Oscillations in Harmonic Analysis

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Problem sets

I'd love to hear your feedback. Feel free to email me at coscohua@mail.sfsu.edu.
See git:icarlitoss/uss-pcmi for updates.

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1 Introduction

← July 2, 2018

Combinatorics

1.0.1 Erdős problem

1. Erdős distinct distance problem (1946).
   What is the least number of distinct distances determined by N points in a plane.

Example 1.1. We have four points $(0,1),(2,2),(0,0),(1,0)$, and if we start listing the distances between each of them we obtain the following:

$$1, 1, \sqrt{2}, \sqrt{5}, \sqrt{5}, \sqrt{8}.$$

However, we care about the distinct number; hence we get a new list

$$1, \sqrt{2}, \sqrt{5}, \sqrt{8}.$$

Upper bound: Notice that the first list is obtain by getting the distance between two points, hence

$$\binom{N}{2} = \frac{1}{2}N^2 - \frac{1}{2}N \sim N^2.$$

are obtained random.

To analyze what happens with the lower bound, we look at the following example.

Example 1.2. (a) Say N is a perfect square.

(b) Then, we have an square of $\sqrt{N}$ lattice.

(c) Now, let's count

$$(\text{distinct distcnes})^2.$$

(d) We obtain the list:

$$1, 2, \ldots, 2N.$$

(e) Hence we get no more than $\sim N$.

(f) Notice that $a^2 + b^2 = 3$ has no solution (number theory). Hence our list (d) have holes.

(g) Hence,

$$\#\text{ distinct distance} \sim \frac{N}{\sqrt{\log(N)}} \text{ as } N \to \infty.$$

Conjecture. Conjecture (Erdős 1946): The answer for Erdos 1946 should be in the order of $\frac{N}{\sqrt{\log(N)}}$ as $N \to \infty$.

Theorem (Erdős 1946)**.** *At least* $\sim \sqrt{N}$ *as* $N \to \infty$.

Theorem (Guth, Katz 2015)**.** *At least* $\sim \frac{N}{\log(N)}$ *as* $N \to \infty$.

2. Crescent Configurations N points in the plane such that distance d_1 appears 1 times, d_2 appears 2 times, and so on, until d_{N-1} appears $N-1$ times. ($N-1$ distinct distances). It is possible to achieve this if you place equally spaced points on a line. Additionally require general position no more than 2 points on a line, and no more than 3 points on a circle. Call a crescent configuration.

Example 1.3. We can go from 3 pts to 8 points in crescent configuration. It is unknown if we could find a 9 point or higher order configurations.

Conjecture (Erdős)**.** Eventually they do not exist.

Question: Find many (all) crescent configurations for some N.

Example 1.4. Given $N = 4$ in $\mathbb{R}^2$.

Question: For $N = 5$. Many known but not all.

2 Review on Vector Spaces

← July 3, 2018

2.1 Inner Product

An *inner product* is a map

$$\langle \cdot, \cdot \rangle : V \times V \to F$$

that satisfies for all $f, g, h \in V$, and $\alpha, \beta \in F$.

1. $\langle f, f \rangle \geq 0$ and $\langle f, f \rangle = 0 \Rightarrow f = 0$.
2. $\langle f, g \rangle = \langle g, f \rangle$.
3. $\langle \alpha f + \beta g, h \rangle = \alpha \langle f, h \rangle + \beta \langle g, h \rangle$.

Example 2.1. In $\mathbb{R}^d$, we have

$$\langle x, y \rangle = x \cdot y = x_1 y_1 + \cdots + x_d y_d.$$

Example 2.2. In $\mathbb{C}^d$, we have

$$\langle x, y \rangle = x \cdot y = x_1 \bar{y_1} + \cdots + x_d \bar{y_d}.$$

Example 2.3. In $\mathcal{C}[a, b]$, we have

$$\langle f, g \rangle = \frac{1}{b-a} \int_a^b f(x) \overline{g(x)} dx$$

2.2 Norm

A *norm* is a function

$$|| \cdot || : V \to \mathbb{R}$$

that satisfies for all $f, g \in V$ and $\alpha \in F$.

1. $||f|| \geq 0$ and if $||f|| = 0$ then $f = 0$.

2. $||\alpha f|| = |\alpha|||f||$.

3. $||f + g|| \leq ||f|| + ||g|| \quad$ (triangle inequality).

In in a vector space V with inner product $\langle \cdot, \cdot \rangle$ get a norm for free.

$$||f|| := \sqrt{\langle f, f \rangle}.$$

Definition (Cauchy-Schwartz Inequality)**.**

$$|\langle f, g \rangle| \leq ||f||||g||.$$

<u>Hint for Problem set:</u> Implies triangle inequality.

$$\begin{aligned} ||f + g|| &= \langle f + g, f + g \rangle \\ &= ||f||^2 + \langle f, g \rangle + \langle f \bar{,} g \rangle + ||g||^2 \\ \text{(by CS)} &\leq ||f||^2 + 2||f||||g|| + ||g||^2 \\ &= (||f|| + ||g||)^2. \end{aligned}$$

Example 2.4. On $\mathcal{C}[a, b]$ with

$$\langle f, g \rangle = \frac{1}{b - a} \int_a^b f(x)\overline{g(x)} dx$$

get

$$||f||_2 = \left(\frac{1}{b - a} \int_a^b |f(x)|^2 dx \right)^{1/2}$$

2.3 Orthogonality

Sat $f, g \in V$ are orthogonal if

$$\langle f, g \rangle = 0.$$

Say $\{\phi_1, \ldots, \phi_n\}$ are orthogonal if $\langle \phi_j, \phi_k \rangle = 0$ whenever $j \neq k$ and $\phi_j \neq 0$ for all j.

If in addition $||\phi_j|| = 1$ for all j then $\{\phi_1, \ldots, \phi_n\}$ is *orthonormal.*
<u>Note:</u> Remember Gram-Schmidt.

Theorem (Pythagorean Theorem)**.** *If* $\langle f, g \rangle =$ *then* $||f + g||^2 = ||f||^2 + ||g||^2$.

2.4 Projections

Let $\phi \in B$ with $||\phi|| = 1$. The projection of f in the direction of ϕ is

$$\text{proj}_\phi(f) := \langle f, \phi \rangle \phi.$$

Example 2.5. Project $f = \begin{bmatrix} 0 \\ 2 \end{bmatrix}$ on $\phi = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}$.

$$\text{proj}_\phi(f) := \begin{bmatrix} 1 \\ 1 \end{bmatrix}.$$

Definition. Let W_n be a subspace of V with an orthonormal basis $\{\phi_1, \ldots, \phi_n\}$. The proejction of f onto W_n is.

$$\mathrm{proj}_{W_n}(f)L = \langle f_1, \phi_1\rangle\phi_1 + \ldots + \langle f_n, \phi_n\rangle\phi_n.$$

Theorem.

$$\mathrm{proj}_{W_n}(f) = 0 \iff f \in W_n.$$

Theorem. $f - \mathrm{proj}_{W_n}$ *is orthonormal to every vector in* W_n.

3 Fourier Series

← July 5, 2018

Theorem. *Let $f \in V$. Let W_n be a subspace of V with an orthonormal basis $\{\phi_1, \ldots, \phi_n\}$. The element $winW_n$ that minimizes $||f - w||$ is*

$$w = \mathrm{proj}_{W_n}(f). \qquad \leftarrow \textit{Best approximation}$$

Proof. Write:

$$w = \sum_{i=1}^{n} \beta_i \phi_i$$

and set

$$\alpha_i = \langle f, \phi_i\rangle, \quad i = 1, \ldots, n.$$

Then,

$$\begin{aligned}
||f - w||^2 &= \langle f - w, f - w\rangle \\
&= ||f||^2 - \langle f, \sum_{i=1}^{n} \beta_i\phi_i\rangle - \overline{\langle f, \sum_{i=1}^{n} \beta_i\phi_i\rangle} + \langle \sum_{i=1}^{n} \beta_i\phi_i, \sum_{j=1}^{n} \beta_j\phi_j\rangle \\
&= ||f||^2 - \sum_{i=1}^{n} \overline{\beta_i}\langle f, \phi_i\rangle - \sum_{i=1}^{n} \overline{\overline{\beta_i}}\ \overline{\langle f, \phi_i\rangle} + \sum_{i=1}^{n}\sum_{j=1}^{n} \beta_i\overline{\beta_j}\langle \phi_i, \phi_j\rangle \\
&= ||f||^2 - \sum_{i=1}^{n} \overline{\beta_i}\alpha_i - \sum_{i=1}^{n} \beta_i\overline{\alpha_i} + \sum_{i=1}^{n} |\beta_i|^2 \\
&= ||f||^2 + \sum_{i=1}^{n} (\beta_i - \alpha_i)\overline{\beta_i - \alpha_i} - \sum_{i=1}^{n} |\alpha_i|^2 \\
&= ||f||^2 - \sum_{i=1}^{n} |\langle f, \phi_i\rangle|^2 + \sum_{i=1}^{n} |\beta_i - \alpha_i|^2.
\end{aligned}$$

So minimized if $\beta_i = \alpha_i = \langle f, \phi_i\rangle$. □

Remark:

$$\sum_{i=1}^{n} \langle f, \phi_i\rangle\phi_i \quad \text{best approximation to } f.$$

Corollary.

$$\sum_{i=1}^{n} |\langle f, \phi_i\rangle|^2 \leq ||f||^2.$$

Bessel's inequality:

$$\sum_{i=1}^{\infty} |\langle f, \phi_i \rangle|^2 \leq ||f||^2.$$

Riemann-Lebesgue Lemma:

$$\lim_{i\to\infty} \langle f, \phi_i \rangle = 0.$$

Motivation:

$$\frac{1}{2\pi}\int_0^{2\pi} \cos(nx)\cos(mx)dx = \begin{cases} 0 & n \neq m \\ \frac{1}{2} & n = m \neq 0 \\ 1 & n = m = 0. \end{cases}$$

$$\frac{1}{2\pi}\int_0^{2\pi} \sin(nx)\sin(mx)dx = \begin{cases} \frac{1}{2} & \text{if } n = m \neq 0 \\ 0 & \text{otherwise.} \end{cases}$$

$$\frac{1}{2\pi}\int_0^{2\pi} \sin(nx)\cos(mx)dx = 0.$$

Note that

$$1, \sqrt{2}\cos(x), \sqrt{2}\sin(x), \sqrt{2}\cos(2x), \sqrt{2}\sin(2x), \ldots$$

orthonormal sequence on $[0, 2\pi]$.
Best finite approximation up to level n of a function f is

$$a_0 \cdot 1 + a_1\sqrt{2}\cos(x) + b_1\sqrt{2}\sin(x) + \ldots$$

where

$$a_0 = \frac{1}{2\pi}\int_0^{2\pi} f(x) \cdot 1dx$$

$$a_j = \frac{1}{2\pi}\int_0^{2\pi} f(x)\sqrt{2}\cos(jx)dx$$

$$b_k = \frac{1}{2\pi}\int_0^{2\pi} f(x) \cdot \sqrt{2}\sin(kx)dx.$$

Trigonometric Series:

$$\frac{1}{2}A_0 + \sum_{n=1}^{\infty} (A_n\cos(nx) + B_n\sin(nx))$$

if in addition

$$A_n = \frac{1}{\pi}\int_0^{2\pi} f(x)\cos(nx)dx$$

and

$$B_n = \frac{1}{\pi}\int_0^{2\pi} f(x)\sin(nx)dx$$

then called *Fourier Series*.

Simplification: We could have started with the orthonormal sequence

$$e^{inx}, n \in \mathbb{Z}, \text{ on } [0, 2\pi].$$

Then,

$$\begin{aligned}
\langle e^{inx}, e^{inx} \rangle &= \frac{1}{2\pi} \int_0^{2\pi} e^{inx} \overline{e^{imx}} dx \\
&= \frac{1}{2\pi} \int_0^{2\pi} e^{i(n-m)x} dx \\
&= \begin{cases} \frac{1}{2\pi} \left[\frac{1}{i(n-m)} e^{i(n-m)x} \right]_0^{2\pi} = 0 \quad \text{if } n \neq m \\ \\ \frac{1}{2} \int_0^{2\pi} 1 dx = 1 \quad \text{if } n = m. \end{cases}
\end{aligned}$$

Give best approximation up to level $n > 0$ of a function f

$$c_{-n} e^{i(-n)x} + \cdots + c_0 \cdot 1 + \cdots + c_n e^{inx}$$

with corresponding series

$$\sum_{n \in \mathbb{Z}} c_n e^{inx}$$

where

$$c_n = \frac{1}{2\pi} \int_0^{2\pi} f(x) \overline{e^{inx}} dx = \frac{1}{2\pi} \int_0^{2\pi} f(x) e^{-inx} dx.$$

Note:

$$c_n = \frac{1}{2\pi} \int_0^{2\pi} f(x) \cos(nx) dx - i \frac{1}{2\pi} \int_0^{2\pi} f(x) \sin(nx) dx$$

$$= \begin{cases} \frac{1}{2}(A_n - iB_n) \quad \text{if } n > 0 \\ \frac{1}{2} A_0 \quad \text{if } n = 0 \\ \frac{1}{2} \left(A_{|n|} + iB_{|n|} \right) \quad \text{if } n < 0. \end{cases} .$$

For $n > 0$, we have

$$c_n e^{inx} + c_{-n} e^{i(-n)x} = A_n \cos(nx) + B_n \sin(nx)$$

All the same terms as before!

Intervals:

e^{inx} works on any interval of length 2π.
$e^{2\pi inx/N}$ works on any interval of length L.

Summary:
Fourier Series: If f is integrable on $[a, b]$ of length of L then the n^{th} *Forier coefficient* of f is defined by

$$\hat{f}(n) = \frac{1}{L} \int_a^b f(x) e^{-2\pi inx/L} dx, \quad n \in \mathbb{Z}$$

and its Forier series is given by

$$\sum_{n=-\infty}^{\infty} \hat{f}(n)e^{-2\pi inx/L}.$$

Question: Does $\sum_{n=-\infty}^{\infty} \hat{f}(n)e^{-2\pi inx/L}$ converges to $f(x)$? ← July 6, 2018
Let's first look at the following example.

Example 3.1. Let $f(x) = x$ on $[0, 2n]$. Then,

$$\hat{f}(n) = \frac{1}{2\pi}\int_0^{2\pi} xe^{-inx}dx = \frac{i}{n}, \quad n \neq 0.$$

and

$$\hat{f}(0) = \frac{1}{2\pi}\int_0^{2\pi} xdx = \pi.$$

Fourier series

$$\sum_{n=-\infty}^{\infty} \frac{i}{n}e^{inx} = \pi - 2\left(\frac{1}{1}\sin(x) + \frac{1}{2}\sin(2x) + \dots\right)$$

$$\uparrow \frac{i}{n}e^{inx} + \frac{i}{-n}e^{-inx} = -\frac{2}{n}\sin(nx).$$

Yields π if $x = 0$ or $x = 2\pi$ while $f(0) = 0$ and $f(2\pi) = 2\pi$.

Consider: [insert graph 1 vs 2 here]:

Note: Fourier series is periodic on $\mathbb{R}$.

3.1 Domains

Consider $[a, b]$ on periodic functions on $\mathbb{R}$ in a circle such that $f(x) = F(e^{ix})$ and $x \in [0, 2\pi]$. Hence, functions on the circle are periodic functions $f(x)$ on $[0, 2\pi]$ with $f(0) = f(2\pi)$.

3.2 Uniqueness

Theorem. *Suppose f is integrable and bounded on an interval with $\hat{f}(n) = 0$ for all $n \in \mathbb{Z}$. Then $f(x_0) = 0$ whenever f is continuous at x_0.*

3.3 Partial Sums

Let

$$S_N(f)(x) := \sum_{n=-N}^{N} \hat{f}(n)e^{-2\pi inx/L} \text{ on } [0, L].$$

Question: In what sense $S_N f \to f$.

Theorem. *Suppose f is continous on the circle and the Fourier series of f is absolutely convergent*

$$\sum_{n=-\infty}^{\infty} |\hat{f}(n)| < \infty.$$

Then

$$\lim_{N\to\infty} S_N(f)(x) = f(x)$$

uniformly in x.

Proof. Since

$$\sum_{n=-\infty}^{\infty} |\hat{f}(n)| < \infty$$

then

$$\sum_{n=-\infty}^{\infty} \hat{f}(n)e^{inx}$$

converges absolutely and in fact uniformly.
If

$$g(x) = \sum_{n=-\infty}^{\infty} \hat{f}(n)e^{inx}$$

then g must be continuous.
Since $f-g$ is continuous and $\widehat{f-g}(n) = 0$ for all $n \in \mathbb{Z}$ we conclude by uniqueness theorem that $f = g$.

$$\begin{aligned}
\hat{g}(n) &= \frac{1}{2\pi}\int_0^{2\pi} g(x)e^{-inx}dx \\
&= \frac{1}{2\pi}\int_0^{2\pi} \left(\lim_{N\to\infty}\sum_{k=-\infty}^{\infty} \hat{f}(k)e^{ikx}\right) e^{-inx}dx \\
&= \lim_{N\to\infty}\sum_{k=-\infty}^{\infty} \hat{f}(k)\frac{1}{2\pi}\int_0^{2\pi} e^{i(k-n)x}dx.
\end{aligned}$$

Note that:

$$\frac{1}{2\pi}\int_0^{2\pi} e^{i(k-n)x}dx = \begin{cases} 1 & \text{if } k = n \\ 0 & else. \end{cases}$$

Hence, we have that

$$\begin{aligned}
\hat{g}(n) &= \lim_{N\to\infty}\sum_{k=-\infty}^{\infty} \hat{f}(k)\frac{1}{2\pi}\int_0^{2\pi} e^{i(k-n)x}dx \\
&= \hat{f}(n).
\end{aligned}$$

□

Theorem. *Let $f \in \mathcal{C}^2[0, 2\pi]$ and 2π period. Then*

$$\hat{f}(n) = \mathcal{O}\left(\frac{1}{n^2}\right) \quad \text{as } |n| \to \infty$$

and thus the Fourier series of f converges absolutely and uniformly to f.

Note: $f(x) = \mathcal{O}(g(x))$ as $x \to a$ means there exists a constant C such that

$$|f(x)| \leq C|g(x)| \text{ as } x \to a.$$

Proof. Since f'' is continous on $[0, 2\pi]$, it is bounded. Say

$$|f''(x)| \leq B \text{ for all } x \in (0, 2\pi].$$

Then

$$\begin{aligned} \hat{f}(n) &= \frac{1}{2\pi} \int_0^{2\pi} f(x) e^{-inx} dx \\ &= \frac{1}{in} \widehat{f'}(n) \quad \text{by int. by parts.} \end{aligned}$$

By iterating $\hat{f}(n) = \frac{1}{i^2 n^2} \widehat{f''}(n)$,

$$\begin{aligned} |\hat{f}(n)| &= \frac{1}{n^2} \left| \frac{1}{2\pi} \int_0^{2\pi} f''(x) e^{-inx} dx \right| \\ &\leq \frac{1}{n^2} \left(\frac{1}{2\pi} \int_0^{2\pi} B dx \right) = \frac{B}{n^2}. \end{aligned}$$

□

Corollary. $\widehat{f'}(n) = in\hat{f}(n)$.

3.4 Convolution

Given 2π periodic integrable functions f and g on $\mathbb{R}$. Define their *convolution* $f * g$ by

$$(f * g)(x) = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(y) g(x - y) dy \qquad x \in [-\pi, \pi].$$

Remarks: It has many good properties by most importantly

- $f * g = g * f$.
- $\widehat{f * g} = \hat{f}(n)\hat{g}(n)$.