Vv156 Lecture 11

Dr Jing Liu

UM-SJTU Joint Institute

October 24, 2016

- Recall the sequence $\{a_n\}$ is said to be increasing if

$$a_{n+1} \geq a_n \qquad \text{for all } n.$$

and it is said to be decreasing if

$$a_{n+1} \leq a_n \qquad \text{for all } n.$$

Q: Let $\mathcal{I} \subset \mathbb{R}$ be an interval, How to define the notion of increasing/decreasing for

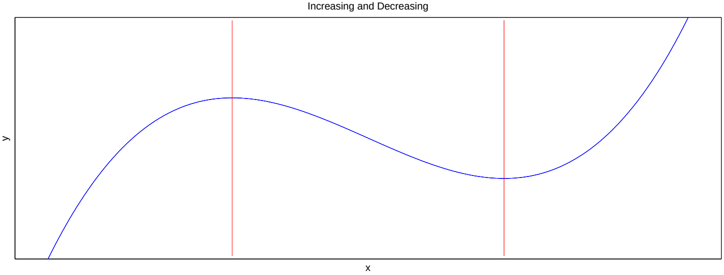
$$\text{a function} \qquad f(x) \qquad \text{where} \qquad x \in \mathcal{I}$$

Definition

Suppose f is defined on an interval $\mathcal{I}$, and x_1 and x_2 denote points in $\mathcal{I}$, then

1. f is increasing on the interval if $f(x_1) \leq f(x_2)$ whenever $x_1 < x_2$.
2. f is decreasing on the interval if $f(x_1) \geq f(x_2)$ whenever $x_1 < x_2$.

Q: Can you think of any connection between increasing/decreasing and $f'(x)$?



Theorem

Suppose $f(x)$ is continuous on an interval $\mathcal{I}$, and differentiable on its interior.

1. If $f'(x) > 0$ for every interior point of $\mathcal{I}$, then f is increasing on $\mathcal{I}$.
2. If $f'(x) < 0$ for every interior point of $\mathcal{I}$, then f is decreasing on $\mathcal{I}$.

Proof

- Consider some interior point c of $\mathcal{I}$, if $f'(x) > 0$ for every interior point $\mathcal{I}$, then

$$f'(c) = \lim_{x \to c} \frac{f(x) - f(c)}{x - c} = L > 0$$

- By definition, for every $\epsilon > 0$ there is a $\delta > 0$ such that

$$\left| \frac{f(x) - f(c)}{x - c} - L \right| < \epsilon \qquad \text{if} \qquad 0 < |x - c| < \delta$$

- Expanding the left, we have

$$-\epsilon + L < \frac{f(x) - f(c)}{x - c} < \epsilon + L$$

- For x sufficiently close to c but greater than c, we have

$$x - c > 0$$

Proof

- So we can rearrange the last inequality

$$\boxed{(L-\epsilon)(x-c) < f(x) - f(c)} < (L+\epsilon)(x-c)$$

- If we look at the lower bound provided of $f(x) - f(c)$ by the last inequality

$$\boxed{(L-\epsilon)(x-c) < f(x) - f(c)}$$

- Since $L >$, there is always some $0 < \epsilon < L$, such that

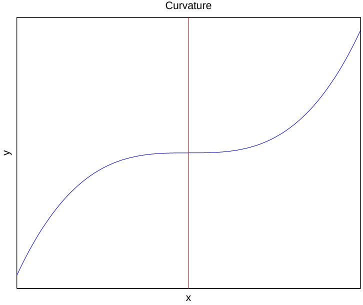
$$f(x) - f(c) > 0 \qquad \text{for} \qquad x - c > 0.$$

- So there is an open interval extending right from c such that the function is

increasing

- Since c is arbitrary, this shows that f is increasing on the entire interval $\mathcal{I}$.
- This proves the first part, the second part is true for a similar reason. $\square$

- The sign of the derivative of f reveals where the graph of f is increasing and where it is decreasing, but it does not reveal the direction of curvature, i.e.



Definition

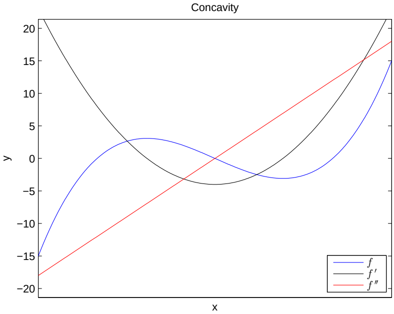
Let $f(x)$ be differentiable on an interval $\mathcal{I}$. The graph of $f(x)$ is said to be

1. concave up on $\mathcal{I}$ if and only if $f'(x)$ is increasing on $\mathcal{I}$.
2. concave down on $\mathcal{I}$ if and only if $f'(x)$ is decreasing on $\mathcal{I}$.

Theorem

Suppose $f(x)$ is twice differentiable on an interval $\mathcal{I}$.

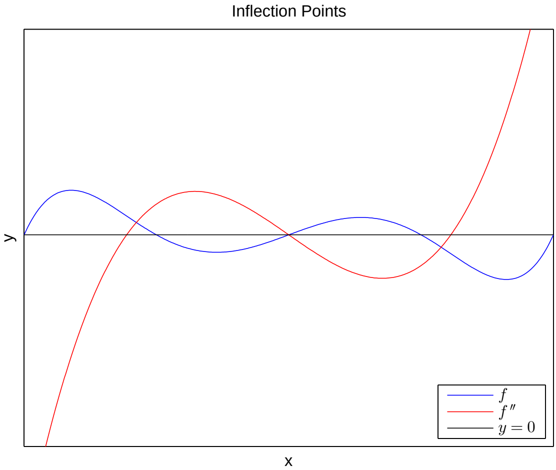
1. If $f''(x) > 0$ for all x in $\mathcal{I}$, then f is concave up on I.
2. If $f''(x) < 0$ for all x in $\mathcal{I}$, then f is concave down on I.



- This theorem follows directly from the last theorem P3.

Definition

If f changes the direction of concavity at the point $(x_0, f(x_0))$, then we say that f has an inflection point at x_0.



Exercise

(a) *Find the intervals on which*

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

is increasing or decreasing.

(b) *Use the first and second derivatives of the function*

$$f(x) = x^3 - 3x^2 + 1$$

to determine the intervals on which $f(x)$ is increasing, decreasing, concave up, and concave down. Identify all inflection points, if any.

(c) *Describe the concavity of the graph of*

$$f(x) = x^4$$

Definition

Let c be a number in the domain $\mathcal{D}$ of a function f. Then $f(c)$ is a

- *global/absolute* maximum of f for a set $\mathcal{I} \subset \mathcal{D}$ which contains c if

$$f(c) \geq f(x) \qquad \text{for all } x \in \mathcal{I}.$$

- *global/absolute* minimum of f for a set $\mathcal{I} \subset \mathcal{D}$ which contains c if

$$f(c) \leq f(x) \qquad \text{for all } x \in \mathcal{I}.$$

- local/relative maximum of f if there is a neighbourhood $\mathcal{U} \subset \mathcal{D}$ of c such that

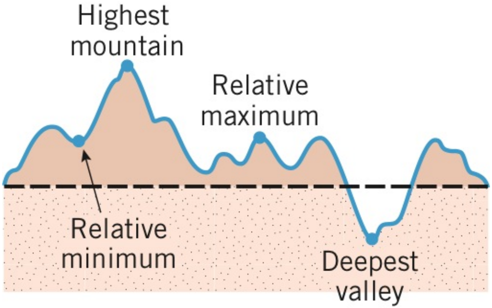
$$f(c) \geq f(x) \qquad \text{for all } x \in \mathcal{U}.$$

- local/relative minimum of f if there is a neighbourhood $\mathcal{U} \subset \mathcal{D}$ of c such that

$$f(c) \leq f(x) \qquad \text{for all } x \in \mathcal{U}.$$

- We say f has an extremum at c if f has either a maximum or a minimum at c

- If we imagine the graph of a function $f(x)$ to be a two-dimensional mountain range with hills and valleys,



- Relative maxima or local maxima are the tops of the hills.
- Relative minima or local maxima are the bottoms of the valleys.
- The relative extrema are the high or low points in their immediate vicinity

Q: Find the relative extrema, if any, for the following functions

1. $f(x) = x^2$:

   Relative minimum at $x = 0$.

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

   No relative extremum.

3. $f(x) = \cos x$:

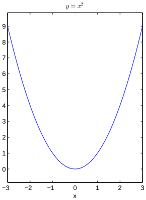
   Relative maxima at even π; Relative minima at odd π.

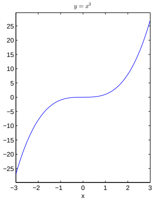
4. $f(x) = x^3 - 3x + 3$:

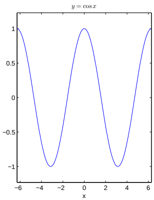
   Relative maximum at $x = -1$; Relative minimum at $x = 1$.

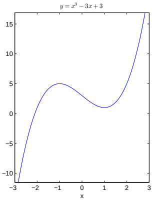
5. $f(x) = \frac{1}{2}x^4 - \frac{4}{3}x^3 - x^2 + 4x + 1$

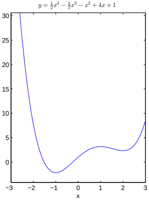
Q: How to find relative extrema for a function, that is differentiable in its domain, except possibly for finite number of points?





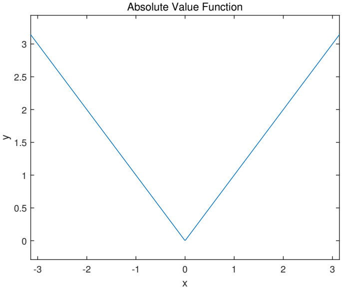






Q: What do you notice regarding extrema and the slope at the extremum?

Q: Is there any other way to have a relative extreme?



Definition

We define a critical point for f to be a point in the domain of f at which either

1. The graph of f has a horizontal tangent line.

$$f' = 0$$

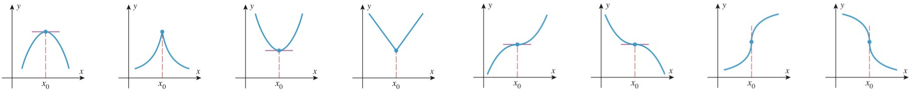
2. The derivative function f' does not exist.

To distinguish between the two types of critical points we call

point c a stationary point of f if $f'(c)$ is defined.

Q: Which of the followings x_0 is a critical point/stationary point?

(a) (b) (c) (d) (e) (f) (g) (h)



Q: What will ensure that a critical point is a relative extrema?

The first derivative test

Suppose c is a critical point for $f(x)$.

1. If f' changes from positive to negative at c, then

   $$f \text{ has a relative maximum at } c.$$

2. If f' changes from negative to positive at c, then

   $$f \text{ has a relative minimum at } c.$$

3. If f' does not change sign at c, then

   $$f \text{ has no local maximum or minimum at } c.$$

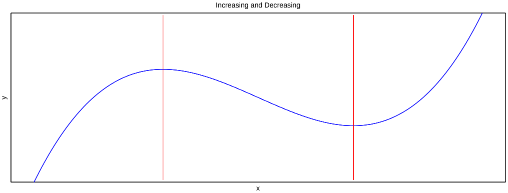
Exercise

Find all critical points of

$$f(x) = 3x^5 - 5x^3$$

and then determine their nature by using the first derivative test.

Q: Is there any connection between the relative extrema of a twice differentiable function $f(x)$ and the concavity of $f(x)$?



The second derivative test

Suppose that f'' exists at the point c.

1. If $f'(c) = 0$ and $f''(c) > 0$, then f has a relative minimum at c.
2. If $f'(c) = 0$ and $f''(c) < 0$, then f has a relative maximum at c.
3. If $f'(c) = 0$ and $f''(c) = 0$, then the test is inconclusive; that is,

f may have a relative maximum, a relative minimum, or neither at c.

- The second derivative test is more convenient than the first derivative test.

Exercise

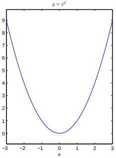
Find all critical points of

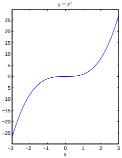
$$f(x) = 3x^5 - 5x^3$$

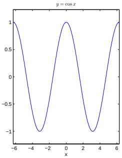
and then determine their nature using the second derivative test.

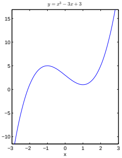
- Neither the first nor the second derivative test gives us a procedure directly to find relative extrema, they are merely tests for points in the domain of f.

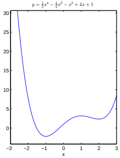
Q: How can we narrow it down to a finite number of points?

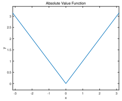












- The next theorem proves our previous formally.

Theorem

If $f(x)$ is differentiable at $x = c$ and $f(c)$ is a relative extremum, then the point c is a stationary point

$$f'(c) = 0$$

Proof

- If f has a relative maximum at c, then

$$f(x) \leq f(c) \qquad \text{for all } x \text{ in a } \delta\text{-neighbourhood of } c$$

so

$$\frac{f(c+h) - f(c)}{h} \leq 0 \qquad \text{for all } 0 < h < \delta,$$

which implies that

$$f'(c) = \lim_{h \to 0^+} \left[\frac{f(c+h) - f(c)}{h} \right] \leq 0.$$

Proof

- Moreover,
$$\frac{f(c+h)-f(c)}{h} \geq 0 \qquad \text{for all } -\delta < h < 0,$$
which implies that
$$f'(c) = \lim_{h\to 0^-} \left[\frac{f(c+h)-f(c)}{h}\right] \geq 0.$$
- If follows that $f'(c) = 0$ in order to have no contradiction of differentiability.
- If f has a relative minimum at c, the argument is similar. The only difference is the signs in these inequalities are reversed and the conclusion remains to be
$$f'(c) = 0 \quad \square$$

- This theorem limits the search for an extremum on the domain to critical points.
- However, the converse of this theorem is not true.

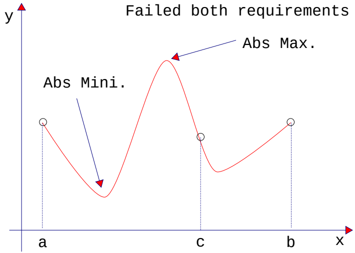
Q: Can you think of an example where a critical point is not a relative extremum?

Q: Is there any curve, which is continuous on a closed interval, and has either not got an absolute maximum or not got an absolute minimum in the interval?

The Extreme-Value Theorem

If a function $f(x)$ is continuous on a closed interval $\mathcal{I}$, then f attains an absolute maximum value $f(c)$ and an absolute minimum value $f(d)$ where $c, d \in \mathcal{I}$.

Q: Is there any curve, which is either not continuous or only defined on an open interval has got both absolute maximum and absolute minimum?



- The extreme-value theorem (EVT) is an example of what mathematicians call an existence theorem. Such theorems state conditions under which certain objects exist, in this case absolute extrema.
- However, knowing that an object exists and finding it are two separate things.
- If f is continuous on the finite closed interval $[a, b]$, the following procedures can be used to find the absolute extrema:

Procedures for finding absolute extrema

1. Find the critical point of f in (a, b)
2. Evaluate f at all the critical points and the end points
3. Compare values in step 2, the largest of them is the absolute maximum of f on $[a, b]$, the smallest is the absolute minimum.

Exercise

Find the absolute extrema of $f(x) = 6x^{4/3} - 3x^{1/3}$ *on the interval* $[-1, 1]$, *and determine where these values occur.*