Elementary Calculus Manual

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Contents

1 Analytic geometry

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Contents

1.1 Vectors

Scalars

Some phenomena of Nature can be described by a number and a unit of measurement.

Definition 1 (Scalar)**.** A *scalar* is a number that expresses a magnitude without direction.

Examples The height or weight of a person, the temperature of a gas or the time it takes a vehicle to travel a distance.

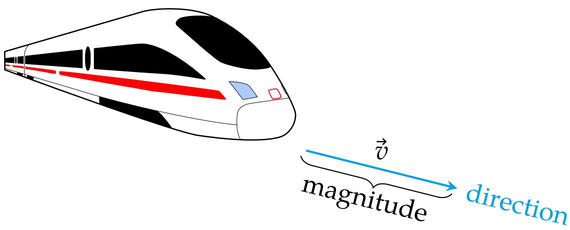
However, there are other phenomena that cannot be described adequately by a scalar. If, for instance, a sailor wants to head for seaport and only knows the intensity of wind, he won't know what direction to take. The description of wind requires two elements: intensity and direction.

Vectors

Definition 2 (Vector)**.** A *vector* is a number that expresses a magnitude and has associated an orientation and a sense.

Examples The velocity of a vehicle or the force applied to an object.

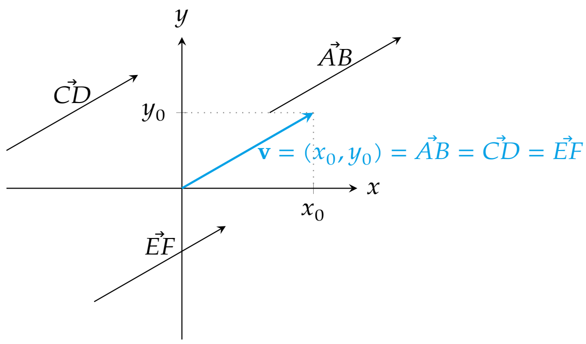
Geometrically, a vector is represented by an directed line segment, that is, an arrow.



Vector representation

An oriented segment can be located in different places in a Cartesian space. However, regardless of where it is located, if the length and the direction of the segment does not change, the segment represents always the same vector.

This allows to represent all vectors with the same origin, the origin of the Cartesian coordinate system. Thus, a vector can be represented by the Cartesian *coordinates* of its final end in any Euclidean space.

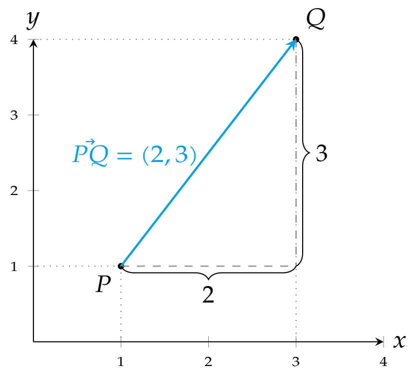


Vector from two points

Given two points P and Q of a Cartesian space, the vector that starts at P and ends at Q has coordinates $\vec{PQ} = Q - P$.

Example Given the points $P = (1, 1)$ and $Q = (3, 4)$ in the real plane $\mathbb{R}^2$, the coordinates of the vector that start at P and ends at Q are

$$\vec{PQ} = Q - P = (3, 4) - (1, 1) = (3 - 2, 4 - 1) = (2, 3).$$



Module of a vector

Definition 3 (Module of a vector). Given a vector $\mathbf{v} = (v_1, \cdots, v_n)$ in $\mathbb{R}^n$, the *module* of $\mathbf{v}$ is

$$|\mathbf{v}| = \sqrt{v_1^2 + \cdots + v_n^2}.$$

The module of a vector coincides with the length of the segment that represents the vector.

Examples Let $\mathbf{u} = (3, 4)$ be a vector in $\mathbb{R}^2$, then its module is

$$|\mathbf{u}| = \sqrt{3^2 + 4^2} = \sqrt{25} = 5$$

Let $\mathbf{v} = (4, 7, 4)$ be a vector in $\mathbb{R}^3$, then its module is

$$|\mathbf{v}| = \sqrt{4^2 + 7^2 + 4^2} = \sqrt{81} = 9$$

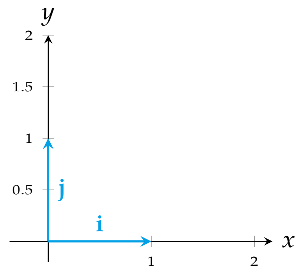
Unit vectors

Definition 4 (Unit vector). A vector $\mathbf{v}$ in $\mathbb{R}^n$ is a *unit vector* if its module is one, that is, $|\mathbf{v}| = 1$.

The unit vectors with the direction of the coordinate axes are of special importance and they form the *standard basis*.

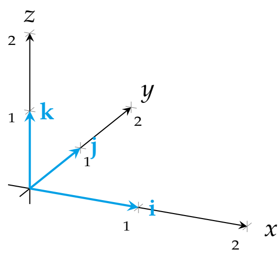
In $\mathbb{R}^2$ the standard basis is formed by two vectors

$$\mathbf{i} = (1,0) \text{ and } \mathbf{j} = (0,1)$$



In $\mathbb{R}^3$ the standard basis is formed by three vectors

$$\mathbf{i} = (1,0,0), \mathbf{j} = (0,1,0) \text{ and } \mathbf{k} = (0,0,1)$$



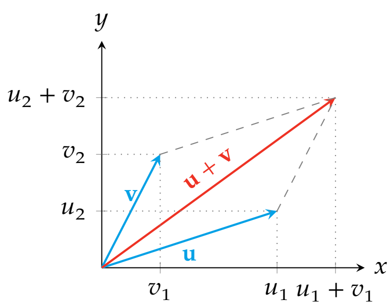
Sum of two vectors

Definition 5 (Sum of two vectors)**.** Given two vectors $\mathbf{u} = (u_1, \cdots, u_n)$ y $\mathbf{v} = (v_1, \cdots, v_n)$ de $\mathbb{R}^n$, the *sum* of $\mathbf{u}$ and $\mathbf{v}$ is

$$\mathbf{u} + \mathbf{v} = (u_1 + v_1, \ldots, u_n + v_n).$$

Example Let $\mathbf{u} = (3,1)$ and $\mathbf{v} = (2,3)$ two vectors in $\mathbb{R}^2$, then the sum of them is

$$\mathbf{u} + \mathbf{v} = (3+2, 1+3) = (5,4).$$



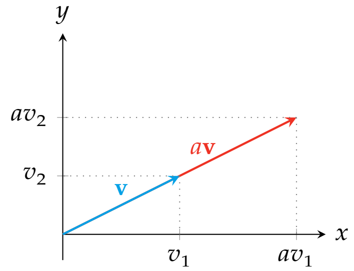
Product of a vector by a scalar

Definition 6 (Product of a vector by a scalar)**.** Given a vector $\mathbf{v} = (v_1, \cdots, v_n)$ in $\mathbb{R}^n$, and a scalar $a \in \mathbb{R}$, the *product* of $\mathbf{v}$ by a is

$$a\mathbf{v} = (av_1, \ldots, av_n).$$

Example Let $\mathbf{v} = (2, 1)$ a vector in $\mathbb{R}^2$ and $a = 2$ a scalar, then the product of a by $\mathbf{v}$ is

$$a\mathbf{v} = 2(2, 1) = (4, 2).$$

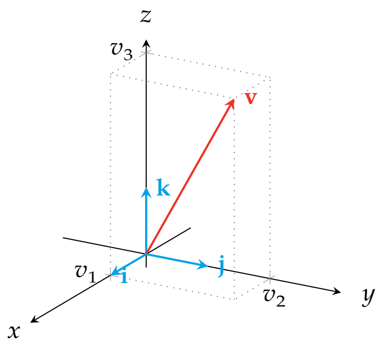


Expressing a vector as a linear combination of the standard basis

The sum of vectors and the product of vector by a scalar allow us to express any vector as a linear combination of the standard basis.

In $\mathbb{R}^3$, for instance, a vector with coordinates $\mathbf{v} = (v_1, v_2, v_3)$ can be expressed as the linear combination

$$\mathbf{v} = (v_1, v_2, v_3) = v_1\mathbf{i} + v_2\mathbf{j} + v_3\mathbf{k}.$$



Dot product of two vectors

Definition 7 (Dot product of two vectors)**.** Given the vectors $\mathbf{u} = (u_1, \cdots, u_n)$ and $\mathbf{v} = (v_1, \cdots, v_n)$ in $\mathbb{R}^n$, the *dot product* of $\mathbf{u}$ and $\mathbf{v}$ is

$$\mathbf{u} \cdot \mathbf{v} = u_1 v_1 + \cdots + u_n v_n.$$

Example Let $\mathbf{u} = (3, 1)$ and $\mathbf{v} = (2, 3)$ two vectors in $\mathbb{R}^2$, then the dot product of them is

$$\mathbf{u} \cdot \mathbf{v} = 3 \cdot 2 + 1 \cdot 3 = 9.$$

It holds that

$$\mathbf{u} \cdot \mathbf{v} = |\mathbf{u}||\mathbf{v}| \cos \alpha$$

where α is the angle between the vectors.

Parallel vectors

Definition 8 (Parallel vectors)**.** Two vectors $\mathbf{u}$ and $\mathbf{v}$ are *parallel* if there is a scalar $a \in \mathbb{R}$ such that

$$\mathbf{u} = a\mathbf{v}.$$

Example The vectors $\mathbf{u} = (-4, 2)$ and $\mathbf{v} = (2, -1)$ in $\mathbb{R}^2$ are parallel, as there is a scalar -2 such that

$$\mathbf{u} = (-4, 2) = -2(2, -1) = -2\mathbf{v}.$$

Orthogonal and orthonormal vectors

Definition 9 (Orthogonal and orthonormal vectors)**.** Two vectors **u** and **v** are *orthogonal* if their dot product is zero,

$$\mathbf{u} \cdot \mathbf{v} = 0.$$

If in addition both vectors are unit vectors, $|\mathbf{u}| = |\mathbf{v}| = 1$, then the vectors are *orthonormal*.

Orthogonal vectors are perpendicular, that is the angle between them is right.

Example The vectors $\mathbf{u} = (2, 1)$ and $\mathbf{v} = (-2, 4)$ in $\mathbb{R}^2$ are orthogonal, as

$$\mathbf{uv} = 2 \cdot -2 + 1 \cdot 4 = 0,$$

but they are not orthonormal since $|\mathbf{u}| = \sqrt{2^2 + 1^2} \neq 1$ and $|\mathbf{v}| = \sqrt{-2^2 + 4^2} \neq 1$.

The vectors $\mathbf{i} = (1, 0)$ and $\mathbf{j} = (0, 1)$ in $\mathbb{R}^2$ are orthonormal, as

$$\mathbf{ij} = 1 \cdot 0 + 0 \cdot 1 = 0, \quad |\mathbf{i}| = \sqrt{1^2 + 0^2} = 1, \quad |\mathbf{j}| = \sqrt{0^2 + 1^2} = 1.$$

1.2 Lines

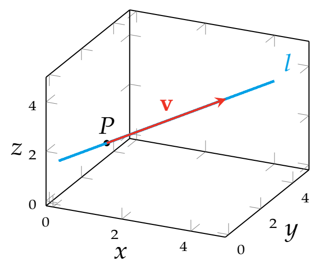
Vectorial equation of a straight line

Definition 10 (Vectorial equation of a straight line)**.** Given a point $P = (p_1, \ldots, p_n)$ and a vector $\mathbf{v} = (v_1, \ldots, v_n)$ of $\mathbb{R}^n$, the *vectorial equation of the line l* that passes through the point P with the direction of **v** is

$$l : X = P + t\mathbf{v} = (p_1, \ldots, p_n) + t(v_1, \ldots, v_n) = (p_1 + tv_1, \ldots, p_n + tv_n), \quad t \in \mathbb{R}.$$

Example Let l the line of $\mathbb{R}^3$ that goes through $P = (1, 1, 2)$ with the direction of $\mathbf{v} = (3, 1, 2)$, then the vectorial equation of l is

$$\begin{aligned} l : X = P + t\mathbf{v} &= (1, 1, 2) + t(3, 1, 2) = \\ &= (1 + 3t, 1 + t, 2 + 2t) \quad t \in \mathbb{R}. \end{aligned}$$



Parametric and Cartesian equations of a line

From the vectorial equation of a line $l : X = P + t\mathbf{v} = (p_1 + tv_1, \ldots, p_n + tv_n)$ is easy to obtain the coordinates of the the points of the line with n *parametric equations*

$$x_1(t) = p_1 + tv_1, \ldots, x_n(t) = p_n + tv_n$$

from where, if **v** is a vector with non-null coordinates ($v_i \neq 0 \ \forall i$), we can solve for t and equal the equations getting the *Cartesian equations*

$$\frac{x_1 - p_1}{v_1} = \cdots = \frac{x_n - p_n}{v_n}$$

Example Given a line with vectorial equation $l : X = (1,1,2) + t(3,1,2) = (1+3t, 1+t, 2+2t)$ in $\mathbb{R}^3$, its parametric equations are

$$x(t) = 1 + 3t, \quad y(t) = 1 + t, \quad z(t) = 2 + 2t,$$

and the Cartesian equations are

$$\frac{x-1}{3} = \frac{y-1}{1} = \frac{z-2}{2}$$

Point-slope equation of a line in the plane

In the particular case of the real plane $\mathbb{R}^2$, if we have a line with vectorial equation $l : X = P + t\mathbf{v} = (x_0, y_0) + t(a,b) = (x_0 + ta, y_0 + tb)$, its parametric equations are

$$x(t) = x_0 + ta, \quad y(t) = y_0 + tb$$

and its Cartesian equation is

$$\frac{x - x_0}{a} = \frac{y - y_0}{b}.$$

From this, moving b to the other side of the equation, we get

$$y - y_0 = \frac{b}{a}(x - x_0),$$

or renaming $m = b/a$,

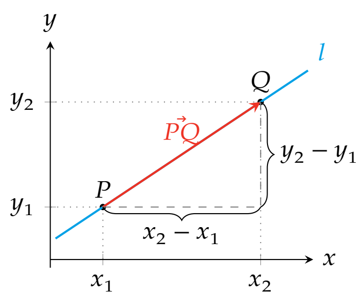
$$y - y_0 = m(x - x_0).$$

This equation is known as the *point-slope equation* of the line.

Slope of a line in the plane

Definition 11 (Slope of a line in the plane)**.** Given a line $l : X = P + t\mathbf{v}$ in the real plane $\mathbb{R}^2$, with direction vector $\mathbf{v} = (a,b)$, the *slope* of l is b/a.

Recall that given two points $P = (x_1, y_1)$ and $Q = (x_2, y_2)$ on the line l, we can take as a direction vector the vector from P to Q, with coordinates $\vec{PQ} = Q - P = (x_2 - x_1, y_2 - y_1)$. Thus, the slope of l is $\dfrac{y_2 - y_1}{x_2 - x_1}$, that is, the ratio between the changes in the vertical and horizontal axes.



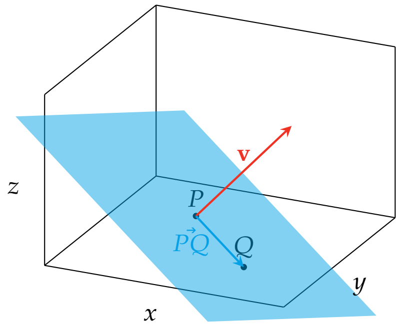
1.3 Planes

Vector equation of a plane in space

To get the equation of a plane in the real space $\mathbb{R}^3$ we can take a point of the plane $P = (x_0, y_0, z_0)$ and an orthogonal vector to the plane $\mathbf{v} = (a, b, c)$. Then, any point $Q = (x, y, z)$ of the plane satisfies that the vector $\vec{PQ} = (x - x_0, y - y_0, z - z_0)$ is orthogonal to $\mathbf{v}$, and therefore their dot product is zero.

$$\vec{PQ} \cdot \mathbf{v} = (x - x_0, y - y_0, z - z_0)(a, b, c) = a(x - x_0) + b(y - y_0) + c(z - z_0) = 0.$$

This equation is known as the *vector equation of the plane*.



Scalar equation of a plane in space

From the vector equation of the plane we can get

$$a(x - x_0) + b(y - y_0) + c(z - z_0) = 0 \Leftrightarrow ax + by + cz = ax_0 + by_0 + cz_0,$$

that, renaming $d = ax_0 + by_0 + cz_0$, can be written as

$$ax + by + cz = d,$$

and is known as the *scalar equation of the plane*.

Example Given the point $P = (2, 1, 1)$ and the vector $\mathbf{v} = (2, 1, 2)$, the vector equation of the plane that passes through P and is orthogonal to $\mathbf{v}$ is

$$(x - 2, y - 1, z - 1)(2, 1, 2) = 2(x - 2) + (y - 1) + 2(z - 1) = 0,$$

and its scalar equation is

$$2x + y + 2z = 7.$$

2 Differential calculus with one real variable

2.1 Concept of derivative

Increment

Definition 12 (Increment of a variable)**.** An *increment* of a variable x is a change in the value of the variable; is it is denoted Δx. The increment of a variable x along an interval $[a, b]$ is given by

$$\Delta x = b - a.$$

Definition 13 (Increment of a function)**.** The *increment* of a function $y = f(x)$ along an interval $[a, b] \subseteq Dom(f)$ is given by

$$\Delta y = f(b) - f(a).$$

Example The increment of x along the interval $[2, 5]$ is $\Delta x = 5 - 2 = 3$ and the increment of the function $y = x^2$ along the same interval is $\Delta y = 5^2 - 2^2 = 21$.

Average rate of change

The study of a function $y = f(x)$ requires to understand how the function changes, that is, how the dependent variable y changes when we change the independent variable x.

Definition 14 (Average rate of change)**.** The *average rate of change* of a function $y = f(x)$ in an interval $[a, a + \Delta x] \subseteq Dom(f)$, is the quotient between the increment of y and the increment of x in that interval, and is denoted by

$$\text{ARC}\, f[a, a + \Delta x] = \frac{\Delta y}{\Delta x} = \frac{f(a + \Delta x) - f(a)}{\Delta x}.$$

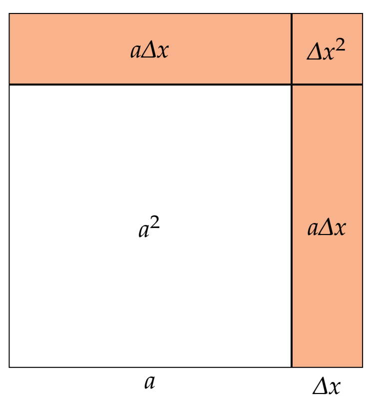
Average rate of change

Example of the area of a square

Let $y = x^2$ be the function that measures the area of a metallic square of side length x.

If at any given time the side of the square is a, and we heat the square uniformly increasing the side by dilatation a quantity Δx, how much will the area of the square increase?

$$\begin{aligned}\Delta y = f(a + \Delta x) - f(a) &= (a + \Delta x)^2 - a^2 = \\ &= a^2 + 2a\Delta x + \Delta x^2 - a^2 = 2a\Delta x + \Delta x^2.\end{aligned}$$

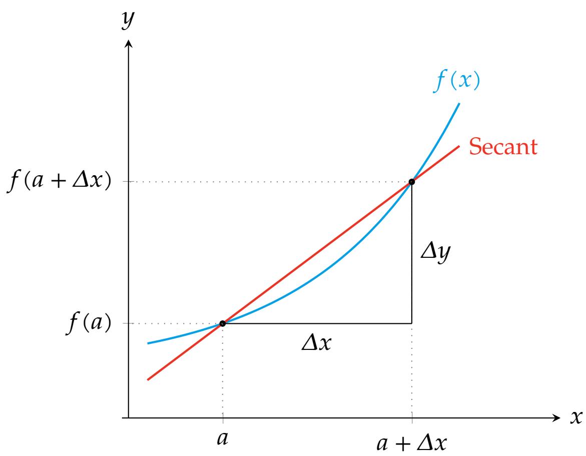


What is the average rate of change in the interval $[a, a+\Delta x]$?

$$\text{ARC}\, f[a, a+\Delta x] = \frac{\Delta y}{\Delta x} = \frac{2a\Delta x + \Delta x^2}{\Delta x} = 2a + \Delta x.$$

Geometric interpretation of the average rate of change

The average rate of change of a function $y = f(x)$ in an interval $[a, a+\Delta x]$ is the slope of the *secant* line to the graph of f through the points $(a, f(a))$ and $(a+\Delta x, f(a+\Delta x))$.



Instantaneous rate of change

Often it is interesting to study the rate of change of a function, not in an interval, but in a point.

Knowing the tendency of change of a function in an instant can be used to predict the value of the function in nearby instants.

Definition 15 (Instantaneous rate of change and derivative)**.** The *instantaneous rate of change* of a function $f(x)$ at a point $x = a$, is the limit of the average rate of change of f in the interval $[a, a+\Delta x]$, when Δx tends to 0, and is denoted by

$$\text{IRC}\, f(a) = \lim_{\Delta x\to 0} \text{ARC}\, f[a, a+\Delta x] = \lim_{\Delta x\to 0} \frac{\Delta y}{\Delta x} = \lim_{\Delta x\to 0} \frac{f(a+\Delta x) - f(a)}{\Delta x}$$

When this limit exists, the function f is said to be *differentiable* at the point a, and its value is called the *derivative* of f at a, and it is denoted $f'(a)$ (Lagrange's notation) or $\frac{df}{dx}(a)$ (Leibniz's notation).

Instantaneous rate of change

Example of the area of a square

Let's take again the function $y = x^2$ that measures the area of a metallic square of side length x.

If at any given time the side of the square is a, and we heat the square uniformly increasing the side, what is the tendency of change of the area in that moment?

$$\begin{aligned}\text{IRC}\, f(a) &= \lim_{\Delta x\to 0} \frac{\Delta y}{\Delta x} = \lim_{\Delta x\to 0} \frac{f(a+\Delta x) - f(a)}{\Delta x} = \\ &= \lim_{\Delta x\to 0} \frac{2a\Delta x + \Delta x^2}{\Delta x} = \lim_{\Delta x\to 0} 2a + \Delta x = 2a.\end{aligned}$$

Thus,

$$f'(a) = \frac{df}{dx}(a) = 2a,$$

indicating that the area of the square tends to increase the double of the side.

Interpretation of the derivative

The derivative of a function $f'(a)$ shows the growth rate of f at point a:

- $f'(a) > 0$ indicates an increasing tendency (y increases as x increases).
- $f'(a) < 0$ indicates a decreasing tendency (y decreases as x increases).

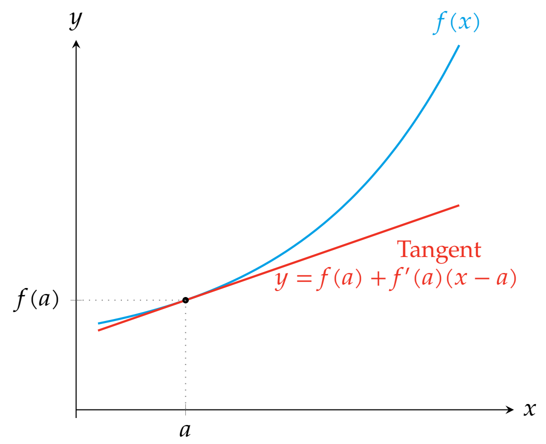
Example A derivative $f'(a) = 3$ indicates that y tends to increase triple of x at point a. A derivative $f'(a) = -0.5$ indicates that y tends to decrease half of x at point a.

Geometric interpretation of the derivative

We have seen that the average rate of change of a function $y = f(x)$ in an interval $[a, a + \Delta x]$ is the slope of the *secant* line, but when Δx tends to 0, the secant line becomes the tangent line.

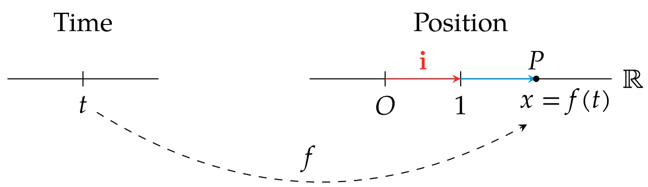
The instantaneous rate of change or derivative of a function $y = f(x)$ at $x = a$ is the slope of the *tangent line* to the graph of f at point $(a, f(a))$. Thus, the equation of the tangent line to the graph of f at the point $(a, f(a))$ is

$$y - f(a) = f'(a)(x - a) \Leftrightarrow y = f(a) + f'(a)(x - a)$$



Kinematic applications: Linear motion

Assume that the function $y = f(t)$ describes the position of an object moving in the real line at time t. Taking as reference the coordinates origin O and the unitary vector $\mathbf{i} = (1)$, we can represent the position of the moving object P at every moment t with a vector $\vec{OP} = x\mathbf{i}$ where $x = f(t)$.



Remark It also makes sense when f measures other magnitudes as the temperature of a body, the concentration of a gas, or the quantity of substance in a chemical reaction at every moment t.

Kinematic interpretation of the average rate of change

In this context, if we take the instants $t = a$ and $t = a + \Delta t$, both in $\text{Dom}(f)$, the vector

$$\mathbf{v}_m = \frac{f(a + \Delta t) - f(a)}{\Delta t}$$

is known as the *average velocity* of the trajectory f in the interval $[a, a + \Delta t]$.

Example A vehicle makes a trip from Madrid to Barcelona. Let $f(t)$ be the function that determine the position of the vehicle at every moment t. If the vehicle departs from Madrid (km 0) at 8:00 and arrives at Barcelona (km 600) at 14:00, then the average velocity of the vehicle in the path is

$$\mathbf{v}_m = \frac{f(14) - f(8)}{14 - 8} = \frac{600 - 0}{6} = 100km/h.$$

Kinematic interpretation of the derivative

In the same context of the linear motion, the derivative of the function $f(t)$ at the moment t_0 is the vector

$$\mathbf{v} = f'(a) = \lim_{\Delta t \to 0} \frac{f(a + \Delta t) - f(a)}{\Delta t},$$

that is known, as long as the limit exists, as the *instantaneous velocity* or simply *velocity* of the trajectory f at moment a.

That is, the derivative of the object position with respect to time is a vector field that is called *velocity along the trajectory f*.

Example Following with the previous example, what indicates the speedometer at any instant is the modulus of the instantaneous velocity vector at that moment.

2.2 Algebra of derivatives

Properties of the derivative

If $y = c$, is a constant function, then $y' = 0$ at any point.

If $y = x$, is the identity function, then $y' = 1$ at any point.

If $u = f(x)$ and $v = g(x)$ are two differentiable functions, then

- $(u + v)' = u' + v'$
- $(u - v)' = u' - v'$
- $(u \cdot v)' = u' \cdot v + u \cdot v'$
- $\left(\frac{u}{v}\right)' = \frac{u' \cdot v - u \cdot v'}{v^2}$

Derivative of a composite function

The chain rule

Theorem 16 (Chain rule). *If the function $y = f \circ g$ is the composition of two functions $y = f(z)$ and $z = g(x)$, then*

$$(f \circ g)'(x) = f'(g(x))g'(x).$$

It is easy to prove this fact using the Leibniz notation

$$\frac{dy}{dx} = \frac{dy}{dz}\frac{dz}{dx} = f'(z)g'(x) = f'(g(x))g'(x).$$

Example If $f(z) = \sin z$ and $g(x) = x^2$, then $f \circ g(x) = \sin(x^2)$. Applying the chain rule the derivative of the composite function is

$$(f \circ g)'(x) = f'(g(x))g'(x) = \cos(g(x))2x = \cos(x^2)2x.$$

On the other hand, $g \circ f(z) = (\sin z)^2$, and applying the chain rule again, its derivative is

$$(g \circ f)'(z) = g'(f(z))f'(z) = 2f(z)\cos z = 2\sin z \cos z.$$

Derivative of the inverse of a function

Theorem 17 (Derivative of the inverse function)**.** *Given a function $y = f(x)$ with inverse $x = f^{-1}(y)$, then*

$$\left(f^{-1}\right)'(y) = \frac{1}{f'(x)} = \frac{1}{f'(f^{-1}(y))},$$

provided that f is differentiable at $f^{-1}(y)$ and $f'(f^{-1}(y)) \neq 0$.

Again, it is easy to prove this equality using the Leibniz notation

$$\frac{dx}{dy} = \frac{1}{dy/dx} = \frac{1}{f'(x)} = \frac{1}{f'(f^{-1}(y))}$$

Derivative of the inverse of a function

Example

The inverse of the exponential function $y = f(x) = e^x$ is the natural logarithm $x = f^{-1}(y) = \ln y$, so we can compute the derivative of the natural logarithm using the previous theorem and we get

$$\left(f^{-1}\right)'(y) = \frac{1}{f'(x)} = \frac{1}{e^x} = \frac{1}{e^{\ln y}} = \frac{1}{y}.$$

Example Sometimes it is easier to apply the chain rule to compute the derivative of the inverse of a function. In this example, as $\ln x$ is the inverse of e^x, we know that $e^{\ln x} = x$, so differentiating both sides and applying the chain rule to the left side we get

$$(e^{\ln x})' = x' \Leftrightarrow e^{\ln x}(\ln(x))' = 1 \Leftrightarrow (\ln(x))' = \frac{1}{e^{\ln x}} = \frac{1}{x}.$$

2.3 Analysis of functions

Analysis of functions: increase and decrease

The main application of derivatives is to determine the variation (increase or decrease) of functions. For that we use the sign of the first derivative.

Theorem 18. *Let $f(x)$ be a function with first derivative in an interval $I \subseteq \mathbb{R}$.*

- *If $\forall x \in I\ f'(x) > 0$ then f is increasing on I.*
- *If $\forall x \in I\ f'(x) < 0$ then f is decreasing on I.*

If $f'(a) = 0$ then a is known as a *critical point* or *stationary point*. At this point the function can be increasing, decreasing or neither increasing nor decreasing.

Example The function $f(x) = x^2$ has derivative $f'(x) = 2x$; it is decreasing on $\mathbb{R}^-$ as $f'(x) < 0$ $\forall x \in \mathbb{R}^-$ and increasing on $\mathbb{R}^+$ as $f'(x) > 0$ $\forall x \in \mathbb{R}^+$.

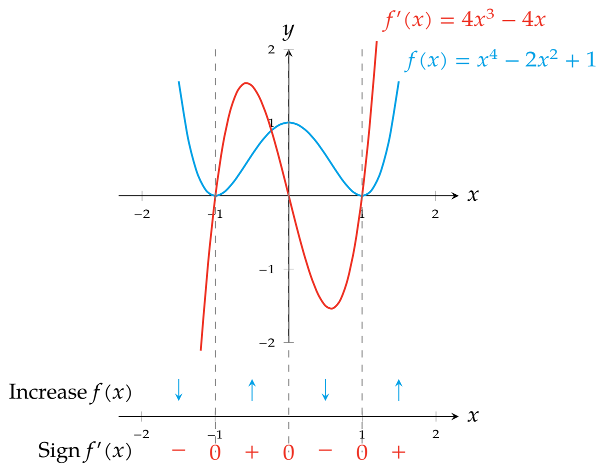
It has a critical point at $x = 0$, as $f'(0) = 0$; at this point the function is neither increasing nor decreasing.

Remark A function can be increasing or decreasing on an interval and not have first derivative.

Analysis of functions: increase and decrease

Example

Let us analyze the increase and decrease of the function $f(x) = x^4 - 2x^2 + 1$. Its first derivative is $f'(x) = 4x^3 - 4x$.



Analysis of functions: relative extrema

As a consequence of the previous result we can also use the first derivative to determine the relative extrema of a function.

Theorem 19 (First derivative test). *Let $f(x)$ be a function with first derivative in an interval $I \subseteq \mathbb{R}$ and let $a \in I$ be a critical point of f ($f'(a) = 0$).*

- *If $f'(x) > 0$ on an open interval extending left from a and $f'(x) < 0$ on an open interval extending right from a, then f has a relative maximum at a.*
- *If $f'(x) < 0$ on an open interval extending left from a and $f'(x) > 0$ on an open interval extending right from a, then f has a relative minimum at a.*
- *If $f'(x)$ has the same sign on both an open interval extending left from a and an open interval extending right from a, then f has an inflection point at a.*

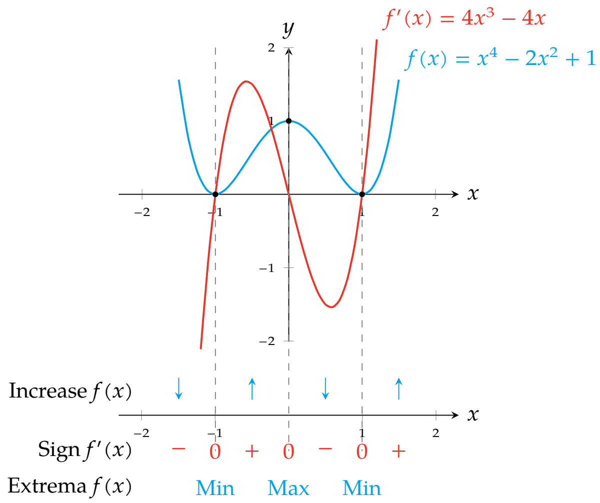
Remark *A vanishing derivative is a necessary but not sufficient condition for the function to have a relative extrema at a point.*

Example The function $f(x) = x^3$ has derivative $f'(x) = 3x^2$; it has a critical point at $x = 0$. However it does not have a relative extrema at that point, but an inflection point.

Analysis of functions: relative extrema

Example

Consider again the function $f(x) = x^4 - 2x^2 + 1$ and let's analyze its relative extrema now. Its first derivative is $f'(x) = 4x^3 - 4x$.



Analysis of functions: concavity

The concavity of a function can be determined by de second derivative.

Theorem 20. *Let $f(x)$ be a function with second derivative in an interval $I \subseteq \mathbb{R}$.*

- *If $\forall x \in I\ f''(x) > 0$ then f is concave up (convex) on I.*
- *If $\forall x \in I\ f''(x) < 0$ then f is concave down (concave) on I.*

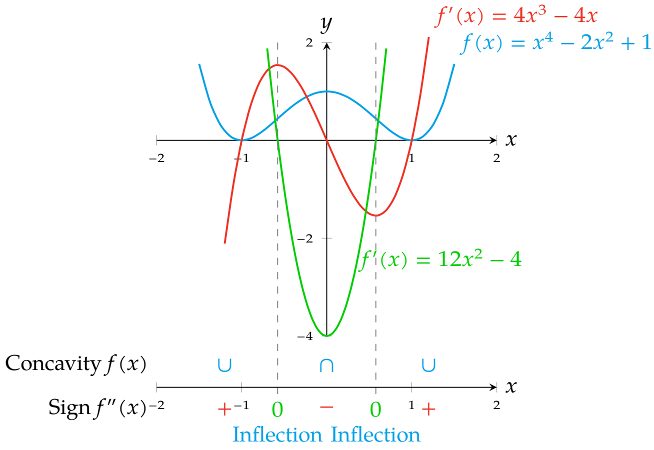
Example The function $f(x) = x^2$ has second derivative $f''(x) = 2 > 0\ \forall x \in \mathbb{R}$, so it is concave up in all $\mathbb{R}$.

Remark *A function can be concave up or down and not have second derivative.*

Analysis of functions: concavity

Example

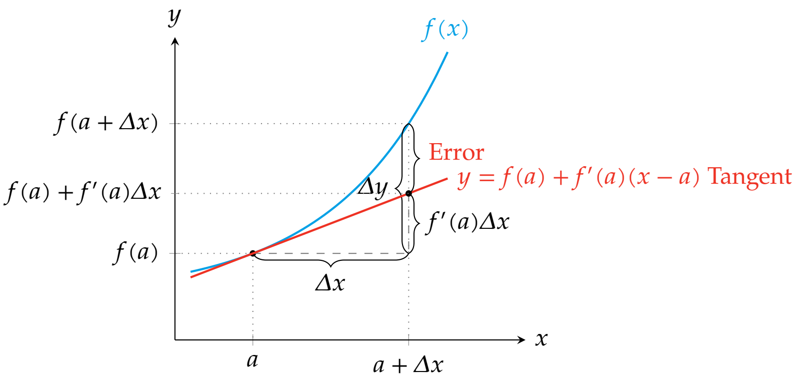
Let us analyze the concavity of the same function of previous examples $f(x) = x^4 - 2x^2 + 1$. Its second derivative is $f''(x) = 12x^2 - 4$.



2.4 Function approximation

Approximating a function with the derivative

The tangent line to the graph of a function $f(x)$ at $x = a$ can be used to approximate f in a neighbourhood of a.



Thus, the increment of a function $f(x)$ in an interval $[a, a+\Delta x]$ can be approximated multiplying the derivative of f at a by the increment of x

$$\Delta y \approx f'(a)\Delta x$$

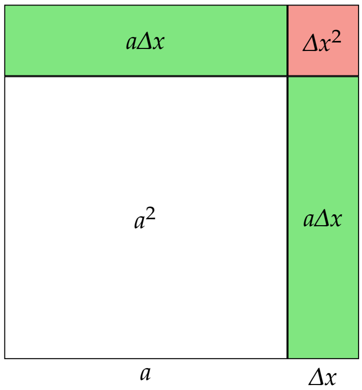
Approximating a function with the derivative

Example of the area of a square

In the previous example of the function $y = x^2$ that measures the area of a metallic square of side x, if the side of the square is a and we increment it by a quantity Δx, then the increment on the area will be approximately

$$\Delta y \approx f'(a)\Delta x = 2a\Delta x.$$

In the figure below we can see that the error of this approximation is Δx^2, which is smaller than Δx when Δx tends to 0.



Approximating a function by a polynomial

Another useful application of the derivative is the approximation of functions by polynomials. Polynomials are functions easy to calculate (sums and products) with very good properties:

- Defined in all the real numbers.
- Continuous.
- Differentiable of all orders with continuous derivatives.

Goal
Approximate a function $f(x)$ by a polynomial $p(x)$ near a point $x = a$.

Approximating a function by a polynomial of order 0

A polynomial of degree 0 has equation

$$p(x) = c_0,$$

where c_0 is a constant.

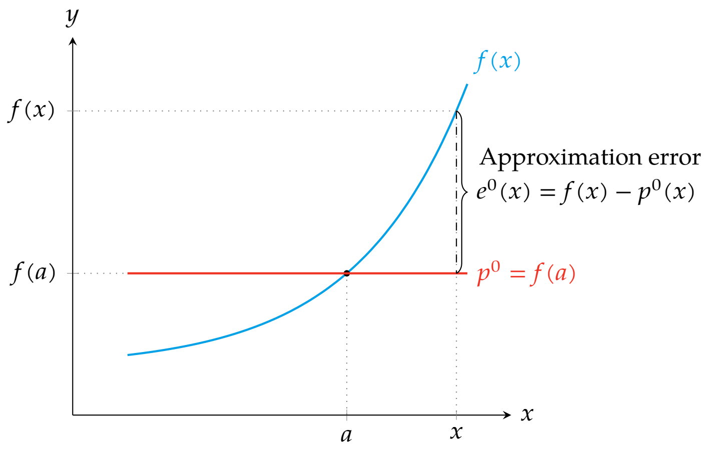
As the polynomial should coincide with the function f at a, it must satisfy

$$p(a) = c_0 = f(a).$$

Therefore, the polynomial of degree 0 that best approximates f near a is

$$p(x) = f(a).$$

Approximating a function by a polynomial of order 0



Approximating a function by a polynomial of order 1

A polynomial of degree 1 has equation

$$p(x) = c_0 + c_1 x,$$

but it can also be written as

$$p(x) = c_0 + c_1(x - a).$$

Among all the polynomials of degree 1, the one that best approximates f near a is that which meets the following conditions

1. p and f coincide at a: $p(a) = f(a)$,
2. p and f have the same rate of change at a: $p'(a) = f'(a)$.

The last condition guarantees that p and f have approximately the same tendency, but it requires the function f to be differentiable at a.

The tangent line: Best approximating polynomial of order 1

Imposing the previous conditions we have

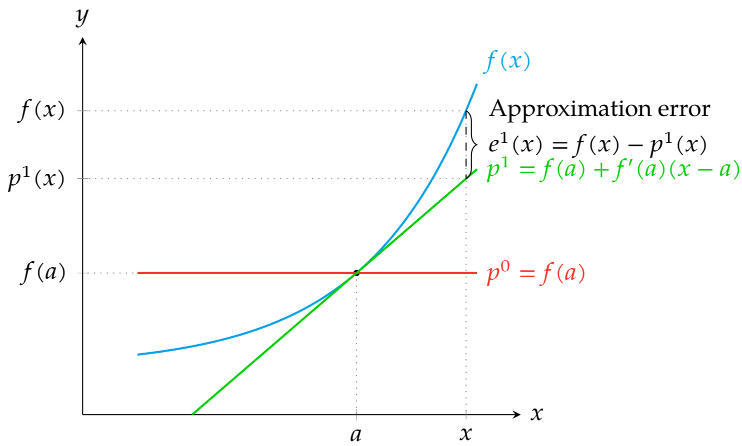
1. $p(x) = c_0 + c_1(x - a) \Rightarrow p(a) = c_0 + c_1(a - a) = c_0 = f(a)$,
2. $p'(x) = c_1 \Rightarrow p'(a) = c_1 = f'(a)$.

Therefore, the polynomial of degree 1 that best approximates f near a is

$$p(x) = f(a) + f'(a)(x - a),$$

which turns out to be the tangent line to f at $(a, f(a))$.

Approximating a function by a polynomial of order 1



Approximating a function by a polynomial of order 2

A polynomial of degree 2 is a parabola with equation

$$p(x) = c_0 + c_1 x + c_2 x^2,$$

but it can also be written as

$$p(x) = c_0 + c_1(x-a) + c_2(x-a)^2.$$

Among all the polynomials of degree 2, the one that best approximate $f(x)$ near a is that which meets the following conditions

1. p and f coincide at a: $p(a) = f(a)$,
2. p and f have the same rate of change at a: $p'(a) = f'(a)$.
3. p and f have the same concavity at a: $p''(a) = f''(a)$.

The last condition requires the function f to be differentiable twice at a.

Best approximating polynomial of order 2

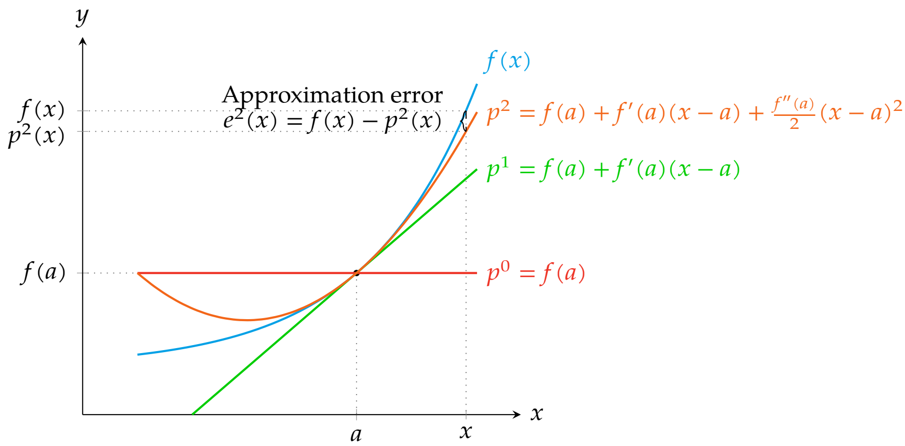
Imposing the previous conditions we have

1. $p(x) = c_0 + c_1(x-a) \Rightarrow p(a) = c_0 + c_1(a-a) = c_0 = f(a)$,
2. $p'(x) = c_1 \Rightarrow p'(a) = c_1 = f'(a)$.
3. $p''(x) = 2c_2 \Rightarrow p''(a) = 2c_2 = f''(a) \Rightarrow c_2 = \frac{f''(a)}{2}$.

Therefore, the polynomial of degree 2 that best approximates f near a is

$$p(x) = f(a) + f'(a)(x-a) + \frac{f''(a)}{2}(x-a)^2.$$

Approximating a function by a polynomial of order 2



Approximating a function by a polynomial of order n

A polynomial of degree n has equation

$$p(x) = c_0 + c_1x + c_2x^2 + \cdots + c_nx^n,$$

but it can also be written as

$$p(x) = c_0 + c_1(x-a) + c_2(x-a)^2 + \cdots + c_n(x-a)^n.$$

Among all the polynomials of degree n, the one that best approximate $f(x)$ near a is that which meets the following $n+1$ conditions

1. $p(a) = f(a)$,
2. $p'(a) = f'(a)$,
3. $p''(a) = f''(a)$,

   ...

n+1. $p^{(n)}(a) = f^{(n)}(a)$.

Observe that these conditions require the function f to be differentiable n times at a.

Coefficients calculation for the best approximating polynomial of order n

The successive derivatives of p are

$$\begin{aligned}
p(x) &= c_0 + c_1(x-a) + c_2(x-a)^2 + \cdots + c_n(x-a)^n,\\
p'(x) &= c_1 + 2c_2(x-a) + \cdots + nc_n(x-a)^{n-1},\\
p''(x) &= 2c_2 + \cdots + n(n-1)c_n(x-a)^{n-2},\\
&\vdots\\
p^{(n)}(x) &= n(n-1)(n-2)\cdots 1c_n = n!\,c_n.
\end{aligned}$$

Imposing the previous conditions we have

1. $p(a) = c_0 + c_1(a-a) + c_2(a-a)^2 + \cdots + c_n(a-a)^n = c_0 = f(a)$,
2. $p'(a) = c_1 + 2c_2(a-a) + \cdots + nc_n(a-a)^{n-1} = c_1 = f'(a)$,
3. $p''(a) = 2c_2 + \cdots + n(n-1)c_n(a-a)^{n-2} = 2c_2 = f''(a) \Rightarrow c_2 = f''(a)/2$,

   ...

n+1. $p^{(n)}(a) = n!\,c_n = f^{(n)}(a) = c_n = \frac{f^{(n)}(a)}{n!}$.

Taylor polynomial of order n

Definition 21 (Taylor polynomial)**.** Given a function $f(x)$ differentiable n times at a, the *Taylor polynomial* of order n of f at a is the polynomial with equation

$$\begin{aligned} p_{f,a}^n(x) &= f(a) + f'(a)(x-a) + \frac{f''(a)}{2}(x-a)^2 + \cdots + \frac{f^{(n)}(a)}{n!}(x-a)^n = \\ &= \sum_{i=0}^{n} \frac{f^{(i)}(a)}{i!}(x-a)^i. \end{aligned}$$

The Taylor polynomial of order n of f at a is the nth degree polynomial that best approximates f near a, as is the only one that meets the previous conditions.

Taylor polynomial calculation

Example

Let us approximate the function $f(x) = \log x$ near the value 1 by a polynomial of order 3.

The equation of the Taylor polynomial of order 3 of f at $a = 1$ is

$$p_{f,1}^3(x) = f(1) + f'(1)(x-1) + \frac{f''(1)}{2}(x-1)^2 + \frac{f'''(1)}{3!}(x-1)^3.$$

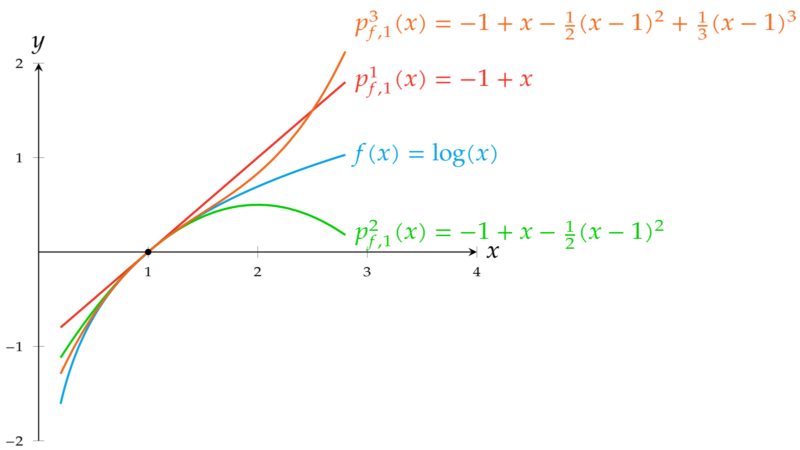
The derivatives of f at 1 up to order 3 are

$$\begin{array}{ll} f(x) = \log x & f(1) = \log 1 = 0, \\ f'(x) = 1/x & f'(1) = 1/1 = 1, \\ f''(x) = -1/x^2 & f''(1) = -1/1^2 = -1, \\ f'''(x) = 2/x^3 & f'''(1) = 2/1^3 = 2. \end{array}$$

And substituting into the polynomial equation we get

$$p_{f,1}^3(x) = 0 + 1(x-1) + \frac{-1}{2}(x-1)^2 + \frac{2}{3!}(x-1)^3 = \frac{2}{3}x^3 - \frac{3}{2}x^2 + 3x - \frac{11}{6}.$$

Taylor polynomials of the logarithmic function



Maclaurin polynomial of order n

The Taylor polynomial equation has a simpler form when the polynomial is calculated at 0. This special case of Taylor polynomial at 0 is known as the *Maclaurin polynomial*.

Definition 22 (Maclaurin polynomial)**.** Given a function $f(x)$ differentiable n times at 0, the *Maclaurin polynomial* of order n of f is the polynomial with equation

$$\begin{aligned} p_{f,0}^n(x) &= f(0) + f'(0)x + \frac{f''(0)}{2}x^2 + \cdots + \frac{f^{(n)}(0)}{n!}x^n = \\ &= \sum_{i=0}^{n} \frac{f^{(i)}(0)}{i!}x^i. \end{aligned}$$

Maclaurin polynomial calculation

Example

Let us approximate the function $f(x) = \sin x$ near the value 0 by a polynomial of order 3.

The Maclaurin polynomial equation of order 3 of f is

$$p_{f,0}^3(x) = f(0) + f'(0)x + \frac{f''(0)}{2}x^2 + \frac{f'''(0)}{3!}x^3.$$

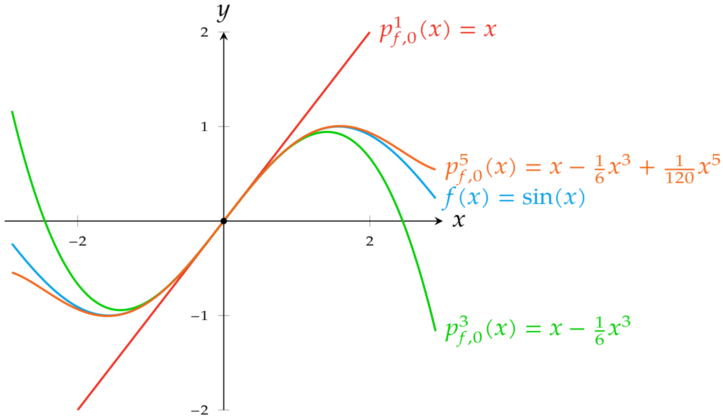
The derivatives of f at 0 up to order 3 are

$$\begin{aligned} f(x) &= \sin x & f(0) &= \sin 0 = 0, \\ f'(x) &= \cos x & f'(0) &= \cos 0 = 1, \\ f''(x) &= -\sin x & f''(0) &= -\sin 0 = 0, \\ f'''(x) &= -\cos x & f'''(0) &= -\cos 0 = -1. \end{aligned}$$

And substituting into the polynomial equation we get

$$p_{f,0}^3(x) = 0 + 1 \cdot x + \frac{0}{2}x^2 + \frac{-1}{3!}x^3 = x - \frac{x^3}{6}.$$

Maclaurin polynomial of the sine function



Maclaurin polynomials of elementary functions

$f(x)$	$p_{f,0}^n(x)$
$\sin x$	$x - \dfrac{x^3}{3!} + \dfrac{x^5}{5!} - \cdots + (-1)^k \dfrac{x^{2k-1}}{(2k-1)!}$ if $n = 2k$ or $n = 2k-1$
$\cos x$	$1 - \dfrac{x^2}{2!} + \dfrac{x^4}{4!} - \cdots + (-1)^k \dfrac{x^{2k}}{(2k)!}$ if $n = 2k$ or $n = 2k+1$
$\arctan x$	$x - \dfrac{x^3}{3} + \dfrac{x^5}{5} - \cdots + (-1)^k \dfrac{x^{2k-1}}{(2k-1)}$ if $n = 2k$ or $n = 2k-1$
e^x	$1 + x + \dfrac{x^2}{2!} + \dfrac{x^3}{3!} + \cdots + \dfrac{x^n}{n!}$
$\log(1+x)$	$x - \dfrac{x^2}{2} + \dfrac{x^3}{3} - \cdots + (-1)^{n-1}\dfrac{x^n}{n}$

Taylor remainder and Taylor formula

Taylor polynomials allow to approximate a function in a neighborhood of a value a, but most of the times there is an error in the approximation.

Definition 23 (Taylor remainder)**.** Given a function $f(x)$ and its Taylor polynomial of order n at a, $p_{f,a}^n(x)$, the *Taylor remainder* of order n of f at a is the difference between the function and the polynomial,

$$r_{f,a}^n(x) = f(x) - p_{f,a}^n(x).$$

The Taylor remainder measures the error in the approximation of $f(x)$ by the Taylor polynomial and allow us to express the function as the Taylor polynomial plus the Taylor remainder

$$f(x) = p_{f,a}^n(x) + r_{f,a}^n(x).$$

This expression is known as the *Taylor formula* of order n or f at a.

It can be proved that

$$\lim_{h\to 0} \frac{r_{f,a}^n(a+h)}{h^n} = 0,$$

which means that the remainder $r_{f,a}^n(a+h)$ is much smaller than h^n.

3 Integrals

Integrals

Contents

3.1 Antiderivative of a function

Antiderivative of a function

Definition 24 (Antiderivative of a function)**.** Given a function $f(x)$, the function $F(X)$ is an *antiderivative* or *primitive function* of f if it satisfies that $F'(x) = f(x)\ \forall x \in \text{Dom}(f)$.

Example The function $F(x) = x^2$ is an antiderivative of the function $f(x) = 2x$ as $F'(x) = 2x$ on $\mathbb{R}$.

Roughly speaking, the calculus of antiderivatives is the reverse process of differentiation, and that is the reason for the name of antiderivative.

Indefinite integral of a function

As two functions that differs in a constant term have the same derivative, if $F(x)$ is an antiderivative of $f(x)$, so will be any function of the form $F(x) + k\ \forall k \in \mathbb{R}$. This means that, when a function has an antiderivative, it has an infinite number of antiderivatives.

Definition 25 (Indefinite integral)**.** The *indefinite integral* of a function $f(x)$ is the set of all its antiderivatives; it is denoted by

$$\int f(x)\,dx = F(x) + C$$

where $F(x)$ is an antiderivative of $f(x)$ and C is a constant.

Example The indefinite integral of the function $f(x) = 2x$ is

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

Interpretation of the integral

We have seen in a previous chapter that the derivative of a function is the instantaneous rate of change of the function. Thus, if we know the instantaneous rate of change of the function at any point, we can compute the change of the function.

Example What is the space covered by an free falling object?

Assume that the only force acting upon an object drop is gravity, with an acceleration of 9.8 m/s^2. As acceleration is the the rate of change of the speed, that is constant at any moment, the antiderivative is the speed of the object,

$$v(t) = 9.8t \text{ m/s}$$

And as the speed is the rate of change of the space covered by object during the fall, the antiderivative of the speed is the space covered by the object,

$$s(t) = \int 9.8t\,dt = 9,8\frac{t^2}{2}.$$

Thus, for instance, after 2 seconds, the covered space is $s(2) = 9.8\frac{2^2}{2} = 19.6$ m.

Linearity of integration

Given two integrable functions $f(x)$ and $g(x)$ and a constant $k \in \mathbb{R}$, it is satisfied that

1. $\int (f(x) + g(x))\,dx = \int f(x)\,dx + \int g(x)\,dx$,
2. $\int kf(x)\,dx = k \int f(x)\,dx$.

This means that the integral of any linear combination of functions equals the same linear combination of the integrals of the functions.

3.2 Elementary integrals

Elementary integrals

- $\int a\,dx = ax + C$, with a constant.
- $\int x^n\,dx = \dfrac{x^{n+1}}{n+1} + C \quad$ if $n \neq -1$.
- $\int \dfrac{1}{x}\,dx = \ln|x| + C$.
- $\int e^x\,dx = e^x + C$.
- $\int a^x\,dx = \dfrac{a^x}{\ln a} + C$.
- $\int \sin x\,dx = -\cos x + C$.
- $\int \cos x\,dx = \sin x + C$.
- $\int \tan x\,dx = \ln|\sec x| + C$.
- $\int \sec x\,dx = \ln|\sec x + \tan x| + C$.
- $\int \csc x\,dx = \ln|\csc x - \cot x| + C$.
- $\int \cot x\,dx = \ln|\sin x| + C$.
- $\int \sec^2 x\,dx = \tan x + C$.
- $\int \csc^2 x\,dx = -\cot x + C$.
- $\int \sec x \tan x\,dx = \sec x + C$.
- $\int \csc x \cot x\,dx = -\csc x + C$.
- $\int \dfrac{dx}{\sqrt{a^2 - x^2}} = \arcsin \dfrac{x}{a} + C$.
- $\int \dfrac{dx}{a^2 + x^2} = \dfrac{1}{a} \arctan \dfrac{x}{a} + C$.
- $\int \dfrac{dx}{x\sqrt{x^2 - a^2}} = \dfrac{1}{a} \sec^{-1} \dfrac{x}{a} + C$.
- $\int \dfrac{dx}{a^2 - x^2} = \dfrac{1}{2a} \ln\left|\dfrac{x+a}{x-a}\right| + C$.

3.3 Techniques of integration

Techniques of integration

Unfortunately, unlike differential calculus, the is not a foolproof procedure to compute the antiderivative of a function. However, there are some techniques that allow to integrate some types of functions. The most common methods of integration are

- Integration by parts
- Integration by reduction
- Integration by substitution
- Integration of rational functions
- Integration of trigonometric functions

Integration by parts

Given two differentiable functions $u(x)$ and $v(x)$, from the rule for differentiating a product we can get

$$\int u(x)v'(x)\,dx = u(x)v(x) - \int u'(x)v(x)\,dx,$$

or, writing $u'(x)dx = du$ and $v'(x)dx = dv$,

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

To apply this method we have to choose the functions u and dv in a way so that the final integral is easier to compute than the original one.

Example To integrate $\int x \sin x\,dx$ we have to choose $u = x$ and $dv = \sin x\,dx$, so $du = dx$ and $v = -\cos x$, getting

$$\int x \sin x\,dx = -x\cos x - \int (-\cos x)\,dx = -x\cos x + \sin x.$$

If we had chosen $u = \sin x$ and $dv = x\,dx$, we would have got a more difficult integral.

Integration by reduction

The reduction technique is used when we have to apply the integration by parts several times.

If we want to compute the antiderivative I_n that depends on a natural number n, the reduction formulas allow us to write I_n as a function of I_{n-1}, that is, we have a recurrent relation

$$I_n = f(I_{n-1}, x, n)$$

so by computing the first antiderivative I_0 we should be able to compute the others.

Example To compute $I_n = \int x^n e^x\,dx$ applying integration by parts, we have to choose $u = x^n$ y $dv = e^x\,dx$, so $du = nx^{n-1}\,dx$ and $v = e^x$, getting

$$I_n = \int x^n e^x\,dx = x^n e^x - n\int x^{n-1}e^x\,dx = x^n e^x - nI_{n-1}.$$

Thus, for instance, for $n = 3$ we have

$$\begin{aligned}\int x^3 e^x\,dx = I_3 = x^3e^x - 3I_2 = x^3e^x - 3(x^2e^x - 2I_1) = x^3e^x - 3(x^2e^x - (xe^x - I_0) = \\ = x^3e^x - 3(x^2e^x - (xe^x - e^x) = e^x(x^3 - 3x^2 + 6x - 6).\end{aligned}$$

Integration by substitution

From the chain rule for differentiating the composition of two functions

$$f(g(x))' = f'(g(x))g'(x),$$

we can make a variable change $u = g(x)$, so $du = g'(x)dx$, and get

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

Example To compute the integral of $\int \frac{1}{x\log x}\,dx$ we can make the substitution $u = \log x$, so $du = \frac{1}{x}dx$, and we have

$$\int \frac{dx}{x\log x} = \int \frac{1}{\log x}\frac{1}{x}\,dx = \int \frac{1}{u}\,du = \log|u| + C.$$

Finally, undoing the substitution we get

$$\int \frac{1}{x\log x}\,dx = \log|\log x| + C.$$

Integration of rational functions

Partial fractions decomposition

A rational function can be written as the sum of a polynomial (with an immediate antiderivative) plus a proper rational function, that is, a rational function in which the degree of the numerator is less than the degree of the denominator.

On the other hand, depending of the factorization of the denominator, a proper rational function can be expressed as a sum of simpler fractions of the following types

- Denominator with a single linear factor: $\dfrac{A}{(x-a)}$
- Denominator with a linear factor repeated n times : $\dfrac{A}{(x-a)^n}$
- Denominator with a single quadratic factor: $\dfrac{Ax+B}{x^2+cx+d}$
- Denominator with a quadratic factor repeated n times: $\dfrac{Ax+B}{(x^2+cx+d)^n}$

Integration of rational functions

Antiderivatives of partial fractions

Using the linearity of integration, we can compute the antiderivative of a rational function from the antiderivative of these partial fractions

$$\int \frac{A}{x-a}\,dx = A\log|x-a| + C,$$

$$\int \frac{A}{(x-a)^n}\,dx = \frac{-A}{(n-1)(x-a)^{n-1}} + C \text{ si } n \neq 1.$$

$$\int \frac{Ax+B}{x^2+cx+d} = \frac{A}{2}\log|x^2+cx+d| + \frac{2B-Ac}{\sqrt{4d-c^2}}\arctan\frac{2x+c}{\sqrt{4d-c^2}} + C.$$

Integration of rational functions

Example of denominator with linear factors

Consider the function $f(x) = \dfrac{x^2+3x-5}{x^3-3x+2}$.

The factorization of the denominator is $x^3-3x+2 = (x-1)^2(x+2)$; it has a single linear factor $(x+2)$ and a linear factor $(x-1)$, repeated two times. In this case the decomposition in partial fractions is:

$$\begin{aligned}\frac{x^2+3x-5}{x^3-3x+2} &= \frac{A}{x-1} + \frac{B}{(x-1)^2} + \frac{C}{x+2} = \\ &= \frac{A(x-1)(x+2)+B(x+2)+C(x-1)^2}{(x-1)^2(x+2)} = \\ &= \frac{(A+C)x^2+(A+B-2C)x+(-2A+2B+C)}{(x-1)^2(x+2)}\end{aligned}$$

and equating the numerators we get $A = 16/9$, $B = -1/3$ and $C = -7/9$, so

$$\frac{x^2+3x-5}{x^3-3x+2} = \frac{16/9}{x-1} + \frac{-1/3}{(x-1)^2} + \frac{-7/9}{x+2}.$$

Finally, integrating each partial fraction we have

$$\begin{aligned}\int \frac{x^2+3x-5}{x^3-3x+2}\,dx &= \int \frac{16/9}{x-1}\,dx + \int \frac{-1/3}{(x-1)^2}\,dx + \int \frac{-7/9}{x+2}\,dx = \\ &= \frac{16}{9}\int \frac{1}{x-1}\,dx - \frac{1}{3}\int (x-1)^{-2}\,dx - \frac{7}{9}\int \frac{1}{x+2}\,dx = \\ &= \frac{16}{9}\ln|x-1| + \frac{1}{3(x-1)} - \frac{7}{9}\ln|x+2| + C.\end{aligned}$$

Integration of rational functions

Example of denominator with simple quadratic factors

Consider the function $f(x) = \dfrac{x+1}{x^2-4x+8}$.

In this case the denominator cannot be factorised as a product of linear factors, but we can write

$$x^2-4x+8 = (x-2)^2+4,$$

so

$$\begin{aligned}\int \frac{x+1}{x^2-4x+8}\,dx &= \int \frac{x-2+3}{(x-2)^2+4}\,dx = \\ &= \int \frac{x-2}{(x-2)^2+4}\,dx + \int \frac{3}{(x-2)^2+4}\,dx = \\ &= \frac{1}{2}\ln|(x-2)^2+4| + \frac{3}{2}\arctan\left(\frac{x-2}{2}\right) + C.\end{aligned}$$

Integration of trigonometric functions

Integration of $\sin^n x\cos^m x$ *with* n *or* m *odd*

If $f(x) = \sin^n x\cos^m x$ with n or m odd, then we can make the substitution $t = \sin x$ or $t = \cos x$, to convert the function into a polynomial.

Example

$$\int \sin^2 x \cos^3 x \, dx = \int \sin^2 x \cos^2 x \cos x \, dx = \int \sin^2 x (1 - \sin^2 x) \cos x \, dx,$$

and making the substitution $t = \sin x$, so $dt = \cos x dx$, we have

$$\int \sin^2 x (1 - \sin^2 x) \cos x \, dx = \int t^2 (1 - t^2) \, dt = \int t^2 - t^4 \, dt = \frac{t^3}{3} - \frac{t^5}{5} + C.$$

Finally, undoing the substitution we have

$$\int \sin^2 x \cos^3 x \, dx = \frac{\sin^3 x}{3} - \frac{\sin^5 x}{5} + C.$$

Integration of trigonometric functions

Integration of $\sin^n x \cos^m x$ *with* n *and* m *even*

If $f(x) = \sin^n x \cos^m x$ with n and m even, then we can make the following substitutions to simplify the integration

$$\begin{aligned} \sin^2 x &= \frac{1}{2}(1 - \cos(2x)) \\ \cos^2 x &= \frac{1}{2}(1 + \cos(2x)) \\ \sin x \cos x &= \frac{1}{2} \sin(2x) \end{aligned}$$

Example

$$\begin{aligned} \int \sin^2 x \cos^4 x \, dx = \int (\sin x \cos x)^2 \cos^2 x \, dx = \int \left(\frac{1}{2} \sin(2x)\right)^2 \frac{1}{2}(1 + \cos(2x)) \, dx = \\ = \frac{1}{8} \int \sin^2(2x) \, dx + \frac{1}{8} \int \sin^2(2x) \cos(2x) \, dx, \end{aligned}$$

the first integral is of the same type and the second one of the previous type, so

$$\int \sin^2 x \cos^4 x \, dx = \frac{1}{32} x - \frac{1}{32} \sin(2x) + \frac{1}{24} \sin^3(2x).$$

Integration of trigonometric functions

Products of sines and cosines

The equalities

$$\begin{aligned} \sin x \cos y &= \frac{1}{2}(\sin(x - y) + \sin(x + y)) \\ \sin x \sin y &= \frac{1}{2}(\cos(x - y) - \cos(x + y)) \\ \cos x \cos y &= \frac{1}{2}(\cos(x - y) + \cos(x + y)) \end{aligned}$$

transform products in sums, simplifying the integration

Example

$$\begin{aligned}\int \sin x \cos 2x \, dx &= \int \frac{1}{2}(\sin(x-2x) + \sin(x+2x))\, dx = \\ &= \frac{1}{2}\int \sin(-x)\, dx + \frac{1}{2}\int \sin 3x \, dx = \\ &= \frac{1}{2}\cos(-x) - \frac{1}{6}\cos 3x + C.\end{aligned}$$

Integration of trigonometric functions

Rational functions of sines and cosines

If $f(x,y)$ is a rational function then the function $f(\sin x, \cos x)$ can be transformed in an rational function of t with the following substitutions

$$\tan\frac{x}{2} = t \quad \sin x = \frac{2t}{1+t^2} \quad \cos x = \frac{1-t^2}{1+t^2} \quad dx = \frac{2}{1+t^2}dt.$$

Example

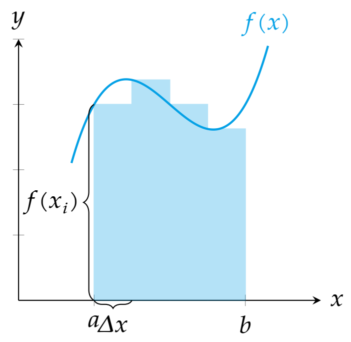
$$\int \frac{1}{\sin x}\, dx = \int \frac{1}{\frac{2t}{1+t^2}} \frac{2}{1+t^2}\, dt = \int \frac{1}{t}\, dt = \log|t| + C = \log|\tan\frac{x}{2}| + C.$$

3.4 Definite integral

Definite integral

Definition 26 (Definite integral)**.** Let $f(x)$ be a function which is continuous on an interval $[a,b]$. Divide this interval into n subintervals of equal width Δx and choose an arbitrary point x_i from each interval. The *definite integral* of f from a to b is defined to be the limit

$$\int_a^b f(x)\, dx = \lim_{n\to\infty} \sum_{i=1}^{n} f(x_i)\Delta x.$$



Definite integral

Theorem 27 (First fundamental theorem of Calculus)**.** *If $f(x)$ is continuous on the interval $[a,b]$ and $F(x)$ is an antiderivative of f on $[a,b]$, then*

$$\int_a^b f(x)\, dx = F(b) - F(a)$$

Example. Given the function $f(x) = x^2$, we have

$$\int_1^2 x^2\,dx = \left[\frac{x^3}{3}\right]_1^2 = \frac{2^3}{3} - \frac{1^3}{3} = \frac{7}{3}.$$

Properties of the definite integral

Given two functions $f(x)$ and $g(x)$ integrable on $[a,b]$ and $k \in \mathbb{R}$ the following properties are satisfied:

- $\int_a^b (f(x) + g(x))\,dx = \int_a^b f(x)\,dx + \int_a^b g(x)\,dx$ (linearity)
- $\int_a^b kf(x)\,dx = k\int_a^b f(x)\,dx$ (linearity)
- $\int_a^b f(x)\,dx \leq \int_a^b g(x)\,dx$ si $f(x) \leq g(x)$ $\forall x \in [a,b]$ (monotony)
- $\int_a^b f(x)\,dx = \int_a^c f(x)\,dx + \int_c^b f(x)\,dx$ for any $c \in (a,b)$ (additivity)
- $\int_a^b f(x)\,dx = -\int_b^a f(x)\,dx$

3.5 Area calculation

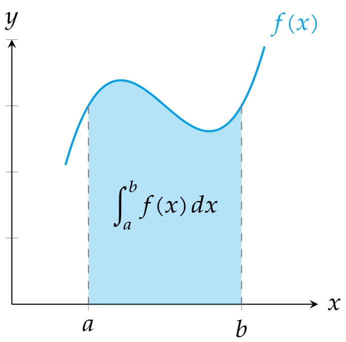
Area calculation

Area between a positive function and the x axis

If $f(x)$ is an integrable function on the interval $[a,b]$ and $f(x) \geq 0$ $\forall x \in [a,b]$, then the definite integral

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

measures the area between the graph of f and the x axis on the interval $[a,b]$.

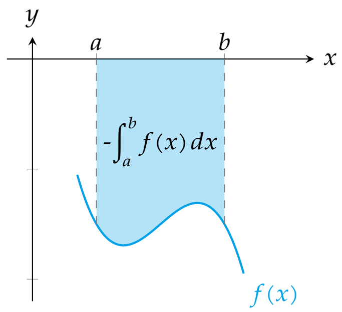


Area calculation

Area between a negative function and the x axis

If $f(x)$ is an integrable function on the interval $[a,b]$ and $f(x) \leq 0$ $\forall x \in [a,b]$, then the area between the graph of f and the x axis on the interval $[a,b]$ is

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

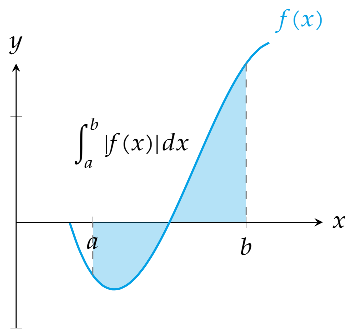


Area calculation

Area between a function and the x axis

In general, if $f(x)$ is an integrable function on the interval $[a,b]$, no matter the sign of f on $[a,b]$, the area between the graph of f and the x axis on the interval $[a,b]$ is

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

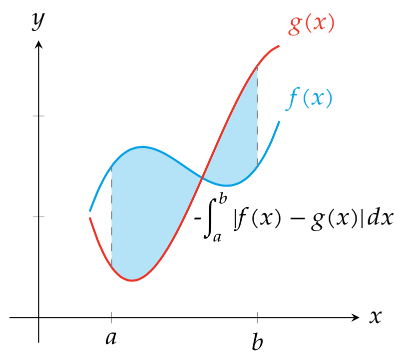


Area calculation

Area between two functions

If $f(x)$ and $g(x)$ are two integrable functions on the interval $[a,b]$, then the area between the graph of f and g on the interval $[a,b]$ is

$$\int_a^b |f(x)-g(x)|\,dx.$$



4 Ordinary Differential Equations

Ordinary Differential Equations

Contents

4.1 Ordinary Differential Equations

Ordinary Differential Equation

Often in Physics, Chemistry, Biology, Geometry, etc they arise equations that relate a function with its derivative or successive derivatives.

Definition 28 (Ordinary differential equation)**.** An *ordinary differential equation* (O.D.E.) is a equation that relates an independent variable x, a function $y(x)$ that depends on x, and the successive derivatives of y, $y', y'', \dots, y^{(n)}$; it can be written as

$$F(x, y, y', y'', \dots, y^{(n)}) = 0.$$

The *order* of a differential equation is the greatest order of the derivatives in the equation.

Thus, for instance, the equation $y''' + sen(x)y' = 2x$ is a differential equation of order 3.

Deducing a differential equation

To deduce a differential equation that explains a natural phenomenon is essential to understand what is a derivative and how to interpret it.

Example One of the Newton's law of cooling states

> *"The rate of change of the temperature of a body in a surrounding medium is proportional to the difference between the temperature of the body T and the temperature of the medium T_a."*

The rate of change of change of the temperature is the derivative of temperature with respect to time dT/dt. Thus, Newton's law of cooling can be explained by the differential equation

$$\frac{dT}{dt} = k(T - T_a),$$

where k is a proportionality constant.

Solution of an ordinary differential equation

Definition 29 (Solution of an ordinary differential equation)**.** Given an ordinary differential equation $F(x, y, y', y'', \dots, y^{(n)}) = 0$, the function $y = f(x)$ is a *solution of the ordinary differential equation* if it satisfies the equation, that is, if

$$F(x, f(x), f'(x), f''(x), \dots, f^{(n}(x)) = 0.$$

The graph of a solution of the ordinary differential equation is known as *integral curve*.

Solving an ordinary differential equations consists in finding all its solutions in a given domain. For that is required the integral calculus.

The same manner than the indefinite integral is a family of antiderivatives, that differ in a constant term, after integrating an ordinary differential equation we get a family of solutions that differ in a constant. Giving values to this constant we can get particular solutions.

General solution of an ordinary differential equation

Definition 30 (General solution of an ordinary differential equation)**.** Given an ordinary differential equation $F(x, y, y', y'', \dots, y^{(n)}) = 0$ of order n, the *general solution* of the differential equation is a family of functions

$$y = f(x, C_1, \dots, C_n),$$

depending on n constants, such that for any value of $C_1, \dots, C_n$ we get a solution of the differential equation.

For every value of the constant we get *particular solution* of the differential equation. Thus, when a differential equation can be solved, it has infinite solutions.

Geometrically, the general solution of a differential equation correspond to a family of integral curves of the differential equation.

Often, it is common to impose conditions to the solutions of a differential equation to reduce the number of solutions. In many cases, these conditions allow to determine the values of the constants in the general solution to get a particular solution.

First order differential equations

In this chapter we are going to study first order differential equations

$$F(x, y, y') = 0.$$

The general solution of a first order differential equation is

$$y = f(x, C),$$

so to get a particular solution from the general one, is enough to set the value of the constant C, and for that we only need to impose an initial condition.

Definition 31 (Initial value problem)**.** The group consisting of a first order differential equation and an initial condition is known as *initial value problem*:

$$\begin{cases} F(x, y, y') = 0, & \text{First order differential equation;} \\ y(x_0) = y_0, & \text{Initial condition.} \end{cases}$$

Solving an initial value problem consists in finding a solution of the first order differential equation that satisfies the initial condition.

Solving an initial value problem

Example

Recall the first order differential equation of the Newton's law of cooling,

$$\frac{dT}{dt} = k(T - T_a),$$

where T is the temperature of the body and T_a is the temperature of the surrounding medium.

It is easy to check that the general solution of this equation is

$$T(t) = Ce^{kt} + T_a.$$

If we impose the initial condition that the temperature of the body at the initial instant is 5 ºC, that is, $T(0) = 5$, we have

$$T(0) = Ce^{k\cdot 0} + T_a = C + T_a = 5,$$

from where we get $C = 5 - T_a$, and this give us the particular solution

$$T(t) = (5 - T_a)e^{kt} + T_a.$$

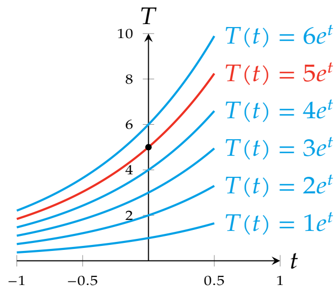
Integral curve of an initial value problem

Example

If we assume in the previous example that the temperature of the surrounding medium is $T_a = 0$ ºC and the cooling constant of the body is $k = 1$, the general solution of the differential equation is

$$T(t) = Ce^t,$$

that is a family of integral curves. From all of them, only the one that passes through the point $(0, 5)$ corresponds to the particular solution of the previous initial value problem.



Existence and uniqueness of solutions

Theorem 32 (Existence and uniqueness of solutions of a first order ODE). *Given an initial value problem*

$$\begin{cases} y' = F(x, y); \\ y(x_0) = y_0; \end{cases}$$

if $F(x, y(x))$ is a function continuous on an open interval around the point (x_0, y_0), then a solution of exist. If, in addition, $\frac{\partial F}{\partial y}$ is continuous in an open interval around (x_0, y_0), the solution is unique.

Although this theorem guarantees the existence and uniqueness of a solution of a first order differential equation, it does not provide a method to compute it. In fact, there is not a general method to solve first order differential equations, but we will see how to solve some types:

- Separable differential equations
- Homogeneous differential equations
- Linear differential equations

4.2 Separable differential equations

Separable differential equations

Definition 33 (Separable differential equation). A *separable differential equation* is a first order differential equation that can be written as

$$y'g(y) = f(x),$$

or what is the same,

$$g(y)dy = f(x)dx,$$

so every variable is on one side of the equation (the variables are separated).

The general solution for a separable differential equation comes after integrating both sides of the equation

$$\int g(y)\, dy = \int f(x)\, dx + C.$$

Solving a separable differential equation

Example

The differential equation of the Newton's law of cooling

$$\frac{dT}{dt} = k(T - T_a),$$

is a separable differential equation since it can be written as

$$\frac{1}{T - T_a} dT = k\,dt.$$

Integrating both sides of the equation we have

$$\int \frac{1}{T - T_a}\,dT = \int k\,dt \Leftrightarrow \log(T - T_a) = kt + C,$$

and solving for T we get the general solution of the equation

$$T(t) = e^{kt+C} + T_a = e^C e^{kt} + T_a = Ce^{kt} + T_a,$$

rewriting $C = e^C$ as an arbitrary constant.

4.3 Homogeneous differential equations

Homogeneous functions

Definition 34 (Homogeneous function)**.** A function $f(x, y)$ is *homogeneous* of degree n, if it is satisfied

$$f(kx, ky) = k^n f(x, y),$$

for any value $k \in \mathbb{R}$.

In particular, a homogeneous function of degree 0 always satisfies

$$f(kx, ky) = f(x, y).$$

Setting $k = 1/x$ we have

$$f(x, y) = f\left(\frac{1}{x}x, \frac{1}{x}y\right) = f\left(1, \frac{y}{x}\right) = g\left(\frac{y}{x}\right).$$

This way, a homogeneous function of degree 0 always can be written as a function of $u = y/x$:

$$f(x, y) = g\left(\frac{y}{x}\right) = g(u).$$

Homogeneous differential equations

Definition 35 (Homogeneous differential equation)**.** A *homogeneous differential equation* is a first order differential equation that can be written

$$y' = f(x, y),$$

where $f(x, y)$ is a homogeneous function of degree 0.

We can solve a homogeneous differential equation making the substitution

$$u = \frac{y}{x} \Leftrightarrow y = ux,$$

so the equation becomes

$$u'x + u = f(u),$$

that is a separable differential equation.

One solved the separable differential equation, the substitution must be undone.

Solving a homogeneous differential equation

Example

Let us consider the following differential equation

$$4x - 3y + y'(2y - 3x) = 0.$$

Rewriting the equation this way

$$y' = \frac{3y - 4x}{2y - 3x}$$

we can check easily that is a homogeneous differential equation.

To solve this equation we have to do the substitution $y = ux$, and we get

$$u'x + u = \frac{3ux - 4x}{2ux - 3x} = \frac{3u - 4}{2u - 3}$$

that is a separable differential equation.

Separating the variables we have

$$u'x = \frac{3u - 4}{2u - 3} - u = \frac{-2u^2 + 6u - 4}{2u - 3} \Leftrightarrow \frac{2u - 3}{-2u^2 + 6u - 4}\,du = \frac{1}{x}\,dx.$$

Solving a homogeneous differential equation

Example

Now, integrating both sides of the equation we have

$$\int \frac{2u - 3}{-2u^2 + 6u - 4}\,du = \int \frac{1}{x}\,dx \Leftrightarrow -\frac{1}{2}\log|u^2 - 3u + 2| = \log|x| + C \Leftrightarrow$$
$$\Leftrightarrow \log|u^2 - 3u + 2| = -2\log|x| - 2C,$$

then, applying the exponential function both sides and simplifying we get the general solution

$$u^2 - 3u + 2 = e^{-2\log|x| - 2C} = \frac{e^{-2C}}{e^{\log|x|^2}} = \frac{C}{x^2},$$

rewriting the constant $C = e^{-2C}$.

Finally, undoing the initial substitution $u = y/x$, we arrive at the general solution of the homogeneous differential equation

$$\left(\frac{y}{x}\right)^2 - 3\frac{y}{x} + 2 = \frac{C}{x^2} \Leftrightarrow y^2 - 3xy + 2x^2 = C.$$

4.4 Linear differential equations

Linear differential equations

Definition 36 (Linear differential equation)**.** A *linear differential equation* is a first order differential equation that can be written

$$y' + g(x)y = h(x).$$

To solve a linear differential equation we try to write the left side of the equation as the derivative of a product. For that we write both sides by the function $f(x)$,

$$f'(x) = g(x)f(x).$$

Thus, we get

$$\begin{gathered} y'f(x) + g(x)f(x)y = h(x)f(x) \\ \Updownarrow \\ y'f(x) + f'(x)y = h(x)f(x) \\ \Updownarrow \\ \frac{d}{dx}(yf(x)) = h(x)f(x) \end{gathered}$$

Solving a linear differential equation

Integrating both sides of the previous equation we get the solution

$$yf(x) = \int h(x)f(x)\,dx + C.$$

On the other hand, the unique function that satisfies $f'(x) = g(x)f(x)$ is

$$f(x) = e^{\int g(x)\,dx},$$

so, substituting this function in the previous solution we arrive at the solution of the linear differential equation

$$ye^{\int g(x)\,dx} = \int h(x)e^{\int g(x)\,dx}\,dx + C,$$

or what is the same

$$y = e^{-\int g(x)\,dx}\left(\int h(x)e^{\int g(x)\,dx}\,dx + C\right).$$

Solving a linear differential equation

Example

If in the differential equation of the Newton's law of cooling the temperature of the surrounding medium is a function of time $T_a(t)$, then the differential equation

$$\frac{dT}{dt} = k(T - T_a(t)),$$

is a linear differential equation since it can be written as

$$T' - kT = -kT_a(t),$$

where the independent term is $-kT_a(t)$ and de coefficient of T is $-k$.

Substituting in the formula of the general solution of a linear differential equation we have

$$y = e^{-\int -k\,dt}\left(\int -kT_a(t)e^{\int -k\,dt}\,dt + C\right) = e^{kt}\left(-\int kT_a(t)e^{-kt}\,dt + C\right).$$

Solving a linear differential equation

Example

In the particular case that $T_a(t) = t$, and the proportionality constant $k = 1$, the general solution of the linear differential equation is

$$y = e^t \left(-\int te^{-kt}\,dt + C\right) = e^t(e^{-t}(t+1) + C) = Ce^t + t + 1.$$

If, in addition, we know that the temperature of the body at time $t = 0$ is 5 ºC, that is, the initial condition $T(0) = 5$, then we can compute the value of the constant C,

$$y(0) = Ce^0 + 0 + 1 = 5 \Leftrightarrow C + 1 = 5 \Leftrightarrow C = 4,$$

and we get the particular solution

$$y(t) = 4e^t + t + 1.$$