

W10 Notes

Ratio test and Root test

Videos, Math Dr. Bob

- [Ratio test](#): Basics
- [Ratio test](#): Ratio test + DCT
- [Root test](#): Basics
- [Root test](#): for $\sum (1 - 1/n^2)^{n^3}$

01 Theory

Ratio Test (RaT)

Applicability: Any series with nonzero terms.

Test Statement:

Suppose that $\left| \frac{a_{n+1}}{a_n} \right| \rightarrow L$ as $n \rightarrow \infty$.

Then:

$$L < 1 : \sum_{n=1}^{\infty} a_n \text{ converges absolutely}$$

$$L > 1 : \sum_{n=1}^{\infty} a_n \text{ diverges}$$

$$L = 1 \text{ or DNE : test inconclusive}$$

Extra - Ratio test: explanation

To understand the ratio test, consider this series:

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

- The term $\frac{2^3}{3!}$ is given by multiplying the prior term by $\frac{2}{3}$.
- The term $\frac{2^4}{4!}$ is given by multiplying the prior term by $\frac{2}{4}$.
- The term a_n is created by multiplying the prior term by $\frac{2}{n}$.

When $n > 3$, the multiplication factor giving the next term is necessarily less than $\frac{2}{3}$.

Therefore, when $n > 3$, the terms shrink *faster than those of a geometric series* having $r = \frac{2}{3}$.

Therefore this series converges.

Similarly, consider this series:

$$\sum_{n=0}^{\infty} \frac{10^n}{n!} = 1 + \frac{10}{1!} + \frac{10^2}{2!} + \frac{10^3}{3!} + \cdots$$

Write $R_n = \frac{a_n}{a_{n-1}}$ for the ratio from the prior term a_{n-1} to the current term a_n . For this series, $R_n = \frac{10}{n}$.

This ratio falls below $\frac{10}{11}$ when $n > 11$, after which the terms necessarily shrink faster than those of a geometric series with $r = \frac{10}{11}$. Therefore this series converges.

The main point of the discussion can be stated like this:

$$R_n \rightarrow L < 1 \quad \text{as } n \rightarrow \infty$$

Whenever this is the case, then *eventually* the ratios are bounded below some $r < 1$, and the series terms are smaller than those of a converging geometric series.

Extra - Ratio test: proof

Let us write $R_n = \left| \frac{a_{n+1}}{a_n} \right|$ for the ratio to the next term from term n .

Suppose that $R_n \rightarrow L$ as $n \rightarrow \infty$, and that $L < 1$. This means: eventually the ratio of terms is close to L ; so eventually it is less than 1.

More specifically, let us define $r = \frac{L+1}{2}$. This is the point halfway between L and 1. Since $R_n \rightarrow L$, we know that eventually $R_n < r$.

Any geometric series with ratio r converges. Set $c = a_N$ for N big enough that $R_N < r$. Then the terms of our series satisfy $|a_{N+n}| \leq cr^n$, and the series starting from a_N is absolutely convergent by comparison to this geometric series.

(Note that the terms a_1, \dots, a_{N-1} do not affect convergence.)

02 Illustration

Example - Ratio test

(a) Observe that $\sum_{n=0}^{\infty} \frac{10^n}{n!}$ has ratio $R_n = \frac{10}{n+1}$ and thus $R_n \rightarrow 0 = L < 1$. Therefore the RaT implies that this series converges.

Notice this technique!

Simplify the ratio:

$$\begin{aligned} \frac{\frac{10^{n+1}}{(n+1)!}}{\frac{n!}{10^n}} &\gg \gg \frac{(n+1)!}{10^{n+1}} \cdot \frac{n!}{10^n} \\ &\gg \gg \frac{10 \cdot 10^n}{(n+1)n!} \cdot \frac{n!}{10^n} \gg \gg \frac{10}{n+1} \xrightarrow{n \rightarrow \infty} 0 \end{aligned}$$

We *frequently* use these rules:

$$10^{n+1} = 10^n \cdot 10, \quad (n+1)! = (n+1)n!$$

to simplify ratios having exponents and factorials.

(b) $\sum_{n=1}^{\infty} \frac{n^2}{2^n}$ has ratio $R_n = \frac{(n+1)^2}{2^{n+1}} \bigg/ \frac{n^2}{2^n}$.

Simplify this:

$$\frac{(n+1)^2}{2^{n+1}} \bigg/ \frac{n^2}{2^n} \gg \gg \frac{(n+1)^2}{2^{n+1}} \cdot \frac{2^n}{n^2}$$

$$\gg \gg \frac{(n+1)^2 \cdot 2^n}{n^2 \cdot 2 \cdot 2^n} \gg \gg \frac{n^2 + 2n + 1}{2n^2} \xrightarrow{n \rightarrow \infty} \frac{1}{2} = L$$

So the series *converges absolutely* by the ratio test.

(c) Observe that $\sum_{n=1}^{\infty} n^2$ has ratio $R_n = \frac{n^2 + 2n + 1}{n^2} \rightarrow 1$ as $n \rightarrow \infty$.

So the ratio test is *inconclusive*, even though this series fails the SDT and obviously diverges.

(d) Observe that $\sum_{n=1}^{\infty} \frac{1}{n^2}$ has ratio $R_n = \frac{n^2}{n^2 + 2n + 1} \rightarrow 1$ as $n \rightarrow \infty$.

So the ratio test is *inconclusive*, even though the series converges as a p -series with $p = 2 > 1$.

(e) More generally, the ratio test is usually *inconclusive for rational functions*; it is more effective to use LCT with a p -series.

03 Theory

Root Test (RootT)

Applicability: Any series.

Test Statement:

Suppose that $\sqrt[n]{|a_n|} \rightarrow L$ as $n \rightarrow \infty$.

Then:

$$L < 1 : \sum_{n=1}^{\infty} a_n \text{ converges absolutely}$$

$$L > 1 : \sum_{n=1}^{\infty} a_n \text{ diverges}$$

$$L = 1 \text{ or DNE : test inconclusive}$$

Extra - Root test: explanation

The fact that $\sqrt[n]{|a_n|} \rightarrow L$ and $L < 1$ implies that eventually $\sqrt[n]{|a_n|} < r$ for all high enough n , where $r = \frac{L+1}{2}$ is the midpoint between L and 1.

Now, the equation $\sqrt[n]{|a_n|} < r$ is equivalent to the equation $|a_n| < r^n$.

Therefore, eventually the terms $|a_n|$ are each less than the corresponding terms of this convergent geometric series:

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

04 Illustration

Root test examples

(a) Observe that $\sum_{n=1}^{\infty} \left(\frac{1}{n}\right)^n$ has roots of terms:

$$|a_n|^{1/n} = \left(\left(\frac{1}{n}\right)^n\right)^{1/n} = \frac{1}{n} \xrightarrow{n \rightarrow \infty} 0 = L$$

Because $L < 1$, the RooT shows that the series converges absolutely.

(b) Observe that $\sum_{n=1}^{\infty} (-1)^n \left(\frac{n}{2n+1}\right)^n$ has roots of terms:

$$\sqrt[n]{|a_n|} = \frac{n}{2n+1} \xrightarrow{n \rightarrow \infty} \frac{1}{2} = L$$

Because $L < 1$, the RooT shows that the series converges absolutely.

(c) Observe that $\sum_{n=1}^{\infty} \left(\frac{3}{n}\right)^n$ converges because $\sqrt[n]{|a_n|} = \frac{3}{n} \rightarrow 0$ as $n \rightarrow \infty$.

≡ Ratio test versus root test

Determine whether the series $\sum_{n=1}^{\infty} \frac{n^2 4^n}{5^{n+2}}$ converges absolutely or conditionally or diverges.

Solution

Before proceeding, rewrite somewhat the general term as $\left(\frac{n}{5}\right)^2 \cdot \left(\frac{4}{5}\right)^n$.

Now we solve the problem first using the ratio test. By plugging in $n+1$ we see that

$$a_{n+1} = \left(\frac{n+1}{5}\right)^2 \cdot \left(\frac{4}{5}\right)^{n+1}$$

So for the ratio R_n we have:

$$\begin{aligned} & \left(\frac{n+1}{5}\right)^2 \cdot \left(\frac{4}{5}\right)^{n+1} \cdot \left(\frac{5}{n}\right)^2 \cdot \left(\frac{5}{4}\right)^n \\ & \gg \gg \frac{n^2 + 2n + 1}{n^2} \cdot \frac{4}{5} \longrightarrow \frac{4}{5} < 1 \text{ as } n \rightarrow \infty \end{aligned}$$

Therefore the series converges absolutely by the ratio test.

Now solve the problem again using the root test. We have for $\sqrt[n]{|a_n|}$:

$$\left(\left(\frac{n}{5}\right)^2 \cdot \left(\frac{4}{5}\right)^n\right)^{1/n} = \left(\frac{n}{5}\right)^{2/n} \cdot \frac{4}{5}$$

To compute the limit as $n \rightarrow \infty$ we must use logarithmic limits and L'Hopital's Rule. So, first take the log:

$$\ln \left(\left(\frac{n}{5}\right)^{2/n} \cdot \frac{4}{5} \right) = \frac{2}{n} \ln \frac{n}{5} + \ln \frac{4}{5}$$

Then for the first term apply L'Hopital's Rule:

$$\frac{\ln \frac{n}{5} \xrightarrow{d/dx} \frac{1}{n/5} \cdot \frac{1}{5}}{n/2 \xrightarrow{d/dx} 1/2} \gg \gg \frac{1/n}{1/2} \gg \gg \frac{2}{n} \longrightarrow 0 \text{ as } n \rightarrow \infty$$

So the first term goes to zero, and the second (constant) term is the value of the limit. So the log limit is $\ln \frac{4}{5}$, and the limit (before taking logs) must be $e^{\ln \frac{4}{5}}$ (inverting the log using e^x) and this is $\frac{4}{5}$. Since $\frac{4}{5} < 1$, the root test also shows that the series converges absolutely.

Series tests: strategy tips

Videos, Math Dr. Bob

- [Series test round-up](#): Part I
- [Series test round-up](#): Part II
- [Series test round-up](#): Part III

05 Theory

It can help to associate certain “strategy tips” to find convergence tests based on certain patterns.

🔗 Matching powers → Simple Divergence Test

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

Use the SDT because we see the highest power is the *same* ($= 1$) in numerator and denominator.

🔗 Rational or Algebraic → Limit Comparison Test

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

Use the LCT because we have a *rational or algebraic* function (positive terms).

🔗 Not rational, not factorials → Integral Test

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

Use the IT because we do *not* have a rational/algebraic function, and we do *not* see factorials.

🔗 Rational, alternating → AST, and LCT or DCT

$$\sum_{n=1}^{\infty} (-1)^n \frac{n^2}{n^4+1}$$

Use the AST because it's alternating. Then use the LCT (to find absolute convergence) because it's a rational function.

🔗 Factorials → Ratio Test

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

Use the RaT because we see a factorial. (In case of alternating + factorial, use RaT first.)

🔗 Recognize geometric → LCT or DCT

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

Use the LCT or DCT comparing to $\frac{1}{3^n}$ because we see similarity to $\frac{1}{3^n}$ (recognize geometric).

Power series: Radius and Interval

Videos, Math Dr. Bob

- [Power series](#): Interval and Radius of Convergence
- [Power series](#): Interval of Convergence Using Ratio Test
 - [Further example](#)
- [Power series](#): Interval of Convergence Using Root Test
- [Power series](#): Finding the Center

06 Theory

A power series looks like this:

$$f(x) = a_0 + a_1x + a_2x^2 + a_3x^3 + \dots$$

Power series are used to *build and study functions*. They allow a uniform “modeling framework” in which many functions can be described and compared. Power series are also convenient for *computers* because they provide a way to store and evaluate *differentiable* functions with numerical (approximate) values.

⚠ Small x needed for power series

The most important fact about power series is that they work for *small values of x* .

Many power series diverge for $|x|$ too big; but even when they converge, for big $|x|$ they converge more slowly, and partial sum approximations are less accurate.

The idea of a power series is a modification of the idea of a geometric series in which the common ratio r becomes a variable x , and each term has an additional *coefficient parameter* a_n controlling the relative contribution of different orders.

07 Theory

Every power series has a **radius of convergence** and an **interval of convergence**.

🏠 Radius of convergence

Consider a power series centered at $x = 0$:

$$f(x) = a_0 + a_1x + a_2x^2 + a_3x^3 + \dots$$

Define L as the limit of coefficient ratios:

$$L = \lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right|$$

Then reciprocal, $R = 1/L$, is the **radius of convergence**; it can be anything in $[0, \infty]$ including either extreme.

The power series necessarily converges for $|x| < R$ and diverges for $|x| > R$.

🔍 Extra - Radius of convergence: explanatory proof

Treat the variable x in the power series $f(x) = a_0 + a_1x + a_2x^2 + \dots$ as a constant.

Apply the ratio test to this series. The ratio function is:

$$R_n = \left| \frac{a_{n+1}}{a_n} \right| \cdot |x|$$

Since $|x|$ is a constant here, we have:

$$\lim_{n \rightarrow \infty} R_n = L|x|$$

Therefore, the ratio test says that the series converges absolutely when $|x| < 1/L$, and diverges when $|x| > 1/L$.

We can build **shifted power series** for x near another value c . Just replace the variable x with a shifted variable $u = x - c$:

$$a_0 + a_1u + a_2u^2 + a_3u^3 + \dots$$

$$\gg \gg a_0 + a_1(x - c) + a_2(x - c)^2 + a_3(x - c)^3 + \dots$$

The radius of convergence of a shifted series is calculated in the same way, using the coefficients:

$$R = \frac{1}{\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right|}$$

However, in the shifted setting, the radius of convergence concerns the **distance from c** : Such a power series converges when $|x - c| < R$ and diverges when $|x - c| > R$.

The **interval of convergence** of a power series is determined by:

- the radius of convergence
- the center point
- special consideration of endpoints

🔍 Interval of convergence

The interval of convergence I of a power series $f(x) = a_0 + a_1x + a_2x^2 + \dots$ is the set of values of x where the series converges.

The interval of convergence I is:

- centered at $x = c$
- extending a distance R to either side of c
- including / excluding the endpoints where $|x - c| = R$ depending on the particular case

To calculate the interval of convergence, follow these steps:

- Observe the center c of the shifted series; $c = 0$ corresponds to no shift.
- Take the limit to compute R .
- Write down the *preliminary interval* $(c - R, c + R)$.
- Plug each endpoint $c - R$ and $c + R$ into the original series
 - \rightarrow check for convergence
- Add in the convergent endpoints. There are 4 total possibilities.

08 Illustration

Example - Radius and interval for a few series

Series	Radius	Interval
$\sum_{n=0}^{\infty} x^n$	$R = 1$	$(-1, 1)$
$\sum_{n=1}^{\infty} \frac{(x-2)^n}{n}$	$R = 1$	$[1, 3)$
$\sum_{n=0}^{\infty} n! x^n$	$R = 0$	$\{0\}$
$\sum_{n=0}^{\infty} \frac{x^n}{(2n)!}$	$R = \infty$	$(-\infty, \infty)$

Example - Radius of convergence

Find the radius of convergence of the series:

$$(a) \sum_{n=0}^{\infty} \frac{x^n}{2^n} \quad (b) \sum_{n=0}^{\infty} \frac{x^{2n}}{(2n)!}$$

Solution

(a) The ratio of coefficients is $R_n = \left| \frac{a_{n+1}}{a_n} \right| = \frac{1/2^{n+1}}{1/2^n} = 1/2$.

Therefore $R = 2$ and the series converges for $|x| < 2$.

(b) This power series has $a_{2n+1} = 0$, meaning it skips all odd terms.

Instead of the standard ratio function, we take the ratio of successive *even terms*. The series of even terms has coefficients $a_n = \frac{1}{(2n)!}$. So:

$$\begin{aligned} \left| \frac{a_{n+1}}{a_n} \right| &\gg \gg \frac{\frac{1}{(2(n+1))!}}{\frac{1}{(2n)!}} \\ &\gg \gg \frac{1}{(2n+2)(2n+1)(2n)!} \cdot \frac{(2n)!}{1} \gg \gg \frac{1}{(2n+2)(2n+1)} \end{aligned}$$

As $n \rightarrow \infty$, this converges to 0, so $L = 0$ and $R = \infty$.

Example - Interval of convergence

Find the interval of convergence of the following series.

$$(a) \sum_{n=1}^{\infty} \frac{(x-3)^n}{n} \quad (b) \sum_{n=0}^{\infty} \frac{(-3)^n x^n}{\sqrt{n+1}}$$

Solution

$$(a) \sum_{n=1}^{\infty} \frac{(x-3)^n}{n}$$

1. Apply ratio test.

- Ratio of successive coefficients:

$$R_n = \left| \frac{1}{n+1} \cdot \frac{n}{1} \right| \gg \gg \frac{n}{n+1}$$

- Limit of ratios:

$$R_n = \frac{n}{n+1} \xrightarrow{n \rightarrow \infty} 1$$

- Deduce $L = 1$ and therefore $R = 1$.
- Therefore:

$$|x-3| < 1 \implies \text{converges}$$

$$|x-3| > 1 \implies \text{diverges}$$

2. Preliminary interval of convergence.

- Translate to interval notation:

$$|x-3| < 1 \gg \gg x \in (3-1, 3+1)$$

$$\gg \gg x \in (2, 4)$$

3. Final interval of convergence.

- Check endpoint $x = 2$:

$$\sum_{n=1}^{\infty} \frac{(2-3)^n}{n} \gg \gg \sum_{n=1}^{\infty} \frac{(-1)^n}{n}$$

$$\gg \gg \text{converges by AST}$$

- Check endpoint $x = 4$:

$$\sum_{n=1}^{\infty} \frac{(4-3)^n}{n} \gg \gg \sum_{n=1}^{\infty} \frac{1}{n}$$

$$\gg \gg \text{diverges as } p\text{-series}$$

- Final interval of convergence: $x \in [2, 4)$

$$(b) \sum_{n=0}^{\infty} \frac{(-3)^n x^n}{\sqrt{n+1}}$$

1. Limit of coefficients ratio.

- Ratio of successive coefficients:

$$R_n = \left| \frac{a_{n+1}}{a_n} \right| \gg \gg \left| \frac{(-3)^{n+1}}{\sqrt{n+2}} \cdot \frac{\sqrt{n+1}}{(-3)^n} \right|$$

$$\gg \gg \frac{3\sqrt{n+1}}{\sqrt{n+2}}$$

- Limit of ratios:

$$\lim_{n \rightarrow \infty} R_n \gg \gg \lim_{n \rightarrow \infty} \frac{3\sqrt{n+1}}{\sqrt{n+2}} \gg \gg 3$$

- Deduce $L = 3$ and thus $R = 1/3$.
- Therefore:

$$|x| < \frac{1}{3} \implies \text{converges}$$

$$|x| > \frac{1}{3} \implies \text{diverges}$$

- Preliminary interval of convergence: $x \in (-\frac{1}{3}, \frac{1}{3})$

2. Check endpoints.

- Check endpoint $x = -1/3$:

$$\sum_{n=0}^{\infty} \frac{(-3 \cdot (-\frac{1}{3}))^n}{\sqrt{n+1}} \gg \gg \sum_{n=0}^{\infty} \frac{1^n}{\sqrt{n+1}}$$

$$\gg \gg \text{diverges by LCT with } b_n = 1/\sqrt{n}$$

- Check endpoint $x = +1/3$:

$$\sum_{n=0}^{\infty} \frac{(-3 \cdot (+\frac{1}{3}))^n}{\sqrt{n+1}} \gg \gg \sum_{n=0}^{\infty} \frac{(-1)^n}{\sqrt{n+1}}$$

$$\gg \gg \text{converges by AST}$$

- Final interval of convergence: $x \in (-1/3, 1/3]$

Interval of convergence - further examples

Find the interval of convergence of the following series.

(a) $\sum_{n=0}^{\infty} \frac{n(x+2)^n}{3^{n+1}}$ (b) $\sum_{n=1}^{\infty} \frac{(4x+1)^n}{n}$

Solution

(a) $\sum_{n=0}^{\infty} \frac{n(x+2)^n}{3^{n+1}}$

- Ratio of coefficients: $R_n = \frac{n+1}{3n} \rightarrow \frac{1}{3}$.
- So the $R = 3$, center is $x = -2$, and the preliminary interval is $(-2-3, -2+3) = (-5, 1)$.
- Check endpoints: $\sum \frac{n(-3)^n}{3^{n+1}}$ diverges and $\sum \frac{n(3)^n}{3^{n+1}}$ also diverges. Final interval is $(-5, 1)$.

$$(b) \sum_{n=1}^{\infty} \frac{(4x+1)^n}{n}$$

- Ratio of coefficients: $R_n = \frac{n+1}{n} \rightarrow 1$.
- So $R = 1$, and the series converges when $|4x+1| < 1$.
- Extract preliminary interval.
 - Divide by 4:

$$|4x+1| < 1 \quad \xrightarrow{\div 4} \quad |x+1/4| < 1/4 \quad \gg \gg \quad x \in (0, 1/2)$$

- Check endpoints: $\sum \frac{(4 \cdot \frac{-1}{2} + 1)^n}{n}$ converges but $\sum \frac{1}{n}$ diverges.
- Final interval of convergence: $[-1/2, 0)$