Constructive Tensor Field Theory through an example

Vincent Rivasseau[1] Fabien Vignes-Tourneret[2]

[1]Université Paris-Saclay

[2]CNRS & Université de Lyon

Outline

Random tensors, random spaces

Loop Vertex Expansion

An example at work

Random tensors, random spaces

Random tensors, random spaces
- Why?
- How?

Loop Vertex Expansion

An example at work

Random surfaces

- $2D$ quantum gravity and matrix models:
  - Matrix models provide a theory of random discrete surfaces weighted by a discretized Einstein-Hilbert action.
  - Evidence for matrices being the right discretization of $2D$ quantum gravity.

- In the last 10 years, much progress from probabilists:
  - Random metric surfaces (*e.g.* Brownian map).
  - Universal limit of large planar maps.
  - Liouville quantum gravity sphere $=$ Brownian map.

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1. Generalize matrix models to higher dimensions
   - w.r.t. their symmetry properties
   - provide a theory of random spaces

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2. LQG $\Rightarrow$ GFT $\Rightarrow$ T(G)FT

Invariant actions

Symmetry

Consider $T, \overline{T} : \mathbb{Z}^D \to \mathbb{C}$, complex rank D tensors with *no symmetry*.

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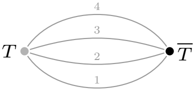
- Invariants as D-coloured graphs



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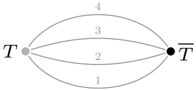

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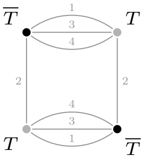

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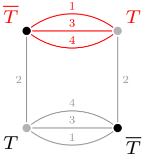

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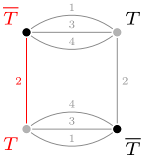

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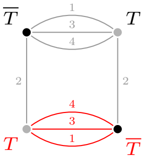

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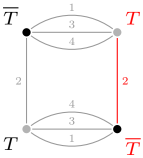

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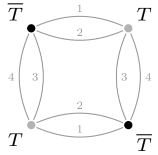

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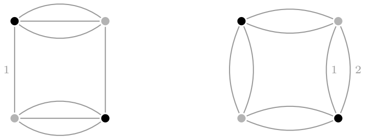

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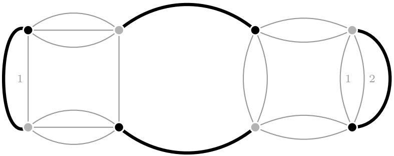

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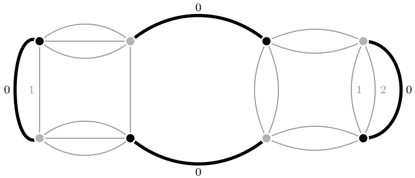

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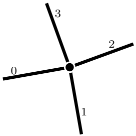

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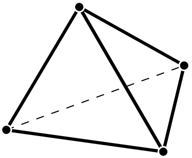

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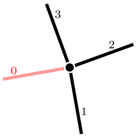
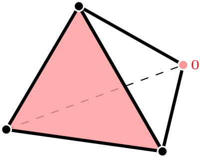


$(D-1)$-face



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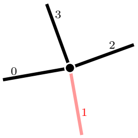

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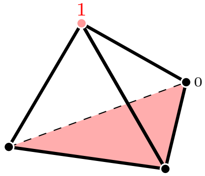

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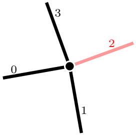

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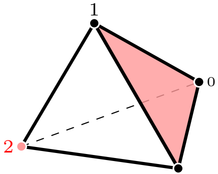

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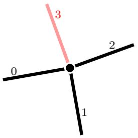

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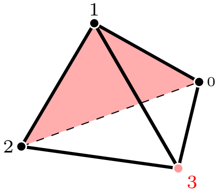

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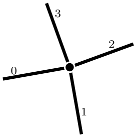

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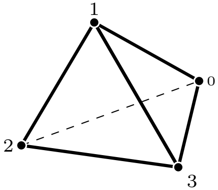

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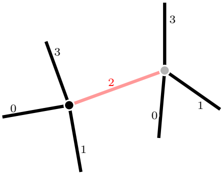
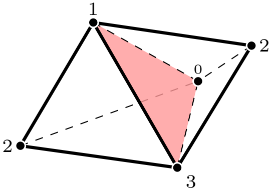


gluing



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LVE = main constructive tool for matrices and tensors

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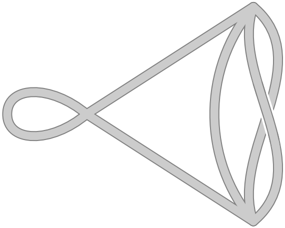
$n+2$ faces at order n



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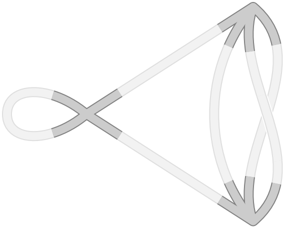
$4n$ indices



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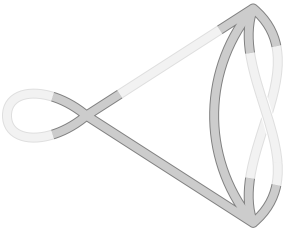
$2n + 2$ free indices



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$$= \sum_{n\geqslant 0} \frac{\lambda^n}{n!} \sum_{T, n(T)=n} A_T, \quad A_T = \sum_{G\supset T} w(G,T) A_G$$

The BKAR forest formula

- Fix an integer $n \geqslant 2$.
- f a function of $\frac{n(n-1)}{2}$ variables x_ℓ, sufficiently differentiable.
- K_n, complete graph on $\{1, 2, \ldots, n\}$. $\#E(K_n) = \frac{n(n-1)}{2}$

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Then,

$$f(1, 1, \ldots, 1) = \sum_{\mathcal{F}} \int dw_{\mathcal{F}} \, \partial_{\mathcal{F}} f(X^{\mathcal{F}}(w_{\mathcal{F}}))$$

where

- the sum is over spanning forests of K_n,
- $\int dw_{\mathcal{F}} := \prod_{\ell \in E(\mathcal{F})} \int_0^1 dw_\ell$,
- $\partial_{\mathcal{F}} := \prod_{\ell \in E(\mathcal{F})} \frac{\partial}{\partial x_\ell}$,
- $X^{\mathcal{F}} = (x_\ell^{\mathcal{F}})_{\ell \in E(K_n)}$ with $x_\ell^{\mathcal{F}}$ the infimum of the $w_{\ell'}$ for ℓ' running over the unique path (if it exists) in $\mathcal{F}$ joining the two ends of ℓ if it exists, 0 otherwise.

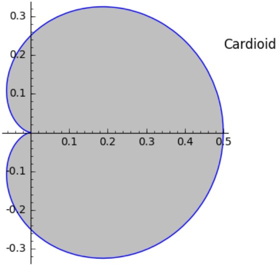
Loop Vertex Expansion

Analyticity of the free energy of ϕ_0^4

$$Z(\lambda) = \int_{\mathbb{R}} e^{-\frac{\lambda}{2}\phi^4}\, d\mu(\phi), \quad d\mu(\phi) = \frac{d\phi}{\sqrt{2\pi}} e^{-\frac{1}{2}\phi^2}$$

Theorem

$\log Z$ is analytic in the cardioid domain $\{\lambda \in \mathbb{C} : |\lambda| < \frac{1}{2}\cos^2(\frac{1}{2}\arg\lambda)\}$.



Loop Vertex Expansion

Analyticity of the free energy of ϕ^4_0

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Theorem

$\log Z$ *is analytic in the cardioid domain* $\left\{\lambda \in \mathbb{C} : |\lambda| < \frac{1}{2}\cos^2\left(\frac{1}{2}\arg\lambda\right)\right\}$.

Proof. LVE is done in 3 steps:

1. Intermediate field representation,
2. Replication of fields,
3. Forest formula.

Loop Vertex Expansion

Analyticity of the free energy of ϕ_0^4

1. Intermediate field representation: $e^{-\frac{\lambda}{2}\phi^4} = \int_{\mathbb{R}} e^{\imath\sigma\phi^2\sqrt{\lambda}}\, d\mu(\sigma)$

$$Z(\lambda) = \int_{\mathbb{R}} e^{-\frac{\lambda}{2}\phi^4}\, d\mu(\phi)$$
$$= \int_{\mathbb{R}} e^{V(\sigma)}\, d\mu(\sigma), \quad V(\sigma) = -\frac{1}{2}\log(1 - \imath\sigma\sqrt{\lambda}).$$

Loop Vertex Expansion

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2. Replication of fields:

$$Z(\lambda) = \sum_{n\geqslant 0} \frac{1}{n!}\int_{\mathbb{R}} V(\sigma)^n\, d\mu(\sigma) = \sum_{n\geqslant 0} \frac{1}{n!}\int_{\mathbb{R}^n} \Big(\prod_{i=1}^{n} V(\sigma_i)\Big)\, d\mu_{\mathbb{1}_n}(\vec{\sigma}).$$

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$$Z = \sum_{n\geqslant 0} \frac{1}{n!} \sum_{\mathcal{F}\subset K_n} \int dw_{\mathcal{F}} \int \Big[\prod_{\ell\in E(\mathcal{F})} \frac{\partial}{\partial\sigma_{i(\ell)}} \frac{\partial}{\partial\sigma_{j(\ell)}} \prod_{i=1}^n V(\sigma_i)\Big]\, d\mu_{C^{\mathcal{F}}(w)}(\vec{\sigma})$$

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Loop Vertex Expansion

Analyticity of the free energy of ϕ_0^4

$$\log Z = \sum_{n\geqslant 1} \frac{1}{n!} \sum_{\mathcal{T}\subset K_n} \int dw_{\mathcal{T}} \int \Big[\prod_{\ell\in E(\mathcal{T})} \frac{\partial}{\partial\sigma_{i(\ell)}} \frac{\partial}{\partial\sigma_{j(\ell)}} \prod_{i=1}^{n} V(\sigma_i) \Big] \, d\mu_{C^{\mathcal{T}}(w)}(\vec{\sigma})$$

$$= \frac{1}{2} \sum_{n\geqslant 1} \frac{(-\lambda/2)^{n-1}}{n!} \sum_{\mathcal{T}\subset K_n} \int dw_{\mathcal{T}} \int \Big[\prod_{i=1}^{n} \frac{(d_i-1)!}{(1-\imath\sigma_i\sqrt{\lambda})^{d_i}} \Big] \, d\mu_{C^{\mathcal{T}}(w)}(\vec{\sigma}).$$

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Using $\left|1-\imath\sigma\sqrt{\lambda}\right| \geqslant \cos(\frac{1}{2}\arg\lambda)$, we get

$$|\log Z| \leqslant \frac{1}{2} \sum_{n=1}^{\infty} \frac{1}{n!} \Big(\frac{|\lambda|}{2\cos^2(\frac{1}{2}\arg\lambda)} \Big)^{n-1} \sum_{\mathcal{T}\subset K_n} \prod_{i=1}^{n} (d_i-1)!$$

$$\leqslant 2 \sum_{n=1}^{\infty} \Big(\frac{2|\lambda|}{\cos^2(\frac{1}{2}\arg\lambda)} \Big)^{n-1}$$

which is convergent for all $\lambda\in\mathbb{C}$ such that $|\lambda| < \frac{1}{2}\cos^2(\frac{1}{2}\arg\lambda)$. $\square$

An example at work

Random tensors, random spaces

Loop Vertex Expansion

An example at work
- Presentation and main result
- Sketch of the proof

The T_4^4 field theory

- Tensor fields:

$$T : \mathbb{Z}^4 \to \mathbb{C}, \qquad T_{\boldsymbol{n}}, \overline{T}_{\overline{\boldsymbol{n}}} \text{ with } \boldsymbol{n}, \overline{\boldsymbol{n}} \in \mathbb{Z}^4.$$

The T_4^4 field theory

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- Free action:

$$d\mu_C(T, \overline{T}) = \left(\prod_{\boldsymbol{n}, \overline{\boldsymbol{n}}} \frac{dT_n d\overline{T}_{\bar{n}}}{2i\pi} \right) \det(C^{-1})\ e^{-\sum_{n,\bar{n}} T_n C^{-1}_{n\bar{n}} \overline{T}_{\bar{n}}},$$

$$C_{\boldsymbol{n},\overline{\boldsymbol{n}}} = \frac{(\mathbf{1}_{\leqslant j_{\max}})_{\boldsymbol{n}\overline{\boldsymbol{n}}}}{\boldsymbol{n}^2 + 1}\, \delta_{\boldsymbol{n},\overline{\boldsymbol{n}}}, \quad \boldsymbol{n}^2 := n_1^2 + n_2^2 + n_3^2 + n_4^2,$$

$$\mathbf{1}_{\leqslant j_{\max}} = 1_{\boldsymbol{n}^2 + 1 \leqslant M^{2j_{\max}}}\, \delta_{\boldsymbol{n},\overline{\boldsymbol{n}}}.$$

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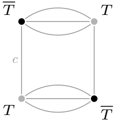
- Interactions:

$$V(T, \overline{T}) = \tfrac{g}{2} \sum_{c=1}^{4} V_c(T, \overline{T}), \qquad V_c(T, \overline{T}) =$$



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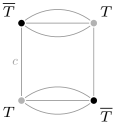

- Formal partition function:

$$Z_0(g) = \int e^{-\frac{g}{2} \sum_c V_c(T, \overline{T})} \, d\mu_C(T, \overline{T}).$$

The T_4^4 field theory

Perturbative renormalisation

Proposition

T_4^4 is renormalisable to all orders of perturbation.

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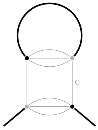
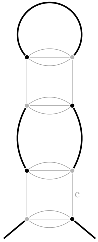
- 2 divergent 2-point graphs:



$\mathcal{M}_1^c$



$\mathcal{M}_2^c$

The T_4^4 field theory

Perturbative renormalisation

Proposition

T_4^4 is renormalisable to all orders of perturbation.

- Power counting similar to the one of ϕ_3^4.
- 2 divergent 2-point graphs: $\mathcal{M}_1^c, \mathcal{M}_2^c$
- 7 divergent melonic vacuum graphs

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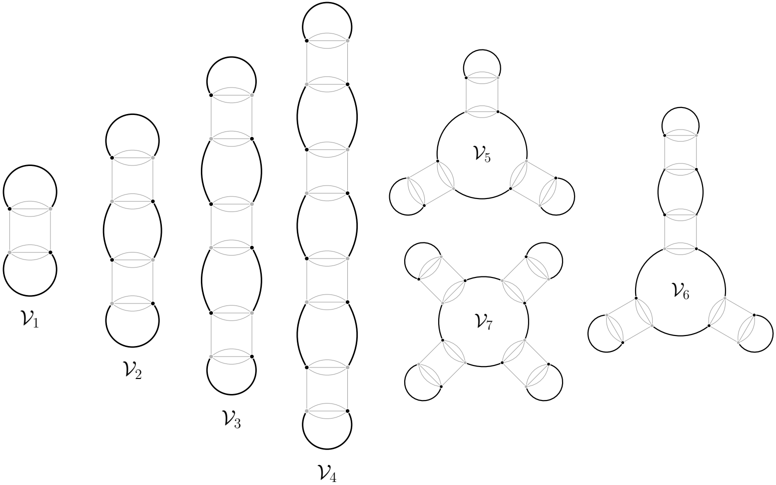

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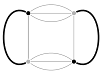
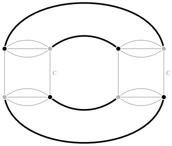
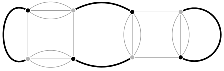
- 2 divergent 2-point graphs: $\mathcal{M}_1^c, \mathcal{M}_2^c$
- 7 divergent melonic vacuum graphs: $\mathcal{V}_i, i = 1, 2, \ldots, 7$
- 3 divergent non melonic vacuum graphs:



$\mathfrak{N}_1$



$\mathfrak{N}_2$



$\mathfrak{N}_3$

The T^4_4 field theory

Analyticity

- Renormalised partition function:

$$Z_{j_{\max}}(g) = \mathcal{N} \int e^{-\frac{g}{2}\sum_c V_c(T,\overline{T}) + T\cdot\overline{T}\left(\sum_{G\in\mathcal{M}} \frac{(-g)^{|G|}}{S_G}\,\delta_G\right)} d\mu_C(T,\overline{T}),$$

$$\mathcal{M} = \{\mathcal{M}_1^c, \mathcal{M}_2^c,\ c = 1,2,3,4\},$$

$\log \mathcal{N}$ = (finite) sum of the counterterms of the divergent vacuum connected graphs.

- Renormalised partition function:

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$$\begin{aligned} \mathcal{M} &= \{\mathcal{M}_1^c, \mathcal{M}_2^c,\ c = 1,2,3,4\}\,, \\ \log\mathcal{N} &= \text{(finite) sum of the counterterms of the divergent} \\ &\quad\ \text{vacuum connected graphs.} \end{aligned}$$

Theorem (Rivasseau, V.-T. 2017)

There exists $\rho > 0$ such that $\lim_{j_{max}\to\infty} \log Z_{j_{max}}(g)$ is analytic in the cardioid domain defined by $|\arg g| < \pi$ and $|g| < \rho\cos^2(\frac{1}{2}\arg g)$.

The general strategy

0. Renormalised partition function:

$$Z_{j_{\max}}(g) = \mathcal{N} \int e^{-\frac{g}{2}\sum_c V_c(T,\overline{T}) + T\cdot\overline{T}\left(\sum_{G\in\mathcal{M}} \frac{(-g)^{|G|}}{S_G}\,\delta_G\right)}\, d\mu_C(T,\overline{T}).$$

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1. Intermediate field representation: $\sigma_c \in \mathrm{Herm}_{M^{j_{\max}}}, \ c = 1,2,3,4$

$$Z_{j_{\max}}(g) = \mathcal{N} e^{\delta_t} \int e^{-\operatorname{Tr}\log(\mathbb{I}-\Sigma) - \imath\lambda \sum_c \delta_m^c \operatorname{Tr}_c \sigma_c}\, d\nu_{\mathbb{I}}(\vec{\sigma})$$

$$\begin{aligned} \lambda &= g^{1/2} \\ \Sigma &= \imath\lambda C^{1/2}\sigma C^{1/2} \\ \sigma &= \sigma_1 \otimes \mathbb{I}_2 \otimes \mathbb{I}_3 \otimes \mathbb{I}_4 + \mathbb{I}_1 \otimes \sigma_2 \otimes \mathbb{I}_3 \otimes \mathbb{I}_4 + \cdots \end{aligned}$$

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2. Renormalised *action*:

$$Z_{j_{\max}}(g) = \int e^{-\operatorname{Tr}\log_3(\mathbb{I}-U) - \operatorname{Tr}(D_1\Sigma^2) - \frac{\lambda^2}{2}:\vec{\sigma}\cdot Q\vec{\sigma}:}\, d\nu_{\mathbb{I}}(\vec{\sigma})$$

$$U = \Sigma + D_1 + D_2$$

$$D_1 = -\lambda^2 C^{1/2} A^{\mathrm{r}}_{\mathcal{M}_1} C^{1/2}, \qquad D_2 = \lambda^4 C^{1/2} A^{\mathrm{r}}_{\mathcal{M}_2} C^{1/2}$$

$$\log_3(\mathbb{I}-U) = \log(\mathbb{I}-U) + U + \frac{U^2}{2}$$

The general strategy

3. Multiscale decomposition:

$$C_{\leqslant j} := \delta_{\boldsymbol{n},\bar{\boldsymbol{n}}} \frac{(\mathbf{1}_{\leqslant j})_{\boldsymbol{n}\bar{\boldsymbol{n}}}}{\boldsymbol{n}^2+1}$$

$$V_{\leqslant j} = \mathrm{Tr}\log_3[\mathbb{I} - U_{\leqslant j}] + \mathrm{Tr}[D_{1,\leqslant j}\Sigma^2_{\leqslant j}] + \frac{\lambda^2}{2} :\vec{\sigma}\cdot Q_{\leqslant j}\vec{\sigma}:$$

$$V_{\leqslant j_{\max}} = \sum_{j=1}^{j_{\max}} (V_{\leqslant j} - V_{\leqslant j-1}) =: \sum_{j=1}^{j_{\max}} V_j$$

$$Z_{j_{\max}}(g) = \int \prod_j e^{-V_j}\, d\nu_{\mathbb{I}}(\vec{\sigma}) = \int e^{-\sum_j \overline{\chi}_j W_j(\sigma)\chi_j}\, d\nu_{\mathbb{I}}(\vec{\sigma}) d\mu(\overline{\chi},\chi)$$

$$W_j = e^{-V_j} - 1$$

The general strategy

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$$Z_{j_{\max}}(g) = \mathcal{N} \int e^{-\frac{g}{2}\sum_c V_c(T,\overline{T}) + T\cdot\overline{T}\left(\sum_{G\in\mathcal{M}} \frac{(-g)^{|G|}}{S_G}\,\delta_G\right)}\, d\mu_C(T,\overline{T}).$$

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The general strategy

4. Multiscale Loop Vertex Expansion: [Gurau, Rivasseau 2014]
   - 2 forest formulas on top of each other (2-jungle formula)
   - First, a Bosonic forest then a Fermionic one

The general strategy

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The general strategy

4. Multiscale Loop Vertex Expansion: [Gurau, Rivasseau 2014]
   - 2 forest formulas on top of each other (2-jungle formula)
   - First, a Bosonic forest then a Fermionic one

$$\log Z_{j_{\max}}(g) = \sum_{n=1}^{\infty} \frac{1}{n!} \sum_{\mathcal{J}\ \text{tree}} \sum_{j_1=1}^{j_{\max}} \cdots \sum_{j_n=1}^{j_{\max}} \int d\boldsymbol{w}_{\mathcal{J}} \int d\nu_{\mathcal{J}}\, \partial_{\mathcal{J}} \Big[\prod_{\mathcal{B}} \prod_{a\in\mathcal{B}} \big(-\bar{\chi}^{\mathcal{B}}_{j_a} W_{j_a}(\vec{\sigma}^a) \chi^{\mathcal{B}}_{j_a}\big) \Big]$$

- $\boldsymbol{w}_{\mathcal{J}}$ = weakening parameters w_ℓ, $\ell \in E(\mathcal{J})$
- $\nu_{\mathcal{J}}$ = interpolated Gaussian Bosonic and Fermionic measures
- $\partial_{\mathcal{J}}$ = derivatives with respect to the σ-, χ- and $\bar{\chi}$-fields

The general strategy

4. Multiscale Loop Vertex Expansion: [Gurau, Rivasseau 2014]
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$$= \sum_{n=1}^{\infty} \frac{1}{n!} \sum_{\mathcal{J} \text{ tree}} \sum_{j_1=1}^{j_{\max}} \cdots \sum_{j_n=1}^{j_{\max}} \int d\mathbf{w}_{\mathcal{J}} \prod_{\mathcal{B}} \Big(\prod_{\substack{a,b \in \mathcal{B} \\ a \neq b}} (1 - \delta_{j_a j_b}) \Big) I_{\mathcal{B}}$$

$$I_{\mathcal{B}} = \int \partial_{\mathcal{B}} \prod_{a \in \mathcal{B}} W_{j_a}(\vec{\sigma}^a)\, d\nu_{\mathcal{B}} = \sum_{\mathrm{G}} \int \Big(\prod_{a \in \mathcal{B}} e^{-V_{j_a}(\vec{\sigma}^a)} \Big) A_{\mathrm{G}}(\vec{\sigma})\, d\nu_{\mathcal{B}}(\vec{\sigma})$$

- Graphs G are plane forests.

The general strategy

Bosonic bounds

$$I_{\mathcal{B}} = \sum_{G} \int \Big(\prod_{a \in \mathcal{B}} e^{-V_{j_a}(\vec{\sigma}^a)} \Big) A_G(\vec{\sigma}) \, d\nu_{\mathcal{B}}(\vec{\sigma})$$

$$|I_{\mathcal{B}}| \leqslant \underbrace{\Big(\int \prod_{a \in \mathcal{B}} e^{2|V_{j_a}(\vec{\sigma}^a)|} \, d\nu_{\mathcal{B}} \Big)^{1/2}}_{I_{\mathcal{B}}^{NP},\ \text{non-perturbative}} \sum_{G} \underbrace{\Big(\int |A_G(\vec{\sigma})|^2 \, d\nu_{\mathcal{B}} \Big)^{1/2}}_{I_{\mathcal{B}}^{P},\ \text{perturbative}}$$

The general strategy

Bosonic bounds

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5. Non-perturbative bound:

Theorem

For ρ small enough and for any value of the w interpolating parameters,

$$I_{\mathcal{B}}^{NP} = \int \prod_{a\in\mathcal{B}} e^{2|V_{j_a}(\vec{\sigma}^a)|}\, d\nu_{\mathcal{B}} \leqslant O(1)^{|\mathcal{B}|}.$$

The general strategy

Bosonic bounds

$$|I_{\mathcal{B}}| \leqslant \underbrace{\Big(\int \prod_{a\in\mathcal{B}} e^{2|V_{j_a}(\vec{\sigma}^a)|}\, d\nu_{\mathcal{B}}\Big)^{1/2}}_{I_{\mathcal{B}}^{NP},\ \text{non-perturbative}} \sum_{\mathrm{G}} \underbrace{\Big(\int |A_{\mathrm{G}}(\vec{\sigma})|^2\, d\nu_{\mathcal{B}}\Big)^{1/2}}_{I_{\mathcal{B}}^{P},\ \text{perturbative}}$$

6. Perturbative bound:

Theorem

Let $\mathcal{B}$ be a Bosonic block. Then there exists $K \in \mathbb{R}_+^*$ such that

$$I_{\mathcal{B}}^P(\mathrm{G}) \leqslant K^{|\mathcal{B}|-1}\big((|\mathcal{B}|-1)!\big)^{37/2} \rho^{e(\mathrm{G})} \prod_{a\in\mathcal{B}} M^{-\frac{1}{48}j_a}.$$

The general strategy

0. Renormalised partition function
1. Intermediate field representation
2. Renormalised action
3. Multiscale decomposition
4. Multiscale Loop Vertex Expansion
5. Non-perturbative Bosonic bound
6. Perturbative Bosonic bound

The general strategy

0. Renormalised partition function
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5. Non-perturbative Bosonic bound
6. Perturbative Bosonic bound
7. Put everything together and cross your fingers... □

Conclusion and perspectives

- Tensor field theory provides a combinatorial theory of random D-spaces.
- In the last 8 years, a lot of results with tensors: $\frac{1}{N}$-expansion, perturbative and constructive renormalisation, continuum limit of the dominant triangulations, double scaling limit, uniform random complexes etc.
- Regarding T_4^4, one could also prove Borel summability and analyticity of the connected correlation functions.

Conclusion and perspectives

- Tensor field theory provides a combinatorial theory of random D-spaces.
- In the last 8 years, a lot of results with tensors: $\frac{1}{N}$-expansion, perturbative and constructive renormalisation, continuum limit of the dominant triangulations, double scaling limit, uniform random complexes etc.
- Regarding T_4^4, one could also prove Borel summability and analyticity of the connected correlation functions.

- T_5^4 (just renormalisable, asymptotically free)
- New Loop Vertex Representation [Rivasseau 2017]
- Simplify Bosonic constructive theory?

Thank you for your attention

Non-perturbative bounds

Theorem

For ρ small enough and for any value of the w interpolating parameters,

$$I_{\mathcal{B}}^{NP} = \int \prod_{a\in\mathcal{B}} e^{2|V_{j_a}(\vec{\sigma}^a)|}\, d\nu_{\mathcal{B}} \leqslant O(1)^{|\mathcal{B}|} e^{O(1)\rho^{3/2}|\mathcal{B}|}.$$

Proof.

1. Expand each node:

$$e^{2|V_{j_a}|} = \sum_{k=0}^{p_a} \frac{(2|V_{j_a}|)^k}{k!} + \int_0^1 dt_{j_a}(1-t_{j_a})^{p_a} \frac{(2|V_{j_a}|)^{p_a+1}}{p_a!} e^{2t_{j_a}|V_{j_a}|}.$$

2. Crude non-perturbative bound: (Quadratic bound)

$$\int \prod_{a\in\mathcal{B}} e^{2|V_{j_a}(\vec{\sigma}^a)|}\, d\nu_{\mathcal{B}} \leqslant K^{|\mathcal{B}|} e^{K'\rho M^{j_1}}.$$

3. Power counting (via quartic bound) beats both combinatorics and the crude non-perturbative bound. □

Perturbative bound

Theorem

Let $\mathcal{B}$ be a Bosonic block. Then there exists $K \in \mathbb{R}_+^*$ such that

$$I_{\mathcal{B}}^{P}(\mathsf{G}) = \int |A_{\mathsf{G}}(\vec{\sigma})|^2 \, d\nu_{\mathcal{B}} \leqslant K^{|\mathcal{B}|-1} \big((|\mathcal{B}|-1)!\big)^{37/2} \rho^{e(\mathsf{G})} \prod_{a \in \mathcal{B}} M^{-\frac{1}{48} j_a}.$$

- $A_{\mathsf{G}}(\vec{\sigma})$ depends on σ (essentially) through resolvents.
- If not for resolvents, A_{G} would be the amplitude of a convergent graph.
- Remove resolvents with iterated Cauchy-Schwarz estimates.