks

**Merit:** 22 marks

**Excellence:** 31 marks

Question:	1	2	3	Total
Points:	12	12	12	36
Score:				

**Available Grades:** *Not Achieved    Achieved    Merit    Excellence*

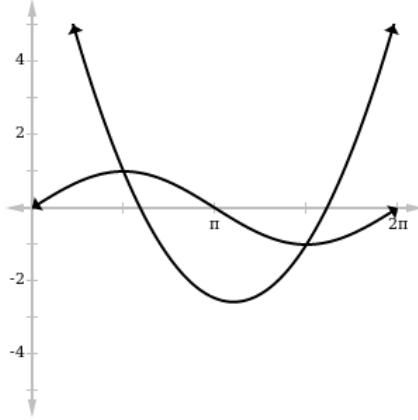


Figure 1: Two intersecting functions.

**Question 1**

- (a) Compute the following indefinite integrals.

i.

$$\int \frac{3t^2 + 2t}{\sqrt{t}} dt \quad (1)$$

ii.

$$\int 2 \sin 2x \sin(\cos 2x) dx \quad (1)$$

- (b) Suppose that the derivative of
- $y$
- is

$$\frac{dy}{dx} = \frac{1}{\ln(2)(x+2)}.$$

If  $y = 3$  when  $x = 0$ , find  $y$  when  $x = -1$ .

- (c) Suppose
- $f$
- is a continuous function. If
- $0 < x < y < 10$
- ,
- $\int_x^{10} f(t) dt = 3$
- ,
- $\int_0^y dt = 4$
- , and
- $\int_y^x f(t) dt = 2$
- , find
- $\int_0^{10} f(t) dt$
- .
- (2)

- (d) The base of a solid is a square with vertices located at
- $(1, 0)$
- ,
- $(0, 1)$
- ,
- $(-1, 0)$
- , and
- $(0, -1)$
- . Each cross-section perpendicular to the
- $x$
- axis is a semicircle (so the semicircle on the
- $x$
- axis itself has radius 1). Form a definite integral and calculate the volume of the solid.
- (5)

**Question 2**

- (a) Compute the following definite integral.
- (2)

$$\int_{\pi/4}^{\pi/3} \csc^2 \theta d\theta$$

- (b) Find the area (to 1 decimal place) between the graphs of
- $y = \sin x$
- and
- $y = x^2 - \frac{2(1+\pi^2)}{\pi}x + \frac{3\pi^2}{4} + 2$
- shown in figure 1, given that their intersection points are
- $(\pi/2, 1)$
- and
- $(3\pi/2, -1)$
- .
- (3)

- (c) The rate of change of a particular animal population over
- $t$
- days is given by

$$\frac{dP}{dt} = 1 - \frac{P}{M},$$

where  $M$  is a constant.

- i. Find an explicit formula for
- $P$
- in terms of
- $M$
- and
- $t$
- , given that
- $P(0) = 100$
- .
- (4)

- ii. If
- $\frac{dP}{dt} = 1$
- when
- $t = 0$
- , find
- $M$
- . Hence, find the population after 100 days.
- (3)

Table 1: Data over a network in gigabits per hour,  $D(t)$ .

$t$	$D(t)$
0	3.2
1	2.7
2	1.9
3	1.7
4	1.3
5	1.0
6	1.1

**Question 3**

- (a) Table 1 gives values of a function  $D(t)$ . Use Simpson's rule with  $n = 6$  to approximate  $\int_0^6 D(t) dt$ . (2)
- (b) Evaluate the following indefinite integral. (2)

$$\int e^x (15 + e^x)^{2017} + 3 dx$$

- (c) Suppose  $n$  is an integer constant. If  $y$  is defined implicitly as a function of  $x$  as follows, and  $y = 0$  when  $x = 0$ , find  $y$  when  $x = \frac{1}{n}$ . (4)

$$\frac{dy}{dx} = -(y+2)(n\pi \sin(xn\pi))$$

- (d) Using the substitution  $x = \sin \theta$ , or otherwise, compute the following indefinite integral. (4)

$$\int \frac{1}{\sqrt{1-x^2}} dx$$

# Solutions to L3 Calculus Integration Exam 1

Alexander Elzenaar

4 September 2017

## Question One

### Part (a)

(i)

$$\int \frac{3t^2 + 2t}{\sqrt{t}} dt = \int 3t^{3/2} + 2t^{1/2} dt = \frac{6}{5}t^{5/2} + \frac{4}{3}t^{3/2} + C.$$

(1 mark)

(ii)

$$\int 2 \sin 2x \sin(\cos 2x) dx = \sin \cos 2x + C.$$

(1 mark)

### Part (b)

$$y = \frac{1}{\ln 2} \int \frac{1}{x+2} = \frac{\ln(x+2)}{\ln 2} + C$$

Since  $3 = \frac{\ln 0+2}{\ln 2} + C = 1 + C$ ,  $C = 2$ . Hence  $y = \frac{\ln(x+2)}{\ln 2} + 2$ , and when  $x = -1$ ,  $y = \frac{\ln(-1+2)}{\ln 2} + 2 = 2$ . (3 marks)

### Part (c)

$$\int_0^{10} f(t) dt = \int_0^y dt + \int_x^{10} f(t) dt - \int_x^y f(t) dt = 4 + 3 - 2 = 5$$

(2 marks)

### Part (d)

We integrate along the  $x$ -axis from  $x = -1$  to  $x = 0$  and then from  $x = 0$  to  $x = 1$ . Over the first half, the radius of each semicircle is  $r = x + 1$ , and over the second half the radius of each semicircle is  $r = -x + 1$ . Hence our volume will be

$$\int_{-1}^0 \frac{1}{2}\pi(x+1)^2 dx + \int_0^1 \frac{1}{2}\pi(-x+1)^2 dx = \frac{\pi}{6}(x+1)^3 \Big|_{-1}^0 - \frac{\pi}{6}(-x+1)^3 \Big|_0^1 = \frac{\pi}{3}$$

(5 marks)

## Question Two

### Part (a)

$$\int_{\pi/4}^{\pi/3} \csc^2 \theta d\theta = -\cot \theta \Big|_{\pi/4}^{\pi/3} = 1 - \frac{1}{\sqrt{3}} \approx 0.4226$$

(2 marks)

**Part (b)**

$$\begin{aligned}
& \int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} \sin x - x^2 + \frac{2(1+\pi^2)}{\pi} x + \left( \frac{3\pi^2}{4} + 2 \right) dx \\
&= -\cos x - \frac{1}{3}x^3 + \frac{(1+\pi^2)}{\pi}x^2 + \left( \frac{3\pi^2}{4} + 2 \right)x \Big|_{\frac{\pi}{2}}^{\frac{3\pi}{2}} \\
&\approx 86.25748 - 22.01398 \approx 64.24350
\end{aligned}$$

(3 marks)

**Part (c)**

(i)

$$\begin{aligned}
\int \frac{dP}{1 - \frac{P}{M}} &= \int dt \\
-M \ln \left( 1 - \frac{P}{M} \right) &= t + C \\
\ln \left( 1 - \frac{P}{M} \right) &= -Mt + C \\
1 - \frac{P}{M} &= Ke^{-Mt} \\
P &= M \left( 1 - Ke^{-Mt} \right)
\end{aligned}$$

At  $t = 0$ ,  $P = 100$ . So  $100 = M(1 - Ke)$  and  $K = \frac{M-100}{Me}$ .  
Hence the explicit formula for  $P$  is

$$P = M \left( 1 - \frac{M-100}{M} e^{-Mt-1} \right) = M + \frac{(100-M)}{e^{Mt+1}}.$$

(4 marks)

(ii) At  $t = 0$ ,  $\frac{dP}{dt} = 1 - \frac{P}{M} = 1$ . Hence:

$$\begin{aligned}
1 &= 1 - \frac{M + \frac{(100-M)}{e^{Mt+1}}}{M} = \frac{(100-M)}{Me} \\
M &= \frac{100}{e+1}
\end{aligned}$$

and therefore

$$P = M + \frac{(100-M)}{e^{Mt+1}} = \frac{100}{e+1} + \frac{\left(100 - \frac{100}{e+1}\right)}{e^{\frac{100t}{e+1}+1}}.$$

At  $t = 100$ ,  $P \approx 26.89$  — or around 27 animals. (3 marks)

## Question Three

### Part (a)

Applying Simpson's rule:

$$\frac{1}{3} \cdot \frac{6-0}{6} \cdot [3.2 + 1.1 + 4(2.7 + 1.7 + 1.0) + 2(1.9 + 1.3)] \approx 10.76.$$

(2 mark)

### Part (b)

$$\int e^x (15 + e^x)^{2017} + 3 \, dx = \frac{(15 + e^x)^{2018}}{2018} + 3x + C.$$

(2 marks)

### Part (c)

$$\begin{aligned} \int \frac{dy}{y+2} &= - \int n\pi \sin(xn\pi) \, dx \\ \ln(y+2) &= \cos(xn\pi) + C \\ y &= Ke^{\cos(xn\pi)} - 2 \end{aligned}$$

Since  $y = 0$  when  $x = 0$ , we have  $2 = Ke$  and so  $K = \frac{2}{e}$ . Hence  $y = 2e^{\cos(xn\pi)-1} - 2$ , and when  $x = \frac{1}{n}$ ,  $y = 2e^{\cos(\pi)-1} - 2 = 2e^{-2} - 2 = \frac{2}{e^2} - 2 \approx -1.729$ . (4 marks)

### Part (d)

Let  $x = \sin \theta$ ; then  $dx = \cos \theta d\theta$ , and:

$$\begin{aligned} \int \frac{1}{\sqrt{1-x^2}} \, dx &= \int \frac{\cos \theta}{\sqrt{1-(\sin \theta)^2}} \, d\theta \\ &= \int \frac{\cos \theta}{\cos \theta} \, d\theta \\ &= \int d\theta \\ &= \theta = \sin^{-1} x. \end{aligned}$$

(4 marks)



## Level Three Calculus Integration

There are three questions, worth a total of 33 marks.

Attempt ALL questions, showing all working.

Read questions carefully before attempting them.

Marks are available for partial answers.

The amount of time expected to be spent per question may not necessarily correlate “nicely” to the number of marks.

Diagrams may be used to support answers.

Candidates who do not provide diagrams for some questions may be disadvantaged.

Some marks are given for clarity and neatness of solutions or proofs.

**Time Allowed:** One Hour

**Achieved:** 13 marks

**Merit:** 21 marks

**Excellence:** 29 marks

Question:	1	2	3	Total
Points:	11	11	11	33
Score:				

**Available Grades:** *Not Achieved    Achieved    Merit    Excellence*

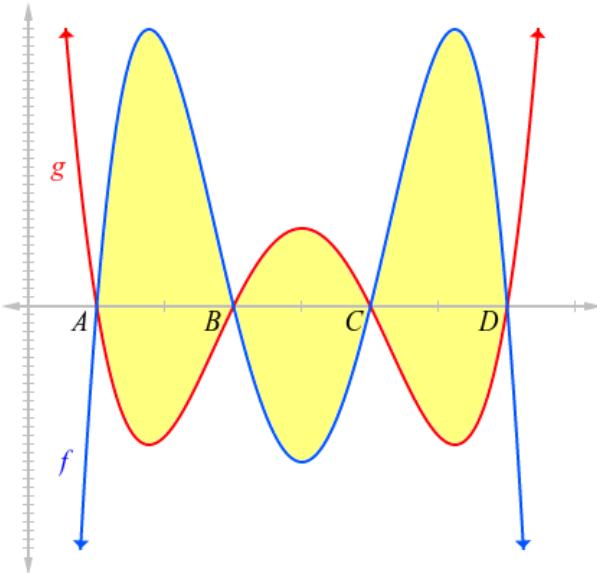


Figure 1: Two functions enclosing an area.

**Question 1**

- (a) Compute the following definite integrals.

i.  $\int_{\pi/4}^{\pi/2} 2 \csc 2x \cot 2x \, dx$

[2]

ii.  $\int_1^4 t \left( \frac{1.5}{\sqrt{t}} + 12 \right) dt$

[2]

- (b) A balloon is being pumped up slowly such that its volume changes at a rate inversely proportional to the time
- $t$
- (in minutes); the rate can be modelled by
- $\frac{dV}{dt} = \frac{k}{t+1}$
- for some constant
- $k$
- . The initial volume of the balloon was
- $0.5 \text{ m}^3$
- , and after three minutes the volume had doubled. After what length of time will the volume of the balloon exceed
- $2 \text{ m}^3$
- ?

[4]

- (c) Find the area between the curves
- $y = -\frac{1}{2}x^2 + \frac{3}{2}x$
- and
- $y = \frac{1}{2}x^2 - \frac{3}{2}x + 2$
- given that they intersect at
- $(1, 1)$
- and
- $(2, 1)$
- .

[3]

**Question 2**

- (a) Compute the following indefinite integrals.

i.  $\int \frac{2x+1}{x^2+x} \, dx$

[1]

ii.  $\int \cos^4 \theta \, d\theta$

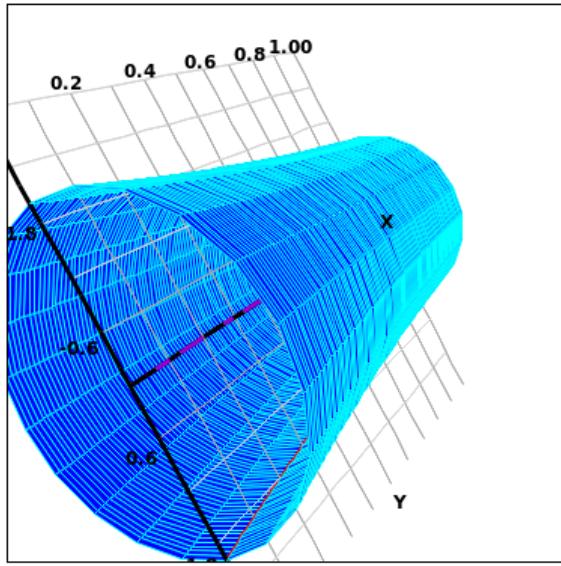
[3]

- (b) Consider the functions
- $f$
- and
- $g$
- graphed in figure 1. Given that the shaded region has a total area of 32 units squared,
- $\int_A^B f(x) - g(x) \, dx = 2$
- , and
- $\int_C^D f(x) - g(x) \, dx = 10$
- , compute

$$\int_B^C f(x) - g(x) \, dx.$$

- (c) Suppose that
- $\frac{dy}{dt} = (y+1)(\sin 2\pi t)$
- , and
- $y(0) = 1$
- . Find
- $y(0.5)$
- .

[4]

Figure 2: The volume of revolution of  $e^{-x} + 1$ .**Question 3**

- (a) The *volume of revolution* of a curve  $y = f(x)$  between two bounds  $x = a$  and  $x = b$  is given by  $\pi \int_a^b y^2 dx$ . Find the volume of revolution of  $y = e^{-x} + 1$  between  $x = 0$  and  $x = 1$  by computing

$$\pi \int_0^1 (e^{-x} + 1)^2 dx.$$

The volume is visualised in figure 2.

- (b) Suppose that the acceleration of a particle is described at time  $t$  by the equation

$$\frac{d^2x}{dt^2} = 12t + 12.$$

If the particle is initially located at  $x = 3$ , and is initially stationary, find the position of the particle at time  $t = 10$ .

- (c) Newton's law of cooling states that the rate of heat loss of an object is directly proportional to the difference in the temperatures between the object and its surroundings. Symbolically, if the environmental temperature is  $T_0$ , then

$$\frac{dT}{dt} = -k(T - T_0).$$

A loaf of bread is removed from an oven at a temperature of  $230^\circ\text{C}$ , and is left to cool in an area with a temperature of  $18^\circ\text{C}$ . How long, in terms of  $k$ , will it take for the bread to cool to  $30^\circ\text{C}$ ?

- (d) Explain why  $\int_0^{2\pi} \tan x dx$  does not exist.

## Solutions to L3 Calculus Integration Exam 2

Alexander Elzenaar

7 September 2017

## Question One

### Part (a)

(i)

$$\int_{\pi/4}^{\pi/2} 2 \csc 2x \cot 2x \, dx = -\csc 2x \Big|_{\pi/4}^{\pi/2} = \frac{-1}{\sin \pi} - \frac{-1}{\sin \frac{\pi}{2}} = 1.$$

(2 marks)

(ii)

$$\begin{aligned} \int_1^4 t \left( \frac{1.5}{\sqrt{t}} + 12 \right) dt &= \int_1^4 1.5t^{0.5} + 12t \, dt \\ &= t^{1.5} + 6t^2 \Big|_1^4 \\ &= t\sqrt{t} + 6t^2 \Big|_1^4 \\ &= (4 \cdot 2 + 6 \cdot 16) - (1 + 6) = 97. \end{aligned}$$

(2 marks)

### Part (b)

$$V = \int \frac{k}{t+1} \, dt = k \ln(t+1) + C.$$

Now, when  $t = 0$  we have  $V = 0.5$ . So  $0.5 = k \ln 1 + C = C$ , and  $V = k \ln(t+1) + 0.5$ . We also know that  $2V_0 = V_3$  so  $1 = k(\ln 4) + 0.5$  and  $k = \frac{1}{2 \ln 4} = \frac{1}{4 \ln 2}$ . Therefore  $V = \frac{\ln(t+1)}{4 \ln 2} + 0.5$ ; we want  $t$  when  $V = 2$  and L2 algebra shows that  $t = 63$  minutes. (4 marks)

### Part (c)

$$\begin{aligned} \int_1^2 \left( -\frac{1}{2}x^2 + \frac{3}{2}x \right) - \left( \frac{1}{2}x^2 - \frac{3}{2}x + 2 \right) \, dx &= \int_1^2 -x^2 + 3x - 2 \, dx \\ &= -\frac{1}{3}x^3 + \frac{3}{2}x^2 - 2x \Big|_1^2 = \frac{8}{3} + 6 - 4 + \frac{1}{3} - \frac{3}{2} + 2 \\ &= 5.5. \end{aligned}$$

The area between the curves is 5.5 square units. (3 marks)

## Question Two

### Part (a)

(i)

$$\int \frac{2x+1}{x^2+x} dx = \ln(x^2+x) + C$$

(1 mark)

(ii)

$$\begin{aligned} \int \cos^4 \theta d\theta &= \int (\cos^2 \theta)^2 d\theta \\ &= \frac{1}{4} \int (\cos 2\theta + 1)^2 d\theta \\ &= \frac{1}{4} \int \cos^2 2\theta + 2 \cos 2\theta + 1 d\theta \\ &= \frac{1}{8} \int \cos 4\theta + 4 \cos 2\theta + 3 d\theta \\ &= \frac{1}{8} \left( \frac{1}{4} \sin 4\theta + 2 \sin 2\theta + 3\theta \right) + C \\ &= \frac{\sin 4\theta}{32} + \frac{\sin 2\theta}{4} + \frac{3\theta}{8} + C. \end{aligned}$$

(3 marks)

### Part (b)

$$\begin{aligned} A &= \int_A^B f(x) - g(x) dx + \int_B^C g(x) - f(x) dx + \int_C^D f(x) - g(x) dx \\ 32 &= 2 + \int_B^C g(x) - f(x) dx + 10 \\ 20 &= \int_B^C g(x) - f(x) dx \\ -20 &= \int_B^C f(x) - g(x) dx \end{aligned}$$

(3 marks)

**Part (c)**

$$\begin{aligned}\int \frac{dy}{y+1} &= \int \sin 2\pi t \, dt \\ \ln(y+1) &= -\frac{1}{2\pi} \cos 2\pi t + C \\ y &= Ke^{-\frac{\cos 2\pi t}{2\pi}} - 1.\end{aligned}$$

At  $t = 0$ ,  $y = 1$ . Hence  $2 = Ke^{-\frac{1}{2\pi}}$  and  $K = 2e^{\frac{1}{2\pi}}$ . So:

$$\begin{aligned}y &= 2e^{\frac{1-\cos 2\pi t}{2\pi}} - 1 \\ &= 2e^{\frac{1-\cos \pi}{2\pi}} - 1 \\ &= 2e^{\frac{1}{\pi}} - 1 \\ &\approx 1.796...\end{aligned}$$

(4 marks)

**Question Three****Part (a)**

$$\begin{aligned}\pi \int_0^1 (e^{-x} + 1)^2 \, dx &= \pi \int_0^1 e^{-2x} + 2e^{-x} + 1 \, dx \\ &= \pi \left[ -\frac{1}{2}e^{-2x} - 2e^{-x} + x \right]_0^1 \\ &= \pi \left[ \left( -\frac{1}{2}e^{-2} - 2e^{-1} + 1 \right) - \left( -\frac{1}{2} - 2 \right) \right] \\ &= \pi \left( \frac{7}{2} - \frac{1}{2e^2} - \frac{2}{e} \right) \\ &\approx 8.4715.\end{aligned}$$

(3 marks)

**Part (b)**

Finding velocity  $\int 12t + 12 \, dt = 6t^2 + 12t + C$ ; at  $t = 0$ ,  $v = 0$  so  $C = 0$  and  $\frac{dx}{dt} = 6t^2 + 12t$ . Then  $\int 6t^2 + 12t \, dt = 2t^3 + 6t + C'$ ; at  $t = 0$ ,  $x = 3$  so  $C' = 3$  and  $x = 2t^3 + 6t^2 + 3$ . Hence  $x(10) = 2603$ . (3 marks)

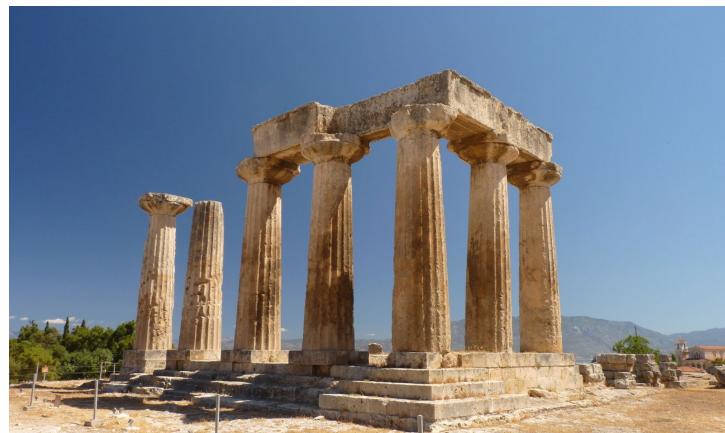
**Part (c)**

$$\begin{aligned}\int \frac{dT}{T - T_0} &= \int -k \, dt \\ \ln(T - T_0) &= -kt + C \\ T &= Ke^{-kt} + T_0\end{aligned}$$

When  $t = 0$ ,  $230 = T = K$ . Since  $T_0 = 18$ ,  $30 = 230e^{-kt} + 18$  and  $t \approx \frac{2.95}{k}$ . (4 marks)

**Part (d)**

The integration bounds include two asymptotes, at  $x = \frac{\pi}{2}$  and  $x = \frac{3\pi}{2}$ . (1 mark)



## Level Three Calculus Integration

There are three questions, worth a total of 24 marks.

Attempt ALL questions, showing all working.

Read questions carefully before attempting them.

Marks are available for partial answers.

The amount of time expected to be spent per question may not necessarily correlate “nicely” to the number of marks.

Diagrams may be used to support answers.

Candidates who do not provide diagrams for some questions may be disadvantaged.

Some marks are given for clarity and neatness of solutions or proofs.

**Time Allowed:** One Hour

**Achieved:** 9 marks

**Merit:** 15 marks

**Excellence:** 21 marks

Question:	1	2	3	Total
Points:	8	8	8	24
Score:				

**Available Grades:** *Not Achieved    Achieved    Merit    Excellence*



Figure 1: A bank.

**Question 1**

- (a) For i. and ii., find the indefinite integrals. **Do not forget the constant of integration.**

i.

$$\int \frac{1}{\sqrt{2x+2}} dx$$

1

ii.

$$\int \sec^2(x) \sec(\tan(x)) \tan(\tan(x)) dx$$

1

- (b) Find the area of the region bounded by  $y = 1/x$ ,  $y = 1/x^2$ , and  $x = 2$ .

3

- (c) Find the general solution to the differential equation  $\frac{dy}{dx} = \tan y \tan x$ .

3

**Question 2**

- (a) Consider the following integral.

$$\pi \int_1^5 (x^2 e^{-x})^2 dx.$$

3

Complete the following table, and use Simpson's rule with an interval length of 0.5 to approximate the value of the definite integral.

$x$	$(x^2 e^{-x})^2$
1.0	
1.5	0.2520
2.0	
2.5	0.2632
3.0	
3.5	0.1368
4.0	0.0859
4.5	0.0506
5.0	0.0284

- (b) Find  $k$  such that  $\int_1^k \frac{\ln x}{x} dx = 5$ .

2

- (c) The Bank of Money (figure 1) advertises that a particular savings account package has continuously compounding interest at a rate of 4% per annum. Express this as a differential equation, and hence find the accumulated interest on an initial deposit of \$2500 after four years.

3



Figure 2: An Egyptian obelisk.

**Question 3**

- (a) The average value of a function
- $f$
- on the interval
- $a \leq x \leq b$
- is defined to be
- [3]

$$f_{\text{avg}} = \frac{\int_a^b f(x) dx}{b - a}.$$

The temperature  $T$  (in °C) of Napier  $t$  hours after 9 am on a particular day was modelled by

$$T(t) = 20 + 8 \sin\left(\frac{\pi t}{12}\right).$$

Find the average temperature during the period from 9 am to 9 pm.

- (b) The height of an obelisk, like that pictured in figure 2, is 18 m. A horizontal cross-section at a distance  $x$  metres from the bottom is a rectangle of side lengths  $(3 - 0.1x)$  and  $(4 - 0.2x)$ . Use integration to find the volume of the obelisk.  
 (c) Suppose that [2]

$$1 = \int_m^{2m} x \cos(mx^2) dx.$$

Show that

$$m = \cos \frac{5m^3}{2} \sin \frac{3m^3}{2},$$

and conclude that  $m \leq 1$ .

## Solutions to L3 Calculus Integration Exam 3

Alexander Elzenaar

19 November 2017

## Question One

### Part (a)

i. Note that  $\frac{d}{dx}\sqrt{x} = \frac{1}{2\sqrt{x}}$ , so we must have

$$\int \frac{1}{\sqrt{2x+2}} dx = \int \frac{2}{2\sqrt{2x+2}} dx = \sqrt{2x+2} + C.$$

ii. Let  $u = \tan x$  so  $du = \sec^2 x dx$  and our integral becomes

$$\int \sec(u) \tan(u) du = \sec u + C = \sec \tan x + C.$$

### Part (b)

First, we find the left-hand integration limit:  $1/x = 1/x^2$  so  $1 = 1/x$  and  $x = 1$ .

$$\begin{aligned} \int_1^2 \frac{1}{x} - \frac{1}{x^2} dx &= \left[ \ln x + \frac{1}{x} \right]_1^2 \\ &= (\ln 2 - \ln 1) + \left( \frac{1}{2} - 1 \right) \\ &= \ln \frac{1}{2} - \frac{1}{2}. \end{aligned}$$

### Part (c)

Separation of variables.

$$\begin{aligned} \int \frac{\cos y}{\sin y} dy &= \int \frac{\sin x}{\cos x} dx \\ \ln \sin y &= -\ln \cos x + C \\ \sin y &= K e^{\ln \sec x} = K \sec x \\ y &= \sin^{-1}(K \sec x). \end{aligned}$$

(where  $K = e^C$ .)

## Question Two

### Part (a)

$x$	$(x^2 e^{-x})^2$
1.0	<b>0.1353</b>
1.5	0.2520
2.0	<b>0.2931</b>
2.5	0.2632
3.0	<b>0.2008</b>
3.5	0.1368
4.0	0.0859
4.5	0.0506
5.0	0.0284

Note that  $n = 8$  (number of intervals is one less than numbers of points),  $a = 1.0$ ,  $b = 5.0$ . Hence:

$$\begin{aligned} \int_1^5 (x^2 e^{-x})^2 dx &\approx \frac{5-1}{8} [0.1353 + 0.0284 + 4(0.2520 + 0.2632 + 0.1368 + 0.0506) + \\ &\quad + 2(0.2931 + 0.2008 + 0.0859)] \\ &= 2.0669 \end{aligned}$$

and the required value is 6.4932.

### Part (b)

We have  $5 = [\frac{1}{2}(\ln x)^2] \Big|_1^k = \frac{1}{2}(\ln k)^2$ , so  $k = \exp(\sqrt{10})$ .

### Part (c)

Let  $B(t)$  be the bank balance after  $t$  years. Then:

$$\frac{dB}{dt} = 0.04B,$$

so  $\ln B = 0.04t + C \Rightarrow B = B_0 e^{0.04t}$  ( $B_0 = e^C$ ). We have  $t = 4$  and  $B_0 = 2500$ , so  $B(4) = 2500e^{0.16} = \$2933.78$ .

## Question Three

### Part (a)

Computing:

$$\begin{aligned} \frac{\int_0^{12} 20 + 8 \sin\left(\frac{\pi t}{12}\right) dt}{12} &= \frac{1}{12} \left[ 20t - \frac{96}{\pi} \cos\left(\frac{\pi t}{12}\right) \right] \Big|_0^{12} \\ &= \frac{1}{12} \left[ \left( 240 + \frac{96}{\pi} \right) + \frac{96}{\pi} \right] \\ &= 25^\circ\text{C}. \end{aligned}$$

### Part (b)

The area of the cross-section at height  $x$  is  $A = (3 - 0.1x)(4 - 0.2x) = 0.02x^2 - x + 12$ ; hence the total volume is:

$$\int_0^{18} 0.02x^2 - x + 12 dx = \frac{0.02 \times 18^3}{3} - \frac{18^2}{2} + 12 \times 18 = 92.88 \text{ m}^3.$$

### Part (c)

$$\begin{aligned} 1 &= \int_m^{2m} x \cos(mx^2) dx \\ &= \left[ \frac{1}{2m} \sin(mx^2) \right] \Big|_m^{2m} \\ &= \frac{1}{2m} (\sin 4m^3 - \sin m^3) \\ &= \frac{1}{2m} 2 \cos \frac{5m^3}{2} \sin \frac{3m^3}{2} \\ m &= \cos \frac{5m^3}{2} \sin \frac{3m^3}{2}. \end{aligned}$$

Since  $\forall x$  we have  $\cos x \leq 1$  and  $\sin x \leq 1$ , it follows that  $\cos \frac{5m^3}{2} \sin \frac{3m^3}{2} \leq 1$  and so  $m \leq 1$ .



## Scholarship Calculus

There are five questions, worth a total of 75 marks.

Attempt ALL questions, showing all working.

Choose ONE option ONLY from 2(b) and 2(c).

Read questions carefully before attempting them.

Marks are available for partial answers.

The amount of time expected to be spent per question may not necessarily correlate "nicely" to the number of marks.

Diagrams may be used to support answers.

Candidates who do not provide diagrams for some questions may be disadvantaged.

Some marks are given for clarity and neatness of solutions or proofs.

**Time Allowed:** Three Hours

**Scholarship:** 45 marks

**Outstanding:** 65 marks

Question:	1	2	3	4	5	Total
Points:	15	15	15	15	15	75
Score:						

**Available Grades:** No Scholarship      Scholarship      Outstanding

**Question 1**

- (a) Consider the sequence of functions

$$f_n(x) = nx(1-x^2)^n \quad (0 \leq x \leq 1, n = 1, 2, 3, \dots). \quad (5)$$

Show that

$$\lim_{n \rightarrow \infty} \int_0^1 f_n(x) dx \neq \int_0^1 \lim_{n \rightarrow \infty} f_n(x) dx.$$

- (b) Compute the following definite integral. (5)

$$\int_0^1 \sin^3 x \cos^4 x + \sin^4 x \cos^3 x dx.$$

- (c) Suppose that
- $f$
- is a function satisfying

$$\begin{cases} \frac{f(x)}{2f'(x)} = 3(x^3 - 2x^2 - x + 2), \\ f(3) = 1. \end{cases}$$

Find  $f(x)$  explicitly. You need only calculate any constants of integration to three decimal places.**Question 2**

- (a) Consider the cubic equation
- $p(x) = x^3 + px + q$
- . (10)

- i. Let the three roots of
- $p(x)$
- be
- $\alpha, \beta$
- , and
- $\gamma$
- . Show that

$$(\alpha - \beta)^2(\beta - \gamma)^2(\gamma - \alpha)^2 = -4p^3 - 27q^2.$$

- ii. Find the nature of the roots of
- $p(x)$
- in the cases where
- $-4p^3 - 27q^2$
- is greater than, less than, or equal to zero.

**Answer ONE of (b) and (c).**

- (b) Find a formula for
- $\binom{n-1}{k} - \binom{n-1}{k-1}$
- in terms of
- $\binom{n}{k}$
- . (5)

- (c) Minimise
- $F(x) = x^3 + y^4 + z^5$
- with respect to the variables
- $x, y$
- , and
- $z$
- subject to: (5)

$$\begin{aligned} x + y + z &\geq 1 \\ x - y + z &\leq 2 \\ z &\geq 2 \\ 0.75x - 5.87y - 5.78z &\geq -31.74. \end{aligned}$$

*A graph of these planes is provided on the final page of this examination.***Question 3**

- (a) Find
- $\frac{d}{dx}(\sec x)(\sec^{-1} x)$
- in terms of
- $x$
- only. (5)

- (b) Consider a circle of radius
- $r$
- that is rolling around the inside of a circle of radius
- $R$
- (
- $R > r$
- ). Let
- $p = (x, y)$
- be the point on the inner circle that is initially touching the outer circle. Show that

$$\begin{aligned} x &= (R - r) \cos \theta + \cos \left( \frac{R-r}{r} \theta \right), \\ y &= (R - r) \sin \theta - \sin \left( \frac{R-r}{r} \theta \right). \end{aligned}$$

*A diagram is provided on the final page of this examination.*

- (c) The Steiner inellipse is the unique ellipse inscribed in a triangle and tangent to the midpoint of each side. Find the coordinates of the two focii of the Steiner inellipse inscribed in the triangle with vertices
- $(1, 7)$
- ,
- $(7, 5)$
- , and
- $(3, 1)$
- . (5)

**Question 4**

- (a) i. By differentiating
- $f(x)g(x)$
- , show that

$$\int f'(x)g(x) \, dx = f(x)g(x) - \int f(x)g'(x) \, dx.$$

- ii. Find an antiderivative of

$$\frac{\sqrt{4x^2 - 9}}{x^2}.$$

- (b) Discuss the significance of the fundamental theorem of calculus. You should write approximately half a page. (5)

- (c) An
- automorphism**
- is a function
- $f$
- such that
- $f(a + b) = f(a) + f(b)$
- and
- $f(ab) = f(a)f(b)$
- for all real numbers
- $a$
- and
- $b$
- . Show that (5)

$$f(x) = \begin{cases} 1 & \text{if } x \text{ is even} \\ -1 & \text{if } x \text{ is odd} \end{cases}$$

is an automorphism.

**Question 5**

You may use the following theorem in answering this question. **Do not attempt to prove this theorem.**

**Mean Value Theorem**

Let  $a$  and  $b$  be real numbers such that  $a < b$ , and let  $f$  be a function satisfying two hypotheses:

1.  $f$  is continuous at all  $x$  such that  $a < x < b$ .
2.  $f$  is differentiable at all  $x$  such that  $a \leq x \leq b$ .

Then there exists some number  $c$  such that

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

- (a) Verify that the function
- $f$
- defined by (5)

$$f(x) = \frac{x}{x+2}$$

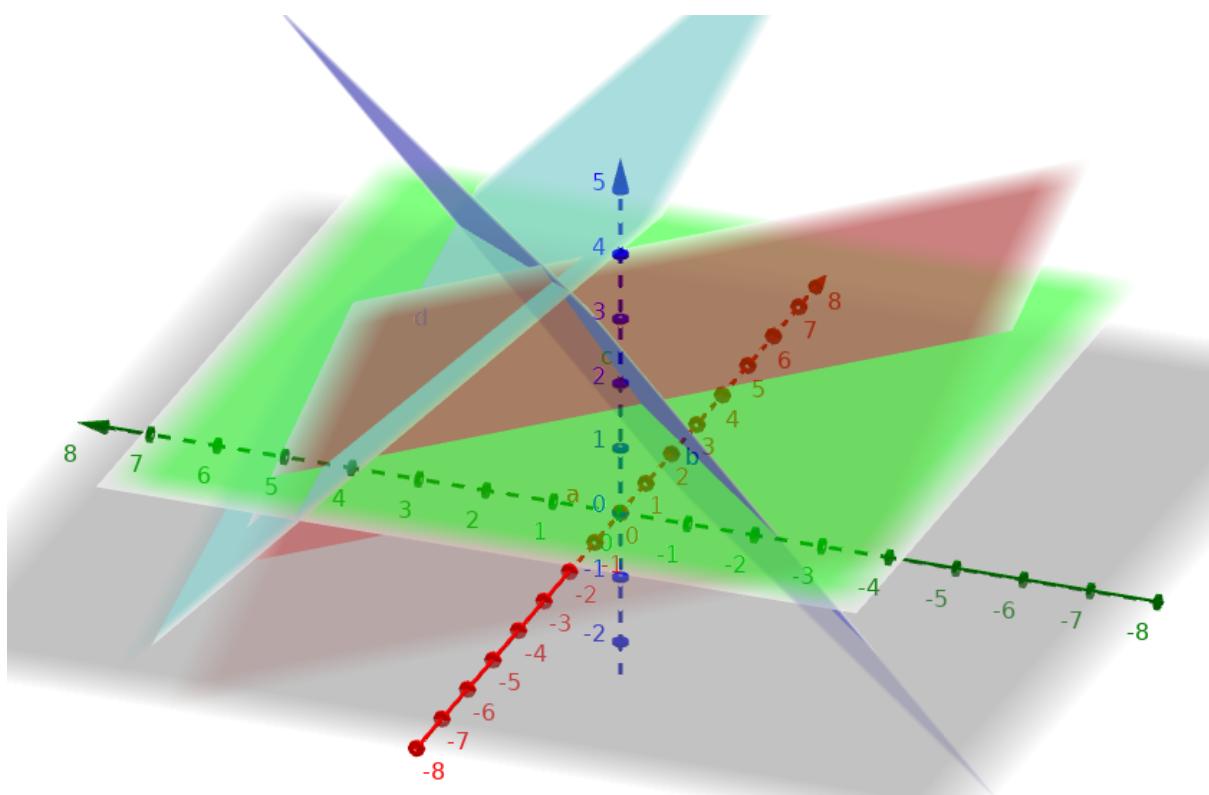
satisfies the hypotheses of the mean value theorem on the interval  $1 < x < 4$ . Find all points  $c$  that satisfy the conclusion of the mean value theorem.

- (b) A point
- $a$
- is called a
- fixed point**
- of a function
- $f$
- if
- $f(a) = a$
- . Suppose that
- $f'(x) \neq 1$
- for all real numbers
- $x$
- ; show that
- $f$
- has at most one fixed point. (5)

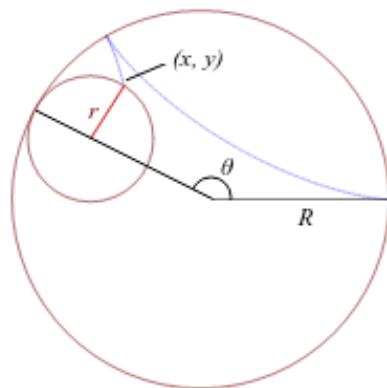
- (c) Find a function
- $f$
- such that
- $f'(-1) = \frac{1}{2}$
- ,
- $f'(0) = 0$
- , and
- $f''(x) > 0$
- for all
- $x$
- , or prove that such a function cannot exist. (5)

**Figures provided overleaf.**

## Useful Figures



*Question 2(c)*

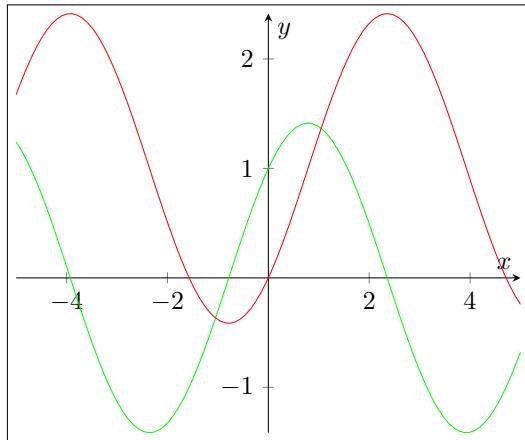


*Question 3(b)*

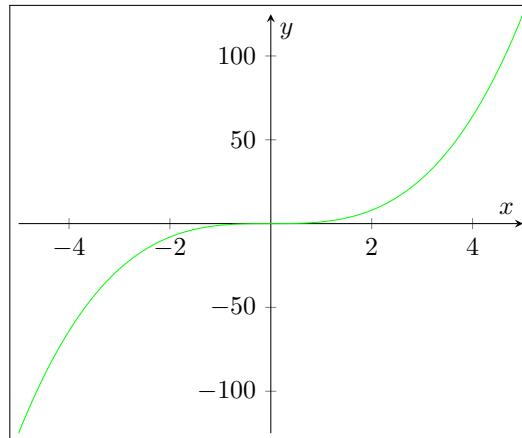
## NCEA Level 3 Calculus Solutions to Homeworks

### 1. The Derivative

1. Green: derivative of function. Red: original function.

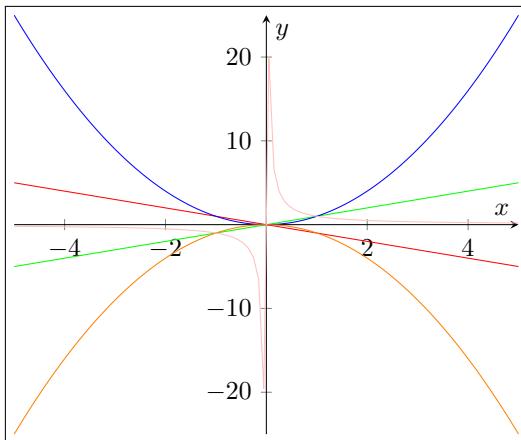


2. (a) At a min or max, the function is momentarily horizontal and so has slope zero; so  $m = 0$ .  
 (b) Consider a graph like the following at  $(0, 0)$ :

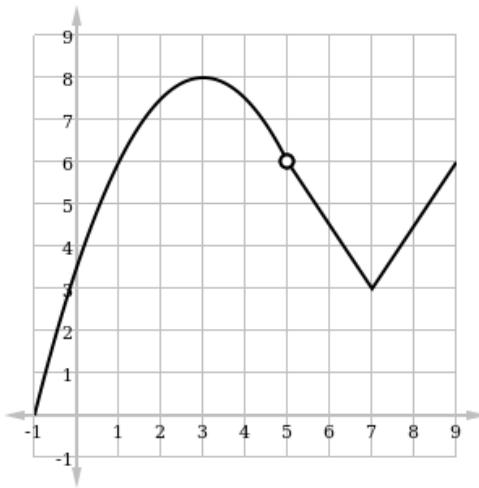


### 2. Limits

1. Increasing: the graph of the function is sloping up (green). Decreasing: the graph of the function is sloping down (red). Concave up: the graph of the function is increasing in slope (it is like a cup  $\cup$ ) (blue). Concave down: the graph of the function is decreasing in slope (it is like a cap  $\cap$ ) (orange). Continuous: the function has no holes (all of them except pink).



2. (a)  $\lim_{x \rightarrow -2} f(x) = 0$ ,  $\lim_{x \rightarrow 2} f(x) = -0.5$ .  
 (b) No, it approaches different values from the left and the right.  
 (c) Yes, because the function is continuous there.  
 (d)  $(-\infty, -3), (-3, -1), (-1, 2), (2, \infty)$ .  
 (e) -3, -1, 2.
3. For example,



### 3. Derivatives of Common Functions

1. (a)  $2x + 1/x$   
 (b)  $t^2 x^{t-1}$   
 (c)  $\cos x + \sin x$   
 (d)  $\frac{4}{5}x^{-1/5} = \frac{4}{5\sqrt[5]{x}}$
2. The power  $x$  is not constant.

3. Consider  $x^{-n}$ . The first derivative is  $-nx^{-n-1}$ , the second is  $n(n+1)x^{-n-2}$ , and so the  $n$ th is  $(-1)^n n(n+1)\cdots(2n-1)(2n)x^{-2n} = (-1)^n \frac{(2n)!}{(n-1)!} x^{-2n}$ . [This can be proved via induction.]
4. (a) Note first that  $10^t = e^{t \ln 10}$ , so  $P = P_0 + e^{t \ln 10}$  and  $\frac{dP}{dt} = (\ln 10)e^{t \ln 10} = (\ln 10)10^t$ . At  $t = 100$ , we have  $\frac{dP}{dt} = 2.3 \times 10^{100}$ .
- (b) Real-world populations don't grow exponentially forever if there are finite resources (e.g. food).

#### 4. The Chain Rule

1.  $\frac{dy}{dx} = \frac{-\csc^2 x}{2\sqrt{\cot x}}$
2. (a) Simply apply the chain rule twice.  
 (b)  $y' = 5x^4(\cos x^5)(-\sin \sin x^5)(\cos \cos \sin x^5)(-\sin \sin \cos \sin x^5)(\cos \cos \sin \cos \sin x^5)$ .
3. (a)  $f'(\theta) = -2 \sin 2\theta$  and  $g'(\theta) = -4 \sin \theta \cos \theta = -2 \sin 2\theta$ , so  $f' = g'$  as they agree everywhere.  
 (b) Since  $f$  and  $g$  have the same derivative, they differ only by a constant. But  $f(0) = 1 = g(0)$ , so that constant is zero; hence  $f = g$ .

#### 5. The Product and Quotient Rules

1. (a)  $\cos x \ln x + \frac{\sin x}{x}$   
 (b)  $\sec kx + kx \sec kx \tan kx$   
 (c)  $\frac{-\pi(\sin \pi\theta + \cos \pi\theta) \sin \pi\theta - \pi(\cos \pi\theta - \sin \pi\theta) \cos \pi\theta}{(\sin \pi\theta + \cos \pi\theta)^2}$   
 (d)  $(\cos t)(3 \sin^2 t)(-\sin(\sin^3 t))(4 \cos^3 \sin^3 t)$ .

2.

$$\begin{aligned}
 F &= \frac{d}{dt} \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}} = a \frac{d}{dv} \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}} \\
 &= a \left( \frac{\frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} + \frac{m_0 v^2}{c^2 \left(1 - \frac{v^2}{c^2}\right)^{3/2}}}{\sqrt{1 - \frac{v^2}{c^2}}} \right) \\
 &= a \left( \frac{\frac{m_0 c^2 \left(1 - \frac{v^2}{c^2}\right)}{c^2 \left(1 - \frac{v^2}{c^2}\right)^{3/2}} + \frac{m_0 v^2}{c^2 \left(1 - \frac{v^2}{c^2}\right)^{3/2}}}{c^2 \left(1 - \frac{v^2}{c^2}\right)^{3/2}} \right) \\
 &= m_0 a \left( \frac{c^2 \left(1 - \frac{v^2}{c^2}\right) + v^2}{c^2 \left(1 - \frac{v^2}{c^2}\right)^{3/2}} \right) \\
 &= m_0 a \left( \frac{c^2 - v^2 + v^2}{c^2 \left(1 - \frac{v^2}{c^2}\right)^{3/2}} \right) \\
 &= \frac{m_0 a}{\left(1 - \frac{v^2}{c^2}\right)^{3/2}}.
 \end{aligned}$$

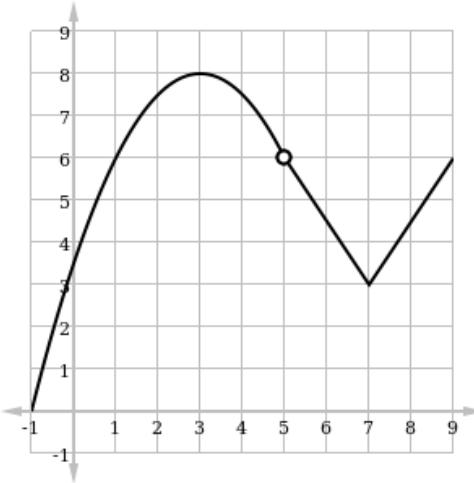
3. We wish to find  $\frac{d}{d\theta} \sin \text{rad}(\theta)$ , where  $\text{rad}(\theta) = \frac{\pi\theta}{180}$ ; so  $\frac{d(\text{rad})}{d\theta} = \frac{\pi}{180}$  and  $\frac{d}{d\theta} \sin \text{rad}(\theta) = \frac{\pi\theta}{180} \cos \text{rad}(\theta)$ . [The reason we have to do this is that the derivative of  $\sin$  uses the limit  $\lim_{x \rightarrow 0} \frac{\sin x}{x} = 1$  which is false if  $x$  is in degrees.]

## 6. Tangent and Normal Lines

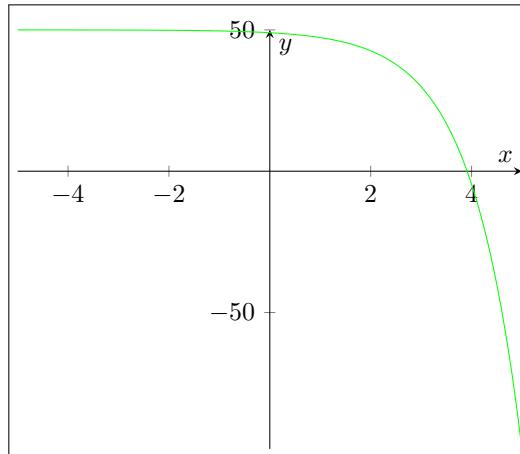
1. The normal to a curve  $f$  at a point  $(x_0, f(x_0))$  is the unique line passing through that point that is perpendicular to the tangent line of  $f$  at that point.
2.  $y' = \frac{-\sin(x+\pi)}{2\sqrt{\cos(x+\pi)}} + \cos x - 4 \sec x \tan^2 x e^{2\tan^2 x}$ ; at  $x = \pi$ ,  $y' = -1$  and so the tangent line (best linear approximation) is  $y = -(x - \pi) = \pi - x$ .
3. Since the normal line has slope 3, the tangent line has slope  $-1/3$ . We can take any curve through  $(1, 0)$  with this slope, so we may as well take the tangent line itself:  $y = -\frac{1}{3}(x - 1) = \frac{1}{3} - \frac{1}{3}x$ .
4.  $\frac{dy}{dx} = \frac{1}{(1+3x)^{2/3}}$  and at  $x = 0$  the slope becomes 1. So the best linear approximation around the point  $(0, 1)$  is just  $\tilde{y} = x + 1$ . So at  $x = 0.01$ , we have  $\tilde{y} = 1.01$  as our approximate value of  $\sqrt[3]{1.03}$ . [The true value is around 1.0099, so we are not too far off.]

## 7. Higher Derivatives and the Geometry of a Function

1. The second derivative tells us the concavity of a function: if the second derivative is positive, the function is curving up and if it is negative then the function is curving down.
2. (a)  $f'(x) = 5x^4 - 5$ ,  $f''(x) = 20x^3$ .  
 (b)  $f'(x) = \frac{x^2 - 2x}{(x-1)^2}$ ,  $f''(x) = \frac{2x-2}{(x-1)^4}$ .  
 (c)  $f'(x) = \frac{1}{2}x^{-1/2} - \frac{1}{4}x^{-3/4}$ ,  $f''(x) = -\frac{1}{4}x^{-3/2} + \frac{3}{16}x^{-5/4} = \frac{3}{16\sqrt[4]{x^5}} - \frac{1}{4\sqrt{x^3}}$ .
3. (a) For example,



- (b) For example,



## 8. Optimisation

1. At some point  $x$ , the distance between the two parabolae is  $\delta(x) = (x^2 + 1) - (x - x^2) = 2x^2 - x + 1$ . Taking the derivative, we find  $\delta'(x) = 4x - 1$  which has a single zero at  $x = 1/4$ ; by looking at the graph of the two parabolae, we see that this must be the location of the minimum distance  $\delta(1/4) = 7/8$  units.

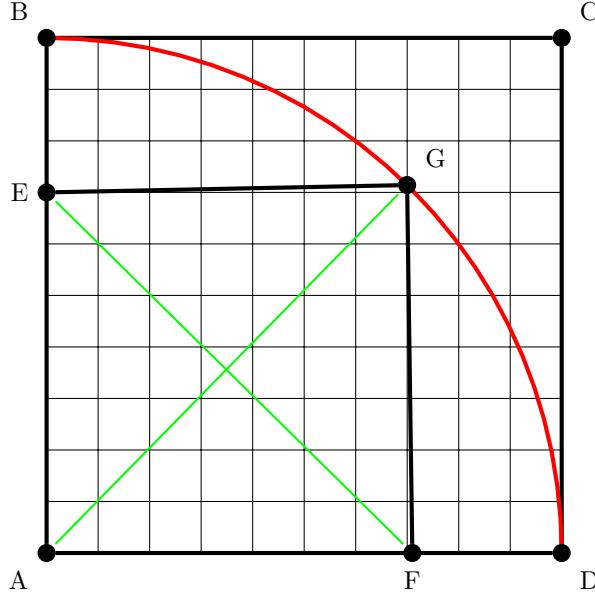
2. If  $y = 3x + 2 \cos x + 5$ , then  $\frac{dy}{dx} = 3 - 2 \sin x$ . Since  $1 \geq \sin x$ ,  $3 - 2 \sin x \geq 1$ . In particular, the function is everywhere increasing. Now, note that when  $x = -200\pi$ ,  $y = -600\pi + 7 < 0$ , and when  $x = 200\pi$ ,  $y = 600\pi + 7 > 0$ . Since the function is continuous over this interval, it follows that at some point it passes through the  $y$ -axis and has at least one root; since it is increasing everywhere, it must have exactly one real root.

3. The area of such a rectangle will be  $A = 4xb\sqrt{1 - \frac{x^2}{a^2}}$ ; so

$$\frac{dA}{dx} = 4b\sqrt{1 - \frac{x^2}{a^2}} - \frac{4x^2b}{a^2\sqrt{1 - \frac{x^2}{a^2}}}.$$

Setting this to zero, we have  $a^2 = 2x^2$  and so  $2x = \sqrt{2}a$ . It follows that  $2y = b\sqrt{2}$ , and so the maximal area is  $2ab$ .

4. Consider the following diagram.



It should be clear that  $AG = 1$ ; call  $\angle AEG = \theta$  and  $\angle AFG = \phi$ , and let  $AE = EG = e$  and  $AF = GF = f$ . By the cosine rule, we have  $1 = 2e^2(1 - \cos \theta)$  and  $1 = 2f^2(1 - \cos \phi)$ . Now, the area of the triangle  $\triangle AEG$  is given by  $\frac{1}{2}\sqrt{e^2 - \frac{1}{4}}$ ; the area of  $\triangle AFG$  is given by  $\frac{1}{2}\sqrt{f^2 - \frac{1}{4}}$ . Since  $AEFG$  is a (convex) quadrilateral with two right angles,  $\theta + \phi = \pi$ . Putting this all together, the area of the quadrilateral is  $A = \frac{1}{2}\sqrt{e^2 - \frac{1}{4}} + \frac{1}{2}\sqrt{f^2 - \frac{1}{4}}$ . We have that  $e^2 = \frac{1}{2(1-\cos \theta)}$  and  $f^2 = \frac{1}{2(1-\cos(\pi-\theta))} = \frac{1}{2(1+\cos(\theta))}$ , so the area in terms of  $\theta$  is

$$A = \frac{1}{2}\sqrt{\frac{1}{2(1-\cos \theta)} - \frac{1}{4}} + \frac{1}{2}\sqrt{\frac{1}{2(1+\cos \theta)} - \frac{1}{4}}.$$

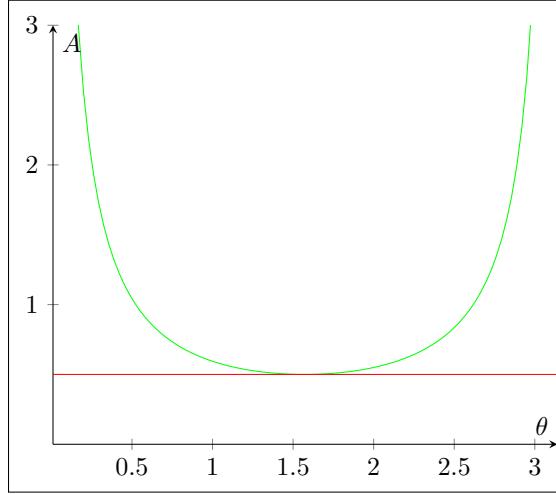
Taking the derivative, we obtain

$$\frac{dA}{d\theta} = \frac{1}{2} \frac{\sin \theta}{4(\cos \theta + 1)^2 \sqrt{\frac{1}{2(1+\cos \theta)} - \frac{1}{4}}} - \frac{1}{2} \frac{\sin \theta}{4(1 - \cos \theta)^2 \sqrt{\frac{1}{2(1-\cos \theta)} - \frac{1}{4}}};$$

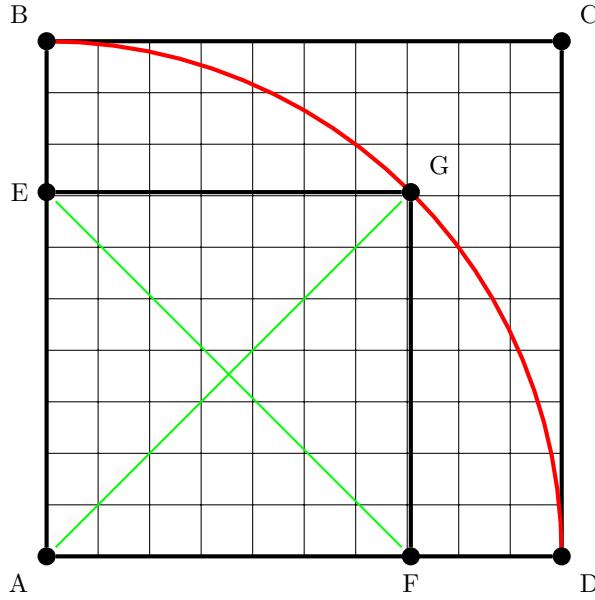
Now we set this to zero. We know that  $0 < \theta < \pi$ , so  $\sin \theta \neq 0$  and hence

$$\begin{aligned} 4(\cos \theta + 1)^2 \sqrt{\frac{1}{2(1+\cos \theta)} - \frac{1}{4}} &= 4(1-\cos \theta)^2 \sqrt{\frac{1}{2(1-\cos \theta)} - \frac{1}{4}} \\ \sqrt{\frac{1}{2} - \frac{\cos \theta + 1}{4}} &= \sqrt{\frac{1}{2} - \frac{1-\cos \theta}{4}} \\ \cos \theta &= -\cos \theta \\ \cos \theta &= 0 \end{aligned}$$

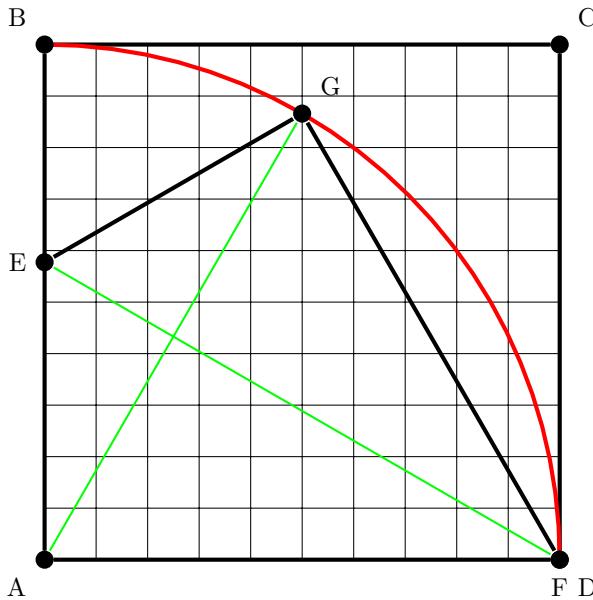
Hence  $\theta = \phi = \pi/2$ . Immediate calculation shows that  $e = f = \frac{1}{\sqrt{2}}$ ; we thus have a square with side length  $1/\sqrt{2}$ , and area  $\frac{1}{2}$ . Is this a maximum or a minimum? We cheat by graphing the area versus  $\theta$ :



so we obviously have the minimum area:



Note that  $\theta \geq \pi/2$ , because otherwise  $e > 1$ . Suppose we take  $\theta = 2\pi/3$ ; here is the graphed figure (with area 1.1547):



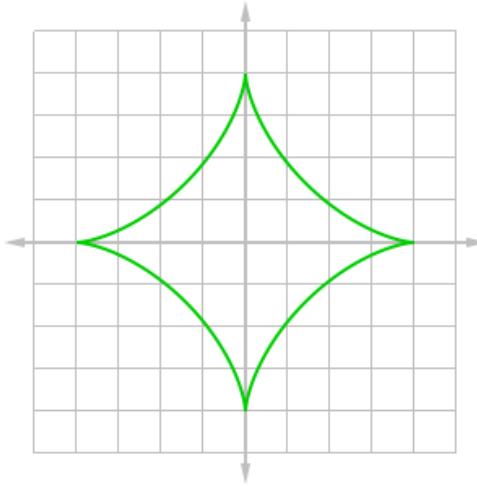
This is the maximum area, since if we increase  $\theta$  any more it requires  $f > 1$ .

## 9. Related Rates

1.  $V = [x(t)]^3$ , so  $\frac{dV}{dt} = 3\frac{dx}{dt}[x(t)]^2$ .
2. The volume of a cone is  $\frac{\pi}{3}r^2h$ . Comparing similar triangles, if the water is at a height  $h$  then it forms a cone with radius  $r = h/2$ . Hence when the water is at a height  $h$  it has volume  $V(t) = \frac{\pi[h(t)]^3}{24}$ , and so  $\frac{dV}{dt} = \frac{\pi[h(t)]^2}{8}\frac{dh}{dt}$ . We know that  $\frac{dV}{dt} = 2$ , so solving for  $\frac{dh}{dt}$  we have that  $\frac{dh}{dt} = \frac{16}{\pi[h(t)]^2}$  and when  $h = 3$  the height is rising at a rate of  $0.57 \text{ m min}^{-1}$ .
3. Let  $x$  be the hypotenuse of the formed triangle, and let  $y$  be the horizontal distance from the boat to the jetty so that  $y = \sqrt{x^2 - 1}$ . Then  $\frac{dy}{dt} = \frac{x}{\sqrt{x^2-1}}\frac{dx}{dt} = \frac{\sqrt{y^2+1}}{y}$ . So at  $y = 8$ ,  $\frac{dy}{dt} = \frac{\sqrt{65}}{8} \approx 1.0078 \text{ m s}^{-1}$ .

## 10. Parametric Functions

1. (a)  $\frac{dx}{dt} = 4t^3 - 6t^2 + 4t$ ,  $\frac{dy}{dt} = 3t^2 - 1$ ,  $\frac{dy}{dx} = \frac{3t^2-1}{4t^3-6t^2+4t}$ ,  $\frac{d^2y}{dx^2} = -\frac{3t^4-6t^2+3t-1}{(4t^3-6t^2+4t)t^2(2t^2-3t+2)^2}$ .  
(b)  $\frac{dx}{dt} = -\sin t - 4 \sin 2t$ ,  $\frac{dy}{dt} = \cos t + 4 \cos 2t$ ,  $\frac{dy}{dx} = -\frac{\cos t + 4 \cos 2t}{\sin t + 4 \sin 2t}$ ,  $\frac{d^2y}{dx^2} = \frac{12 \cos(t) + 33}{(\sin t - 4 \sin 2t)(8 \cos(t) + 1)^2 (\cos(t)^2 - 1)}$
2. We have  $t^2 = (x-1)^2$ , so  $y = e^{(x-1)^2}$  and  $\frac{dy}{dx} = 2(x-1)e^{(x-1)^2}$ . At  $x = 2$ ,  $\frac{dy}{dx} = 2e$ ; so the best linear approximation is  $y - e = 2e(x-2)$ , or  $y = e(2x-3)$ .
3. (a) Should look something like this:



- (b)  $\frac{dx}{dt} = -12 \sin t \cos^2 t$ ,  $\frac{dy}{dt} = 12 \cos t \sin^2 t$ , so the slope at some  $t$  is simply

$$\frac{dy}{dx} = \frac{12 \cos t \sin^2 t}{-12 \sin t \cos^2 t} = -\frac{\sin t}{\cos t}.$$

- (c) Cusps will be at precisely those points with turning points in the  $x$  or  $y$  direction (for  $0 \leq t \leq 2\pi$ ). In other words, places where either  $\sin t$  or  $\cos t$  vanishes. These are at  $t \in \{0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}, 2\pi\}$ ; substituting these into the equation gives us the four points  $(\pm 4, 0)$  and  $(0, \pm 4)$ .

## 11. Implicit Differentiation

1. (a)  $y' = \frac{3x^2+6x}{2y}$ .
- (b)  $(1+y') \sin(x+y) = 2 - 2y' \implies y' = \frac{2-\sin(x+y)}{2+\sin(x+y)}$ .
- (c)  $y' = \frac{20x^3-2x}{2y}$ .
2.  $2x + 2y + 2xy' - 2yy' + 1 = 0 \implies y' = \frac{-1-2x-2y}{2x-2y}$ , so  $y'(1, 2) = \frac{-1-2-4}{2-4} = 7/2$ ; hence the slope of the normal is  $-2/7$ , and the equation of the normal line is  $y - 2 = -\frac{2}{7}(x - 1)$ .
3. We have  $\frac{1}{2\sqrt{x}} + \frac{1}{2\sqrt{y}}y' = 0$ ; suppose we have a tangent line passing through  $(x_0, (\sqrt{c} - \sqrt{x_0})^2)$ . Then the equation of this tangent is  $y - (\sqrt{c} - \sqrt{x_0})^2 = -\frac{\sqrt{c}-\sqrt{x_0}}{\sqrt{x_0}}(x - x_0)$ . When  $y = 0$  we obtain the  $x$ -intercept;  $0 = (\sqrt{c} - \sqrt{x_0})^2 - \frac{\sqrt{c}-\sqrt{x_0}}{\sqrt{x_0}}(x - x_0)$  and so  $x = \sqrt{x_0}c$ . Similarly, when  $x = 0$  we obtain  $y = \sqrt{x_0}c - x_0$ . Their sum is therefore  $2\sqrt{x_0}c - x_0 = 2\sqrt{c}(\sqrt{c} - \sqrt{y_0}) - (\sqrt{c} - \sqrt{y_0})^2 = c$ .

## 12. Kinematics

1. (a)  $v = \frac{dh}{dt} = 122.5 - 9.8t$ , so the initial velocity of the flare is  $122.5 \text{ m s}^{-1}$ .
- (b) Zero.
- (c) When  $v = 0$ ,  $t = 12$  and the height at this time is around 764 metres.

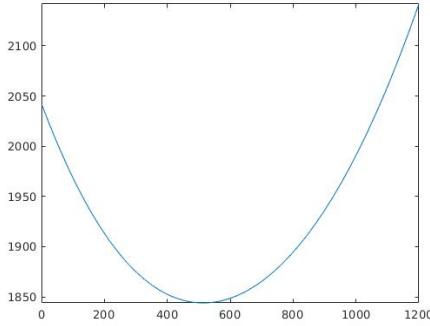
2. Let  $x$  be the distance from the point on the beach directly away from B. Then the total distance travelled is simply  $D = \sqrt{600^2 + x^2} + \sqrt{800^2 + (1200 - x)^2}$ ; taking the derivative:

$$\frac{dD}{dx} = \frac{x}{\sqrt{600^2 + x^2}} - \frac{1200 - x}{\sqrt{800^2 + (1200 - x)^2}}$$

Setting to zero, we have

$$\begin{aligned} x\sqrt{800^2 + (1200 - x)^2} &= (1200 - x)\sqrt{600^2 + x^2} \\ 800^2x^2 + (1200 - x)^2x^2 &= (1200 - x)^2(600^2 + x^2) \\ 0 &= 1200^2600^2 - 600^22400x + (600^2 - 800^2)x^2 \\ x &\in \{-3600, 3600/7\}. \end{aligned}$$

Since  $x \geq 0$ ,  $x = 3600/7 \approx 514$ . The total distance travelled is therefore around 1844 metres. By graphing  $D$  versus  $x$ , we see that this is indeed the required medium:



### 13. Inverse Functions

1. (a)  $y' = \frac{2x}{1+x^4}$ .

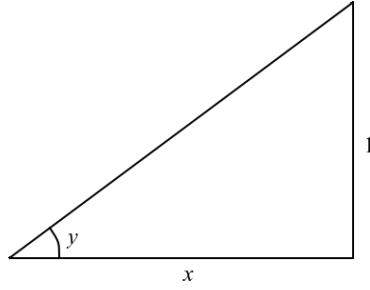
(b)  $f'(x) = \frac{1}{1+x^2}$ .

(c)  $g'(x) = \frac{1}{2\sqrt{x}} \frac{1}{\sqrt{1-x}} \frac{1}{1+(\sin^{-1}\sqrt{x})^2}$ .

2.

$$\begin{aligned} \frac{d}{dx} \left( \frac{1}{2} \tan^{-1} x + \frac{1}{4} \ln \frac{(x+1)^2}{x^2+1} \right) &= \frac{1}{2+2x^2} + \frac{1}{4(x+1)^2} \frac{2-2x^2}{(x^2+1)^2} \\ &= \frac{1}{2+2x^2} + \frac{1}{2} \frac{1-x^2}{(x+1)^2(x^2+1)} \\ &= \frac{1}{2} \frac{(x+1)^2 + 1 - x^2}{(x+1)^2(1+x^2)} \\ &= \frac{1}{2} \frac{2x+2}{(x+1)^2(1+x^2)} \\ &= \frac{1}{(x+1)(x^2+1)}. \end{aligned}$$

3. Let  $y = \cot^{-1} x$ , so that  $x = \cot y$  and  $\frac{dx}{dy} = -\csc^2 y$ ; hence  $\frac{dy}{dx} = -\sin^2 y$ . Consider the following triangle:



So  $\sin y = \frac{1}{\sqrt{1+x^2}}$ , and  $\frac{dy}{dx} = -\frac{1}{1+x^2}$ .

#### 14. Differentiation Revision

1. (a)  $f'(x) = (2017 \times 3)x^{2016} - \frac{1}{19x^{20}} + \frac{1}{2017^{2017}\sqrt{(x+2)^{2016}}}$ .
- (b)  $f'(h) = \pi r^2$ .
- (c)  $f'(\theta) = -\frac{\mu mg(\mu \cos \theta - \sin \theta)}{(\mu \sin \theta + \cos \theta)^2}$ .
- (d)  $f'(g) = \frac{(g^2 + \ln g) \cos g - (2g + 1/g) \sin g}{(g^2 + \ln g)^2}$ .
- (e)  $3f(x) + 3xf'(x) + 2f(x)f''(x) = \frac{3+f(x)-xf'(x)}{[3+f(x)]^2}$  so  $f'(x) = \frac{3+f(x)-3[3+f(x)]^2 f(x)}{3[3+f(x)]^2 x + 2[3+f(x)]^2 f(x) + x}$ .
2. Let  $\theta$  between the angle of the kite string, and let  $x$  be the horizontal distance to the kite along the ground (so the length of the string is  $\sqrt{50^2 + x^2}$ ). Then  $\sin \theta = 50/x$ , so  $\cos \theta \frac{d\theta}{dt} = -\frac{50}{x^2} \frac{dx}{dt}$ . When the length of the string is 100,  $x \approx 86.6$ ; so  $\cos \theta = x/100 \approx 0.866$ . Substituting  $\frac{dx}{dt} = 2$ , we have  $\frac{d\theta}{dt} = -\frac{100}{86.6^2} \cdot \frac{1}{0.866} = -0.0154$ .
3. The surface area of a cone is  $S = \pi r \sqrt{h^2 + r^2}$ ; we also have  $27 = \frac{1}{3}\pi r^2 h$ , so  $r^2 = \frac{81}{\pi h}$  and

$$\begin{aligned} S &= \pi \sqrt{\frac{81}{\pi h} \left( h^2 + \frac{81}{\pi h} \right)} = \pi \sqrt{\frac{81h}{\pi} + \frac{81^2}{\pi^2 h^2}} \\ \frac{dS}{dh} &= \frac{\pi \left( \frac{81}{\pi} - 2 \frac{81^2}{\pi^2 h^3} \right)}{2 \sqrt{\frac{81h}{\pi} + \frac{81^2}{\pi^2 h^2}}} \end{aligned}$$

In order to find a minimum, we set this derivative to zero and obtain  $0 = \frac{81}{\pi} - 2 \frac{81^2}{\pi^2 h^3}$ , so

$$h = \sqrt[3]{2 \frac{81}{\pi}} \approx 3.722 \text{ cm.}$$

From this, we find  $r = \sqrt{81/\pi h} = 2.63 \text{ cm}$ .

4. We begin by parameterising the hyperbola; completing the square, we can transform our equation into standard form:

$$\frac{(x-1)^2}{3} - \frac{y^2}{3} = 1$$

A parameterisation of this is  $(1 + \sqrt{3} \sec t, \sqrt{3} \tan t)$ . Now, given any point  $(x_0, y_0)$  we wish to minimise  $D(t) = \sqrt{(x_0 - 1 - \sqrt{3} \sec t)^2 + (y_0 - \sqrt{3} \tan t)^2}$  with respect to  $t$ .

- (a) Firstly, consider  $(x_0, y_0) = (2, 1)$ . Then  $\mathcal{D}(t) = \sqrt{(1 - \sqrt{3} \sec t)^2 + (1 - \sqrt{3} \tan t)^2}$ . Taking the derivative, we find that:

$$\frac{d\mathcal{D}}{dt} = \frac{(\sqrt{3} \sec t - 1)(\sqrt{3} \sec t \tan t) + (\sqrt{3} \tan t - 1)(\sqrt{3} \sec^2 t)}{\sqrt{(1 - \sqrt{3} \sec t)^2 + (1 - \sqrt{3} \tan t)^2}}$$

Using MATLAB to compute the solution of  $\frac{d\mathcal{D}}{dt} = 0$ ,

```
vpa(solve((sqrt(3) * sec(t) - 1)*(sqrt(3) * sec(t) * tan(t))
           == (1 - sqrt(3)*tan(t))*(sqrt(3)*(sec(t))^2), t))
```

we find  $t \approx 0.3759$ ; so  $(x, y) = (2.8621, 0.6835)$ .

- (b) Note that  $(3, 1)$  is already on the hyperbola. ☺

## 15. Approximating Areas

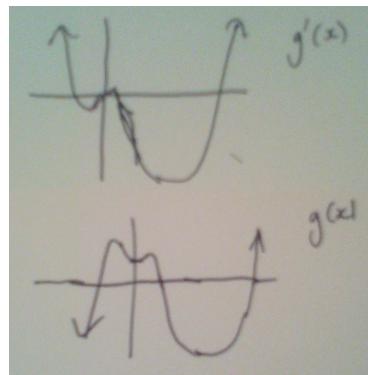
1. I use Simpson's rule with  $n = 8$ :

$$\int_0^{1.6} g(x) dx \approx \frac{0.2}{3} (12.1 + 13.2 + 4(11.6 + 11.1 + 12.2 + 13.0) + 2(11.3 + 11.7 + 12.6)) = 19.21.$$

2. Measure the height of the shaded area at each point (using  $n = 10$  is probably easiest), collapsing the empty area down (e.g. the height of the function at  $x = -1$  is just  $3 + 1 = 4$ ). Then use some numerical integration method.  
3. Like 2. but simpler.

## 16. Anti-differentiation

1. (a)  $F(x) = \frac{1}{2}x^2 - 3x + C$   
(b)  $f(x) = x^2 + 3x + 2$ , so  $F(x) = \frac{1}{3}x^3 + \frac{3}{2}x^2 + 2x + C$   
(c)  $F(\theta) = 2\theta^3 - 7 \tan \theta + C$   
(d)  $G(h) = \pi^2 h$   
(e)  $F(x) = \frac{x^{4.7}}{4.7} + \frac{2}{3}\sqrt{x^3} + \sqrt{7}x^{\sqrt{7}}$
2.  $\varphi(x) = x^2 + x + C$ ; but  $\varphi(1) = 6$ , so  $1 + 1 + C = 6$  and  $C = 4$ . Hence  $\varphi(x) = x^2 + x + 4$ , and  $\varphi(2) = 10$ .
3. See following image.



## 17. The Fundamental Theorem of Calculus

1.  $\int_0^{\pi/4} \sec^2 \theta d\theta = [\tan \theta] \Big|_0^{\pi/4} = 1.$

2.  $\int_1^2 f(x) dx = \int_1^3 f(x) dx - \int_2^3 f(x) dx = 10.$

3. First we find the intersection points; we have  $6x = x^2$ , so  $x \in \{0, 6\}$ . Hence we compute

$$\int_0^6 2x - \frac{x^2}{3} dx = [x^2 - \frac{x^3}{9}] \Big|_0^6 = 36 - 6^3/9 = 12.$$

## 18. Substitution

1. (a)  $\frac{\csc 3x}{3} + C.$

(b)  $-\frac{\tan 3x^2}{6} + C.$

(c)  $2\sqrt{x} + 3x - 2\ln x + C.$

(d)  $\frac{\sin^3 x}{3} - \frac{\sin^5 x}{5} + C.$

2. Use trig identity:  $2\sin 5x \cos 3x = \sin 8x + \sin 2x$ . Then

$$\int_0^{\pi/6} \sin 8x + \sin 2x dx = \left[ -\frac{\cos 8x}{8} - \frac{\cos 2x}{2} \right] \Big|_0^{\pi/6} = 0.4375.$$

3.  $\frac{1}{2} \tan^{-1} x^2 + C$ . (Substitute  $u = x^2$ .)

## 19. Differential Equations

1. (a)  $\int e^y dy = \int e^t dt$ , so  $e^y = e^t + C$  and  $y = \ln(e^t + C)$ .

(b)  $\int \frac{dy}{y^2} = \int t dt$ , so  $-\frac{1}{y} = \frac{1}{2}t^2 + \frac{C}{2}$  and  $y = -\frac{2}{t^2+C}$ .

(c)  $\int \sec^2 y dy = \int dt$ , so  $\tan y = t + C$  and  $y = \tan^{-1}(t + C)$ .

(d)  $\int \sin y dy = \int -t \cos t dt$ , so  $-\cos y = \cos t - t \sin t - C$  (by the hint) and  $y = \cos^{-1}(t \sin t - \cos t + C)$ .

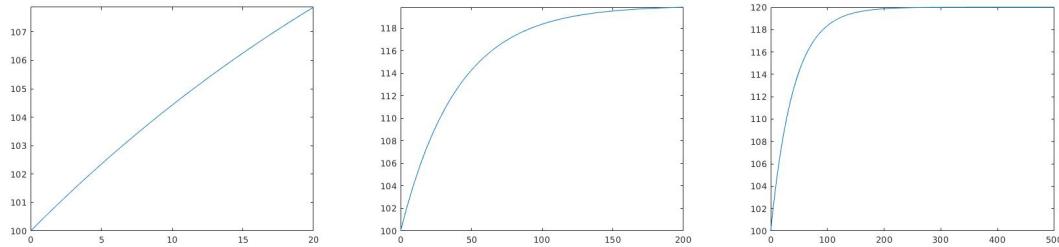
2. Using Newton's law of cooling,  $\frac{dT}{dt} = k(T - T_\infty)$  (where  $T_\infty$  is the ambient temperature). Solving this differential equation, we find  $\int \frac{1}{T-T_\infty} dT = \int k dt$  and so  $T = T_0 e^{kt} + T_\infty$ . We have  $T_\infty = 30^\circ$ , and  $T_0 = 100^\circ$ ; also, at  $t = 3$  we have  $T = 70$  so  $70 = 100e^{3k} + 30$ ; hence  $k = \frac{\ln 0.4}{3} = -0.31$  and by direct substitution  $T = 100e^{-0.31t} + 30$ . Let  $T = 31$ ; then  $t = 14.86$  and so the temperature will drop to  $31^\circ$  after around fifteen minutes.

3. (a) We have  $\frac{dV}{dt} = \text{rate in} - \text{rate out} = 3 - kV$ . Hence  $\int \frac{1}{3-kV} dV = \int dt$ , so  $-\frac{\ln(3-kV)}{k} = t + C$  and  $V = \frac{3-Ke^{-kt}}{k}$ . At  $t = 0$ ,  $V = 100$ ; so  $100k = (3 - K)$ . We also have  $kV = 3$  where  $V = 120$ , so  $k = 1/40 = 0.025$ . Hence  $2.5 = 3 - K$  and  $K = 0.5$ . It immediately follows that

$$V = \frac{3 - 0.5e^{-0.025t}}{0.025}$$

and at  $t = 10$ ,  $V = 104$  litres.

- (b) The rate of water flow out is  $kV = 3 - 0.5e^{-0.025t}$ , which is always less than 3 (the rate in). In fact, as  $t \rightarrow \infty$ , the volume tends to 120L and the rate in tends to equal the rate out.



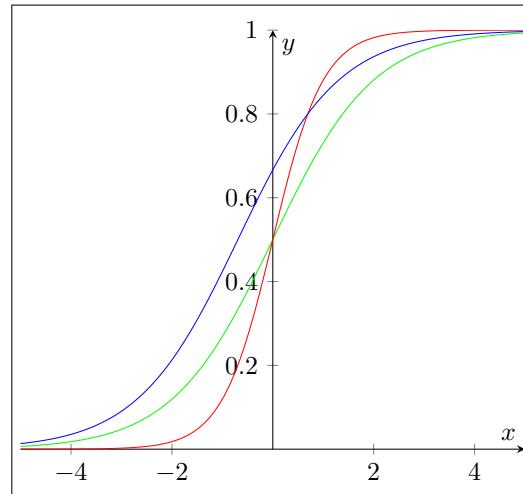
## 20. Partial Fractions

1. (a)

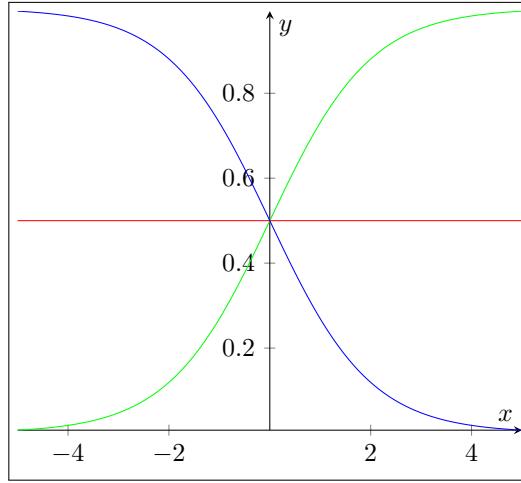
$$\begin{aligned} \int r dt &= \int \frac{dP}{P(1-P)} = \\ &= \int \frac{1}{P} + \frac{1}{1-P} dP \\ rt + C &= \ln \frac{P}{1-P} \\ Ke^{rt} &= \frac{P}{1-P} \\ \frac{Ke^{rt}}{1+Ke^{rt}} &= P. \end{aligned}$$

- (b) It should be clear that as  $t \rightarrow \infty$ ,  $P \rightarrow 1$ . (If we look at  $\frac{dP}{dt} = \frac{rP}{P_\infty}(P_\infty - P)$ ,  $P \rightarrow P_\infty$ .)

Green:  $r = K = 1$ ; red:  $r = 2, K = 1$ ; blue:  $r = 1, K = 2$ .



- (c)  $r$  lets us vary how fast the population gets to the maximum. Green:  $r = K = 1$ ; red:  $r = 0$ ; blue:  $r = -1$ .



- (d) Write it yourself.
2. (a) Draw a triangle with angle  $x/2$ , hypotenuse  $\sqrt{1+t^2}$ , adjacent edge 1, and opposite edge  $t$ .
- (b)

$$\sin x = 2 \sin(x/2) \cos(x/2) = \frac{2t}{1+t^2}$$

$$\cos x = (\cos(x/2))^2 - (\sin(x/2))^2 = \left(\frac{1}{\sqrt{1+t^2}}\right)^2 - \left(\frac{t}{\sqrt{1+t^2}}\right)^2 = \frac{1-t^2}{1+t^2}.$$

(c) We have  $x = \tan^{-1} 2t$ , so the result follows immediately.

(d) i. Let  $t = \tan(x/2)$ . Then, substituting, we have

$$\int \frac{1}{1-\frac{1-t^2}{1+t^2}} \cdot \frac{2}{1+t^2} dt = \int \frac{1}{t^2} dt = -\frac{1}{t} + C = -\frac{1}{\tan \frac{x}{2}} + C.$$

ii. Similarly,

$$\begin{aligned} \int \frac{1}{3\frac{2t}{1+t^2} - 4\frac{1-t^2}{1+t^2}} \cdot \frac{2}{1+t^2} dt &= \int \frac{1}{3t-2+2t^2} dt = \int \frac{1}{(2t-1)(t+2)} dt \\ &= \frac{1}{5} \ln \frac{1-2t}{t+2} + C = \frac{1}{5} \ln \frac{1-2\tan \frac{x}{2}}{\tan \frac{x}{2} + 2} + C. \end{aligned}$$

## 21. Integration by Parts

1. (a)

$$\int x \cos 5x dx = \frac{1}{5} x \sin 5x - \int \frac{1}{5} \sin 5x dx = \frac{1}{5} (x \sin 5x + \cos 5x) + C.$$

- (b)

$$\begin{aligned} \int \cos x \ln \sin x dx &= \sin x \ln \sin x - \int \sin x \frac{\cos x}{\sin x} dx \\ &= \sin x \ln \sin x - \int \cos x dx = \sin x (\ln \sin x - 1) + C. \end{aligned}$$

(c) Let  $u = \sqrt{x}$ , so  $dx = 2u du$  and our integral becomes

$$\int 2u \cos u du = 2u \sin u - \int 2 \sin u du = 2u \sin u + 2 \cos u + C = 2\sqrt{x} \sin \sqrt{x} + 2 \cos \sqrt{x} + C.$$

2. (a) Let  $u = \theta^2$ , so our integral becomes  $\frac{1}{2} \int_{\pi/2}^{\pi} u \cos u du$ . From 1(c) above, we know that  $\int u \cos u du = u \sin u + \cos u + C$ . Hence the required result is

$$\frac{1}{2} \int_{\pi/2}^{\pi} u \cos u du = \frac{1}{2} [u \sin u + \cos u] \Big|_{u=\pi/2}^{\pi} = -\frac{1}{2} - \frac{\pi}{4}.$$

(b) We use integration by parts twice.

$$\begin{aligned} \int (x^2 + 1)e^{-x} dx &= -e^{-x}(x^2 + 1) + \int 2xe^{-x} dx \\ &= -e^{-x}(x^2 + 1) - 2xe^{-x} + \int 2e^{-x} dx \\ &= -e^{-x}(x^2 + 1) - 2xe^{-x} - 2e^{-x} + C. \end{aligned}$$

Hence the result we are looking for is  $3 - 6e^{-1}$ .

3. (a) Apply integration by parts to  $\int 1 \cdot (\ln x)^n dx$  by integrating 1 and differentiating  $(\ln x)^n$ .  
(b) Applying (a), we find

$$\begin{aligned} \int (\ln x)^3 dx &= x(\ln x)^3 - \int (\ln x)^2 dx \\ &= x(\ln x)^3 - (x(\ln x)^2 - \int \ln x dx) \\ &= x(\ln x)^3 - (x(\ln x)^2 - (x \ln x - x)) \\ &= x(\ln x)^3 - x(\ln x)^2 + x \ln x - x. \end{aligned}$$

## 22. Lengths, Volumes, and Areas

1. We simply calculate the relevant integral:

$$\pi \int_1^2 x^{-2} dx = \pi[(-2^{-1}) - (-1^{-1})] = \frac{\pi}{2}.$$

2. Calculating the surface area:

$$\begin{aligned} 2\pi \int_0^{\pi} \sin x \sqrt{1 - \cos^2 x} dx &= 2\pi \int_0^{\pi} \sin^2 x dx \\ &= \pi [x - \sin 2x] \Big|_0^{\pi} \\ &= \pi^2 \end{aligned}$$

So the radius of the equivalent circle is  $\sqrt{\pi}$ .

3. Summing along the axis from base to point, each slice has an area  $\left(\frac{L}{H}x\right)^2 = \frac{L^2}{H^2}x^2$ ; hence the total volume is

$$V = \int_0^H \frac{L^2}{H^2}x^2 dx = \frac{1}{3}L^2H.$$

4. We have  $r = a(1 - \cos \theta)$  so  $\frac{dr}{d\theta} = a \sin \theta$ . Hence:

$$\begin{aligned} S &= \int_0^{2\pi} \sqrt{a^2(1 - \cos \theta)^2 + a^2 \sin^2 \theta} d\theta \\ &= \int_0^{2\pi} \sqrt{a^2 - 2a^2 \cos \theta + a^2(\sin^2 \theta + \cos^2 \theta)} d\theta \\ &= a\sqrt{2} \int_0^{2\pi} \sqrt{1 - \cos \theta} d\theta. \end{aligned}$$

We turn our attention, then, to the integral  $\int \sqrt{1 - \cos \theta} d\theta$ . Let  $u = 1 - \cos \theta$ ; then  $du = \sin \theta d\theta$ ; but  $\sin \cos^{-1}(1 - u) = \sqrt{2u - u^2}$  (this can be verified by drawing a suitable triangle). Hence  $du = \sqrt{2u - u^2} d\theta$ , and

$$\begin{aligned} \int \sqrt{1 - \cos \theta} d\theta &= \int \frac{\sqrt{u}}{\sqrt{2u - u^2}} du \\ &= \int \frac{1}{\sqrt{2 - u}} \\ &= -2\sqrt{2 - u} + C \\ &= -2\sqrt{1 + \cos \theta} + C. \end{aligned}$$

Therefore (and changing our integral to double the integral from 0 to  $\pi$  to avoid the problem of having a closed loop),

$$\begin{aligned} S &= 2a\sqrt{2} \int_0^\pi \sqrt{1 - \cos \theta} d\theta \\ &= 2a\sqrt{2} \left[ -2\sqrt{1 + \cos \theta} \right]_0^\pi \\ &= 2a\sqrt{2} \left[ (-2\sqrt{1 + \cos \pi}) - (-2\sqrt{1 + \cos 0}) \right] \\ &= 2a\sqrt{2} \left[ (-2\sqrt{0}) - (-2\sqrt{2}) \right] \\ &= 2a\sqrt{2} \times 2\sqrt{2} = 8a. \end{aligned}$$

## 23. Trigonometric Substitution

*These ones are tedious and can be checked by the computer, so I have not written full answers for all of them.*

1. Let  $x = 2 \tan \theta$ , so  $dx = 2 \sec^2 \theta$ :

$$\int \frac{2 \sec^2 \theta}{\sqrt{x^2 + 4}} dx = \int \frac{\sec^2 \theta}{\sqrt{1 + \tan^2 x}} dx = \int \sec \theta dx = \ln \left( \sqrt{\left(\frac{x}{2}\right)^2 + 1} + \frac{x}{2} \right) + C.$$

2. First, let  $u = x^7$  so  $du = 7x^6 dx$  and our integral becomes

$$\frac{1}{7} \int \frac{du}{\sqrt{1-u^2}} = \frac{1}{14} \ln \frac{1+u}{1-u} + C = \frac{1}{14} \ln \frac{1+x^7}{1-x^7} + C.$$

- 3. Use  $x = \frac{2}{5} \sec \theta$ .
- 4. Use  $x = \frac{2}{3} \sin \theta$ .
- 5. Use  $x = \frac{1}{6} \tan \theta$  and simplify.
- 6. Use integration by parts; the resulting integral  $-\frac{\ln x}{4x^4} + \int \frac{dx}{4x^5}$  is much simpler.
- 7. Use partial fractions.

## 24. Formal Definitions of $\exp$ and $\ln$

$$\int \frac{1}{\text{cabin}} d(\text{cabin}) = \log \text{cabin} + \text{sea}.$$

## 25. Integration Revision

1. (a)  $\int_1^2 \sin x dx = [-\cos x] \Big|_1^2 = \cos 1 - \cos 2.$

(b)  $\int \frac{u^2+1}{u^3+3u} = \frac{1}{3} \ln(u^3 + 3u) + C.$

(c)  $\int_0^{\pi/6} \tan x dx = [\ln \sec x] \Big|_0^{\pi/6} \approx 0.1438.$

2. We have  $\frac{dy}{dx} = \frac{3x^2+4x-4}{2y-4}$ , so  $\int 2y - 4 dy = \int 3x^2 + 4x - 4 dx$ . Hence  $y^2 - 4y = x^3 + 2x^2 - 4x + C$ ; we also have  $C = -2$ , so  $y^2 - 4y = x^3 + 2x - 4x - 2$ . We are trying to find  $y$  if  $x = 2$ ; so  $y^2 - 4y = 8 + 4 - 4 - 2 = 6$ . Solving  $y^2 - 4y - 6 = 0$ , we find  $y = \frac{4 \pm \sqrt{38}}{2}$ .

3. (a) Let  $t = a \tan \theta$ . Then:

$$\begin{aligned} \int \frac{a^3}{t^2 + a^2} dt &= \int \frac{a^4 \sec^2 \theta}{a^2 \tan^2 + a^2} d\theta \\ &= \int \frac{a^2 \sec^2 \theta}{\sec^2 \theta} d\theta \\ &= a^2 \theta = a^2 \tan^{-1} \left( \frac{t}{a} \right); \end{aligned}$$

hence  $\omega(a, x) = a^2 \tan^{-1} \left( \frac{x}{a} \right)$ .

(b) It follows that  $\omega(2, 2) = 4 \tan^{-1} 1 = \pi$ .

(c) We wish to find  $x$  such that  $\pi = 3 \tan^{-1} \left( \frac{x}{\sqrt{3}} \right)$ ; in other words,  $x = \sqrt{3} \tan \left( \frac{\pi}{3} \right) = 3$ .

4. Note first that  $\int_{-\pi/2}^{\pi/2} \sin^5 x \, dx = 0$  since  $\sin^5$  is odd. Then, we argue as follows:

$$\begin{aligned}\int \cos^5 x \, dx &= \int \cos x(1 - \sin^2 x)^2 \, dx \\&= \int (1 - t^2)^2 \, dt \quad (t = \sin x) \\&= \int 1 - 2t^2 + t^4 \, dt \\&= t - \frac{2}{3}t^3 + \frac{t^5}{5} + C \\&= \sin x - \frac{2}{3} \sin^3 x + \frac{1}{5} \sin^5 x + C.\end{aligned}$$

Hence

$$\int_{-\pi/2}^{\pi/2} \sin^5 x \, dx = (\sin \frac{\pi}{2} - \frac{2}{3} \sin^3 \frac{\pi}{2} + \frac{1}{5} \sin^5 \frac{\pi}{2}) - (\sin \frac{-\pi}{2} - \frac{2}{3} \sin^3 \frac{-\pi}{2} + \frac{1}{5} \sin^5 \frac{-\pi}{2}).$$

But  $\sin(\pi/2) = 1$ ; so we have  $(1 - \frac{2}{3} + \frac{1}{5}) - (-1 + \frac{2}{3} - \frac{1}{5}) = 2(1 - \frac{2}{3} + \frac{1}{5}) = \frac{16}{15}$ .

**S-CALCF**

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**QUALIFY FOR THE FUTURE WORLD  
KIA NOHO TAKATŪ KI TŌ ĀMUA AO!**

## Scholarship 2015 Calculus

2.00 p.m. Tuesday 17 November 2015

### FORMULAE AND TABLES BOOKLET

Refer to this booklet to answer the questions for Scholarship Calculus 93202Q.

Check that this booklet has pages 2–4 in the correct order and that none of these pages is blank.

**YOU MAY KEEP THIS BOOKLET AT THE END OF THE EXAMINATION.**



**CALCULUS****Differentiation**

$y = f(x)$	$\frac{dy}{dx} = f'(x)$
$\ln x$	$\frac{1}{x}$
$e^{ax}$	$ae^{ax}$
$\sin x$	$\cos x$
$\cos x$	$-\sin x$
$\tan x$	$\sec^2 x$
$\sec x$	$\sec x \tan x$
$\operatorname{cosec} x$	$-\operatorname{cosec} x \cot x$
$\cot x$	$-\operatorname{cosec}^2 x$

**Integration**

$f(x)$	$\int f(x) dx$
$x^n$	$\frac{x^{n+1}}{n+1} + c$ $(n \neq -1)$
$\frac{1}{x}$	$\ln x  + c$
$\frac{f'(x)}{f(x)}$	$\ln f(x)  + c$

**First principles**

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

**Parametric Function**

$$\frac{dy}{dx} = \frac{dy}{dt} \cdot \frac{dt}{dx}$$

$$\frac{d^2y}{dx^2} = \frac{d}{dt} \left( \frac{dy}{dx} \right) \cdot \frac{dt}{dx}$$

**Product Rule**

$$(f \cdot g)' = f \cdot g' + g \cdot f' \text{ or if } y = uv \text{ then } \frac{dy}{dx} = u \frac{dv}{dx} + v \frac{du}{dx}$$

**Quotient Rule**

$$\left( \frac{f}{g} \right)' = \frac{g \cdot f' - f \cdot g'}{g^2} \text{ or if } y = \frac{u}{v} \text{ then } \frac{dy}{dx} = \frac{v \frac{du}{dx} - u \frac{dv}{dx}}{v^2}$$

**Composite Function or Chain Rule**

$$(f(g))' = f'(g) \cdot g'$$

$$\text{or if } y = f(u) \text{ and } u = g(x) \text{ then } \frac{dy}{dx} = \frac{dy}{du} \cdot \frac{du}{dx}$$

**NUMERICAL METHODS****Trapezium Rule**

$$\int_a^b f(x) dx \approx \frac{1}{2} h \left[ y_0 + y_n + 2(y_1 + y_2 + \dots + y_{n-1}) \right]$$

$$\text{where } h = \frac{b-a}{n} \text{ and } y_r = f(x_r)$$

**Simpson's Rule**

$$\int_a^b f(x) dx \approx \frac{1}{3} h \left[ y_0 + y_n + 4(y_1 + y_3 + \dots + y_{n-1}) + 2(y_2 + y_4 + \dots + y_{n-2}) \right]$$

$$\text{where } h = \frac{b-a}{n}, y_r = f(x_r) \text{ and } n \text{ is even.}$$

## 202 TRIGONOMETRY

$$\operatorname{cosec} \theta = \frac{1}{\sin \theta}$$

$$\sec \theta = \frac{1}{\cos \theta}$$

$$\cot \theta = \frac{1}{\tan \theta}$$

$$\cot \theta = \frac{\cos \theta}{\sin \theta}$$

### 4. EXAMS AND ASSIGNMENTS

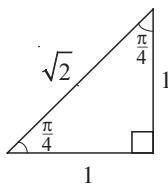
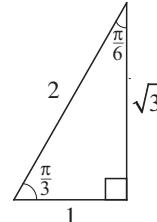
#### Products

$$2 \sin A \cos B = \sin(A+B) + \sin(A-B)$$

$$2 \cos A \sin B = \sin(A+B) - \sin(A-B)$$

$$2 \cos A \cos B = \cos(A+B) + \cos(A-B)$$

$$2 \sin A \sin B = \cos(A-B) - \cos(A+B)$$



#### Sine Rule

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$$

#### Cosine Rule

$$c^2 = a^2 + b^2 - 2ab \cos C$$

#### Identities

$$\cos^2 \theta + \sin^2 \theta = 1$$

$$\tan^2 \theta + 1 = \sec^2 \theta$$

$$\cot^2 \theta + 1 = \operatorname{cosec}^2 \theta$$

#### General Solutions

If  $\sin \theta = \sin \alpha$  then  $\theta = n\pi + (-1)^n \alpha$

If  $\cos \theta = \cos \alpha$  then  $\theta = 2n\pi \pm \alpha$

If  $\tan \theta = \tan \alpha$  then  $\theta = n\pi + \alpha$

where  $n$  is any integer

#### Compound Angles

$$\sin(A \pm B) = \sin A \cos B \pm \cos A \sin B$$

$$\cos(A \pm B) = \cos A \cos B \mp \sin A \sin B$$

$$\tan(A \pm B) = \frac{\tan A \pm \tan B}{1 \mp \tan A \tan B}$$

#### Double Angles

$$\sin 2A = 2 \sin A \cos A$$

$$\tan 2A = \frac{2 \tan A}{1 - \tan^2 A}$$

$$\begin{aligned}\cos 2A &= \cos^2 A - \sin^2 A \\ &= 2 \cos^2 A - 1 \\ &= 1 - 2 \sin^2 A\end{aligned}$$

#### Sums

$$\sin C + \sin D = 2 \sin \frac{C+D}{2} \cos \frac{C-D}{2}$$

$$\sin C - \sin D = 2 \cos \frac{C+D}{2} \sin \frac{C-D}{2}$$

$$\cos C + \cos D = 2 \cos \frac{C+D}{2} \cos \frac{C-D}{2}$$

$$\cos C - \cos D = -2 \sin \frac{C+D}{2} \sin \frac{C-D}{2}$$

#### MEASUREMENT

##### Triangle

$$\text{Area} = \frac{1}{2} ab \sin C$$

##### Trapezium

$$\text{Area} = \frac{1}{2}(a+b)h$$

##### Sector

$$\text{Area} = \frac{1}{2} r^2 \theta$$

$$\text{Arc length} = r\theta$$

##### Cylinder

$$\text{Volume} = \pi r^2 h$$

$$\text{Curved surface area} = 2\pi r h$$

##### Cone

$$\text{Volume} = \frac{1}{3} \pi r^2 h$$

$$\text{Curved surface area} = \pi r l \text{ where } l = \text{slant height}$$

##### Sphere

$$\text{Volume} = \frac{4}{3} \pi r^3$$

$$\text{Surface area} = 4\pi r^2$$