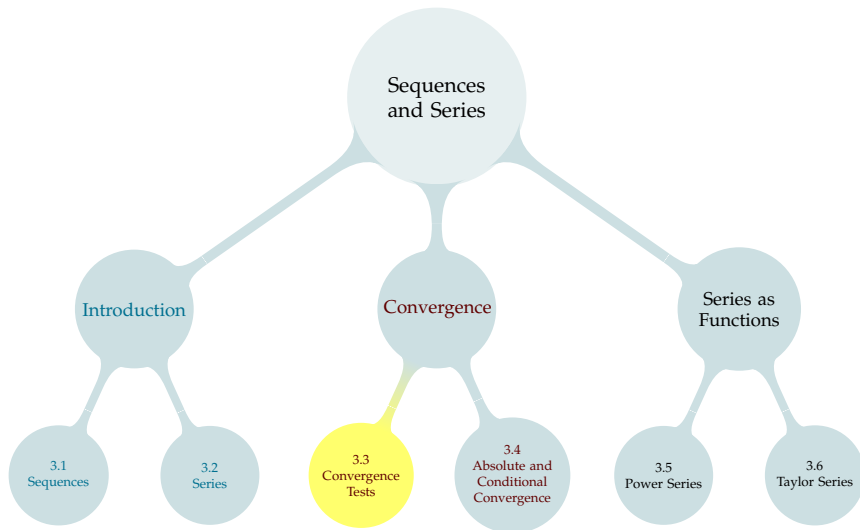


# TABLE OF CONTENTS



For a convergent geometric or telescoping series, we can easily determine what the series converges *to*.

For other types of series, finding out what the series converges to can be very difficult. It is often necessary to resort to approximating the full sum by, for example, using a computer to find the sum of the first  $N$  terms, for some large  $N$ . But before we even try to do that, we should at least know *whether or not the series converges*.

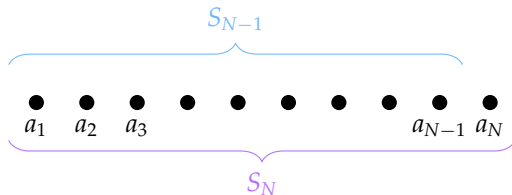
Suppose a series  $\sum_{n=1}^{\infty} a_n$  converges to a limit  $L$ . Let  $S_N = \sum_{n=1}^N a_n$ .

$$\lim_{N \rightarrow \infty} S_N =$$

$$\lim_{N \rightarrow \infty} S_{N-1} =$$

$$\lim_{N \rightarrow \infty} [S_N - S_{N-1}] =$$

$$\lim_{N \rightarrow \infty} a_N =$$



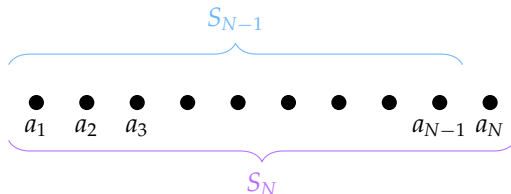
Suppose a series  $\sum_{n=1}^{\infty} a_n$  converges to a limit  $L$ . Let  $S_N = \sum_{n=1}^N a_n$ .

$$\lim_{N \rightarrow \infty} S_N = L$$

$$\lim_{N \rightarrow \infty} S_{N-1} = L$$

$$\lim_{N \rightarrow \infty} [S_N - S_{N-1}] = L - L = 0$$

$$\lim_{N \rightarrow \infty} a_N = 0$$



**Every** convergent series has its  $N^{\text{th}}$  term,  $a_N$ , tending to 0 as  $N \rightarrow \infty$ .

## Divergence Test

If the sequence  $\{a_n\}_{n=c}^{\infty}$  fails to converge to zero as  $n \rightarrow \infty$ , then the series  $\sum_{n=c}^{\infty} a_n$  diverges.

## Divergence Test

If the sequence  $\{a_n\}_{n=c}^{\infty}$  fails to converge to zero as  $n \rightarrow \infty$ , then the series  $\sum_{n=c}^{\infty} a_n$  diverges.

Do the following series diverge?

▶  $\sum_{n=0}^{\infty} (-1)^n$

▶  $\sum_{n=10}^{\infty} \left( \frac{1}{10} + \frac{1}{2^n} \right)$

▶  $\sum_{n=15}^{\infty} \frac{e^n}{2e^n - 1}$

▶  $\sum_{n=15}^{\infty} \frac{1}{n}$

## Divergence Test

If the sequence  $\{a_n\}_{n=c}^{\infty}$  fails to converge to zero as  $n \rightarrow \infty$ , then the series  $\sum_{n=c}^{\infty} a_n$  diverges.

Do the following series diverge?

$$\blacktriangleright \sum_{n=0}^{\infty} (-1)^n$$

yes, it diverges

$$\blacktriangleright \sum_{n=10}^{\infty} \left( \frac{1}{10} + \frac{1}{2^n} \right)$$

yes, it diverges

$$\blacktriangleright \sum_{n=15}^{\infty} \frac{e^n}{2e^n - 1}$$

yes, it diverges

$$\blacktriangleright \sum_{n=15}^{\infty} \frac{1}{n}$$

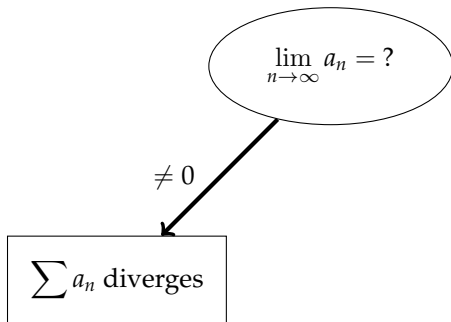
at this point, unclear: maybe, maybe not

# USING THE DIVERGENCE TEST FOR $\sum a_n$

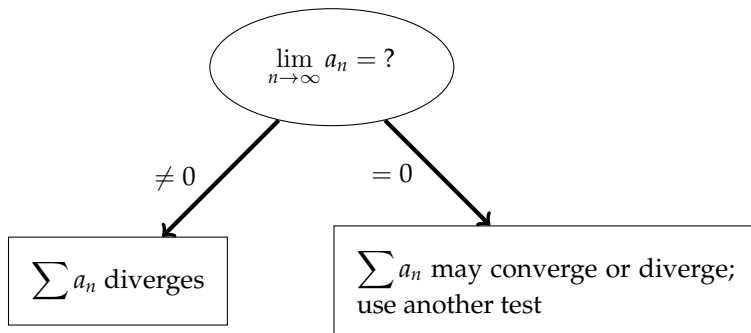
$$\lim_{n \rightarrow \infty} a_n = ?$$



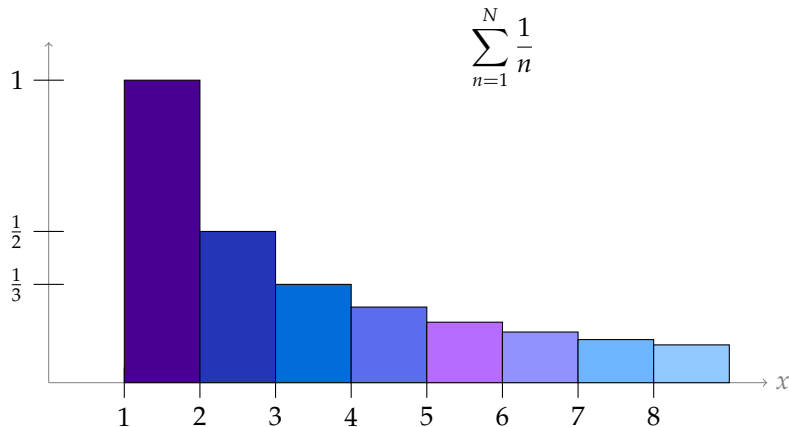
# USING THE DIVERGENCE TEST FOR $\sum a_n$



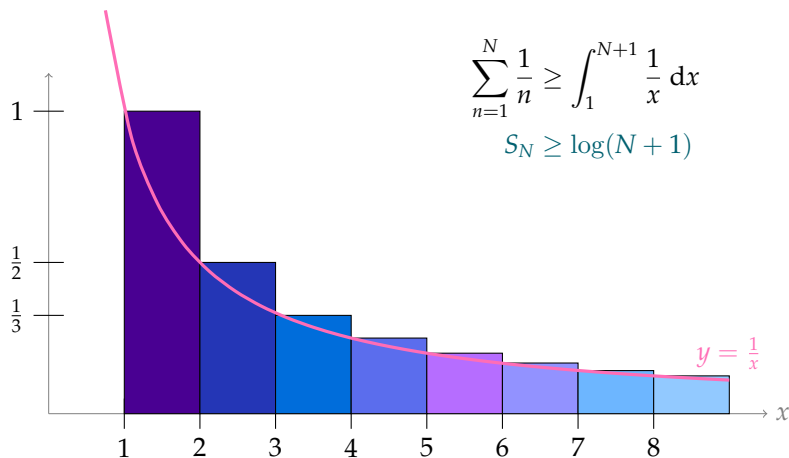
# USING THE DIVERGENCE TEST FOR $\sum a_n$



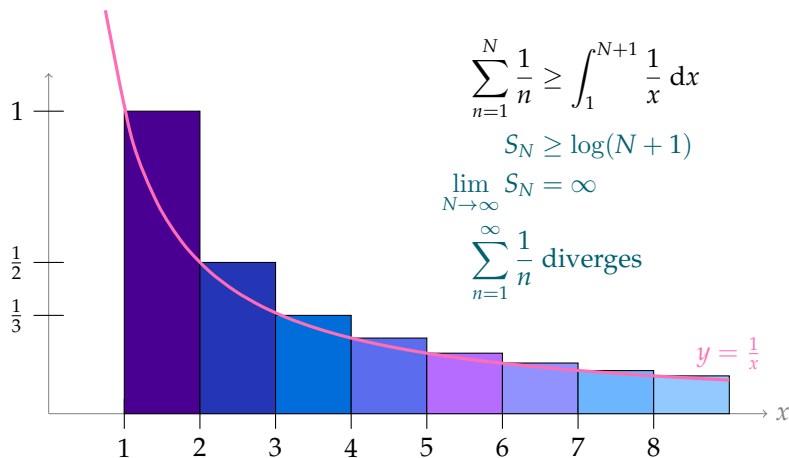
# HARMONIC SERIES: $\sum_{n=1}^{\infty} \frac{1}{n}$



# HARMONIC SERIES: $\sum_{n=1}^{\infty} \frac{1}{n}$



# HARMONIC SERIES: $\sum_{n=1}^{\infty} \frac{1}{n}$

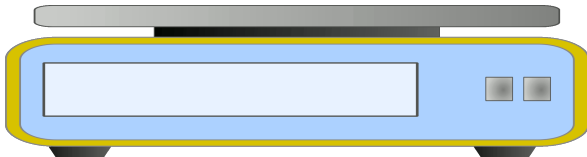


$$\sum_{n=1}^{\infty} \frac{1}{n}$$

DIVERGES



1

 $\frac{1}{2}$  $\frac{1}{3}$  $\frac{1}{4}$  $\frac{1}{5}$ 

$$\sum_{n=1}^{\infty} \frac{1}{n}$$

DIVERGES

$$S_1 = 1.0000$$

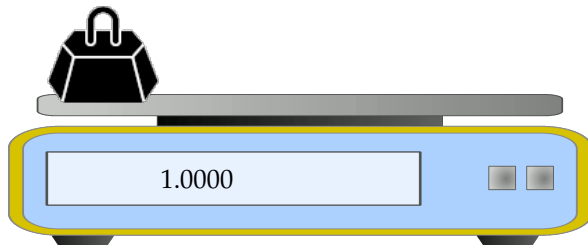


$$\frac{1}{2}$$

$$\frac{1}{3}$$

$$\frac{1}{4}$$

$$\frac{1}{5}$$

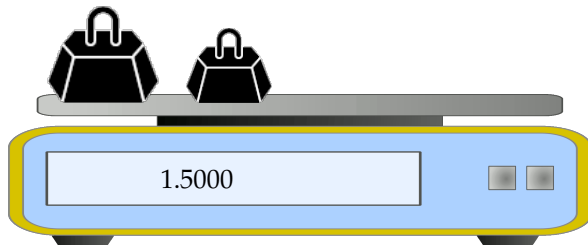
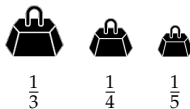


$$\sum_{n=1}^{\infty} \frac{1}{n}$$

DIVERGES

$$S_1 = 1.0000$$

$$S_2 = 1.5000$$





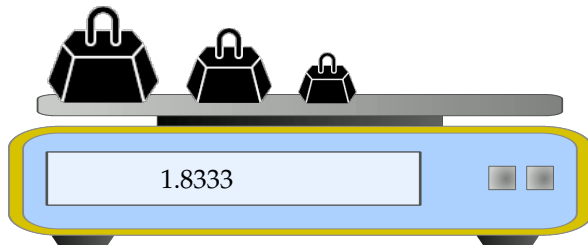
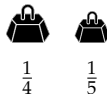
$$\sum_{n=1}^{\infty} \frac{1}{n}$$

DIVERGES

$$S_1 = 1.0000$$

$$S_2 = 1.5000$$

$$S_3 = 1.8333$$



$$\sum_{n=1}^{\infty} \frac{1}{n}$$

DIVERGES

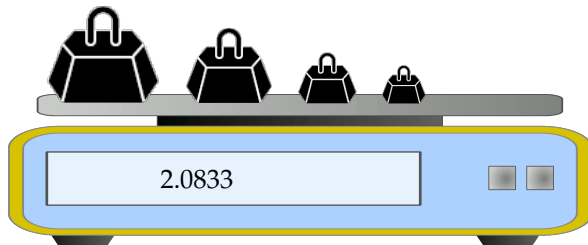
$$S_1 = 1.0000$$

$$S_2 = 1.5000$$

$$S_3 = 1.8333$$

$$S_4 = 2.0833$$



$$\frac{1}{5}$$


$$\sum_{n=1}^{\infty} \frac{1}{n}$$

DIVERGES

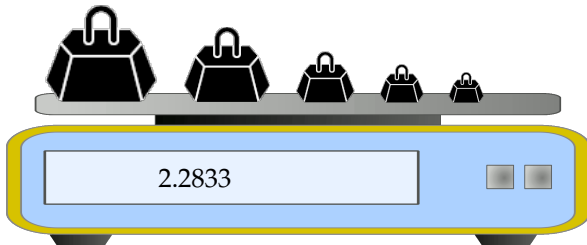
$$S_1 = 1.0000$$

$$S_2 = 1.5000$$

$$S_3 = 1.8333$$

$$S_4 = 2.0833$$

$$S_5 = 2.2833$$

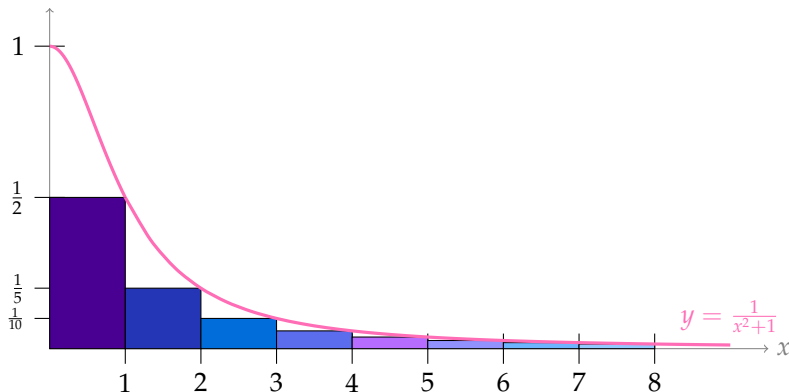


$$\sum_{n=1}^{\infty} \frac{1}{n^2+1}$$

○○●○○○○○○○○○○○○

○○○○○○○○○○○○○○○○○○

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



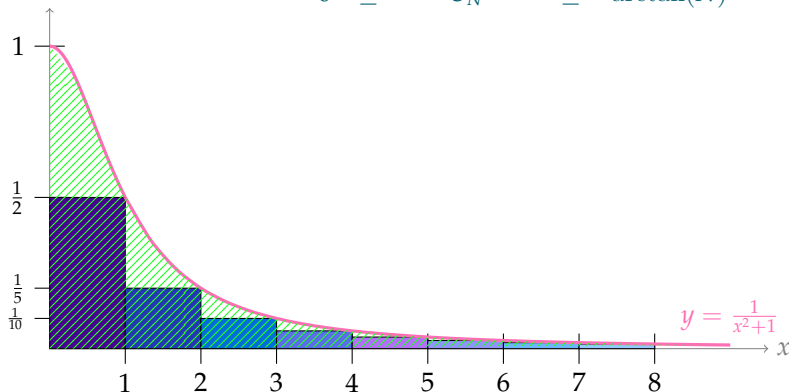
$$\sum_{n=1}^{\infty} \frac{1}{n^2+1}$$

○○●○○○○○○○○○○○○

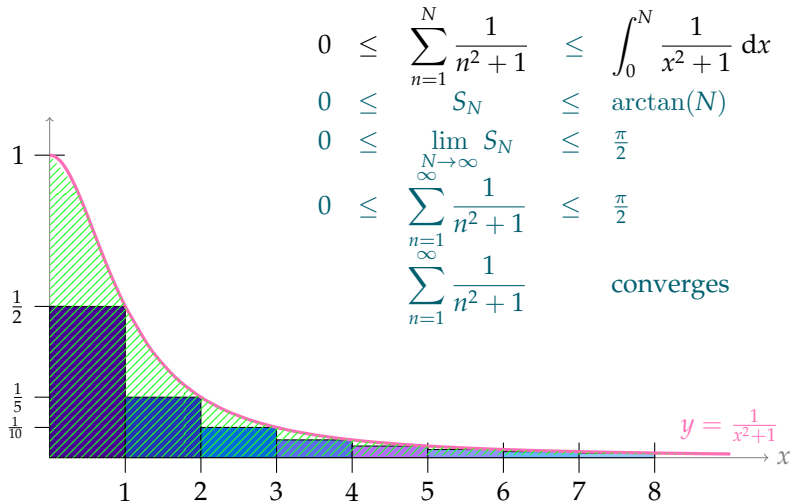
○○○○○○○○○○○○○○○○○○

$$0 \leq \sum_{n=1}^N \frac{1}{n^2+1} \leq \int_0^N \frac{1}{x^2+1} dx$$

$$0 \leq S_N \leq \arctan(N)$$

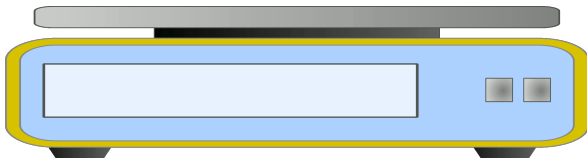


$$\sum_{n=1}^{\infty} \frac{1}{n^2+1}$$



$$\sum_{n=1}^{\infty} \frac{1}{n^2 + 1}$$

CONVERGES

 $\frac{1}{2}$  $\frac{1}{5}$  $\frac{1}{10}$  $\frac{1}{17}$  $\frac{1}{26}$ 

$$\sum_{n=1}^{\infty} \frac{1}{n^2 + 1}$$

CONVERGES

$$S_1 = 0.5000$$



$$\frac{1}{5}$$



$$\frac{1}{10}$$



$$\frac{1}{17}$$



$$\frac{1}{26}$$



0.5000





$$\sum_{n=1}^{\infty} \frac{1}{n^2 + 1}$$

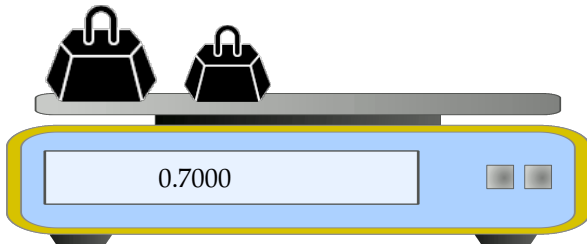
CONVERGES

$$S_1 = 0.5000$$

$$S_2 = 0.7000$$



$$\frac{1}{10} \quad \frac{1}{17} \quad \frac{1}{26}$$



$$\sum_{n=1}^{\infty} \frac{1}{n^2 + 1}$$

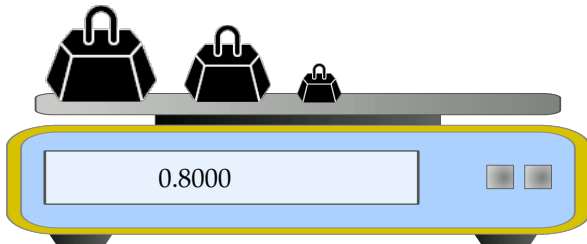
CONVERGES

$$S_1 = 0.5000$$

$$S_2 = 0.7000$$

$$S_3 = 0.8000$$

$$\frac{1}{17} \quad \frac{1}{26}$$



$$\sum_{n=1}^{\infty} \frac{1}{n^2 + 1}$$

CONVERGES

$$S_1 = 0.5000$$

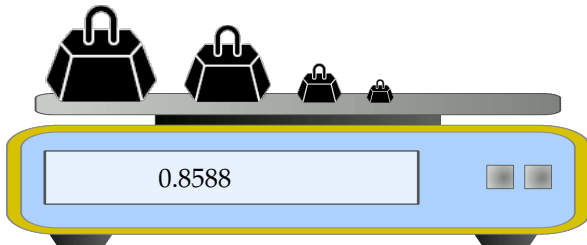
$$S_2 = 0.7000$$

$$S_3 = 0.8000$$

$$S_4 = 0.8588$$



$$\frac{1}{26}$$



$$\sum_{n=1}^{\infty} \frac{1}{n^2 + 1}$$

CONVERGES

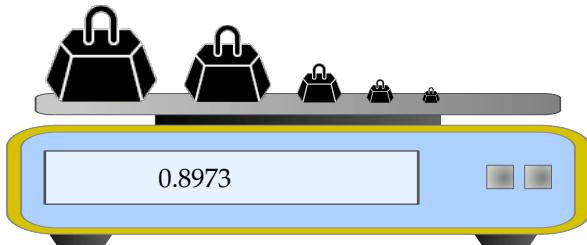
$$S_1 = 0.5000$$

$$S_2 = 0.7000$$

$$S_3 = 0.8000$$

$$S_4 = 0.8588$$

$$S_5 = 0.8973$$

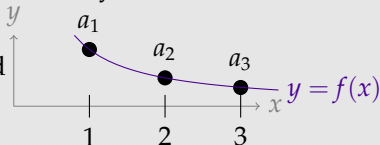


## Integral Test

Let  $N_0$  be any natural number. If  $f(x)$  is a function which is defined and continuous for all  $x \geq N_0$  and which obeys

- (i)  $f(x) \geq 0$  for all  $x \geq N_0$  and
- (ii)  $f(x)$  decreases as  $x$  increases and
- (iii)  $f(n) = a_n$  for all  $n \geq N_0$ .

Then



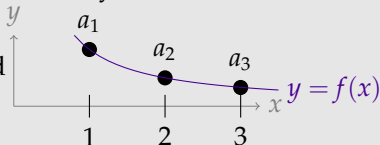
$$\sum_{n=1}^{\infty} a_n \text{ converges} \iff \int_{N_0}^{\infty} f(x) \, dx \text{ converges}$$

## Integral Test

Let  $N_0$  be any natural number. If  $f(x)$  is a function which is defined and continuous for all  $x \geq N_0$  and which obeys

- (i)  $f(x) \geq 0$  for all  $x \geq N_0$  and
- (ii)  $f(x)$  decreases as  $x$  increases and
- (iii)  $f(n) = a_n$  for all  $n \geq N_0$ .

Then



$$\sum_{n=1}^{\infty} a_n \text{ converges} \iff \int_{N_0}^{\infty} f(x) \, dx \text{ converges}$$

Furthermore, when the series converges, the truncation error satisfies

$$0 \leq \sum_{n=1}^{\infty} a_n - \sum_{n=1}^N a_n \leq \int_N^{\infty} f(x) \, dx \quad \text{for all } N \geq N_0$$

Does the series  $\sum_{n=10}^{\infty} \frac{1}{n \log n}$  converge or diverge?

Does the series  $\sum_{n=10}^{\infty} \frac{1}{n \log n}$  converge or diverge?

## Divergence Test

If  $\lim_{n \rightarrow \infty} a_n \neq 0$ , then  $\sum_{n=a}^{\infty} a_n$  diverges.



Does the series  $\sum_{n=10}^{\infty} \frac{1}{n \log n}$  converge or diverge?

## Divergence Test

If  $\lim_{n \rightarrow \infty} a_n \neq 0$ , then  $\sum_{n=a}^{\infty} a_n$  diverges.

No use here: we need another test.

Does the series  $\sum_{n=10}^{\infty} \frac{1}{n \log n}$  converge or diverge?

## Divergence Test

If  $\lim_{n \rightarrow \infty} a_n \neq 0$ , then  $\sum_{n=a}^{\infty} a_n$  diverges.

No use here: we need another test.

Set  $f(x) = \frac{1}{x \log x}$ .

- (i)  $f(x) \geq 0$  for all  $x \geq 10$  and
- (ii)  $f(x)$  decreases as  $x$  increases and
- (iii)  $f(n) = a_n$  for all  $n \geq 10$ .

So, the integral test applies.

Does the series  $\sum_{n=10}^{\infty} \frac{1}{n \log n}$  converge or diverge?

$$\int_{10}^{\infty} \frac{1}{x \log x} dx =$$

Does the series  $\sum_{n=10}^{\infty} \frac{1}{n \log n}$  converge or diverge?

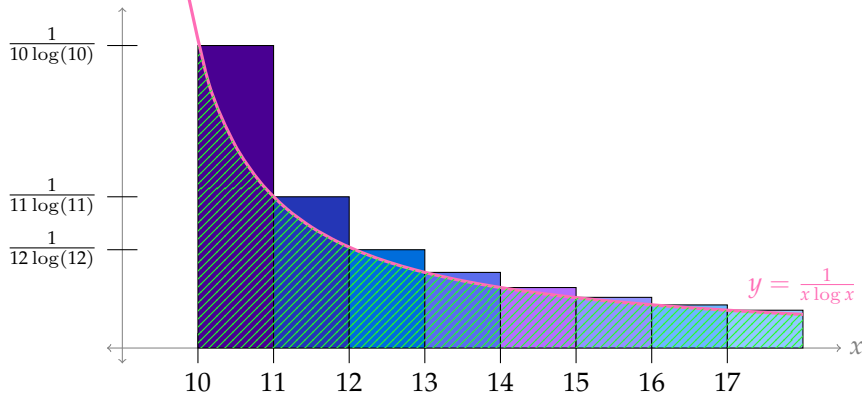
$$\int_{10}^{\infty} \frac{1}{x \log x} \, dx = \lim_{b \rightarrow \infty} \int_{10}^b \frac{1}{x \log x} \, dx$$

Using the substitution  $u = \log x$ ,  $du = \frac{1}{x} dx$ ,

$$\begin{aligned} &= \lim_{b \rightarrow \infty} \int_{\log(10)}^{\log(b)} \frac{1}{u} \, du \\ &= \lim_{b \rightarrow \infty} [\log(\log(b)) - \log(\log 10)] = \infty \end{aligned}$$

Since the integral **diverges**, and since  $f(x) = \frac{1}{x \log x}$  fulfils the requirements of the integral test, our series **diverges** as well.

Does the series  $\sum_{n=10}^{\infty} \frac{1}{n \log n}$  converge or diverge?

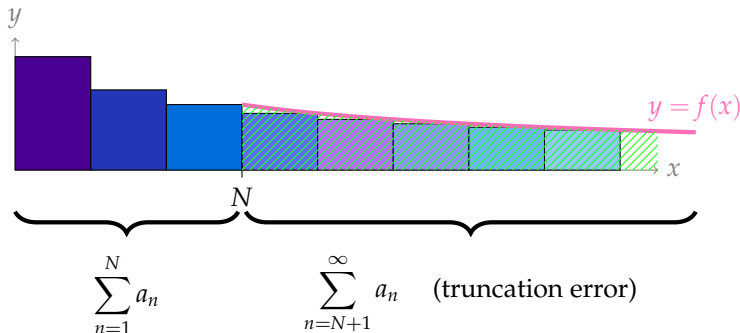


$$\int_{10}^{\infty} \frac{1}{x \log x} dx = \infty$$

## Integral Test, abridged

... When the series converges, the truncation error satisfies

$$0 \leq \sum_{n=1}^{\infty} a_n - \sum_{n=1}^N a_n \leq \int_N^{\infty} f(x) \, dx$$



## Integral Test, abridged

When the series converges, the truncation error satisfies

$$0 \leq \sum_{n=1}^{\infty} a_n - \sum_{n=1}^N a_n \leq \int_N^{\infty} f(x) \, dx$$

We already decided that the series  $\sum_{n=1}^{\infty} \frac{1}{n^2 + 1}$  converges.

Suppose we had a computer add up the terms  $n = 1$  through  $n = 100$ .

Use the integral test to bound the error,  $\sum_{n=1}^{\infty} \frac{1}{n^2 + 1} - \sum_{n=1}^{100} \frac{1}{n^2 + 1}$ .

We already decided that the series  $\sum_{n=1}^{\infty} \frac{1}{n^2 + 1}$  converges.

Suppose we had a computer add up the terms  $n = 1$  through  $n = 100$ .

Use the integral test to bound the error,  $\sum_{n=1}^{\infty} \frac{1}{n^2 + 1} - \sum_{n=1}^{100} \frac{1}{n^2 + 1}$ .



We already decided that the series  $\sum_{n=1}^{\infty} \frac{1}{n^2 + 1}$  converges.

Suppose we had a computer add up the terms  $n = 1$  through  $n = 100$ .

Use the integral test to bound the error,  $\sum_{n=1}^{\infty} \frac{1}{n^2 + 1} - \sum_{n=1}^{100} \frac{1}{n^2 + 1}$ .

$$\begin{aligned} \sum_{n=1}^{\infty} \frac{1}{n^2 + 1} - \sum_{n=1}^{100} \frac{1}{n^2 + 1} &\leq \int_{100}^{\infty} \frac{1}{x^2 + 1} dx \\ &= \lim_{b \rightarrow \infty} [\arctan(b) - \arctan(100)] = \frac{\pi}{2} - \arctan(100) \approx 0.01 \end{aligned}$$

By computer,  $\sum_{n=1}^{100} \frac{1}{n^2 + 1} \approx 1.0667$ . Using the truncation error of about 0.01, give a (small) range of possible values for  $\sum_{n=1}^{\infty} \frac{1}{n^2 + 1}$ .

$$0 \leq \sum_{n=1}^{\infty} \frac{1}{n^2 + 1} - \sum_{n=1}^{100} \frac{1}{n^2 + 1} \leq \int_{100}^{\infty} \frac{1}{x^2 + 1} dx$$

By computer,  $\sum_{n=1}^{100} \frac{1}{n^2 + 1} \approx 1.0667$ . Using the truncation error of about 0.01, give a (small) range of possible values for  $\sum_{n=1}^{\infty} \frac{1}{n^2 + 1}$ .

$$\begin{aligned}
 0 &\leq \sum_{n=1}^{\infty} \frac{1}{n^2 + 1} - \sum_{n=1}^{100} \frac{1}{n^2 + 1} \leq \int_{100}^{\infty} \frac{1}{x^2 + 1} dx \\
 0 &\leq \sum_{n=1}^{\infty} \frac{1}{n^2 + 1} - 1.0667 \leq 0.01 \\
 1.0667 &\leq \sum_{n=1}^{\infty} \frac{1}{n^2 + 1} \leq 1.0767
 \end{aligned}$$

# $p$ -TEST

Let  $p$  be a positive constant. When we talked about improper integrals, we showed:

$$\int_1^{\infty} \frac{1}{x^p} dx \quad \begin{cases} \text{converges if } p > 1 \\ \text{diverges if } p \leq 1 \end{cases}$$

# $p$ -TEST

Let  $p$  be a positive constant. When we talked about improper integrals, we showed:

$$\int_1^{\infty} \frac{1}{x^p} dx \quad \begin{cases} \text{converges if } p > 1 \\ \text{diverges if } p \leq 1 \end{cases}$$

Set  $f(x) = \frac{1}{x^p}$ .

- (i)  $f(x) \geq 0$  for all  $x \geq 1$ , and
- (ii)  $f(x)$  decreases as  $x$  increases

$$\sum_{n=1}^{\infty} \frac{1}{n^p} \quad \left\{ \right.$$

# $p$ -TEST

Let  $p$  be a positive constant. When we talked about improper integrals, we showed:

$$\int_1^{\infty} \frac{1}{x^p} dx \quad \begin{cases} \text{converges if } p > 1 \\ \text{diverges if } p \leq 1 \end{cases}$$

Set  $f(x) = \frac{1}{x^p}$ .

- (i)  $f(x) \geq 0$  for all  $x \geq 1$ , and
- (ii)  $f(x)$  decreases as  $x$  increases

$$\sum_{n=1}^{\infty} \frac{1}{n^p} dx \quad \begin{cases} \text{converges if } p > 1 \\ \text{diverges if } p \leq 1 \end{cases}$$

Consider the series

$$\sum_{n=1}^{\infty} \frac{1}{n^3}.$$

By the  $p$ -test, we know this series

Consider the series

$$\sum_{n=1}^{\infty} \frac{1}{n^3}.$$

By the  $p$ -test, we know this series converges.

How many terms should we add up to approximate the series to within an error of no more than 0.02?



Consider the series

$$\sum_{n=1}^{\infty} \frac{1}{n^3}.$$

By the  $p$ -test, we know this series converges.

How many terms should we add up to approximate the series to within an error of no more than 0.02?

$$\sum_{n=1}^{\infty} \frac{1}{n^3} - \sum_{n=1}^N \frac{1}{n^3} \leq \int_N^{\infty} \frac{1}{x^3} dx = \lim_{b \rightarrow \infty} \left[ -\frac{1}{2x^2} \right]_N^b = \frac{1}{2N^2}$$

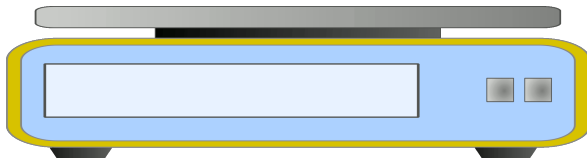
$$\frac{1}{2N^2} \leq \frac{2}{100} \implies N \geq 5$$

5 terms will suffice.

$\sum_{n=1}^{\infty} \frac{1}{n^3}$  converges to within 0.02 of  $\sum_{n=1}^5 \frac{1}{n^3}$ .



1

 $\frac{1}{2^3}$  $\frac{1}{3^3}$  $\frac{1}{4^3}$  $\frac{1}{5^3}$ 

$\sum_{n=1}^{\infty} \frac{1}{n^3}$  converges to within 0.02 of  $\sum_{n=1}^5 \frac{1}{n^3}$ .

$$S_1 = 1.0000$$



$$\frac{1}{2^3}$$



$$\frac{1}{3^3}$$



$$\frac{1}{4^3}$$



$$\frac{1}{5^3}$$



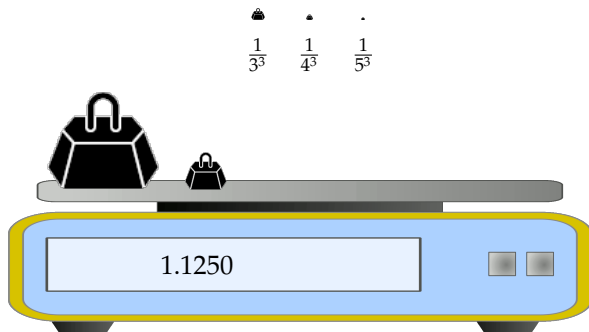
1.0000



$\sum_{n=1}^{\infty} \frac{1}{n^3}$  converges to within 0.02 of  $\sum_{n=1}^5 \frac{1}{n^3}$ .

$$S_1 = 1.0000$$

$$S_2 = 1.1250$$



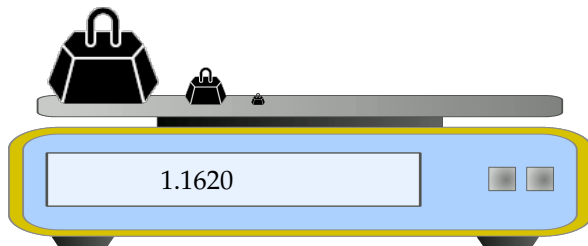
$\sum_{n=1}^{\infty} \frac{1}{n^3}$  converges to within 0.02 of  $\sum_{n=1}^5 \frac{1}{n^3}$ .

$$S_1 = 1.0000$$

$$S_2 = 1.1250$$

$$S_3 = 1.1620$$

$$\frac{1}{4^3} \quad \frac{1}{5^3}$$



$\sum_{n=1}^{\infty} \frac{1}{n^3}$  converges to within 0.02 of  $\sum_{n=1}^5 \frac{1}{n^3}$ .

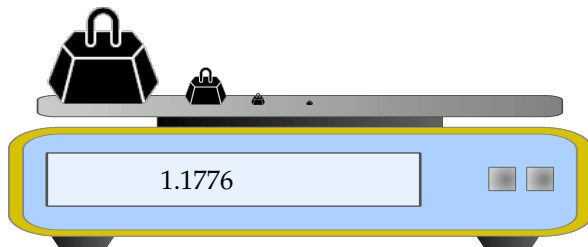
$$S_1 = 1.0000$$

$$S_2 = 1.1250$$

$$S_3 = 1.1620$$

$$S_4 = 1.1776$$

$$\frac{1}{5^3}$$



$\sum_{n=1}^{\infty} \frac{1}{n^3}$  converges to within 0.02 of  $\sum_{n=1}^5 \frac{1}{n^3}$ .

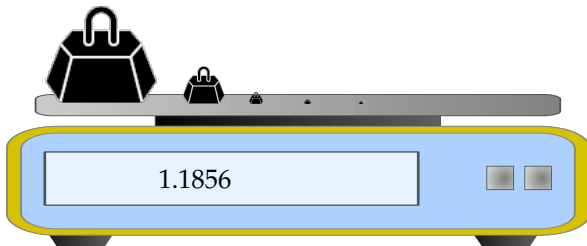
$$S_1 = 1.0000$$

$$S_2 = 1.1250$$

$$S_3 = 1.1620$$

$$S_4 = 1.1776$$

$$S_5 = 1.1856$$



$\sum_{n=1}^{\infty} \frac{1}{n^3}$  converges to within 0.02 of  $\sum_{n=1}^5 \frac{1}{n^3}$ .

$$0 \leq \sum_{n=1}^{\infty} \frac{1}{n^3} - \sum_{n=1}^5 \frac{1}{n^3} \leq 0.02$$

$$0 \leq \sum_{n=1}^{\infty} \frac{1}{n^3} - 1.1856 \leq 0.02$$

$$1.1856 \leq \sum_{n=1}^{\infty} \frac{1}{n^3} \leq 1.2056$$

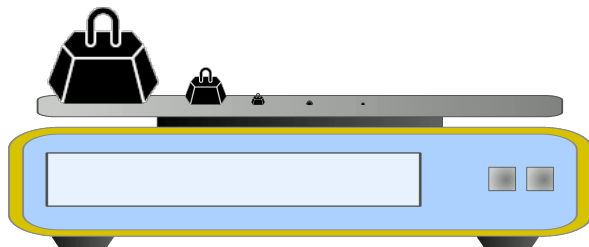
$$S_1 = 1.0000$$

$$S_2 = 1.1250$$

$$S_3 = 1.1620$$

$$S_4 = 1.1776$$

$$S_5 = 1.1856$$





## Observation

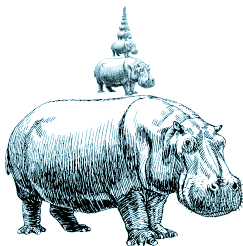
In a series with **positive** terms, the series either **converges**, or **diverges to infinity**.

If terms are “too big,” series will diverge.

## Observation

In a series with **positive** terms, the series either **converges**, or **diverges to infinity**.

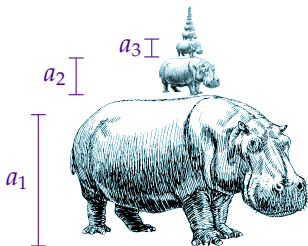
If terms are “too big,” series will diverge.



## Observation

In a series with **positive** terms, the series either **converges**, or **diverges to infinity**.

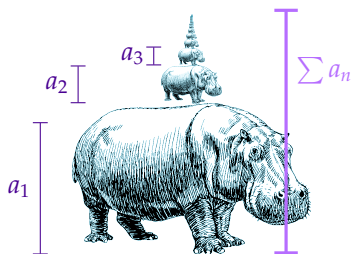
If terms are “too big,” series will diverge.



## Observation

In a series with **positive** terms, the series either **converges**, or **diverges to infinity**.

If terms are “too big,” series will diverge.



## Observation

In a series with **positive** terms, the series either **converges**, or **diverges to infinity**.

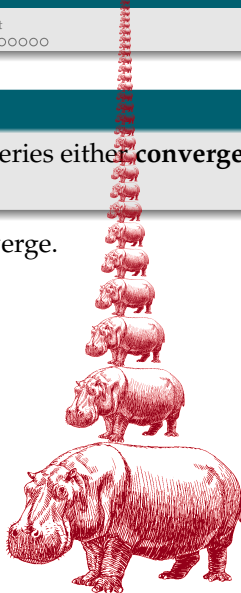
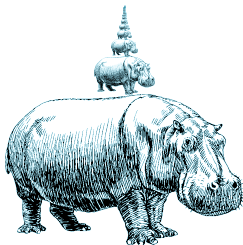
If terms are “too big,” series will diverge.



## Observation

In a series with **positive** terms, the series either **converges**, or **diverges to infinity**.

If terms are “too big,” series will diverge.

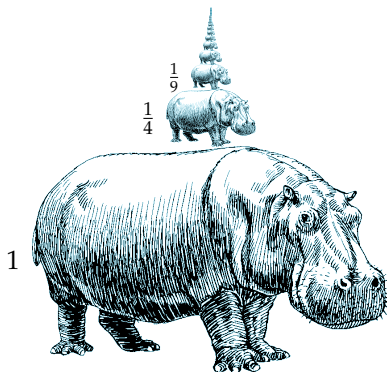


$$\sum \frac{1}{n^2} \text{ converges}$$

$$\sum \frac{1}{n^2 + n}$$

$$\sum \frac{1}{n^2} \text{ converges}$$

$$\sum \frac{1}{n^2 + n}$$

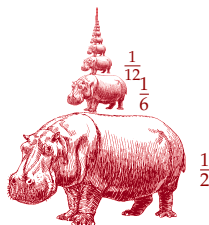
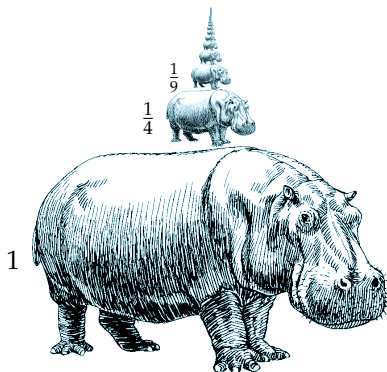


Terms are “small enough” for  
sum to converge



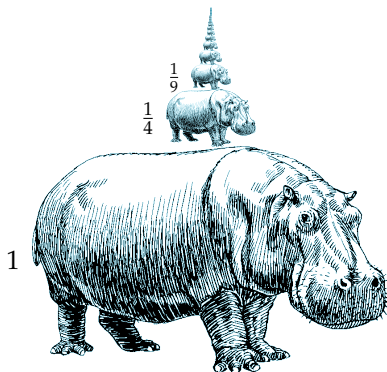
$$\sum \frac{1}{n^2} \text{ converges}$$

$$\sum \frac{1}{n^2 + n}$$



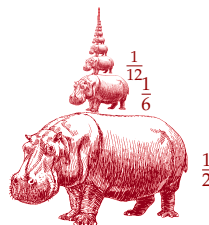
Terms are “small enough” for  
sum to converge

$$\sum \frac{1}{n^2} \text{ converges}$$



Terms are “small enough” for  
sum to converge

$$\sum \frac{1}{n^2 + n} \text{ converges, too}$$



Terms are also “small enough”  
for sum to converge

## The Comparison Test

Let  $N_0$  be a natural number and let  $K > 0$ .

- (a) If  $|a_n| \leq Kc_n$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} c_n$  converges, then  $\sum_{n=0}^{\infty} a_n$  converges.
- (b) If  $a_n \geq Kd_n \geq 0$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} d_n$  diverges, then  $\sum_{n=0}^{\infty} a_n$  diverges.

## The Comparison Test

Let  $N_0$  be a natural number and let  $K > 0$ .

(a) If  $|a_n| \leq Kc_n$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} c_n$  converges, then  $\sum_{n=0}^{\infty} a_n$  converges.

(b) If  $a_n \geq Kd_n \geq 0$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} d_n$  diverges, then  $\sum_{n=0}^{\infty} a_n$  diverges.

Consider  $\sum_{n=1}^{\infty} \frac{1}{n^{0.1}}$ .

## The Comparison Test

Let  $N_0$  be a natural number and let  $K > 0$ .

- (a) If  $|a_n| \leq Kc_n$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} c_n$  converges, then  $\sum_{n=0}^{\infty} a_n$  converges.
- (b) If  $a_n \geq Kd_n \geq 0$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} d_n$  diverges, then  $\sum_{n=0}^{\infty} a_n$  diverges.

Consider  $\sum_{n=1}^{\infty} \frac{1}{n-0.1}$ .

- We know  $0 < \frac{1}{n} < \frac{1}{n-0.1}$

## The Comparison Test

Let  $N_0$  be a natural number and let  $K > 0$ .

- (a) If  $|a_n| \leq Kc_n$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} c_n$  converges, then  $\sum_{n=0}^{\infty} a_n$  converges.
- (b) If  $a_n \geq Kd_n \geq 0$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} d_n$  diverges, then  $\sum_{n=0}^{\infty} a_n$  diverges.

Consider  $\sum_{n=1}^{\infty} \frac{1}{n-0.1}$ .

- ▶ We know  $0 < \frac{1}{n} < \frac{1}{n-0.1}$
- ▶ We know  $\sum_{n=1}^{\infty} \frac{1}{n}$  diverges (harmonic series)

## The Comparison Test

Let  $N_0$  be a natural number and let  $K > 0$ .

- (a) If  $|a_n| \leq Kc_n$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} c_n$  converges, then  $\sum_{n=0}^{\infty} a_n$  converges.
- (b) If  $a_n \geq Kd_n \geq 0$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} d_n$  diverges, then  $\sum_{n=0}^{\infty} a_n$  diverges.

Consider  $\sum_{n=1}^{\infty} \frac{1}{n-0.1}$ .

- ▶ We know  $0 < \frac{1}{n} < \frac{1}{n-0.1}$
- ▶ We know  $\sum_{n=1}^{\infty} \frac{1}{n}$  diverges (harmonic series)
- ▶ So, by the comparison test,  $\sum_{n=1}^{\infty} \frac{1}{n-0.1}$  diverges as well.

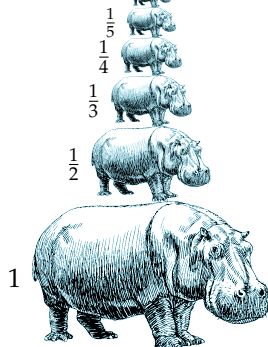
$$\sum \frac{1}{n} \text{ diverges}$$

$$\sum \frac{1}{n - 0.1}$$

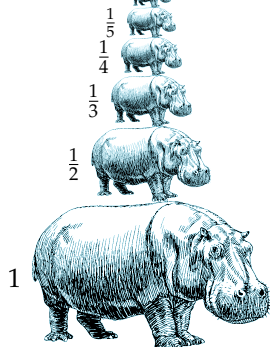


$$\sum \frac{1}{n} \text{ diverges}$$

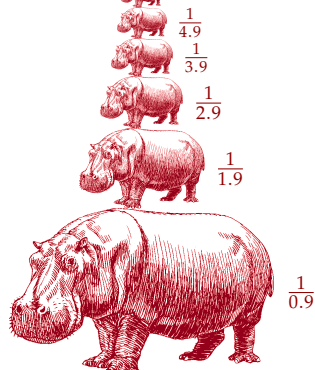
$$\sum \frac{1}{n - 0.1}$$



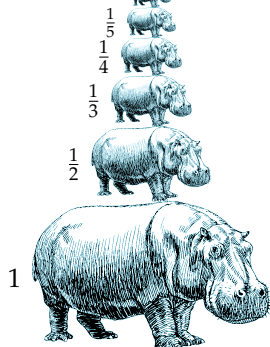
$$\sum \frac{1}{n} \text{ diverges}$$



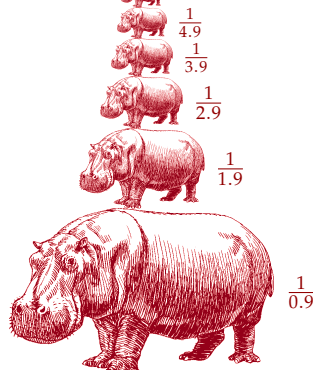
$$\sum \frac{1}{n - 0.1}$$



$$\sum \frac{1}{n} \text{ diverges}$$



$$\sum \frac{1}{n - 0.1} \text{ diverges, too}$$



Does the series  $\sum_{n=1}^{\infty} \frac{n + \cos n}{n^3 - 1/3}$  converge or diverge?

**Step 1: Intuition.**

When  $n$  is very large, we expect:

►  $n + \cos n \approx$

►  $n^3 + \frac{1}{3} \approx$

► So, we expect  $\frac{n + \cos n}{n^3 - 1/3} \approx$

Since  $\sum_{n=1}^{\infty} \frac{1}{n^2} \dots$

we expect  $\sum_{n=1}^{\infty} \frac{n + \cos n}{n^3 - 1/3}$  to also ....

Does the series  $\sum_{n=1}^{\infty} \frac{n + \cos n}{n^3 - 1/3}$  converge or diverge?

**Step 1: Intuition.**

When  $n$  is very large, we expect:

►  $n + \cos n \approx n$

►  $n^3 + \frac{1}{3} \approx n^3$

► So, we expect  $\frac{n + \cos n}{n^3 - 1/3} \approx \frac{n}{n^3} = \frac{1}{n^2}$ .

Since  $\sum_{n=1}^{\infty} \frac{1}{n^2}$  converges (by the  $p$ -test),

we expect  $\sum_{n=1}^{\infty} \frac{n + \cos n}{n^3 - 1/3}$  to also converge.

Does the series  $\sum_{n=1}^{\infty} \frac{n + \cos n}{n^3 - 1/3}$  converge or diverge?

**Step 2: Choose comparison series.**

### The Comparison Test, abridged

Let  $N_0$  be a natural number and let  $K > 0$ .

If  $|a_n| \leq Kc_n$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} c_n$  converges, then  $\sum_{n=0}^{\infty} a_n$  converges.

To show that original series **converges**, we should find a comparison series that also **converges** and whose terms (times some positive constant) are **larger** than the original terms. *There are many possibilities.* For  $n \geq 1$ ,

- ▶  $n + \cos n <$
- ▶  $n^3 - \frac{1}{3} >$
- ▶ So  $\frac{n + \cos n}{n^3 - 1/3} <$

Does the series  $\sum_{n=1}^{\infty} \frac{n + \cos n}{n^3 - 1/3}$  converge or diverge?

**Step 2: Choose comparison series.**

## The Comparison Test, abridged

Let  $N_0$  be a natural number and let  $K > 0$ .

If  $|a_n| \leq Kc_n$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} c_n$  converges, then  $\sum_{n=0}^{\infty} a_n$  converges.

To show that original series **converges**, we should find a comparison series that also **converges** and whose terms (times some positive constant) are **larger** than the original terms. *There are many possibilities.* For  $n \geq 1$ ,

- ▶  $n + \cos n < n + n = 2n$
- ▶  $n^3 - \frac{1}{3} > n^3 - \frac{n^3}{2} = \frac{1}{2}n^3$
- ▶ So  $\frac{n + \cos n}{n^3 - 1/3} < \frac{2n}{\frac{1}{2}n^3} = 4 \cdot \frac{1}{n^2}$

Does the series  $\sum_{n=1}^{\infty} \frac{n + \cos n}{n^3 - 1/3}$  converge or diverge?

**Step 3: Verify.**

### The Comparison Test, abridged

Let  $N_0$  be a natural number and let  $K > 0$ .

If  $|a_n| \leq Kc_n$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} c_n$  converges, then  $\sum_{n=0}^{\infty} a_n$  converges.



Does the series  $\sum_{n=1}^{\infty} \frac{n + \cos n}{n^3 - 1/3}$  converge or diverge?

**Step 3: Verify.**

### The Comparison Test, abridged

Let  $N_0$  be a natural number and let  $K > 0$ .

If  $|a_n| \leq Kc_n$  for all  $n \geq N_0$  and  $\sum_{n=0}^{\infty} c_n$  converges, then  $\sum_{n=0}^{\infty} a_n$  converges.

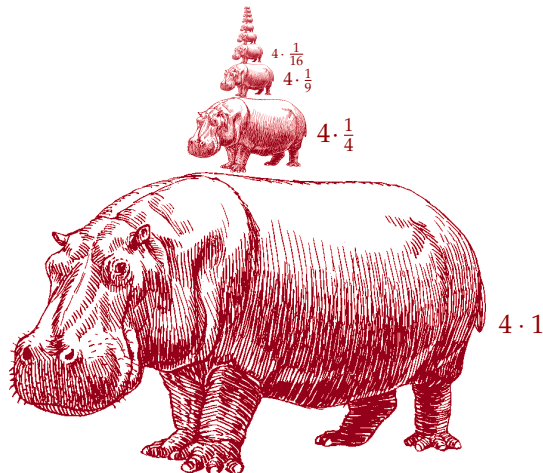
Set  $c_n = \frac{1}{n^2}$  and  $K = 4$ . Note  $\sum_{n=1}^{\infty} c_n$  converges.

Note also  $\left| \frac{n + \cos n}{n^3 - 1/3} \right| < \frac{n + n}{n^3 - \frac{n^3}{2}} = 4 \cdot \frac{1}{n^2}$  for all  $n \geq 1$ .

By the comparison test,  $\sum_{n=1}^{\infty} \frac{n + \cos n}{n^3 - 1/3}$  converges.

$\sum \frac{1}{n^2}$  converges, so

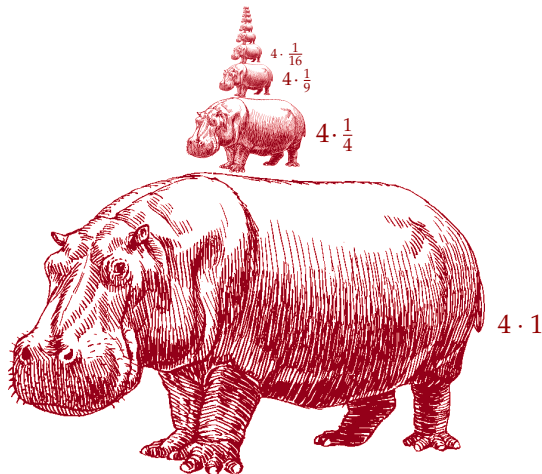
$\sum 4 \cdot \frac{1}{n^2}$  converges, too



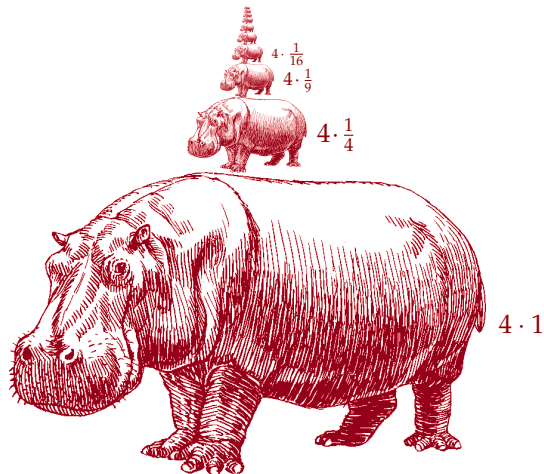
$\sum \frac{1}{n^2}$  converges, so



$\sum 4 \cdot \frac{1}{n^2}$  converges, too

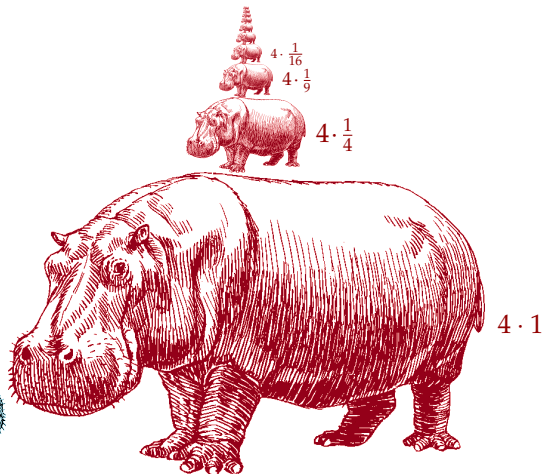
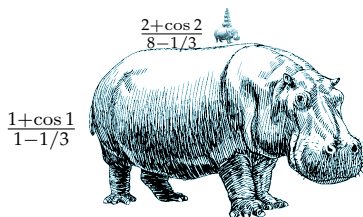


$$\sum 4 \cdot \frac{1}{n^2} \text{ converges}$$

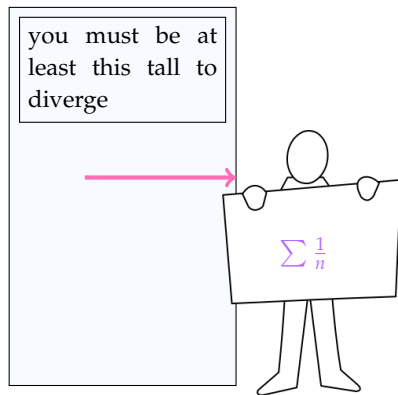


So,  $\sum \frac{n + \cos n}{n^3 - 1/3}$  converges too.

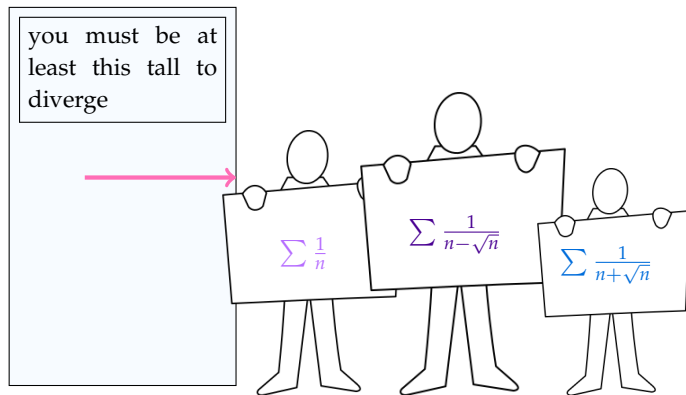
$\sum 4 \cdot \frac{1}{n^2}$  converges



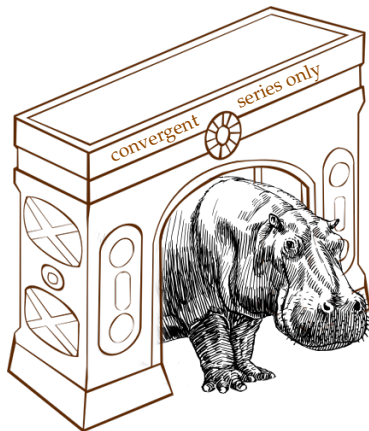
For the comparison test as we have seen it so far, to conclude that a given series **diverges**, we have to find a divergent comparison series whose terms are **smaller** than (a positive multiple of) those of our original series .



For the comparison test as we have seen it so far, to conclude that a given series **diverges**, we have to find a divergent comparison series whose terms are **smaller** than (a positive multiple of) those of our original series .

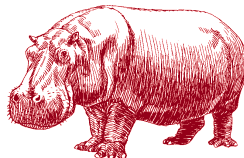
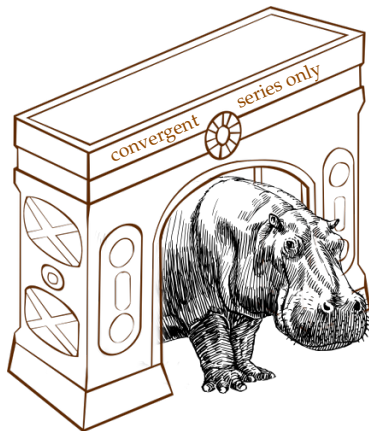


For the comparison test as we've seen it so far, to conclude that a given series **converges**, we have to find a convergent comparison series whose terms are **larger** than (a positive multiple of) those of our original series .

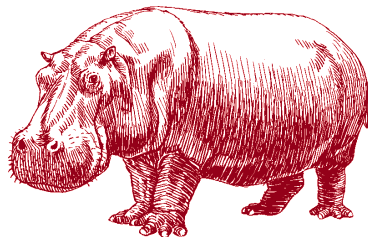
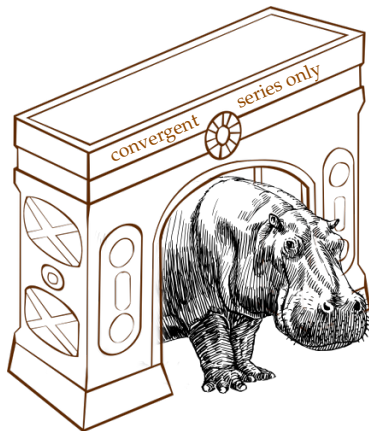




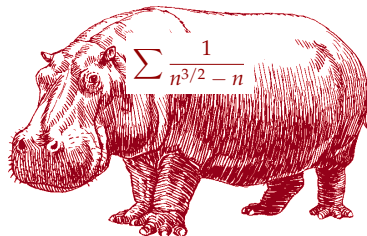
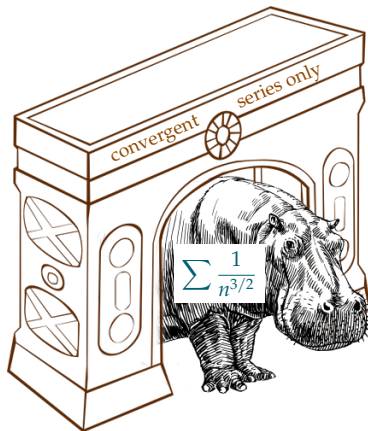
For the comparison test as we've seen it so far, to conclude that a given series **converges**, we have to find a convergent comparison series whose terms are **larger** than (a positive multiple of) those of our original series .



For the comparison test as we've seen it so far, to conclude that a given series **converges**, we have to find a convergent comparison series whose terms are **larger** than (a positive multiple of) those of our original series .



For the comparison test as we've seen it so far, to conclude that a given series **converges**, we have to find a convergent comparison series whose terms are **larger** than (a positive multiple of) those of our original series .



## Limit Comparison Theorem

Let  $\sum_{n=1}^{\infty} a_n$  and  $\sum_{n=1}^{\infty} b_n$  be two series with  $b_n > 0$  for all  $n$ . Assume that

$$\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = L$$

exists.

(a) If  $\sum_{n=1}^{\infty} b_n$  converges, then  $\sum_{n=1}^{\infty} a_n$  converges too.

(b) If  $L \neq 0$  and  $\sum_{n=1}^{\infty} b_n$  diverges, then  $\sum_{n=1}^{\infty} a_n$  diverges too.

In particular, if  $L \neq 0$ , then  $\sum_{n=1}^{\infty} a_n$  converges if and only if  $\sum_{n=1}^{\infty} b_n$  converges.

## Limit Comparison Theorem

Let  $\sum_{n=1}^{\infty} a_n$  and  $\sum_{n=1}^{\infty} b_n$  be two series with  $b_n > 0$  for all  $n$ . Assume that

$$\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = L$$

exists.

(a) If  $\sum_{n=1}^{\infty} b_n$  converges, then  $\sum_{n=1}^{\infty} a_n$  converges too.

(b) If  $L \neq 0$  and  $\sum_{n=1}^{\infty} b_n$  diverges, then  $\sum_{n=1}^{\infty} a_n$  diverges too.

In particular, if  $L \neq 0$ , then  $\sum_{n=1}^{\infty} a_n$  converges if and only if  $\sum_{n=1}^{\infty} b_n$  converges.

## Limit Comparison Theorem

Let  $\sum_{n=1}^{\infty} a_n$  and  $\sum_{n=1}^{\infty} b_n$  be two series with  $b_n > 0$  for all  $n$ . Assume that

$$\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = L$$

exists.

(a) If  $\sum_{n=1}^{\infty} b_n$  converges, then  $\sum_{n=1}^{\infty} a_n$  converges too.

(b) If  $L \neq 0$  and  $\sum_{n=1}^{\infty} b_n$  diverges, then  $\sum_{n=1}^{\infty} a_n$  diverges too.

In particular, if  $L \neq 0$ , then  $\sum_{n=1}^{\infty} a_n$  converges if and only if  $\sum_{n=1}^{\infty} b_n$  converges.

► For large  $n$ ,  $a_n \approx L \cdot b_n$ ;

## Limit Comparison Theorem

Let  $\sum_{n=1}^{\infty} a_n$  and  $\sum_{n=1}^{\infty} b_n$  be two series with  $b_n > 0$  for all  $n$ . Assume that

$$\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = L$$

exists.

- (a) If  $\sum_{n=1}^{\infty} b_n$  converges, then  $\sum_{n=1}^{\infty} a_n$  converges too.
- (b) If  $L \neq 0$  and  $\sum_{n=1}^{\infty} b_n$  diverges, then  $\sum_{n=1}^{\infty} a_n$  diverges too.

In particular, **if  $L \neq 0$ , then  $\sum_{n=1}^{\infty} a_n$  converges if and only if  $\sum_{n=1}^{\infty} b_n$  converges.**

- ▶ For large  $n$ ,  $a_n \approx L \cdot b_n$ ;
- ▶ so we expect  $\sum a_n$  to behave roughly like  $\sum (L \cdot b_n)$ ;

## Limit Comparison Theorem

Let  $\sum_{n=1}^{\infty} a_n$  and  $\sum_{n=1}^{\infty} b_n$  be two series with  $b_n > 0$  for all  $n$ . Assume that

$$\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = L$$

exists.

- (a) If  $\sum_{n=1}^{\infty} b_n$  converges, then  $\sum_{n=1}^{\infty} a_n$  converges too.
- (b) If  $L \neq 0$  and  $\sum_{n=1}^{\infty} b_n$  diverges, then  $\sum_{n=1}^{\infty} a_n$  diverges too.

In particular, **if  $L \neq 0$ , then  $\sum_{n=1}^{\infty} a_n$  converges if and only if  $\sum_{n=1}^{\infty} b_n$  converges.**

- ▶ For large  $n$ ,  $a_n \approx L \cdot b_n$ ;
- ▶ so we expect  $\sum a_n$  to behave roughly like  $\sum (L \cdot b_n)$ ;
- ▶ and since  $L \neq 0$ , we expect  $\sum (L \cdot b_n)$  to converge if and only if  $\sum b_n$  converges.



By the  $p$ -test,  $\sum_{n=1}^{\infty} \frac{1}{n^{3/2}}$  converges.

Can we conclude that  $\sum_{n=1}^{\infty} \frac{1}{n^{3/2} - n + 1}$  also converges?

By the  $p$ -test,  $\sum_{n=1}^{\infty} \frac{1}{n^{3/2}}$  converges.

Can we conclude that  $\sum_{n=1}^{\infty} \frac{1}{n^{3/2} - n + 1}$  also converges?

$$a_n = \frac{1}{n^{3/2}} \quad b_n = \frac{1}{n^{3/2} - n + 1}$$

By the  $p$ -test,  $\sum_{n=1}^{\infty} \frac{1}{n^{3/2}}$  converges.

Can we conclude that  $\sum_{n=1}^{\infty} \frac{1}{n^{3/2} - n + 1}$  also converges?

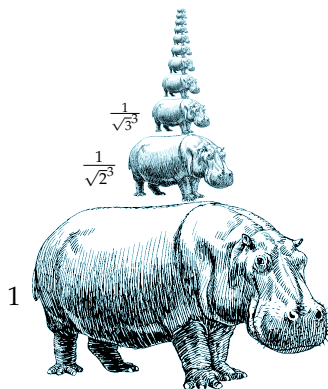
$$a_n = \frac{1}{n^{3/2}} \quad b_n = \frac{1}{n^{3/2} - n + 1}$$

$$\frac{a_n}{b_n} = \frac{n^{3/2} - n + 1}{n^{3/2}} = 1 - \frac{1}{\sqrt{n}} + \frac{1}{n^{3/2}}$$

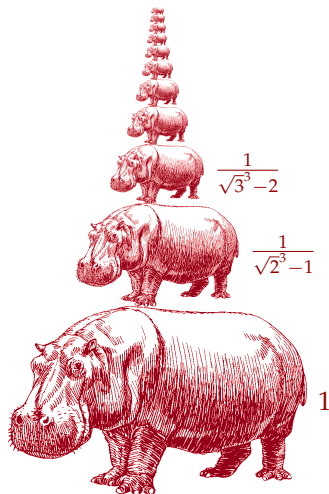
$$L = \lim_{n \rightarrow \infty} \frac{a_n}{b_n} = 1 - 0 + 0 = 1$$

Since  $L$  is a nonzero real number, the two series either both converge or both diverge. By the  $p$ -test,  $\sum \frac{1}{n^{3/2}}$  converges. So, by the limit comparison test,  $\sum \frac{1}{n^{3/2} - n + 1}$  also converges.

$$\sum \frac{1}{n^{3/2}} \text{ converges.}$$



$$\text{So, } \sum \frac{1}{n^{3/2} - n + 1} \text{ converges too.}$$



Does the series  $\sum_{n=1}^{\infty} \frac{\sqrt{n+1}}{n^2 - 2n + 3}$  converge or diverge?

Step 1: Intuition

For large  $n$ ,

Does the series  $\sum_{n=1}^{\infty} \frac{\sqrt{n+1}}{n^2 - 2n + 3}$  converge or diverge?

Step 1: Intuition

For large  $n$ ,

$$\frac{\sqrt{n+1}}{n^2 - 2n + 3} \approx \frac{\sqrt{n}}{n^2} = \frac{1}{n^{3/2}}$$

So, we'll use  $\sum_{n=1}^{\infty} \frac{1}{n^{3/2}}$  as our comparison series. Since this converges, we expect our original series to converge as well.

Does the series  $\sum_{n=1}^{\infty} \frac{\sqrt{n+1}}{n^2 - 2n + 3}$  converge or diverge?

Step 2: Verify Intuition

Let  $a_n = \frac{\sqrt{n+1}}{n^2 - 2n + 3}$  and  $b_n = \frac{1}{n^{3/2}}$ .

$$\lim_{n \rightarrow \infty} \frac{a_n}{b_n} =$$

Does the series  $\sum_{n=1}^{\infty} \frac{\sqrt{n+1}}{n^2-2n+3}$  converge or diverge?

Step 2: Verify Intuition

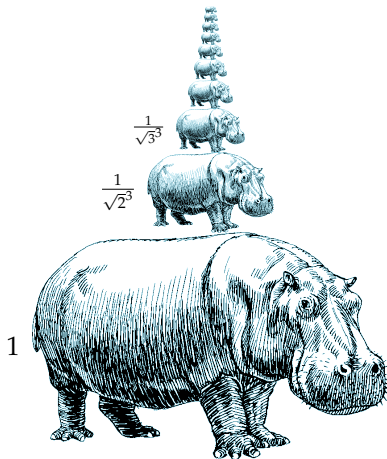
Let  $a_n = \frac{\sqrt{n+1}}{n^2-2n+3}$  and  $b_n = \frac{1}{n^{3/2}}$ .

$$\begin{aligned} \lim_{n \rightarrow \infty} \frac{a_n}{b_n} &= \lim_{n \rightarrow \infty} \frac{\frac{\sqrt{n+1}}{n^2-2n+3}}{\frac{1}{n^{3/2}}} = \lim_{n \rightarrow \infty} \frac{\frac{\sqrt{n+1}}{n^2-2n+3}}{\frac{\sqrt{n}}{n^2}} \\ &= \lim_{n \rightarrow \infty} \frac{\sqrt{n+1} \cdot \frac{1}{\sqrt{n}}}{(n^2-2n+3) \cdot \frac{1}{n^2}} = \lim_{n \rightarrow \infty} \frac{\sqrt{1+\frac{1}{n}}}{1-\frac{2}{n}+\frac{3}{n^2}} \\ &= \frac{\sqrt{1+0}}{1+0+0} = 1 \end{aligned}$$

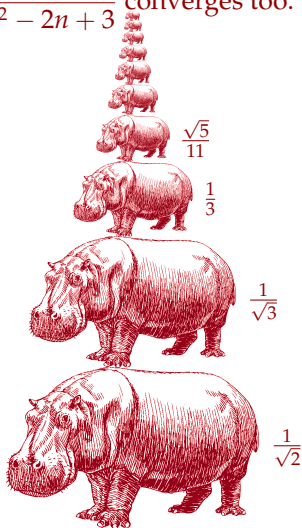
Since  $\sum_{n=1}^{\infty} \frac{1}{n^{3/2}}$  converges (by the  $p$ -test), the original series converges as well, by the Limit Comparison Theorem.



$$\sum \frac{1}{n^{3/2}} \text{ converges.}$$



$$\text{So, } \sum \frac{\sqrt{n+1}}{n^2 - 2n + 3} \text{ converges too.}$$



# COMPARISON STRATEGIES

- Before you can use either comparison test, you need to guess a series to compare.

# COMPARISON STRATEGIES

- ▶ Before you can use either comparison test, you need to guess a series to compare.
- ▶ The series you guess should be easy to deal with.

# COMPARISON STRATEGIES

- ▶ Before you can use either comparison test, you need to guess a series to compare.
- ▶ The series you guess should be easy to deal with.
  - ▶  $p$ -series
  - ▶ geometric series

# COMPARISON STRATEGIES

- ▶ Before you can use either comparison test, you need to guess a series to compare.
- ▶ The series you guess should be easy to deal with.
  - ▶  $p$ -series
  - ▶ geometric series
- ▶ Common guess (especially if monotone): consider “largest” piece of numerator and denominator  
(constant) < (logarithm) < (polynomial) < (exponential)

# COMPARISON STRATEGIES

- ▶ Before you can use either comparison test, you need to guess a series to compare.
- ▶ The series you guess should be easy to deal with.
  - ▶  $p$ -series
  - ▶ geometric series
- ▶ Common guess (especially if monotone): consider “largest” piece of numerator and denominator  
 (constant) < (logarithm) < (polynomial) < (exponential)
- ▶ After you guess a comparison series, **show it works** by finding the correct inequality (comparison test), or computing the limit of the ratio (limit comparison test).

# CHOOSE A SERIES TO COMPARE

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

$$\sum_{n=1}^{\infty} \frac{n^2 + n + 1}{n^5 - n}$$

$$\sum_{k=1}^{\infty} \frac{k(2 + \sin k)}{k^{\sqrt{2}}}$$

$$\sum_{m=1}^{\infty} \frac{3m + \sin \sqrt{m}}{m^2}$$

# CHOOSE A SERIES TO COMPARE

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

One option:  $\sum_{n=1}^{\infty} \frac{3n}{n^2} = \sum_{n=1}^{\infty} \frac{3}{n}$

$$\sum_{n=1}^{\infty} \frac{n^2 + n + 1}{n^5 - n}$$

One option:  $\sum_{n=1}^{\infty} \frac{n^2}{n^5} = \sum_{n=1}^{\infty} \frac{1}{n^3}$

$$\sum_{k=1}^{\infty} \frac{k(2 + \sin k)}{k\sqrt{2}}$$

One option:  $\sum_{k=1}^{\infty} \frac{2k}{k\sqrt{2}} = \sum_{k=1}^{\infty} \frac{2}{k\sqrt{2}-1}$


$$\sum_{m=1}^{\infty} \frac{3m + \sin \sqrt{m}}{m^2}$$


One option:  $\sum_{m=1}^{\infty} \frac{3m}{m^2} = \sum_{m=1}^{\infty} \frac{3}{m}$



## Included Work

 [Vector illustration of role play game map icon for an arch](#) is in the Public Domain (accessed Jan 8, 2021), 88–91

 [Hippopotamus vector image](#) is in the Public Domain (accessed January 2021), 57–66, 72–75, 82–85, 88–91, 100, 105

 [‘Waage/Libra’](#) by [B. Lachner](#) is in the public domain (accessed April 2021, edited), 14–19, 23–28, 50–56

 [‘Weight’](#) by [Kris Brauer](#) is licensed under [CC-BY](#) (accessed May 2021), 14–19, 23–28, 50–56

 [‘Notebook’](#) by [Iconic](#) is licensed under [CC BY 3.0](#) (accessed 9 June 2021, modified),

42

 [‘Notebook’](#) by [Iconic](#) is licensed under [CC BY 3.0](#) (accessed 9 June 2021), 34, 39