

# MATHEMATICS FOR SCIENCE STUDENTS

An open-source book

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with contributions from others

$$\begin{aligned}a^b &= e^{b \log(a)} & (a+b)^n &= \sum_{k=0}^n \binom{n}{k} a^{n-k} b^k \\ \binom{n}{k} &= \frac{n!}{k!(n-k)!} & T(\alpha \vec{u} + \beta \vec{v}) &= \alpha T(\vec{u}) + \beta T(\vec{v}) \\ R(\theta) &= \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} & A &= Q \Lambda Q^{-1} \\ e^{\pi i} + 1 &= 0 & \frac{df}{dx} &= \lim_{\Delta x \rightarrow 0} \frac{f(x+\Delta x) - f(x)}{\Delta x} \\ \langle \hat{e}_i, \hat{e}_j \rangle &= \delta_{ij} & \Gamma(z) &= \int_0^\infty t^{z-1} e^{-t} dt \\ \int_a^b f(x) dx &= F(b) - F(a) & \vec{v} &= \sum_{i=1}^n \alpha_i \hat{e}_i \\ \cos(x) &= \sum_{n=0}^\infty \frac{(-1)^n}{(2n)!} x^{2n}\end{aligned}$$



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**! To be written/to do:** Rights, lefts, etc. will be written here in the future **!**

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# CHAPTER

# 0



# INTRODUCTION

In this chapter we introduce key concepts that will be used in later chapters. For this reason, unlike other chapters it contains many statements, sometimes given without thorough explanations or reasoning. While all of these statements are grounded in deep ideas and can be formulated in a rigorous manner, it is advised to first get an intuitive understanding of the ideas before diving into their more formal construction.

## **Note 0.1 In case you are already familiar with the topics**

It is recommended for readers who are familiar with the topics to at least gloss over this chapter and make sure they know and understand all the concepts presented here.



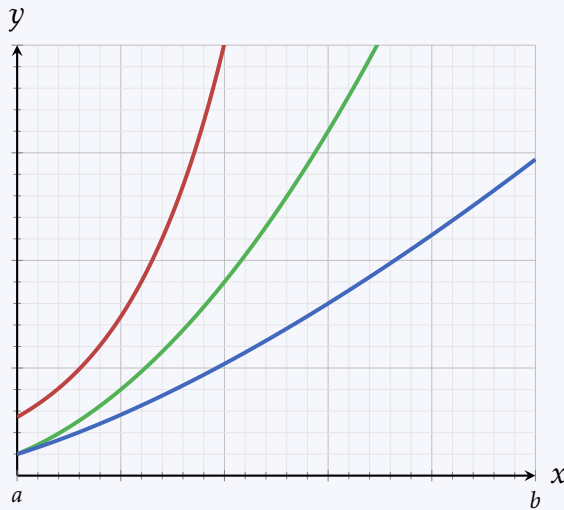
## 0.1 DERIVATIVES

### 0.1.1 Introduction

One of the most important tools in analyzing real functions is the ability to quantitatively describe the way they behave as we change the argument  $x$ . At any given point a function can either increase in its value, decrease in its value, stay constant or be undefined. In this section we will explore a method which enables us to quantitatively measure the change in a function's value at (almost) any point in its domain.

#### Example 0.1 Quantitative measure of change

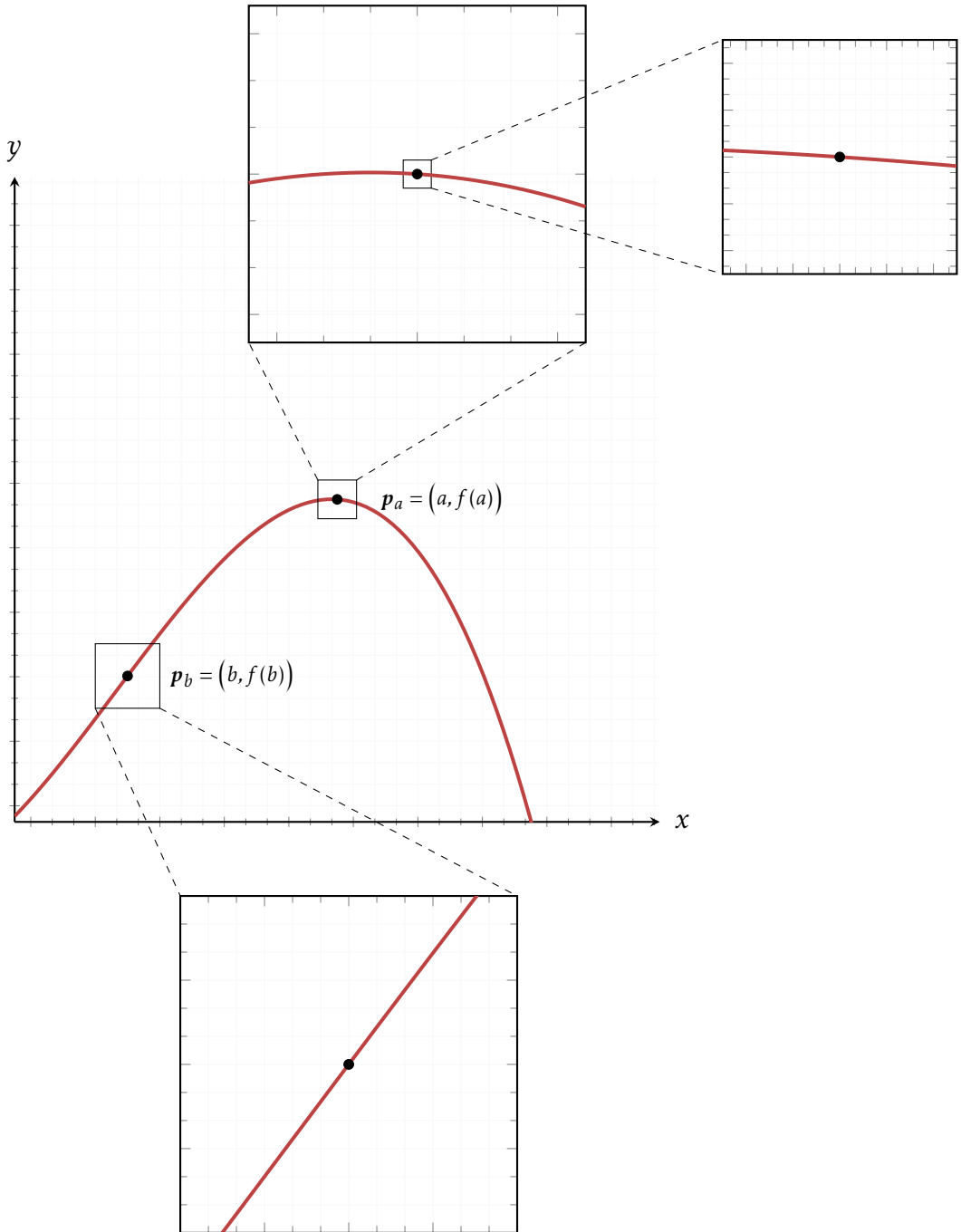
Compare the following three functions on the domain  $x \in [a, b]$ :



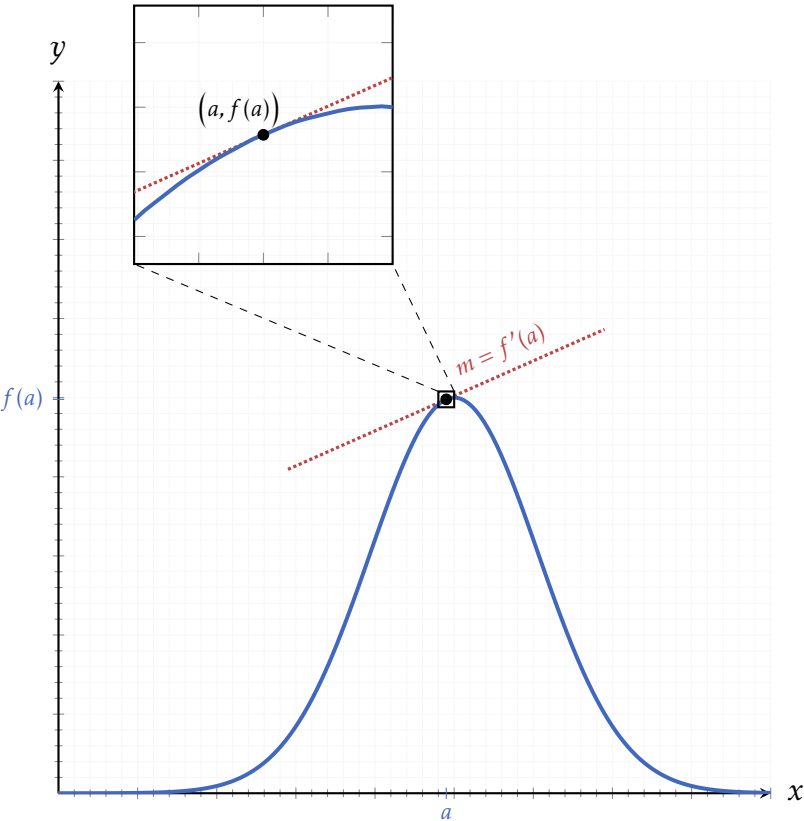
While all three functions are increasing on  $[a, b]$  it is clear that the rate of increase is different in each function: the red function increases faster than the green one, which in turn increases faster than the blue one. In fact, even within each function the increase is not uniform: the more  $x$  increases so does the rate of increase of each of the functions.



Any fundamental real function has the following property: if we zoom in enough on some point  $\mathbf{p} = (a, f(a))$  on the function, we would see that it behaves somewhat like a straight line around  $\mathbf{p}$  (Figure 0.1). In fact, the more we zoom in, the more the function becomes linear around  $\mathbf{p}$ . At the limit where the zoom factor is infinite, the function is exactly linear around  $\mathbf{p}$ , and has the same direction (i.e. slope) as the tangent line to the function at  $\mathbf{p}$  (Figure 0.2). We call this slope the **derivative** of  $f$  at  $x = a$ , and denote it as  $f'(a)$ .

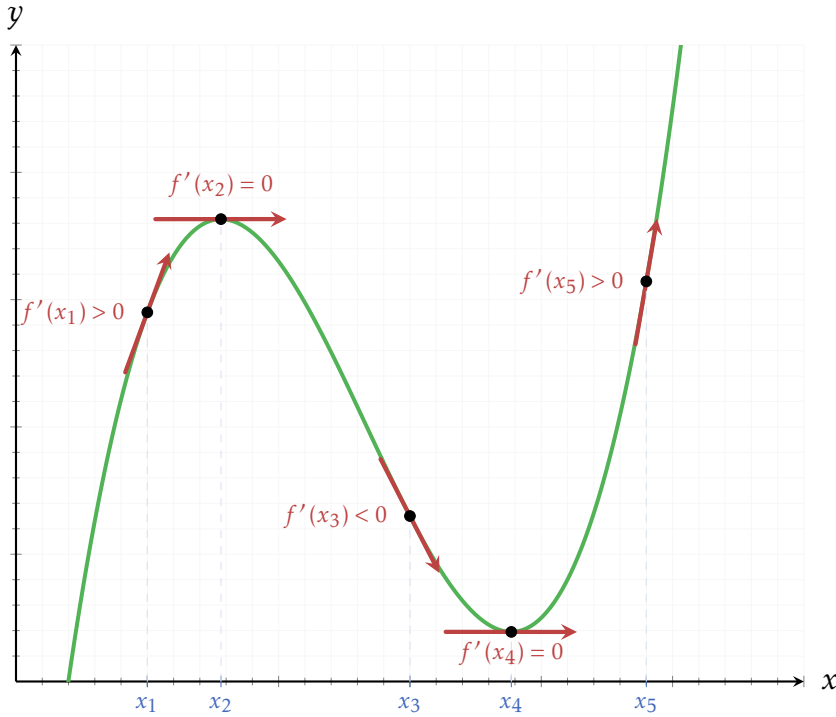


**Figure 0.1** Zooming in on a real function  $f$  at two points:  $p_a = (a, f(a))$  (upper right) and  $p_b = (b, f(b))$  (bottom right). Note how around each of the points, the function looks somewhat linear: this is more pronounced around  $p_b$  where the function looks linear in the entire zoomed-in area, while near  $p_a$  it looks linear only near the point itself even though the zoom factor is higher.



**Figure 0.2** The derivative of the function  $f(x)$  at  $x = a$  is equal to the slope of the tangent line to  $f$  at the point  $(a, f(a))$ .





**Figure 0.3** The derivative of a function  $f(x)$  at some points  $p_i = (x_i, f(x_i))$  on the function: when  $f$  increases the derivative is positive ( $p_1, p_5$ ), when it decreases the derivative is negative ( $p_3$ ), and when it is stationary the derivative equals zero ( $p_2, p_4$ ). The slope of the tangent line to  $f$  at each of the points  $p_i$  is drawn as an arrow to make its sign (positive, negative or zero) more clear.

### 0.1.2 Sign and stationary points

The derivative of a function  $f$  at the point  $a$  can be one of four possible categories (Figure 0.3):

- $f'(a) > 0$ , meaning that  $f$  **increases** at  $a$ .
- $f'(a) < 0$ , meaning that  $f$  **decreases** at  $a$ .
- $f'(a) = 0$ , meaning that  $a$  is a **stationary point**.
- $f'(a)$  is undefined, which can mean different things and which we will address later.

### 0.1.3 Calculating the derivative

How can we quantify the derivative? Let us consider some real function  $f$  and a point  $p_0 = (x_0, f(x_0))$  on the function. We can then define another point to the right of  $x_0$ :

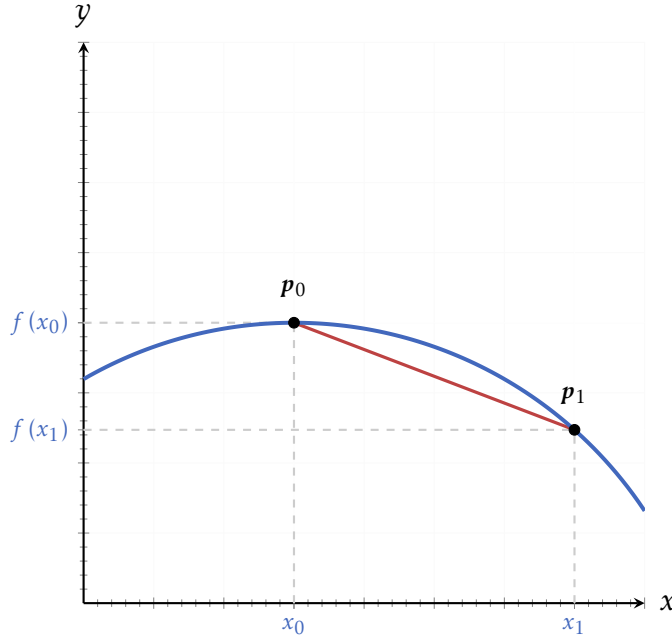


Figure 0.4 Text.

$p_1 = (x_1, f(x_1))$ . Since  $x_1$  is to the right of  $x_0$  we can write it as  $x_1 = x_0 + \Delta x$ , where  $\Delta x > 0$ . We then connect the two points with a line (Figure 0.4). The slope of this line can then be calculated using ??:

$$m = \frac{\Delta y}{\Delta x} = \frac{f(x_1) - f(x_0)}{x_1 - x_0} = \frac{f(x_0 + \Delta x) - f(x_0)}{x_0 + \Delta x - x_0} = \frac{f(x_0 + \Delta x) - f(x_0)}{\Delta x}. \quad (0.1.1)$$

We can then take the limit of Equation 0.1.1 as  $\Delta x \rightarrow 0$  (Figure 0.5):

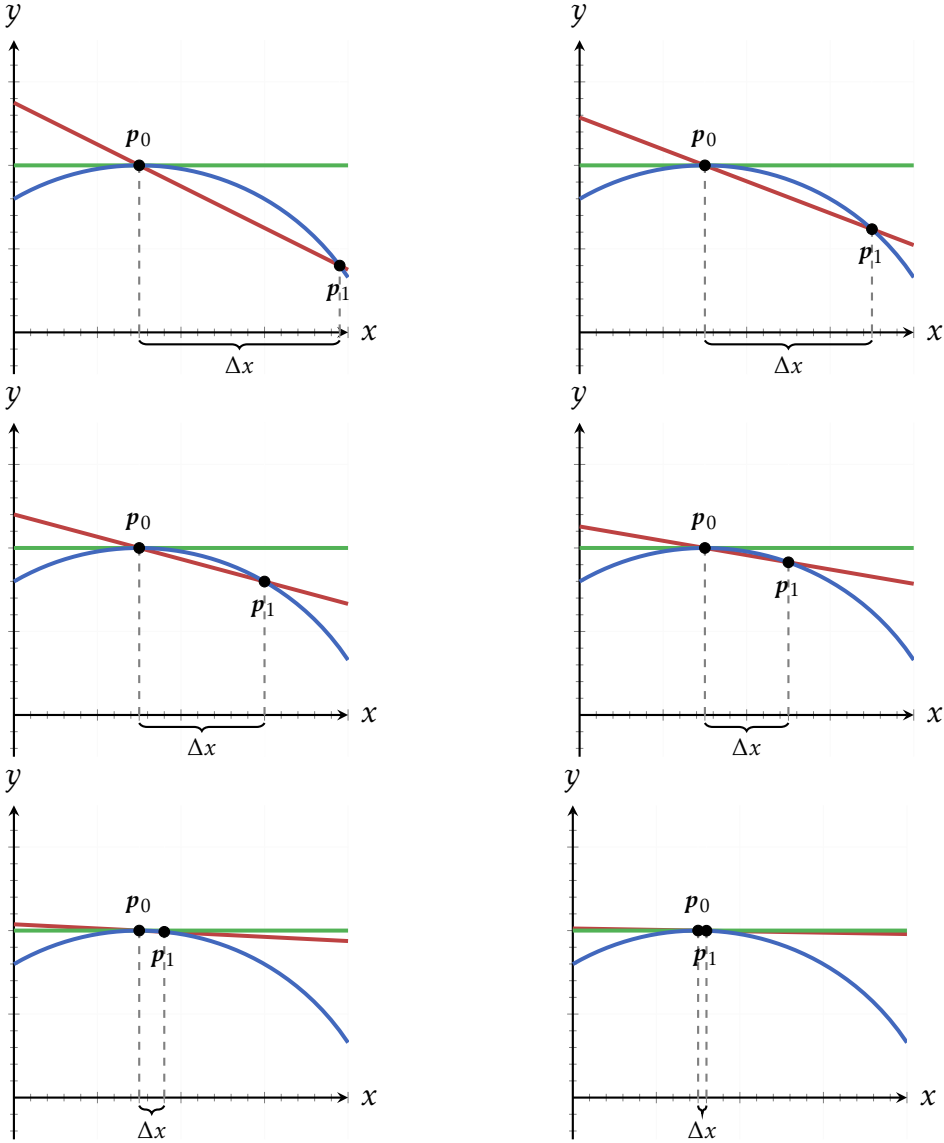
$$M = \lim_{\Delta x \rightarrow 0} \frac{f(x_0 + \Delta x) - f(x_0)}{\Delta x}. \quad (0.1.2)$$

This limit is defined as **the derivative** of  $f$  at the point  $x = x_0$ , and it tells us, quantitatively, how  $f$  locally behaves at  $x_0$ , i.e. how much does it increase, decrease or stay the same around  $x_0$ .

### Example 0.2 Validation of the derivative using a linear function

Given a linear function  $f(x) = mx + b$ , we expect that the derivative of  $f$  at any point  $x_0$  would equal  $m$ , since the entire function is a line connecting all the points on the function itself. Let us check that:

$$\begin{aligned} M &= \lim_{\Delta x \rightarrow 0} \frac{f(x_0 + \Delta x) - f(x_0)}{\Delta x} \\ &= \lim_{\Delta x \rightarrow 0} \frac{m(x_0 + \Delta x) + \cancel{b} - (mx_0 + \cancel{b})}{\Delta x} \end{aligned}$$



**Figure 0.5** As  $\Delta x \rightarrow 0$ ,  $p_1$  approaches  $p_0$  and the slope of the red line connecting the two points approaches the slope  $M$  of the green line at  $p_0$ .

$$\begin{aligned}
 &= \lim_{\Delta x \rightarrow 0} \frac{\cancel{mx_0} + m\Delta x - \cancel{mx_0}}{\Delta x} \\
 &= \lim_{\Delta x \rightarrow 0} \frac{m\cancel{\Delta x}}{\cancel{\Delta x}} \\
 &= m.
 \end{aligned}$$



### Example 0.3 Derivative of $x^2$

Unlike for a linear function, we shouldn't expect the derivative of  $f(x) = x^2$  to be constant at any point. However, we can easily calculate what the derivative would be at some point  $x_0$ :

$$\begin{aligned}
 M &= \lim_{\Delta x \rightarrow 0} \frac{(x_0 + \Delta x)^2 - x_0^2}{\Delta x} \\
 &= \lim_{\Delta x \rightarrow 0} \frac{\cancel{x_0^2} + 2x_0\Delta x - (\Delta x)^2 - \cancel{x_0^2}}{\Delta x} \\
 &= \lim_{\Delta x \rightarrow 0} \frac{\cancel{\Delta x}(2x_0 - \Delta x)}{\cancel{\Delta x}} \\
 &= \lim_{\Delta x \rightarrow 0} 2x_0 - \Delta x \\
 &= 2x_0.
 \end{aligned}$$

I.e. we see that any point  $x_0$  the derivative of  $f(x) = x^2$  is simply  $2x_0$ . For example, at  $x_0 = 3$  the derivative is  $M = 6$ , and at  $x_0 = 0$  the derivative is  $M = 0$ .



Up until now we have regarded the derivative as a property of some point on some function  $f$ . However, since we can calculate the derivative at each point of the function<sup>1</sup>, we can collect all these points together to form a new function, which we call the **derivative** of  $f$  and denote as  $f'$  (read: “ $f$ -prime”).

In [Example 0.2](#) we saw that the derivative of a linear function at any point gives the same value  $m$  (namely the slope of the linear function). Therefore, this derivative is itself a *constant* function  $f'(x) = m$ . When we calculated the derivative of  $f(x) = x^2$  ([Example 0.3](#)), we found that it depends on the point where it was calculated, using the relation  $f'(x) = 2x$ , which is a linear function with slope 2 that goes through the origin.

Let us now calculate the derivative of some common functions.

### Example 0.4 Derivative of $ax^n$

The derivative of the function  $f(x) = ax^n$  (where  $a \in \mathbb{R}$  is a constant) is (recall the

<sup>1</sup>except for some points which we will discuss later.

binomial expansion, ??):

$$\begin{aligned} f'(x) &= \lim_{\Delta x \rightarrow 0} \frac{a(x + \Delta x)^n - ax^n}{\Delta x} \\ &= \lim_{\Delta x \rightarrow 0} \frac{a \left[ \cancel{x^n} + nx^{n-1} \Delta x + \binom{2}{n} x^{n-2} (\Delta x)^2 + \cdots + nx (\Delta x)^{n-1} + (\Delta x)^n \right] - \cancel{ax^n}}{\Delta x}. \end{aligned}$$

We can take  $\Delta x$  out of the numerator and cancel it out with the  $\Delta x$  in the denominator:

$$\begin{aligned} f'(x) &= \lim_{\Delta x \rightarrow 0} \frac{a \cancel{\Delta x} \left[ nx^{n-1} + \binom{2}{n} x^{n-2} \Delta x + \cdots + nx (\Delta x)^{n-2} + (\Delta x)^{n-1} \right]}{\cancel{\Delta x}} \\ &= \lim_{\Delta x \rightarrow 0} a \left[ nx^{n-1} + \binom{2}{n} x^{n-2} \Delta x + \cdots + nx (\Delta x)^{n-2} + (\Delta x)^{n-1} \right]. \end{aligned}$$

Since all expressions except  $nx^{n-1}$  have some power of  $\Delta x$  in them, in the limit  $\Delta x \rightarrow 0$  they all vanish, leaving us with

$$f'(x) = anx^{n-1}.$$

This derivative is commonly described as the power of  $x$  being reduced by 1 and the expression gaining a factor of  $n$  (i.e. the power before reducing it).



#### Example 0.5 Derivative of $a^x$

**! To be written/to do: Note ! :**

Use the fact that  $\lim_{h \rightarrow 0} \frac{a^h - 1}{h} = \log(a)$ . Therefore we also get that  $\lim_{h \rightarrow 0} \frac{e^h - 1}{h} = \log(e) = 1$ .



#### Example 0.6 Derivative of $\sin(x)$

Calculating the derivative of  $\sin(x)$ :

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

We can separate the three terms into three limits:

$$\sin'(x) = \lim_{\Delta x \rightarrow 0} \frac{\sin(x) [\cos(\Delta x) - 1]}{\Delta x} + \lim_{\Delta x \rightarrow 0} \frac{\cos(x) \sin(\Delta x)}{\Delta x}.$$

The second limit equals  $\cos(x)$ , since  $\lim_{c \rightarrow 0} \frac{\sin(c)}{c} = 1$  (??). Since  $\sin(x)$  does not change as we decrease  $\Delta x$ , we can regard it as a constant and take it out of the

limit:

$$\sin'(x) = \sin(x) \lim_{\Delta x \rightarrow 0} \frac{\cos(\Delta x) - 1}{\Delta x} + \cos(x).$$

Using the double angle identity (??) on  $\cos(\Delta x)$  we get that

$$\cos(\Delta x) = 1 - 2\sin^2\left(\frac{\Delta x}{2}\right),$$

and by plugging this back into the derivative calculation we get:

$$\begin{aligned} \sin'(x) &= \lim_{\Delta x \rightarrow 0} \frac{-2\sin^2\left(\frac{\Delta x}{2}\right)}{\Delta x} + \cos(x) \\ &= \lim_{\Delta x \rightarrow 0} \frac{-\cancel{2}\sin^2\left(\frac{\Delta x}{2}\right)}{\frac{\Delta x}{\cancel{2}}} + \cos(x) \\ &= \cos(x), \end{aligned}$$

since  $\lim_{h \rightarrow 0} \frac{\sin^2(h)}{h} = 0$  (??).

**! To be written/to do:** in the limit section show and prove this limit !



### Example 0.7 Derivative of $\sqrt{x}$

The derivative of the function  $f(x) = \sqrt{x}$  is:

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

We can multiply the numerator and denominator each by  $\sqrt{x + \Delta x} + \sqrt{x}$ . This would allow us to use the relation  $(a - b)(a + b) = a^2 - b^2$ :

$$\begin{aligned} f'(x) &= \lim_{\Delta x \rightarrow 0} \frac{\sqrt{x + \Delta x} - \sqrt{x}}{\Delta x} \\ &= \lim_{\Delta x \rightarrow 0} \frac{\cancel{\sqrt{x}} + \Delta x - \cancel{\sqrt{x}}}{\Delta x (\sqrt{x + \Delta x} + \sqrt{x})} \\ &= \frac{1}{\sqrt{x} + \sqrt{x}} \\ &= \frac{1}{2\sqrt{x}}. \end{aligned}$$



Table 0.1 lists some common functions and their derivatives.

**Table 0.1** Some common real functions and their derivatives.

$f(x)$	$f'(x)$	Remarks
$c$	$0$	$c \in \mathbb{R}$
$mx + b$	$m$	$m, b \in \mathbb{R}$
$ax^2$	$2ax$	$a \in \mathbb{R}$
$ax^n$	$nax^{n-1}$	$a \in \mathbb{R}$
$\sqrt{x}$	$\frac{1}{2\sqrt{x}}$	$x \geq 0$
$e^x$	$e^x$	
$a^x$	$a^x \log(a)$	$a > 0$
$\log(x)$	$\frac{1}{x}$	$x > 0$
$\log_b(x)$	$\frac{1}{x \log(b)}$	$x, b > 0$
$\sin(x)$	$\cos(x)$	
$\cos(x)$	$-\sin(x)$	
$\tan(x)$	$\frac{1}{\cos^2(x)} = 1 + \tan^2(x)$	$x \notin \left\{ \frac{\pi}{2} + k \right\}, k \in \mathbb{Z}$
$\arcsin(x)$	$\frac{1}{\sqrt{1-x^2}}$	$-1 < x < 1$
$\arccos(x)$	$-\frac{1}{\sqrt{1-x^2}}$	$-1 < x < 1$
$\arctan(x)$	$\frac{1}{1+x^2}$	
$\sinh(x)$	$\cosh(x)$	
$\cosh(x)$	$\sinh(x)$	
$\tanh(x)$	$1 - \tanh^2(x)$	

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## **0.2 LINEARITY AND COMBINED FUNCTIONS**

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