Calculus 1 - 14

Applications of differential calculus

L'Hospital's rule

Theorem (L'Hospital's rule).
Assume that $a \in \overline{\mathbb{R}} = \mathbb{R} \cup \{-\infty, \infty\}$, I is a neighbourhood of a, the functions f and g are differentiable on $I \setminus \{a\}$ and $g(x) \neq 0$, $g'(x) \neq 0$ for all $x \in I \setminus \{a\}$. Assume moreover that

$$\lim_{x \to a} f(x) = \lim_{x \to a} g(x) = 0 \quad \text{or} \quad \lim_{x \to a} |f(x)| = \lim_{x \to a} |g(x)| = \infty.$$

If $\exists \lim_{x \to a} \frac{f'(x)}{g'(x)} = b \in \overline{\mathbb{R}}$ then $\exists \lim_{x \to a} \frac{f(x)}{g(x)} = b$.

Remark. The theorem holds for right-hand and left-hand limits as well.

Proof. We prove it in the case when $a \in \mathbb{R}$ (for right-hand limit).

Assume that $a \in \mathbb{R}$, $\lim_{x \to a+} f(x) = \lim_{x \to a+} g(x) = 0$ and $\exists \lim_{x \to a+} \frac{f'(x)}{g'(x)} = b \in \mathbb{R}$.

Extend the functions f and g such that $f(a) = g(a) = 0$ and let $x \in I$, $x > a$.

Then f and g are continuous on $[a, x]$ and differentiable on (a, x),

so by Cauchy's mean value theorem there exists $c \in (a, x)$ such that

$$\frac{f(x)}{g(x)} = \frac{f(x) - f(a)}{g(x) - g(a)} = \frac{f'(c)}{g'(c)}.$$

Let (x_n) be a sequence such that $x_n \longrightarrow a$ and choose $c_n \in (a, x_n)$ for all n.

Then $c_n \longrightarrow a$ and $\frac{f(x_n)}{g(x_n)} = \frac{f'(c_n)}{g'(c_n)}$ for all $n \in \mathbb{N}$.

Therefore $\lim_{n \to \infty} \frac{f(x_n)}{g(x_n)} = \lim_{n \to \infty} \frac{f'(c_n)}{g'(c_n)} = b$ and by the sequential criterion for the limit, $\lim_{x \to a} \frac{f(x)}{g(x)} = b$.

Undefined forms

Remark. The theorem can be applied for limits of the following type:

1) $\frac{0}{0}$, $\frac{\infty}{\infty}$ $\Longrightarrow$ L'Hospital's rule can be applied directly

2) $0 \cdot \infty$ $\Longrightarrow$ transformation: $f(x)\,g(x) = \frac{f(x)}{\frac{1}{g(x)}}$ or $f(x)\,g(x) = \frac{g(x)}{\frac{1}{f(x)}}$

3) $\infty - \infty \Longrightarrow f(x) - g(x) = \frac{1}{h(x)} - \frac{1}{k(x)} = \frac{k(x) - h(x)}{h(x)\,k(x)} \quad \left(\frac{0}{0}\right)$

4) 0^0, 1^∞, ∞^0 $\Longrightarrow$ $(f(x))^{g(x)} = e^{g(x) \cdot \ln(f(x))}$

Exercises

Pages 171-172 of the pdf file (first 9 examples):
https://math.bme.hu/~tasnadi/merninf_anal_1/anal1_elm.pdf

Pages 72-73 of the pdf file, exercise 26:
https://math.bme.hu/~tasnadi/merninf_anal_1/anal1_gyak.pdf
In exercises 26. g), h) the L'Hospital's rule cannot be applied.

Local properties and the derivative

Definition. Assume that $x_0 \in D_f$ and there exists $\delta > 0$ such that
for all $x, y \in D_f$, if $x_0 - \delta < x < x_0 < y < x_0 + \delta$,

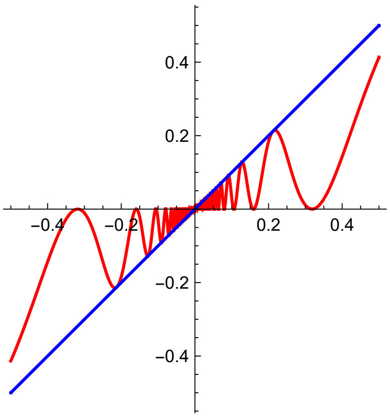
then $\begin{cases} f(x) \le f(x_0) \le f(y) \\ f(x) \ge f(x_0) \ge f(y) \\ f(x) < f(x_0) < f(y) \\ f(x) > f(x_0) > f(y) \end{cases}$. Then we say that f is $\begin{cases} \text{locally increasing} \\ \text{locally decreasing} \\ \text{strictly locally increasing} \\ \text{strictly locally decreasing} \end{cases}$ at x_0.

Remarks. (1) If f is monotonically increasing on (a, b), then f is locally increasing for all $x_0 \in (a, b)$.

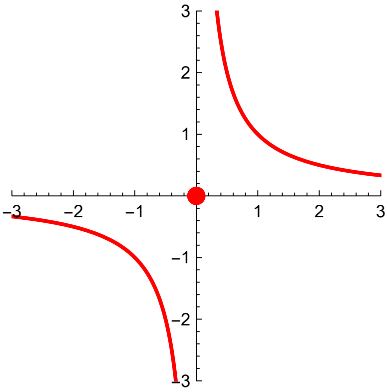
(2) If f is locally increasing **for all** $x_0 \in (a, b)$, then f is monotonically increasing on (a, b).

(3) However, if f is locally increasing at x_0 then it doesn't imply that there exists a neighbourhood $B(x_0, r)$ where f is monotonically increasing.
The following functions are locally increasing at $x_0 = 0$ but on any interval that contains 0, the functions are not monotonically increasing.

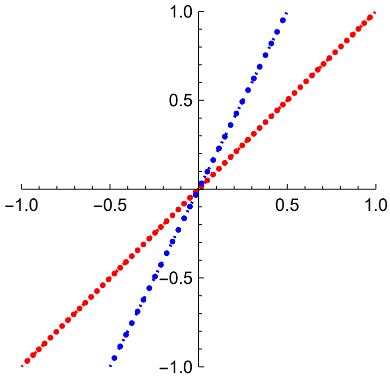
1. $f(x) = \begin{cases} x \sin^2 \frac{1}{x} & \text{if } x \neq 0 \\ 0 & \text{if } x = 0 \end{cases}$



2. $f(x) = \begin{cases} \frac{1}{x} & \text{if } x \neq 0 \\ 0 & \text{if } x = 0 \end{cases}$



3. $f(x) = \begin{cases} x & \text{if } x \in \mathbb{Q} \\ 2x & \text{if } x \in \mathbb{R} \setminus \mathbb{Q} \end{cases}$



Theorem. Assume that f is differentiable at x_0.

(1) If f is locally increasing at x_0 then $f'(x_0) \geq 0$.

(2) If f is locally decreasing at x_0 then $f'(x_0) \leq 0$.

(3) If $f'(x_0) > 0$ then f is strictly locally increasing at x_0.

(4) If $f'(x_0) < 0$ then f is strictly locally decreasing at x_0.

Proof. (1) If f is locally increasing at x_0 then $\exists\, \delta > 0$ such that

$$0 < |x - x_0| < \delta \Longrightarrow \frac{f(x) - f(x_0)}{x - x_0} \geq 0.$$

(If $x < x_0$ then $x - x_0 < 0$ and $f(x) - f(x_0) \leq 0$ and
if $x > x_0$ then $x - x_0 > 0$ and $f(x) - f(x_0) \geq 0$.)

Since f is differentiable at x_0 then $f'(x_0) = \lim_{x \to x_0} \frac{f(x) - f(x_0)}{x - x_0} \geq 0$.

(2) Similar to case (1).

(3) If $f'(x_0) = \lim_{x \to x_0} \frac{f(x) - f(x_0)}{x - x_0} > 0$, then there exists $\delta > 0$ such that

if $0 < |x - x_0| < \delta$ then $\frac{f(x) - f(x_0)}{x - x_0} > 0$.

$$\Longrightarrow \text{ if } \begin{cases} x_0 < x < x_0 + \delta \\ x_0 - \delta < x < x_0 \end{cases} \text{ then } \begin{cases} f(x) > f(x_0) \\ f(x) < f(x_0) \end{cases}$$

$\Longrightarrow f$ is strictly locally increasing at x_0.

(3) Similar to case (4).

Remarks. Assume that f is differentiable at x_0.

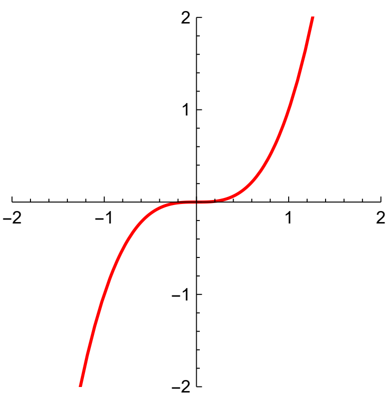
(1) If f is strictly locally increasing at x_0 then it doesn't imply that $f'(x_0) > 0$.

If f is strictly locally increasing at x_0 then $f'(x_0) \geq 0$, since $\exists\, \delta > 0$ such that

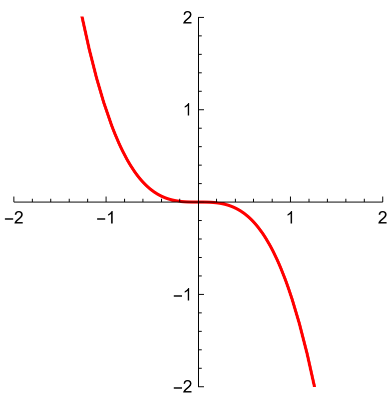
$0 < |x - x_0| < \delta \Longrightarrow \frac{f(x) - f(x_0)}{x - x_0} > 0$, but for the limit $\lim_{x \to x_0} \frac{f(x) - f(x_0)}{x - x_0} \geq 0$.

For example $f(x) = x^3$ is strictly locally increasing at $x_0 = 0$, but $f'(0) = 3x^2 \,|_{x=0} = 0$.

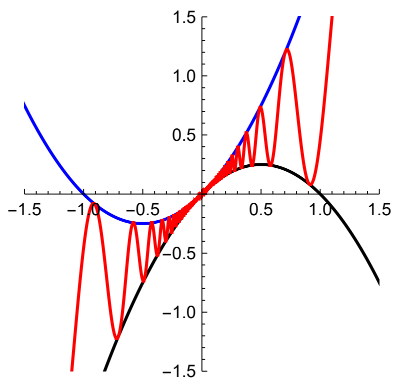
1. $f(x) = x^3$



2. $f(x) = -x^3$



3. $f(x) = \begin{cases} x + x^2 \sin\left(\frac{10}{x}\right) & \text{if } x \neq 0 \\ 0 & \text{if } x = 0 \end{cases}$



(2) If $f'(x_0) \geq 0$ then it doesn't imply that f is locally increasing at x_0.
For example $f(x) = -x^3$ is not locally increasing at $x_0 = 0$, but $f'(0) = \ \geq 0$.

(3) If $f'(x_0) > 0$ then it doesn't imply that f is monotonically increasing on an interval containing x_0.
For example, let f be a function such that $x - x^2 \leq f(x) \leq x + x^2 \ \forall x \implies f(0) = 0$.
If $x > 0$ then $1 - x \leq \frac{f(x)}{x} = \frac{f(x) - f(0)}{x - 0} \leq 1 + x$,
If $x < 0$ then $1 - x \geq \frac{f(x) - f(0)}{x - 0} \geq 1 + x$, so by the sandwich theorem
$f'(0) = \lim_{x \to x_0} \frac{f(x) - f(x_0)}{x - x_0} = 1 > 0$. For example, let $f(x) = \begin{cases} x + x^2 \sin\left(\frac{10}{x}\right) & \text{if } x \neq 0 \\ 0 & \text{if } x = 0 \end{cases}$

Darboux's theorem

Theorem. Assume that $f : [a, b] \longrightarrow \mathbb{R}$ is differentiable and $f'(a) < y < f'(b)$ or $f'(b) < y < f'(a)$.
Then there exists $c \in (a, b)$ such that $f'(c) = y$.

Remark. We say that f' has the intermediate value property of Darboux property.

Proof. 1) Let $g : [a, b] \longrightarrow \mathbb{R}$, $g(x) = f(x) - y \cdot x \implies g$ is differentiable and $g'(x) = f'(x) - y$.
2) Assume that $f'(a) < y < f'(b) \implies g'(a) = f'(a) - y < 0 < f'(b) - y < g'(b)$
3) g is differentiable, so it is continuous on $[a, b]$
$\implies$ by Weierstrass extreme value theorem it has a minimum and a maximum on $[a, b]$.
4) Since $\begin{cases} g'(a) < 0 \\ g'(b) > 0 \end{cases}$ then $\begin{cases} g \text{ is strictly locally decreasing at } a \\ g \text{ is strictly locally increasing at } b \end{cases}$
$\implies g$ does not have a minimum at a and b but on the open interval (a, b)
$\implies$ there exists $c \in (a, b)$ such that g has a local minimum at c
$\implies g'(c) = 0 = f'(c) - y \implies f'(c) = y$ for some $c \in (a, b)$.

Example. The sign function or signum function is defined as $\operatorname{sgn} x = \begin{cases} -1 & \text{if } x < 0 \\ 0 & \text{if } x = 0 \\ 1 & \text{if } x > 0 \end{cases}$.
This function is not continuous at $x_0 = 0$, so there is no function $f : \mathbb{R} \longrightarrow \mathbb{R}$ for which $f'(x) = \operatorname{sgn} x$ on $\mathbb{R}$ (or on any interval that contains $x_0 = 0$).

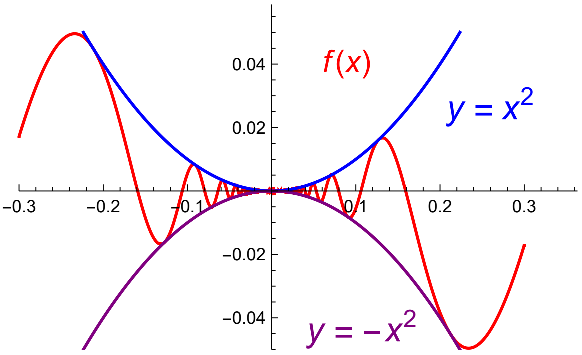
Remark. From Darboux's theorem it follows that if f' is not continuous at a point then f' cannot have a discontinuity of the first type at that point, so at least one of the one-sided limits doesn't exist or exists but is not finite
$\implies f'$ has an essential discontinuity at the given point.

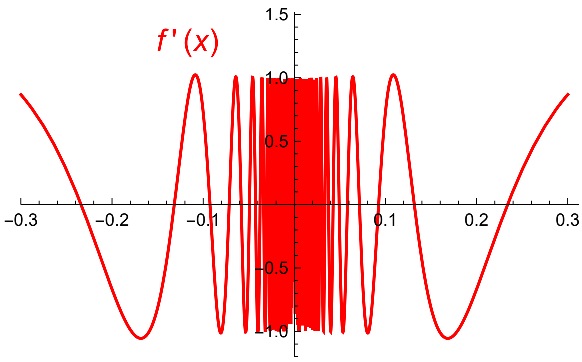
Statement. If f is differentiable on $[a, a+\delta)$ $(\delta > 0)$ and f' has a discontinuity at a then the limit $\lim\limits_{x\to a+0} f(x)$ doesn't exist or $\exists \lim\limits_{x\to a+0} f(x) \notin \mathbb{R}$.

Continuously differentiable functions

Definition. Assume that I is a neighbourhood of $a \in D_f$ and f is differentiable on $I \cap D_f$.
Then f is **continuous differentiable at a** if f' is continuous at a.
f is **continuously differentiable** on A if f is continuous differentiable $\forall x \in A$.
Notation: $C^1(A) = \{f :\ f \text{ is continuously differentiable on } A\}$.

Example: The function $f(x) = \begin{cases} x^2 \sin\left(\frac{1}{x}\right) & \text{if } x \neq 0 \\ 0 & \text{if } x = 0 \end{cases}$ is differentiable but f' is not continuous at $x_0 = 0$, since $f'(x) = \begin{cases} 2x \sin\left(\frac{1}{x}\right) - \cos\left(\frac{1}{x}\right) & \text{if } x \neq 0 \\ 0 & \text{if } x = 0 \end{cases}$.





Higher order derivatives

Definition. If f' is differentiable at x then we say that f is twice differentiable at x and the second derivative or second order derivative of f at x_0 is $f''(x) = (f')'(x)$.
Differentiating f repeatedly, we get the third, ..., nth derivative of f.

Notation: $f''(x) = f^{(2)}(x) = \dfrac{d^2 f(x)}{d x^2}$

$f'''(x) = f^{(3)}(x) = \dfrac{d^3 f(x)}{d x^3}$

...

$f^{(n)}(x) = \dfrac{d^n f(x)}{d x^n}$

By definition: $f^{(0)}(x) = f(x)$

Example: $f(x) = \sin x \implies f'(x) = \cos x,\ f''(x) = -\sin x,\ f'''(x) = -\cos x,\ f^{(4)}(x) = \sin x,\ \ldots$
$f(x) = e^x \implies f^{(n)}(x) = e^x \quad \forall n \in \mathbb{N}$

Investigation of differentiable functions

Monotonicity on an interval

Theorem. Assume that $f : (a, b) \longrightarrow \mathbb{R}$ is differentiable. Then

(1) f is monotonically increasing $\iff$ $f'(x) \geq 0$ for all $x \in (a, b)$

(2) f is monotonically decreasing $\iff$ $f'(x) \leq 0$ for all $x \in (a, b)$

(3) f is constant $\iff$ $f'(x) = 0$ for all $x \in (a, b)$

(4) $f'(x) > 0$ for all $x \in (a, b) \Longrightarrow$ f is strictly monotonically increasing

(5) $f'(x) < 0$ for all $x \in (a, b) \Longrightarrow$ f is strictly monotonically decreasing

Proof. (1)

(i) If f is monotonically increasing then f is locally monotonically increasing for all $x \in (a, b)$
$\Longrightarrow f'(x) \geq 0 \;\; \forall x \in (a, b)$.

(ii) Assume that $f'(x) \geq 0$ for all $x \in (a, b)$. Let $a < x_1 < x_2 < b$ and apply Lagrange's mean value theorem for $[x_1, x_2]$. Then there exists $c \in (x_1, x_2) \subset (a, b)$ such that

$$\frac{f(x_2) - f(x_1)}{x_2 - x_1} = f'(c) \geq 0 \;\Longrightarrow\; f(x_2) \geq f(x_1)$$

Therefore if $x_1 < x_2$ then $f(x_1) \leq f(x_2)$, so f is monotonically increasing on (a, b).

(2) Similar to case (1).

(3) f is constant $\iff$ f is monotonically increasing and decreasing
$\iff f'(x) \geq 0$ and $f'(x) \leq 0 \;\; \forall x \in (a, b) \iff f'(x) = 0 \;\; \forall x \in (a, b)$

(4) and (5): similar to case (1) (ii)

Remark. Statements (4) and (5) cannot be reversed.
For example, $f(x) = x^3$ is strictly monotonically increasing on $\mathbb{R}$, however $f'(x) > 0$ does not hold for all $x \in \mathbb{R}$, since $f'(x) = 3x^2 \Longrightarrow f'(0) = 0$.

Remark. If the domain of f is not an interval then the above theorem is not true, as the following examples show.

1) Let $f : \mathbb{R} \setminus \mathbb{Z} \longrightarrow \mathbb{R}$, $f(x) = \{x\} = x - [x]$. Then f is differentiable on $\mathbb{R} \setminus \mathbb{Z}$ and $f'(x) = 1 > 0$ for all $x \in \mathbb{R} \setminus \mathbb{Z}$ but f is not monotonically increasing.

2) Let $f : \mathbb{R} \setminus \mathbb{Z} \longrightarrow \mathbb{R}$, $f(x) = [x]$. Then f is differentiable on $\mathbb{R} \setminus \mathbb{Z}$ and $f'(x) = 0$ for all $x \in \mathbb{R} \setminus \mathbb{Z}$ but f is not constant.

Local extremum, sufficient conditions

Definition. If f is differentiable at x_0 and $f'(x_0) = 0$ then x_0 is a **stationary point** of f.
If $f'(x_0) = 0$ or f is not differentiable at x_0 then x_0 is a **critical point** of f.

Remark. Recall that if f is differentiable at $x_0 \in \operatorname{int} D_f$ and f has a local extremum at x_0 then $f'(x_0) = 0$.
This is a necessary condition for the existence of a local extremum.
The next two theorems formulate sufficient conditions.

Theorem (Sufficient condition for a local extremum, first derivative test).
Assume that f is differentiable at $x_0 \in \operatorname{int} D_f$.
If $f'(x_0) = 0$ and f' changes sign at x_0, then f has a local extremum at x_0.

Namely, if $f'(x_0) = 0$ and f' is (strictly) locally $\begin{cases} \text{increasing} \\ \text{decreasing} \end{cases}$ at x_0

then f has a (strict) local $\begin{cases} \text{minimum} \\ \text{maximum} \end{cases}$ at x_0.

Proof. Assume that $f'(x_0) = 0$ and f' is locally increasing at x_0
(that is, f' changes sign from negative to positive)

$$\Longrightarrow \exists\, \delta > 0 \text{ such that } \begin{cases} f'(x) \le 0 & \text{if } x_0 - \delta < x < x_0 \\ f'(x) \ge 0 & \text{if } x_0 < x < x_0 + \delta \end{cases}$$

$$\Longrightarrow \begin{cases} f \text{ is monotonically decreasing on } (x_0 - \delta, x_0) \\ f \text{ is monotonically increasing on } (x_0, x_0 + \delta) \end{cases}$$

$$\Longrightarrow \begin{cases} f(x) \ge f(x_0) & \text{if } x_0 - \delta < x < x_0 \\ f(x) \ge f(x_0) & \text{if } x_0 < x < x_0 + \delta \end{cases} \Longrightarrow f \text{ has a local minimum at } x_0.$$

Theorem (Sufficient condition for a local extremum, second derivative test).
Assume that f is twice differentiable at $x_0 \in \operatorname{int} D_f$.
If $f'(x_0) = 0$ and $f''(x_0) \neq 0$ then f has a local extremum at x_0.
If $\begin{cases} f''(x_0) > 0 \\ f''(x_0) < 0 \end{cases}$ then f has a strict local $\begin{cases} \text{minimum} \\ \text{maximum} \end{cases}$ at x_0.

Proof. $f''(x_0) > 0 \Longrightarrow f'$ is locally increasing at x_0 and $f'(x_0) = 0$
$\Longrightarrow$ by the previous theorem f has a local minimum at x_0.

Remark. The sign change of f' at x_0 is only a sufficient but not a necessary condition
for the existence of a local extremum at x_0.

For example, if $f(x) = \begin{cases} x^2\left(2 + \sin\left(\frac{1}{x}\right)\right) & \text{if } x \neq 0 \\ 0 & \text{if } x = 0 \end{cases}$

then f is differentiable for all $x \in \mathbb{R}$. At $x = 0$:

$$f'(0) = \lim_{x\to 0}\frac{f(x)-f(0)}{x-0} = \lim_{x\to 0}\frac{x^2\left(2+\sin\left(\frac{1}{x}\right)\right)}{x} = \lim_{x\to 0} x\left(2+\sin\left(\frac{1}{x}\right)\right) = 0 \text{ (since it is } 0\cdot\text{bounded),}$$

so the necessary condition holds at $x_0 = 0$.

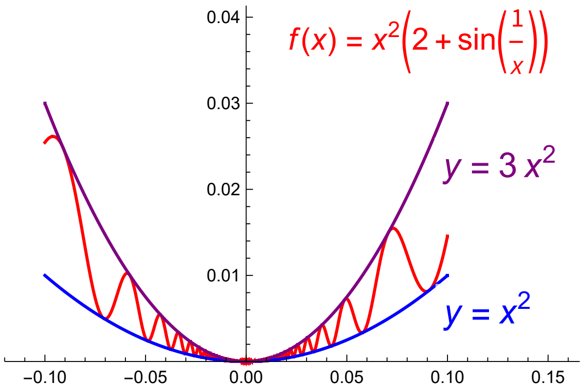
However, in any neighbourhood of $x_0 = 0$:

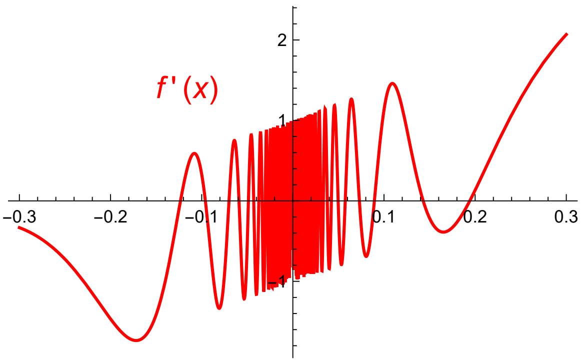
f has strictly monotonic increasing and decreasing sections $\Longrightarrow$

f' has both positive and negative values $\Longrightarrow$

f' doesn't change sign at $x_0 = 0$.

Yet f has a local extreme value at $x_0 = 0$, and it is even an absolute minimum here.





Local extremum and higher order derivatives

Remark. If $f'(x_0) = 0$ and $f''(x_0) = 0$ then it cannot be decided whether f has a local extremum at x_0. For example:

1) $f(x) = x^3$ does not have a local extremum at $x_0 = 0$,

2) $f(x) = x^4$ has a local minimum at $x_0 = 0$,

3) $f(x) = -x^4$ has a local maximum at $x_0 = 0$, and in each case $f'(0) = f''(0) = 0$.

Theorem. (1) Assume that f is $2k$ times differentiable at x_0, $k \geq 1$.

If $f'(x_0) = \ldots = f^{(2k-1)}(x_0) = 0$ and $\begin{cases} f^{(2k)}(x_0) > 0 \\ f^{(2k)}(x_0) < 0 \end{cases}$

then f has a strict local $\begin{cases} \text{minimum} \\ \text{maximum} \end{cases}$ at x_0.

(2) Assume that f is $2k+1$ times differentiable at x_0, $k \geq 1$.

If $f'(x_0) = \ldots = f^{(2k)}(x_0) = 0$ and $f^{(2k+1)}(x_0) \neq 0$, then f is strictly monotonic in a neighbourhood of x_0, so f doesn't have a local extremum at x_0.

Remark. Part (1) in other words: If the first non-zero derivative (after the first one) has an even order then f has a local extremum at x_0.

Proof. (1) We prove the statement for a strict local minimum by induction.

(i) If $k = 1$ then the statement is true.

(ii) Assume that the statement holds for $k - 1$ and let $g = f''$.

($\Longrightarrow g' = f'''$, ..., $g^{(2k-3)} = f^{(2k-1)}$, $g^{(2k-2)} = f^{(2k)}$.)

From the induction hypothesis it follows that

if $\mathbf{g'(x_0) = .. = g^{(2k-3)}(x_0) = 0}$ and $\mathbf{g^{(2k-2)}(x_0) > 0}$ then the function

$g = f''$ has a strict local minimum at x_0.

(iii) We want to prove that if

$f'(x_0) = \mathbf{f''(x_0) = f'''(x_0) = .. = f^{(2k-1)}(x_0) = 0}$ and $\mathbf{f^{(2k)}(x_0) > 0}$ then

f has a strict local minimum at x_0.

Since $\mathbf{f''(x_0) = 0}$ and f'' has a strict local minimum at x_0,

then $\exists\, \delta > 0$ such that $f''(x) > 0,\ \forall\, x \in (x_0 - \delta, x_0 + \delta) \setminus \{x_0\}$

$\Longrightarrow f'$ is strictly monotonically increasing on $(x_0 - \delta, x_0 + \delta)$

$\Longrightarrow f'$ is strictly locally increasing at x_0

$\Longrightarrow f$ has a strict local minimum at x_0.

(2) Assume that $\mathbf{f'(x_0) = f''(x_0) = .. = f^{(2k)}(x_0) = 0}$ and $\mathbf{f^{(2k+1)}(x_0) \neq 0}$.

Let $g = f'$, then $\mathbf{g'(x_0) = .. = g^{(2k-1)}(x_0) = 0}$ and $\mathbf{g^{(2k)}(x_0) \neq 0}$.

$\Longrightarrow$ by part (1), $g = f'$ has a strict local extremum at x_0.

Since $\mathbf{f'(x_0) = 0}$, then either $f'(x) > 0$ or $f'(x) < 0$, $\forall\, x \in (x_0 - \delta, x_0 + \delta) \setminus \{x_0\}$

$\Longrightarrow$ f is strictly monotonic on $(x_0 - \delta, x_0 + \delta)$

$\Longrightarrow$ f doesn't have a local extremum at x_0.

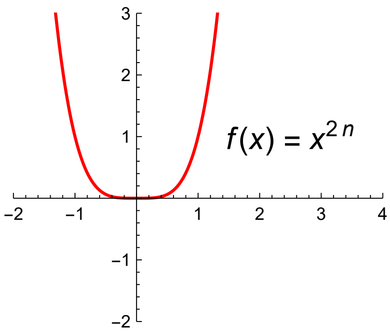
Example. $f(x) = x^n$ is n times differentiable,

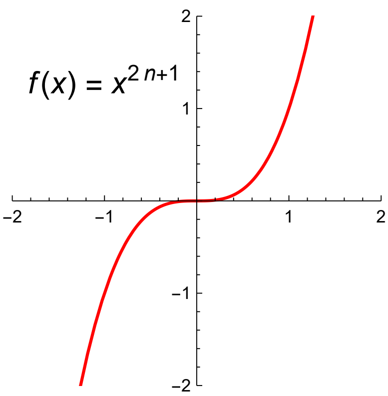
$f^{(k)}(x) = n(n-1)(n-2) \ldots (n-k+1)\, x^{n-k}, \quad k = 1, 2, \ldots, n-1$

$f^{(n)}(x) = n!$

$\Longrightarrow$ if $x_0 = 0$, then $f'(0) = f''(0) = .. = f^{(n-1)}(0) = 0$, $f^{(n)}(0) = n! > 0$

$\Longrightarrow$ at $x_0 = 0$ f has a local minimum if n is even and f doesn't have a local extremum if n is odd.





Convexity / concavity on an interval

Theorem (Necessary and sufficient condition for convexity).

If f is differentiable on the interval I, then the following statements are equivalent.

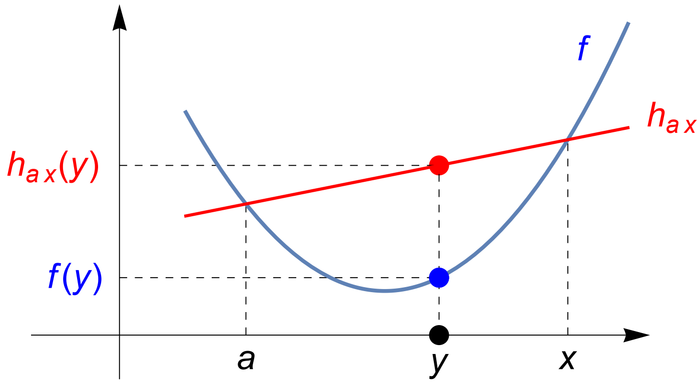
(1) f is convex on I

(2) $f(x) \geq f(a) + f'(a)(x - a)$ if $x, a \in I$

(3) f' is monotonically increasing on I

Remark. The geometrical meaning of (2) is that for all $a \in I$, the graph of f lies above the tangent line at a.

Proof of (1) $\Longrightarrow$ (2):



$y = \lambda a + (1 - \lambda) x$

$h_{ax}(y) = \lambda f(a) + (1 - \lambda) f(x)$

f is convex $\Longrightarrow f(y) \leq h_{ax}(y)$

If $a < x$ and $y \in (a, x)$ then $\exists \lambda \in (0, 1)$ such that

$$y = \lambda a + (1 - \lambda) x \Longrightarrow y - a = (\lambda - 1) a + (1 - \lambda) x$$

$$\Longrightarrow \mathbf{y - a = (1 - \lambda)(x - a)}$$

f is convex $\Longrightarrow f(y) \leq \lambda f(a) + (1 - \lambda) f(x)$

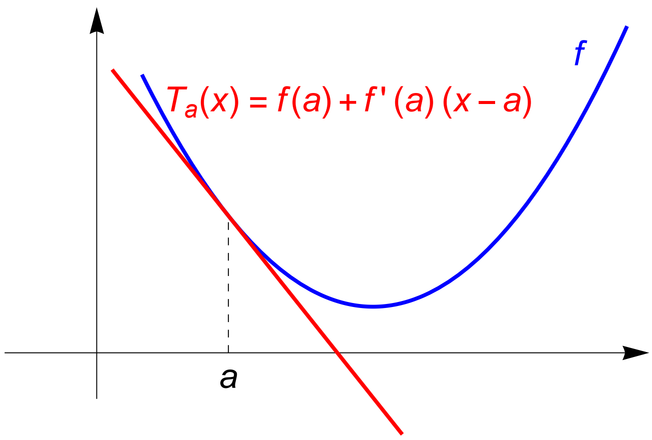
$$\Longrightarrow f(y) - f(a) \leq (\lambda - 1) f(a) + (1 - \lambda) f(x)$$

$$\Longrightarrow \mathbf{f(y) - f(a) \leq (1 - \lambda)(f(x) - f(a))}$$

Dividing both sides by $\mathbf{y - a = (1 - \lambda)(x - a) > 0} \Longrightarrow \dfrac{\mathbf{f(y) - f(a)}}{\mathbf{y - a}} \leq \dfrac{\mathbf{f(x) - f(a)}}{\mathbf{x - a}}$

If $y \longrightarrow a+$, then $f'(a) \leq \dfrac{f(x) - f(a)}{x - a} \Longrightarrow f(x) \geq f(a) + f'(a)(x - a)$ if $x, a \in I$.

If $a > x$ then the proof is similar and if $a = x$ then the statement is obvious.

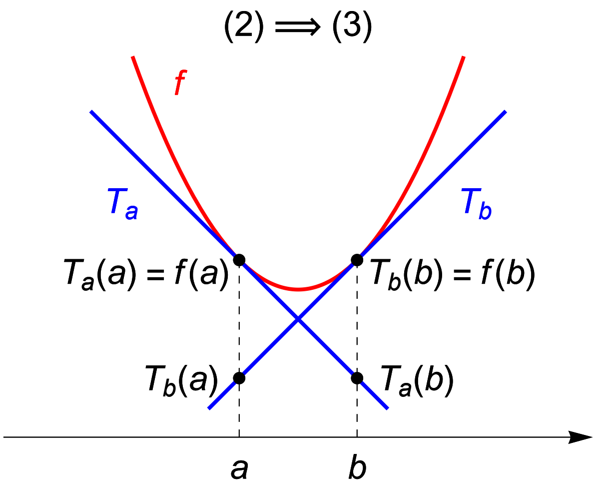


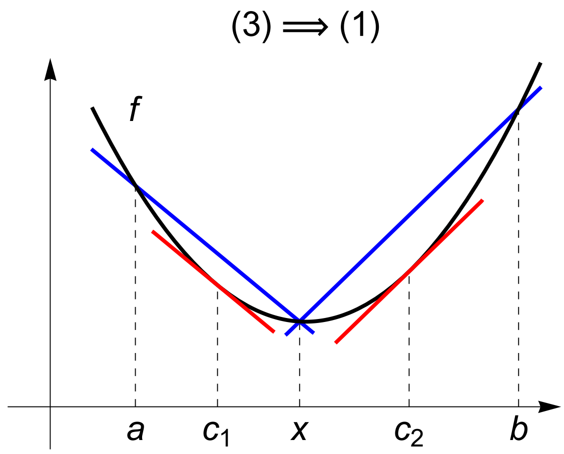
Proof of (2) ⟹ (3): Let $T_a(x) = f(a) + f'(a)(x - a)$.

If $a, b \in I,\ a < b \implies T_a(a) = f(a) \geq T_b(a)$ and $T_a(b) \leq f(b) = T_b(b)$

$$\implies f'(a) = \frac{T_a(b) - T_a(a)}{b - a} = \frac{T_a(b) - f(a)}{b - a} \leq \frac{f(b) - T_b(a)}{b - a} = \frac{T_b(b) - T_b(a)}{b - a} = f'(b)$$

$\implies f'$ is monotonically increasing on I





Proof of (3) ⟹ (1): Let $a, b \in I,\ a < b,\ \lambda \in (0, 1)$ for which $x = \lambda a + (1 - \lambda) b$

$\implies$ $\boldsymbol{x - a = (1 - \lambda)(b - a)}$

$\boldsymbol{b - x = \lambda(b - a)}$

Then by Lagrange's mean value theorem there exist $c_1 \in (a, x)$ and $c_2 \in (x, b)$ such that

$$\frac{f(x) - f(a)}{x - a} = f'(c_1) \text{ and } f'(c_2) = \frac{f(b) - f(x)}{b - x}.$$

f' is monotonically increasing $\implies f'(c_1) \leq f'(c_2)$

$$\implies \frac{f(x) - f(a)}{\boldsymbol{x - a}} \leq \frac{f(b) - f(x)}{\boldsymbol{b - x}} \implies \frac{f(x) - f(a)}{\boldsymbol{(1 - \lambda)(b - a)}} \leq \frac{f(b) - f(x)}{\boldsymbol{\lambda(b - a)}} \implies f(x) \leq \lambda f(a) + (1 - \lambda) f(b)$$

$\implies f$ is convex on I.

Consequence (Necessary and sufficient condition for convexity).

Assume that f is twice differentiable on the interval I. Then

(1) $f''(x) \geq 0\ \forall x \in I$ if and only if f is convex on I.

(2) $f''(x) \leq 0\ \forall x \in I$ if and only if f is concave on I.

Consequence.

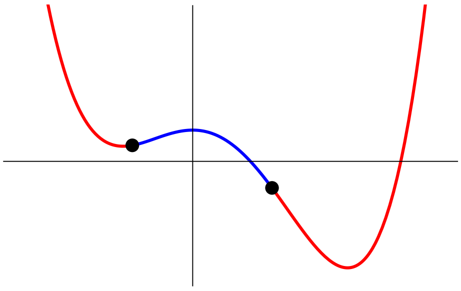
Assume that f is twice differentiable on the interval I. Then

(1) If $f''(x) > 0\ \forall x \in I$ then f is strictly convex on I.

(2) If $f''(x) < 0\ \forall x \in I$ then f is strictly concave on I.

Inflection point

Definition. Assume that f is continuous at $a \in \text{int}\, D_f$ and there exists $\delta > 0$ such that
f is convex on $(a - \delta, a)$ and concave on $(a, a + \delta)$
or f is concave on $(a - \delta, a)$ and convex on $(a, a + \delta)$.
Then a is called a point of inflection of the function f.



Theorem (Necessary condition for an inflection point, second derivative test).
If f is twice differentiable at x_0 and f has an inflection point at x_0 then $f''(x_0) = 0$.

Proof. If f is convex on $(x_0 - \delta, x_0]$ and concave on $[x_0, x_0 + \delta)$ then
f' is monotonically increasing on $(x_0 - \delta, x_0]$ and monotonically decreasing on $[x_0, x_0 + \delta)$
$\Longrightarrow$ f' has a local maximum at x_0 $\Longrightarrow$ $f''(x_0) = 0$.

Theorem (Sufficient condition for an inflection point, second derivative test).
If f is twice differentiable in a neighbourhood of x_0,
$f''(x_0) = 0$ and f'' changes sign at x_0,
then f has an inflection point at x_0.

Theorem (Sufficient condition for an inflection point, third derivative test).
If f is three times differentiable in a neighbourhood of x_0,
$f''(x_0) = 0$ and $f'''(x_0) \neq 0$,
then f has an inflection point at x_0.

Inflection point and higher order derivatives

Theorem. (1) Assume that f is $2k + 1$ times differentiable at x_0, $k \geq 1$.
If $f''(x_0) = ... = f^{(2k)}(x_0) = 0$ and $f^{(2k+1)}(x_0) \neq 0$
then f has an inflection point at x_0.

(2) Assume that f is $2k$ times differentiable at x_0, $k \geq 1$.
If $f''(x_0) = ... = f^{(2k-1)}(x_0) = 0$ and $f^{(2k)}(x_0) \neq 0$, then f is strictly convex or concave in a neighbourhood of x_0, so f doesn't have an inflection point at x_0.

Remark. Part (1) in other words: If the first non-zero derivative (after the second one) has an odd order then f has a local extremum at x_0.

Linear asymptotes

Definition. The straight line $x = a$ is a **vertical asymptote** of the function f if

$$\lim_{x\to a+} f(x) = \pm\infty \text{ or } \lim_{x\to a-} f(x) = \pm\infty.$$

Definition. The straight line $g(x) = A\,x + B$ is a **linear asymptote** of the function f at ∞ or $-\infty$ if

$$\lim_{x\to\infty} (f(x) - g(x)) = 0 \text{ or } \lim_{x\to-\infty} (f(x) - g(x)) = 0.$$

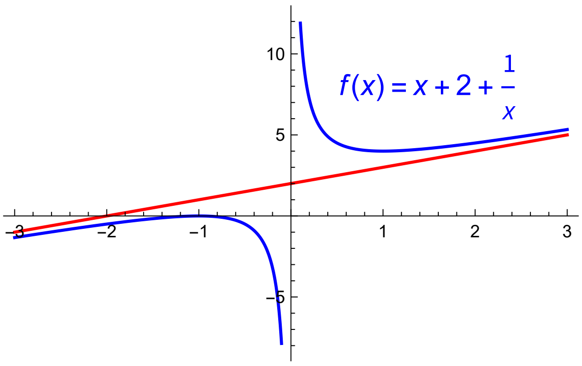
$g(x)$ is a **horizontal asymptote** if $A = 0$ and an **oblique or slant asymptote** if $A \neq 0$.

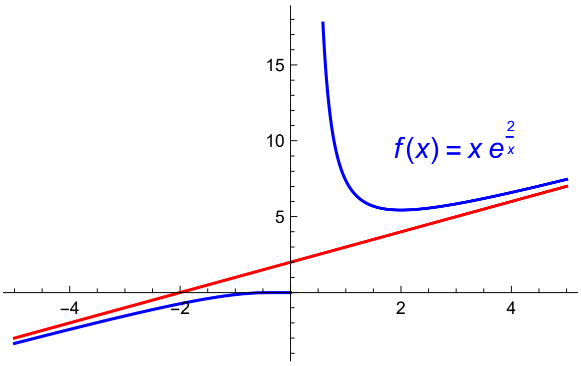
Statement. $g(x) = A\,x + B$ is a linear asymptote of f at $\pm\infty$ if and only if

$$A = \lim_{x\to\pm\infty} \frac{f(x)}{x} \quad \text{and} \quad B = \lim_{x\to\pm\infty} (f(x) - A\,x)$$

Example. $\lim_{x\to\frac{\pi}{2}\pm} \tan x = \mp\infty \implies x = \frac{\pi}{2}$ is a vertical asymptote of $f(x) = \tan(x)$.

Example. If $f(x) = x + 2 + \frac{1}{x}$ then $g(x) = x + 2$ is a linear asymptote of f at $\pm\infty$.





Example. If $f(x) = x\,e^{\frac{2}{x}}$ then $g(x) = x + 2$ is a linear asymptote of f at $\pm\infty$.

Solution. $A = \lim_{x\to\pm\infty} \frac{f(x)}{x} = \lim_{x\to\pm\infty} \frac{x\,e^{\frac{2}{x}}}{x} = \lim_{x\to\pm\infty} e^{\frac{2}{x}} = e^0 = 1$

$B = \lim_{x\to\pm\infty} \left(x\,e^{\frac{2}{x}} - x\right) = \lim_{x\to\pm\infty} \frac{e^{\frac{2}{x}} - 1}{\frac{1}{x}}$. Let $y = \frac{2}{x}$, then $B = \lim_{y\to 0\pm} \frac{e^y - 1}{\frac{1}{2}\cdot y} = 2$,

using that $\lim_{x\to 0} \frac{e^x - 1}{x} = 1$. The limit can also be calculate with the L'Hospital's rule.

So $g(x) = x + 2$.

Extreme values on a closed interval

Remark. If f is continuous on a closed and bounded interval then by the Weierstrass extreme value theorem f has a minimum and a maximum.

The possible points are:

1) the points where f is not differentiable
2) the points where the derivative of f is 0
3) the endpoints of the interval

Finally the largest and smallest of the possible values must be selected.

Analyzing graphs of functions

Summary of the steps:

1) finding the domain of f
2) finding the zeros of f
3) parity, periodicity
4) limits at the endpoints of the intervals constituting the domain
5) investigation of f' $\Longrightarrow$ monotonicity, extreme values
6) investigation of f'' $\Longrightarrow$ convexity/concavity, inflection points
7) linear asymptotes
8) plotting the graph of f, finding the range of f

Exercises

https://math.bme.hu/~nagyi/calculus1/functions.pdf

Examples

1. $f(x) = \frac{x}{x^3+1}$

$D_f = (-\infty, -1) \cup (-1, \infty)$; $f(x) = 0 \iff x = 0$;

$\lim\limits_{x\to\pm\infty} f(x) = 0$, $\lim\limits_{x\to -1+0} f(x) = -\infty$, $\lim\limits_{x\to -1-0} f(x) = +\infty$

Monotonicity, local extremum:

$$f'(x) = \frac{1-2x^3}{(x^3+1)^2} = 0 \iff x = \frac{1}{\sqrt[3]{2}} \approx 0.79$$

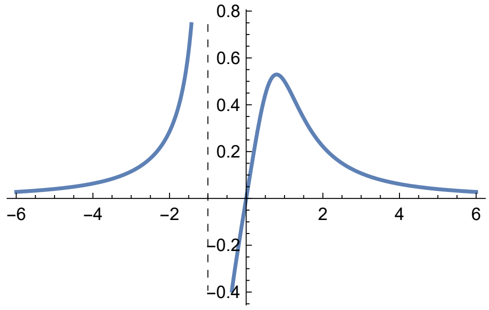
x	x<−1	$-1<x<\frac{1}{\sqrt[3]{2}}$	$x=\frac{1}{\sqrt[3]{2}}$	$x>\frac{1}{\sqrt[3]{2}}$
f'	+	+	0	−
f	↗	↗	max: $\frac{\sqrt[3]{4}}{3}$ ≈0.53	↘

Convexity / concavity, inflection points:

$$f''(x) = \frac{6x^2(x^3-2)}{(x^3+1)^3} = 0 \iff x = 0 \text{ or } x = \sqrt[3]{2} \approx 1.26$$

x	x<−1	−1<x<0	x=0	$0<x<\sqrt[3]{2}$	$x=\sqrt[3]{2}$	$x>\sqrt[3]{2}$
f''	+	−	0	−	0	+
f	∪	∩		∩	infl: $\frac{\sqrt[3]{2}}{3}$ ≈0.42	∪

The graph of f:



$\Longrightarrow R_f = \mathbb{R}$

2. $f(x) = 2\sin x + \sin 2x$

$D_f = \mathbb{R}$; f is odd;
f is periodic with period 2π $\Longrightarrow$ it may be assumed that $0 \le x \le 2\pi$;
$\Longrightarrow$ on this interval $f(x) = 0 \Longleftrightarrow x = 0$ or $x = \pi$ or $x = 2\pi$

Monotonicity, local extremum:
$f'(x) = 2\cos x + 2\cos 2x = 2\left(\cos x + \cos^2 x - \left(1 - \cos^2 x\right)\right) =$

$$= 2\cdot\left(2\cos^2 x + \cos x - 1\right) = 0 \Longrightarrow (\cos x)_{1,2} = \frac{-1 \pm 3}{4} \Longrightarrow \cos x = -1 \text{ or } \cos x = \frac{1}{2}$$

$$\Longrightarrow x_1 = \frac{\pi}{3},\ x_2 = \pi,\ x_3 = \frac{5\pi}{3}$$

x	0	$\left(0, \frac{\pi}{3}\right)$	$\frac{\pi}{3}$	$\left(\frac{\pi}{3}, \pi\right)$	π	$\left(\pi, \frac{5\pi}{3}\right)$	$\frac{5\pi}{3}$	$\left(\frac{5\pi}{3}, 2\pi\right)$	2π
f'	+	+	0	–	0	–	0	+	+
f		↗	max: $\frac{3\sqrt{3}}{2}$	↘		↘	min: $-\frac{3\sqrt{3}}{2}$	↗	

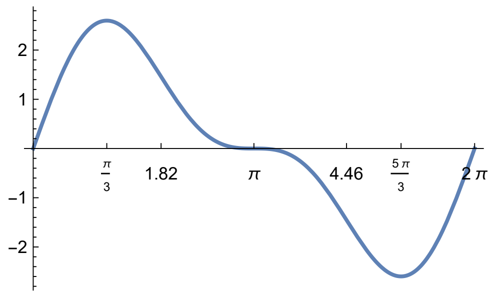
Convexity / concavity, inflection points:
$f''(x) = -2\sin x - 4\sin 2x = -2\sin x - 8\sin x\cos x =$

$$= -2\sin x(1 + 4\cos x) = 0 \Longrightarrow \sin x = 0 \text{ or } \cos x = -\frac{1}{4}$$

$$\Longrightarrow x_1 = 0,\ x_2 = \pi,\ x_3 = 2\pi,\ x_4 = \arccos\left(-\frac{1}{4}\right) \approx 1.82,\ x_5 = 2\pi - \arccos\left(-\frac{1}{4}\right) \approx 4.46$$

x	0	(0, 1.82)	1.82	(1.82, π)	π	(π, 4.46)	4.46	(4.46, 2 π)	2π
f''	0	–	0	+	0	–	0	+	0
f	infl:0	⋂	infl:\n $\frac{3\sqrt{15}}{8}$	⋃	infl:0	⋂	infl:\n $-\frac{3\sqrt{15}}{8}$	⋃	infl:0

The graph of f:



$\Longrightarrow R_f = \left[-\frac{3\sqrt{3}}{2}, \frac{3\sqrt{3}}{2}\right]$

Implicitely given curve

Example. The curve $y = y(x)$ is given by the following implicit equation:

$$x \sinh x - y \cosh y = 0$$

Study the properties of this curve in a neighbourhood of (0, 0).

Solution. The point (0, 0) is on the curve: $y(0) = 0$.

1) The first derivative of $x \sinh x - y(x) \cosh y(x) = 0$ with respect to x:

$$\sinh x + x \cosh x - y'(x) \cosh y(x) - y(x)\, y'(x) \sinh y(x) = 0$$

If $x = 0,\ y = 0 \Longrightarrow 0 + 0 \cdot 1 - y'(0) \cdot 1 - 0 \cdot y'(0) \cdot 0 = 0 \Longrightarrow y'(0) = 0$

2) The second derivative with respect to x:

$$\cosh x + \cosh x + x \sinh x - y''(x) \cosh y(x) - y'(x)\, y'(x) \sinh y(x)$$
$$- y'(x)\, y'(x) \sinh y(x) - y(x)\, y''(x) \sinh y(x) - y(x)\, y'(x)\, y'(x) \cosh y(x) = 0$$

If $x = 0, y = 0 \Longrightarrow 1 + 1 + 0 - y''(0) - 0 - 0 - 0 - 0 = 0 \Longrightarrow y''(0) = 2$

Since $y'(0) = 0$ and $y''(0) = 2 > 0$ then the curve $y = y(x)$ has local minimum at $x = 0$ and it is convex in some neighbourhood of $x = 0$.