

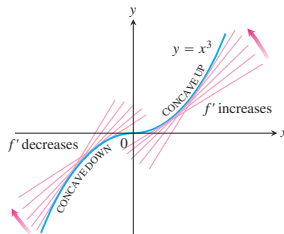
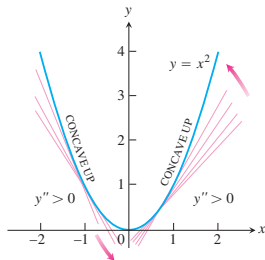
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2425-MA140 Engineering Calculus

Week 06, Lecture 2 Curve sketching

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A sketch of today's class...

1 The First Derivative Test (again)

- Review
- The Test
- Example

2 Concave up and down functions

3 Inflection points

4 Second derivative test

5 Curve Sketching

6 Exercises

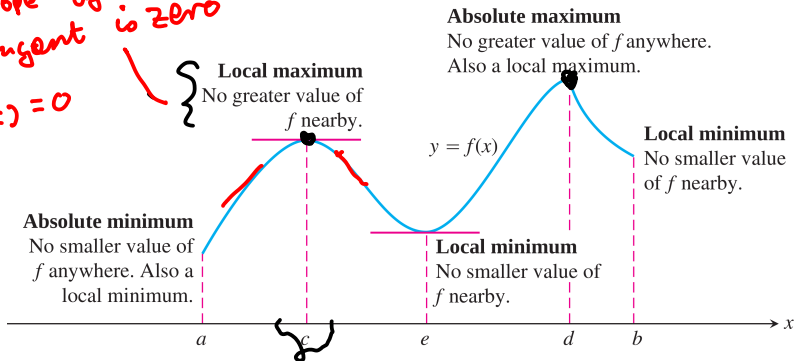
See also: Section 4.5 (Derivatives and the Shape of a Graph) of **Calculus** by Strang & Herman: Section 4.3 (Maxima and Minima) of **Calculus** by Strang & Herman: [https://math.libretexts.org/Bookshelves/Calculus/Calculus_\(OpenStax\)](https://math.libretexts.org/Bookshelves/Calculus/Calculus_(OpenStax))

Yesterday, we started studying the application of differentiation in locating (local) maxima and minima in functions.

There are the key points to recall:

- **maximum** and **minimum** points are collectively called **extreme** points.

Slope of tangent is zero
 $f'(c) = 0$



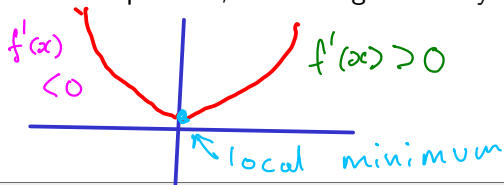
- ▶ $x = c$ is a **critical point** of $f(x)$ if either $f'(c) = 0$ or $f'(c)$ does not exist.
- ▶ All extreme points occur at critical points. (but not all critical points correspond to extreme points).
- ▶ To find a maximum or minimum of f , we first find the critical points.
- ▶ If $f'(x) > 0$ at each point $x \in [a, b]$, then f is increasing on $[a, b]$.
- ▶ If $f'(x) < 0$ at each point $x \in [a, b]$, then f is decreasing on $[a, b]$.

First Derivative Test for local maxima and minima

Suppose that c is a critical point of a differentiable function f .

1. If f' changes sign from positive when $x < c$ to negative when $x > c$, then $f(c)$ is a **local maximum** of f .
2. If f' changes sign from negative when $x < c$ to positive when $x > c$ then $f(c)$ is a **local minimum** of f .
3. If f' has the same sign for $x < c$ and $x > c$ then $f(c)$ is neither a local maximum nor a local minimum of f .

We finished yesterday with an example that was overly complicated, and wrong! Let's try a better one.



Example (Example 4.5.1 from textbook)

Use the first derivative test to find the location of all local extrema of $f(x) = x^3 - 3x^2 - 9x - 1$. *and characterize them*

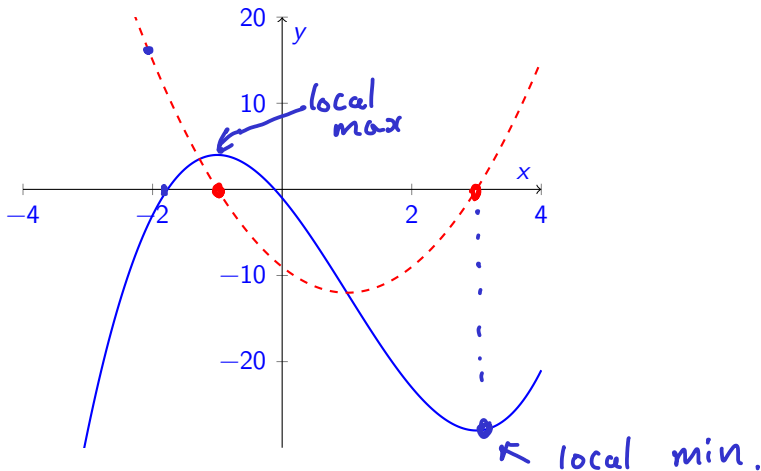
1. Differentiate $f(x)$ to get $f'(x) = 3x^2 - 6x - 9$.
2. Solve for the critical points. Since $f'(x)$ is defined everywhere, we just need to solve $3x^2 - 6x - 9 = 0$. Simplifying, this is $x^2 - 2x - 3 = 0$. That factorizes as $f'(x) = (x + 1)(x - 3)$, which has two zeros: at $x = -1$, and $x = 3$.
3. Now we need to know how f' is changing sign at these points. Check the text-book for a technical approach, we'll use a simple one.

"Characterize an Extremum" = "say if it is a max or min".

4. By calculation (e.g., with a calculator), we'll check $x = -1$. We see $f'(-1.1) = 1.23$ and $f'(-0.9) = -11.97$. So f' changes from **positive** to **negative** at $x = -1$, so we have a **local maximum**.
5. Similarly, we'll check $x = 3$. We see $f'(2.9) = -1.17$ and $f'(3.1) = 1.23$. So f' changes from **negative** to **positive** at $x = 3$, so we have a **local minimum** there.



A plot of $f(x)$ and $f'(x)$ (but which is which??)



Concave up and down functions

Definition

The graph of a differentiable function $y = f(x)$ is:

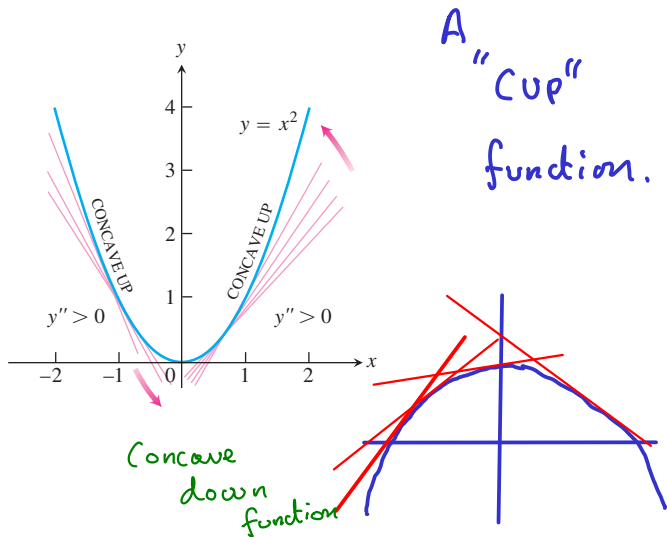
- ▶ **concave up** on an open interval (a, b) if f' is increasing on (a, b) ;
- ▶ **concave down** on an open interval (a, b) if f' is decreasing on (a, b)

Note:

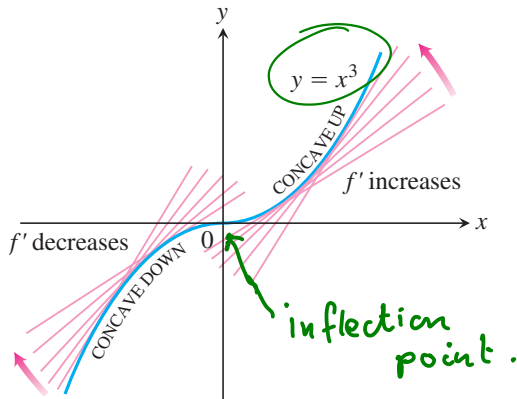


- ▶ If the graph of f is **concave up** (“cup”), it is **above** its tangents.
- ▶ If the graph of f is **concave down**, it is **below** its tangents.

Concave up and down functions



Concave up and down functions



Concave up and down functions

Relating concavity to f''

Let $y = f(x)$ be twice-differentiable on an open interval (a, b) .

- ▶ If $f'' > 0$ on (a, b) , the graph of f is **concave up**
- ▶ If $f'' < 0$ on (a, b) , the graph of f is **concave down**

Example: $f(x) = x^2$ is concave up (for all x) and $g(x) = -x^2$ is concave down.

↓

$$f'(x) = 2x$$

and $f''(x) = 2$

And $2 > 0.$

$$g'(x) = -2x$$
$$g''(x) = -2 < 0$$

Inflection points

Definition: inflection point

A **point of inflection** is a point at which the concavity of a function changes.

At such a point, either f'' is zero or does not exist.

Example

Find a point of inflection of the graph of $f(x) = x^3$.

"Concavity changes" means "switch from concave up to concave down" or vice versa.

$$f(x) = x^3 \Rightarrow f'(x) = 3x^2 \Rightarrow f''(x) = 6x \quad \begin{cases} \text{negative} & \text{if } x < 0 \\ \text{positive} & \text{if } x > 0. \end{cases}$$

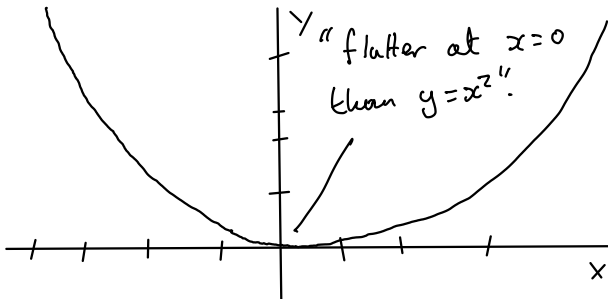
Note $f''(0) = 0, \dots$

Inflection points

Warning: Having $f''(c) = 0$ does not necessarily mean that f has an inflection point at $x = c$.

Example

The curve $y = x^4$ has no inflection point at $x = 0$. Even though $y'' = 12x^2$ is zero there, it does not change sign.



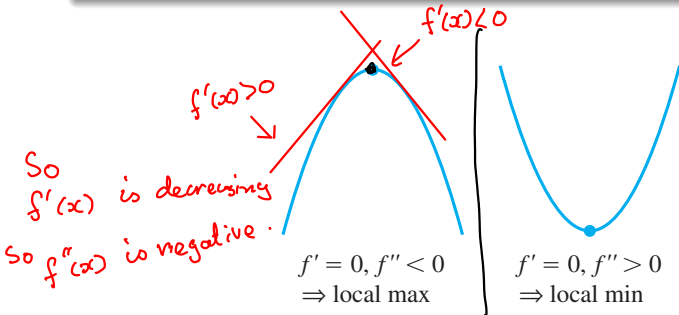
Second derivative test

c is a critical point.

Second Derivative Test

Suppose that f'' is continuous on an interval that contains c .

- ▶ If $f'(c) = 0$ and $f''(c) < 0$ then f has a **local max** at $x = c$.
- ▶ If $f'(c) = 0$ and $f''(c) > 0$, then f has a **local min** at $x = c$.
- ▶ If $f'(c) = 0$ and $f''(c) = 0$, then the test is inconclusive. The function f may have a local max, a local min, or neither.



Second derivative test

Example

Find and classify the critical and inflection points of

$$f(x) = 4x^3 - 21x^2 + 18x + 6.$$

1 We have $f'(x) = 12x^2 - 42x + 18$.

divide by 6

When $f'(x) = 0$, we have

$$12x^2 - 42x + 18 = 0 \Leftrightarrow 2x^2 - 7x + 3 = 0$$



$$\Leftrightarrow (2x - 1)(x - 3) = 0.$$

Solve $2x - 1 = 0 \Rightarrow x = \frac{1}{2}$,

Solve $x - 3 = 0 \Rightarrow x = 3$.

So the critical points are at $x = \frac{1}{2}$ and $x = 3$.

2 Next $f''(x) = 24x - 42$ so

$$f''\left(\frac{1}{2}\right) = 24\left(\frac{1}{2}\right) - 42 = 12 - 42 = -30 < 0$$

which means there is a local **maximum** at $x = \frac{1}{2}$.

Second derivative test

Also, we have a local **minimum** at $x = 3$ because

$$f''(3) = 24(3) - 42 = 72 - 42 = 30 > 0$$

Now solve for $f''(x) = 0$ for any inflection point.

Now, recall that $f''(x) = 24x - 42$. Thus,

$$f''(x) = 0 \Leftrightarrow x = \frac{42}{24} = \frac{7}{4}$$

Note that

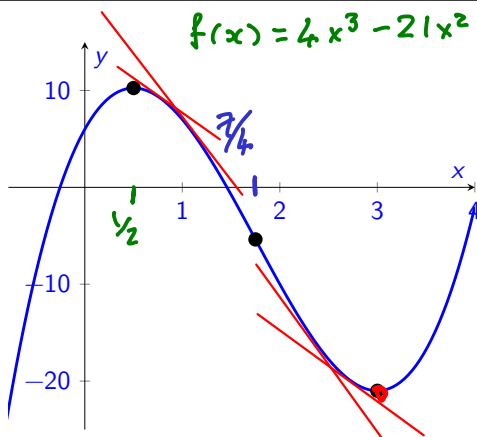
$$x < \frac{7}{4} \Rightarrow f''(x) < 0$$

$$x > \frac{7}{4} \Rightarrow f''(x) > 0.$$

Therefore, $f(x)$ has a point of inflection at $x = \frac{7}{4}$.

✓ because $f''(x)$ changes sign.

Second derivative test



Local max at
 $x = 1/2$

Local minimum
at $x = 3$

Inflection
point at
 $x = 7/4$

Second derivative test

Review

If a function f is differentiable on an interval (a, b) , then

- ▶ $f'(x) > 0$ for $a < x < b$, then ~~it~~ it is increasing on (a, b) .
- ▶ $f'(x) < 0$ for $a < x < b$, then ~~it~~ it is decreasing on (a, b) .
- ▶ $f''(x) > 0$ for $a < x < b$, then it is concave up on (a, b) .
- ▶ $f''(x) < 0$ for $a < x < b$, then it is concave down on (a, b) .

Second derivative test

Review (continued)

1st Derivative Test:

If f' changes sign at a critical point, c , it is a local maximum or minimum.

2nd Derivative Test:

- ▶ If $f''(c) < 0$, then there is a local maximum at $x = c$. ✓
- ▶ If $f''(c) > 0$, then there is a local minimum at $x = c$. ✓
- ▶ If $f''(c) = 0$ at a critical point c , then the test is inconclusive.

Curve Sketching

In order to roughly **sketch the graph** of a function, f , we can use the following steps:

1. Compute $f'(x)$ and find the critical (~~stationary~~) points and inflection points of f . Find the corresponding y -value of these points.
2. If necessary, compute $f''(x)$, and use the second derivative test (optional).
3. Make a table showing the intervals on which f is increasing and/or decreasing, and where f is concave up and/or concave down.
4. Plot some specific points (e.g. local max/ min, points of inflection, intercepts) and sketch the general shape of the graph of f .
ie where it cuts the axes.

Curve Sketching

Example

Sketch the graph of the function $f(x) = x^4 - 4x^3 + 10$

① Find $f'(x)$. $f'(x) = 4x^3 - 12x^2$

Solve $f'(x) = 0$ i.e. $4x^3 - 12x^2 = 0$
 $\Rightarrow x^2(4x - 12) = 0$

So $f'(x) = 0$ if $x = 0$ or $4x - 12 = 0$
 $\Rightarrow x = 0$ or $x = 3$

So f has critical points at $x = 0, x = 3$.

② $f''(x) = 12x^2 - 24x$.

Check $f''(0) = 0 \Rightarrow$ test is inconclusive

Check $f''(3) = 12(9) - 24(3) = 108 - 72 = 36 > 0$
so local min.

Curve Sketching

Step 3: Make table to find intervals on which f is increasing/decreasing and on which f is concave up and concave down

	0		2		3	
$4x^2$	+	•	+		+	
$x - 3$	-		-		-	•
$f'(x)$	-	•	-		-	•
$12x$	-	•	+		+	
$x - 2$	-		-	•	+	
$f''(x)$	+	•	-	•	+	

Curve Sketching

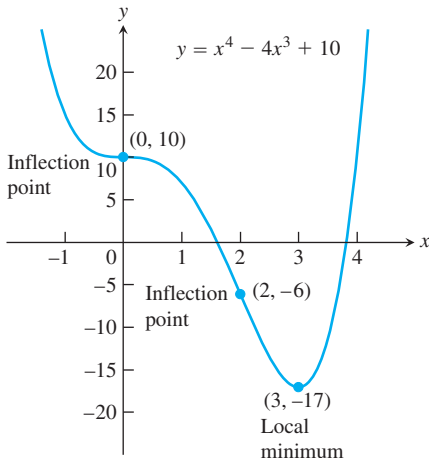
Step 4: Plot specific points (such as local max/min, points of inflection, intercepts) - and sketch general shape of graph of f

Didn't get to finish this in class, so details will be added to the (unannotated) notes later!

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Curve Sketching

Step 5: Plot specific points (such as local max/min, points of inflection, intercepts) - and sketch general shape of graph of f



Exercise 6.2.1 : 23/24 Exam, Q3(a)

Let $f(x) = \ln(x^2 + 1)$.

- (i) Find all critical point(s) of f and determine whether f has a local minimum, local maximum or neither.
- (ii) Determine the interval on which f is increasing.
- (iii) Determine the interval on which f is decreasing.
- (iv) Find all point(s) of inflection of f , justifying your answer.

Exer 6.2.2 (Based on 2019/20 Exam, Q3(a))

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

1. Find all asymptotes of the graph $f(x)$
2. Determine the interval(s) on which $f(x)$ is increasing and decreasing.
3. Determine the interval(s) on which $f(x)$ is concave up (convex) and concave down (or concave).
4. Find all point(s) of inflection for the graph of $f(x)$.
5. Give a rough sketch the graph of $f(x)$ (your axes need not necessarily have the same scale).