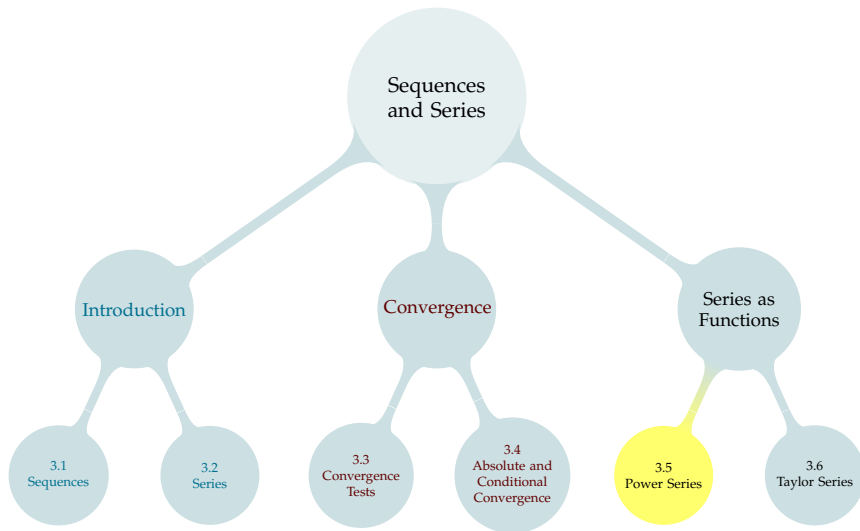


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Recall the geometric series: for a constant r , with $|r| < 1$:

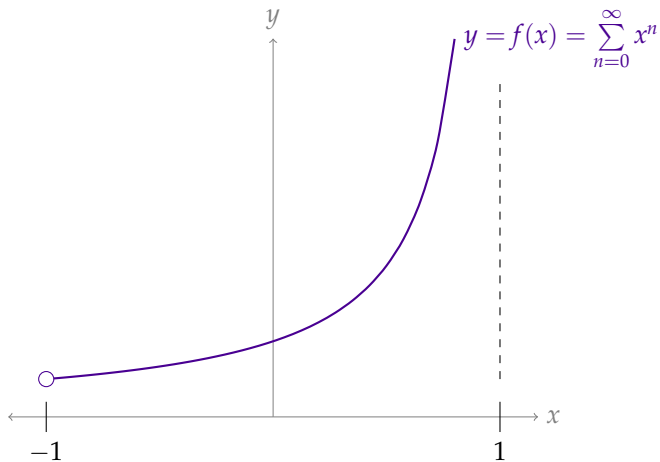
$$\sum_{n=0}^{\infty} r^n = \frac{1}{1-r}$$

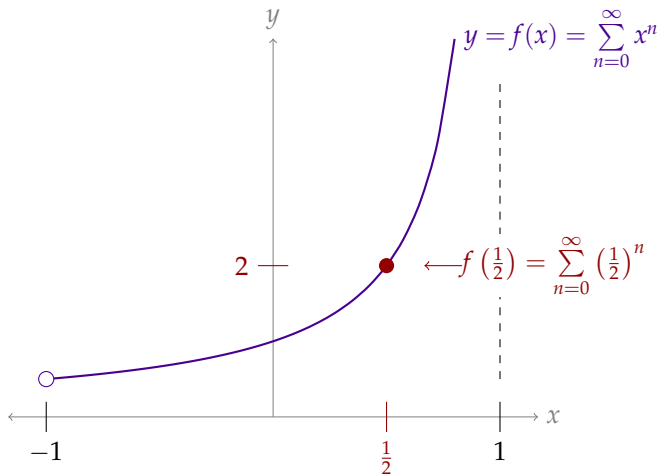
We can think of this as a function. If we set

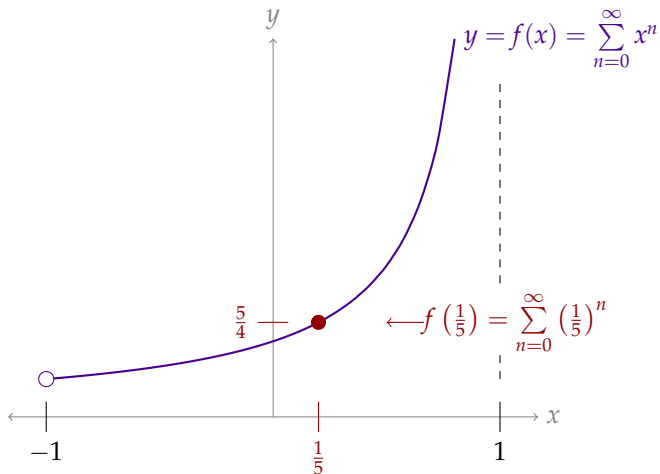
$$f(x) = \sum_{n=0}^{\infty} x^n$$

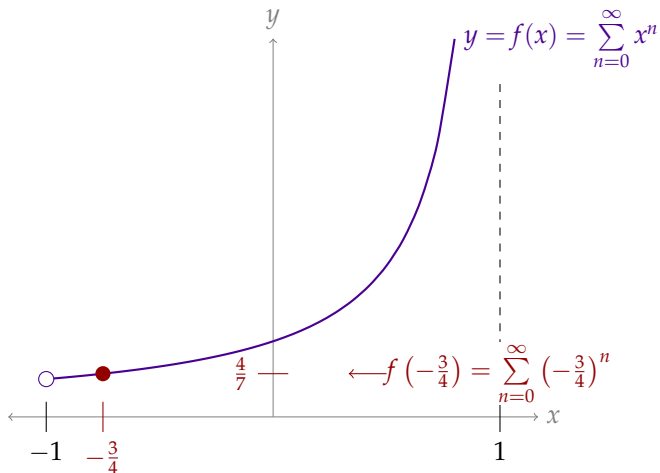
and restrict our domain to $-1 < x < 1$, then

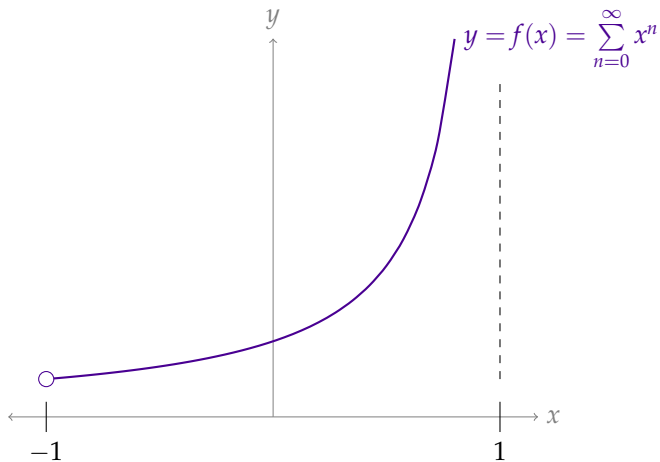
$$f(x) = \sum_{n=0}^{\infty} x^n = \frac{1}{1-x}$$











Why would we ever prefer to write $\sum_{n=0}^{\infty} x^n$ instead of $\frac{1}{1-x}$?

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The function

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

isn't a polynomial, but in certain ways it behaves like one. For $|x| < 1$:

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$$\int \frac{1}{1-x} dx = \int \left(\sum_{n=0}^{\infty} x^n \right) dx = \sum_{n=0}^{\infty} \left(\int x^n dx \right) = \sum_{n=0}^{\infty} \frac{x^{n+1}}{n+1}$$

Definition

A series of the form

$$\sum_{n=0}^{\infty} A_n(x-c)^n = A_0 + A_1(x-c) + A_2(x-c)^2 + A_3(x-c)^3 + \cdots$$

is called a *power series in $(x-c)$* or a *power series centered on c* . The numbers A_n are called the coefficients of the power series.

One often considers power series centered on $c = 0$ and then the series reduces to

$$A_0 + A_1x + A_2x^2 + A_3x^3 + \cdots = \sum_{n=0}^{\infty} A_nx^n$$

$$\sum_{n=0}^{\infty} A_n (x - c)^n = A_0 + A_1(x - c) + A_2(x - c)^2 + A_3(x - c)^3 + \cdots$$

In a power series, we think of the coefficients A_n as fixed constants, and we think of x as the variable of a function.

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Evaluate the power series $\sum_{n=0}^{\infty} A_n(x-c)^n$ when $x = c$:



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Evaluate the power series $\sum_{n=0}^{\infty} A_n(x-c)^n$ when $x = c$:

$$\sum_{n=0}^{\infty} A_n(x-c)^n = A_0 + A_1(x-c) + A_2(x-c)^2 + A_3(x-c)^3 + \cdots$$

$$\sum_{n=0}^{\infty} A_n(c-c)^n = A_0 + A_1 \underbrace{(c-c)}_0 + A_2 \underbrace{(c-c)^2}_0 + A_3 \underbrace{(c-c)^3}_0 + \cdots$$

$$= A_0 \quad (\text{In particular, the series converges when } x = c.)$$

A fundamental question we want to ask when we see a series is whether it converges or diverges. So, let's find all values of x for which the power series

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

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converges.

This looks somewhat like a geometric series, but not exactly, so the ratio test is a good option.

$$\begin{aligned} \lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| &= \lim_{n \rightarrow \infty} \left| \frac{\frac{x^{n+1}}{n+1}}{\frac{x^n}{n}} \right| = \lim_{n \rightarrow \infty} \left| \frac{x^{n+1}}{x^n} \right| \left(\frac{n}{n+1} \right) \\ &= \lim_{n \rightarrow \infty} |x| \left(\frac{n}{n+1} \right) = |x| \end{aligned}$$

So the series converges when $|x| < 1$ and diverges when $|x| > 1$.

A fundamental question we want to ask when we see a series is whether it converges or diverges. So, let's find all values of x for which the power series

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converges.

When $x = 1$, we have the harmonic series, which diverges. When $x = -1$, we have the alternating harmonic series, which converges.

So, all together, the series converges when $-1 \leq x < 1$, and diverges everywhere else.



A fundamental question we want to ask when we see a series is whether it converges or diverges. So, let's find all values of x for which the power series

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

converges.

Definition

Consider the power series

$$\sum_{n=0}^{\infty} A_n(x - c)^n.$$

The set of real x -values for which it converges is called the interval of convergence of the series.

Find the interval of convergence of the power series

$$\sum_{n=0}^{\infty} 2^n (x-1)^n = 1 + 2(x-1) + 2^2(x-1)^2 + 2^3(x-1)^3 + \cdots .$$

Find the interval of convergence of the power series

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This still looks somewhat like a geometric series, so the ratio test is a still good option to start.

$$\begin{aligned} \lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| &= \lim_{n \rightarrow \infty} \left| \frac{2^{n+1}(x-1)^{n+1}}{2^n(x-1)^n} \right| = \lim_{n \rightarrow \infty} \left| \frac{(x-1)^{n+1}}{(x-1)^n} \right| \left(\frac{2^{n+1}}{2^n} \right) \\ &= 2|x-1| \end{aligned}$$

So we see that the series converges when $|x-1| < \frac{1}{2}$ and diverges when $|x-1| > \frac{1}{2}$.

Find the interval of convergence of the power series

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

When $x-1 = -\frac{1}{2}$, i.e. $x = \frac{1}{2}$, our series is

$$\sum_{n=0}^{\infty} 2^n \left(\frac{1}{2} - 1\right)^n = \sum_{n=0}^{\infty} 2^n \left(-\frac{1}{2}\right)^n = \sum_{n=0}^{\infty} (-1)^n$$

When $x-1 = \frac{1}{2}$, i.e. $x = \frac{3}{2}$, our series is

$$\sum_{n=0}^{\infty} 2^n \left(\frac{3}{2} - 1\right)^n = \sum_{n=0}^{\infty} 2^n \left(\frac{1}{2}\right)^n = \sum_{n=0}^{\infty} 1$$

In both cases, the series diverge by the divergence test. All together, the interval of convergence is $\frac{1}{2} < x < \frac{3}{2}$.



What happens if we apply the ratio test to a generic power series,

$$\sum_{n=0}^{\infty} A_n(x - c)^n?$$

What happens if we apply the ratio test to a generic power series,

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$$\lim_{n \rightarrow \infty} \left| \frac{A_{n+1}(x - c)^{n+1}}{A_n(x - c)^n} \right| = \lim_{n \rightarrow \infty} \left| \frac{A_{n+1}}{A_n} (x - c) \right| = |x - c| \lim_{n \rightarrow \infty} \left| \frac{A_{n+1}}{A_n} \right|$$

- ▶ If $\left| \frac{A_{n+1}}{A_n} \right|$ does not approach a limit as $n \rightarrow \infty$, the ratio test tells us nothing. (We should try other tests.)
- ▶ If $\lim_{n \rightarrow \infty} \left| \frac{A_{n+1}}{A_n} \right| = 0$, then
- ▶ If $\lim_{n \rightarrow \infty} \left| \frac{A_{n+1}}{A_n} \right| = \infty$, then
- ▶ If $\lim_{n \rightarrow \infty} \left| \frac{A_{n+1}}{A_n} \right| = A$ for some real number A , then

What happens if we apply the ratio test to a generic power series,

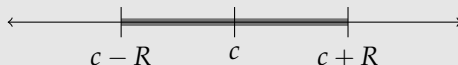
$$\sum_{n=0}^{\infty} A_n(x - c)^n?$$

$$\lim_{n \rightarrow \infty} \left| \frac{A_{n+1}(x - c)^{n+1}}{A_n(x - c)^n} \right| = \lim_{n \rightarrow \infty} \left| \frac{A_{n+1}}{A_n} (x - c) \right| = |x - c| \lim_{n \rightarrow \infty} \left| \frac{A_{n+1}}{A_n} \right|$$

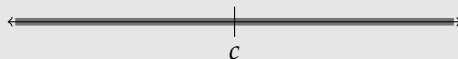
- ▶ If $\left| \frac{A_{n+1}}{A_n} \right|$ does not approach a limit as $n \rightarrow \infty$, the ratio test tells us nothing. (We should try other tests.)
- ▶ If $\lim_{n \rightarrow \infty} \left| \frac{A_{n+1}}{A_n} \right| = 0$, then the series converges for all x .
- ▶ If $\lim_{n \rightarrow \infty} \left| \frac{A_{n+1}}{A_n} \right| = \infty$, then the series converges when $x = c$, and diverges otherwise.
- ▶ If $\lim_{n \rightarrow \infty} \left| \frac{A_{n+1}}{A_n} \right| = A$ for some real number A , then the series converges when $|x - c| < \frac{1}{A}$, and diverges for $|x - c| > \frac{1}{A}$. The cases $|x - c| = \frac{1}{A}$ need further inspection.

Definition: Radius of Convergence

- (a) Let $0 < R < \infty$. If $\sum_{n=0}^{\infty} A_n(x - c)^n$ converges for $|x - c| < R$, and diverges for $|x - c| > R$, then we say that the series has radius of convergence R .



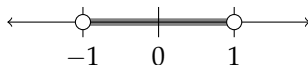
- (b) If $\sum_{n=0}^{\infty} A_n(x - c)^n$ converges for every number x , we say that the series has an infinite radius of convergence.



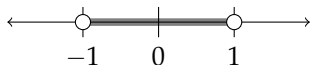
- (c) If $\sum_{n=0}^{\infty} A_n(x - c)^n$ diverges for every $x \neq c$, we say that the series has radius of convergence zero.



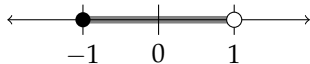
- We saw that $\sum_{n=0}^{\infty} x^n$ converges when $|x| < 1$ and diverges when $|x| > 1$, so this series has radius of convergence $R =$



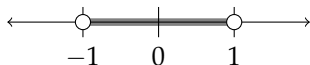
- We saw that $\sum_{n=0}^{\infty} x^n$ converges when $|x| < 1$ and diverges when $|x| > 1$, so this series has radius of convergence $R = 1$.



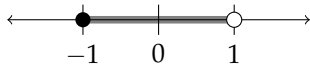
- We saw that $\sum_{n=1}^{\infty} \frac{x^n}{n}$ converges when $|x| < 1$ and diverges when $|x| > 1$, so this series also has radius of convergence $R =$



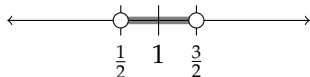
- We saw that $\sum_{n=0}^{\infty} x^n$ converges when $|x| < 1$ and diverges when $|x| > 1$, so this series has radius of convergence $R = 1$.



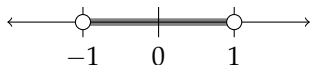
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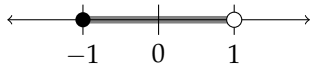
- We saw that $\sum_{n=1}^{\infty} 2^n(x-1)^n$ converges when $|x-1| < \frac{1}{2}$ and diverges when $|x-1| > \frac{1}{2}$, so this series has radius of convergence $R =$



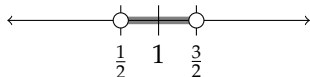
- We saw that $\sum_{n=0}^{\infty} x^n$ converges when $|x| < 1$ and diverges when $|x| > 1$, so this series has radius of convergence $R = 1$.



- We saw that $\sum_{n=1}^{\infty} \frac{x^n}{n}$ converges when $|x| < 1$ and diverges when $|x| > 1$, so this series also has radius of convergence $R = 1$.



- We saw that $\sum_{n=1}^{\infty} 2^n(x-1)^n$ converges when $|x-1| < \frac{1}{2}$ and diverges when $|x-1| > \frac{1}{2}$, so this series has radius of convergence $R = \frac{1}{2}$.



What is the radius of convergence for the series $\sum_{n=0}^{\infty} \frac{x^n}{n!}$?

Recall: $n! = (n)(n-1)(n-2) \cdots (2)(1)$.

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Recall: $n! = (n)(n-1)(n-2) \cdots (2)(1)$.

$$\begin{aligned} \lim_{n \rightarrow \infty} \left| \frac{\frac{x^{n+1}}{(n+1)!}}{\frac{x^n}{n!}} \right| &= \lim_{n \rightarrow \infty} \left| \frac{x^{n+1}}{x^n} \right| \frac{n!}{(n+1)!} \\ &= \lim_{n \rightarrow \infty} |x| \frac{(n)(n-1)(n-2) \cdots (2)(1)}{(n+1)(n)(n-1)(n-2) \cdots (2)(1)} \\ &= \lim_{n \rightarrow \infty} \frac{|x|}{n+1} = 0 \end{aligned}$$

For every real x , the limit is less than one, so the series converges. That is, its radius of convergence is ∞ .



What is the radius of convergence for the series $\sum_{n=0}^{\infty} n! \cdot (x - 3)^n$?

What is the radius of convergence for the series $\sum_{n=0}^{\infty} n! \cdot (x - 3)^n$?

$$\begin{aligned} \lim_{n \rightarrow \infty} \left| \frac{(n+1)!(x-3)^{n+1}}{(n!)(x-3)^n} \right| &= \lim_{n \rightarrow \infty} \frac{(n+1)!}{n!} \left| \frac{(x-3)^{n+1}}{(x-3)^n} \right| \\ &= \lim_{n \rightarrow \infty} \frac{(n+1)(n)(n-1)(n-2) \cdots (2)(1)}{(n)(n-1)(n-2) \cdots (2)(1)} |x-3| \\ &= \lim_{n \rightarrow \infty} (n+1) |x-3| \end{aligned}$$

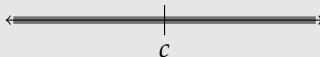
For every real x except $x = 3$, the limit is greater than one, so the series diverges. The series only converges at $x = 3$. That is, its radius of convergence is 0.



Theorem

Given a power series (say with centre c), one of the following holds.

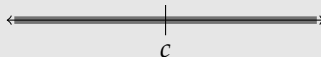
- (a) The power series converges for every number x . In this case we say that the radius of convergence is ∞ .



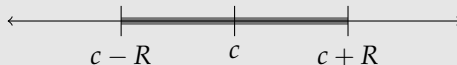
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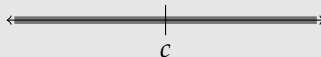
- (b) There is a number $0 < R < \infty$ such that the series converges for $|x - c| < R$ and diverges for $|x - c| > R$. Then R is called the radius of convergence.



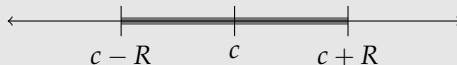
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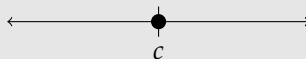
- (a) The power series converges for every number x . In this case we say that the radius of convergence is ∞ .



- (b) There is a number $0 < R < \infty$ such that the series converges for $|x - c| < R$ and diverges for $|x - c| > R$. Then R is called the radius of convergence.



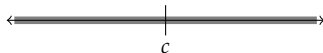
- (c) The series converges for $x = c$ and diverges for all $x \neq c$. In this case, we say that the radius of convergence is 0.



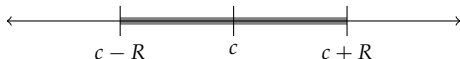
We are told that a certain power series with centre $c = 3$ converges at $x = 4$ and diverges at $x = 1$. What else can we say about the convergence or divergence of the series for other values of x ?

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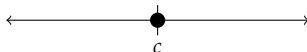
- (a) The power series converges for every number x . In this case we say that the radius of convergence is ∞ .



- (b) There is a number $0 < R < \infty$ such that the series converges for $|x - c| < R$ and diverges for $|x - c| > R$. Then R is called the radius of convergence.



- (c) The series converges for $x = c$ and diverges for all $x \neq c$. In this case, we say that the radius of convergence is 0.



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We are told that a certain power series with centre $c = 3$ converges at $x = 4$ and diverges at $x = 1$. What else can we say about the convergence or divergence of the series for other values of x ?

From the theorem, we know that there is some real number R such that the series converges when $|x - 3| < R$ and diverges when $|x - 3| > R$.

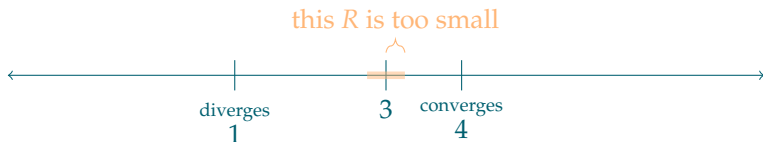


- ▶ The series converges at $x = 4$, so $|4 - 3| \not> R$, so $R \geq 1$.
- ▶ The series diverges at $x = 1$, so $|1 - 3| \not< R$, so $R \leq 2$.

So for some number $1 \leq R \leq 2$, the series converges for $|x - 3| < R$, and diverges for $|x - 3| > R$.

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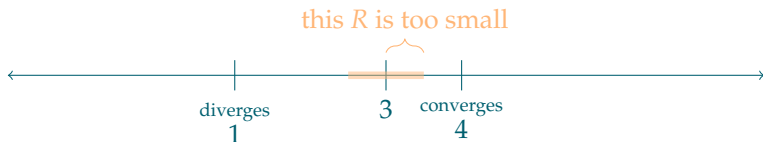


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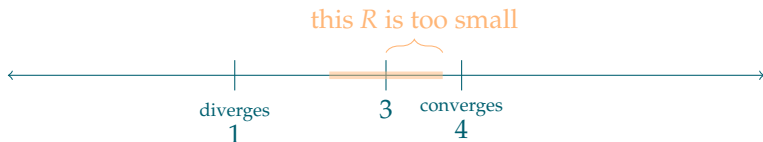


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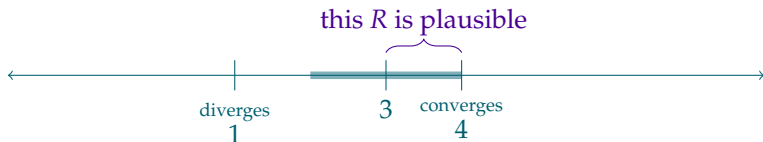


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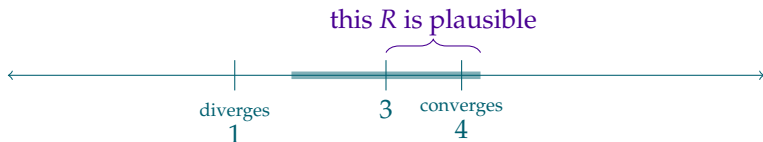


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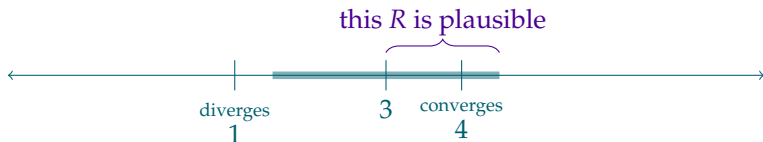


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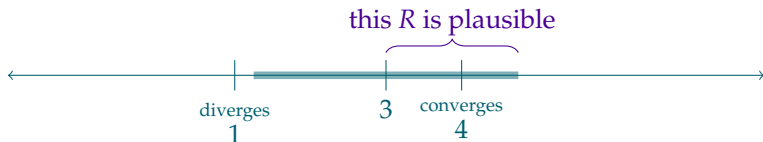


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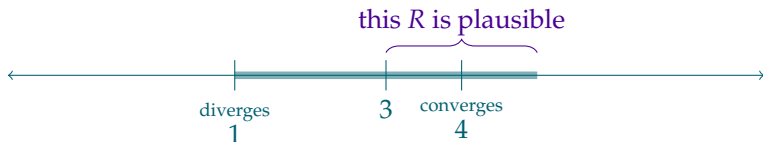


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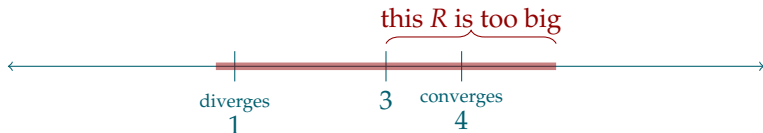


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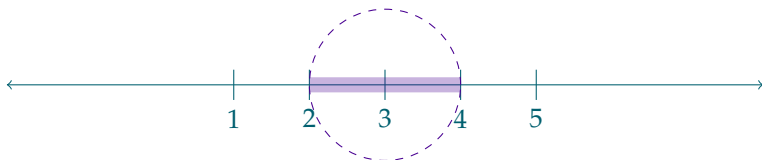
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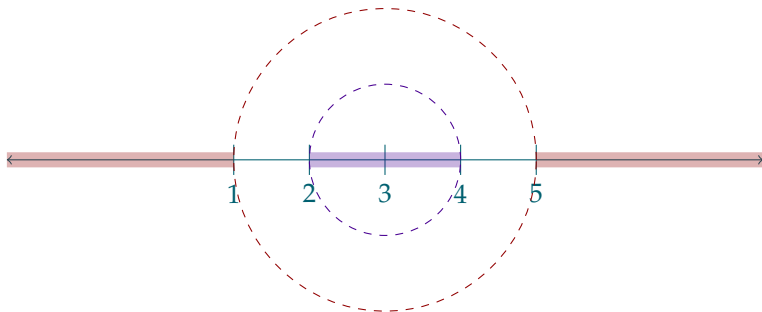
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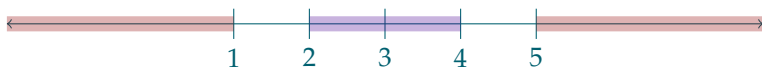
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- ▶ From $R \geq 1$, we know the series converges for x in the interval $(2, 4]$.
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- ▶ From $R \geq 1$, we know the series converges for x in the interval $(2, 4]$.
- ▶ From $R \leq 2$, we know the series diverges for x in the $(-\infty, 1] \cup (5, \infty)$.
- ▶ We do not know whether the series converges for other x .

Operations on Power Series

Assume that the functions $f(x)$ and $g(x)$ are given by the power series

$$f(x) = \sum_{n=0}^{\infty} A_n (x - c)^n \quad g(x) = \sum_{n=0}^{\infty} B_n (x - c)^n$$

for all x obeying $|x - c| < R$. Let K be a constant. Then:

$$f(x) + g(x) = \sum_{n=0}^{\infty} [A_n + B_n] (x - c)^n$$

$$Kf(x) = \sum_{n=0}^{\infty} K A_n (x - c)^n$$

for all x obeying $|x - c| < R$.

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for all x obeying $|x - c| < R$. Then:

$$\begin{aligned} (x - c)^N f(x) &= \sum_{n=0}^{\infty} A_n (x - c)^{n+N} \quad \text{for any integer } N \geq 1 \\ &= \sum_{k=N}^{\infty} A_{k-N} (x - c)^k \quad \text{where } k = n + N \end{aligned}$$

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for all x obeying $|x - c| < R$. Then:

$$f'(x) = \sum_{n=0}^{\infty} A_n n (x - c)^{n-1} = \sum_{n=1}^{\infty} A_n n (x - c)^{n-1}$$

$$\int_c^x f(t) \, dt = \sum_{n=0}^{\infty} A_n \frac{(x - c)^{n+1}}{n + 1}$$

$$\int f(x) \, dx = \left[\sum_{n=0}^{\infty} A_n \frac{(x - c)^{n+1}}{n + 1} \right] + C \quad \text{with } C \text{ an arbitrary constant}$$

for all x obeying $|x - c| < R$.

Operations on Power Series

Assume that the functions $f(x)$ and $g(x)$ are given by the power series

$$f(x) = \sum_{n=0}^{\infty} A_n(x-c)^n \qquad g(x) = \sum_{n=0}^{\infty} B_n(x-c)^n$$

for all x obeying $|x-c| < R$.

Differentiating, antidifferentiating, multiplying by a nonzero constant, and multiplying by a positive power of $(x-c)$ do not change the radius of convergence of $f(x)$ (although they may change the interval of convergence).

Given that $\frac{d}{dx} \left\{ \frac{1}{1-x} \right\} = \frac{1}{(1-x)^2}$, find a power series representation for $\frac{1}{(1-x)^2}$ when $|x| < 1$.

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$$\begin{aligned}
 \frac{1}{(1-x)^2} &= \frac{d}{dx} \left\{ \frac{1}{1-x} \right\} \\
 &= \frac{d}{dx} \left\{ \sum_{n=0}^{\infty} x^n \right\} \\
 &= \sum_{n=0}^{\infty} \left(\frac{d}{dx} \{x^n\} \right) \\
 &= \sum_{n=0}^{\infty} nx^{n-1} \\
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Find a power series representation for $\log(1 + x)$ when $|x| < 1$.

Find a power series representation for $\log(1+x)$ when $|x| < 1$.

First, note $\frac{d}{dx}\{\log(1+x)\} = \frac{1}{1+x}$. Our plan is to antidifferentiate a power series representation of $\frac{1}{1+x}$. For $|x| < 1$:

$$\begin{aligned}\frac{1}{1+x} &= \frac{1}{1-(-x)} = \sum_{n=0}^{\infty} (-x)^n = \sum_{n=0}^{\infty} (-1)^n x^n \\ \int \frac{1}{1+x} dx &= \int \left(\sum_{n=0}^{\infty} (-1)^n x^n \right) dx \\ &= \sum_{n=0}^{\infty} \left(\int (-1)^n x^n dx \right)\end{aligned}$$

So, for some constant C ,

$$\log(1+x) = C + \sum_{n=0}^{\infty} (-1)^n \frac{x^{n+1}}{n+1} = C + \sum_{n=1}^{\infty} (-1)^{n+1} \frac{x^n}{n}$$



Find a power series representation for $\log(1 + x)$ when $|x| < 1$.

To find C , let's plug in a value for x where both sides of the equation are easy to evaluate: $x = 0$.

$$\log(1 + 0) = C + \sum_{n=1}^{\infty} (-1)^{n+1} \frac{0^n}{n}$$

$$0 = C$$

$$\text{So, } \log(1 + x) = \sum_{n=1}^{\infty} (-1)^{n+1} \frac{x^n}{n}$$

when $|x| < 1$.



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First, note $\frac{d}{dx} \{\arctan x\} = \frac{1}{1+x^2}$. To obtain a power series representation of $\frac{1}{1+x^2}$, we'll substitute into the geometric series.

Let $y = -x^2$ with $|y| < 1$. Then:

$$\begin{aligned}\frac{1}{1-y} &= \sum_{n=0}^{\infty} y^n \\ \Rightarrow \frac{1}{1+x^2} &= \sum_{n=0}^{\infty} (-x^2)^n = \sum_{n=0}^{\infty} (-1)^n x^{2n} \\ \Rightarrow \int \frac{1}{1+x^2} dx &= \int \left(\sum_{n=0}^{\infty} (-1)^n x^{2n} \right) dx = \sum_{n=0}^{\infty} \left(\int (-1)^n x^{2n} dx \right) \\ \Rightarrow \arctan x &= C + \sum_{n=0}^{\infty} (-1)^n \frac{x^{2n+1}}{2n+1}\end{aligned}$$

for some constant C .



Find a power series representation for $\arctan(x)$ when $|x| < 1$.

To find C , we'll plug in $x = 0$, which makes both sides of the last equation easy to evaluate.

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

$$0 = C$$

$$\text{So, } \arctan x = \sum_{n=0}^{\infty} (-1)^n \frac{x^{2n+1}}{2n+1}$$

when $|x| < 1$, i.e. when $|x| < 1$.



Substituting in a Power Series

Assume that the function $f(x)$ is given by the power series

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

for all x in the interval I . Also let K and k be real constants. Then

$$f(Kx^k) = \sum_{n=0}^{\infty} A_n K^n x^{kn}$$

whenever Kx^k is in I . In particular, if $\sum_{n=0}^{\infty} A_n x^n$ has radius of convergence R , K is nonzero and k is a natural number, then $\sum_{n=0}^{\infty} A_n K^n x^{kn}$ has radius of convergence $\sqrt[k]{R/|K|}$.

Find a power series representation for $\frac{1}{5-x}$ with centre 3.



Find a power series representation for $\frac{1}{5-x}$ with centre 3.

We know that $\frac{1}{1-(x-3)} = \sum_{n=0}^{\infty} (x-3)^n$ when $|x-3| < 1$. To take advantage of our ability to substitute into power functions, we'd like to write $\frac{1}{5-x}$ in the form $\frac{1}{1-K(x-3)^k}$ for some constant K and some whole number k .

$$\frac{1}{5-x} = \frac{1}{2-(x-3)} = \frac{1}{2} \cdot \frac{1}{1-\left(\frac{x-3}{2}\right)}$$

Set $y = \frac{x-3}{2}$. When $|y| < 1$:

$$\begin{aligned} \frac{1}{2} \cdot \frac{1}{1-y} &= \frac{1}{2} \sum_{n=0}^{\infty} y^n \\ \Rightarrow \frac{1}{2} \cdot \frac{1}{1-\left(\frac{x-3}{2}\right)} &= \frac{1}{2} \sum_{n=0}^{\infty} \left(\frac{x-3}{2}\right)^n \\ \Rightarrow \frac{1}{5-x} &= \sum_{n=0}^{\infty} \frac{(x-3)^n}{2^{n+1}}. \end{aligned}$$



Find a power series representation for $\frac{1}{5-x}$ with centre 3.

The series converges when:

$$\begin{aligned} |y| &< 1 \\ \left| \frac{x-3}{2} \right| &< 1 \\ |x-3| &< 2 \end{aligned}$$

So the radius of convergence of our series is 2.



Included Work



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