Topic 11 – Review of power series

- power series

- thm 37.24

- radii of convergence
  - $e^x$
  - $x^2+1$
  - $\frac{1}{1-x}$
  - do $e^{x^2}$

approximate $\frac{1}{1-x}$ by succesive terms

HW
- add up first few terms of power series to approximate

- analytic

- tayler series

$$f(x) = f(x_0) + f'(x_0)(x-x_0) + \dots$$

- <u>ex:</u> Suppose you know $f(0)=2$, $f'(0)=1$, $f''(0)=5, \dots$ find first few terms of power series

term by term

- derivatives thm

$$f(x) = \sum_{n=0}^{\infty} a_n (x-x_0)^n = \dots$$

$$f'(x) = \sum_{n=1}^{\infty} a_n \cdot n \cdot (x-x_0)^{n-1} = \dots$$

talk about index

$$f''(x) = \sum_{n=2}^{\infty} a_n \cdot n \cdot (n-1) \cdot (x-x_0)^{n-2} = \dots$$

Def: An infinite sum is a sum of the form

$$\sum_{n=0}^{\infty} a_n = a_0 + a_1 + a_2 + a_3 + a_4 + \cdots$$

where the $a_i$ are real numbers.

We say that the sum above converges if there exists a real number $S$ where

$$\lim_{N\to\infty} \underbrace{\sum_{n=0}^{N} a_n}_{} = \lim_{N\to\infty} \Big( \underbrace{a_0 + a_1 + a_2 + \cdots + a_N}_{\text{Summing the first } N \text{ terms}} \Big) = S$$

these are called partial sums

In this case we write

$$\sum_{n=0}^{\infty} a_n = S$$

If the above limit doesn't exist then we say that the infinite sum diverges.

Ex: Consider the sum

$$\sum_{n=0}^{\infty} \frac{1}{2^n} = 1 + \frac{1}{2} + \frac{1}{2^2} + \frac{1}{2^3} + \frac{1}{2^4} + \cdots$$

Let's calculate some partial sums

$$\sum_{n=0}^{N} \frac{1}{2^N} = \frac{1}{1} + \frac{1}{2} + \cdots + \frac{1}{2^N}$$

| $N$ | $1+\frac{1}{2}+\frac{1}{2^2}+\frac{1}{2^3}+\cdots+\frac{1}{2^N}$ |
|---|---|
| 0 | $1$ |
| 1 | $1+\frac{1}{2} = 1.5$ |
| 2 | $1+\frac{1}{2}+\frac{1}{2^2} = 1.75$ |
| 3 | $1+\frac{1}{2}+\frac{1}{2^2}+\frac{1}{2^3} = 1.875$ |
| 4 | $1+\frac{1}{2}+\frac{1}{2^2}+\frac{1}{2^3}+\frac{1}{2^4} = 1.9375$ |
| 5 | $1.96875$ |
| 6 | $1.98438$ |
| $\vdots$ | |
| 50 | $1.\underbrace{999999999999999}_{15\ 9\text{'s}}11182\ldots$ |
| $\vdots$ | |
| 100 | $1.\underbrace{999\cdots99}_{30\ 9\text{'s}}211139\ldots$ |

In Calculus you showed that this limit as $N \to \infty$ is equal to 2

and so

$$\underbrace{\sum_{n=0}^{\infty} \frac{1}{2^n} = 2}_{}$$

in Calculus this is called a geometric sum

**Def:** A **power series** is an infinite sum of the form

$$\sum_{n=0}^{\infty} a_n (x-x_0)^n = a_0 + a_1(x-x_0) + a_2(x-x_0)^2 + a_3(x-x_0)^3 + \cdots$$

Above $x$ is a variable and the $a_n$ and $x_0$ are constants. The power series is said to be **centered at $x_0$**.

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**Ex:** (Geometric series)

$$\sum_{n=0}^{\infty} x^n = 1 + x + x^2 + x^3 + x^4 + \cdots$$

$$\sum_{n=0}^{\infty} a_n (x-x_0)^n$$

$a_n = 1$ for all $n$

$x_0 = 0$

This power series is centered at $x_0 = 0$

In Calculus you showed that

Case 1: If $-1<x<1$, then the geometric sum converges and

$$\sum_{n=0}^{\infty} x^n = 1+x+x^2+x^3+\dots = \frac{1}{1-x}$$

Case 2: If $-1<x$ or $1<x$, then the geometric sum

$$\sum_{n=0}^{\infty} x^n = 1+x+x^2+x^3+\dots$$

diverges (it doesn't have a limit)

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Ex: $$\sum_{n=0}^{\infty}\left(\frac{1}{2}\right)^n = 1+\frac{1}{2}+\frac{1}{2^2}+\frac{1}{2^3}+\dots$$

$$= \frac{1}{1-\frac{1}{2}} = \frac{1}{\left(\frac{1}{2}\right)} = 2$$

$x=\frac{1}{2}$
$-1<x<1$

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Ex:

$$\sum_{n=0}^{\infty} 5^n = 1+5+5^2+5^3+\dots$$

diverges

Idea:

Think of $\sum_{n=0}^{\infty} x^n$ as a function $f(x)$.

So, $f(x) = \sum_{n=0}^{\infty} x^n = 1 + x + x^2 + x^3 + x^4 + \dots$

this equals $\frac{1}{1-x}$ when $-1 < x < 1$

Then

$$f(0) = 1 + 0 + 0^2 + 0^3 + \dots = \frac{1}{1-0} = 1$$

$$f\left(\tfrac{1}{3}\right) = 1 + \frac{1}{3} + \frac{1}{3^2} + \frac{1}{3^3} + \dots = \frac{1}{1-\frac{1}{3}} = \frac{3}{2}$$

$$f\left(-\tfrac{1}{4}\right) = 1 + \left(-\frac{1}{4}\right) + \left(-\frac{1}{4}\right)^2 + \left(-\frac{1}{4^3}\right) + \dots$$

$$= 1 - \frac{1}{4} + \frac{1}{4^2} - \frac{1}{4^3} + \dots$$

$$= \frac{1}{1-\left(-\frac{1}{4}\right)} = \frac{4}{5}$$

$f(0) = 1$

$f\left(\frac{1}{3}\right) = \frac{3}{2}$

$f\left(-\frac{1}{4}\right) = \frac{4}{5}$

However,

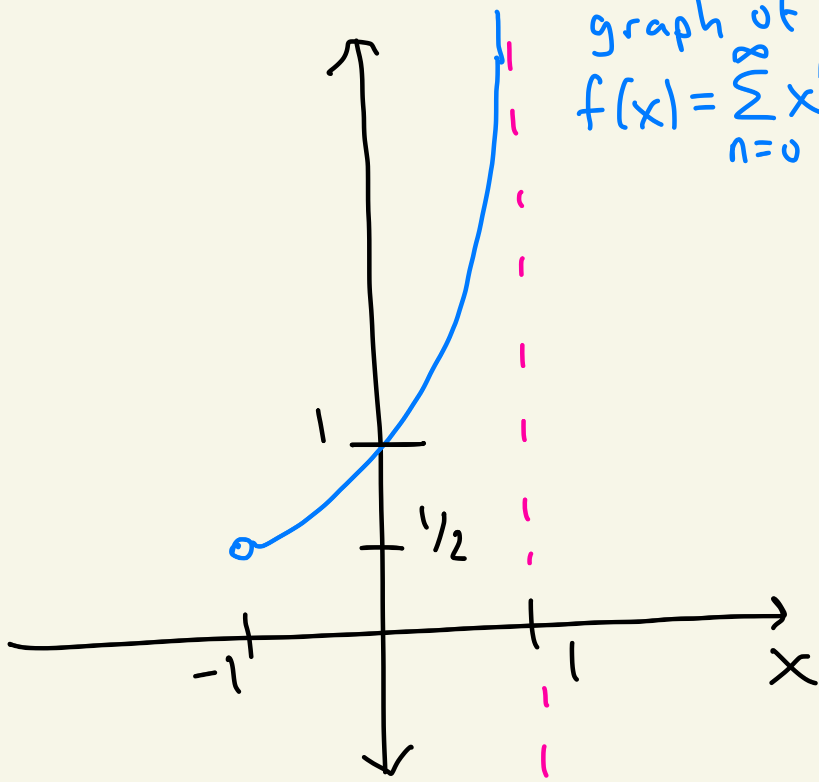
$$f(2) = 1 + 2 + 2^2 + 2^3 + \dots$$

$$f(-3.2) = 1 - 3.2 + (-3.2)^2 + (-3.2)^3 + \dots$$

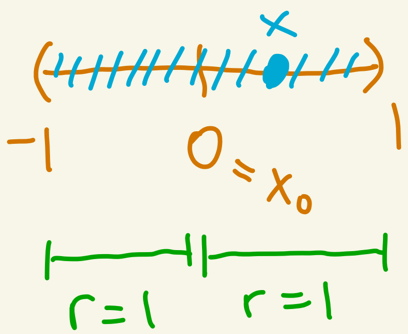
are undefined.

# Picture:

graph of $f(x) = \sum_{n=0}^{\infty} x^n$




f is only defined in this interval

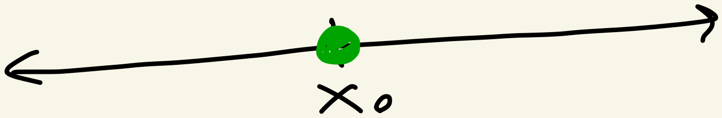



you can only plug in x's in this range into the power series.
r = 1 is called the radius of convergence

**Theorem:** There are three possible scenarios for a power series

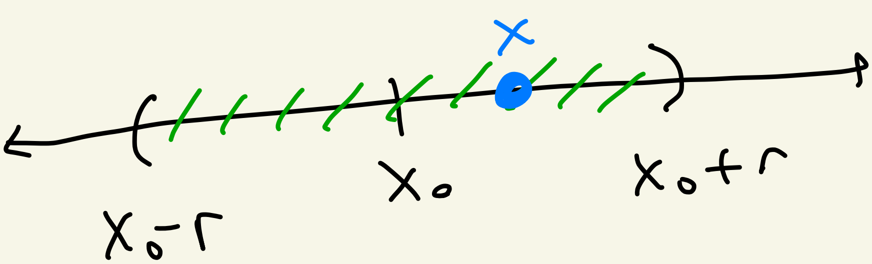
$$\sum_{n=0}^{\infty} a_n (x-x_0)^n = a_0 + a_1(x-x_0) + a_2(x-x_0)^2 + \cdots$$

① The series converges only when $x = x_0$.




Here you can only plug $x = x_0$ into the series. In this case we say the radius of convergence is $r = 0$

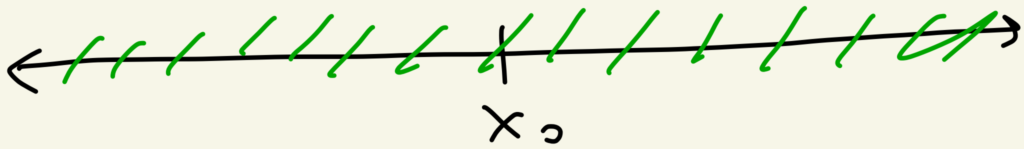
② There exists $r > 0$ where the series converges for all $x$ when $x_0 - r < x < x_0 + r$, but it doesn't converge if $x < x_0 - r$ or $x_0 + r < x$




$r$ is called the radius of convergence

In this case as long as $x$ is in this interval the series converges past the endpoints it will diverge. At endpoints can either converge or diverge.

(3) The series converges for all $x$.




Here $r = \infty$ is the radius of convergence.

The next examples are from Calculus.

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Ex:

$$e^x = \sum_{n=0}^{\infty} \frac{1}{n!} x^n = 1 + x + \frac{1}{2!} x^2 + \frac{1}{3!} x^3 + \cdots$$

converges for all $x$.

Here $x_0 = 0$, $r = \infty$

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Ex: The sine/cosine series centered at $x_0 = 0$ are:

$$\sin(x) = \sum_{n=0}^{\infty} (-1)^n \frac{1}{(2n+1)!} x^{2n+1}$$

$$= x - \frac{1}{3!} x^3 + \frac{1}{5!} x^5 - \frac{1}{7!} x^7 + \cdots$$

$$\cos(x) = \sum_{n=0}^{\infty} (-1)^n \frac{1}{(2n)!} x^{2n}$$

$$= 1 - \frac{1}{2!} x^2 + \frac{1}{4!} x^4 - \frac{1}{6!} x^6 + \cdots$$

These both converge for all $x$

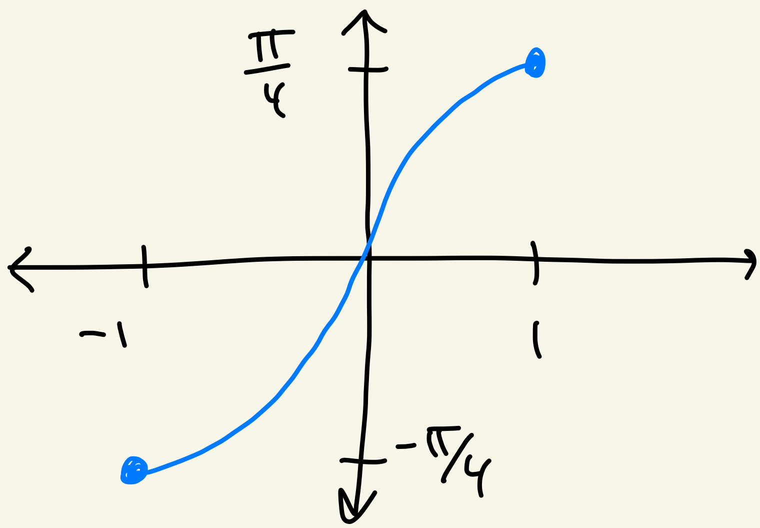
So, $r = \infty$.

Ex: If $-1 \leq x \leq 1$, then

$$\tan^{-1}(x) = \sum_{n=0}^{\infty} (-1)^n \frac{1}{(2n+1)!} x^{2n+1}$$

$$= x - \frac{1}{3!}x^3 + \frac{1}{5!}x^5 - \frac{1}{7!}x^7 + \cdots$$

sum is only defined when $-1 \leq x \leq 1$




radius of convergence is

$r = 1$

centered at $x_0 = 0$

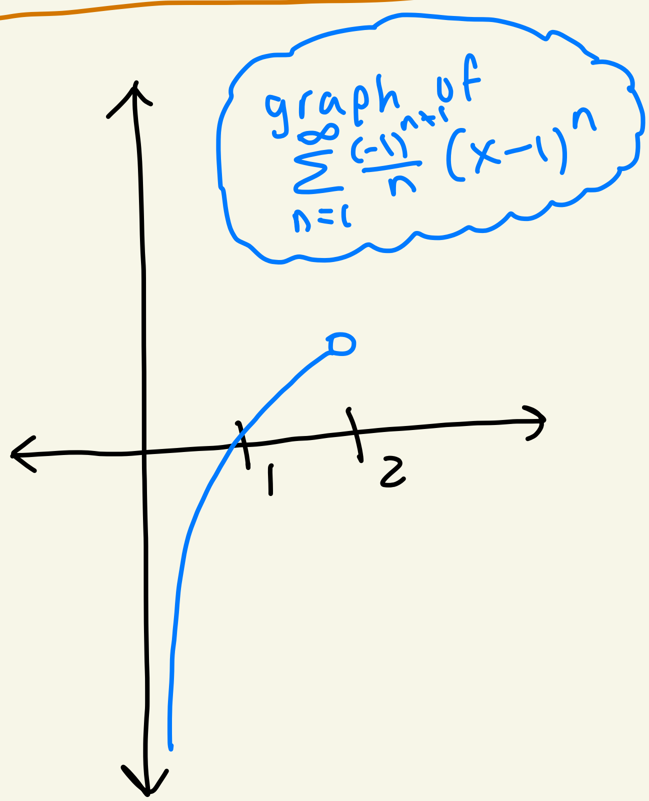
Ex: We can make a power series centered at $x_0 = 1$ that converges to $\ln(x)$. It is,

$$\ln(x) = \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n}(x-1)^n$$

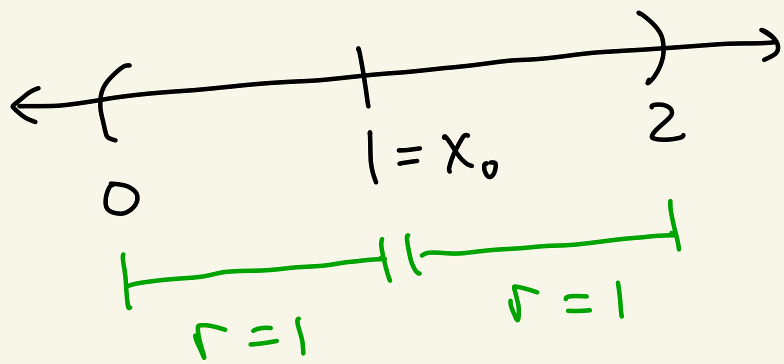
from calculus

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

It converges on when $0 < x < 2$.




Here we have:




So,

$x_0 = 1$

$r = 1$

radius of convergence

**Theorem:** Suppose

$$f(x) = \sum_{n=0}^{\infty} a_n (x-x_0)^n = a_0 + a_1(x-x_0) + a_2(x-x_0)^2 + a_3(x-x_0)^3 + \cdots$$

has radius of convergence $r > 0$.

Then,

$$a_n = \frac{f^{(n)}(x_0)}{n!}$$

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**Ex:** $\boxed{x_0 = 0}$

$$\sin(x) = x - \frac{1}{3!}x^3 + \frac{1}{5!}x^5 - \frac{1}{7!}x^7 + \cdots$$

$$= 0 + 1 \cdot x + 0 \cdot x^2 - \frac{1}{3!}x^3 + 0 \cdot x^4 - \frac{1}{5!}x^5 + \cdots$$

$f(x) = \sin(x)$
$f(0) = 0$

$f'(x) = \cos(x)$
$f'(0) = 1$
$\frac{f'(0)}{1!} = 1$

$f''(x) = -\sin(x)$
$f''(0) = 0$
$\frac{f''(0)}{2!} = 0$

$f^{(3)}(x) = -\cos(x)$
$f^{(3)}(0) = -1$
$\frac{f^{(3)}(0)}{3!} = \frac{-1}{3!}$

Ex: Find a power series for $f(x) = x^2$ centered at $x_0 = 2$.

Let's use the formula above to hopefully get an answer.

$f(x) = x^2 \rightarrow f(2) = 4$

$f'(x) = 2x \rightarrow f'(2) = 4$

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

$f^{(3)}(x) = 0 \rightarrow f'''(2) = 0$

$\underset{k \geq 4}{f^{(k)}(x) = 0} \rightarrow \underset{k \geq 4}{f^{(k)}(2) = 0}$

$$f(2) + f'(2)(x-2) + \frac{f''(2)}{2!}(x-2)^2 + \frac{f^{(3)}(2)}{3!}(x-2)^3 + \frac{f^{(4)}(2)}{4!}(x-2)^4 + \cdots$$

$$= 4 + 4(x-2) + \frac{2}{2}(x-2)^2 + 0(x-2)^3 + 0(x-2)^4 + \cdots$$

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

One can check: $x^2 = 4 + 4(x-2) + (x-2)^2$

And the right-hand side always converges since its a finite sum. The radius of convergence is $r = \infty$, ie the formula works for all $x$.

Theorem: If

$$f(x) = \sum_{n=0}^{\infty} a_n (x-x_0)^n = a_0 + a_1(x-x_0) + a_2(x-x_0)^2 + \cdots$$

has radius of convergence $r > 0$, then

$$f'(x) = \sum_{n=1}^{\infty} n \cdot a_n (x-x_0)^{n-1}$$

$$= a_1 + 2a_2(x-x_0) + 3a_3(x-x_0)^2 + \cdots$$

and

$$\int f(x)\,dx = \sum_{n=0}^{\infty} \frac{a_n}{n+1}(x-x_0)^{n+1}$$

$$= a_0(x-x_0) + \frac{a_1}{2}(x-x_0)^2 + \frac{a_2}{3}(x-x_0)^3 + \cdots$$

where the power series for $f'(x)$ and $\int f(x)\,dx$ also have radii of convergence $r$.

Ex: Find a power series expansion for $f(x) = \frac{1}{x}$ at $x_0 = 1$.

If we only look at $x > 0$, then

$$\frac{1}{x} = \frac{d}{dx}\ln(x)$$

$$\overset{\boxed{0<x<2}}{=} \frac{d}{dx}\left[\sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n}(x-1)^n\right]$$

$$= \frac{d}{dx}\left[(x-1) - \frac{1}{2}(x-1)^2 + \frac{1}{3}(x-1)^3 - \ldots\right]$$

$$= 1 - (x-1) + (x-1)^2 - \ldots$$

So,

$$\frac{1}{x} = \sum_{n=1}^{\infty} (-1)^{n+1}(x-1)^{n-1} = 1 - (x-1) + (x-1)^2 - \ldots$$

which as radius of convergence $r = 1$ about $x_0 = 1$.

So the series converges for $0 < x < 2$