Extrema of two-dimensional discrete Gaussian Free Field

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Discrete Gaussian Free Field (DGFF)

$D \subset \mathbb{R}^d$ (or $\mathbb{C}$ in $d = 2$) bounded, open, "nice" boundary
$D_N := \{x \in \mathbb{Z}^d : x/N \in D\}$
$G_N^D :=$ Green function of SRW on D_N killed upon exit

$$G_N^D(x,y) = E^x\left(\sum_{k=0}^{\tau-1} 1_{\{X_k=y\}}\right)$$

where $\tau :=$ first exit time from D_N

Definition

DGFF := Gaussian process $\{h_x : x \in \mathbb{Z}^d\}$ with

$$E(h_x) = 0 \quad \text{and} \quad E(h_x h_y) = G_N^D(x,y)$$

Other ways to define same object

Hilbert space valued Gaussian:

Vector space: $\mathscr{H}_N := \{f \in \ell^2(\mathbb{Z}^d) \colon f = 0 \text{ on } D_N^{\mathrm{c}}, \sum_x f(x) = 0\}$
Dirichlet inner product: $\langle f, g\rangle := \sum_x \nabla f(x) \cdot \nabla g(x)$

$$h_x := \sum_{n=1}^{|D_N|} Z_n \varphi_n(x)$$

where $\{\varphi_n\}$ ONB in $\mathscr{H}_N$, $\{Z_n\}$ i.i.d. $\mathscr{N}(0,1)$

Other ways to define same object

Dynamical equilibrium:

DGFF = stationary law for **Glauber dynamics** with transition rule

$$h_x \to Z + \frac{1}{2d} \sum_{y\colon |y-x|=1} h_y$$

where $Z = \mathcal{N}(0,1)$. Similarly for **Langevin dynamics**

$$\mathrm{d}h_x = \Bigl(\frac{1}{2d} \sum_{y\colon |y-x|=1} h_y - h_x\Bigr)\mathrm{d}t + \mathrm{d}B_x$$

Other ways to define same object

Law of DGFF = finite-volume Gibbs measure characterized by

The Gibbs-Markov property:
Assume $\widetilde{D} \subset D$. Then

$$h^D \overset{\text{law}}{=} h^{\widetilde{D}} + \varphi^{D,\widetilde{D}}$$

where

(1) $h^{\widetilde{D}}$ and $\varphi^{D,\widetilde{D}}$ independent Gaussian fields

(2) $x \mapsto \varphi^{D,\widetilde{D}}(x)$ discrete harmonic on $\widetilde{D}_N$

Why 2D?

For x with $\mathrm{dist}(x, D_N^c) > \delta N$,

$$\mathrm{Var}(h_x) = G_N(x,x) \asymp \begin{cases} N, & \text{if } d = 1, \\ \log N, & \text{if } d = 2, \\ 1, & \text{if } d \geq 3. \end{cases}$$

In $d = 2$:

$$\begin{aligned} G_N(x,y) &= g \log N - a(x,y) + o(1), & N \gg 1 \\ a(x,y) &= g \log |x-y| + O(1), & |x-y| \gg 1 \end{aligned}$$

where

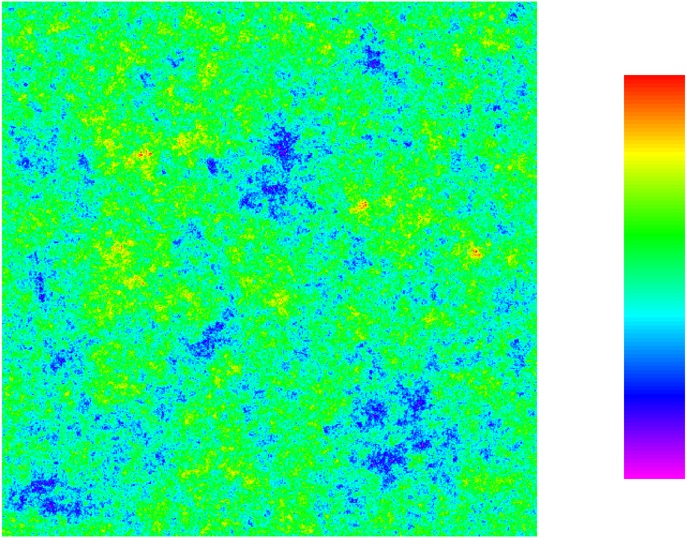
$$g := \frac{2}{\pi} \qquad (\text{In physics, } g := \tfrac{1}{2\pi})$$

The model is **assymptotically scale invariant:**

$$G_{2N}(2x, 2y) = G_N(x,y) + o(1)$$

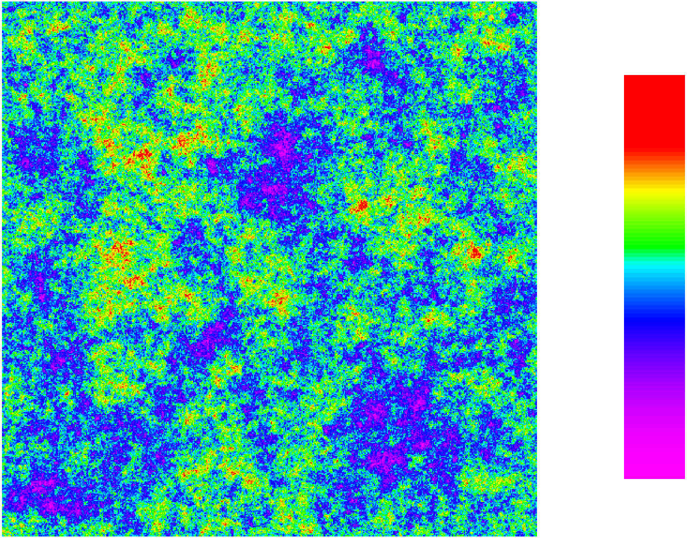
DGFF on 500×500 square

Uniform color system



DGFF on 500×500 square

Emphasizing the extreme values



Some known facts

Absolute maximum

Setting and notation: $D_N := (0, N)^2 \cap \mathbb{Z}^2$

$$M_N := \max_{x \in D_N} h_x \quad \text{and} \quad m_N := EM_N$$

Leading scale (Bolthausen, Deuschel & Giacomin):

$$m_N \sim 2\sqrt{g} \log N$$

Tightness for a subsequence (Bolthausen, Deuschel & Zeitouni):

$$2E\big|M_N - m_N\big| \le m_{2N} - m_N$$

Full tightness (Bramson & Zeitouni):

$$EM_N = 2\sqrt{g} \log N - \frac{3}{4}\sqrt{g} \log\log N + O(1)$$

Convergence in law (Bramson, Ding & Zeitouni)

Some known facts
Extreme points

Extreme level set:

$$\Gamma_N(t) := \{x \in D_N \colon h_x \geq m_N - t\}$$

Extreme point tightness (Ding & Zeitouni):

$$\exists c, C \in (0,\infty)\colon \qquad \lim_{\lambda\to\infty} \liminf_{N\to\infty} P\big(\mathrm{e}^{c\lambda} \leq |\Gamma_N(\lambda)| \leq \mathrm{e}^{C\lambda}\big) = 1$$

and $\exists c > 0$ s.t.

$$\lim_{r\to\infty} \limsup_{N\to\infty} P\Big(\exists x, y \in \Gamma_N(c \log\log r)\colon r \leq |x-y| \leq N/r\Big) = 0$$

Note:

- $O(1)$-level sets are SLE_4 curves (Schramm & Sheffield)
- αm_N-level sets have Hausdorff dimension $2(1-\alpha^2)$ (Daviaud)

Extreme point process

Full process: Measure η_N on $\overline{D} \times \mathbb{R}$

$$\eta_N := \sum_{x \in D_N} \delta_{x/N} \otimes \delta_{h_x - m_N}$$

Problem: Values in one peak strongly correlated

Local maxima only: $\Lambda_r(x) := \{z \in \mathbb{Z}^2 \colon |z - x| \le r\}$

$$\eta_{N,r} := \sum_{x \in D_N} 1_{\{h_x = \max_{z \in \Lambda_r(x)} h_z\}} \delta_{x/N} \otimes \delta_{h_x - m_N}$$

Main result
Extreme process convergence

Theorem (Convergence to Cox process)

There is a random Borel measure Z^D on $\overline{D}$ with $0 < Z^D(\overline{D}) < \infty$ a.s. such that for any $r_N \to \infty$ and $N/r_N \to \infty$,

$$\eta_{N,r_N} \xrightarrow[N\to\infty]{\text{law}} \mathrm{PPP}\Big(Z^D(\mathrm{d}x) \otimes \mathrm{e}^{-\alpha h}\mathrm{d}h\Big)$$

where $\alpha := 2/\sqrt{g} = \sqrt{2\pi}$.

Corollaries

Asymptotic law of maximum: Setting $Z := Z^D(\overline{D})$,

$$P\big(M_N \le m_N + t\big) \underset{N\to\infty}{\longrightarrow} E\big(\mathrm{e}^{-\alpha^{-1} Z \mathrm{e}^{-\alpha t}}\big)$$

Note: Laplace transform of Z on the right

Joint law position/value: $A \subset D$ open, $\widehat{Z}(A) = Z^D(A)/Z^D(\overline{D})$

$$P\Big(M_N \le m_N + t,\, N^{-1}\mathrm{argmax}\,(h) \in A\Big) \underset{N\to\infty}{\longrightarrow} E\big(\widehat{Z}(A)\mathrm{e}^{-\alpha^{-1} Z \mathrm{e}^{-\alpha t}}\big)$$

In fact: Key steps of the proof

Note: $\{\eta_{N,r_N} : N \geq 1\}$ tight, can extract converging subsequences
Denote

$$\langle \eta, f \rangle := \int \eta(\mathrm{d}x, \mathrm{d}h) f(x,h)$$

Proposition (Distributional invariance)

Suppose $\eta :=$ *a weak-limit point of some* $\{\eta_{N_k, r_{N_k}}\}$. *Then for any* $f\colon D \times \mathbb{R} \to [0,\infty)$ *continuous, compact support,*

$$E\big(\mathrm{e}^{-\langle \eta, f \rangle}\big) = E\big(\mathrm{e}^{-\langle \eta, f_t \rangle}\big), \qquad t > 0,$$

where

$$f_t(x,h) := -\log E \mathrm{e}^{-f(x, h + B_t - \frac{\alpha}{2} t)}$$

with $B_t :=$ *standard Brownian motion.*

Proposition explained

We may write

$$\eta = \sum_{i \geq 1} \delta_{x_i, h_i}$$

Letting $\{B_t^{(i)}\}$ be independent standard Brownian motions, set

$$\eta_t := \sum_{i \geq 1} \delta_{x_i, h_i + B_t^{(i)} - \frac{\alpha}{2} t}$$

Well defined as $t \mapsto |\Gamma_N(t)|$ grows only exponentially. Then

$$E\big(\mathrm{e}^{-\langle \eta_t, f \rangle}\big) = E\big(\mathrm{e}^{-\langle \eta, f_t \rangle}\big)$$

and so Proposition in fact says

$$\eta_t \overset{\text{law}}{=} \eta, \qquad t > 0$$

Proof of Proposition I

Gaussian interpolation: $h', h'' \stackrel{\text{law}}{=} h$, independent

$$h \stackrel{\text{law}}{=} \left(1 - \frac{t}{g \log N}\right)^{1/2} h' + \left(\frac{t}{g \log N}\right)^{1/2} h''$$

Now let x be such that $h'_x \geq m_N - \lambda$. Then

$$\begin{aligned} \left(1 - \frac{t}{g \log N}\right)^{1/2} h'_x &= h'_x - \frac{1}{2} \frac{t}{g \log N} h'_x + o(1) \\ &= h'_x - \frac{t}{2} \frac{m_N}{g \log N} + o(1) \\ &= h'_x - \frac{\alpha}{2} t + o(1) \end{aligned}$$

Proof of Proposition II

Concerning h'', abbreviate

$$\widetilde{h}''_x := \left(\frac{t}{g\log N}\right)^{1/2} h''_x$$

By properties of G_N^D we have

$$\mathrm{Cov}(\widetilde{h}''_x, \widetilde{h}''_y) = \begin{cases} t + o(1), & \text{if } |x-y| \le r \\ o(1), & \text{if } |x-y| \ge N/r \end{cases}$$

So we conclude: The law of

$$\left\{\widetilde{h}''_x\colon x \in D_L,\, h'_x \ge m_N - \lambda,\, h'_x = \max_{z\in\Lambda_r(x)} h'_z\right\}$$

is asymptotically that of independent B.M.'s □

Question: Which point processes on $\overline{D} \times \mathbb{R}$ are invariant under independent Dysonization

$$(x,h) \mapsto \left(x, h + B_t - \frac{\alpha}{2} t\right)$$

of (the second coordinate of) its points?

Easy to check: $\mathrm{PPP}(\nu(\mathrm{d}x) \otimes \mathrm{e}^{-\alpha h} \mathrm{d}h)$ okay for any ν (even random)

Any other solutions?

Liggett's 1977 derivation

For $t > 0$ define Markov kernel P on $\overline{D} \times \mathbb{R}$ by

$$(\mathrm{P}g)(x,h) := E^0 g\big(x, h + B_t - \tfrac{\alpha}{2} t\big)$$

Set $g(x,h) := \mathrm{e}^{-f(x,h)}$ for $f \geq 0$ continuous with compact support. Proposition implies

$$E\big(\mathrm{e}^{-\langle \eta, f\rangle}\big) = E\big(\mathrm{e}^{-\langle \eta, f^{(n)}\rangle}\big)$$

where

$$f^{(n)}(x,h) = -\log(\mathrm{P}^n \mathrm{e}^{-f})(x,h)$$

P has **uniform dispersivity property:** For $C \subset \overline{D} \times \mathbb{R}$ compact

$$\sup_{x,h} \mathrm{P}^n\big((x,h), C\big) \underset{n\to\infty}{\longrightarrow} 0$$

and thus $\mathrm{P}^n \mathrm{e}^{-f} \to 1$ uniformly on $\overline{D} \times \mathbb{R}$. Expanding the log,

$$f^{(n)} \sim 1 - \mathrm{P}^n \mathrm{e}^{-f} \qquad \text{as } n \to \infty$$

Liggett's 1977 derivation (continued)

Hence

$$E\left(e^{-\langle \eta, f\rangle}\right) = \lim_{n\to\infty} E\left(e^{-\langle \eta, 1-\mathsf{P}^n e^{-f}\rangle}\right) \qquad (*)$$

But, as P is Markov,

$$\langle \eta, 1-\mathsf{P}^n e^{-f}\rangle = \langle \eta\mathsf{P}^n, 1-e^{-f}\rangle$$

$(*)$ shows that $\{\eta\mathsf{P}^n\colon n\geq 1\}$ is tight. Along a subsequence

$$\eta\mathsf{P}^{n_k}(\mathrm{d}x,\mathrm{d}h) \xrightarrow[k\to\infty]{\text{law}} M(\mathrm{d}x,\mathrm{d}h)$$

and so

$$E\left(e^{-\langle \eta, f\rangle}\right) = E\left(e^{-\langle M, 1-e^{-f}\rangle}\right)$$

i.e., $\eta = \mathrm{PPP}(M(\mathrm{d}x,\mathrm{d}h))$. Clearly,

$$M\mathsf{P} \overset{\text{law}}{=} M$$

Proof of Theorem
Key question II

Question: What M can we get in our case?

Theorem (Liggett 1977)

$MP \overset{\text{law}}{=} M$ implies $MP = M$ a.s. when P is a kernel of

(1) *an irreducible, recurrent Markov chain*

(2) *a random walk on a closed abelian group w/o proper closed invariant subset*

(2) covers our case.
Note: $MP = M$ means M invariant for the chain. Choquet-Deny (or $t \downarrow 0$) show

$$M(\mathrm{d}x, \mathrm{d}h) = Z^D(\mathrm{d}x) \otimes \mathrm{e}^{-\alpha h}\mathrm{d}h + \widetilde{Z}^D(\mathrm{d}x) \otimes \mathrm{d}h$$

Tightness of maximum forces $\widetilde{Z}^D = 0$ a.s. □

Proof of Theorem
Finishing touch: Uniqueness of the limit

We thus know $\eta_{N_k,r_{N_k}} \xrightarrow{\text{law}} \eta$ implies

$$\eta = \mathrm{PPP}\big(Z^D(\mathrm{d}x) \otimes \mathrm{e}^{-\alpha h}\mathrm{d}h\big)$$

for some random Z^D — albeit possibly depending on subsequence.
But for $Z := Z^D(\overline{D})$, this reads

$$P\big(M_{N_k} \le m_{N_k} + t\big) \underset{k\to\infty}{\longrightarrow} E\big(\mathrm{e}^{-\alpha^{-1} Z \mathrm{e}^{-\alpha t}}\big)$$

Hence the law of $Z^D(\overline{D})$ unique if limit law of maximum unique (and we know this for a fact from Bramson & Ding & Zeitouni)

Existence of joint limit of maxima in finite number of disjoint subsets of $D \Rightarrow$ uniqueness of law of $Z^D(\mathrm{d}x)$ $\square$

Some literature

Details for above derivation for $D := (0,1)^2$:
Biskup-Louidor (arXiv:1306.2602)

Maxima for log-correlated fields:
Madaule (arXiv:1307.1365), Acosta (arXiv:1311.2000)
Ding, Roy and Zeitouni (in preparation)

Properties of Z-measure

Theorem

The measure Z^D satisfies:

(1) $Z^D(A) = 0$ *a.s. for any Borel* $A \subset \overline{D}$ *with* $\mathrm{Leb}(A) = 0$

(2) $\mathrm{supp}(Z^D) = \overline{D}$ *and* $Z^D(\partial D) = 0$ *a.s.*

(3) Z^D *is non-atomic a.s.*

Property (3) is only barely true:

Conjecture

Z^D is supported on a set of zero Hausdorff dimension

Fancy properties

Gibbs-Markov for Z^D measure

Recall $\widetilde{D} \subset D$ yields $h^D \overset{\text{law}}{=} h^{\widetilde{D}} + \varphi^{D,\widetilde{D}}$

Fact: $\varphi^{D,\widetilde{D}} \xrightarrow{\text{law}} \Phi^{D,\widetilde{D}}$ on $\widetilde{D}$ where

(1) $\{\Phi^{D,\widetilde{D}}(x) \colon x \in \widetilde{D}\}$ Gaussian with $E\Phi^{D,\widetilde{D}}(x) = 0$ and

$$\mathrm{Cov}\big(\Phi^{D,\widetilde{D}}(x), \Phi^{D,\widetilde{D}}(y)\big) = G^D(x,y) - G^{\widetilde{D}}(x,y)$$

(2) $x \mapsto \Phi^{D,\widetilde{D}}(x)$ harmonic on $\widetilde{D}$ a.s.

Theorem (Gibbs-Markov property)

Suppose $\widetilde{D} \subset D$ *be such that* $\mathrm{Leb}(D \smallsetminus \widetilde{D}) = 0$. *Then*

$$Z^D(\mathrm{d}x) \overset{\text{law}}{=} \mathrm{e}^{\alpha \Phi^{D,\widetilde{D}}(x)} Z^{\widetilde{D}}(\mathrm{d}x)$$

Fancy properties
Conformal invariance (CFI)

Theorem (Conformal invariance)

Suppose $f : D \to \widetilde{D}$ analytic bijection. Then

$$Z^{\widetilde{D}} \circ f(\mathrm{d}x) \stackrel{\text{law}}{=} |f'(x)|^4 Z^D(\mathrm{d}x)$$

In particular, for D simply connected and $rad_D(x)$ conformal radius

$$\mathrm{rad}_D(x)^{-4} Z^D(\mathrm{d}x)$$

is invariant under conformal maps of D.

Note:

(1) $\mathrm{Leb} \circ f(\mathrm{d}x) = |f'(x)|^2 \mathrm{Leb}(\mathrm{d}x)$ and so $\mathrm{rad}_D(x)^{-2}\mathrm{Leb}(\mathrm{d}x)$ is invariant under conformal maps.

(2) For D simply connected, it suffices to know $Z^{\mathbb{D}}$ for $\mathbb{D} :=$ unit disc. So this is a **statement of universality**

Unifying scheme?

Continuum Gaussian Free Field

Continuum GFF := Gaussian on $\mathrm{H}_0^1(D)$ w.r.t. norm $f \mapsto \pi \|\nabla f\|_2^2$

Formal expression: $h(x) = \sum_{n \geq 1} Z_n \varphi_n(x)$
Exists only as a linear functional on $\mathrm{H}_0^1(D)$:

$$h(f) = \sqrt{\pi} \sum_{n \geq 1} Z_n \langle \nabla f, \nabla \varphi_n \rangle_{L^2(D)}$$

Derivative martingale:

$$M'(\mathrm{d}x) = \left[2\mathrm{Var}(h(x)) - h(x)\right] \mathrm{e}^{2h(x) - 2\mathrm{Var}(h(x))} \mathrm{d}x$$

Can be defined by smooth approximations to h or expansion in ONB (Duplantier, Sheffield, Rhodes, Vargas)

KPZ relation links M'-measure of sets to Lebesgue measure

Unifying scheme?
Liouville Quantum Gravity

For D simply connected,

$$M^D(\mathrm{d}x) := \mathrm{rad}_D(x)^2\, M'(\mathrm{d}x)$$

This is the **Liouville Quantum Gravity** measure constructed in (Duplantier, Sheffield, Rhodes, Vargas)

Theorem (B-Louidor, in progress)

There is constant $c_\star \in (0,\infty)$ s.t. for all D

$$Z^D(\mathrm{d}x) \overset{\text{law}}{=} c_\star\, M^D(\mathrm{d}x)$$

Based on characterization of Z^D measure by GM property, conformal invariance and tail behavior

Full extreme process

Recall we were interested in $\eta_N := \sum_{x \in D_N} \delta_{x/N} \otimes \delta_{h_x - m_N}$
A better representation by **cluster process** on $\overline{D} \times \mathbb{R} \times \mathbb{R}^{\mathbb{Z}^2}$:

$$\widehat{\eta}_{N,r} := \sum_{x \in D_N} 1_{\{h_x = \max_{z \in \Lambda_r(x)} h_z\}} \, \delta_{x/N} \otimes \delta_{h_x - m_N} \otimes \delta_{\{h_x - h_{x+z} \colon z \in \mathbb{Z}^2\}}$$

Theorem (B-Louidor, in progress)

There is a measure μ on $\mathbb{Z}^2$ such that (for $r_N \to \infty$, $N/r_N \to \infty$)

$$\widehat{\eta}_{N,r_N} \xrightarrow[N\to\infty]{\text{law}} \mathrm{PPP}\Big(Z^D(\mathrm{d}x) \otimes \mathrm{e}^{-\alpha h} \mathrm{d}h \otimes \mu(\mathrm{d}\phi)\Big)$$

where $\alpha := 2/\sqrt{g} = \sqrt{2\pi}$.

Capable of capturing **universality** w.r.t. short-range perturbations

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Result for measure $\mathrm{e}^{\beta h_x}$: Arguin and Zindy (arXiv:1310.2159)

THE END