# Title

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# 1 Undergraduate Analysis: Uniform Convergence

## 1.1 Fall 2018 # 1 ✨

Let $f(x) = \dfrac{1}{x}$. Show that $f$ is uniformly continuous on $(1, \infty)$ but not on $(0, \infty)$.

**Solution:**

**Concepts Used:**

- Uniform continuity:

$$\forall \varepsilon > 0, \exists \delta(\varepsilon) > 0 \quad \text{such that} \quad |x - y| < \delta \implies |f(x) - f(y)| < \varepsilon.$$

- Negating uniform continuity: $\exists \varepsilon > 0$ such that $\forall \delta(\varepsilon)$ there exist $x, y$ such that $|x - y| < \delta$ *and* $|f(x) - f(y)| > \varepsilon$.

**Claim**: $f(x) = \dfrac{1}{x}$ is uniformly continuous on $(c, \infty)$ for any $c > 0$.

- Note that

$$|x|, |y| > c > 0 \implies |xy| = |x||y| > c^2 \implies \frac{1}{|xy|} < \frac{1}{c^2}.$$

- Letting $\varepsilon$ be arbitrary, choose $\delta < \varepsilon c^2$.
  - Note that $\delta$ does not depend on $x, y$.
- Then

$$\begin{aligned} |f(x) - f(y)| &= \left| \frac{1}{x} - \frac{1}{y} \right| \\ &= \frac{|x - y|}{xy} \\ &\leq \frac{\delta}{xy} \\ &< \frac{\delta}{c^2} \\ &< \varepsilon, \end{aligned}$$

  which shows uniform continuity.

**Claim**: $f$ is *not* uniformly continuous when $c = 0$.

- Toward a contradiction, let $\varepsilon < 1$.
- Let $x_n = \dfrac{1}{n}$ for $n \geq 1$.
- Choose $n$ large enough such that $|x_n - x_{n+1}| = \dfrac{1}{n} - \dfrac{1}{n+1} < \delta$.
  - Why this can be done: by the archimedean property of $\mathbb{R}$, choose $n$ such that $\dfrac{1}{n} < \varepsilon$.
  - Then

$$\frac{1}{n} - \frac{1}{n+1} = \frac{1}{n(n+1)} \leq \frac{1}{n} < \varepsilon \quad \text{since } n + 1 > 1.$$

- Note $f(x_n) = n$ and thus

$$|f(x_{n+1}) - f(x_n)| = (n + 1) - n = 1 > \varepsilon,$$

a contradiction.

## 1.2 Fall 2017 # 1 ✨

Let

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

Describe the intervals on which $f$ does and does not converge uniformly.

Walk through.

Add concepts.

**Solution:**

**Concepts Used:**

- $f_N \longrightarrow f$ uniformly $\iff \|f_N - f\| \longrightarrow 0$.
- $\sum_{n=0}^{\infty} c_n x^n \coloneqq \lim_{N\longrightarrow\infty} \sum_{n=0}^{N} c_n x^n$, i.e. an infinite sum is defined pointwise as the limit of its partial sums.

- Set $f_N(x) = \sum_{n=1}^{N} \frac{x^n}{n!}$.
  - Then by definition, $f_N(x) \longrightarrow f(x)$ pointwise on $\mathbb{R}$.
- For any compact interval $[-M, M]$, we have

$$\begin{aligned}
\|f_N(x) - f(x)\|_\infty &= \sup_{-M\leq x\leq M} \left| \sum_{n=N+1}^{\infty} \frac{x^n}{n!} \right| \\
&\leq \sup_{-M\leq x\leq M} \sum_{n=N+1}^{\infty} \left| \frac{x^n}{n!} \right| \\
&\leq \sum_{n=N+1}^{\infty} \frac{M^n}{n!} \\
&\leq \sum_{n=0}^{\infty} \frac{M^n}{n!} \\
&= e^M \\
&< \infty,
\end{aligned}$$

  so $f_N \longrightarrow f$ uniformly on $[-M, M]$ by the M-test.
- Thus $f$ converges on any bounded interval.

It does not converge on $\mathbb{R}$, since $x^N$ is unbounded.

## 1.3 Fall 2014 # 1

Let $\{f_n\}$ be a sequence of continuous functions such that $\sum f_n$ converges uniformly.

Prove that $\sum f_n$ is also continuous.

## 1.4 Spring 2017 # 4 ✨

Let $f(x,y)$ on $[-1,1]^2$ be defined by

$$f(x,y) = \begin{cases} \dfrac{xy}{(x^2+y^2)^2} & (x,y) \neq (0,0) \\ 0 & (x,y) = (0,0) \end{cases}$$

Determine if $f$ is integrable.

Redo, may just be wrong.

Add concepts.

**Solution:**

**Concepts Used:**

- ?

Switching to polar coordinates and integrating over a half-circle contained in $I^2$, we have

$$\int_{I^2} f \geq \int_0^{\pi} \int_0^1 \frac{\cos(\theta)\sin(\theta)}{r^2}\, dr\, d\theta = \infty,$$

so $f$ is not integrable.

## 1.5 Spring 2015 # 1 ✨

Let $(X,d)$ and $(Y,\rho)$ be metric spaces, $f : X \longrightarrow Y$, and $x_0 \in X$.

Prove that the following statements are equivalent:

1. For every $\varepsilon > 0 \quad \exists \delta > 0$ such that $\rho(f(x), f(x_0)) < \varepsilon$ whenever $d(x, x_0) < \delta$.
2. The sequence $\{f(x_n)\}_{n=1}^{\infty} \longrightarrow f(x_0)$ for every sequence $\{x_n\} \longrightarrow x_0$ in $X$.

## 1.6 Fall 2014 # 2

Let $I$ be an index set and $\alpha : I \longrightarrow (0, \infty)$.

1. Show that

$$\sum_{i \in I} a(i) := \sup_{\substack{J \subset I \\ J \text{ finite}}} \sum_{i \in J} a(i) < \infty \implies I \text{ is countable.}$$

2. Suppose $I = \mathbb{Q}$ and $\sum_{q\in\mathbb{Q}} a(q) < \infty$. Define

$$f(x) := \sum_{\substack{q\in\mathbb{Q}\\ q\leq x}} a(q).$$

Show that $f$ is continuous at $x \iff x \notin \mathbb{Q}$.

### 1.7 Spring 2014 # 2

Let $\{a_n\}$ be a sequence of real numbers such that

$$\{b_n\} \in \ell^2(\mathbb{N}) \implies \sum a_n b_n < \infty.$$

Show that $\sum a_n^2 < \infty$.

Note: Assume $a_n, b_n$ are all non-negative.

## 2 General Analysis

### 2.1 Spring 2020 # 1

Prove that if $f : [0,1] \longrightarrow \mathbb{R}$ is continuous then

$$\lim_{k\longrightarrow\infty} \int_0^1 k x^{k-1} f(x)\, dx = f(1).$$

**Solution:**

**Concepts Used:**

- DCT
- Weierstrass Approximation Theorem

- Suppose $p$ is a polynomial, then

$$\begin{aligned}
\lim_{k\longrightarrow\infty} \int_0^1 k x^{k-1} p(x)\, dx &= \lim_{k\longrightarrow\infty} \int_0^1 \left(\frac{\partial}{\partial x} x^k\right) p(x)\, dx \\
&= \lim_{k\longrightarrow\infty} \left[ x^k p(x)\Big|_0^1 - \int_0^1 x^k \left(\frac{\partial}{\partial x} p(x)\right) dx \right] \quad \text{integrating by parts} \\
&= p(1) - \lim_{k\longrightarrow\infty} \int_0^1 x^k \left(\frac{\partial}{\partial x} p(x)\right) dx,
\end{aligned}$$

- Thus it suffices to show that

$$\lim_{k\longrightarrow\infty} \int_0^1 x^k \left(\frac{\partial}{\partial x} p(x)\right) dx = 0.$$

- Integrating by parts a second time yields

$$\begin{aligned}
\lim_{k\longrightarrow\infty}\int_0^1 x^k\left(\frac{\partial}{\partial x}\,p(x)\right)dx &= \lim_{k\longrightarrow\infty}\frac{x^{k+1}}{k+1}p'(x)\Big|_0^1 - \int_0^1 \frac{x^{k+1}}{k+1}\left(\frac{\partial^2}{\partial x^2}\,p(x)\right)dx \\
&= -\lim_{k\longrightarrow\infty}\int_0^1 \frac{x^{k+1}}{k+1}\left(\frac{\partial^2}{\partial x^2}\,p(x)\right)dx \\
&= -\int_0^1 \lim_{k\longrightarrow\infty}\frac{x^{k+1}}{k+1}\left(\frac{\partial^2}{\partial x^2}\,p(x)\right)dx \quad \text{by DCT} \\
&= -\int_0^1 0\left(\frac{\partial^2}{\partial x^2}\,p(x)\right)dx \\
&= 0.
\end{aligned}$$

  - The DCT can be applied here because $f''$ is continuous and $[0,1]$ is compact, so $f''$ is bounded on $[0,1]$ by a constant $M$ and

$$\int_0^1 \left|x^k f''(x)\right| \leq \int_0^1 1\cdot M = M < \infty.$$

- Now use the Weierstrass approximation theorem:
  - If $f:[a,b]\longrightarrow\mathbb{R}$ is continuous, then for every $\varepsilon>0$ there exists a polynomial $p_\varepsilon(x)$ such that $\|f-p_\varepsilon\|_\infty<\varepsilon$.
- Thus

$$\begin{aligned}
\left|\int_0^1 kx^{k-1}p_\varepsilon(x)\,dx - \int_0^1 kx^{k-1}f(x)\,dx\right| &= \left|\int_0^1 kx^{k-1}(p_\varepsilon(x)-f(x))\,dx\right| \\
&\leq \left|\int_0^1 kx^{k-1}\|p_\varepsilon - f\|_\infty\,dx\right| \\
&= \|p_\varepsilon - f\|_\infty \cdot \left|\int_0^1 kx^{k-1}\,dx\right| \\
&= \|p_\varepsilon - f\|_\infty \cdot x^k\Big|_0^1 \\
&= \|p_\varepsilon - f\|_\infty \overset{\varepsilon\longrightarrow 0}{\longrightarrow} 0
\end{aligned}$$

  and the integrals are equal.
- By the first argument,

$$\int_0^1 kx^{k-1}p_\varepsilon(x)\,dx = p_\varepsilon(1) \text{ for each } \varepsilon$$

- Since uniform convergence implies pointwise convergence, $p_\varepsilon(1)\overset{\varepsilon\longrightarrow 0}{\longrightarrow} f(1)$.

## 2.2 Fall 2019 # 1 ✨

Let $\{a_n\}_{n=1}^\infty$ be a sequence of real numbers.

### 2.2.1 a

Prove that if $\lim_{n\longrightarrow\infty} a_n = 0$, then

$$\lim_{n\to\infty} \frac{a_1 + \cdots + a_n}{n} = 0$$

### 2.2.2 b

Prove that if $\sum_{n=1}^{\infty} \frac{a_n}{n}$ converges, then

$$\lim_{n\to\infty} \frac{a_1 + \cdots + a_n}{n} = 0$$

**Solution:**

**Concepts Used:**

- Cesaro mean/summation.
- Break series apart into pieces that can be handled separately.

### 2.2.3 a

Prove a stronger result:

$$a_k \longrightarrow S \implies S_N \coloneqq \frac{1}{N}\sum_{k=1}^{N} a_k \longrightarrow S.$$

Idea: once $N$ is large enough, $a_k \approx S$, and all smaller terms will die off as $N \longrightarrow \infty$.
See this MSE answer.

- Use convergence $a_k \longrightarrow S$: choose $M$ large enough such that

$$k \geq M+1 \implies |a_k - S| < \varepsilon.$$

Then

$$\begin{aligned}
\left|\left(\frac{1}{N}\sum_{k=1}^{N} a_k\right) - S\right| &= \frac{1}{N}\left|\left(\sum_{k=1}^{N} a_k\right) - NS\right| \\
&= \frac{1}{N}\left|\left(\sum_{k=1}^{N} a_k\right) - \sum_{k=1}^{N} S\right| \\
&= \frac{1}{N}\left|\sum_{k=1}^{N} (a_k - S)\right| \\
&\leq \frac{1}{N}\sum_{k=1}^{N} |a_k - S| \\
&= \frac{1}{N}\sum_{k=1}^{M} |a_k - S| + \sum_{k=M+1}^{N} |a_k - S| \\
&\leq \frac{1}{N}\sum_{k=1}^{M} |a_k - S| + \sum_{k=M+1}^{N} \frac{\varepsilon}{2} \\
&= \frac{1}{N}\sum_{k=1}^{M} |a_k - S| + (N-M)\frac{\varepsilon}{2} \\
&\overset{\varepsilon \longrightarrow 0}{\longrightarrow} \frac{1}{N}\sum_{k=1}^{M} |a_k - S| + 0 \\
&\overset{N \longrightarrow \infty}{\longrightarrow} 0 + 0.
\end{aligned}$$

Note: $M$ is fixed, so the last sum is some constant $c$, and $c/N \longrightarrow 0$ as $N \longrightarrow \infty$ for any constant. To be more careful, choose $M$ first to get $\varepsilon/2$ for the tail, then choose $N(M) > M$ for the remaining truncated part of the sum.

### 2.2.4 b

- Define

$$\Gamma_n \coloneqq \sum_{k=n}^{\infty} \frac{a_k}{k}.$$

- $\Gamma_1 = \sum_{k=1}^{n} \frac{a_k}{k}$ is the original series and each $\Gamma_n$ is a tail of $\Gamma_1$, so by assumption $\Gamma_n \overset{n \longrightarrow \infty}{\longrightarrow} 0$.
- Compute

$$\frac{1}{n}\sum_{k=1}^{n} a_k = \frac{1}{n}(\Gamma_1 + \Gamma_2 + \cdots + \Gamma_n - \mathbf{\Gamma_{n+1}})$$

.

- This comes from consider the following summation:

$$
\begin{array}{lllllll}
\Gamma_1: & a_1 & +\frac{a_2}{2} & +\frac{a_3}{3} & +\cdots & & \\
\Gamma_2: & & \frac{a_2}{2} & +\frac{a_3}{3} & +\cdots & & \\
\Gamma_3: & & & \frac{a_3}{3} & +\cdots & & \\
\hline
\sum_{i=1}^{n}\Gamma_i: & a_1 & +a_2 & +a_3 & +\cdots & a_n & +\frac{a_{n+1}}{n+1} \quad +\cdots
\end{array}
$$

- Use part (a): since $\Gamma_n \overset{n\to\infty}{\longrightarrow} 0$, we have $\frac{1}{n}\sum_{k=1}^{n}\Gamma_k \overset{n\to\infty}{\longrightarrow} 0$.
- Also a minor check: $\Gamma_n \longrightarrow 0 \implies \frac{1}{n}\Gamma_n \longrightarrow 0$.
- Then

$$
\begin{aligned}
\frac{1}{n}\sum_{k=1}^{n} a_k &= \frac{1}{n}(\Gamma_1 + \Gamma_2 + \cdots + \Gamma_n - \mathbf{\Gamma_{n+1}}) \\
&= \left(\frac{1}{n}\sum_{k=0}^{n}\Gamma_k\right) - \left(\frac{1}{n}\Gamma_{n+1}\right) \\
&\overset{n\to\infty}{\longrightarrow} 0.
\end{aligned}
$$

## 2.3 Fall 2018 # 4 ✨

Let $f \in L^1([0,1])$. Prove that

$$\lim_{n\to\infty}\int_0^1 f(x)|\sin nx|\,dx = \frac{2}{\pi}\int_0^1 f(x)\,dx$$

> Hint: Begin with the case that $f$ is the characteristic function of an interval.

Add concepts.

**Solution:**

**Concepts Used:**

- ?

Case of characteristic function

- First suppose $f(x) = \chi_{[0,1]}(x)$.
- Note that $\sin(nx)$ has a period of $2\pi/n$, and thus $\left\lfloor \frac{n}{2\pi} \right\rfloor$ full periods in $[0,1]$.
- Taking the absolute value yields a new function with half the period, so a period of $\pi/n$ and $\lfloor \pi/n \rfloor$ full periods in $[0,1]$.

- We can compute the integral over one full period (which is independent of *which* period is chosen), and since $\sin(x)$ is positive and agrees with $|\sin(nx)|$ on the first period, we have

$$\begin{aligned}\int_{\text{One Period}} |\sin(nx)|\,dx &= \int_0^{\pi/n} \sin(nx)\,dx \\ &= \frac{1}{n}\int_0^{\pi} \sin(u)\,du \quad u = nx \\ &= \frac{1}{n} - \cos(u)\,\Big|_0^{\pi} \\ &= \frac{2}{n}.\end{aligned}$$

- Then break the integral up into integrals over periods $P_1, P_2, \cdots, P_N$ where $N \coloneqq \lfloor n/\pi \rfloor$:

$$\begin{aligned}\int_0^1 |\sin(nx)|\,dx &= \left(\sum_{j=1}^{N} \int_{P_j} |\sin(nx)|\,dx\right) + \int_{N\lfloor \pi/n\rfloor}^1 |\sin(nx)|\,dx \\ &= \left(\sum_{j=1}^{N} \frac{2}{n}\right) + \int_{N\lfloor \pi/n\rfloor}^1 |\sin(nx)|\,dx \\ &= N\left(\frac{2}{n}\right) + \int_{N\lfloor \pi/n\rfloor}^1 |\sin(nx)|\,dx \\ &\coloneqq \left\lfloor \frac{n}{\pi} \right\rfloor \frac{2}{n} + \int_{N\lfloor \pi/n\rfloor}^1 |\sin(nx)|\,dx \\ &= \frac{2}{\pi} + \int_{N\lfloor \pi/n\rfloor}^1 |\sin(nx)|\,dx \\ &\coloneqq \frac{2}{\pi} + R(n)\end{aligned}$$

  so it suffices to show that $R(n) \overset{n\to\infty}{\longrightarrow} 0$.

  Need to justify removing floor function and cancellation.

- Showing this: ????????????

  No clue how to show this.

General case

Not sure. Approximate $f$ by simple functions...?

## 2.4 Fall 2017 # 4 ✨

Let

$$f_n(x) = nx(1-x)^n, \quad n \in \mathbb{N}.$$

1. Show that $f_n \longrightarrow 0$ pointwise but not uniformly on $[0,1]$.

   Hint: Consider the maximum of $f_n$.

2.

$$\lim_{n\longrightarrow\infty}\int_0^1 n(1-x)^n\sin x\,dx = 0$$

Add concepts.

Walk through.

**Solution:**

**Concepts Used:**

- ?

### 2.4.1 a

Let $G(x) = \sum_{n=1}^{\infty} nx(1-x)^n$. Applying the ratio test, we have

$$\left|\frac{(n+1)x(1-x)^{n+1}}{nx(1-x)^n}\right| = \frac{n+1}{n}|1-x| \overset{n\longrightarrow\infty}{\longrightarrow} |1-x| < 1 \iff 0 \le x \le 2,$$

and in particular, this series converges on $[0,2]$. Thus its terms go to zero, and $nx(1-x)^n \longrightarrow 0$ on $[0,1] \subset [0,2]$.

To see that the convergence is not uniform, let $x_n = \frac{1}{n}$ and $\varepsilon > \frac{1}{e}$, then

$$\sup_{x\in[0,1]} |nx(1-x)^n - 0| \ge |nx_n(1-x_n)^n| = \left|\left(1-\frac{1}{n}\right)^n\right| \overset{n\longrightarrow\infty}{\longrightarrow} e^{-1} > \varepsilon.$$

### 2.4.2 b

Note: could use the first part with $\sin(x) \le x$, but then integral ends up more complicated.

Noting that $\sin(x) \le 1$, we have We have

$$\begin{aligned}
\left|\int_0^1 n(1-x)^n\sin(x)\right| &\le \int_0^1 |n(1-x)^n\sin(x)| \\
&\le \int_0^1 |n(1-x)^n| \\
&= n\int_0^1 (1-x)^n \\
&= -\frac{n(1-x)^{n+1}}{n+1} \\
&\overset{n\longrightarrow\infty}{\longrightarrow} 0.
\end{aligned}$$

## 2.5 Spring 2017 # 3 ✨

Let

$$f_n(x) = ae^{-nax} - be^{-nbx} \quad \text{where } 0 < a < b.$$

Show that

a. $\sum_{n=1}^{\infty} |f_n|$ is not in $L^1([0,\infty), m)$

Hint: $f_n(x)$ has a root $x_n$.

b.

$$\sum_{n=1}^{\infty} f_n \text{ is in } L^1([0,\infty), m) \quad \text{and} \quad \int_0^{\infty} \sum_{n=1}^{\infty} f_n(x)\, dm = \ln \frac{b}{a}$$

Not complete.

Add concepts.

Walk through.

**Solution:**

**Concepts Used:**

- ?

### 2.5.1 a

Letting $x_n \coloneqq \frac{1}{n}$, we have

$$\sum_{k=1}^{\infty} |f_k(x)| \geq |f_n(x_n)| = \left| ae^{-ax} - be^{-bx} \right| \coloneqq M.$$

In particular, $\sup_x |f_n(x)| \not\longrightarrow 0$, so the terms do not go to zero and the sum can not converge.

### 2.5.2 b

?

## 2.6 Fall 2016 # 1 ✨

Define

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

Show that $f$ converges to a differentiable function on $(1,\infty)$ and that

$$f'(x) = \sum_{n=1}^{\infty} \left(\frac{1}{n^x}\right)'.$$

Hint:

$$\left(\frac{1}{n^x}\right)' = -\frac{1}{n^x} \ln n$$

Add concepts.

**Solution:**

**Concepts Used:**

- ?

- Set $f_N(x) \coloneqq \sum_{n=1}^{N} n^{-x}$, so $f(x) = \lim_{N\longrightarrow\infty} f_N(x)$.
- If an interchange of limits is justified, we have

$$\begin{aligned}
\frac{\partial}{\partial x} \lim_{N\longrightarrow\infty} \sum_{n=1}^{N} n^{-x} &= \lim_{h\longrightarrow 0} \lim_{N\longrightarrow\infty} \frac{1}{h}\left[\left(\sum_{n=1}^{N} n^{-x}\right) - \left(\sum_{n=1}^{N} n^{-(x+h)}\right)\right] \\
&\overset{?}{=} \lim_{N\longrightarrow\infty} \lim_{h\longrightarrow 0} \frac{1}{h}\left[\left(\sum_{n=1}^{N} n^{-x}\right) - \left(\sum_{n=1}^{N} n^{-(x+h)}\right)\right] \\
&= \lim_{N\longrightarrow\infty} \lim_{h\longrightarrow 0} \frac{1}{h}\left[\sum_{n=1}^{N} n^{-x} - n^{-(x+h)}\right] \quad (1) \\
&= \lim_{N\longrightarrow\infty} \sum_{n=1}^{N} \lim_{h\longrightarrow 0} \frac{1}{h}\left[n^{-x} - n^{-(x+h)}\right] \quad \text{since this is a finite sum} \\
&\coloneqq \lim_{N\longrightarrow\infty} \sum_{n=1}^{N} \frac{\partial}{\partial x}\left(\frac{1}{n^x}\right) \\
&= \lim_{N\longrightarrow\infty} \sum_{n=1}^{N} -\frac{\ln(n)}{n^x},
\end{aligned}$$

  where the combining of sums in (1) is valid because $\sum n^{-x}$ is absolutely convergent for $x > 1$ by the $p$-test.
- Thus it suffices to justify the interchange of limits and show that the last sum converges on $(1, \infty)$.
- Claim: $\sum n^{-x}\ln(n)$ converges.
  - Use the fact that for any fixed $\varepsilon > 0$,

$$\lim_{n\longrightarrow\infty} \frac{\ln(n)}{n^{\varepsilon}} \overset{L.H.}{=} \lim_{n\longrightarrow\infty} \frac{1/n}{\varepsilon n^{\varepsilon-1}} = \lim_{n\longrightarrow\infty} \frac{1}{\varepsilon n^{\varepsilon}} = 0,$$

  - This implies that for a fixed $\varepsilon > 0$ and for any constant $c > 0$ there exists an $N$ large enough such that $n \geq N$ implies $\ln(n)/n^{\varepsilon} < c$, i.e. $\ln(n) < cn^{\varepsilon}$.
  - Taking $c = 1$, we have $n \geq N \implies \ln(n) < n^{\varepsilon}$

- We thus break up the sum:

$$\begin{aligned}\sum_{n\in\mathbb{N}} \frac{\ln(n)}{n^x} &= \sum_{n=1}^{N-1} \frac{\ln(n)}{n^x} + \sum_{n=N}^{\infty} \frac{\ln(n)}{n^x} \\ &\leq \sum_{n=1}^{N-1} \frac{\ln(n)}{n^x} + \sum_{n=N}^{\infty} \frac{n^\varepsilon}{n^x} \\ &:= C_\varepsilon + \sum_{n=N}^{\infty} \frac{n^\varepsilon}{n^x} \quad \text{with } C_\varepsilon < \infty \text{ a constant} \\ &= C_\varepsilon + \sum_{n=N}^{\infty} \frac{1}{n^{x-\varepsilon}},\end{aligned}$$

  where the last term converges by the $p$-test if $x - \varepsilon > 1$.
- But $\varepsilon$ can depend on $x$, and if $x \in (1, \infty)$ is fixed we can choose $\varepsilon < |x - 1|$ to ensure this.

- Claim: the interchange of limits is justified.

  ?

## 2.7 Fall 2016 # 5 ✨

Let $\varphi \in L^\infty(\mathbb{R})$. Show that the following limit exists and satisfies the equality

$$\lim_{n\longrightarrow\infty} \left( \int_{\mathbb{R}} \frac{|\varphi(x)|^n}{1+x^2}\, dx \right)^{\frac{1}{n}} = \|\varphi\|_\infty.$$

Walk through.

Add concepts.

**Solution:**

**Concepts Used:**

- ?

Let $L$ be the LHS and $R$ be the RHS.

Claim: $L \leq R$. - Since $|\varphi| \leq \|\varphi\|_\infty$ a.e., we can write

$$\begin{aligned} L^{\frac{1}{n}} &\coloneqq \int_{\mathbb{R}} \frac{|\varphi(x)|^n}{1+x^2} \\ &\leq \int_{\mathbb{R}} \frac{\|\varphi\|_\infty^n}{1+x^2} \\ &= \|\varphi\|_\infty^n \int_{\mathbb{R}} \frac{1}{1+x^2} \\ &= \|\varphi\|_\infty^n \arctan(x)\Big|_{-\infty}^{\infty} \\ &= \|\varphi\|_\infty^n \left(\frac{\pi}{2} - \frac{-\pi}{2}\right) \\ &= \pi \|\varphi\|_\infty^n \end{aligned}$$

$$\begin{aligned} \implies L^{\frac{1}{n}} &\leq \sqrt[n]{\pi \|\varphi\|_\infty^n} \\ \implies L &\leq \pi^{\frac{1}{n}} \|\varphi\|_\infty \\ &\overset{n\to\infty}{\longrightarrow} \|\varphi\|_\infty, \end{aligned}$$

where we've used the fact that $c^{\frac{1}{n}} \overset{n\to\infty}{\longrightarrow} 1$ for any constant $c$.

Actually true? Need conditions?

Claim: $R \leq L$.

- We will show that $R \leq L + \varepsilon$ for every $\varepsilon > 0$.
- Set

$$S_\varepsilon \coloneqq \left\{ x \in \mathbb{R}^n \;\middle|\; |\varphi(x)| \geq \|\varphi\|_\infty - \varepsilon \right\}.$$

- Then we have

$$\begin{aligned} \int_{\mathbb{R}} \frac{|\varphi(x)|^n}{1+x^2}\,dx &\geq \int_{S_\varepsilon} \frac{|\varphi(x)|^n}{1+x^2}\,dx \quad S_\varepsilon \subset \mathbb{R} \\ &\geq \int_{S_\varepsilon} \frac{(\|\varphi\|_\infty - \varepsilon)^n}{1+x^2}\,dx \qquad \text{by definition of } S_\varepsilon \\ &= (\|\varphi\|_\infty - \varepsilon)^n \int_{S_\varepsilon} \frac{1}{1+x^2}\,dx \\ &= (\|\varphi\|_\infty - \varepsilon)^n C_\varepsilon \qquad \text{where } C_\varepsilon \text{ is some constant} \end{aligned}$$

$$\begin{aligned} \implies \left(\int_{\mathbb{R}} \frac{|\varphi(x)|^n}{1+x^2}\,dx\right)^{\frac{1}{n}} &\geq (\|\varphi\|_\infty - \varepsilon) C_\varepsilon^{\frac{1}{n}} \\ &\overset{n\to\infty}{\longrightarrow} (\|\varphi\|_\infty - \varepsilon) \cdot 1 \\ &\overset{\varepsilon\to 0}{\longrightarrow} \|\varphi\|_\infty, \end{aligned}$$

where we've again used the fact that $c^{\frac{1}{n}} \longrightarrow 1$ for any constant.

## 2.8 Fall 2016 # 6 ✨

Let $f, g \in L^2(\mathbb{R})$. Show that

$$\lim_{n \longrightarrow \infty} \int_{\mathbb{R}} f(x)g(x+n)\,dx = 0$$

Add concepts.

**Solution:**

**Concepts Used:**

- ?

- Use the fact that $L^p$ has small tails: if $h \in L^2(\mathbb{R})$, then for any $\varepsilon > 0$,

$$\forall \varepsilon,\ \exists N \in \mathbb{N} \quad \text{such that} \quad \int_{|x| \geq N} |h(x)|^2\,dx < \varepsilon.$$

How to prove small tails in $L^p$?

- So choose $n$ large enough so the tails of both $f$ and $g$ are smaller than $\varepsilon$.
- Apply Cauchy-Schwarz:

$$\begin{aligned} \left| \int_{\mathbb{R}} f(x)g(x+n)\,dx \right| &\leq \int_{\mathbb{R}} |f(x)g(x+n)|\,dx \\ &\leq \int_{\mathbb{R}} . \end{aligned}$$

## 2.9 Spring 2016 # 1 🚩

For $n \in \mathbb{N}$, define

$$]e_n = \left(1 + \frac{1}{n}\right)^n \quad \text{and} \quad E_n = \left(1 + \frac{1}{n}\right)^{n+1}$$

Show that $e_n < E_n$, and prove Bernoulli's inequality:

$$(1+x)^n \geq 1 + nx \text{ for } -1 < x < \infty \text{ and } n \in \mathbb{N}$$

Use this to show the following:

1. The sequence $e_n$ is increasing.
2. The sequence $E_n$ is decreasing.
3. $2 < e_n < E_n < 4$.
4. $\lim_{n \longrightarrow \infty} e_n = \lim_{n \longrightarrow \infty} E_n$.

## 2.10 Fall 2015 # 1

Define

$$f(x) = c_0 + c_1 x^1 + c_2 x^2 + \ldots + c_n x^n \text{ with } n \text{ even and } c_n > 0.$$

Show that there is a number $x_m$ such that $f(x_m) \leq f(x)$ for all $x \in \mathbb{R}$.