Chapter 1: Numerical Series

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Contents

1 Preamble

1.1 Vocabulary

In this chapter, we will use CVG for Convergence and DVG for Divergence. We will also use GT for General Term.

1.2 Remark

Be careful, the series $\sum U_n$ is not the same as the sequence $(U_n)_{n\in\mathbb{N}}$. $\sum U_n$ is the series of general term U_n and $(U_n)_{n\in\mathbb{N}}$ is the sequence U_n.

2 General approach Convergence and Divergence

2.1 Definition

Let $(\mathbf{U_n})_{\mathbf{n}\in\mathbb{N}}$ a sequence of real numbers, we call series of general term $\mathbf{U_k}$ and denote $\sum \mathbf{U_k}$ the sequence of partial sums $(\mathbf{S_n})_{\mathbf{n}\in\mathbb{N}}$ where for any integer $\mathbf{n} \in \mathbb{N}$, $\mathbf{S_n} = \sum\limits_{\mathbf{k=0}}^{\mathbf{n}} \mathbf{U_k}$. We say $\sum \mathbf{U_k}$ is convergent if and only if $(\mathbf{S_n})_{\mathbf{n}\in\mathbb{N}}$ is convergent.

2.1.1 Example: the geometric series

Let $\mathbf{q} \in \mathbb{R}^\star$ and let us consider the series $\sum \mathbf{q^k}$. We have:

$$\forall n \in \mathbb{N}, S_n = \sum_{k=0}^{n} q^k = \left| \begin{array}{lll} \frac{1-q^{n+1}}{1-q} & \text{if } q \neq 1 & \Longrightarrow \left| \begin{array}{l} \text{if } -1 < q < 1, \sum\limits_{k=0}^{+\infty} q^k = \frac{1}{1-q} \sum U_k\text{: CVG} \\ \text{if } q > 1 \text{ or } q < -1, \sum U_k\text{: DVG} \end{array} \right. \\ (n+1) & \text{if } q = 1 & \Longrightarrow \sum U_k\text{: DVG} \end{array} \right.$$

2.2 Propositions

Let $\sum \mathbf{U_k}$ and $\sum \mathbf{V_k}$ two series of general terms and $\lambda \in \mathbb{R}$. We have:

- If $[\sum \mathbf{U_k}$ CVG and $\sum \mathbf{V_k}$ CVG], then $\sum(\mathbf{U_k} + \mathbf{V_k})$ CVG
- If $[\sum \mathbf{U_k}$ CVG], then $\sum \lambda\mathbf{U_k}$ CVG
- If $[\sum \mathbf{U_k}$ CVG and $\sum \mathbf{V_k}$ DVG], then $\sum(\mathbf{U_k} + \mathbf{V_k})$ DVG
- $\sum \mathbf{U_k}$ DVG and $\sum \mathbf{V_k}$ DVG <u>does not imply</u> $\sum(\mathbf{U_k} + \mathbf{V_k})$ DVG

2.3 Sum and Remainder of a convergent series

Let $\sum \mathbf{U_k}$ a <u>convergent series</u>. We call sum of the series $\sum \mathbf{U_k}$ the following real number: $\sum\limits_{\mathbf{k=0}}^{+\infty} \mathbf{U_k} = \lim\limits_{\mathbf{n}\to+\infty} \mathbf{S_n}$ where $\mathbf{S_n} = \sum\limits_{\mathbf{k=0}}^{\mathbf{n}} \mathbf{U_k}$. And we call remainder of the series

$\sum \mathbf{U_k}$ sequence $(\mathbf{R_n})$ defined as follows:

$$\forall n \in \mathbb{N}, R_n = \sum_{k=n+1}^{+\infty}$$

2.3.1 Example

$\sum \mathbf{q^k}$ CVG $\Leftrightarrow -1 < q < 1$: $\mathbf{S} = \lim_{\mathbf{n}\to+\infty} \mathbf{S_n} = \frac{\mathbf{1}}{\mathbf{1-q}}$

2.4 Convergence necessary condition

2.4.1 Proposition

Let $\sum(\mathbf{U_k})_{\mathbf{k}\in\mathbb{N}}$ a sequence. We have:

$$\sum U_k \text{ CVG } \underset{\not\Leftarrow}{\Longrightarrow} \left(U_k \xrightarrow[k\to+\infty]{} 0\right)$$

2.4.2 Example

- Harmonic series: $\sum \frac{\mathbf{1}}{\mathbf{n}}$, $(\frac{\mathbf{1}}{\mathbf{n}}) \xrightarrow[\mathbf{n}\to+\infty]{} \mathbf{0}$ but $\sum \frac{\mathbf{1}}{\mathbf{n}}$ DVG
- $\sum \frac{\mathbf{e^n}}{\mathbf{n^{2023}}}$, $\frac{e^n}{n^{2023}} \xrightarrow[n\to+\infty]{} +\infty \implies \sum \frac{e^n}{n^{2023}}$ DVG

3 Positive Term Series (P.T.S.)

3.1 Definition

Let $\sum \mathbf{U_k}$ a series. We say $\sum \mathbf{U_k}$ is a P.T.S., if and only if $\forall \mathbf{k} \in \mathbb{N}, \mathbf{U_k} \geq \mathbf{0}$.
We say $\sum \mathbf{U_k}$ is a P.T.S. from $\mathbf{p} \in \mathbb{N}$ onwards, if and only if $\forall \mathbf{k} \in \mathbb{N}, \mathbf{k} \geq \mathbf{p} \implies \mathbf{U_k} \geq \mathbf{0}$.

3.2 Propositions

- Let $\sum \mathbf{U_k}$ a P.T.S. and $(\mathbf{S_n})_{\mathbf{n}\in\mathbb{N}}$ the associated partial sum sequence. Then:

$$\sum U_k \text{ CVG } \Leftrightarrow (S_n)_{n\in\mathbb{N}} \text{ is upper-bounded}$$

- Let $\sum \mathbf{U_k}$ and $\sum \mathbf{V_k}$ two series such that:
  $\forall \mathbf{k} \in \mathbb{N}, \mathbf{0} \leq \mathbf{U_k} \leq \mathbf{V_k}$. Then:
  1. If $\sum \mathbf{V_k}$ CVG, then $\sum \mathbf{U_k}$ CVG
  2. If $\sum \mathbf{U_k}$ DVG, then $\sum \mathbf{V_k}$ DVG

3.2.1 Example

What's the nature of $\sum \frac{\mathbf{1}}{|\mathbf{n}\cdot\sin(\mathbf{n})|}$?

$\forall n \in \mathbb{N}^\star, 0 < |\sin(n)| \leq 1 \implies 0 < \frac{1}{n} \leq \frac{1}{|n\cdot\sin(n)|}$
$\sum \frac{\mathbf{1}}{\mathbf{n}}$ (Harmonic) DVG $\implies \sum \frac{\mathbf{1}}{|\mathbf{n}\cdot\sin(\mathbf{n})|}$ DVG

3.3 Riemann's series

3.3.1 Definition

We call Riemann's series any series of General Terms (GT) $\sum \frac{\mathbf{1}}{\mathbf{n}^{\alpha}}$ where $\alpha \in \mathbb{R}$.

3.3.2 Theorem (Riemann)

Let $\alpha \in \mathbb{R}$. Then:

$$\sum \frac{1}{n^{\alpha}} \text{ CVG } \iff \alpha > 1$$

3.3.2.1 Example

- $\sum \frac{\mathbf{1}}{\sqrt{\mathbf{2}}} = \sum \frac{\mathbf{1}}{\mathbf{2}^{\frac{1}{2}}} \implies$ DVG
- $\sum \frac{\mathbf{1+cos(n)}}{\mathbf{n^4}}$: $\forall n \in \mathbb{N}^{\star}, 0 \leq 1 + cos(n) \leq 2 \implies 0 \leq \frac{1+cos(n)}{n^4} \leq \frac{2}{n^4}$
  And $\sum \frac{\mathbf{2}}{\mathbf{n^4}}$ of same nature as $\sum \frac{\mathbf{1}}{\mathbf{n^4}}$ (Riemann's series) CVG $\implies \sum \frac{\mathbf{1+cos(n)}}{\mathbf{n^4}}$ CVG

3.4 Comparison criteria

3.4.1 Proposition

Let $\sum \mathbf{U_n}$ and $\sum \mathbf{V_n}$ two P.T.S.

1. If $\mathbf{U_n} \underset{+\infty}{\sim} \mathbf{V_n}$ then $\sum \mathbf{U_n}$ and $\sum \mathbf{V_n}$ are of same nature

2. If $\mathbf{U_n} = \mathbf{o}(\mathbf{V_n})$ then [If $\sum \mathbf{V_n}$ CVG then $\sum \mathbf{U_n}$ CVG]

3.4.1.1 Example

What's the nature of $\sum \mathbf{U_n}$?

- $\mathbf{U_n = e^{-\sqrt{n}}}$: Step 1: $n^2 \times U_n = \frac{n^2}{e^{\sqrt{n}}} = \frac{(\sqrt{n})^4}{e^{\sqrt{n}}} \xrightarrow[n \to +\infty]{} 0 \implies U_n = o(\frac{1}{n^2})$
  Step 2: $\sum \frac{1}{n^2}$ CVG (Riemann's series $\alpha = 2 > 1$) $\implies \sum U_n$ CVG

$$\forall n \in \mathbb{N}^{\star}, \frac{n+1}{n} = 1 + \frac{1}{n} \implies \ln(1 + \frac{1}{n}) \underset{+\infty}{=} \frac{1}{n} + o(\frac{1}{n})$$

- $\mathbf{U_n} = \ln(\frac{\mathbf{n+1}}{\mathbf{n}})$: ⚠ $\implies$
  1. $\forall n \in \mathbb{N}, U_n > 0$ since $1 + \frac{1}{n} > 1$
  2. $U_n \underset{+\infty}{=} \frac{1}{n}$

  $\implies \sum U_n$ and $\sum \frac{1}{n}$ of same nature
  and $\sum \frac{1}{n}$ DVG (Harmonic series)

3.4.2 Proposition

Let $\sum \mathbf{U_n}$ a numerical sequence. We have:

$$\sum \overbrace{(U_{n+1} - U_n)}^{W_n} \text{ CVG} \iff (U_n) \text{ CVG}$$

3.4.2.1 Example

1. General Example, limit calculation:

$$\begin{aligned}
\mathbf{S_n} = \sum_{\mathbf{k=0}}^{\mathbf{n}} \mathbf{W_k} = \sum_{\mathbf{k=0}}^{\mathbf{n}} (\mathbf{U_{k+1}} - \mathbf{U_k}) &= \sum_{k=0}^{n} U_{k+1} - \sum_{k=0}^{n} U_k \\
&= \sum_{k=1}^{n+1} U_k - \sum_{k=0}^{n} U_k \\
&= \left(\sum_{k=1}^{n} U_k + U_{n+1} \right) - \left(U_0 + \sum_{k=1}^{n} U_k \right) \\
Sn = \sum_{k=0}^{n} (U_{k+1} - U_k) &= U_{n+1} - U_0
\end{aligned}$$

2. $$\sum \overbrace{\left(\tfrac{1}{n+1} - \tfrac{1}{n}\right)}^{W_n} : \left| \begin{array}{l} \sum W_n \text{ of same nature as } \sum \left(\frac{1}{n}{}_{n\in\mathbb{N}^\star}\right) \left(\begin{array}{l} \frac{1}{n} \xrightarrow[n\to+\infty]{} 0 \text{ CVG} \\ \text{So: } \sum W_n \text{ CVG} \end{array} \right) \\ \text{calculation of the limit:} \\ S = \lim\limits_{n\to+\infty} S_n = \sum\limits_{k=1}^{+\infty} W_k = \lim\limits_{n\to+\infty} \left(\frac{1}{n+1} - 1\right) = -1 \end{array} \right.$$

3.5 Riemann's Rule

Let $\sum \mathbf{U_n}$ a <u>Positive</u> numerical series. If $\exists \alpha > \mathbf{1}, \mathbf{n}^\alpha \times \mathbf{U_n} \underset{+\infty}{\sim} \mathbf{0}$ then $\sum \mathbf{U_n}$ CVG

3.5.1 Proof

$$\exists \alpha > \mathbf{1}, \mathbf{n}^\alpha \times \mathbf{U_n} \xrightarrow[\mathbf{n}\to+\infty]{} \mathbf{0} \implies \frac{\mathbf{U_n}}{\frac{\mathbf{1}}{\mathbf{n}^\alpha}} \xrightarrow[\mathbf{n}\to+\infty]{} \mathbf{0}$$

$$\implies \left\{ \begin{array}{r|} U_n = o(\frac{1}{n^\alpha}) \\ \text{and} \\ \alpha > 1 \\ \text{and} \\ \sum U_n \text{ P.T.S.} \end{array} \right. \left[\sum \tfrac{1}{n^\alpha} \text{ CVG (Riemann's series)} \implies \sum U_n \text{ CVG} \right]$$

3.6 D'Alembert's Rule

Let $(\mathbf{U_n})$ be a strictly positive sequence such that:

$$\frac{U_{n+1}}{U_n} \xrightarrow[n\to+\infty]{} \ell \in \mathbb{R}_+ \cup \{+\infty\}$$

$$\text{Then: } \begin{array}{l} \ell < 1 \implies \sum U_n \text{ CVG} \\ \ell > 1 \implies \sum U_n \text{ DVG} \\ \ell = 1 \implies \text{ no conclusion} \end{array}$$

3.6.1 Example

$\sum \frac{\mathbf{1}}{\mathbf{n!}}$: $\forall n \in \mathbb{N}, \frac{1}{n!} > 0$ (P.T.S.) and $\frac{U_{n+1}}{U_n} = \frac{\frac{1}{(n+1)!}}{\frac{1}{n!}} = \frac{1}{n+1} \xrightarrow[n\to+\infty]{} 0 < 1 \implies \sum \frac{1}{n!}$ CVG

3.7 Cauchy's Rule

Let $(\mathbf{U_n})$ be a strictly positive sequence such that:

$$\sqrt[n]{U_n} \xrightarrow[n\to+\infty]{} \ell \in \mathbb{R}_+ \cup \{+\infty\}$$

$$\text{Then: } \begin{array}{l} \ell < 1 \implies \sum U_n \text{ CVG} \\ \ell > 1 \implies \sum U_n \text{ DVG} \\ \ell = 1 \implies \text{ no conclusion} \end{array}$$

3.7.1 Example

$\sum (\frac{\mathbf{n}}{\mathbf{n+1}})^{\mathbf{n^2}}$: $\forall n \in \mathbb{N}, (\frac{n}{n+1})^{n^2} > 0$ (P.T.S.), $\sqrt[n]{U_n} = \left((\frac{n}{n+1})^{n^2}\right)^{\frac{1}{n}} = (\frac{n}{n+1})^n = e^{n\ln(1-\frac{n}{n+1})}$
$\ln(1-\frac{n}{n+1}) \sim n\times(-\frac{n}{n+1}) \xrightarrow[n\to+\infty]{} -1 < 0 \implies \sqrt[n]{U_n} \xrightarrow[n\to+\infty]{} e^{-1} = \frac{1}{e} < 1 \underset{\text{Cauchy}}{\implies} \sum U_n$ CVG

3.8 Examples

① $\sum(1+\frac{1}{n})^n$: $1+\frac{1}{n} \underset{n\to+\infty}{\not\longrightarrow} 0$ (don't have the necessary condition) $\implies \sum(1+\frac{1}{n})^n$ DVG

② $\sum \left((1+\frac{1}{n})^n - e\right)$:

(a)

$$\begin{aligned}\left((1+\frac{1}{n})^n - e\right) = e^{n\times\ln(1+\frac{1}{n})} - e &= e^{n\times(\frac{1}{n}-\frac{1}{2n^2}+o(\frac{1}{n^2}))} - e \\ &= e^{1-\frac{1}{2n}+o(\frac{1}{n})} - e \\ &= e \times e^{-\frac{1}{2n}+o(\frac{1}{n})} - e \\ &= e \times (1 - \frac{1}{2n} + o(\frac{1}{n})) - e \\ &= -\frac{e}{2n} + o(\frac{1}{n})\end{aligned}$$

So $\left((1+\frac{1}{n})^n - e\right) \underset{+\infty}{\sim} -\frac{e}{2n}$ (Can't use P.T.S. property)

(b) $\sum -\frac{e}{2n} < 0$ for $n \in \mathbb{N}^\star$

(c) $\exists p \in \mathbb{N}^\star, (n \geq p) \implies (\left((1+\frac{1}{n})^n - e\right) \leq 0)$ (Same sign as $\sum -\frac{e}{2n}$)
$\implies \sum \left((1+\frac{1}{n})^n - e\right)$ has the same nature as $\sum -\frac{e}{2n}$ wich is of same nature as $\sum \frac{1}{n}$ DVG

③ $\sum n^{2023} \times e^{-n} = \sum \frac{n^{2023}}{e^n}$: $n^{2023} = o(e^n)$ (growth comparison) $n^{2025} \times e^{-n} = \frac{\frac{n^{2023}}{e^n}}{\frac{1}{n^2}} \xrightarrow[n \to +\infty]{} 0 \implies U_n = o(\frac{1}{n^2}) \underset{\text{Riemann}(\alpha=2>1)}{\implies} \sum U_n$ CVG

④ $\sum n! \times e^{-n}$

4 Alternating Series

4.1 Definition

Let $(\mathbf{U_n}) \in \mathbb{R}^{\mathbb{N}}$, we say $(\mathbf{U_n})$ is an alternating sequence thus $\sum \mathbf{U_n}$ an alternating series, if there exists $\left| \begin{array}{l} \text{a positive} \\ \text{a negative} \end{array} \right.$ sequence $(\mathbf{a_n})$ such that:

$$\forall \mathbf{n} \in \mathbb{N}, \left| \begin{array}{l} U_n = (-1)^n \times a_n \\ U_n = (-1)^{n+1} \times a_n \end{array} \right.$$

4.1.1 Example

$\sum \frac{(-1)^\mathbf{n}}{\mathbf{n}}$ is an alternating series because $\forall \mathbf{n} \in \mathbb{N}, \frac{(-1)^\mathbf{n}}{\mathbf{n}} = (-1)^\mathbf{n} \times \frac{1}{\mathbf{n}}$

4.2 Alternating Series Special Criteria (A.S.S.C.)

4.2.1 Theorem

Let $(\mathbf{U_n})$ an alternating sequence, such that:

$$\left. \begin{array}{l} U_n \xrightarrow[n \to +\infty]{} 0 \\ (|U_n|)_{n \in \mathbb{N}} \text{ is decreasing} \end{array} \right] \implies \sum \mathbf{U_n} \text{ CVG}$$

4.2.2 Explanation

An alternating sequence is of the form

$$\begin{array}{rcr} \mathbf{U_n} = (-1)^\mathbf{n} \times \mathbf{a_n} & \text{or} & \mathbf{U_n} = (-1)^{\mathbf{n+1}} \times \mathbf{a_n} \\ |\mathbf{U_n}| = |(-1)^\mathbf{n} \times \mathbf{a_n}| = |\mathbf{a_n}| & \text{or} & |\mathbf{U_n}| = \left|(-1)^{\mathbf{n+1}} \times \mathbf{a_n}\right| = |\mathbf{a_n}| \end{array}$$

$$\text{So } (|\mathbf{U_n}|)_{\mathbf{n} \in \mathbb{N}} = (\mathbf{a_n})_{\mathbf{n} \in \mathbb{N}}$$

5 Absolute Convergence

5.1 Definition

Let $(\mathbf{U_n})$ a sequence, we say $\sum \mathbf{U_n}$ is absolutely convergent if $\sum |\mathbf{U_n}|$ is convergent.

5.1.1 Example

$\sum \frac{(-1)^n}{n^2}$ is absolutely convergent because $\sum \left|\frac{(-1)^n}{n^2}\right| = \sum \frac{1}{n^2}$ is convergent.

5.2 Proposition

Let $\sum \mathbf{U_n}$ a series, if $\sum \mathbf{U_n}$ is absolutely convergent then $\sum \mathbf{U_n}$ is convergent.

$$\sum |\mathbf{U_n}| \text{ CVG } \underset{\not\Longleftarrow}{\Longrightarrow} \sum \mathbf{U_n} \text{ CVG.}$$

5.2.1 Counter Example

$\sum \frac{(-1)^n}{n}$ is convergent BUT $\sum \left|\frac{(-1)^n}{n}\right| = \sum \frac{1}{n}$ is divergent.