

Determinantal point processes

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CHAPTER 1

Discrete determinantal point processes

Determinantal point processes are examples of simple point processes, meaning that different particles cannot occupy the same location, for which the correlation functions take a determinantal form. If the underlying space is continuous, a rigorous definition requires some effort. However, simple point processes on discrete spaces are easier to define and we choose to do this before we come to the general situation in the next chapter.

1. Discrete point processes

In this chapter we will always consider point processes on a countable set \mathbb{X} . Such point processes can be constructed by considering the power set $2^{\mathbb{X}}$.

If \mathbb{X} is finite, then so is $2^{\mathbb{X}}$.

If \mathbb{X} is countably infinite, then we assume that \mathbb{X} is a complete metric space with no accumulation points (that is, every bounded subset of \mathbb{X} has finitely many points). We then equip $2^{\mathbb{X}}$ with the topology generated by the sets

$$\{X \in 2^{\mathbb{X}} \mid B \subset X\}$$

for bounded sets B .¹

DEFINITION 1. *A simple point process on a discrete \mathbb{X} is a (Borel) probability measure on $2^{\mathbb{X}}$.*

1.1. Finite dimensional distributions. An important notion to study point processes is that of counting statistics and finite dimensional distributions.

DEFINITION 2. *Let $A \subset \mathbb{X}$. For a point process on \mathbb{X} with random configuration $X \subset \mathbb{X}$, the counting statistic $N(A)$ on a set A is defined as*

$$N(A) = \sum_{x \in X} \chi_A(x),$$

where $\chi_A(x) = 1$ if $x \in A$ and $\chi_A(x) = 0$ otherwise.

DEFINITION 3. *For $m \in \mathbb{N}_0$, bounded sets $A_1, \dots, A_m \subset \mathbb{X}$ and $k_1, \dots, k_m \in \mathbb{N}_0$ we define the finite dimensional distribution as*

$$P_m(A_1, \dots, A_m; k_1, \dots, k_m) = \mathbb{P}(N(A_1) = k_1, \dots, N(A_m) = k_m).$$

The first important result is the following standard theorem.

¹Equivalently, this is the smallest topology such that $A_n \rightarrow A$ if and only if for every bounded set B we have $A_n \cap B = A \cap B$ for sufficiently large n . If $\mathbb{X} = \mathbb{N}$ then $f : 2^{\mathbb{N}} \rightarrow [0, 1]$ defined by $f(A) = \sum_{x \in A} 2^{-x}$ is a bijection and the topology on $2^{\mathbb{N}}$ is the pullback of the standard topology on $[0, 1]$.

THEOREM 4. *A point process is uniquely determined by its finite dimensional distributions.*

PROOF. See [2]. □

A natural question is to ask when a given collection of distributions $P_m(A_1, \dots, A_m; k_1, \dots, k_m)$ are the finite dimensional distributions for a point process. This question has been studied in the literature and we mention the following characterization due to Kolmogorov.

THEOREM 5. *Let $P_m(A_1, \dots, A_m; k_1, \dots, k_m)$ for $m \in \mathbb{N}_0$, bounded sets A_1, \dots, A_m and $k_1, \dots, k_m \in \mathbb{N}_0$, be a collection of probability distributions. In order for them to be the finite dimensional distributions of a point process it is necessary and sufficient that the following properties hold:*

(1) *For any permutation i_1, \dots, i_m of $1, \dots, m$ we have*

$$P_m(A_1, \dots, A_m; k_1, \dots, k_m) = P_m(A_{i_1}, \dots, A_{i_m}; k_{i_1}, \dots, k_{i_m}).$$

(2) *For all m ,*

$$\sum_{r=0}^{\infty} P_{m+1}(A_1, \dots, A_m, A_{m+1}; k_1, \dots, k_m, r) = P_m(A_1, \dots, A_m; k_1, \dots, k_m).$$

(3) *For each disjoint pair of Borel sets A_1 and A_2 , we have*

$$P_3(A_1, A_2, A_1 \cup A_2; n_1, n_2, n_3) = 0 \quad \text{if } n_1 + n_2 \neq n_3.$$

PROOF. See [2, Theorem 9.2.X]. □

Since Theorems 4 and 33 only play a minor role for us and our text is not intended as a thorough treatment of the abstract theory of point processes, we only provide references for these statements.

1.2. Correlation functions. An important role is played by the probability generating function defined as

$$(1) \quad \Phi(g) = \mathbb{E} \left[\prod_{x \in X} (1 + g(x)) \right],$$

where g is a function with bounded support in \mathbb{X} . By taking $g = (z - 1)\chi_A$ for a bounded set A and $|z| \leq 1$ we find

$$\Phi(g) = \mathbb{E}[z^{N(A)}],$$

and, more generally, if $g = \sum_{j=1}^m (z_j - 1)\chi_{A_j}$ for disjoint bounded sets A_j and $|z_j| \leq 1$ we have²

$$\Phi(g) = \mathbb{E} \left[\prod_{j=1}^m z_j^{N(A_j)} \right].$$

Note that this implies that the $\Phi(g)$ determine the finite dimensional distributions uniquely and hence the point process.

²Since \mathbb{X} is discrete, any function g with finite support can be written in the form $g = \sum_{j=1}^k (z_j - 1)\chi_{A_j}$.

The correlation functions can be defined by expanding the product in (1). First we introduce some notation: For any $A \subset \mathbb{X}$ set

$$(2) \quad A^{(m)} = \{(x_1, \dots, x_m) \in A^m \mid \forall j \neq k : x_j \neq x_k\}.$$

Then we have the following theorem.

THEOREM 6. *For any function g with finite support we have*

$$\Phi(g) = 1 + \sum_{m=1}^{\infty} \frac{1}{m!} \sum_{(x_1, \dots, x_m) \in \mathbb{X}^{(m)}} g(x_1) \cdots g(x_m) \rho_m(x_1, \dots, x_m),$$

where

$$\rho_m(x_1, \dots, x_m) = \mathbb{P}(\{x_1, \dots, x_m\} \subset X).$$

For $m \geq 1$, the function ρ_m is called the **m -point correlation function** of the point process.

PROOF. First note that

$$\prod_{x \in \mathbb{X}} (1 + f(x)) = \sum_{m=0}^{\infty} \sum_{S \subset \mathbb{X}: |S|=m} \prod_{x \in S} f(x),$$

for any f with finite support. Also note that the sum is finite since f has finite support and, therefore, the product vanishes if m exceeds the number of points in the support of f . An important step is now to organize the terms in the sum in a different way by introducing an order on the set S by putting the elements in m -tuples. The entries of these m -tuples should all be different.

With the notation (2) we see that

$$\prod_{x \in S} f(x) = \frac{1}{m!} \sum_{(x_1, \dots, x_m) \in S^{(m)}} f(x_1) \cdots f(x_m),$$

where the division by $m!$ is needed to account for all possible orderings of the elements in S . Moreover,

$$\prod_{x \in \mathbb{X}} (1 + f(x)) = \sum_{m=0}^{\infty} \frac{1}{m!} \sum_{(x_1, \dots, x_m) \in \mathbb{X}^{(m)}} f(x_1) \cdots f(x_m).$$

By setting $f(x) = g(x)\chi_X(x)$ we see that

$$\prod_{x \in X} (1 + g(x)) = \prod_{x \in \mathbb{X}} (1 + f(x)),$$

and thus

$$\Phi(g) = \mathbb{E} \left[\prod_{x \in X} (1 + g(x)) \right] = \sum_{m=0}^{\infty} \frac{1}{m!} \sum_{(x_1, \dots, x_m) \in \mathbb{X}^{(m)}} g(x_1) \cdots g(x_m) \mathbb{E}[\chi_{\{x_1, \dots, x_m\} \subset X}].$$

Since $\mathbb{E}[\chi_{\{x_1, \dots, x_m\} \subset X}] = \mathbb{P}(\{x_1, \dots, x_m\} \subset X)$, the statement follows. \square

The fact that the correlation functions are probabilities is special for discrete processes. As we will see later, if \mathbb{X} is not discrete then there is still an analogue of Theorem 6, but the correlation functions are no longer probabilities and are slightly more elaborate to define. We will do this using the notion of factorial moments.³

³The next paragraph can be skipped on first reading.

1.3. Factorial moments. We recall the Pochhammer symbol: for $a \in \mathbb{R}$ and $\ell \in \mathbb{N}$ we set

$$(a)_\ell = a(a-1)\cdots(a-\ell+1).$$

Then, for $m \in \mathbb{N}$, we will construct a measure μ_m on $\mathbb{X}^{(m)}$ as follows. Start with $1 \leq k \leq m$, pairwise disjoint sets $A_1, \dots, A_k \subset \mathbb{X}$ and $\ell_j \in \mathbb{N}$ such that $\ell_1 + \dots + \ell_k = m$. Then we define the **factorial moments** by

$$\mu_m(A_1^{(\ell_1)} \times \dots \times A_k^{(\ell_k)}) = \mathbb{E} \left[\prod_{j=1}^k (N(A_j))_{\ell_j} \right].$$

It can be shown that μ_m has a unique extension to a measure on \mathbb{X}^m , which we will still denote by μ_m .⁴ This measure has a density $\tilde{\rho}_m$ such that

$$\mu_m(A_1^{(\ell_1)} \times \dots \times A_k^{(\ell_k)}) = \sum_{(x_1, \dots, x_m) \in A_1^{(\ell_1)} \times \dots \times A_k^{(\ell_k)}} \tilde{\rho}_m(x_1, \dots, x_m).$$

By taking $A_j = \{x_j\}$ and $\ell_j = 1$ for $j = 1, \dots, m$, we see that $\tilde{\rho}_m = \rho_m$. In other words, the correlation functions are densities for the factorial moments viewed as measures on $\mathbb{X}^{(m)}$.

That the factorial moments are natural objects can be seen from the following expansion:

$$\begin{aligned} (3) \quad \mathbb{E} \left[\prod_{j=1}^k z_j^{N(A_j)} \right] &= \mathbb{E} \left[\prod_{j=1}^k (1 + (z_j - 1))^{N(A_j)} \right] \\ &= \mathbb{E} \left[\prod_{j=1}^k \left(\sum_{\ell_j=0}^{N(A_j)} \frac{(N(A_j))_{\ell_j}}{\ell_j!} (z_j - 1)^{\ell_j} \right) \right] \\ &= \mathbb{E} \left[\prod_{j=1}^k \left(\sum_{\ell_j=0}^{\infty} \frac{(N(A_j))_{\ell_j}}{\ell_j!} (z_j - 1)^{\ell_j} \right) \right] \\ &= \sum_{\ell_1, \dots, \ell_k=0}^{\infty} \frac{\prod_{j=1}^k (z_j - 1)^{\ell_j}}{\ell_1! \cdots \ell_k!} \mathbb{E} \left[\prod_{j=1}^k (N(A_j))_{\ell_j} \right] \\ &= \sum_{m=0}^{\infty} \frac{1}{m!} \sum_{\ell_1+ \dots + \ell_k=m} \binom{m}{\ell_1 \ \ell_2 \ \dots \ \ell_k} \prod_{j=1}^k (z_j - 1)^{\ell_j} \mathbb{E} \left[\prod_{j=1}^k (N(A_j))_{\ell_j} \right]. \end{aligned}$$

We see that $\mathbb{E} \left[\prod_{j=1}^k z_j^{N(A_j)} \right]$ can be viewed as a generating function for the factorial moments.

⁴The collection of sets $A_1^{(\ell_1)} \times \dots \times A_k^{(\ell_k)}$ forms a semi-ring. The extension to a measure is a standard exercise that is worth working out.

In fact, the factorial moments can be used for an alternative derivation of Theorem 6. To this end, let $g = \sum_{j=1}^k (z_j - 1)\chi_{A_j}$. Then

$$\begin{aligned} \prod_{j=1}^k (z_j - 1)^{\ell_j} \mathbb{E} \left[\prod_{j=1}^k (N(A_j))_{\ell_j} \right] \\ = \sum_{(x_1, \dots, x_m) \in A_1^{(\ell_1)} \times \dots \times A_k^{(\ell_k)}} \prod_{r=1}^m g(x_r) \rho_m(x_1, \dots, x_m). \end{aligned}$$

Now since $\prod_{r=1}^m g(x_r) \rho_m(x_1, \dots, x_m)$ is symmetric we have

$$\begin{aligned} \sum_{\ell_1 + \dots + \ell_k = m} \binom{m}{\ell_1 \ \ell_2 \ \dots \ \ell_k} \sum_{(x_1, \dots, x_m) \in A_1^{(\ell_1)} \times \dots \times A_k^{(\ell_k)}} \prod_{r=1}^m g(x_r) \rho_m(x_1, \dots, x_m) \\ = \sum_{(x_1, \dots, x_m) \in \mathbb{X}^{(m)}} \prod_{r=1}^m g(x_r) \rho_m(x_1, \dots, x_m). \end{aligned}$$

By inserting this into (9) we find

$$\begin{aligned} \mathbb{E} \left[\prod_{x \in X} (1 + g(x)) \right] &= \mathbb{E} \left[\prod_{j=1}^k z_j^{N(A_j)} \right] \\ &= \sum_{m=0}^{\infty} \frac{1}{m!} \sum_{(x_1, \dots, x_m) \in \mathbb{X}^{(m)}} \prod_{r=1}^m g(x_r) \rho_m(x_1, \dots, x_m), \end{aligned}$$

for $g = \sum_{j=1}^k (z_j - 1)\chi_{A_j}$ and, since \mathbb{X} is discrete, therefore for any function g with finite support. We thus arrive at the conclusion of Theorem 6. We will use this alternative derivation when introducing correlation functions for continuous point processes.

2. Discrete determinantal point processes

DEFINITION 7. *A determinantal point process on a discrete set \mathbb{X} is a simple point process on \mathbb{X} such that there exists a function $K : \mathbb{X} \times \mathbb{X} \rightarrow \mathbb{C}$ such that⁵*

$$(4) \quad \mathbb{P}(\{x_1, \dots, x_k\} \subset X) = \det(K(x_i, x_j))_{i,j=1}^k$$

for $k \in \mathbb{N}$ and distinct points $x_1, \dots, x_k \in \mathbb{X}$. The function K is called a **correlation kernel** for the process.

Before we continue we emphasize that the correlation kernel is not unique. Indeed, if K is a correlation kernel for a determinantal point process on a discrete space \mathbb{X} and $G : \mathbb{X} \rightarrow \mathbb{C} \setminus \{0\}$ is a nowhere vanishing function, then⁶

$$K_G(x_1, x_2) = \frac{G(x_1)}{G(x_2)} K(x_1, x_2), \quad x_1, x_2 \in \mathbb{X},$$

⁵The right-hand side is symmetric in x_1, \dots, x_k .

⁶This conjugation of the kernel is the easiest way to see that the kernel is not unique. It is far less clear if this conjugation is the only freedom that exists. This, in fact, is an open problem.

is also a correlation kernel for the same determinantal point process.

From the definition we have the special cases

$$\mathbb{P}(x \in X) = K(x, x)$$

and also, for $x \neq y$,

$$\mathbb{P}(x \in X, y \in X) = K(x, x)K(y, y) - K(x, y)K(y, x),$$

which means⁷

$$(5) \quad \mathbb{P}(x \in X, y \in X) - \mathbb{P}(x \in X)\mathbb{P}(y \in X) = -K(x, y)K(y, x).$$

We thus see that $K(x, y)K(y, x)$ measures how strongly the two events $x \in X$ and $y \in X$ are correlated.

A natural statistic for point processes is the number of points in a given set.

PROPOSITION 8. *Let K be a correlation kernel for a determinantal point process on a discrete space \mathbb{X} . Let $A \subset \mathbb{X}$ be bounded. Then*

$$(1) \quad \mathbb{E}[N(A)] = \sum_{x \in A} K(x, x),$$

$$(2) \quad \text{Var}[N(A)] = \sum_{x \in A} K(x, x) - \sum_{x \in A} \sum_{y \in A} K(x, y)K(y, x).$$

PROOF. 1. The expectation is straightforward:

$$\mathbb{E}[N(A)] = \sum_{x \in A} \mathbb{P}(x \in X) = \sum_{x \in A} K(x, x).$$

2. This is the result of a computation.

$$\begin{aligned} \mathbb{E}\left[\sum_{x \in A} \sum_{y \in A} \chi_X(x)\chi_X(y)\right] &= \sum_{x \in A} \sum_{y \in A, y \neq x} \mathbb{E}[\chi_X(x)\chi_X(y)] + \sum_{x \in A} \mathbb{E}[\chi_X(x)] \\ &= \sum_{x \in A} \sum_{y \in A, y \neq x} \det \begin{pmatrix} K(x, x) & K(x, y) \\ K(y, x) & K(y, y) \end{pmatrix} + \sum_{x \in A} K(x, x) \\ &= \sum_{x \in A} \sum_{y \in A} \det \begin{pmatrix} K(x, x) & K(x, y) \\ K(y, x) & K(y, y) \end{pmatrix} + \sum_{x \in A} K(x, x) \\ &= \sum_{x \in A} \sum_{y \in A} (K(x, x)K(y, y) - K(x, y)K(y, x)) + \sum_{x \in A} K(x, x) \\ &= \sum_{x \in A} K(x, x) - \sum_{x \in A} \sum_{y \in A} K(x, y)K(y, x) + \left(\sum_{x \in A} K(x, x)\right)^2. \end{aligned}$$

By subtracting $(\mathbb{E}[N(A)])^2 = (\sum_{x \in A} K(x, x))^2$ the statement follows. \square

It should be clear now that the computation in the proof can be extended to the higher moments of $N(A)$ and even to joint moments of $N(A_j)$. It follows then from Theorem 4 that the process is completely determined by a correlation kernel K . The results are rather complicated expressions. However, the Laplace transforms

⁷As we will see, in many interesting cases we have $K(y, x) = \overline{K(x, y)}$. If so, then the right-hand side of (5) is negative and thus such determinantal point processes are negatively correlated. Moreover, $K(x, y)$ can be solved from (5) up to a phase factor. However, requiring $K(y, x) = \overline{K(x, y)}$ would be too restrictive, since many interesting point processes that arise in modern research do not obey this symmetry.

will have a very elegant expression. Indeed, the $\Phi(g)$ can be expressed in terms of determinants involving the correlation kernel K :

THEOREM 9. *Let K be the correlation kernel for a determinantal point process on a discrete space \mathbb{X} . For any $g : \mathbb{X} \rightarrow \mathbb{C}$ with finite support S , we have⁸*

$$\begin{aligned}
 (6) \quad & \mathbb{E} \left[\prod_{x \in X} (1 + g(x)) \right] \\
 &= 1 + \sum_{k=1}^{\infty} \frac{1}{k!} \sum_{x_1, \dots, x_k \in \mathbb{X}} g(x_1) \cdots g(x_k) \det(K(x_i, x_j))_{i,j=1}^k \\
 &= \det(I + gK),
 \end{aligned}$$

where $\det(I + gK)$ is the determinant of the $|S| \times |S|$ matrix $(\delta_{x,y} + g(x)K(x,y))_{x,y \in S}$.⁹

PROOF. The first equality is a straightforward consequence of (4), Theorem 6 and the fact that the determinant vanishes whenever $x_i = x_j$ for $i \neq j$.

The fact that we can write this series as a determinant follows from the following standard identity for matrices:

$$\det(I + A) = 1 + \sum_{k=1}^n \frac{1}{k!} \sum_{i_1, \dots, i_k \in \{1, \dots, n\}} \det(A_{i_j, i_\ell})_{j, \ell=1}^k$$

for any $n \times n$ matrix A . □

COROLLARY 10 (Gap probabilities). *Let K be the correlation kernel for a determinantal point process on a discrete space \mathbb{X} . Then*

$$\mathbb{P}(\{y_1, \dots, y_k\} \cap X = \emptyset) = \det(\delta_{j\ell} - K(y_j, y_\ell))_{j, \ell=1}^k$$

for any $k \in \mathbb{N}$ and distinct points $y_1, \dots, y_k \in \mathbb{X}$.

PROOF. Define the function $g(x) = -1$ if $x \in \{y_1, \dots, y_k\}$ and $g(x) = 0$ otherwise. Then

$$\prod_{x \in X} (1 + g(x)) = \begin{cases} 1, & \text{if } \{y_1, \dots, y_k\} \cap X = \emptyset, \\ 0, & \text{if } \{y_1, \dots, y_k\} \cap X \neq \emptyset. \end{cases}$$

And thus,

$$\mathbb{E} \left[\prod_{x \in X} (1 + g(x)) \right] = \mathbb{P}(\{y_1, \dots, y_k\} \cap X = \emptyset).$$

The statement then follows from Theorem 9. □

There is an interesting consequence to this result.

COROLLARY 11 (Particle-hole duality). ¹⁰ *Consider a determinantal point process on \mathbb{X} that has K as a correlation kernel. We say that there is a particle at x if there is a point at x . If there is no point, we say that there is a hole at x . The holes also define a determinantal point process with kernel $I - K$.*

⁸Note that the determinant in the summand vanishes if $x_i = x_j$ for $i \neq j$ and hence we can drop the condition that the points need to be distinct.

⁹The infinite series is in fact only a sum with at most $|S|$ terms.

¹⁰Whereas the theorems and propositions here all have generalizations to continuous determinantal point processes, this particle-hole duality only makes sense for *discrete* point processes.

Finally, we mention the following result on the finite dimensional distribution of a determinantal point process.

THEOREM 12. *For bounded A_j and non-negative integers n_j we have*

$$P_k(A_1, \dots, A_k; n_1, \dots, n_k) = \frac{1}{(2\pi i)^k} \oint \cdots \oint \det \left(I + (z_1^{X_{A_1}} \cdots z_k^{X_{A_k}} - 1) K \chi_{\cup_{j=1}^k A_j} \right) \frac{dz_1 \cdots dz_k}{z_1^{n_1+1} \cdots z_k^{n_k+1}}.$$

3. Determinants of (infinite) matrices

We will also sometimes need to use the expression (6), but for functions g with unbounded support. An example is the distribution of the largest point in a point process on \mathbb{Z} , which can be represented as a gap probability for an infinite set.

If g has unbounded support, the matrix gK is infinite and we have to be careful when dealing with (6). To this end, we will recall some theory about traces and determinants of infinite matrices.

Let R be a $\mathbb{X} \times \mathbb{X}$ matrix. We define the norm of R by

$$\|R\|_F = \max \left(\sum_{x \in \mathbb{X}} |R(x, x)|, \left(\sum_{x, y \in \mathbb{X}} |R(x, y)|^2 \right)^{\frac{1}{2}} \right).$$

Following [1]¹¹ we call the space

$$\mathcal{D} = \{R \mid \|R\|_F < \infty\}$$

the von Koch–Riesz algebra. This is a Banach algebra of infinite matrices that act as operators on $\ell_2(\mathbb{X})$. The finite rank operators are dense in this algebra.

DEFINITION 13. *For $R \in \mathcal{D}$ we define the **trace** $\text{Tr}R$ by*

$$\text{Tr}R = \sum_{x \in \mathbb{X}} R(x, x)$$

and the **determinant** of $I + R$ by

$$(7) \quad \det(I + R) = 1 + \sum_{k=1}^{\infty} \frac{1}{k!} \sum_{x_1, \dots, x_k \in \mathbb{X}} \det(R(x_i, x_j))_{i,j=1}^k.$$

At this point, it is not clear that the determinant is well defined.

LEMMA 14. *Both $R \mapsto \text{Tr}R$ and $R \mapsto \det(I + R)$ are well-defined. The map $R \mapsto \text{Tr}R$ is Lipschitz continuous and $R \mapsto \det(I + R)$ is locally Lipschitz continuous with respect to $\|\cdot\|_F$.*

PROOF. The proof can be found in [1, Theorem II.7.1]. □

LEMMA 15. *The trace and determinant have the following properties:*

- (1) $\text{Tr}(R_1 + R_2) = \text{Tr}R_1 + \text{Tr}R_2$,
- (2) $\det(I + R_1 + R_2 + R_1 R_2) = \det(I + R_1) \det(I + R_2)$,
- (3) $\det(I + R_1 R_2) = \det(I + R_2 R_1)$.

PROOF. This follows from the fact that the identities are standard for finite matrices and a continuity argument. □

¹¹To be precise, [1] apply this with $\mathbb{X} = \mathbb{Z}$.

THEOREM 16. *Suppose that K is the correlation kernel of a determinantal point process and $g : \mathbb{X} \rightarrow [-1, 0]$ is such that the $\mathbb{X} \times \mathbb{X}$ matrix with entries $g(x)K(x, y)$ is in the von Koch–Riesz algebra, then*

$$\mathbb{E}\left[\prod_{x \in \mathbb{X}}(1 + g(x))\right] = \det(I + gK).$$

PROOF. If \mathbb{X} is finite then this is Theorem 9.

If \mathbb{X} is infinite, then the product $\prod_{x \in \mathbb{X}}(1 + g(x))$ is an infinite product of numbers in $[0, 1]$ and therefore well-defined. Moreover,

$$\prod_{x \in X}(1 + g(x)) = \lim_{r \rightarrow \infty} \prod_{x \in X \cap B_{x_0, r}}(1 + g(x)) = \lim_{r \rightarrow \infty} \prod_{x \in X}(1 + \chi_{B_{x_0, r}}(x)g(x))$$

and the limit is independent of the choice of x_0 . By dominated convergence, we also have

$$\mathbb{E}\left[\prod_{x \in X}(1 + g(x))\right] = \lim_{r \rightarrow \infty} \mathbb{E}\left[\prod_{x \in X}(1 + \chi_{B_{x_0, r}}(x)g(x))\right].$$

Now by Theorem 9 we have

$$\mathbb{E}\left[\prod_{x \in X}(1 + \chi_{B_{x_0, r}}(x)g(x))\right] = \det(I + \chi_{B_{x_0, r}}gK).$$

The statement now follows by taking the limit $r \rightarrow \infty$ and using the continuity of the determinant. \square

It is important to note that K does not have to be in the von Koch–Riesz algebra. The function g can be used to mollify the kernel K . In the result above, it only does this by acting on the first variable.

Often we need to mollify K in both arguments and use a more symmetric version:

$$K_g(x, y) = \text{sgn}(g(x))\sqrt{|g(x)g(y)|}K(x, y).$$

If gK is in the von Koch–Riesz algebra then $\det(I + gK) = \det(I + K_g)$, but it can happen that K_g is in this algebra while gK is not.

THEOREM 17. *Suppose that K is the correlation kernel of a determinantal point process and $g : \mathbb{X} \rightarrow [-1, 0]$ is such that the $\mathbb{X} \times \mathbb{X}$ matrix K_g is in the von Koch–Riesz algebra. Then*

$$\mathbb{E}\left[\prod_{x \in \mathbb{X}}(1 + g(x))\right] = \det(I + K_g).$$

The fact that g takes values in $[-1, 0]$ ensures that the infinite products are well-defined. There are of course other ways of ensuring this.

THEOREM 18. *Theorems 16 and 17 also hold for general $g : \mathbb{X} \rightarrow \mathbb{C}$ under the extra condition $\sum_{x \in \mathbb{X}}|g(x)| < \infty$.*

CHAPTER 2

Examples

We now discuss several examples of determinantal point processes.

1. Self-adjoint kernels

Suppose that K is an $\mathbb{X} \times \mathbb{X}$ matrix that defines a self-adjoint bounded operator on $\ell_2(\mathbb{X})$. When is this operator the correlation kernel for a determinantal point process?

It is clear from (6) that the principal minors of K should be non-negative and thus the matrix needs to be positive semidefinite. By the particle-hole duality, also $I - K$ must be positive semidefinite. We thus need that $0 \leq K \leq I$. In fact, this is also sufficient.

THEOREM 19. *Let K be a self-adjoint bounded operator on $\ell_2(\mathbb{X})$. Then K is a correlation kernel for a determinantal point process if and only if $0 \leq K \leq I$.*

PROOF. As we already discussed that the conditions are necessary, it remains to prove that they are sufficient. Let $0 \leq K \leq I$ and consider the family of functions

$$(8) \quad P_k(A_1, \dots, A_k; n_1, \dots, n_k) = \frac{1}{(2\pi i)^k} \oint \cdots \oint \det(I + (z_1^{\chi_{A_1}} \cdots z_k^{\chi_{A_k}} - 1)K) \frac{dz_1 \cdots dz_k}{z_1^{n_1+1} \cdots z_k^{n_k+1}}.$$

We claim that this is a family of probability functions satisfying the criteria of Theorem 33 and thus these are the finite dimensional distributions of a point process. Once we have proved this claim, it is also straightforward that this point process is determinantal with K as a correlation kernel.

The most elaborate part of the work is to prove that the numbers in (8) are indeed non-negative. To this end, we replace K by $K_t = tK$ for $0 < t < 1$. Then, by continuity,

$$P_k(A_1, \dots, A_k; n_1, \dots, n_k) = \lim_{t \uparrow 1} \frac{1}{(2\pi i)^k} \oint \cdots \oint \det(I + (z_1^{\chi_{A_1}} \cdots z_k^{\chi_{A_k}} - 1)K_t) \frac{dz_1 \cdots dz_k}{z_1^{n_1+1} \cdots z_k^{n_k+1}}.$$

The benefit of working with K_t instead of K is that $I - K_t$ is invertible (if $K < I$, then we can take $t = 1$ and this extra step is unnecessary). Thus

$$\begin{aligned} \det(I + (z_1^{\chi_{A_1}} \cdots z_k^{\chi_{A_k}} - 1)K_t) \\ = \det(I - K_t) \det(I + z_1^{\chi_{A_1}} \cdots z_k^{\chi_{A_k}} K_t (I - K_t)^{-1}). \end{aligned}$$

It is therefore sufficient to prove that (8) with K replaced by K_t is non-negative.

Now $0 \leq \det(I - K_t)$ and also $K_t(I - K_t)^{-1} \geq 0$. By expanding the second determinant on the right-hand side using (7), we see that the coefficients in front of the term $z_1^{n_1} \cdots z_k^{n_k}$ are non-negative, and thus the numbers in (8) are indeed non-negative.

That the expressions in (8) are probability distributions can be easily seen by summing over n_1, \dots, n_k from 0 to ∞ and then invoking the residue theorem from complex analysis k times.

Similar computations (the details are left to the reader) can be used to verify that the conditions of Theorem 33 are satisfied, and this finishes the proof. \square

The latter result directly gives us a wide class of determinantal point processes, and many important examples are of this type. Having a correlation kernel that is a self-adjoint operator also has some important consequences, since properties of self-adjoint operators can be used to prove properties of the determinantal point processes that they generate.

PROPOSITION 20. *Let K be the correlation kernel for a determinantal point process on a discrete space \mathbb{X} . Assume that K is self-adjoint. The probability that the number of points in the random configuration is infinite is either 0 or 1. It is 1 if $\text{Tr}K = \sum_{x \in \mathbb{X}} K(x, x) = +\infty$ and 0 if $\text{Tr}K = \sum_{x \in \mathbb{X}} K(x, x) < \infty$.*

PROOF. If $\mathbb{E}[N(\mathbb{X})] = \text{Tr}K = \sum_{x \in \mathbb{X}} K(x, x) < \infty$ then $\mathbb{P}(N(\mathbb{X}) = +\infty) = 0$.

On the other hand, assume that $\mathbb{E}[N(\mathbb{X})] = \text{Tr}K = \sum_{x \in \mathbb{X}} K(x, x) = +\infty$. First we note that for any self-adjoint operator $0 \leq B \leq I$ we have

$$\det(I - B) \leq e^{-\text{Tr}B}.$$

Then, for any bounded set R and $k \in \mathbb{N}$ we have

$$\mathbb{P}(N(R) = k) \leq 2^k \mathbb{E}[2^{-N(R)}] = 2^k \det(I - \frac{1}{2}K_R) \leq \exp(-\frac{1}{2}\text{Tr}K_R),$$

where K_R is the restriction of K to $R \times R$.

Now, by taking a sequence of bounded sets R_n such that $R_n \uparrow \mathbb{X}$ and $\text{Tr}K_{R_n} \rightarrow +\infty$, we find

$$\mathbb{P}(N(\mathbb{X}) = k) = \lim_{n \rightarrow \infty} \mathbb{P}(N(R_n) = k) = 0.$$

Since this is true for every k , we must have $\mathbb{P}(N(\mathbb{X}) = +\infty) = 1$. \square

2. Self-adjoint projections

Another important class of examples comes from orthogonal projections, that is, kernels K that satisfy $K^* = K$ and $K^2 = K$. Of special interest are the orthogonal projections onto n -dimensional subspaces, i.e., kernels of the form

$$K(x, y) = \sum_{j=1}^n f_j(x) f_j(y),$$

where $\{f_j\}_{j=1}^n$ is a set of orthonormal functions in $\ell_2(\mathbb{X})$.

PROPOSITION 21. *Let K be the correlation kernel for a determinantal point process on a discrete space \mathbb{X} . Assume that K is self-adjoint. Then the following are equivalent:*

- (1) *The number of points in the random configuration equals n with probability 1.*
- (2) *K is a self-adjoint projection onto an n -dimensional subspace.*

PROOF. $1 \Leftarrow 2$. Since $K^2 = K$ we know that $\text{Var}[N(\mathbb{X})] = 0$. Moreover, $\mathbb{E}[N(\mathbb{X})] = \text{Tr}K = n$.

$1 \Rightarrow 2$. Since K is self-adjoint we know by Theorem 19 that $0 \leq K \leq I$ and hence $K^2 \leq K$. Combining this with the assumption $\text{Var}[N(\mathbb{X})] = \text{Tr}(K - K^2) = 0$ we see that $K^2 - K = 0$ and hence K is a projection. That it projects onto an n -dimensional subspace follows again from $\mathbb{E}[N(\mathbb{X})] = \text{Tr}K = n$. \square

3. Translation invariant processes

LEMMA 22. Let $f : \mathbb{T} \rightarrow [0, 1]$ be a measurable function on the unit circle and denote its Fourier coefficients by

$$\hat{f}_k = \frac{1}{2\pi i} \oint f(z) \frac{dz}{z^{k+1}}.$$

Then $K(x, y) = \hat{f}_{x-y}$ for $x, y \in \mathbb{Z}$ defines a determinantal point process on \mathbb{Z} .

The process is **translation invariant**. That is, if g is a function of bounded support and $g_y(x) = g(x - y)$ for $y \in \mathbb{Z}$, then

$$\Phi(g) = \Phi(g_y).$$

EXAMPLE 23. If $f(z) = \rho$ with $0 < \rho < 1$, then the determinantal point process is the (product) Bernoulli point process on \mathbb{Z} with constant intensity ρ . In this case,

$$\det(K(x_i, x_j))_{i,j=1}^n = \prod_{i=1}^n K(x_i, x_i) = \rho^n.$$

EXAMPLE 24. Take $f(z) = \frac{1}{4}(2 + z + 1/z)$.

EXAMPLE 25. Take $f = \chi_A$, the characteristic function of a measurable set A . In this case, the kernel has the additional property that $K^2 = K$ and thus K is a self-adjoint projection.

In the special case $A = \{e^{it} \mid -c \leq t \leq c\}$, we have

$$K(x, y) = \frac{\sin c(x - y)}{\pi(x - y)},$$

and the determinantal point process with this kernel is called the **discrete sine process**.

4. L-ensembles

We start with some notation. Let \mathbb{X} be a discrete space and $(L(x, y))_{x,y \in \mathbb{X}}$ be a $|\mathbb{X}| \times |\mathbb{X}|$ matrix. For any $X \subset \mathbb{X}$ the matrix L_X is defined as the $|X| \times |X|$ matrix

$$L_X = (L(x, y))_{x,y \in X}.$$

We will also use the notation \overline{Y} for the complement of $Y \subset \mathbb{X}$.

DEFINITION 26. Let \mathbb{X} be a discrete space and $(L(x, y))_{x,y \in \mathbb{X}}$ be a $|\mathbb{X}| \times |\mathbb{X}|$ matrix with non-negative principal minors. Then, the L-ensemble corresponding to L is the point process on \mathbb{X} defined by

$$\mathbb{P}(X) = \frac{\det L_X}{\det(I + L)}.$$

THEOREM 27. *Let \mathbb{X} be a discrete space and $(L(x, y))_{x, y \in \mathbb{X}}$ be a $|\mathbb{X}| \times |\mathbb{X}|$ matrix with non-negative principal minors. Then the associated L -ensemble is a determinantal point process with kernel*

$$K = L(I + L)^{-1} = I - (I + L)^{-1}.$$

PROOF. This follows by a computation. Let $Y \subset \mathbb{X}$. Then

$$\begin{aligned} \mathbb{P}(Y \subset X) &= \sum_{X \supset Y} \mathbb{P}(X) = \sum_{X \supset Y} \frac{\det L_X}{\det(I + L)} \\ &= \frac{\det(I_{\bar{Y}} + L)}{\det(I + L)}. \end{aligned}$$

Then we invoke some linear algebra:

$$\begin{aligned} \frac{\det(I_{\bar{Y}} + L)}{\det(I + L)} &= \det((I_{\bar{Y}} + L)(I + L)^{-1}) \\ &= \det(I - I_{\bar{Y}}(I + L)^{-1}) = \det K_Y. \end{aligned}$$

This proves the statement. \square

Not every determinantal point process is an L -ensemble. For instance, in an L -ensemble the number of points is not necessarily fixed.

There is however a modification of L -ensembles that will be useful to us.

Let \mathbb{X} be a discrete space and $\mathbb{S} \subset \mathbb{X}$. Then, given an L -ensemble on \mathbb{X} we can define a point process on \mathbb{S} by requiring the random point-configuration for the L -ensemble to contain $\bar{\mathbb{S}}$.

DEFINITION 28. *The **conditional L -ensemble** is the point process on \mathbb{S} defined by*

$$\mathbb{P}(X) = \frac{\det L_{X \cup \bar{\mathbb{S}}}}{\det(I_{\mathbb{S}} + L)}.$$

THEOREM 29. *The conditional L -ensemble is a determinantal point process with kernel*

$$K = I_{\mathbb{S}} - ((I_{\mathbb{S}} + L)^{-1})_{\mathbb{S}}.$$

CHAPTER 3

Determinantal point processes

1. Random measures

Let E be a complete separable metric space. Denote by $\mathcal{M}(E)$ the space of all non-negative Borel measures on E , and by $\mathcal{M}^\#(E)$ the subset of all measures that are finite on bounded subsets of E . Such measures are called *boundedly finite*.

We equip $\mathcal{M}^\#(E)$ with the topology of vague convergence: $\mu_n \rightarrow \mu$ if and only if

$$\int f \, d\mu_n \rightarrow \int f \, d\mu$$

for all bounded continuous functions f with bounded support. The corresponding Borel σ -algebra is the smallest σ -algebra for which $\mu \mapsto \mu(A)$ is measurable for all bounded Borel sets A . With this topology, $\mathcal{M}^\#(E)$ is itself a complete separable metric space (see [2, Proposition 9.1.IV]).

A *random measure* on E is a random element of $\mathcal{M}^\#(E)$, i.e. a measurable mapping from a probability space into $\mathcal{M}^\#(E)$.

There are various ways to characterize random measures. Any random measure μ gives rise to a family of real-valued random variables, indexed by $A \in \mathcal{B}(E)$, via

$$\mu(A) : \Omega \rightarrow [0, \infty).$$

The distribution function of $\mu(A)$ is

$$F(A; x) = \mathbb{P}(\mu(A) \leq x), \quad x \in [0, \infty).$$

In fact, the law of μ is completely determined by the joint distributions

$$F(A_1, \dots, A_k; x_1, \dots, x_k) = \mathbb{P}(\mu(A_1) \leq x_1, \dots, \mu(A_k) \leq x_k),$$

where $k \in \mathbb{N}$ and A_1, \dots, A_k are disjoint sets taken from any semi-ring of bounded sets that generates the Borel σ -algebra.

Another important characterization uses linear functionals. For any Borel function $f : E \rightarrow \mathbb{R}$ with bounded support, the integral

$$\int f(x) \, d\mu(x)$$

is finite almost surely. For such f we consider the characteristic functional

$$\mathcal{L}_f = \mathbb{E} \left[\exp \left(i \int f(x) \, d\mu(x) \right) \right].$$

Since μ is boundedly finite, these expectations are well-defined for all bounded f with bounded support. By taking f of the form $f = \sum_{j=1}^k t_j \chi_{A_j}$, where $t_j \in \mathbb{R}$ and the sets A_j are disjoint and bounded, we see that the collection of all \mathcal{L}_f (over such f) determines the distribution of the random measure.

2. Point processes

Let $\mathcal{N}^\#(E)$ be the subset of $\mathcal{M}^\#(E)$ consisting of those measures ν such that

$$\nu(\{x\}) \in \{0, 1\} \quad \text{for all } x \in E.$$

Thus $\nu \in \mathcal{N}^\#(E)$ if and only if there exists a discrete subset $X \subset E$ such that

$$\nu = \sum_{x \in X} \delta_x.$$

Since ν is boundedly finite, we have $|X \cap A| < \infty$ for any bounded Borel set A , and therefore X has no accumulation points in E .

For such a measure $\nu = \sum_{x \in X} \delta_x$ and any function f with bounded support, we have

$$\int f(x) d\nu(x) = \sum_{x \in X \cap \text{supp}(f)} f(x),$$

and the sum on the right-hand side has only finitely many terms.

DEFINITION 30. *A simple point process on E is a probability measure on $\mathcal{M}^\#(E)$ such that*

$$\mathbb{P}(\nu \in \mathcal{N}^\#(E)) = 1.$$

Equivalently, it is a random element of $\mathcal{N}^\#(E)$.

DEFINITION 31. *For a simple point process $\nu = \sum_{x \in X} \delta_x$ and a Borel set $A \subset E$, the counting statistic $N(A)$ is defined by*

$$N(A) = \nu(A) = |X \cap A|.$$

Note that $N(A)$ is almost surely finite for bounded A , but it can take any value in \mathbb{N}_0 , and there is no a priori bound.

PROPOSITION 32. *A point process is completely determined by its finite-dimensional distributions*

$$P_m(A_1, \dots, A_m; n_1, \dots, n_m) = \mathbb{P}(N(A_j) = n_j, j = 1, \dots, m),$$

for $m \in \mathbb{N}$, $n_1, \dots, n_m \in \mathbb{N}_0$, and bounded sets A_1, \dots, A_m .

PROOF. See [2]. □

THEOREM 33 (Kolmogorov-type consistency). *Let*

$$P_m(A_1, \dots, A_m; n_1, \dots, n_m),$$

for $m \in \mathbb{N}_0$, bounded sets A_1, \dots, A_m , and $n_1, \dots, n_m \in \mathbb{N}_0$, be a collection of probability distributions. These are the finite-dimensional distributions of a point process if and only if the following properties hold:

(1) **Symmetry:** For every permutation (i_1, \dots, i_m) of $\{1, \dots, m\}$,

$$P_m(A_1, \dots, A_m; n_1, \dots, n_m) = P_m(A_{i_1}, \dots, A_{i_m}; n_{i_1}, \dots, n_{i_m}).$$

(2) **Consistency:** For all $m \geq 0$ and bounded A_1, \dots, A_{m+1} ,

$$\sum_{r=0}^{\infty} P_{m+1}(A_1, \dots, A_m, A_{m+1}; n_1, \dots, n_m, r) = P_m(A_1, \dots, A_m; n_1, \dots, n_m).$$

(3) **Additivity:** For each pair of disjoint Borel sets A_1 and A_2 ,

$$P_3(A_1, A_2, A_1 \cup A_2; n_1, n_2, n_3) = 0 \quad \text{whenever } n_1 + n_2 \neq n_3.$$

(4) **Continuity from above:** For $n \in \mathbb{N}$ and any sequence of bounded sets A_N such that $A_N \downarrow \emptyset$,

$$\lim_{N \rightarrow \infty} P_1(A_N; 0) = 1.$$

PROOF. See [2, Theorem 9.2.X]. ¹ \square

3. Factorial moments and correlation functions

We recall the Pochhammer symbol: for $a \in \mathbb{R}$ and $\ell \in \mathbb{N}$,

$$(a)_\ell = a(a-1) \cdots (a-\ell+1).$$

For $m \in \mathbb{N}$, we will construct a measure μ_m on E^m as follows. Let $1 \leq k \leq m$, let $A_1, \dots, A_k \subset E$ be pairwise disjoint bounded Borel sets, and let $\ell_1, \dots, \ell_k \in \mathbb{N}$ satisfy

$$\ell_1 + \dots + \ell_k = m.$$

We set

$$A_j^{(\ell_j)} = \{(x_1^{(j)}, \dots, x_{\ell_j}^{(j)}) \in A_j^{\ell_j} : x_p^{(j)} \neq x_q^{(j)} \text{ for } p \neq q\}.$$

Then we define the *factorial moments* by

$$\mu_m(A_1^{(\ell_1)} \times \dots \times A_k^{(\ell_k)}) = \mathbb{E} \left[\prod_{j=1}^k (N(A_j))_{\ell_j} \right].$$

It can be shown that μ_m has a unique extension to a measure on E^m . ²

The factorial moments arise naturally from the following expansion. Let A_1, \dots, A_k be bounded Borel sets and $z_1, \dots, z_k \in \mathbb{C}$. Then

$$\begin{aligned} (9) \quad \mathbb{E} \left[\prod_{j=1}^k z_j^{N(A_j)} \right] &= \mathbb{E} \left[\prod_{j=1}^k (1 + (z_j - 1))^{N(A_j)} \right] \\ &= \mathbb{E} \left[\prod_{j=1}^k \left(\sum_{\ell_j=0}^{\infty} \frac{(N(A_j))_{\ell_j}}{\ell_j!} (z_j - 1)^{\ell_j} \right) \right] \\ &= \mathbb{E} \left[\prod_{j=1}^k \left(\sum_{\ell_j=0}^{\infty} \frac{(N(A_j))_{\ell_j}}{\ell_j!} (z_j - 1)^{\ell_j} \right) \right] \\ &\stackrel{*}{=} \sum_{\ell_1, \dots, \ell_k=0}^{\infty} \frac{\prod_{j=1}^k (z_j - 1)^{\ell_j}}{\ell_1! \cdots \ell_k!} \mathbb{E} \left[\prod_{j=1}^k (N(A_j))_{\ell_j} \right] \\ &= \sum_{m=0}^{\infty} \frac{1}{m!} \sum_{\ell_1+...+\ell_k=m} \binom{m}{\ell_1 \ \ell_2 \ \dots \ \ell_k} \left(\prod_{j=1}^k (z_j - 1)^{\ell_j} \right) \mathbb{E} \left[\prod_{j=1}^k (N(A_j))_{\ell_j} \right]. \end{aligned}$$

Thus $\mathbb{E} \left[\prod_{j=1}^k z_j^{N(A_j)} \right]$ can be viewed as a generating function for the factorial moments.

¹In the discrete case, one of the conditions is redundant; here we state the general version.

²The collection of sets $A_1^{(\ell_1)} \times \dots \times A_k^{(\ell_k)}$ forms a semi-ring. The extension to a measure is a standard exercise that is worth working out.

The step indicated by $\stackrel{*}{=}$ requires justification, since we interchange an infinite sum and an expectation. For this we need an extra assumption.

LEMMA 34. *Assume that, for every bounded $A \subset E$, we have*

$$\frac{\mu_{m+1}(A^{(m+1)})}{m \mu_m(A^{(m)})} \rightarrow 0 \quad \text{as } m \rightarrow \infty,$$

where $A^{(m)}$ denotes the subset of A^m of m -tuples of distinct points. Then, for bounded A_1, \dots, A_k and $z_1, \dots, z_k \in \mathbb{C}$, the expectation

$$\mathbb{E} \left[\prod_{j=1}^k z_j^{N(A_j)} \right]$$

is well-defined and finite, and

$$\begin{aligned} \mathbb{E} \left[\prod_{j=1}^k z_j^{N(A_j)} \right] &= \sum_{m=0}^{\infty} \frac{1}{m!} \sum_{\ell_1+\dots+\ell_k=m} \binom{m}{\ell_1 \ \ell_2 \ \dots \ \ell_k} \left(\prod_{j=1}^k (z_j - 1)^{\ell_j} \right) \\ &\quad \times \mu_m(A_1^{(\ell_1)} \times \dots \times A_k^{(\ell_k)}). \end{aligned}$$

The series converges uniformly for (z_1, \dots, z_k) in compact subsets of \mathbb{C}^k .

DEFINITION 35. *We say that a point process has m -point correlation functions (with respect to a reference measure μ_0) if there exists a measure μ_0 on E and symmetric functions $\rho_m : E^m \rightarrow [0, \infty)$, $m = 1, 2, \dots$, such that*

$$d\mu_m(x_1, \dots, x_m) = \rho_m(x_1, \dots, x_m) d\mu_0(x_1) \cdots d\mu_0(x_m), \quad m = 1, 2, \dots.$$

In this case, the functions ρ_m are called the m -point correlation functions of the point process, with respect to the reference measure μ_0 .

In the discrete case, the correlation functions ρ_m are probabilities (see the previous chapter). If E is not discrete, this is no longer true, but the ρ_m still have a natural probabilistic interpretation.

PROPOSITION 36. *If the m -point correlation functions exist, then for distinct points $x_1, \dots, x_m \in E$,*

$$\rho_m(x_1, \dots, x_m) = \lim_{\Delta \downarrow 0} \frac{\mathbb{P}(\text{each neighbourhood } [x_j, x_j + \Delta] \text{ contains at least one point})}{\prod_{j=1}^m \mu_0([x_j, x_j + \Delta])},$$

whenever the limit exists and the intervals are chosen in a suitable local coordinate system.

PROOF. Here comes a proof. □

THEOREM 37. *Suppose that the m -point correlation functions exist with μ_0 as a boundedly finite reference measure, and that, for every bounded $A \subset E$,*

$$(10) \quad \frac{\mu_{m+1}(A^{(m+1)})}{m \mu_m(A^{(m)})} \rightarrow 0 \quad \text{as } m \rightarrow \infty.$$

Then for any bounded function $g : E \rightarrow \mathbb{C}$ with bounded support, we have

$$\mathbb{E} \left[\prod_{x \in X} (1 + g(x)) \right] = \sum_{m=0}^{\infty} \frac{1}{m!} \int_{E^m} \prod_{j=1}^m g(x_j) \rho_m(x_1, \dots, x_m) d\mu_0(x_1) \cdots d\mu_0(x_m).$$

The series converges absolutely and locally uniformly in g .

PROOF. It suffices (why?) to prove the statement for functions of the form

$$g = \sum_{j=1}^k (z_j - 1) \chi_{A_j}$$

with bounded disjoint sets A_1, \dots, A_k and complex numbers z_1, \dots, z_k . Then

$$\begin{aligned} & \left(\prod_{j=1}^k (z_j - 1)^{\ell_j} \right) \mathbb{E} \left[\prod_{j=1}^k (N(A_j))_{\ell_j} \right] \\ &= \int_{A_1^{(\ell_1)} \times \dots \times A_k^{(\ell_k)}} \prod_{j=1}^m (z_{c(j)} - 1) \rho_m(x_1, \dots, x_m) d\mu_0(x_1) \dots d\mu_0(x_m), \end{aligned}$$

where $c(j)$ indicates to which block $A_{c(j)}$ the variable x_j belongs. Since $g(x) = z_j - 1$ for $x \in A_j$, this becomes

$$\int_{A_1^{(\ell_1)} \times \dots \times A_k^{(\ell_k)}} \prod_{j=1}^m g(x_j) \rho_m(x_1, \dots, x_m) d\mu_0(x_1) \dots d\mu_0(x_m).$$

Now the integrand $\prod_{j=1}^m g(x_j) \rho_m(x_1, \dots, x_m)$ is symmetric in (x_1, \dots, x_m) , so

$$\begin{aligned} & \sum_{\ell_1 + \dots + \ell_k = m} \begin{pmatrix} m & & & \\ \ell_1 & \ell_2 & \dots & \ell_k \end{pmatrix} \int_{A_1^{(\ell_1)} \times \dots \times A_k^{(\ell_k)}} \prod_{j=1}^m g(x_j) \rho_m(x_1, \dots, x_m) d\mu_0^m \\ &= \int_{E^{(m)}} \prod_{j=1}^m g(x_j) \rho_m(x_1, \dots, x_m) d\mu_0^m, \end{aligned}$$

where $E^{(m)}$ denotes the set of m -tuples of distinct points in E . Inserting this into (9) yields the desired expansion for such g , and by approximation for all bounded g with bounded support. \square

4. Determinantal point processes

DEFINITION 38. A determinantal point process is a simple point process for which the m -point correlation functions exist for all $m \geq 1$ and are given by

$$\rho_m(x_1, \dots, x_m) = \det(K(x_i, x_j))_{i,j=1}^m, \quad m = 1, 2, \dots,$$

for some function $K : E \times E \rightarrow \mathbb{C}$. We call K a correlation kernel for the determinantal point process.

If K is a correlation kernel for a determinantal point process, then it is clear from the definition that all information about the process is encoded in K . However, the correlation kernel is not unique. Indeed, for any nowhere vanishing function $G : E \rightarrow \mathbb{C} \setminus \{0\}$,

$$\tilde{K}(x, y) = K(x, y) \frac{G(x)}{G(y)}$$

is also a correlation kernel for the same determinantal point process.

To express the quantity

$$\Phi(g) = \mathbb{E} \left[\prod_{x \in X} (1 + g(x)) \right]$$

in terms of a determinant, we need additional assumptions on K . These assumptions will be imposed on the restrictions

$$K_A(x, y) = \chi_A(x) K(x, y) \chi_A(y), \quad x, y \in E,$$

for bounded sets $A \subset E$.

ASSUMPTION 1. *The simplest (but strong) assumption is that K is continuous on $E \times E$ when E is not discrete. In that case, many technical subtleties disappear, and most examples of interest to us satisfy this condition. For a fully general theory of determinantal point processes, however, this assumption is too restrictive.*

ASSUMPTION 2. *A common assumption in the literature is that K defines a locally trace class operator. That is, for each bounded $A \subset E$, the operator \mathcal{K}_A on $L_2(A, \mu_0)$,*

$$\mathcal{K}_A f(x) = \int_A K(x, y) f(y) d\mu_0(y)$$

is trace class. This allows one to use the well-developed theory of trace class operators and their determinants and traces. The drawback is that, if the diagonal $\{(x, x) : x \in E\}$ has μ_0 -measure zero in $E \times E$, then the operator is insensitive to the values of K on the diagonal, while for point processes the diagonal values $K(x, x)$ encode the local intensities and are therefore very important. Although there are ways to handle this issue, we find that the purely operator-theoretic approach becomes unnecessarily complicated for our purposes.

ASSUMPTION 3. *We now introduce a more flexible assumption.*

For a measurable function $R : E \times E \rightarrow \mathbb{C}$, define

$$\|R\|_S = \max \left(\left(\iint_{E \times E} |R(x, y)|^2 d\mu_0(x) d\mu_0(y) \right)^{1/2}, \int_E |R(x, x)| d\mu_0(x) \right).$$

Strictly speaking, to make this into a norm we pass to equivalence classes: declare $R_1 \equiv R_2$ if

$$R_1(x, y) = R_2(x, y) \quad \text{for } \mu_0 \times \mu_0\text{-a.e. } (x, y)$$

and

$$R_1(x, x) = R_2(x, x) \quad \text{for } \mu_0\text{-a.e. } x.$$

The space of equivalence classes with finite $\|\cdot\|_S$ is a normed vector space, which we denote by \mathcal{B} . It is a Banach space; in fact it is naturally isomorphic to a subspace of $L_2(E \times E, \mu_0 \otimes \mu_0) \oplus L_1(E, \mu_0)$.

Our assumption on the correlation kernel is that $\|K_A\|_S < \infty$ for each bounded $A \subset E$.

REMARK 39. *A function R with $\|R\|_S < \infty$ need not define a trace class operator. There exist continuous kernels K for which the associated integral operator is not trace class. We refer to the appendix for further discussion. From the viewpoint of determinantal point processes, this is not a defect: the diagonal values $K(x, x)$ are crucial and should be part of the data.*

In what follows we will mostly work under the first assumption, namely that the correlation kernel K is continuous.

THEOREM 40. *Let X be a determinantal point process with continuous correlation kernel K and reference measure μ_0 . Then, for any bounded function $g : E \rightarrow \mathbb{C}$ with bounded support,*

$$\mathbb{E} \left[\prod_{x \in X} (1 + g(x)) \right] = \sum_{m=0}^{\infty} \frac{1}{m!} \int_{E^m} \prod_{j=1}^m g(x_j) \det(K(x_i, x_j))_{i,j=1}^m d\mu_0(x_1) \cdots d\mu_0(x_m),$$

and the series converges absolutely.

PROOF. We only need to verify the assumption (10) from Theorem 37. This can be done using Hadamard's inequality for determinants:

$$|\det(K(x_i, x_j))_{i,j=1}^m| \leq \prod_{i=1}^m \left(\sum_{j=1}^m |K(x_i, x_j)|^2 \right)^{1/2}.$$

Using this inequality and the boundedness of K on bounded sets, one shows that

$$\begin{aligned} \mu_m(A^{(m)}) &= \int_{A^m} \det(K(x_i, x_j))_{i,j=1}^m d\mu_0(x_1) \cdots d\mu_0(x_m) \\ &\leq m^{m/2} \|K_A\|_{\Phi}^m (\mu_0(A))^{m/2}, \end{aligned}$$

where $\|\cdot\|_{\Phi}$ is the uniform norm used in the Fredholm theory (see the appendix). From this bound one checks that (10) holds, and the theorem follows from Theorem 37. \square

Under the continuity assumption, the right-hand side is precisely the Fredholm determinant of the integral operator with kernel $g(x)K(x, y)$, acting on $L_2(S_g, \mu_0)$, where S_g is the support of g . We write

$$\mathbb{E} \left[\prod_{x \in X} (1 + g(x)) \right] = \det_{\Phi}(I + gK_{S_g}),$$

or, with a slight abuse of notation, simply $\det_{\Phi}(I + gK)$.

We refer to the appendix for a rigorous treatment of the Fredholm determinant and its properties. For now, we only use that the Fredholm determinant enjoys the usual identities one expects from determinants of finite matrices.

An important class of observables are the *gap probabilities*.

DEFINITION 41. *For $A \subset E$ we define the gap probability as*

$$\mathbb{P}(N(A) = 0).$$

PROPOSITION 42. *For any bounded Borel set $A \subset E$,*

$$\mathbb{P}(N(A) = 0) = \det_{\Phi}(I - K_A).$$

PROOF. Apply Theorem 40 with the choice $g(x) = -\chi_A(x)$. \square

We can also define a trace for continuous kernels $R : E \times E \rightarrow \mathbb{C}$ by

$$\text{Tr}_{\Phi} R = \int_E R(x, x) d\mu_0(x),$$

whenever the integral is absolutely convergent (e.g. if $R(x, x)$ has bounded support).

PROPOSITION 43. *For the counting statistic $N(A)$ we have:*

- $\mathbb{E}[N(A)] = \text{Tr}_\Phi K_A = \int_A K(x, x) d\mu_0(x),$
- $\text{Var}[N(A)] = \text{Tr}_\Phi K_A - \text{Tr}_\Phi K_A^2 = \int_A K(x, x) d\mu_0(x) - \int_A \int_A K(x, y) K(y, x) d\mu_0(x) d\mu_0(y).$

PROOF. First note that

$$\mathbb{E}[N(A)] = \frac{d}{dz} \Big|_{z=1} \mathbb{E}[z^{N(A)}].$$

For $|z - 1|$ small, we have the expansion

$$\det_\Phi(I + (z - 1)K_A) = \exp \left(\sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{j} (z - 1)^j \text{Tr}_\Phi K_A^j \right),$$

and differentiation at $z = 1$ gives the first identity. The variance follows similarly by differentiating twice. \square

5. Convergence of determinantal point processes

(Here one can discuss convergence of kernels and the corresponding convergence in distribution of the associated determinantal point processes; we omit the details.)

6. Examples

We now discuss some examples of determinantal point processes. A particularly important class comes from Hermitian kernels.³ Let K be a continuous Hermitian kernel on $E \times E$, i.e.

$$K(y, x) = \overline{K(x, y)} \quad \text{for all } x, y \in E.$$

THEOREM 44. *Let K be a continuous Hermitian kernel such that the associated integral operator \mathcal{K} on $L_2(E, \mu_0)$ is bounded. Then K is a correlation kernel for a determinantal point process if and only if the spectrum $\sigma(\mathcal{K})$ is contained in $[0, 1]$.*

PROOF. Here comes a proof (compare with the discrete case in the previous chapter; the general case is based on the same ideas). \square

THEOREM 45. *Let K be a continuous Hermitian kernel such that the associated integral operator \mathcal{K} is bounded. Then the total number of points $N(E)$ is almost surely either finite or infinite, and*

$$\mathbb{P}(N(E) = \infty) = 0 \quad \text{if } \text{Tr}_\Phi K = \int_E K(x, x) d\mu_0(x) < \infty,$$

and

$$\mathbb{P}(N(E) = \infty) = 1 \quad \text{if } \text{Tr}_\Phi K = \int_E K(x, x) d\mu_0(x) = \infty.$$

PROOF. Here comes a proof (see the discrete case in the previous chapter). \square

THEOREM 46. *Let K be a continuous Hermitian kernel such that the associated integral operator \mathcal{K} is bounded. Then the following statements are equivalent:*

- (1) *There exists $n \in \mathbb{N}$ such that $N(E) = n$ almost surely.*

³There are also important examples for which no Hermitian correlation kernel exists.

(2) *The operator \mathcal{K} is an orthogonal projection on an n -dimensional subspace, i.e. $\mathcal{K}^2 = \mathcal{K}$ and $\text{rank } \mathcal{K} = n$.*

PROOF. Here comes a proof (see the discrete case in the previous chapter). \square

THEOREM 47. *Let $E = \mathbb{R}$ and let $K : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$ be a continuous Hermitian kernel such that $\sigma(\mathcal{K}) \subset [0, 1]$. Assume that, for some $s \in \mathbb{R}$,*

$$\int_s^\infty K(x, x) d\mu_0(x) < \infty.$$

Then the point process has a largest point ξ_{\max} with probability 1, and

$$\mathbb{P}(\xi_{\max} \leq s) = \det_{\Phi}(I - K_{[s, \infty)}).$$

SKETCH OF PROOF. Since

$$\mathbb{E}[N([s, \infty))] = \int_s^\infty K(x, x) d\mu_0(x) < \infty,$$

the probability of having infinitely many points in $[s, \infty)$ is zero. Thus there must be a largest point. Note that

$$\mathbb{P}(\xi_{\max} \leq s) = \mathbb{P}(N([s, \infty)) = 0) = \mathbb{E} \left[\prod_{x \in X} (1 + g(x)) \right],$$

where $g(x) = -1$ for $x \geq s$ and $g(x) = 0$ otherwise. The statement then follows from Theorem 40, after justifying the passage to the limit for the unbounded set $[s, \infty)$ via an exhaustion by bounded intervals. \square

6.1. The sine process. The sine process is the determinantal point process on \mathbb{R} with correlation kernel

$$K_{\text{sine}}(x, y) = \frac{\sin \pi(x - y)}{\pi(x - y)} = \frac{1}{2\pi} \int_{-\pi}^{\pi} e^{it(x-y)} dt.$$

The corresponding operator on $L_2(\mathbb{R})$ is convolution with the sinc function. Its Fourier transform is the indicator function of $[-\pi, \pi]$, so K_{sine} is the kernel of an orthogonal projection. Hence it defines a determinantal point process.

The sine process is translation invariant.

6.2. The Airy point process. The Airy function $\text{Ai}(x)$ is the unique solution of

$$y''(x) = x y(x),$$

satisfying the asymptotics

$$y(x) \sim \frac{1}{2\sqrt{\pi}} x^{-1/4} \exp\left(-\frac{2}{3}x^{3/2}\right), \quad x \rightarrow +\infty.$$

It can be shown that

$$\text{Ai}'(x) = \mathcal{O}(x^{1/4} \exp(-\frac{2}{3}x^{3/2})), \quad \text{Ai}''(x) = \mathcal{O}(x^{3/4} \exp(-\frac{2}{3}x^{3/2}))$$

as $x \rightarrow +\infty$.

Define the Airy kernel

$$K_{\text{Airy}}(x, y) = \begin{cases} \frac{\text{Ai}(x) \text{Ai}'(y) - \text{Ai}(y) \text{Ai}'(x)}{x - y}, & x \neq y, \\ (\text{Ai}'(x))^2 + \text{Ai}(x) \text{Ai}''(x), & x = y. \end{cases}$$

One can show that K_{Airy} is the kernel of an orthogonal projection, hence it defines a determinantal point process, called the *Airy point process*.

Since

$$\int_s^\infty K_{\text{Airy}}(x, x) dx < \infty \quad \text{for each } s \in \mathbb{R},$$

the corresponding determinantal point process has a largest point ξ_{\max} with probability one. The distribution

$$\mathbb{P}(\xi_{\max} \leq s) = \det_{\Phi}(I - K_{\text{Airy}})_{L_2(s, \infty)}$$

is called the *Tracy–Widom distribution* and is usually denoted by $F_{\text{TW}}(s)$.

6.3. Orthogonal polynomial ensembles. Let μ be a measure on \mathbb{R} with finite moments:

$$\int |x|^k d\mu(x) < \infty \quad \text{for all } k \in \mathbb{N}_0.$$

We define the family of orthonormal polynomials $\{p_k\}_{k \geq 0}$ by the conditions:

- p_k is a polynomial of degree k with positive leading coefficient;
- $\int p_k(x)p_j(x) d\mu(x) = \delta_{jk}$ for $j = 0, \dots, k$.

Then the reproducing kernel

$$K_n(x, y) = \sum_{k=0}^{n-1} p_k(x) p_k(y)$$

(together with the reference measure μ) defines a determinantal point process on \mathbb{R} . Since K_n is the kernel of a self-adjoint projection of rank n , this determinantal point process has exactly n points almost surely.

CHAPTER 4

Biorthogonal ensembles

1. Definition

DEFINITION 48. *Let \mathbb{X} be a complete metric space and μ a Borel measure on \mathbb{X} . A probability measure \mathbb{P}_n on \mathbb{X}^n is called a **biorthogonal ensemble** of size n (with reference measure μ) if and only if there exist*

$$\phi_1, \dots, \phi_n \in L_2(\mathbb{X}, \mu), \quad \psi_1, \dots, \psi_n \in L_2(\mathbb{X}, \mu),$$

such that

$$d\mathbb{P}_n(x_1, \dots, x_n) = \frac{1}{Z_n} \det(\phi_j(x_k))_{j,k=1}^n \det(\psi_j(x_k))_{j,k=1}^n \prod_{k=1}^n d\mu(x_k),$$

for some normalizing constant $Z_n > 0$.

Note that the families of functions $\{\phi_j\}_{j=1}^n$ and $\{\psi_j\}_{j=1}^n$ in the definition are not unique. Indeed, by performing row operations in the determinants one can replace each function ϕ_k (resp. ψ_k) with a linear combination of the ϕ_j 's (resp. ψ_j 's), possibly changing the normalization constant, as long as all the new functions remain linearly independent. This means that a biorthogonal ensemble is determined by the n -dimensional subspaces

$$V_\phi = \text{span}\{\phi_1, \dots, \phi_n\}, \quad V_\psi = \text{span}\{\psi_1, \dots, \psi_n\}.$$

The functions ϕ_j and ψ_k in Definition 48 can be replaced by any other systems of functions $\tilde{\phi}_1, \dots, \tilde{\phi}_n$ and $\tilde{\psi}_1, \dots, \tilde{\psi}_n$ that span the spaces V_ϕ and V_ψ respectively.

LEMMA 49. *With the notation above,*

$$Z_n = n! \det G, \quad G_{ij} = \int_{\mathbb{X}} \phi_i(x) \psi_j(x) d\mu(x).$$

PROOF. This follows directly from Andreiéf's identity stated in Lemma 53. \square

A biorthogonal ensemble is a probability measure on \mathbb{X}^n and hence it defines a point process on \mathbb{X} with exactly n points.

THEOREM 50. *Let \mathbb{P}_n be a biorthogonal ensemble given by*

$$d\mathbb{P}_n(x_1, \dots, x_n) = \frac{1}{Z_n} \det(\phi_j(x_k))_{j,k=1}^n \det(\psi_j(x_k))_{j,k=1}^n \prod_{k=1}^n d\mu(x_k),$$

and let

$$G_{ij} = \int_{\mathbb{X}} \phi_i(x) \psi_j(x) d\mu(x), \quad i, j = 1, \dots, n.$$

Assume that G is invertible. Then this point process is determinantal with correlation kernel

$$(11) \quad K(x, y) = \sum_{i,j=1}^n \phi_i(x) (G^{-1})_{ij} \psi_j(y).$$

PROOF. Let g be a function with bounded support on \mathbb{X} . Then

$$\mathbb{E} \left[\prod_{k=1}^n (1+g(x_k)) \right] = \frac{1}{Z_n} \int_{\mathbb{X}} \cdots \int_{\mathbb{X}} \prod_{k=1}^n (1+g(x_k)) \det(\phi_j(x_k))_{j,k=1}^n \det(\psi_j(x_k))_{j,k=1}^n \prod_{k=1}^n d\mu(x_k).$$

By Andreief's identity (Lemma 53) with

$$f_j(x) = (1+g(x)) \phi_j(x), \quad g_j(x) = \psi_j(x),$$

we obtain

$$\begin{aligned} \mathbb{E} \left[\prod_{k=1}^n (1+g(x_k)) \right] &= \frac{1}{Z_n} n! \det \left(\int_{\mathbb{X}} (1+g(x)) \phi_i(x) \psi_j(x) d\mu(x) \right)_{i,j=1}^n \\ &= \frac{1}{\det G} \det(G + H), \end{aligned}$$

where

$$H_{ij} = \int_{\mathbb{X}} g(x) \phi_i(x) \psi_j(x) d\mu(x).$$

Thus

$$\mathbb{E} \left[\prod_{k=1}^n (1+g(x_k)) \right] = \det(I + G^{-1} H).$$

By Lemma 57, this is the Fredholm determinant of an operator with kernel

$$K_g(x, y) = g(x) K(x, y), \quad K(x, y) = \sum_{i,j=1}^n \phi_i(x) (G^{-1})_{ij} \psi_j(y).$$

Comparing with the general determinantal formula for generating functionals (see Theorem 9), we conclude that K is indeed the correlation kernel, proving (11). \square

LEMMA 51. *The kernel K of a biorthogonal ensemble is the integral kernel of a projection (not necessarily orthogonal), i.e. the associated operator \mathcal{K} satisfies $\mathcal{K}^2 = \mathcal{K}$.*

PROOF. The operator \mathcal{K} has finite rank at most n and its range coincides with the span of the functions ϕ_1, \dots, ϕ_n . From the representation

$$K(x, y) = \sum_{i,j=1}^n \phi_i(x) (G^{-1})_{ij} \psi_j(y)$$

and the definition of G , a direct computation shows that $\mathcal{K}^2 = \mathcal{K}$. \square

To compute the correlation kernel for a biorthogonal ensemble, we need, in principle, to invert the Gram matrix G . Note that G is an $n \times n$ matrix and in applications n is often very large, so inverting G explicitly can be difficult.

Instead of trying to invert G , we can use the observation at the beginning of this section and choose different systems $\{\tilde{\phi}_j\}_{j=1}^n$ and $\{\tilde{\psi}_j\}_{j=1}^n$ such that

$$\tilde{G}_{jk} = \int_{\mathbb{X}} \tilde{\phi}_j(x) \tilde{\psi}_k(x) d\mu(x) = \delta_{jk}.$$

We say that $\{\tilde{\phi}_j\}$ and $\{\tilde{\psi}_j\}$ are *biorthogonal*. In this basis the Gram matrix is the identity and hence trivial to invert. This is best seen through examples.

REMARK 52. *It is always possible to find such biorthogonal functions. Indeed, since G is invertible we can take*

$$\tilde{\phi}_j = \sum_{k=1}^n (G^{-1})_{jk} \phi_k, \quad \tilde{\psi}_j = \psi_j,$$

which yields $\int \tilde{\phi}_j(x) \tilde{\psi}_k(x) d\mu(x) = \delta_{jk}$.

We also note that there is no unique way of constructing biorthogonal systems. Different choices may have different advantages.

2. Orthogonal polynomial ensembles

Let μ be a measure on \mathbb{R} with all moments finite, i.e.

$$\int_{\mathbb{R}} |x|^m d\mu(x) < \infty, \quad m = 0, 1, 2, \dots$$

Denote by $S(\mu) = \text{supp } \mu$ the support of μ . Consider the probability measure on $S(\mu)^n$ defined by

$$\frac{1}{Z_n} \prod_{1 \leq i < j \leq n} (x_i - x_j)^2 \prod_{j=1}^n d\mu(x_j).$$

The Vandermonde determinant can be written as

$$\prod_{1 \leq i < j \leq n} (x_i - x_j) = \det(x_i^{j-1})_{i,j=1}^n,$$

so the density can be written as

$$\frac{1}{Z_n} \det(x_i^{j-1})_{i,j=1}^n \det(x_i^{j-1})_{i,j=1}^n \prod_{j=1}^n d\mu(x_j).$$

In other words, this is a biorthogonal ensemble with

$$\phi_j(x) = x^{j-1}, \quad \psi_j(x) = x^{j-1}, \quad j = 1, \dots, n.$$

Now, by performing column operations on the matrices inside the determinants, we can rewrite this measure as

$$\frac{1}{Z_n} \det(p_{j-1}(x_i))_{i,j=1}^n \det(p_{j-1}(x_i))_{i,j=1}^n \prod_{j=1}^n d\mu(x_j),$$

where p_j are the orthonormal polynomials with respect to μ , so that

$$G_{ij} = \int_{\mathbb{R}} p_i(x) p_j(x) d\mu(x) = \delta_{ij}.$$

Applying Theorem 50 we therefore obtain a determinantal point process with kernel

$$K_n(x, y) = \sum_{j=0}^{n-1} p_j(x) p_j(y),$$

and this determinantal point process is precisely the orthogonal polynomial ensemble introduced earlier.

APPENDIX A

Determinants and trace of kernels

1. Introduction

Let μ be a finite Borel measure on a metric space S and let $K : S \times S \rightarrow \mathbb{C}$ be a $\mu \times \mu$ -measurable function satisfying

$$(12) \quad \iint_{S \times S} |K(x, y)|^2 d\mu(x) d\mu(y) < \infty.$$

Note that such measurable functions form a vector space, and an algebra when equipped with the product

$$(K_1 \cdot K_2)(x, y) = \int_S K_1(x, z) K_2(z, y) d\mu(z).$$

We will denote this algebra by \mathcal{B} .

Special examples of interest are the kernels that are finite sums of separable kernels:

$$\mathcal{F} = \left\{ \sum_{j=1}^n f_j(x) g_j(y) \mid n \in \mathbb{N}, f_j, g_j \in L_2(S, \mu), j = 1, \dots, n \right\}.$$

At various places (but certainly not always) we will identify K with the integral operator \mathcal{K} on $L_2(S, \mu)$ given by

$$\mathcal{K}f(x) = \int_S K(x, y) f(y) d\mu(y),$$

for $x \in S$. The condition (12) ensures that \mathcal{K} is a bounded operator. In fact, it makes the operator Hilbert–Schmidt, as we will see later on. The elements of \mathcal{F} correspond to the finite rank operators on $L_2(S, \mu)$.

For integral operators with continuous kernel one can naturally extend the notions of trace and determinant. The idea is the following:

- (1) Define $\text{Tr}\mathcal{K}$ and $\det(I + \mathcal{K})$ for $K \in \mathcal{F}$ by viewing them as finite rank operators.
- (2) Introduce a norm on \mathcal{F} such that $K \mapsto \text{Tr}\mathcal{K}$ and $K \mapsto \det(I + \mathcal{K})$ are locally Lipschitz continuous.
- (3) Extend the definition of determinant and trace by continuity.

There are various different norms that one can define such that the maps $K \mapsto \text{Tr}\mathcal{K}$ and $K \mapsto \det(I + \mathcal{K})$ are locally Lipschitz continuous. Interestingly, these definitions (and their values!) may depend on the chosen norm. We will discuss three norms:

- uniform norm for continuous kernels,
- trace norm for trace class operators,
- a new norm that is specially adapted for determinantal point processes.

The first two are classical ways of defining trace and determinants. The third is new to the best of our knowledge. An important feature of this third norm is that it depends on the values on the diagonal $K(x, x)$. As a consequence we should no longer identify the kernels with their integral operators (indeed, for continuous measures, the integral operator does not depend on the diagonal $K(x, x)$, as it is a set of $\mu \times \mu$ -measure zero).

Finally, we remark that there are subtle differences between these theories. We will illustrate this in a separate section.

2. Preliminaries

We first recall three well-known results that will be important to us.

LEMMA 53 (Andreiéf's identity). *Let (X, ν) be a measure space. Then*

$$\begin{aligned} \int_X \cdots \int_X \det(f_j(x_k))_{j,k=1}^n \det(g_j(x_k))_{j,k=1}^n d\nu(x_1) \cdots d\nu(x_n) \\ = n! \det \left(\int_X f_j(x) g_k(x) d\nu(x) \right)_{j,k=1}^n, \end{aligned}$$

for any $n \in \mathbb{N}$ and square integrable functions $f_1, \dots, f_n, g_1, \dots, g_n$.

PROOF. The proof follows from a straightforward computation:

$$\begin{aligned} & \int_X \cdots \int_X \det(f_j(x_k))_{j,k=1}^n \det(g_j(x_k))_{j,k=1}^n d\nu(x_1) \cdots d\nu(x_n) \\ &= \int_X \cdots \int_X \sum_{\sigma \in S_n} \sum_{\tau \in S_n} \text{sign}(\sigma) \text{sign}(\tau) \prod_{j=1}^n f_{\sigma(j)}(x_j) \prod_{j=1}^n g_{\tau(j)}(x_j) d\nu(x_1) \cdots d\nu(x_n) \\ &= \sum_{\sigma \in S_n} \sum_{\tau \in S_n} \text{sign}(\sigma) \text{sign}(\tau) \prod_{j=1}^n \left(\int_X f_{\sigma(j)}(x) g_{\tau(j)}(x) d\nu(x) \right) \\ &= \sum_{\sigma \in S_n} \sum_{\tau \in S_n} \text{sign}(\sigma^{-1}) \text{sign}(\tau) \prod_{j=1}^n \left(\int_X f_j(x) g_{\tau \circ \sigma^{-1}(j)}(x) d\nu(x) \right), \end{aligned}$$

where the last equality holds by reordering the product according to the permutation σ^{-1} .

Since $\text{sign}(\sigma^{-1}) \text{sign}(\tau) = \text{sign}(\tau \circ \sigma^{-1})$, the double sum simplifies to a sum over $\sigma' = \tau \circ \sigma^{-1} \in S_n$ and we thus arrive at

$$\begin{aligned} & \int_X \cdots \int_X \det(f_j(x_k))_{j,k=1}^n \det(g_j(x_k))_{j,k=1}^n d\nu(x_1) \cdots d\nu(x_n) \\ &= n! \sum_{\sigma' \in S_n} \text{sign}(\sigma') \prod_{j=1}^n \left(\int_X f_j(x) g_{\sigma'(j)}(x) d\nu(x) \right), \end{aligned}$$

and thus the statement follows. \square

If ν is the counting measure on $\{1, \dots, m\}$, then by setting $C_{jk} = f_j(x_k)$ and $D_{jk} = g_j(x_k)$, this is the Cauchy–Binet identity for the determinant of the product of two rectangular matrices. If in addition $n = m$ then it follows (after a symmetrization) that $\det(CD) = \det C \det D$ for square matrices C and D .

LEMMA 54 (Sylvester's identity). *For any $A \in \mathbb{C}^{k \times m}$ and $B \in \mathbb{C}^{m \times k}$ we have*

$$\det(I_k + AB) = \det(I_m + BA).$$

PROOF. The statement follows from the following trick:

$$\begin{aligned} \det(I_k + AB) &= \det \begin{pmatrix} I_k + AB & A \\ 0 & I_m \end{pmatrix} \\ &= \det \begin{pmatrix} I_k & A \\ -B & I_m \end{pmatrix} \det \begin{pmatrix} I_k & 0 \\ B & I_m \end{pmatrix} \\ &= \det \begin{pmatrix} I_k & 0 \\ B & I_m \end{pmatrix} \det \begin{pmatrix} I_k & A \\ -B & I_m \end{pmatrix} \\ &= \det \left(\begin{pmatrix} I_k & 0 \\ B & I_m \end{pmatrix} \begin{pmatrix} I_k & A \\ -B & I_m \end{pmatrix} \right) \\ &= \det \begin{pmatrix} I_k & A \\ 0 & I_m + BA \end{pmatrix} = \det(I_m + BA). \end{aligned}$$

Here we used that $\det(CD) = \det C \det D$ for any square matrices C and D . \square

LEMMA 55 (von Koch form of the determinant). *Let A be an $n \times n$ matrix. Then*

$$\det(I + A) = 1 + \sum_{k=1}^n \frac{1}{k!} \sum_{i_1, \dots, i_k \in \{1, \dots, n\}} \det(A_{i_j, i_\ell})_{j, \ell=1}^k.$$

PROOF. A proof can be found in standard texts on determinants; we omit the details. \square

3. Trace and determinant for finite rank operators

For finite rank operators the obvious way of defining the trace and determinant is via their matrix representation. Let \mathcal{K} be a finite rank operator and let M be a subspace of $L_2(S, \mu)$ such that both the range and the cokernel of \mathcal{K} are subspaces of M . In other words, \mathcal{K} acts trivially on M^\perp . Then we take an orthonormal basis $\{e_1, \dots, e_N\}$ for M (where $N = \dim M$) and define

$$\text{Tr}\mathcal{K} = \sum_{i=1}^N (\mathcal{K}e_i, e_i)$$

and

$$\det(I + \mathcal{K}) = \det(\delta_{jk} + (\mathcal{K}e_k, e_j))_{j, k=1}^N.$$

Here $(f, g) = \int_S f(x) \overline{g(x)} d\mu(x)$ denotes the $L_2(S, \mu)$ inner product between f and g .

The definitions of $\text{Tr}\mathcal{K}$ and $\det(I + \mathcal{K})$ do not depend on the chosen basis, which can be seen from the following lemmas.

LEMMA 56. *Let $K(x, y) = \sum_{j=1}^r f_j(x) g_j(y)$ be the kernel for the finite rank operator \mathcal{K} . Then the following hold:*

- (1) $\text{Tr}\mathcal{K} = \sum_{j=1}^r \lambda_j$, where λ_j are the eigenvalues of \mathcal{K} (counted with algebraic multiplicity);

$$(2) \quad \text{Tr}\mathcal{K} = \int_S K(x, x) d\mu(x) = \sum_{j=1}^r (f_j, g_j).$$

PROOF. The first property is standard. The second property is a straightforward consequence of Plancherel's theorem (or simply of the definition of the trace in terms of an orthonormal basis). \square

LEMMA 57. *Let $K(x, y) = \sum_{j=1}^r f_j(x) g_j(y)$ be the kernel for the finite rank operator \mathcal{K} . Then the following hold:*

$$(1) \quad \det(I + \mathcal{K}) = \prod_{j=1}^r (1 + \lambda_j);$$

$$(2) \quad \det(I + \mathcal{K}) = \det(\delta_{jk} + (f_j, g_k))_{j,k=1}^r.$$

PROOF. The first property is again standard.

For the second property, note that

$$(\mathcal{K}e_i, e_j) = \sum_{\ell=1}^r (g_\ell, e_i) (f_\ell, e_j).$$

Define the matrices

$$A_{i\ell} = \langle g_\ell, e_i \rangle, \quad i = 1, \dots, N, \quad \ell = 1, \dots, r,$$

$$B_{\ell j} = \langle f_\ell, e_j \rangle, \quad \ell = 1, \dots, r, \quad j = 1, \dots, N.$$

Then $(\mathcal{K}e_i, e_j) = (AB)_{ij}$ and thus the determinant can be written as $\det(I_N + AB)$. By Sylvester's identity (Lemma 54) we get

$$\det(I_N + \mathcal{K}) = \det(I_N + AB) = \det(I_r + BA).$$

A direct computation shows that $(BA)_{jk} = \int_S f_j(x) g_k(x) d\mu(x)$, proving the second property. \square

For the next important form of the determinant we use Andreiéf's identity.

LEMMA 58. *For a finite rank operator \mathcal{K} with kernel K we have*

$$(13) \quad \det(I + \mathcal{K}) = \sum_{m=0}^{\infty} \frac{1}{m!} \int_S \cdots \int_S \det(K(x_i, x_j))_{i,j=1}^m d\mu(x_1) \cdots d\mu(x_m),$$

and the series truncates at $m = r$, where r is the rank of \mathcal{K} .

PROOF. Write $K(x, y) = \sum_{\ell=1}^r f_\ell(x) g_\ell(y)$. By applying Andreiéf's identity twice we obtain

$$\begin{aligned} & \int_S \cdots \int_S \det(K(x_i, x_j))_{i,j=1}^m d\mu(x_1) \cdots d\mu(x_m) \\ &= \frac{1}{m!} \sum_{k_1=1}^r \cdots \sum_{k_m=1}^r \int_S \cdots \int_S \det(f_{k_j}(x_i))_{i,j=1}^m \det(g_{k_j}(x_i))_{i,j=1}^m d\mu(x_1) \cdots d\mu(x_m) \\ &= \sum_{k_1=1}^r \cdots \sum_{k_m=1}^r \det((f_{k_j}, g_{k_i}))_{i,j=1}^m. \end{aligned}$$

Thus

$$\begin{aligned} \sum_{m=0}^r \frac{1}{m!} \int_S \cdots \int_S \det(K(x_i, x_j))_{i,j=1}^m d\mu(x_1) \cdots d\mu(x_m) \\ = \sum_{m=0}^r \frac{1}{m!} \sum_{k_1=1}^r \cdots \sum_{k_m=1}^r \det((f_{k_j}, g_{k_i}))_{i,j=1}^m. \end{aligned}$$

Hence the statement follows by applying Lemma 55 and part (2) of Lemma 57. \square

The trace and determinant have many important properties. We will especially use the ones in the following lemma.

LEMMA 59. *The determinant has the following properties for finite rank operators:*

- (1) $\det(I + K_1)\det(I + K_2) = \det(I + K_1 + K_2 + K_1 K_2)$.
- (2) $\log \det(I + zK) = \sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{j} z^j \text{Tr} K^j$, valid for $|z|$ sufficiently small (for example, $|z| \leq 1/\max_j |\lambda_j(K)|$).

4. Continuous extensions

Let \mathcal{B}_* be a subalgebra of \mathcal{B} that is equipped with a norm $\|\cdot\|_*$ such that:

- (1) \mathcal{B}_* is a Banach algebra, i.e., \mathcal{B}_* is complete and

$$\|K_1 K_2\|_* \leq \|K_1\|_* \|K_2\|_*.$$

- (2) The finite rank operators (i.e. kernels in \mathcal{F}) form a dense subspace of \mathcal{B}_* ; we denote this dense subspace by \mathcal{B}_F .
- (3) The map $K \mapsto \text{Tr} K$ is a continuous linear functional on \mathcal{B}_F with respect to $\|\cdot\|_*$.

Strictly speaking, in our examples $\|\cdot\|_*$ will be a seminorm that will be turned into a norm by considering equivalence classes in a standard fashion: we say $K_1 \sim K_2$ if and only if $\|K_1 - K_2\|_* = 0$. The continuity of the trace then shows that $\|K_1 - K_2\|_* = 0$ implies $\text{Tr} K_1 = \text{Tr} K_2$, making the trace a well-defined function on the equivalence classes. This is not a trivial point, since our equivalence classes will be different in the upcoming examples.

The fact that \mathcal{B}_* is a Banach algebra is a useful property that we will exploit at several places.

LEMMA 60. *Let $K \in \mathcal{B}_*$. Then*

- (1) $K^j \in \mathcal{B}_*$ and $\|K^j\|_* \leq \|K\|_*^j$ for $j = 1, 2, \dots$;
- (2) $\exp(K) = \sum_{j=0}^{\infty} \frac{K^j}{j!} \in \mathcal{B}_*$ and $\|\exp K\|_* \leq \exp(\|K\|_*)$.

If $\|K\|_* < 1$, then

- (3) $(I - K)^{-1} = \sum_{j=0}^{\infty} K^j \in \mathcal{B}_*$ and $\|(I - K)^{-1}\|_* \leq (1 - \|K\|_*)^{-1}$;
- (4) $\log(I - K) = -\sum_{j=1}^{\infty} \frac{K^j}{j} \in \mathcal{B}_*$ and $\|\log(I - K)\|_* \leq -\log(1 - \|K\|_*)$.

PROOF. The proof is standard: it relies on the completeness of \mathcal{B}_* and the submultiplicative property of $\|\cdot\|_*$. \square

All the arguments in the following paragraph are copied from [1].

THEOREM 61. *The map $K \mapsto \det(I + K)$ on \mathcal{B}_F is locally Lipschitz continuous with respect to $\|\cdot\|_*$ and thus has a continuous extension to the whole of \mathcal{B}_* .*

PROOF. We first prove that $K \mapsto \det(I + K)$ is continuous on the ball in \mathcal{B}_F of radius $0 < r < 1$. Indeed, for any $F, G \in \mathcal{B}_F$ such that $\|F\|_*, \|G\|_* < r$ we have

$$\begin{aligned} |\det(I + F) - \det(I + G)| &= \left| \exp\left(\sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{j} \text{Tr} F^j\right) - \exp\left(\sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{j} \text{Tr} G^j\right) \right| \\ &\leq c \left| \sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{j} \text{Tr} F^j - \sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{j} \text{Tr} G^j \right| \\ &\leq c_1 \sum_{j=1}^{\infty} \frac{1}{j} |\text{Tr} F^j - \text{Tr} G^j| \leq c_1 c_2 \sum_{j=1}^{\infty} \frac{1}{j} \|F^j - G^j\|_*, \end{aligned}$$

for some constants $c, c_1, c_2 > 0$. Using that \mathcal{B}_* is a Banach algebra we find

$$\|F^j - G^j\|_* = \left\| \sum_{\ell=0}^{j-1} F^\ell (F - G) G^{j-\ell-1} \right\|_* \leq \sum_{\ell=0}^{j-1} \|F\|_*^\ell \|F - G\|_* \|G\|_*^{j-\ell-1} \leq j r^{j-1} \|F - G\|_*,$$

and thus

$$|\det(I + F) - \det(I + G)| \leq \frac{c_1 c_2}{1 - r} \|F - G\|_*,$$

which proves that $F \mapsto \det(I + F)$ is continuous (in fact Lipschitz continuous) in the ball with radius $r < 1$.

Next we prove that $K \mapsto \det(I + K)$ is continuous on all of \mathcal{B}_F . To this end, fix $F \in \mathcal{B}_F$ and note that

$$\det(I + F) - \det(I + G) = \det(I + G) \left(\det(I + (I + G)^{-1}(F - G)) - 1 \right),$$

for any $F, G \in \mathcal{B}_F$. Then by the argument above there exist $\rho > 0$ and $c_3 > 0$ such that

$$|\det(I + F) - \det(I + G)| \leq c_3 |\det(I + G)| \|(I + G)^{-1}\|_* \|F - G\|_*$$

whenever $\|F - G\|_* < \rho$. This proves the local Lipschitz continuity. \square

We are now ready to define the trace and determinant by continuous extension.

DEFINITION 62. *We denote the continuous extensions of $K \mapsto \text{Tr} K$ and $K \mapsto \det(I + K)$ from \mathcal{B}_F to \mathcal{B}_* by Tr_* and \det_* . That is, for $K \in \mathcal{B}_*$ we set*

$$\text{Tr}_* K = \lim_{n \rightarrow \infty} \text{Tr} F_n, \quad \det_*(I + K) = \lim_{n \rightarrow \infty} \det(I + F_n),$$

where $\{F_n\}_n \subset \mathcal{B}_F$ is any sequence converging to K in \mathcal{B}_* .

Many of the properties of the trace and determinant for finite matrices transfer directly (by continuity) to elements of \mathcal{B}_* . We mention two important identities.

LEMMA 63. *For $K_1, K_2, K \in \mathcal{B}_*$ we have*

- (1) $\det_*(I + K_1) \det_*(I + K_2) = \det_*(I + K_1 + K_2 + K_1 K_2)$;
- (2) $\log \det_*(I + zK) = \sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{j} z^j \text{Tr}_* K^j$, valid for $|z|$ sufficiently small (depending on K and $\|\cdot\|_*$).

PROOF. The first property follows directly from continuity and the fact that the identity is correct in \mathcal{B}_F .

For the second property, first recall that the identity holds if $K \in \mathcal{B}_F$ and z is sufficiently small. Since the right-hand side is a well-defined analytic function for z in a neighborhood of the origin, the identity extends to that neighborhood. For a general $K \in \mathcal{B}_*$, take $F_n \in \mathcal{B}_F$ such that $F_n \rightarrow K$ as $n \rightarrow \infty$:

$$\log \det_*(I + zK) = \lim_{n \rightarrow \infty} \log \det(I + zF_n) = \lim_{n \rightarrow \infty} \sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{j} z^j \operatorname{Tr} F_n^j.$$

What is left to prove is that we can take the limit term by term. This follows from the estimate

$$|\operatorname{Tr} F_n^j| \leq c_1 \|F_n\|_*^j,$$

and thus the series converges uniformly in n for z in a sufficiently small disk. We can therefore interchange limits. Then, by continuity of the trace we find $\operatorname{Tr} F_n^j \rightarrow \operatorname{Tr}_* K^j$ and this proves the statement. \square

A consequence of the latter lemma is that $z \mapsto \det_*(I + zK)$ is analytic in a sufficiently small disk around the origin. In fact, it is an entire function, as we now prove.

THEOREM 64. *For $K \in \mathcal{B}_*$ the map $z \mapsto \det_*(I + zK)$ is an entire function.*

PROOF. Let $\{F_n\}_n \subset \mathcal{B}_F$ be such that $F_n \rightarrow K$ in \mathcal{B}_* as $n \rightarrow \infty$. We will prove that $z \mapsto \det_*(I + zK)$ is analytic on a disk around the origin of arbitrary radius $R > 0$. Fix $R > 0$ and choose N such that $\|K - F_n\|_* \leq 1/R$ for all $n \geq N$. Then, for $n \geq N$ we write

$$(14) \quad \det_*(I + zK) = \det_*(I + z(K - F_n)) \det_*(I + z(I + z(K - F_n))^{-1} F_n).$$

By Lemma 63 we know that $\det_*(I + z(K - F_n))$ is analytic for $|z| < R$. It remains to show that the second factor is also analytic. To this end, write

$$\det_*(I + z(I + z(K - F_n))^{-1} F_n) = \lim_{M \rightarrow \infty} \det_*(I + z \sum_{j=0}^M (-z)^j (K - F_n)^j F_n),$$

where the convergence is uniform for z in compact subsets of the disk $|z| < R$. Now \mathcal{B}_F is an ideal in \mathcal{B}_* and thus

$$T_{n,M}(z) := z \sum_{j=0}^M (-z)^j (K - F_n)^j F_n \in \mathcal{B}_F,$$

and hence

$$\det_*(I + T_{n,M}(z)) = \det(I + T_{n,M}(z))$$

is a polynomial in z . Moreover, by uniform convergence, these polynomials converge to an analytic function for $|z| < R$.

We thus see that both terms on the right-hand side of (14) are analytic for $|z| < R$ and thus so is $\det_*(I + zK)$. Since R is arbitrary the statement follows. \square

COROLLARY 65. *For every $K \in \mathcal{B}_*$ we have an entire series expansion*

$$\det_*(I + zK) = 1 + \sum_{k=1}^{\infty} a_k(K) z^k,$$

with

$$\lim_{k \rightarrow \infty} |a_k(K)|^{1/k} = 0.$$

THEOREM 66. *Let $K \in \mathcal{B}_*$ and $\{F_n\}_n \subset \mathcal{B}_F$ such that $F_n \rightarrow K$ as $n \rightarrow \infty$. Then*

$$\det_*(I + K) = 1 + \sum_{m=1}^{\infty} \frac{1}{m!} \lim_{n \rightarrow \infty} \int_S \cdots \int_S \det(F_n(x_i, x_j))_{i,j=1}^m d\mu(x_1) \cdots d\mu(x_m).$$

It is tempting to try to interchange the limit with the integral and simply replace the integrand by $\det(K(x_i, x_j))_{i,j=1}^m$, but this is not necessarily correct (for instance, for general trace class operators this does not necessarily hold). However, for certain explicit choices for \mathcal{B}_* this can be justified, as we will see later on.

Another theorem that is useful to us is the following.

THEOREM 67. *Suppose that for some monotone increasing function $G : [0, \infty) \rightarrow [0, \infty)$ we have that*

$$|\det(I + \mathcal{K})| \leq G(\|\mathcal{K}\|_*)$$

for all $\mathcal{K} \in \mathcal{B}_F$. Then, for any $\mathcal{K}_1, \mathcal{K}_2 \in \mathcal{B}_*$,

$$|\det_*(I + \mathcal{K}_1) - \det_*(I + \mathcal{K}_2)| \leq \|\mathcal{K}_1 - \mathcal{K}_2\|_* G(\|\mathcal{K}_1\|_* + \|\mathcal{K}_2\|_* + 1).$$

PROOF. For the trace, the corresponding statement is immediate from linearity and continuity.

For the determinant, fix $\mathcal{K}_1, \mathcal{K}_2 \in \mathcal{B}_*$ and define

$$f(z) = \det_*(I + \frac{1}{2}(\mathcal{K}_1 + \mathcal{K}_2) + z(\mathcal{K}_2 - \mathcal{K}_1)).$$

Then f is entire in z and $f(-\frac{1}{2}) = \det_*(I + \mathcal{K}_1)$ and $f(\frac{1}{2}) = \det_*(I + \mathcal{K}_2)$.

Moreover,

$$f(\frac{1}{2}) - f(-\frac{1}{2}) = f'(\xi)$$

for some $\xi \in (-\frac{1}{2}, \frac{1}{2})$ by the mean value theorem. Since f is entire, we can use Cauchy's inequality to deduce

$$\sup_{|\xi| \leq 1/2} |f'(\xi)| \leq \frac{1}{R} \sup_{|z|=R+1/2} |f(z)|,$$

for any $R > 0$. Take $R = \|\mathcal{K}_1 - \mathcal{K}_2\|_*^{-1}$ (if $\mathcal{K}_1 \neq \mathcal{K}_2$; otherwise there is nothing to prove) and invoke the assumed bound on the determinant to obtain

$$\begin{aligned} |f(\frac{1}{2}) - f(-\frac{1}{2})| &\leq \|\mathcal{K}_1 - \mathcal{K}_2\|_* \sup_{|z|=R+1/2} |f(z)| \\ &\leq \|\mathcal{K}_1 - \mathcal{K}_2\|_* \sup_{|z|=R+1/2} G(\|\frac{1}{2}(\mathcal{K}_1 + \mathcal{K}_2) + z(\mathcal{K}_2 - \mathcal{K}_1)\|_*). \end{aligned}$$

By using the fact that G is monotone increasing we further deduce that

$$\sup_{|z|=R+1/2} G(\|\frac{1}{2}(\mathcal{K}_1 + \mathcal{K}_2) + z(\mathcal{K}_2 - \mathcal{K}_1)\|_*) \leq G(\|\mathcal{K}_1\|_* + \|\mathcal{K}_2\|_* + 1),$$

and this gives the stated inequality. \square

5. Fredholm determinants

Let us now assume that $S \subset \mathbb{R}^d$ is compact and the kernel K is continuous. We denote the space of all integral operators with continuous kernel by \mathcal{B}_Φ and endow this space with the norm

$$\|\mathcal{K}\|_\Phi = \mu(S) \max_{x,y \in S} |K(x,y)|.$$

Equipped with this norm, \mathcal{B}_Φ is a Banach algebra, i.e., it is both a Banach space and an algebra, and

$$\|K_1 K_2\|_\Phi \leq \|K_1\|_\Phi \|K_2\|_\Phi.$$

Note also that $\|K\|_\infty \leq \|\mathcal{K}\|_\Phi$.

LEMMA 68. *The subspace \mathcal{F} of finite rank operators in \mathcal{B}_Φ forms a dense subalgebra.*

PROOF. That \mathcal{F} is a subalgebra is immediate. That it is dense follows, for instance, by Féjer's theorem from Fourier analysis. Indeed, using a multivariate version of Féjer's theorem we see that any continuous K can be uniformly approximated by sums of products of trigonometric polynomials. Since these sums give finite rank operators, we obtain the statement. \square

PROPOSITION 69. *The trace and determinant on $\mathcal{B}_\Phi \cap \mathcal{B}_F$ are continuous with respect to the norm $\|\cdot\|_\Phi$ and can therefore be continuously extended to \mathcal{B}_Φ . These extensions will be denoted by Tr_Φ and \det_Φ .*

The trace $\text{Tr}_\Phi \mathcal{K}$ satisfies

$$(15) \quad \text{Tr}_\Phi \mathcal{K} = \int_S K(x, x) d\mu(x).$$

The Fredholm determinant $\det_\Phi(I + \mathcal{K})$ satisfies

$$(16) \quad \det_\Phi(I + \mathcal{K}) = \sum_{m=0}^{\infty} \frac{1}{m!} \int_S \cdots \int_S \det(K(x_i, x_j))_{i,j=1}^m d\mu(x_1) \cdots d\mu(x_m),$$

and the right-hand side is absolutely convergent.

PROOF. It follows from Lemma 56 (second property) that

$$|\text{Tr}_\Phi \mathcal{K}_1 - \text{Tr}_\Phi \mathcal{K}_2| \leq \|\mathcal{K}_1 - \mathcal{K}_2\|_\Phi,$$

for any $\mathcal{K}_1, \mathcal{K}_2 \in \mathcal{B}_\Phi \cap \mathcal{B}_F$. This means that we can indeed extend the definition of the trace and determinant continuously to all of \mathcal{B}_Φ .

It remains to check that the formulas (15) and (16) are indeed correct. For $\mathcal{K} \in \mathcal{B}_\Phi$, let $\mathcal{K}_n \in \mathcal{B}_\Phi \cap \mathcal{B}_F$ be a sequence converging to \mathcal{K} in $\|\cdot\|_\Phi$. Then

$$\text{Tr}_\Phi \mathcal{K} = \lim_{n \rightarrow \infty} \text{Tr} \mathcal{K}_n = \lim_{n \rightarrow \infty} \int_S K_n(x, x) d\mu(x),$$

and

$$\det_\Phi(I + \mathcal{K}) = \lim_{n \rightarrow \infty} \sum_{m=0}^{\infty} \frac{1}{m!} \int_S \cdots \int_S \det(K_n(x_i, x_j))_{i,j=1}^m d\mu(x_1) \cdots d\mu(x_m).$$

By uniform convergence of $K_n \rightarrow K$, we can take the limit under the integrals, which proves the statement. \square

LEMMA 70. Let $G(x) = \sum_{m=0}^{\infty} \frac{m^{m/2} x^m}{m!}$. Then

$$|\det_{\Phi}(I + \mathcal{K})| \leq G(\|\mathcal{K}\|_{\Phi}).$$

PROOF. By Hadamard's inequality we have

$$|\det(K(x_i, x_j))_{i,j=1}^m| \leq m^{m/2} \|\mathcal{K}\|_{\Phi}^m.$$

Together with Lemma 58 this implies that

$$(17) \quad |\det(I + \mathcal{K})| \leq \sum_{m=0}^{\infty} \frac{m^{m/2} \|\mathcal{K}\|_{\Phi}^m}{m!},$$

proving the statement. \square

We list the most important properties.

LEMMA 71. For $K_1, K_2, K \in \mathcal{B}_{\Phi}$ we have

- (1) $|\mathrm{Tr}_{\Phi} \mathcal{K}_1 - \mathrm{Tr}_{\Phi} \mathcal{K}_2| \leq \|\mathcal{K}_1 - \mathcal{K}_2\|_{\Phi};$
- (2) $|\det_{\Phi}(I + \mathcal{K}_1) - \det_{\Phi}(I + \mathcal{K}_2)| \leq \|\mathcal{K}_1 - \mathcal{K}_2\|_{\Phi} G(\|\mathcal{K}_1\|_{\Phi} + \|\mathcal{K}_2\|_{\Phi} + 1);$
- (3) $\det_{\Phi}(I + \mathcal{K}_1) \det_{\Phi}(I + \mathcal{K}_2) = \det_{\Phi}(I + \mathcal{K}_1 + \mathcal{K}_2 + \mathcal{K}_1 \mathcal{K}_2);$
- (4) $\log \det_{\Phi}(I + zK) = \sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{j} z^j \mathrm{Tr}_{\Phi} K^j,$ valid for $|z|$ sufficiently small (depending on K and $\|\cdot\|_{\Phi}$).

Here $G(x) = \sum_{m=0}^{\infty} \frac{m^{m/2} x^m}{m!}.$

6. A generalization

We now consider a generalization of the Fredholm determinant.

Consider the space \mathcal{B}_R of kernels $K : S \times S \rightarrow \mathbb{C}$ such that

$$\|K\|_R = \max \left(\left(\iint_{S \times S} |K(x, y)|^2 d\mu(x) d\mu(y) \right)^{1/2}, \int_S |K(x, x)| d\mu(x) \right) < \infty.$$

After introducing equivalence classes by saying that $K_1 = K_2$ if and only if

- (1) $K_1(x, y) = K_2(x, y)$ for $\mu \times \mu$ -almost every $(x, y) \in S \times S$, and
- (2) $K_1(x, x) = K_2(x, x)$ for μ -almost every $x \in S$,

we see that \mathcal{B}_R is a Banach space.

We stress that, in general, one should not consider the elements of \mathcal{B}_R as integral kernels for bounded operators. Indeed, if the diagonal $D = \{(x, x) \mid x \in S\}$ is a set of measure 0 then the values of K on D do not contribute to the operator. But as an element of \mathcal{B}_R these values are highly relevant. For instance, if we take $K(x, y) = 0$ for $x \neq y$ and assume that D has measure 0, then the corresponding operator is trivial, but its norm in \mathcal{B}_R is positive if $K(x, x) \neq 0$ for x in a set of positive measure.

This is not a problem. In fact, it will turn out to be very useful for us. Indeed, for determinantal point processes the values along the diagonal are mean densities of points, and thus highly relevant. From this point of view it is somewhat unfortunate to view the kernel only as an operator.

THEOREM 72. *The set*

$$\mathcal{B}_F = \left\{ \sum_{j=1}^m f_j(x) g_j(y) \mid m \in \mathbb{N}, f_1, \dots, f_m, g_1, \dots, g_m \in L_2(S, \mu) \right\}$$

is dense in \mathcal{B}_R .

THEOREM 73. *The trace and determinant are continuous with respect to the norm $\|\cdot\|_R$ and can therefore be continuously extended to \mathcal{B}_R . These extensions will be denoted by Tr_R and \det_R .*

The trace $\text{Tr}_R \mathcal{K}$ satisfies

$$(18) \quad \text{Tr}_R \mathcal{K} = \int_S K(x, x) d\mu(x).$$

The determinant $\det_R(I + \mathcal{K})$ satisfies

$$(19) \quad \det_R(I + \mathcal{K}) = \sum_{m=0}^{\infty} \frac{1}{m!} \int_S \cdots \int_S \det(K(x_i, x_j))_{i,j=1}^m d\mu(x_1) \cdots d\mu(x_m),$$

and the right-hand side is absolutely convergent.

7. Trace class operators

In the next discussion, we return to the more general situation where K is a compact operator on $L_2(S, \mu)$ and S is a general measure space. If K is compact, then K^*K is both compact and self-adjoint. By the spectral theorem K^*K has eigenvalues $\sigma_j(K)^2$ that we order in decreasing order

$$\sigma_1(K)^2 \geq \sigma_2(K)^2 \geq \dots \geq 0.$$

The positive square roots $\sigma_j(K)$ are called the singular values of K . The p -Schatten class of operators is then defined as the set of all operators K such that

$$\sum_{j=1}^{\infty} \sigma_j(K)^p < \infty,$$

and we define

$$\|K\|_p = \left(\sum_{j=1}^{\infty} \sigma_j(K)^p \right)^{1/p}.$$

We also define

$$\mathcal{B}_p = \{K \text{ compact} \mid \|K\|_p < \infty\}.$$

In case $p = 1$, the operators in \mathcal{B}_1 are called trace class operators and $\|\cdot\|_1$ is called the trace norm. In case $p = 2$, the operators in \mathcal{B}_2 are called Hilbert–Schmidt operators and $\|\cdot\|_2$ is called the Hilbert–Schmidt norm. It can be shown that

$$\|K\|_2^2 = \iint_{S \times S} |K(x, y)|^2 d\mu(x) d\mu(y),$$

but no such simple expression for the trace norm is known. In fact, it is often rather difficult to verify that a certain operator is trace class. A useful idea is to show that $K = AB$ where A, B are Hilbert–Schmidt operators. Indeed, in that case K is trace class since

$$\|K\|_1 = \|AB\|_1 \leq \|A\|_2 \|B\|_2.$$

This implies in particular that if K is Hilbert–Schmidt, then K^j is trace class for all $j \geq 2$.

The finite rank operators on $L_2(S, \mu)$ are dense in the trace class operators. Moreover, it can be shown that if we order the eigenvalues of K as $|\lambda_1| \geq |\lambda_2| \geq \dots$, then $\sigma_j(K) \geq |\lambda_j(K)|$. This implies that for finite rank operators K we have

$$|\mathrm{Tr}K| \leq \|K\|_1.$$

The trace is thus Lipschitz continuous with respect to the trace norm and we can continuously extend the definition of the trace to all trace class operators. This extension will be denoted by Tr_1 .

As for the determinant, if $\mathcal{K} \in \mathcal{B}_1$ has eigenvalues λ_j , we have

$$|\det(I + \mathcal{K})| = \left| \prod_{j=1}^{\infty} (1 + \lambda_j) \right| \leq \exp\left(\sum_{j=1}^{\infty} |\lambda_j|\right) \leq \exp\left(\sum_{j=1}^{\infty} \sigma_j(K)\right) \leq \exp(\|\mathcal{K}\|_1).$$

As a consequence we also see that the determinant can be extended to a locally Lipschitz continuous function on \mathcal{B}_1 and this extension will be denoted by \det_1 .

LEMMA 74. *For $K_1, K_2, K \in \mathcal{B}_1$ we have*

- (1) $|\mathrm{Tr}_1 K_1 - \mathrm{Tr}_1 K_2| \leq \|K_1 - K_2\|_1$;
- (2) $|\det_1(I + K_1) - \det_1(I + K_2)| \leq \|K_1 - K_2\|_1 \exp(\|K_1\|_1 + \|K_2\|_1 + 1)$;
- (3) $\det_1(I + K_1)\det_1(I + K_2) = \det_1(I + K_1 + K_2 + K_1 K_2)$;
- (4) $\log \det_1(I + zK) = \sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{j} z^j \mathrm{Tr}_1 K^j$, valid for z in a sufficiently small neighborhood of 0.

8. Comparison between \det_{Φ} , \det_R and \det_1

It is important to note that \det_{Φ} , \det_R and \det_1 are not necessarily the same. To start with, they are not necessarily defined on the same sets. Clearly, not all trace class operators have continuous kernels. Moreover, Carleman showed the existence of a continuous K with $S = [0, 1]$ and Lebesgue measure μ , such that \mathcal{K} is not trace class. For such operators $\det_{\Phi} = \det_R$ is well defined but \det_1 is not. But even when all determinants and traces are well defined, they do not necessarily take the same value.

PROPOSITION 75. *There exists $K \in \mathcal{B}_R$ such that \mathcal{K} is trace class, but $\mathrm{Tr}_R K \neq \mathrm{Tr}_1 K$ and $\det_R(I + K) \neq \det_1(I + K)$.*

It is important to note that such examples are not pathological, but are relevant in our discussion of determinantal point processes.

We end this section with some positive results.

PROPOSITION 76. *If K is continuous and S is compact, then $K \in \mathcal{B}_R$ and*

$$\mathrm{Tr}_R K = \mathrm{Tr}_{\Phi} K, \quad \det_R(I + K) = \det_{\Phi}(I + K).$$

PROPOSITION 77. *If K is continuous and Hermitian non-negative, then $\det_{\Phi} = \det_1 = \det_*$ and $\mathrm{Tr}_{\Phi} = \mathrm{Tr}_1 = \mathrm{Tr}_*$ (whenever these are defined).*

PROPOSITION 78. *If K is continuous and \mathcal{K} is trace class, then $\det_{\Phi} = \det_1 = \det_*$ and $\mathrm{Tr}_{\Phi} = \mathrm{Tr}_1 = \mathrm{Tr}_*$.*

PROPOSITION 79. *If K is continuous and Hermitian non-negative, then \mathcal{K} is trace class.*

The fact that K is Hermitian is important here, as the proof relies on Mercer's theorem.

Bibliography

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