From the Manhattan Project to Elliptic Curves: Introduction to Random Matrix Theory

Steven J Miller
Dept of Math/Stats, Williams College

sjm1@williams.edu, Steven.Miller.MC.96@aya.yale.edu
http://www.williams.edu/Mathematics/sjmiller

Williams College, June 13, 2018

Introduction

Goals

- Determine correct scale and statistics to study eigenvalues and zeros of *L*-functions.

- See similar behavior in different systems.

- Discuss the tools and techniques needed to prove the results.

Fundamental Problem: Spacing Between Events

General Formulation: Studying system, observe values at $t_1, t_2, t_3, \ldots$.

Question: What rules govern the spacings between the t_i?

Fundamental Problem: Spacing Between Events

General Formulation: Studying system, observe values at $t_1, t_2, t_3, \ldots$.

Question: What rules govern the spacings between the t_i?

Examples: Spacings between

- Energy Levels of Nuclei.
- Eigenvalues of Matrices.
- Zeros of *L*-functions.
- Summands in Zeckendorf Decompositions.
- Primes.
- $n^k \alpha$ mod 1.

Fundamental Problem: Spacing Between Events

General Formulation: Studying system, observe values at $t_1, t_2, t_3, \ldots$.

Question: What rules govern the spacings between the t_i?

Examples: Spacings between

- Energy Levels of Nuclei.
- Eigenvalues of Matrices.
- Zeros of *L*-functions.
- Summands in Zeckendorf Decompositions.
- Primes.
- $n^k \alpha$ mod 1.

Sketch of proofs

In studying many statistics, often three key steps:

1. Determine correct scale for events.

2. Develop an explicit formula relating what we want to study to something we understand.

3. Use an averaging formula to analyze the quantities above.

It is not always trivial to figure out what is the correct statistic to study!

Eigenvalue Review: I

$z \in \mathbb{C} : z = x + iy$ with $i = \sqrt{-1}$; $\overline{z} = z^H = x - iy$.

Eigenvalue/Eigenvector: $\lambda \in \mathbb{C}$, $\overrightarrow{v} \neq \overrightarrow{0}$:

$$A\overrightarrow{v} = \lambda \overrightarrow{v}.$$

Can find by $\det(A - \lambda I) = 0$ but computational nightmare!
Real Symmetric: $A = A^T$; Hermitian: $A = A^H$ (complex conjugate transpose).

Length of $\overrightarrow{v}$ is $\sqrt{\overrightarrow{v}^H \overrightarrow{v}}$; $||\overline{v}||^2 = \overrightarrow{v}^H \overrightarrow{v}$; $\overrightarrow{v} \cdot \overrightarrow{w} = \overrightarrow{v}^H \overrightarrow{w}$.

Eigenvalue Review: II

A real implies eigenvalues real: If $A\vec{v} = \lambda\vec{v}$ then

$$
\begin{array}{rcl}
\vec{v}^H A^H \vec{v} & = & \vec{v}^H A \vec{v} \\
(A\vec{v})^H \vec{v} & = & \vec{v}^H (A\vec{v}) \\
(\lambda\vec{v})^H \vec{v} & = & \vec{v}^H (\lambda\vec{v}) \\
\overline{\lambda}\vec{v}^H \vec{v} & = & \lambda\vec{v}^H \vec{v} \\
\overline{\lambda}||\vec{v}||^2 & = & \lambda||\vec{v}||^2,
\end{array}
$$

and thus as length is non-zero have $\lambda = \overline{\lambda}$ and is real, and then get coefficients of $\vec{v}$ real.

A complex Hermitian: similar proof shows eigenvalues real (coefficients can be complex).

Eigenvalue Review: III

Orthogonal: $Q^T Q = QQ^T = I$; Unitary: $U^H U = UU^H = I$.

Spectral Theorem: If A is real symmetric or complex Hermitian than can diagonalize (real symmetric: $A = Q^T \Lambda Q$, complex Hermitian $A = U^H \Lambda U$).

Proof: 'Trivial' if distinct eigenvalues as each has an eigenvector, mutually orthogonal, choose unit length and let these be columns of Q:

$$\begin{aligned}
\overrightarrow{v_1}^T A^T \overrightarrow{v_2} &= \overrightarrow{v_1}^T A \overrightarrow{v_2} \\
\left(A \overrightarrow{v_1} \right)^T \overrightarrow{v_2} &= \overrightarrow{v_1}^T \left(A \overrightarrow{v_2} \right) \\
\lambda_1 \overrightarrow{v_1}^T \overrightarrow{v_2} &= \lambda_2 \overrightarrow{v_1}^T \overrightarrow{v_2}.
\end{aligned}$$

Classical Random Matrix Theory

With Olivia Beckwith, Leo Goldmakher, Chris Hammond, Steven Jackson, Cap Khoury, Murat Koloğlu, Gene Kopp, Victor Luo, Adam Massey, Eve Ninsuwan, Vincent Pham, Karen Shen, Jon Sinsheimer, Fred Strauch, Nicholas Triantafillou, Wentao Xiong

Origins of Random Matrix Theory

Classical Mechanics: 3 Body Problem intractable.

Origins of Random Matrix Theory

Classical Mechanics: 3 Body Problem intractable.

Heavy nuclei (Uranium: 200+ protons / neutrons) worse!

Get some info by shooting high-energy neutrons into nucleus, see what comes out.

Fundamental Equation:

$$H\psi_n = E_n\psi_n$$

H : matrix, entries depend on system

E_n : energy levels

ψ_n : energy eigenfunctions

Origins of Random Matrix Theory
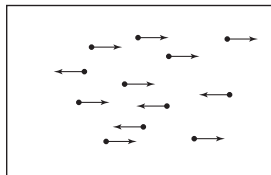
- Statistical Mechanics: for each configuration, calculate quantity (say pressure).
- Average over all configurations – most configurations close to system average.
- Nuclear physics: choose matrix at random, calculate eigenvalues, average over matrices (real Symmetric $A = A^T$, complex Hermitian $\overline{A}^T = A$).

Random Matrix Ensembles

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1N} \\ a_{12} & a_{22} & a_{23} & \cdots & a_{2N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{1N} & a_{2N} & a_{3N} & \cdots & a_{NN} \end{pmatrix} = A^T, \quad a_{ij} = a_{ji}$$

Fix p, define

$$\text{Prob}(A) = \prod_{1 \le i \le j \le N} p(a_{ij}).$$

This means

$$\text{Prob}\left(A : a_{ij} \in [\alpha_{ij}, \beta_{ij}]\right) = \prod_{1 \le i \le j \le N} \int_{x_{ij}=\alpha_{ij}}^{\beta_{ij}} p(x_{ij}) dx_{ij}.$$

Want to understand eigenvalues of A.

Eigenvalue Distribution

$\delta(x - x_0)$ is a unit point mass at x_0:
$\int f(x)\delta(x - x_0)dx = f(x_0)$.

Eigenvalue Distribution

$\delta(x - x_0)$ is a unit point mass at x_0:
$\int f(x)\delta(x - x_0)dx = f(x_0)$.

To each A, attach a probability measure:

$$\mu_{A,N}(x) \;=\; \frac{1}{N} \sum_{i=1}^{N} \delta\left(x - \frac{\lambda_i(A)}{2\sqrt{N}}\right)$$

Eigenvalue Distribution

$\delta(x - x_0)$ is a unit point mass at x_0:
$\int f(x)\delta(x - x_0)dx = f(x_0)$.

To each A, attach a probability measure:

$$\mu_{A,N}(x) = \frac{1}{N}\sum_{i=1}^{N}\delta\left(x - \frac{\lambda_i(A)}{2\sqrt{N}}\right)$$

$$\int_a^b \mu_{A,N}(x)dx = \frac{\#\left\{\lambda_i : \frac{\lambda_i(A)}{2\sqrt{N}} \in [a, b]\right\}}{N}$$

Eigenvalue Distribution

$\delta(x - x_0)$ is a unit point mass at x_0:
$\int f(x)\delta(x - x_0)dx = f(x_0)$.

To each A, attach a probability measure:

$$
\begin{aligned}
\mu_{A,N}(x) &= \frac{1}{N} \sum_{i=1}^{N} \delta\left(x - \frac{\lambda_i(A)}{2\sqrt{N}}\right) \\
\int_a^b \mu_{A,N}(x)dx &= \frac{\#\left\{\lambda_i : \frac{\lambda_i(A)}{2\sqrt{N}} \in [a, b]\right\}}{N} \\
\mathrm{k^{th}\ moment} &= \frac{\sum_{i=1}^{N} \lambda_i(A)^k}{2^k N^{\frac{k}{2}+1}} = \frac{\mathrm{Trace}(A^k)}{2^k N^{\frac{k}{2}+1}}.
\end{aligned}
$$

Wigner's Semi-Circle Law

Wigner's Semi-Circle Law

$N \times N$ real symmetric matrices, entries i.i.d.r.v. from a fixed $p(x)$ with mean 0, variance 1, and other moments finite. Then for almost all A, as $N \to \infty$

$$\mu_{A,N}(x) \longrightarrow \begin{cases} \frac{2}{\pi}\sqrt{1-x^2} & \text{if } |x| \le 1 \\ 0 & \text{otherwise.} \end{cases}$$

SKETCH OF PROOF: Eigenvalue Trace Lemma

Want to understand the eigenvalues of *A*, but choose the matrix elements randomly and independently.

Eigenvalue Trace Lemma

Let *A* be an $N \times N$ matrix with eigenvalues $\lambda_i(A)$. Then

$$\text{Trace}(A^k) = \sum_{n=1}^{N} \lambda_i(A)^k,$$

where

$$\text{Trace}(A^k) = \sum_{i_1=1}^{N} \cdots \sum_{i_k=1}^{N} a_{i_1 i_2} a_{i_2 i_3} \cdots a_{i_N i_1}.$$

SKETCH OF PROOF: Correct Scale

$$\text{Trace}(A^2) \ = \ \sum_{i=1}^{N} \lambda_i(A)^2.$$

By the Central Limit Theorem:

$$\text{Trace}(A^2) \ = \ \sum_{i=1}^{N}\sum_{j=1}^{N} a_{ij}a_{ji} = \sum_{i=1}^{N}\sum_{j=1}^{N} a_{ij}^2 \sim \ N^2$$

$$\sum_{i=1}^{N} \lambda_i(A)^2 \ \sim \ N^2$$

Gives $N\text{Ave}(\lambda_i(A)^2) \ \sim \ N^2$ or $\text{Ave}(\lambda_i(A)) \sim \sqrt{N}$.

SKETCH OF PROOF: Averaging Formula

Recall k-th moment of $\mu_{A,N}(x)$ is $\mathrm{Trace}(A^k)/2^k N^{k/2+1}$.

Average k-th moment is

$$\int \cdots \int \frac{\mathrm{Trace}(A^k)}{2^k N^{k/2+1}} \prod_{i \leq j} p(a_{ij}) da_{ij}.$$

Proof by method of moments: Two steps

- Show average of k-th moments converge to moments of semi-circle as $N \to \infty$;
- Control variance (show it tends to zero as $N \to \infty$).

SKETCH OF PROOF: Averaging Formula for Second Moment

Substituting into expansion gives

$$\frac{1}{2^2 N^2} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \sum_{i=1}^{N} \sum_{j=1}^{N} a_{ji}^2 \cdot p(a_{11})da_{11} \cdots p(a_{NN})da_{NN}$$

Integration factors as

$$\int_{a_{ij}=-\infty}^{\infty} a_{ij}^2 p(a_{ij})da_{ij} \cdot \prod_{\substack{(k,l)\neq(i,j)\\k<l}} \int_{a_{kl}=-\infty}^{\infty} p(a_{kl})da_{kl} = 1.$$

Higher moments involve more advanced combinatorics (Catalan numbers).

SKETCH OF PROOF: Averaging Formula for Higher Moments

Higher moments involve more advanced combinatorics (Catalan numbers).

$$\frac{1}{2^k N^{k/2+1}} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \sum_{i_1=1}^{N} \cdots \sum_{i_k=1}^{N} a_{i_1 i_2} \cdots a_{i_k i_1} \cdot \prod_{i \leq j} p(a_{ij}) da_{ij}.$$

Main contribution when the $a_{i_\ell i_{\ell+1}}$'s matched in pairs, not all matchings contribute equally (if did would get a Gaussian and not a semi-circle; this is seen in Real Symmetric Palindromic Toeplitz matrices).

Distribution of eigenvalues of real symmetric palindromic Toeplitz matrices and circulant matrices (with Adam

Massey and John Sinsheimer), Journal of Theoretical Probability **20** (2007), no. 3, 637–662.

http://arxiv.org/abs/math/0512146

Numerical examples
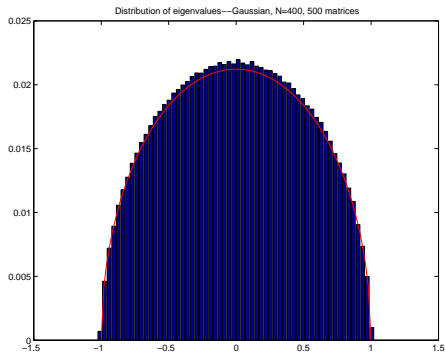
500 Matrices: Gaussian 400×400

$$p(x) = \frac{1}{\sqrt{2\pi}} \, e^{-x^2/2}$$

Numerical examples

The eigenvalues of the Cauchy distribution are NOT semicircular.
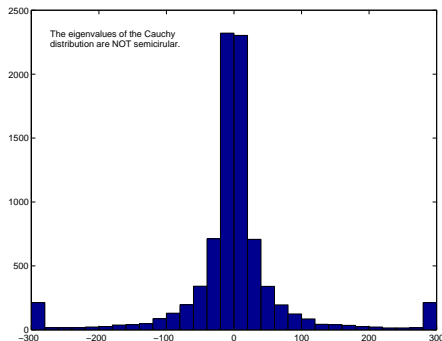
Cauchy Distribution: $p(x) = \frac{1}{\pi(1+x^2)}$

I. Zakharevich, *A generalization of Wigner's law*, Comm. Math. Phys. **268** (2006), no. 2, 403–414.

http://web.williams.edu/Mathematics/sjmiller/public_html/book/papers/innaz.pdf

GOE Conjecture

> **GOE Conjecture:**
>
> As $N \to \infty$, the probability density of the spacing b/w consecutive normalized eigenvalues approaches a limit independent of p.

Until recently only known if p is a Gaussian.

$$\text{GOE}(x) \approx \tfrac{\pi}{2} x e^{-\pi x^2/4}.$$

Numerical Experiment: Uniform Distribution

Let $p(x) = \frac{1}{2}$ for $|x| \leq 1$.

The local spacings of the central 3/5 of the eigenvalues of 5000 300x300 uniform matrices, normalized in batches of 20.

5000: 300×300 uniform on $[-1, 1]$

Cauchy Distribution

Let $p(x) = \frac{1}{\pi(1+x^2)}$.

The local spacings of the central 3/5 of the eigenvalues of 5000 100x100 Cauchy matrices, normalized in batches of 20.
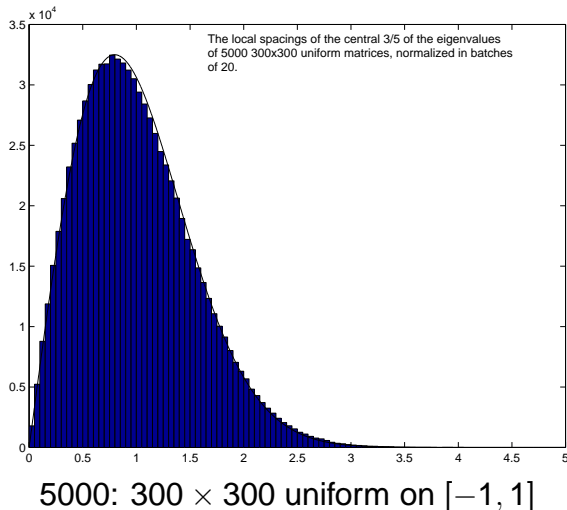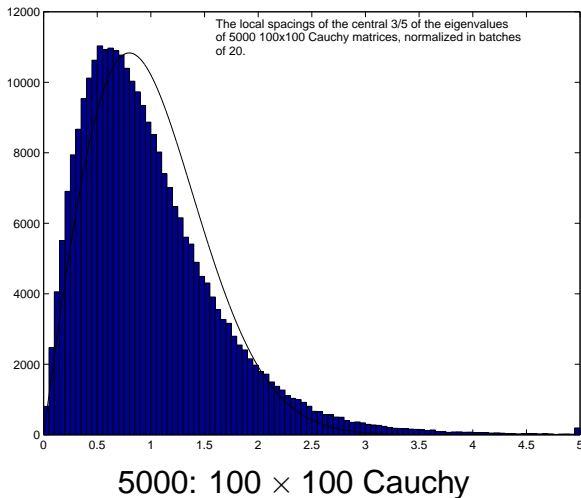
5000: 100×100 Cauchy

Cauchy Distribution

Let $p(x) = \frac{1}{\pi(1+x^2)}$.
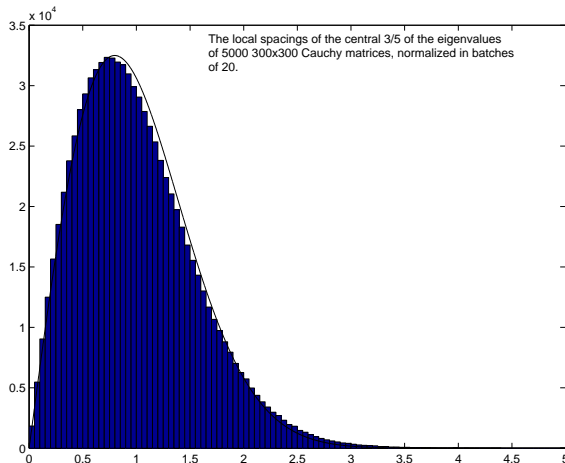
5000: 300×300 Cauchy

Random Graphs
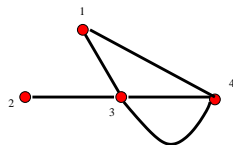
Degree of a vertex = number of edges leaving the vertex.
Adjacency matrix: a_{ij} = number edges b/w Vertex i and
Vertex j.

$$A = \begin{pmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 2 \\ 1 & 0 & 2 & 0 \end{pmatrix}$$

These are Real Symmetric Matrices.

McKay's Law (Kesten Measure) with $d = 3$

Density of Eigenvalues for d-regular graphs

$$f(x) = \begin{cases} \frac{d}{2\pi(d^2-x^2)}\sqrt{4(d-1)-x^2} & |x| \le 2\sqrt{d-1} \\ 0 & \text{otherwise.} \end{cases}$$
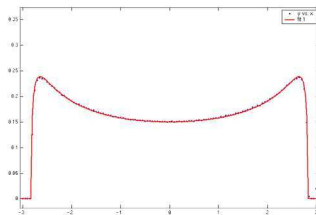
McKay's Law (Kesten Measure) with $d = 6$
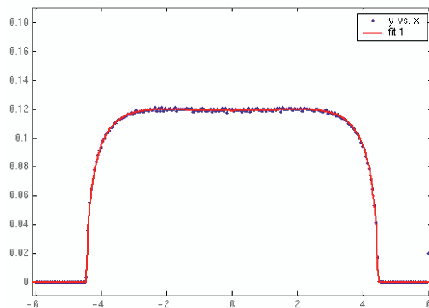
Fat Thin: fat enough to average, thin enough to get something different than semi-circle (though as $d \to \infty$ recover semi-circle).

3-Regular Graph with 2000 Vertices: Comparison with the GOE

Spacings between eigenvalues of 3-regular graphs and the GOE:
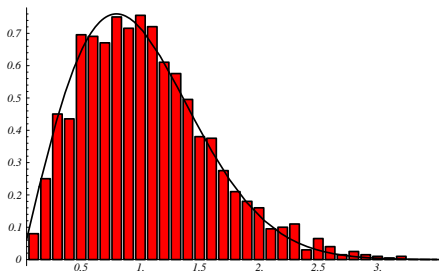
Real Symmetric Toeplitz Matrices
Chris Hammond and Steven J. Miller

Toeplitz Ensembles

Toeplitz matrix is of the form

$$\begin{pmatrix}
b_0 & b_1 & b_2 & \cdots & b_{N-1} \\
b_{-1} & b_0 & b_1 & \cdots & b_{N-2} \\
b_{-2} & b_{-1} & b_0 & \cdots & b_{N-3} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
b_{1-N} & b_{2-N} & b_{3-N} & \cdots & b_0
\end{pmatrix}$$

- Will consider Real Symmetric Toeplitz matrices.
- Main diagonal zero, $N - 1$ independent parameters.
- Normalize Eigenvalues by $\sqrt{N}$.

Eigenvalue Density Measure

$$\mu_{A,N}(x)dx \ = \ \frac{1}{N} \sum_{i=1}^{N} \delta \left(x - \frac{\lambda_i(A)}{\sqrt{N}} \right) dx.$$

The kth moment of $\mu_{A,N}(x)$ is

$$M_k(A, N) \ = \ \frac{1}{N^{\frac{k}{2}+1}} \sum_{i=1}^{N} \lambda_i^k(A) \ = \ \frac{\text{Trace}(A^k)}{N^{\frac{k}{2}+1}}.$$

Let

$$M_k \ = \ \lim_{N \to \infty} \mathbb{E}_A \left[M_k(A, N) \right];$$

have $M_2 = 1$ and $M_{2k+1} = 0$.

Even Moments

$$M_{2k}(N) = \frac{1}{N^{k+1}} \sum_{1 \le i_1, \cdots, i_{2k} \le N} \mathbb{E}(b_{|i_1 - i_2|} b_{|i_2 - i_3|} \cdots b_{|i_{2k} - i_1|}).$$

Main Term: b_j's matched in pairs, say

$$b_{|i_m - i_{m+1}|} = b_{|i_n - i_{n+1}|}, \quad x_m = |i_m - i_{m+1}| = |i_n - i_{n+1}|.$$

Two possibilities:

$$i_m - i_{m+1} = i_n - i_{n+1} \quad \text{or} \quad i_m - i_{m+1} = -(i_n - i_{n+1}).$$

$(2k - 1)!!$ ways to pair, 2^k choices of sign.

Main Term: All Signs Negative (else lower order contribution)

$$M_{2k}(N) = \frac{1}{N^{k+1}} \sum_{1 \le i_1, \cdots, i_{2k} \le N} \mathbb{E}(b_{|i_1-i_2|} b_{|i_2-i_3|} \cdots b_{|i_{2k}-i_1|}).$$

Let $x_1, \ldots, x_k$ be the values of the $|i_j - i_{j+1}|$'s, $\epsilon_1, \ldots, \epsilon_k$ the choices of sign. Define $\widetilde{x}_1 = i_1 - i_2, \widetilde{x}_2 = i_2 - i_3, \ldots$.

$$\begin{aligned}
i_2 &= i_1 - \widetilde{x}_1 \\
i_3 &= i_1 - \widetilde{x}_1 - \widetilde{x}_2 \\
&\vdots \\
i_1 &= i_1 - \widetilde{x}_1 - \cdots - \widetilde{x}_{2k} \\
\widetilde{x}_1 + \cdots + \widetilde{x}_{2k} &= \sum_{j=1}^{k} (1 + \epsilon_j) \eta_j x_j = 0, \quad \eta_j = \pm 1.
\end{aligned}$$

Even Moments: Summary

Main Term: paired, all signs negative.

$$M_{2k}(N) \leq (2k-1)!! + O_k\left(\frac{1}{N}\right).$$

Bounded by Gaussian.

The Fourth Moment
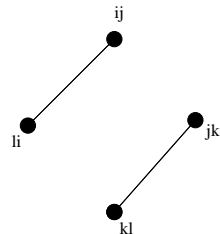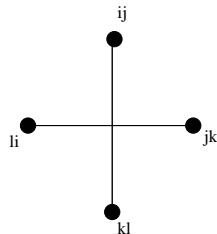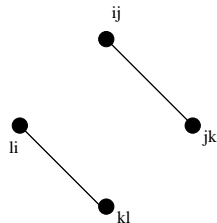
$$M_4(N) = \frac{1}{N^3} \sum_{1 \le i_1, i_2, i_3, i_4 \le N} \mathbb{E}(b_{|i_1-i_2|} b_{|i_2-i_3|} b_{|i_3-i_4|} b_{|i_4-i_1|})$$

Let $x_j = |i_j - i_{j+1}|$.

The Fourth Moment

Case One: $x_1 = x_2$, $x_3 = x_4$:

$$i_1 - i_2 = -(i_2 - i_3) \quad \text{and} \quad i_3 - i_4 = -(i_4 - i_1).$$

Implies

$$i_1 = i_3, \quad i_2 \text{ and } i_4 \text{ arbitrary.}$$

Left with $\mathbb{E}[b_{x_1}^2 b_{x_3}^2]$:
  $N^3 - N$ times get 1, N times get $p_4 = \mathbb{E}[b_{x_1}^4]$.

Contributes 1 in the limit.

The Fourth Moment

$$M_4(N) = \frac{1}{N^3} \sum_{1 \leq i_1, i_2, i_3, i_4 \leq N} \mathbb{E}(b_{|i_1-i_2|} b_{|i_2-i_3|} b_{|i_3-i_4|} b_{|i_4-i_1|})$$

Case Two: Diophantine Obstruction: $x_1 = x_3$ and $x_2 = x_4$.

$$i_1 - i_2 = -(i_3 - i_4) \quad \text{and} \quad i_2 - i_3 = -(i_4 - i_1).$$

This yields

$$i_1 = i_2 + i_4 - i_3, \quad i_1, i_2, i_3, i_4 \in \{1, \ldots, N\}.$$

If $i_2, i_4 \geq \frac{2N}{3}$ and $i_3 < \frac{N}{3}$, $i_1 > N$: at most $(1 - \frac{1}{27})N^3$ valid choices.

44

The Fourth Moment

Theorem: Fourth Moment: Let p_4 be the fourth moment of p. Then

$$M_4(N) = 2\frac{2}{3} + O_{p_4}\left(\frac{1}{N}\right).$$
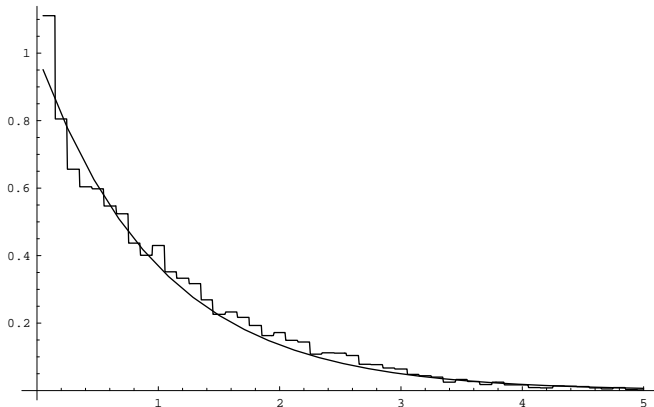
500 Toeplitz Matrices, 400×400.
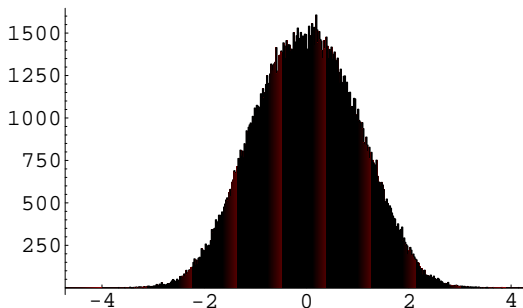
Main Result

Theorem: HM '05

For real symmetric Toeplitz matrices, the limiting spectral measure converges in probability to a unique measure of unbounded support which is not the Gaussian. If p is even have strong convergence).

Massey, Miller and Sinsheimer '07 proved that if first row is a palindrome converges to a Gaussian.

Poissonian Behavior?

Not rescaled. Looking at middle 11 spacings, 1000
Toeplitz matrices (1000 $\times$ 1000), entries iidrv from the
standard normal.

Block Circulant Ensemble

With Murat Koloğlu, Gene Kopp, Fred Strauch and Wentao Xiong.

The Ensemble of m-Block Circulant Matrices

Symmetric matrices periodic with period m on wrapped diagonals, i.e., symmetric block circulant matrices.

8-by-8 real symmetric 2-block circulant matrix:

$$\begin{pmatrix} c_0 & c_1 & c_2 & c_3 & c_4 & d_3 & c_2 & d_1 \\ c_1 & d_0 & d_1 & d_2 & d_3 & d_4 & c_3 & d_2 \\ c_2 & d_1 & c_0 & c_1 & c_2 & c_3 & c_4 & d_3 \\ c_3 & d_2 & c_1 & d_0 & d_1 & d_2 & d_3 & d_4 \\ c_4 & d_3 & c_2 & d_1 & c_0 & c_1 & c_2 & c_3 \\ d_3 & d_4 & c_3 & d_2 & c_1 & d_0 & d_1 & d_2 \\ c_2 & c_3 & c_4 & d_3 & c_2 & d_1 & c_0 & c_1 \\ d_1 & d_2 & d_3 & d_4 & c_3 & d_2 & c_1 & d_0 \end{pmatrix}.$$

Choose distinct entries i.i.d.r.v.

Oriented Matchings and Dualization

Compute moments of eigenvalue distribution (as m stays fixed and $N \to \infty$) using the combinatorics of pairings. Rewrite:

$$
\begin{aligned}
M_n(N) &= \frac{1}{N^{\frac{n}{2}+1}} \sum_{1 \le i_1, \ldots, i_n \le N} \mathbb{E}(a_{i_1 i_2} a_{i_2 i_3} \cdots a_{i_n i_1}) \\
&= \frac{1}{N^{\frac{n}{2}+1}} \sum_{\sim} \eta(\sim) m_{d_1(\sim)} \cdots m_{d_l(\sim)}.
\end{aligned}
$$

where the sum is over oriented matchings on the edges $\{(1, 2), (2, 3), \ldots, (n, 1)\}$ of a regular n-gon.
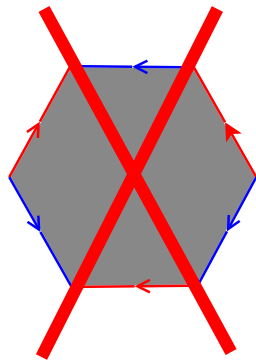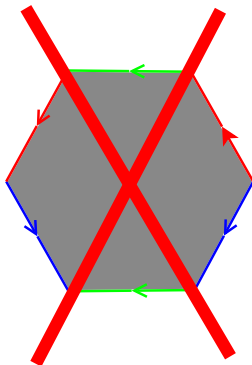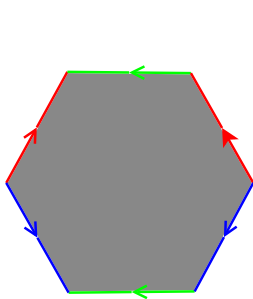
Oriented Matchings and Dualization
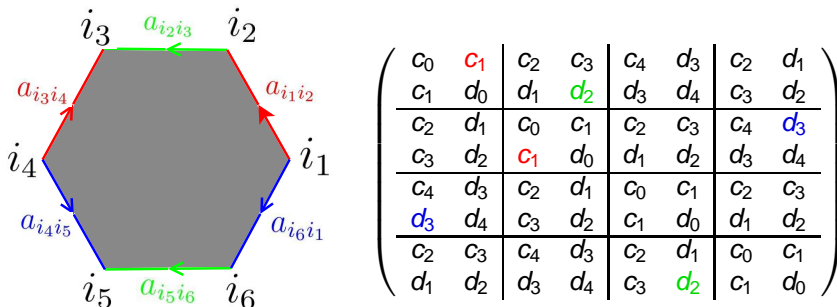
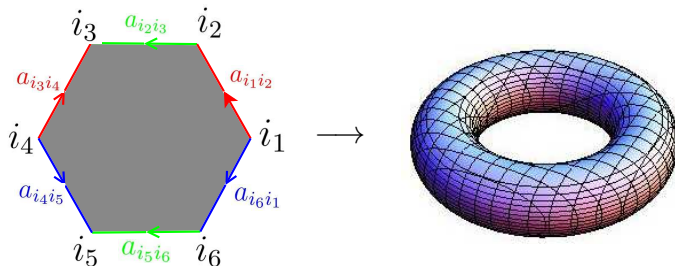**Figure:** An oriented matching in the expansion for $M_n(N) = M_6(8)$.

Contributing Terms

As $N \to \infty$, the only terms that contribute to this sum are those in which the entries are matched in pairs and with opposite orientation.

Only Topology Matters

Think of pairings as topological identifications; the contributing ones give rise to orientable surfaces.

Contribution from such a pairing is m^{-2g}, where g is the genus (number of holes) of the surface. Proof: combinatorial argument involving Euler characteristic.

Computing the Even Moments

> **Theorem: Even Moment Formula**
>
> $$M_{2k} = \sum_{g=0}^{\lfloor k/2 \rfloor} \varepsilon_g(k) m^{-2g} + O_k\left(\frac{1}{N}\right),$$
>
> with $\varepsilon_g(k)$ the number of pairings of the edges of a $(2k)$-gon giving rise to a genus g surface.

J. Harer and D. Zagier (1986) gave generating functions for the $\varepsilon_g(k)$.

Harer and Zagier

$$\sum_{g=0}^{\lfloor k/2 \rfloor} \varepsilon_g(k) r^{k+1-2g} \; = \; (2k - 1)!! \; c(k, r)$$

where

$$1 + 2 \sum_{k=0}^{\infty} c(k, r) x^{k+1} \; = \; \left(\frac{1 + x}{1 - x} \right)^r.$$

Thus, we write

$$M_{2k} \; = \; m^{-(k+1)}(2k - 1)!! \, c(k, m).$$

A multiplicative convolution and Cauchy's residue formula yield the characteristic function of the distribution.

$$
\begin{aligned}
\phi(t) &= \sum_{k=0}^{\infty} \frac{(it)^{2k} M_{2k}}{(2k)!} = \frac{1}{m} \sum_{k=0}^{\infty} \frac{(-t^2/2m)^k}{k!} c(k, m) \\
&= \frac{1}{2\pi i m} \oint_{|z|=2} \frac{1}{2z^{-1}} \left(\left(\frac{1 + z^{-1}}{1 - z^{-1}} \right)^m - 1 \right) e^{-t^2 z/2m} \frac{dz}{z} \\
&= \frac{1}{m} e^{\frac{-t^2}{2m}} \sum_{\ell=1}^{m} \binom{m}{\ell} \frac{1}{(\ell-1)!} \left(\frac{-t^2}{m} \right)^{\ell-1}.
\end{aligned}
$$

Results

Fourier transform and algebra yields

Theorem: Koloğlu, Kopp and Miller

The limiting spectral density function $f_m(x)$ of the real symmetric m-block circulant ensemble is given by

$$f_m(x) = \frac{e^{-\frac{mx^2}{2}}}{\sqrt{2\pi m}} \sum_{r=0}^{m} \frac{1}{(2r)!} \sum_{s=0}^{m-r} \binom{m}{r+s+1} \frac{(2r+2s)!}{(r+s)!s!} \left(-\frac{1}{2}\right)^s (mx^2)^r.$$

Fixed m equals $m \times m$ GOE, as $m \to \infty$ converges to the semicircle distribution.
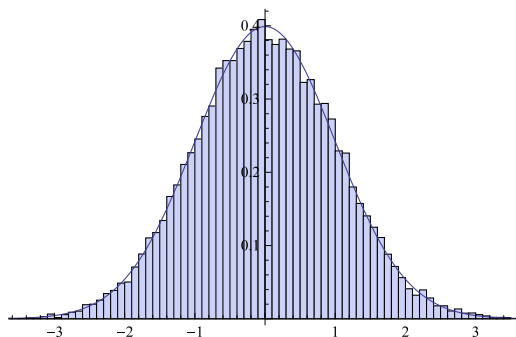
Results (continued)

Figure: Plot for f_1 and histogram of eigenvalues of 100 circulant matrices of size 400×400.
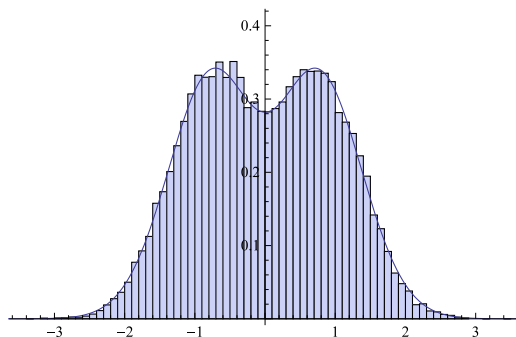
Results (continued)

Figure: Plot for f_2 and histogram of eigenvalues of 100 2-block circulant matrices of size 400×400.
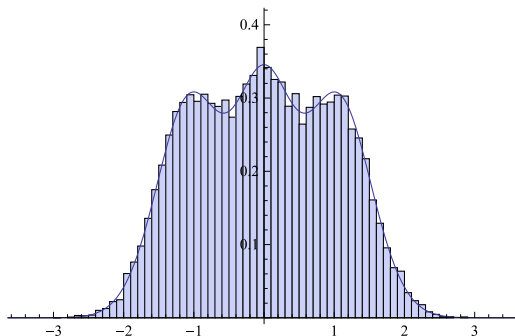
Results (continued)

Figure: Plot for f_3 and histogram of eigenvalues of 100 3-block circulant matrices of size 402×402.
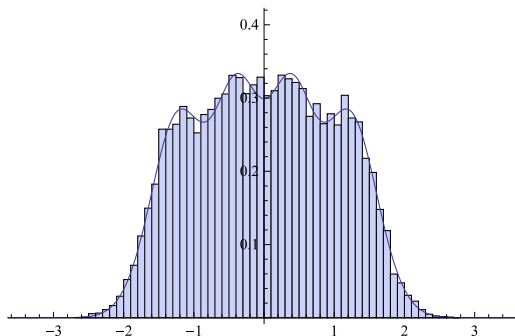
Results (continued)

Figure: Plot for f_4 and histogram of eigenvalues of 100 4-block circulant matrices of size 400×400.
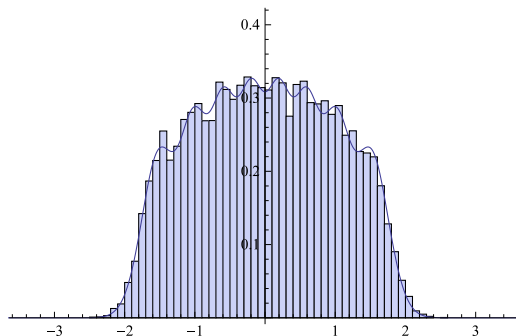
Results (continued)

Figure: Plot for f_8 and histogram of eigenvalues of 100 8-block circulant matrices of size 400×400.

Results (continued)
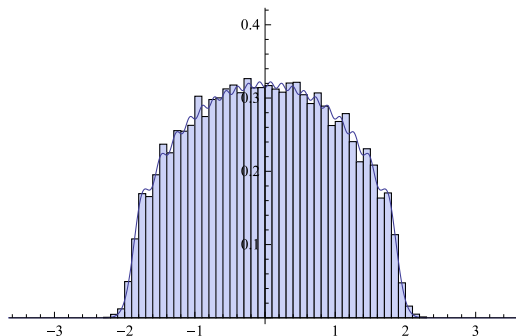

Figure: Plot for f_{20} and histogram of eigenvalues of 100 20-block circulant matrices of size 400×400.

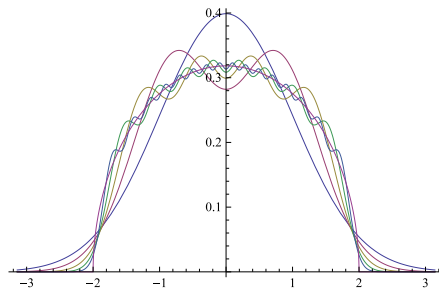**Results (continued)**

Figure: Plot of convergence to the semi-circle.

The Limiting Spectral Measure for Ensembles of Symmetric Block Circulant Matrices (with Murat Koloğlu, Gene S. Kopp, Frederick W. Strauch and Wentao Xiong), Journal of Theoretical Probability **26** (2013), no. 4, 1020–1060. http://arxiv.org/abs/1008.4812

Checkerboard Martrices

Joint with Paula Burkhardt, Peter Cohen, Jonathan Dewitt, Max Hlavacek, Eyvindur A. Palsson, Aaditya Sharma, Carsten Sprunger, Yen Nhi Truong Vu, Roger Van Peski and Kevin Yang.

Checkerboard Matrices

An $N \times N$ matrix A is a *random real symmetric checkerboard matrix* if

$$A = \begin{pmatrix} w & b_{0,1} & w & b_{0,3} & w & \cdots & b_{0,N-1} \\ b_{0,1} & w & b_{1,2} & w & b_{1,4} & \cdots & w \\ w & b_{1,2} & w & b_{2,3} & w & \cdots & b_{2,N-1} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ b_{0,N-1} & w & b_{2,N-1} & w & b_{4,N-1} & \cdots & w \end{pmatrix},$$

where the $b_{i,j}$ are i.i.d.r.v, and w is a random variable.

It is *k*-checkerboard if w occurs every k entries in row starting with the entry at the index ($i \bmod k$) of the ith row.

Evolving Results

Last summer proved all but k eigenvalues in bulk and converge to semi-circle, remaining k in *blip* of size N/k.

Evolving Results:

- Variance in blip like $1/N$.
- There are two peaks; for $k = 2$ from the $(1, 1, \ldots, 1)$ and the $(1, -1, 1, -1, \ldots, 1, -1)$ eigenvectors.
- The limiting spectral distribution in blip is a double delta spike for any k.

Evolving Results

Last summer proved all but k eigenvalues in bulk and converge to semi-circle, remaining k in *blip* of size N/k.

Evolving Results:

- Variance in blip like $1/N$. False. Is order k.
- There are two peaks; for $k = 2$ from the $(1, 1, \ldots, 1)$ and the $(1, -1, 1, -1, \ldots, 1, -1)$ eigenvectors. False.
- The limiting spectral distribution in blip is a double delta spike for any k. False. Goes to nice $k \times k$ GOE!

Key ideas

Weights: To concentrate in blip, let
$f(n) = (n-1)x^n - nx^{n-1}$, and set

$$\mu_{A;N}^{\text{blip}}(x) \; = \; \frac{1}{k} \sum_\lambda f\left(\frac{\lambda}{N/k} \right) \delta \left(x - \left(\lambda - \frac{N}{k} \right) \right).$$
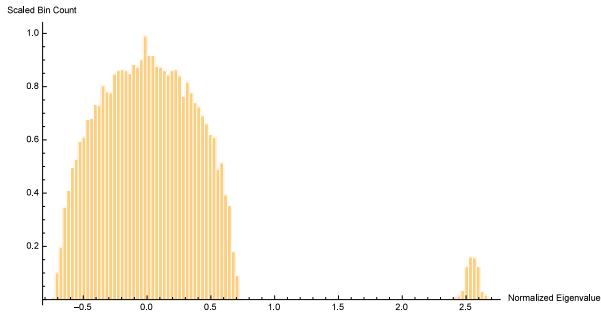
Combinatorics: Reduce to $k \times k$ GOE.

Results

Figure: 2-Checkerboard: $N = 100$, 100 trials.
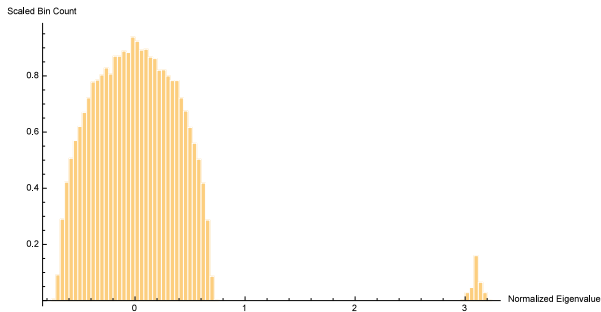
Results

Figure: 2-Checkerboard: $N = 150$, 100 trials.

Results

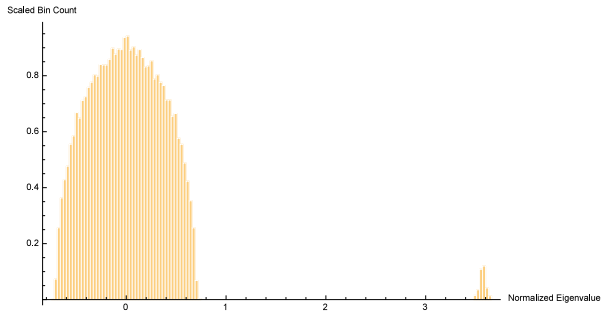**Figure:** 2-Checkerboard: $N = 200$, 100 trials.

Results
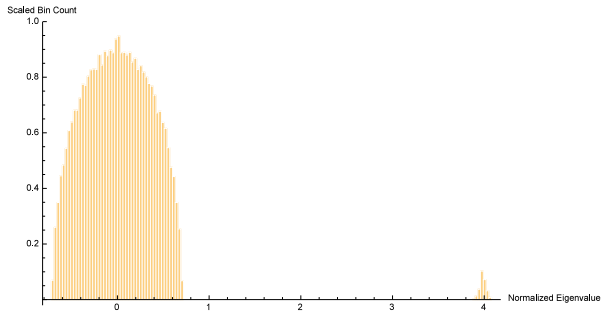
Figure: 2-Checkerboard: $N = 250$, 100 trials.

Results
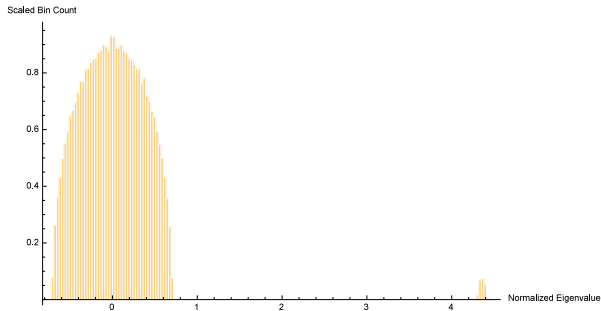
Figure: 2-Checkerboard: $N = 300$, 100 trials.

Results
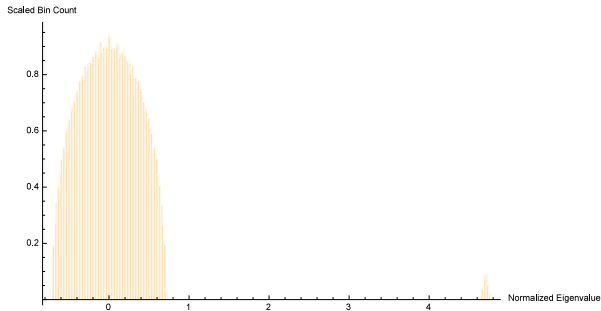
Figure: 2-Checkerboard: $N = 350$, 100 trials.

Split Eigenvalue Distribution: Checkerboard and Generalizations
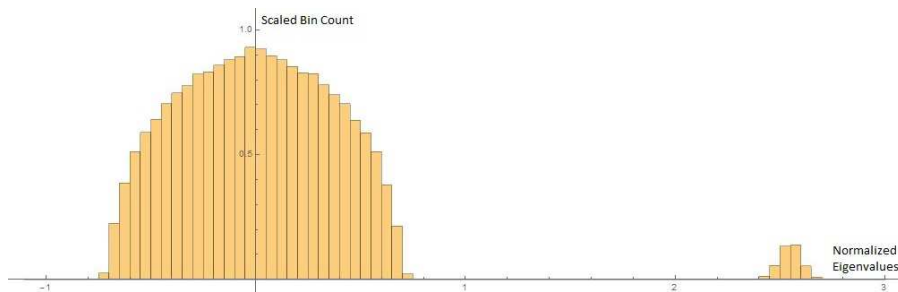
Figure: Histogram of normalized eigenvalues for 500 100 × 100 2-checkerboard matrices.

Split Eigenvalue Distribution: Checkerboard and Generalizations
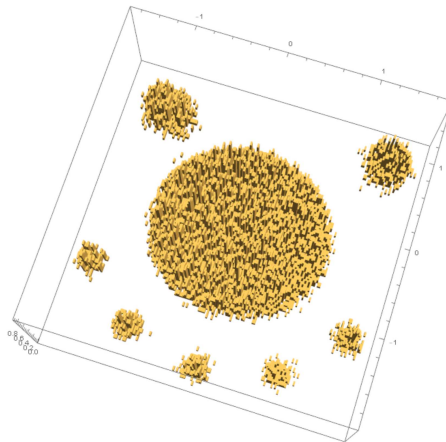
Figure: Complex Generalization I.

Split Eigenvalue Distribution: Checkerboard and Generalizations
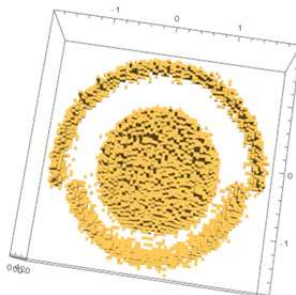
Figure: Complex Generalization II.

Introduction
to *L*-Functions

Riemann Zeta Function

$$\zeta(s) \,=\, \sum_{n=1}^{\infty} \frac{1}{n^s} \,=\, \prod_{p \text{ prime}} \left(1 - \frac{1}{p^s}\right)^{-1}, \quad \text{Re}(s) > 1.$$

Riemann Zeta Function

$$\zeta(s) \;=\; \sum_{n=1}^{\infty} \frac{1}{n^s} \;=\; \prod_{p \text{ prime}} \left(1 - \frac{1}{p^s}\right)^{-1}, \quad \text{Re}(s) > 1.$$

Unique Factorization: $n = p_1^{r_1} \cdots p_m^{r_m}$.

Riemann Zeta Function

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s} = \prod_{p \text{ prime}} \left(1 - \frac{1}{p^s}\right)^{-1}, \quad \text{Re}(s) > 1.$$

Unique Factorization: $n = p_1^{r_1} \cdots p_m^{r_m}$.

$$\prod_p \left(1 - \frac{1}{p^s}\right)^{-1} = \left[1 + \frac{1}{2^s} + \left(\frac{1}{2^s}\right)^2 + \cdots\right]\left[1 + \frac{1}{3^s} + \left(\frac{1}{3^s}\right)^2 + \cdots\right]\cdots$$

$$= \sum_n \frac{1}{n^s}.$$

Riemann Zeta Function (cont)

$$\zeta(s) = \sum_n \frac{1}{n^s} = \prod_p \left(1 - \frac{1}{p^s}\right)^{-1}, \quad \text{Re}(s) > 1$$

$$\pi(x) = \#\{p : p \text{ is prime}, p \leq x\}$$

Properties of $\zeta(s)$ and Primes:

Riemann Zeta Function (cont)

$$\zeta(s) = \sum_n \frac{1}{n^s} = \prod_p \left(1 - \frac{1}{p^s}\right)^{-1}, \quad \text{Re}(s) > 1$$

$$\pi(x) = \#\{p : p \text{ is prime}, p \leq x\}$$

Properties of $\zeta(s)$ and Primes:

- $\lim_{s \to 1^+} \zeta(s) = \infty$, $\pi(x) \to \infty$.

Riemann Zeta Function (cont)

$$\zeta(s) = \sum_n \frac{1}{n^s} = \prod_p \left(1 - \frac{1}{p^s}\right)^{-1}, \quad \text{Re}(s) > 1$$

$$\pi(x) = \#\{p : p \text{ is prime}, p \leq x\}$$

Properties of $\zeta(s)$ and Primes:

- $\lim_{s \to 1^+} \zeta(s) = \infty$, $\pi(x) \to \infty$.
- $\zeta(2) = \frac{\pi^2}{6}$, $\pi(x) \to \infty$.

Riemann Zeta Function

$$\zeta(s) \,=\, \sum_{n=1}^{\infty} \frac{1}{n^s} \,=\, \prod_{p \text{ prime}} \left(1 - \frac{1}{p^s}\right)^{-1}, \quad \text{Re}(s) > 1.$$

Functional Equation:

$$\xi(s) \,=\, \Gamma\left(\frac{s}{2}\right)\pi^{-\frac{s}{2}}\zeta(s) \,=\, \xi(1 - s).$$

Riemann Hypothesis (RH):

All non-trivial zeros have $\text{Re}(s) = \frac{1}{2}$; can write zeros as $\frac{1}{2}+i\gamma$.

Observation: Spacings b/w zeros appear same as b/w eigenvalues of Complex Hermitian matrices $\overline{A}^T = A$.

General *L*-functions

$$L(s, f) = \sum_{n=1}^{\infty} \frac{a_f(n)}{n^s} = \prod_{p \text{ prime}} L_p(s, f)^{-1}, \quad \text{Re}(s) > 1.$$

Functional Equation:

$$\Lambda(s, f) = \Lambda_{\infty}(s, f) L(s, f) = \Lambda(1 - s, f).$$

Generalized Riemann Hypothesis (RH):

All non-trivial zeros have $\text{Re}(s) = \frac{1}{2}$; can write zeros as $\frac{1}{2} + i\gamma$.

Observation: Spacings b/w zeros appear same as b/w eigenvalues of Complex Hermitian matrices $\overline{A}^T = A$.

Elliptic Curves: Mordell-Weil Group

Elliptic curve $y^2 = x^3 + ax + b$ with rational solutions
$P = (x_1, y_1)$ and $Q = (x_2, y_2)$ and connecting line
$y = mx + b$.
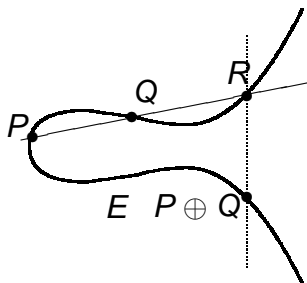
Addition of distinct points P and Q
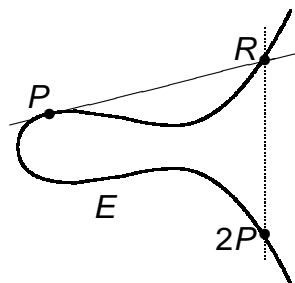
Adding a point P to itself

$$E(\mathbb{Q}) \approx E(\mathbb{Q})_{\text{tors}} \oplus \mathbb{Z}^r$$

Elliptic curve *L*-function

$E : y^2 = x^3 + ax + b$, associate *L*-function

$$L(s, E) = \sum_{n=1}^{\infty} \frac{a_E(n)}{n^s} = \prod_{p \text{ prime}} L_E(p^{-s}),$$

where

$$a_E(p) = p - \#\{(x, y) \in (\mathbb{Z}/p\mathbb{Z})^2 : y^2 \equiv x^3 + ax + b \bmod p\}.$$

Elliptic curve *L*-function

$E : y^2 = x^3 + ax + b$, associate *L*-function

$$L(s, E) \; = \; \sum_{n=1}^{\infty} \frac{a_E(n)}{n^s} \; = \; \prod_{p \text{ prime}} L_E(p^{-s}),$$

where

$$a_E(p) = p - \#\{(x, y) \in (\mathbb{Z}/p\mathbb{Z})^2 : y^2 \equiv x^3 + ax + b \bmod p\}.$$

Birch and Swinnerton-Dyer Conjecture

Rank of group of rational solutions equals order of
vanishing of $L(s, E)$ at $s = 1/2$.

Properties of zeros of *L*-functions

- infinitude of primes, primes in arithmetic progression.

- Chebyshev's bias: $\pi_{3,4}(x) \geq \pi_{1,4}(x)$ 'most' of the time.

- Birch and Swinnerton-Dyer conjecture.

- Goldfeld, Gross-Zagier: bound for $h(D)$ from *L*-functions with many central point zeros.

- Even better estimates for $h(D)$ if a positive percentage of zeros of $\zeta(s)$ are at most $1/2 - \epsilon$ of the average spacing to the next zero.

Distribution of zeros

- $\zeta(s) \neq 0$ for $\mathfrak{Re}(s) = 1$: $\pi(x)$, $\pi_{a,q}(x)$.

- GRH: error terms.

- GSH: Chebyshev's bias.

- Analytic rank, adjacent spacings: $h(D)$.

Explicit Formula (Contour Integration)

$$-\frac{\zeta'(s)}{\zeta(s)} \;\; = \;\; -\frac{\mathrm{d}}{\mathrm{d}s}\log\zeta(s) \;=\; -\frac{\mathrm{d}}{\mathrm{d}s}\log\prod_{p}\left(1-p^{-s}\right)^{-1}$$

Explicit Formula (Contour Integration)

$$
\begin{aligned}
-\frac{\zeta'(s)}{\zeta(s)} &= -\frac{d}{ds}\log\zeta(s) = -\frac{d}{ds}\log\prod_p \left(1 - p^{-s}\right)^{-1} \\
&= \frac{d}{ds}\sum_p \log\left(1 - p^{-s}\right) \\
&= \sum_p \frac{\log p \cdot p^{-s}}{1 - p^{-s}} = \sum_p \frac{\log p}{p^s} + \text{Good}(s).
\end{aligned}
$$

Explicit Formula (Contour Integration)

$$
-\frac{\zeta'(s)}{\zeta(s)} = -\frac{d}{ds}\log\zeta(s) = -\frac{d}{ds}\log\prod_p \left(1 - p^{-s}\right)^{-1}
$$

$$
= \frac{d}{ds}\sum_p \log\left(1 - p^{-s}\right)
$$

$$
= \sum_p \frac{\log p \cdot p^{-s}}{1 - p^{-s}} = \sum_p \frac{\log p}{p^s} + \text{Good}(s).
$$

Contour Integration:

$$
\int -\frac{\zeta'(s)}{\zeta(s)}\frac{x^s}{s}\,ds \quad \text{vs} \quad \sum_p \log p \int \left(\frac{x}{p}\right)^s \frac{ds}{s}.
$$

Explicit Formula (Contour Integration)

$$
\begin{aligned}
-\frac{\zeta'(s)}{\zeta(s)} &= -\frac{\mathrm{d}}{\mathrm{d}s}\log\zeta(s) = -\frac{\mathrm{d}}{\mathrm{d}s}\log\prod_p\left(1-p^{-s}\right)^{-1} \\
&= \frac{\mathrm{d}}{\mathrm{d}s}\sum_p\log\left(1-p^{-s}\right) \\
&= \sum_p\frac{\log p \cdot p^{-s}}{1-p^{-s}} = \sum_p\frac{\log p}{p^s} + \mathrm{Good}(s).
\end{aligned}
$$

Contour Integration:

$$
\int -\frac{\zeta'(s)}{\zeta(s)}\,\phi(s)ds \quad\text{vs}\quad \sum_p\log p\int\phi(s)p^{-s}ds.
$$

Explicit Formula (Contour Integration)

$$
\begin{aligned}
-\frac{\zeta'(s)}{\zeta(s)} &= -\frac{d}{ds}\log\zeta(s) = -\frac{d}{ds}\log\prod_p \left(1 - p^{-s}\right)^{-1} \\
&= \frac{d}{ds}\sum_p \log\left(1 - p^{-s}\right) \\
&= \sum_p \frac{\log p \cdot p^{-s}}{1 - p^{-s}} = \sum_p \frac{\log p}{p^s} + \text{Good}(s).
\end{aligned}
$$

Contour Integration (see Fourier Transform arising):

$$
\int -\frac{\zeta'(s)}{\zeta(s)}\,\phi(s)ds \quad \text{vs} \quad \sum_p \log p \int \phi(s)e^{-\sigma\log p}e^{-it\log p}ds.
$$

Knowledge of zeros gives info on coefficients.

Explicit Formula: Example

Dirichlet *L*-functions: Let ϕ be an even Schwartz function and $L(s, \chi) = \sum_n \chi(n)/n^s$ a Dirichlet *L*-function from a non-trivial character χ with conductor m and zeros $\rho = \frac{1}{2} + i\gamma_\chi$. Then

$$\sum_\rho \phi\left(\gamma_\chi \frac{\log(m/\pi)}{2\pi}\right) = \int_{-\infty}^\infty \phi(y) dy$$

$$-2 \sum_p \frac{\log p}{\log(m/\pi)} \widehat{\phi}\left(\frac{\log p}{\log(m/\pi)}\right) \frac{\chi(p)}{p^{1/2}}$$

$$-2 \sum_p \frac{\log p}{\log(m/\pi)} \widehat{\phi}\left(2 \frac{\log p}{\log(m/\pi)}\right) \frac{\chi^2(p)}{p} + O\left(\frac{1}{\log m}\right).$$

Takeaways

Very similar to Central Limit Theorem.

- Universal behavior: main term controlled by first two moments of Satake parameters, agrees with RMT.

- First moment zero save for families of elliptic curves.

- Higher moments control convergence and can depend on arithmetic of family.

Modeling lowest zero of $L_{E_{11}}(s, \chi_d)$ with $0 < d < 400,000$
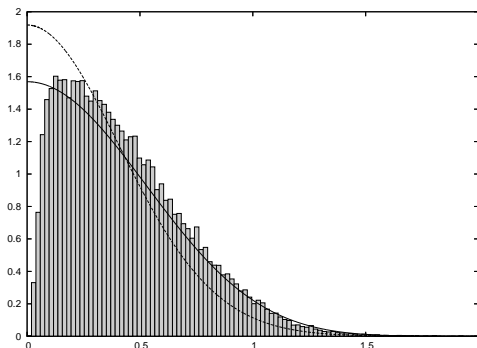
Lowest zero for $L_{E_{11}}(s, \chi_d)$ (bar chart), lowest eigenvalue
of SO(2N) with N_{eff} (solid), standard N_0 (dashed).

Modeling lowest zero of $L_{E_{11}}(s, \chi_d)$ with $0 < d < 400,000$
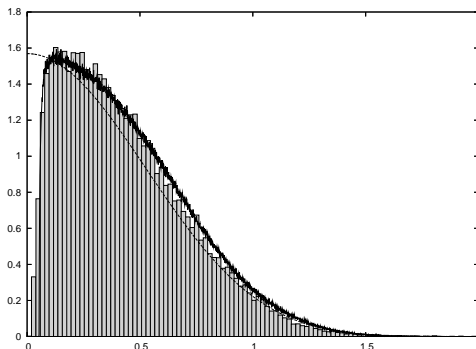
Lowest zero for $L_{E_{11}}(s, \chi_d)$ (bar chart); lowest eigenvalue of SO(2N): $N_{\text{eff}} = 2$ (solid) with discretisation, and $N_{\text{eff}} = 2.32$ (dashed) without discretisation.

The lowest eigenvalue of Jacobi Random Matrix Ensembles and Painlevé VI, (with E. Dueñez, D. K. Huynh, J. Keating and N. Snaith), Journal of Physics A: Mathematical and Theoretical **43** (2010) 405204 (27pp). http://arxiv.org/pdf/1005.1298
Models for zeros at the central point in families of elliptic curves (with E. Dueñez, D. K. Huynh, J. Keating and N. Snaith), J. Phys. A: Math. Theor. **45** (2012) 115207 (32pp). http://arxiv.org/pdf/1107.4426

Open Questions
and References

Open Questions: Low-lying zeros of *L*-functions

- Generalize excised ensembles for higher weight GL_2 families where expect different discretizations.

- Obtain better estimates on vanishing at the central point by finding optimal test functions for the second and higher moment expansions.

- Further explore *L*-function Ratios Conjecture to predict lower order terms in families, compute these terms on number theory side.

See Dueñez-Huynh-Keating-Miller-Snaith, Miller, and the Ratios papers.

Publications: Random Matrix Theory

1 *Distribution of eigenvalues for the ensemble of real symmetric Toeplitz matrices* (with Christopher Hammond), Journal of Theoretical Probability **18** (2005), no. 3, 537–566.
http://arxiv.org/abs/math/0312215

2 *Distribution of eigenvalues of real symmetric palindromic Toeplitz matrices and circulant matrices* (with Adam Massey and John Sinsheimer), Journal of Theoretical Probability **20** (2007), no. 3, 637–662.
http://arxiv.org/abs/math/0512146

3 *The distribution of the second largest eigenvalue in families of random regular graphs* (with Tim Novikoff and Anthony Sabelli), Experimental Mathematics **17** (2008), no. 2, 231–244.
http://arxiv.org/abs/math/0611649

4 *Nuclei, Primes and the Random Matrix Connection* (with Frank W. K. Firk), Symmetry **1** (2009), 64–105; doi:10.3390/sym1010064. http://arxiv.org/abs/0909.4914

5 *Distribution of eigenvalues for highly palindromic real symmetric Toeplitz matrices* (with Steven Jackson and Thuy Pham), Journal of Theoretical Probability **25** (2012), 464–495.
http://arxiv.org/abs/1003.2010

6 *The Limiting Spectral Measure for Ensembles of Symmetric Block Circulant Matrices* (with Murat Koloğlu, Gene S. Kopp, Frederick W. Strauch and Wentao Xiong), Journal of Theoretical Probability **26** (2013), no. 4, 1020–1060. http://arxiv.org/abs/1008.4812

7 *Distribution of eigenvalues of weighted, structured matrix ensembles* (with Olivia Beckwith, Karen Shen), submitted December 2011 to the Journal of Theoretical Probability, revised September 2012.
http://arxiv.org/abs/1112.3719 .

8 *The expected eigenvalue distribution of large, weighted d-regular graphs* (with Leo Goldmahker, Cap Khoury and Kesinee Ninsuwan), preprint.

Publications: *L*-Functions

1 *The low lying zeros of a GL*(4) *and a GL*(6) *family of L-functions* (with Eduardo Dueñez), Compositio Mathematica **142** (2006), no. 6, 1403–1425. http://arxiv.org/abs/math/0506462

2 *Low lying zeros of L–functions with orthogonal symmetry* (with Christopher Hughes), Duke Mathematical Journal **136** (2007), no. 1, 115–172. http://arxiv.org/abs/math/0507450

3 *Lower order terms in the 1-level density for families of holomorphic cuspidal newforms*, Acta Arithmetica **137** (2009), 51–98. http://arxiv.org/abs/0704.0924

4 *The effect of convolving families of L-functions on the underlying group symmetries* (with Eduardo Dueñez), Proceedings of the London Mathematical Society, 2009; doi: 10.1112/plms/pdp018. http://arxiv.org/pdf/math/0607688.pdf

5 *Low-lying zeros of number field L-functions* (with Ryan Peckner), Journal of Number Theory **132** (2012), 2866–2891. http://arxiv.org/abs/1003.5336

6 *The low-lying zeros of level 1 Maass forms* (with Levent Alpoge), preprint 2013. http://arxiv.org/abs/1301.5702

7 *The n-level density of zeros of quadratic Dirichlet L-functions* (with Jake Levinson), submitted September 2012 to Acta Arithmetica. http://arxiv.org/abs/1208.0930

8 *Moment Formulas for Ensembles of Classical Compact Groups* (with Geoffrey Iyer and Nicholas Triantafillou), preprint 2013.

Publications: Elliptic Curves

1 *1- and 2-level densities for families of elliptic curves: evidence for the underlying group symmetries*, Compositio Mathematica **140** (2004), 952–992. http://arxiv.org/pdf/math/0310159

2 *Variation in the number of points on elliptic curves and applications to excess rank*, C. R. Math. Rep. Acad. Sci. Canada **27** (2005), no. 4, 111–120. http://arxiv.org/abs/math/0506461

3 *Investigations of zeros near the central point of elliptic curve L-functions*, Experimental Mathematics **15** (2006), no. 3, 257–279. http://arxiv.org/pdf/math/0508150

4 *Constructing one-parameter families of elliptic curves over* $\mathbb{Q}(T)$ *with moderate rank* (with Scott Arms and Álvaro Lozano-Robledo), Journal of Number Theory **123** (2007), no. 2, 388–402. http://arxiv.org/abs/math/0406579

5 *Towards an 'average' version of the Birch and Swinnerton-Dyer Conjecture* (with John Goes), Journal of Number Theory **130** (2010), no. 10, 2341–2358. http://arxiv.org/abs/0911.2871

6 *The lowest eigenvalue of Jacobi Random Matrix Ensembles and Painlevé VI*, (with Eduardo Dueñez, Duc Khiem Huynh, Jon Keating and Nina Snaith), Journal of Physics A: Mathematical and Theoretical **43** (2010) 405204 (27pp). http://arxiv.org/pdf/1005.1298

7 *Models for zeros at the central point in families of elliptic curves* (with Eduardo Dueñez, Duc Khiem Huynh, Jon Keating and Nina Snaith), J. Phys. A: Math. Theor. **45** (2012) 115207 (32pp). http://arxiv.org/pdf/1107.4426

8 *Effective equidistribution and the Sato-Tate law for families of elliptic curves* (with M. Ram Murty), Journal of Number Theory **131** (2011), no. 1, 25–44. http://arxiv.org/abs/1004.2753

9 *Moments of the rank of elliptic curves* (with Siman Wong), Canad. J. of Math. **64** (2012), no. 1, 151–182. http://web.williams.edu/Mathematics/sjmiller/public_html/math/papers/mwMomentsRanksEC81

Publications: *L*-Function Ratio Conjecture

1. *A symplectic test of the L-Functions Ratios Conjecture*, Int Math Res Notices (2008) Vol. 2008, article ID rnm146, 36 pages, doi:10.1093/imrn/rnm146. `http://arxiv.org/abs/0704.0927`

2. *An orthogonal test of the L-Functions Ratios Conjecture*, Proceedings of the London Mathematical Society 2009, doi:10.1112/plms/pdp009. `http://arxiv.org/abs/0805.4208`

3. *A unitary test of the L-functions Ratios Conjecture* (with John Goes, Steven Jackson, David Montague, Kesinee Ninsuwan, Ryan Peckner and Thuy Pham), Journal of Number Theory **130** (2010), no. 10, 2238–2258. `http://arxiv.org/abs/0909.4916`

4. *An Orthogonal Test of the L-functions Ratios Conjecture, II* (with David Montague), Acta Arith. **146** (2011), 53–90. `http://arxiv.org/abs/0911.1830`

5. *An elliptic curve family test of the Ratios Conjecture* (with Duc Khiem Huynh and Ralph Morrison), Journal of Number Theory **131** (2011), 1117–1147. `http://arxiv.org/abs/1011.3298`

6. *Surpassing the Ratios Conjecture in the 1-level density of Dirichlet L-functions* (with Daniel Fiorilli). submitted September 2012 to Proceedings of the London Mathematical Society. `http://arxiv.org/abs/1111.3896`