La relation maîtresse qui simplifie les cartes et libère les cumulants

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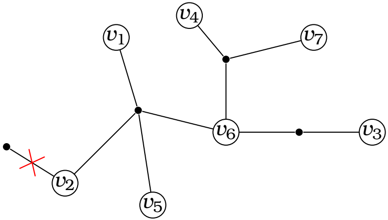
(Based on joint work with G. Borot, S. Charbonnier, F. Leid, S. Shadrin: arXiv:2112.12184)



Journées de Combinatoire de Bordeaux

10 juin, 2022

Outline

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3 contexts:

- **Free probability:**

  Moments φ $\leftrightarrow$ Free cumulants κ

- **Combinatorics:**

  Maps $\leftrightarrow$ Fully simple maps

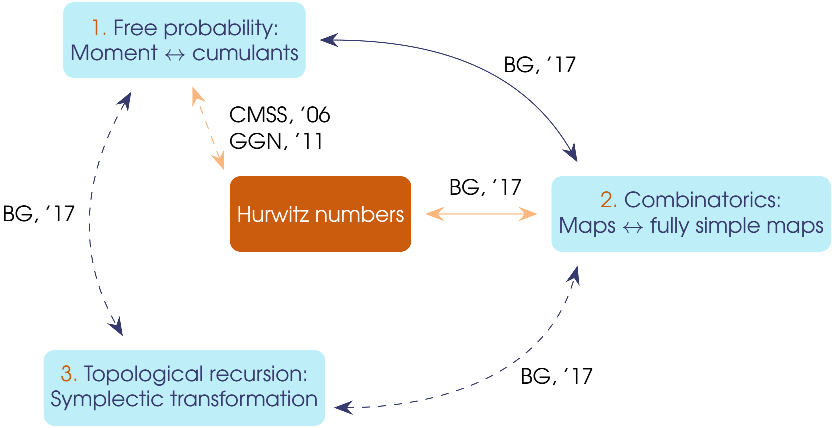
- **Topological recursion (TR):**

$$\begin{cases} \Sigma \text{ Riemann surface} \\ x\colon \Sigma \to \mathbb{C}\mathrm{P}^1,\ y\colon \Sigma \to \mathbb{C}\mathrm{P}^1 \\ \omega_{0,1} = y\,\mathrm{d}x \text{ 1-form} \\ \omega_{0,2} \text{ bidifferential} \end{cases} \xrightarrow[\quad\quad\quad]{\textbf{TR}} \begin{array}{l} \text{Multi-differentials} \\ \omega_{g,n}(z_1,\ldots,z_n),\ z_i \in \Sigma, \\ \forall g,n \geq 0. \end{array}$$

$$(x,y) \overset{\mathrm{TR}}{\rightsquigarrow} \omega_{g,n} \quad \leftrightarrow \quad (\check{x},\check{y}) \overset{\mathrm{TR}}{\rightsquigarrow} \check{\omega}_{g,n},$$

with $\mathrm{d}x \wedge \mathrm{d}y = \mathrm{d}\check{x} \wedge \mathrm{d}\check{y}$ (symplectic transformation).

3 incarnations of the master relation: symplectic, simple and free



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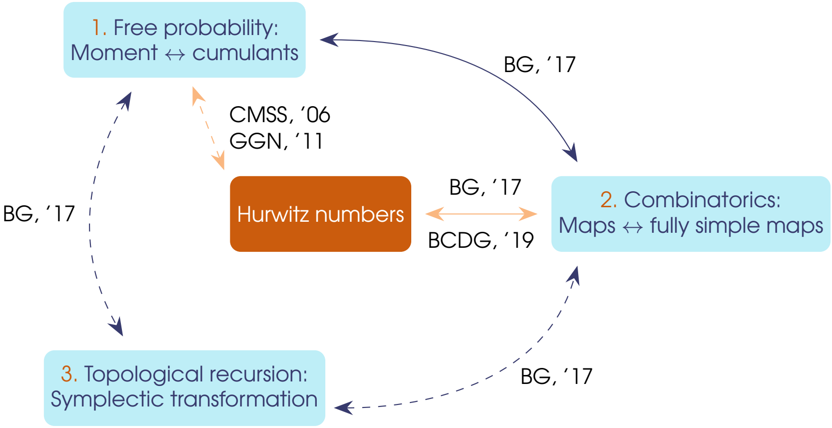

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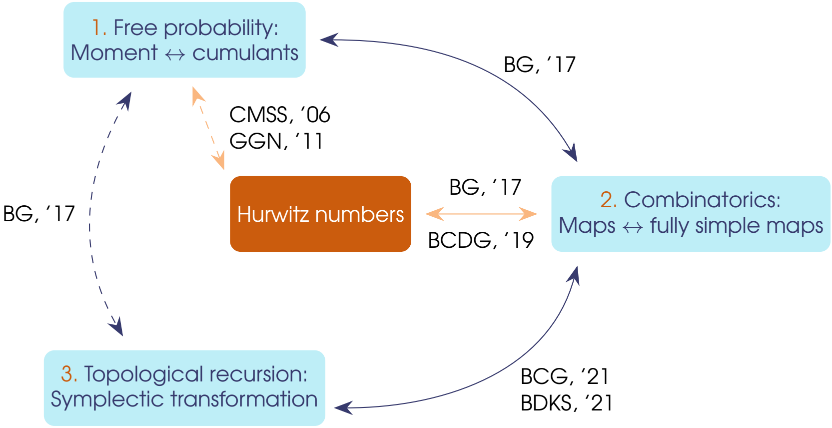

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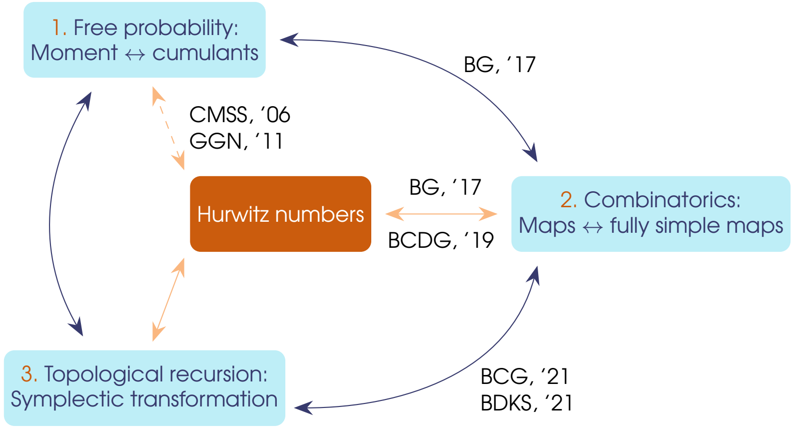

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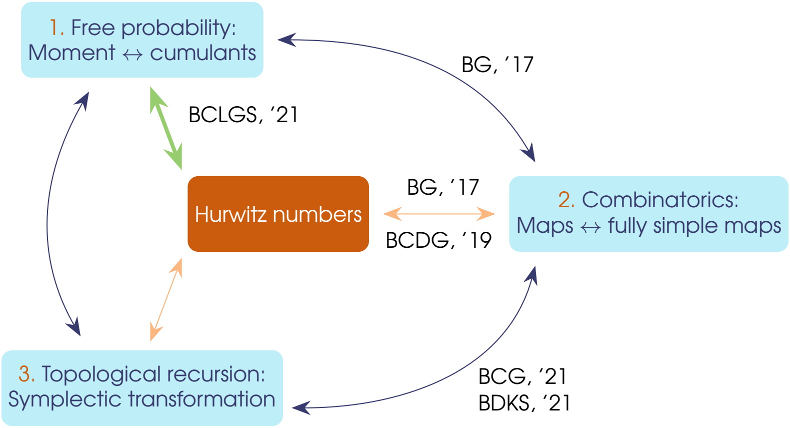

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Double monotone Hurwitz numbers

$k, d \in \mathbb{Z}_{\geq 0}$, $\lambda, \mu \vdash d$.

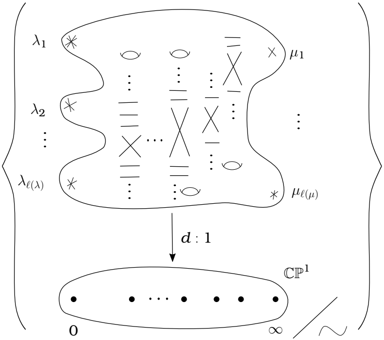
Definition

Double Hurwitz number $H_k(\lambda, \mu) \rightsquigarrow$ number of possibly disconnected coverings of the sphere with ramification profile

- λ over 0, μ over ∞,
- simply ramified over k points in $\mathbb{P}^1 \setminus \{0, \infty\}$,

weighted by $|\mathrm{Aut}|$.

$H_k(\lambda, \mu) := \#$



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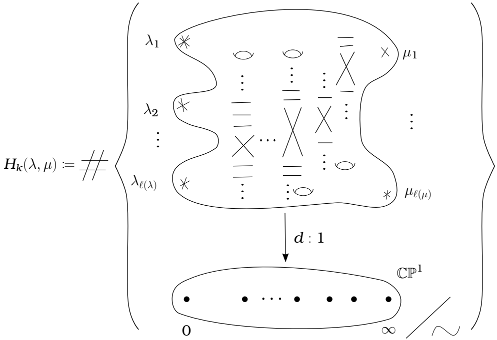

- $C_\lambda \rightsquigarrow$ Conjugacy class in $\mathfrak{S}_d$ of elements of cycle type $\lambda \vdash d$.

$$H_k(\lambda, \mu) = \frac{1}{d!} \left| \{(\sigma, \tau_1, \ldots, \tau_k) \mid \sigma \in C_\lambda,\ \tau_i \in C_{(2,1\ldots,1)},\ \sigma\tau_1 \cdots \tau_k \in C_\mu\} \right| .$$

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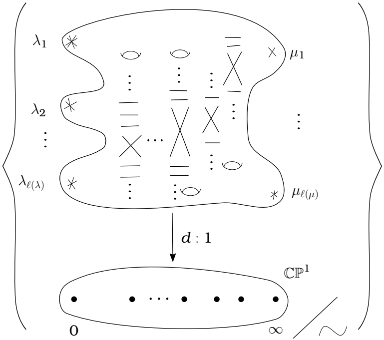

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Transpositions $\tau_i = (a_i\ b_i)$, with $a_i < b_i$, $i = 1, \dots, k$:

- $b_i \leq b_{i+1} \rightsquigarrow$ *Weakly monotone:* $H_k^{\leq}(\lambda, \mu)$ (Goulden–Guay-Paquet–Novak,'11).
- $b_i < b_{i+1} \rightsquigarrow$ *Strictly monotone:* $H_k^{<}(\lambda, \mu)$.

$$\boxed{H^{<}(\lambda, \mu) = \sum_{k=0}^{d-1} H_k^{<}(\lambda, \mu)\hbar^k \in \mathbb{Q}[\hbar] \quad \text{and} \quad H^{\leq}(\lambda, \mu) = \sum_{k \geq 0} H_k^{\leq}(\lambda, \mu)\,(-\hbar)^k \in \mathbb{Q}[\![\hbar]\!].}$$

Topological partition functions and master relation

Fock space $\rightsquigarrow$ completion of the ring of symmetric polynomials with coefficients formal series in $\hbar$:

$$\mathcal{F}_R := R[\![p_1, p_2, p_3, \ldots]\!] , \qquad \mathcal{F}_{R,\hbar} := \mathcal{F}_R \otimes \mathbb{Q}(\!(\hbar)\!) .$$

- $\lambda \in \mathcal{Y} \rightsquigarrow$ Young diagrams. Consider $p_\lambda = p_{\lambda_1} \cdots p_{\lambda_{\ell(\lambda)}}$.
- $z(\lambda) = \prod_{i=1}^{\ell(\lambda)} \lambda_i \prod_{j>1} m_j(\lambda)!$, where $m_j(\lambda)$ is the number of $j's$ in λ.

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Topological partition function: $Z = e^F \in \mathcal{F}_{R,\hbar}$, $F = \sum_{g\geq 0} \hbar^{2g-2} F_g$, $F_g \in \mathcal{F}_R$.

$$Z = \exp\Bigg(\sum_{\substack{g\geq 0 \\ \lambda\in\mathcal{Y}}} \hbar^{2g-2} \frac{F_g(\lambda)}{z(\lambda)} p_\lambda \Bigg) = 1 + \sum_{\lambda\in\mathcal{Y}} \hbar^{-|\lambda|-\ell(\lambda)} Z(\lambda) p_\lambda.$$

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Two topological partition functions Z and $Z^\vee$ satisfy the master relation if

$$\boxed{Z(\lambda) = z(\lambda) \sum_{\mu\vdash|\lambda|} H^<(\lambda,\mu) Z^\vee(\mu)} \qquad (\star)$$

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Dual formulation of the master relation:

$$(\star) \Leftrightarrow Z^\vee(\lambda) = z(\lambda) \sum_{\mu\vdash|\lambda|} H^{\leq}(\lambda,\mu) Z(\mu).$$

Multiplicative functions, correlators, open problem and strategy

Topological partition function $Z = e^F \leftrightarrow$ multiplicative function $\Phi_{Z,\hbar} : PS \to R[\![\hbar]\!]$, with PS the poset of partitioned permutations.

Topological partition function $Z = e^F \leftrightarrow$ correlators ($= n$-point functions) $G_{g,n}$:

$$G_{g,n}(x_1, \ldots, x_n) = \sum_{\ell_1,\ldots,\ell_n > 0} F_{g;\ell_1,\ldots,\ell_n} x_1^{\ell_1} \cdots x_n^{\ell_n} + \delta_{g,0}\delta_{n,1}.$$

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Open problem in free probability:

$$G_{0,n} \xleftrightarrow{\text{M-C}} G^\vee_{0,n}, \quad \text{for } n > 3?$$

Known for $n = 1, 2$ in free probability (and combinatorics) and (for $n = 3$ in topological recursion).

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Maps and fully simple maps

Definition

A map of genus g and n *boundaries* is a connected graph Γ embedded into a closed oriented surface X of genus g such that

$$X \setminus \Gamma \cong \bigsqcup \mathbb{D} \quad \textit{(faces)}, \text{ with } n \text{ distinguished faces, (up to iso).}$$

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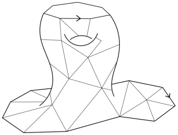

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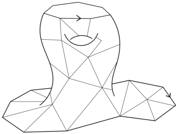

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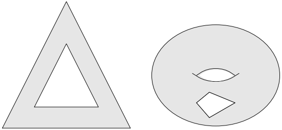

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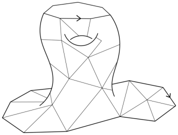

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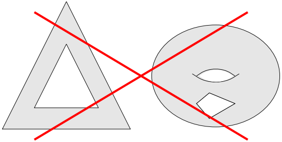

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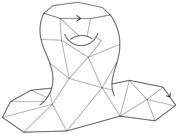

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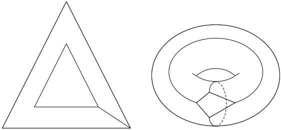

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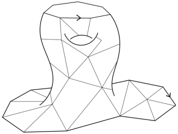

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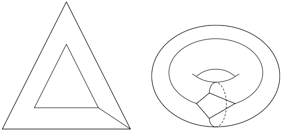
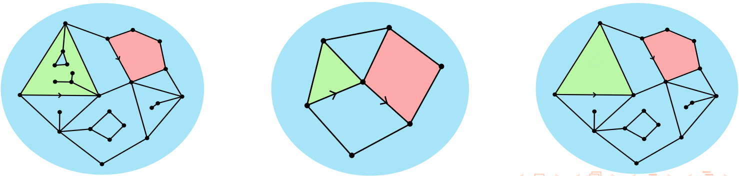


Simple: Boundaries are simple polygons.

Fully simple: Simple and pairwise disjoint boundaries.



Maps and formal hermitian matrix models

Generating series of maps of genus g and n boundaries of lengths $l_1, \ldots, l_n$:

$$\mathrm{Map}^{[g]}_{l_1,\ldots,l_n} := \sum_{\mathcal{M} \in \mathbb{M}^{[g]}_n(l_1,\ldots,l_n)} \prod_{f \in \mathrm{IFaces}(\mathcal{M})} t_{\text{length}(f)} \cdot$$

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$\mathcal{H}_N$: $N \times N$ hermitian matrices. $V(x) = \frac{x^2}{2} - \sum_{k\geq 1} \frac{t_k}{k} x^k$ and the (unitary invariant) measure on $\mathcal{H}_N$:

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Maps and formal hermitian matrix models

Generating series of maps of genus g and n boundaries of lengths $l_1, \ldots, l_n$:

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Moments and classical cumulants:

$$\left\langle \prod_{i=1}^{n} \mathrm{Tr}\, M^{\ell_i} \right\rangle \quad \text{and} \quad c_n\left(\mathrm{Tr}\, M^{\ell_1}, \ldots, \mathrm{Tr}\, M^{\ell_n}\right).$$

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- $\gamma = (c_1\, c_2\, \dots\, c_{\ell(\gamma)})$ cycle in $\mathfrak{S}_N \rightsquigarrow \mathcal{P}_\gamma(M) := \prod_{i=1}^{\ell(\gamma)} M_{c_i,\gamma(c_i)}$.

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where γ_i are pairwise disjoint cycles of $\mathfrak{S}_N$ ($N \geq \sum_{i=1}^{n} \ell(\gamma_i)$).

From maps to free probability via matrix models

Free probability from matrix model:

$$\varphi_{\ell_1,\dots,\ell_n} = \lim_{N\to\infty} N^{n-2} c_n\big(\mathrm{Tr}\, M^{\ell_1}, \dots, \mathrm{Tr}\, M^{\ell_n}\big),$$

$$\kappa_{\ell_1,\dots,\ell_n} = \lim_{N\to\infty} N^{n-2+d} c_n\big(\mathcal{P}_{\gamma_1}(M), \dots, \mathcal{P}_{\gamma_n}(M)\big),\ d = \sum_{i=1}^{n} \ell_i.$$

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Proposition (Brézin–Itzykson–Parisi–Zuber, '78, Borot–G-F, '17)

$$c_n\big(\mathrm{Tr}\, M^{\ell_1}, \ldots, \mathrm{Tr}\, M^{\ell_n}\big) = \sum_{g\geq 0} N^{2-2g-n} \mathrm{Map}^{[g]}_{\ell_1,\ldots,\ell_n},$$

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Remark: For more general multi-tracial hermitian measures, stuffed maps.

From maps to free probability

$$\varphi_{\ell_1,\ldots,\ell_n} = \mathrm{Map}^{[0]}_{\ell_1,\ldots,\ell_n}, \quad \kappa_{\ell_1,\ldots,\ell_n} = \mathrm{FSMap}^{[0]}_{\ell_1,\ldots,\ell_n}.$$

From maps to free probability via matrix models

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From maps to free probability (with genus corrections)

$$\varphi^{[g]}_{\ell_1,\ldots,\ell_n} = \mathrm{Map}^{[g]}_{\ell_1,\ldots,\ell_n},\quad \kappa^{[g]}_{\ell_1,\ldots,\ell_n} = \mathrm{FSMap}^{[g]}_{\ell_1,\ldots,\ell_n}.$$

The origin of the master relation

$\lambda \vdash d$. $\mathrm{Map}^{\bullet}_{\lambda}$ and $\mathrm{FSMap}^{\bullet}_{\lambda}$ generating series of possibly disconnected maps with boundary lengths given by λ and with weight $N^{\chi(\mathcal{M})}$.

Theorem (Borot–G-F, '17, Borot–Charbonnier–Do–G-F, '19)

$$\mathrm{FSMap}^{\bullet}_{\lambda} = z(\mu) \sum_{\lambda \vdash d} H^{\leq}(\lambda, \mu)\big|_{\hbar = \frac{1}{N}} \mathrm{Map}^{\bullet}_{\mu}, \tag{1}$$

$$\mathrm{Map}^{\bullet}_{\lambda} = z(\lambda) \sum_{\mu \vdash d} H^{<}(\lambda, \mu)\big|_{\hbar = \frac{1}{N}} \mathrm{FSMap}^{\bullet}_{\mu}. \tag{2}$$

3 proofs:

- Via matrix models: Express

$$\mathrm{FSMap}^{\bullet}_{\lambda} = \Big\langle \mathcal{P}_{\lambda}(A) \Big\rangle = \Big\langle \prod_{i=1}^{n} \mathcal{P}_{\gamma_i}(A) \Big\rangle = \Big\langle \int_{\mathcal{U}_N} \mathcal{P}_{\lambda}(UAU^{-1}) \mathrm{d}U \Big\rangle$$

  in terms of the $\Big\langle \prod_{i=1}^{n} \mathrm{Tr}\, M^{\lambda_i} \Big\rangle$, using Weingarten calculus.
- 2 combinatorial proofs $\rightsquigarrow$ 1 via bijective combinatorics.

Proof via bijective combinatorics (joint work with G. Borot, S. Charbonnier and N. Do)

Definition

Dessin d'enfant $\rightsquigarrow$ map with each edge adjacent to one boundary face and one internal face. Boundary faces $\rightsquigarrow$ blue faces and internal faces $\rightsquigarrow$ red faces.

Proof via bijective combinatorics (joint work with G. Borot, S. Charbonnier and N. Do)

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$D_k(\lambda, \mu) \rightsquigarrow$ number of (possibly disconnected) dessins d'enfant with blue face degrees by λ and red face degrees by μ, and with k more edges than vertices.

$$D_k(\lambda, \mu) = z(\lambda) H_k^{<}(\lambda, \mu).$$

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Idea: Construct a bijective function:

map $\longmapsto$ (fully simple map, dessin d'enfant)

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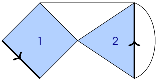
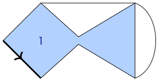
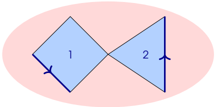


ordinary map

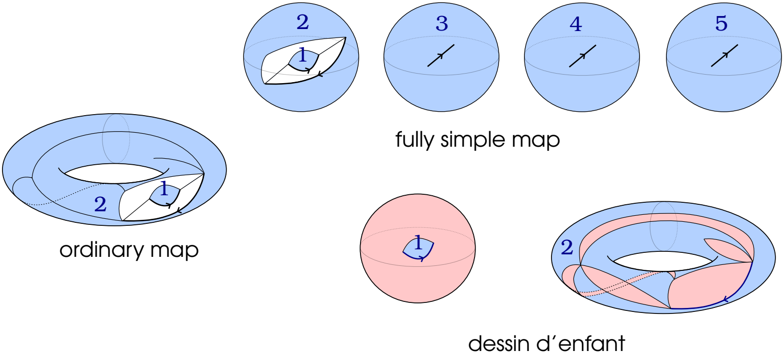


fully simple map



dessin d'enfant

Proof via bijective combinatorics (joint work with G. Borot, S. Charbonnier and N. Do)



Slogan: The fully simple map encodes the internal faces of the map while the dessin encodes how the boundaries of the map intersect.

Topological recursion (TR, Chekhov–Eynard–Orantin '04-'07)

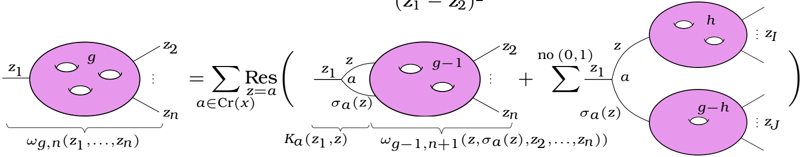
Goal: "Count surfaces $S_{g,n}$ of genus g with n boundaries (topology (g,n))."

Spectral curve

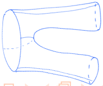
$$\mathbf{TR}: \begin{cases} \Sigma \text{ Riemann surface} \\ x\colon \Sigma \to \mathbb{C}P^1 \\ \omega_{0,1} = y\,\mathrm{d}x \text{ 1-form (discs)} \\ \omega_{0,2} \quad (1,1)\text{-form (cylinders)} \end{cases} \xrightarrow[\text{recursion on } |\chi(S_{g,n})| = 2g-2+n]{} \begin{array}{l}\text{Differential forms} \\ \omega_{g,n}(z_1,\dots,z_n),\ z_i \in \Sigma, \\ \forall g,n \geq 0.\end{array}$$

- x finitely many simple ramification points ($\mathrm{Cr}(x)$) and y holomorphic around $a \in \mathrm{Cr}(x)$ and $\mathrm{d}y(a) \neq 0 \Rightarrow$ Local involution σ around every ramification point: $x(z) = x(\sigma(z))$.
- $\omega_{0,2}$ symmetric bi-differential on $\Sigma \times \Sigma$ with only double poles along the diagonal and vanishing residues, that is when $z_1 \to z_2$

$$\omega_{0,2}(z_1,z_2) = \frac{\mathrm{d}z_1\mathrm{d}z_2}{(z_1-z_2)^2} + \overbrace{h(z_1,z_2)}^{\text{holomorphic}}.$$



- Terms in correspondence with the ways of cutting a **pair of pants** $(0,3)$ from $S_{g,n}$.



Symplectic invariance

$$(\Sigma, (x, y)) \overset{\mathrm{TR}}{\rightsquigarrow} \omega_{g,n}(z_1, \ldots, z_n) \ (\omega_{g,0} = \mathfrak{F}_g \in \mathbb{C})$$

Symplectic invariance

$$\begin{array}{ccc} (\Sigma,(x,y)) & \overset{\mathsf{TR}}{\rightsquigarrow} & \omega_{g,n}(z_1,\ldots,z_n) \quad (\omega_{g,0}=\mathfrak{F}_g\in\mathbb{C}) \\ \Phi \text{ preserving } |\mathrm{d}x\wedge\mathrm{d}y| \Big\downarrow & & \\ (\Sigma,(\check{x},\check{y})) & & \end{array}$$

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\begin{tikzcd}
(\Sigma,(x,y)) \arrow[r, squiggly, "\mathrm{TR}"] \arrow[d, mapsto, "\begin{array}{r}\Phi \\ \text{preserving} \\ |\mathrm{d}x\wedge\mathrm{d}y|\end{array}"'] & \omega_{g,n}(z_1,\ldots,z_n)\ (\omega_{g,0}=\mathfrak{F}_g\in\mathbb{C}) \arrow[d, equal, "?"] \\
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$\Phi = \mathcal{E} : (x,y) \mapsto (y,x)$ not well understood.

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Let $x(z)=\alpha+\gamma(z+\frac{1}{z})$.

Theorem (Eynard, '05)

$$(\mathbb{CP}^1,(x,y=W_1^{[0]}(x)),\omega_{0,2}=B)$$

$$\Big\downarrow \mathrm{TR}$$

$$\frac{\omega_{g,n}(z_1,\ldots,z_n)}{\mathrm{d}x_1\cdots\mathrm{d}x_n}=W_n^{[g]}(x_1,\ldots,x_n),$$

$$\forall 2g-2+n>0,\ z_i\to\infty.$$

Maps

$\overset{\mathcal{E}}{\longleftrightarrow}$

Symplectic invariance

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Maps

$$\xleftrightarrow{(0,1) \text{ et } (0,2)\ \checkmark} \qquad \xleftrightarrow{\mathcal{E}}$$

Theorem (Borot–Charbonnier–G-F, '21)

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$$\frac{\check{\omega}_{g,n}(z_1,\dots,z_n)}{\mathrm{d}y_1\cdots\mathrm{d}y_n}=X_n^{[g]}(y_1,\dots,y_n),$$

$$\forall 2g-2+n>0,\ z_i\to\infty.$$

Fully simple maps

- Our proof (Borot–Charbonnier–G-F, '21): combinatorial, via ciliated maps.
- Proof by Bychkov–Dunin-Barkowsi–Kazarian–Shadrin, '21: via Fock space formalism (x replaced by $1/x$, as later).

Outline

Partitioned permutations (Collins, Mingo, Śniady, Speicher ,'06)

Partitioned permutations: $(\mathcal{U},\gamma)\in PS(d), \mathcal{U}\in P(d), \gamma\in S(d), \mathcal{U}\geq \mathbf{0}_\gamma$.

$$|(\mathcal{U},\gamma)| := d+\#\mathrm{cyc}(\gamma)-2\#\mathrm{blocks}(\mathcal{U})\geq 0, \quad |(\mathbf{0}_{\mathrm{id}},\mathrm{id})| = d+d-2d=0.$$

Example: $\mathcal{U}=\{\{1,2,3,4,5\},\{6,7,8,9\}\}, \gamma=(1,2,3)(4,5)(6,7,8)$.

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Product on $PS(d)$:

$$(\mathcal{U},\gamma)\cdot(\mathcal{V},\pi) := \begin{cases} (\mathcal{U}\vee\mathcal{V},\gamma\pi), & \text{if } |(\mathcal{U},\gamma)| + |(\mathcal{V},\pi)| = |(\mathcal{U}\vee\mathcal{V},\gamma\pi)| \quad \text{(planarity)} \\ 0, & \text{otherwise.} \end{cases}$$

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Convolution: $f,g\colon PS\to\mathbb{C}$

$$(f*g)(\mathcal{U},\gamma) := \sum_{(\mathcal{V},\pi)\cdot(\mathcal{W},\sigma)=(\mathcal{U},\gamma)} f(\mathcal{V},\pi)g(\mathcal{W},\sigma)$$

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Delta function:

$$\delta(\mathcal{A},\alpha) = \begin{cases} 1 & \text{if } \mathcal{A}=\mathbf{0}_{\mathrm{id}} \text{ and } \alpha=\mathrm{id}, \\ 0 & \text{otherwise}. \end{cases}$$

Zeta function:

$$\zeta(\mathcal{A},\alpha) := \begin{cases} 1 & \text{if } \mathcal{A}=\mathbf{0}_\alpha, \\ 0 & \text{otherwise}. \end{cases}$$

Möbius function: $\exists!\mu\colon PS(d)\to\mathbb{C}$ such that $\mu*\zeta=\zeta*\mu=\delta$.

The open problem

$f : PS \to \mathbb{C}$ multiplicative function (i.e. $f(1_d, \gamma)$ depends only on the conjugacy class of γ and $f(\mathcal{U}, \gamma) = \prod_{U \in \mathcal{U}} f(1_U, \gamma|_U)$).

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$$f_{\ell_1,\dots,\ell_n} := f(1_{\ell_1+\dots+\ell_n}, \gamma_1 \cdots \gamma_n), \quad \gamma_i \text{ a cycle of length } \ell_i.$$

$\varphi, \kappa\colon PS \to \mathbb{C}$ multiplicative functions such that $\varphi = \zeta * \kappa$.

- $\varphi \rightsquigarrow$ moments of a higher order probability space.
- $\kappa \rightsquigarrow$ free cumulants defined by $\kappa = \mu * \varphi$ ($\Leftrightarrow \varphi = \zeta * \kappa$, with $\zeta * \cdot \;\Leftrightarrow$ sum over non-crossing partitioned permutations).

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Encode $\varphi_{\ell_1,\dots,\ell_n}$ and $\kappa_{\ell_1,\dots,\ell_n}$ into the generating series:

$$n = 1: \quad M(x) := 1 + \sum_{\ell \geq 1} \varphi_\ell x^\ell, \quad C(w) := 1 + \sum_{\ell \geq 1} \kappa_\ell w^\ell.$$

Higher order:

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Question: Functional relation between $M_n(x_1, \ldots, x_n)$ and $C_n(w_1, \ldots, w_n)$?

First and second orders

R-transform machinery:

- $n = 1$: (Voiculescu,'86)

$$C(xM(x)) = M.$$

Originally: Relation between the R-transform $R(w)$ and the Stieltjes transform $W(x)$, $C(w) = 1 + wR(w)$ and $W(x) = x^{-1}M(x^{-1})$.
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$$M_2(x_1, x_2) + \frac{x_1 x_2}{(x_1 - x_2)^2} = \frac{\mathrm{d}\ln w_1}{\mathrm{d}\ln x_1}\frac{\mathrm{d}\ln w_2}{\mathrm{d}\ln x_2}\left(C_2(w_1, w_2) + \frac{w_1 w_2}{(w_1 - w_2)^2}\right),$$

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$\mathbf{n = 1, 2}$: (Borot, G-F ,'17) from combinatorics of fully simple maps.
$\mathbf{n = 3}$: (Borot, Charbonnier, G-F ,'21) for specific unitary invariant hermitian matrix models, from topological recursion.

Higher order probability space $(\mathcal{A}, \varphi)$ and free cumulants κ

$\mathcal{A}$ algebra, $\varphi = (\varphi_n)_{n\geq 1}$ moments, with $\varphi_n : \mathcal{A}^n \to \mathbb{C}$ linear.
Decorate PS with $\mathcal{A}$: $PS(\mathcal{A}) := \bigcup_{d\geq 0} PS(d) \times \mathcal{A}^d$.
For $1 \leq j \leq n$, set $L_j = \sum_{i=1}^{j} \ell_i$. Moments are multiplicative functions:

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Definition (Higher order freeness)

$(\mathcal{A}_i)_{i\in I}$ are free if $\kappa(1_n,\pi)[a_1,\ldots,a_d] = 0$, $\forall \pi \in S(d)$ whenever $\exists i(p) \neq i(q)$ such that $a_p \in \mathcal{A}_{i(p)}$ and $a_q \in \mathcal{A}_{i(q)}$.

If $\varphi_n = 0$ for $n \geq 2$: recover first order freeness.
As classical cumulants linearise adding independent variables, free cumulants linearise adding free variables: If $a, b \in \mathcal{A}$ are free,

$$\kappa(1_{|\lambda|},\gamma)[a+b,\ldots,a+b] = \kappa(1_{|\lambda|},\gamma)[a,\ldots,a] + \kappa(1_{|\lambda|},\gamma)[b,\ldots,b],$$

for $\lambda \vdash d$ and $\gamma \in C_\lambda$.

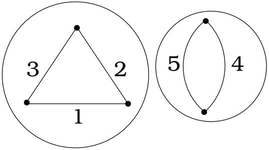
Surfaced free probability

Extended multiplication on partioned permutations:

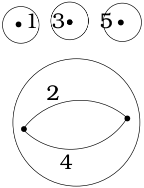
$$(\mathcal{U},\gamma)\odot(\mathcal{V},\pi) := (\mathcal{U}\vee\mathcal{V},\gamma\circ\pi).$$

(Can also be understood as multiplication on surfaced permutations).

$\gamma = (1,2,3)(4,5)$



$\pi = (2,4)$



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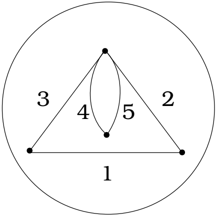

$$|(\mathbf{0}_\gamma,\gamma)|+|(\mathbf{0}_\pi,\pi)| = 5+2-2\cdot 2+5+4-2\cdot 4 = 3+1 = 4 = 5+1-2 = |(\mathbf{0}_{\gamma\pi},\gamma\pi)|.$$

$$|(\mathcal{U},\gamma)| := d + \#\mathrm{cyc}(\gamma) - 2\#\mathrm{blocks}(\mathcal{U})$$

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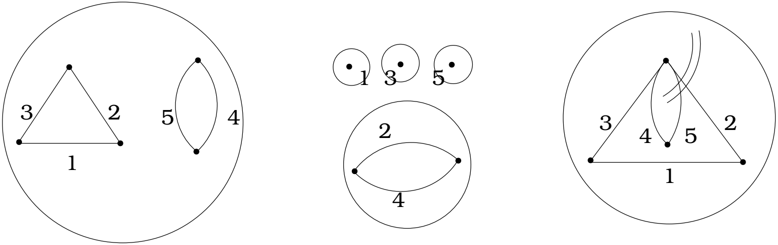

$$|(\mathbf{0}_\gamma,\gamma)|+|(\mathbf{0}_\pi,\pi)| = 5+2-2\cdot1+5+4-2\cdot4 = 5+1 = 6 \neq 4 = 5+1-2 = |(\mathbf{0}_{\gamma\pi},\gamma\pi)|.$$

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Extended convolution:

$$(f_1 \circledast f_2)(\mathcal{C}, \gamma) := \sum_{(\mathcal{A},\alpha)\odot(\mathcal{B},\beta)=(\mathcal{C},\gamma)} f_1(\mathcal{A}, \alpha) f_2(\mathcal{B}, \beta)\,.$$

Extended zeta function:

$$\zeta_\hbar(\mathcal{A}, \alpha) := \hbar^{|\alpha|} \zeta(\mathcal{A}, \alpha), \quad |\alpha| = d - \#\mathbf{0}_\alpha.$$

Extended Möbius function $\mu_\hbar \colon PS(d) \to \mathbb{C}[\![\hbar]\!]$ uniquely determined by

$$\mu_\hbar \circledast \zeta_\hbar = \zeta_\hbar \circledast \mu_\hbar = \delta\,.$$

$\Rightarrow$ Notion of (g, n)-freeness.

Theorem (Borot, Charbonnier, Leid, Shadrin, G-F, '21)

$(A_N)_N, (B_N)_N$ ensembles of random matrices of size N, $(A_N)_N$ unitarily invariant, A_N independent of B_N. Then $A_N \to a$, $B_N \to b$, when $N \to \infty$, and a and b are (g, n)-free, $\forall (g, n)$.

Generalises a theorem of Voiculescu from '91 (first order freeness).

Outline

Moment-free cumulant functional relations

- $\mathcal{G}_{0,n}(\mathbf{r}+1)$: set of bicoloured trees with white vertices labeled from 1 to n having valency $r_1+1,\ldots,r_n+1$, and without univalent black vertices.

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Theorem (Borot, Charbonnier, Leid, Shadrin, G-F, '21)

Let $x_i = w_i/C(w_i)$. For $n \geq 3$,

$$M_n(x_1,\ldots,x_n) = \sum_{r_1,\ldots,r_n\geq 0}\ \sum_{T\in\mathcal{G}_{0,n}(\mathbf{r}+1)} \left(\prod_{i=1}^{n} \mathrm{O}_{r_i}(w_i)\right) \prod_{I\in\mathcal{I}(T)}' C_{\#I}(w_I)\,.$$

- Weight per tree: $\mathcal{W}(T) := \prod'_{I\in\mathcal{I}(T)} C_{\#I}(w_I)$.
- $\prod' \rightsquigarrow C_2(w_i,w_j)$ should be replaced with $C_2(w_i,w_j) + \frac{w_i w_j}{(w_i-w_j)^2}$, if $i \neq j$.

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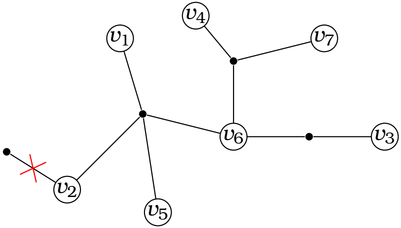
Example: n=7



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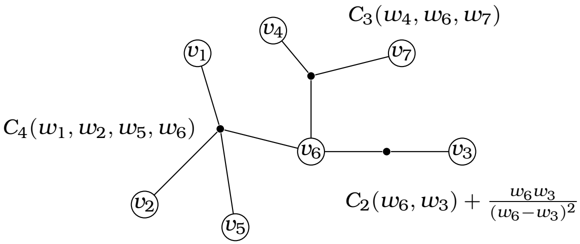
Example: $T\in\mathcal{G}_{0,7}(1,1,1,1,1,3,1)$



$$\mathcal{W}(T)=C_4(w_1,w_2,w_5,w_6)C_3(w_4,w_6,w_7)\Big(C_2(w_6,w_3)+\frac{w_6w_3}{(w_6-w_3)^2}\Big).$$

Finite sums and example

- $\mathcal{G}_{0,n}(\mathbf{r}+1)$: set of bicoloured trees with white vertices labeled from 1 to n having valency $r_1+1,\ldots,r_n+1$, and without univalent black vertices.

Remark

For n fixed, $\mathcal{G}_{0,n}(\mathbf{r}+1) \neq \emptyset$ only for finitely many $\mathbf{r}=(r_1,\ldots,r_n)\in\mathbb{N}^n$.

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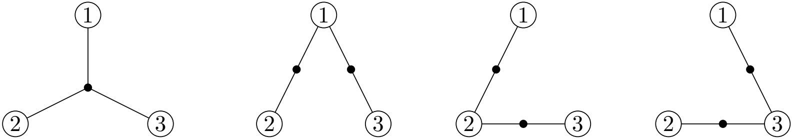

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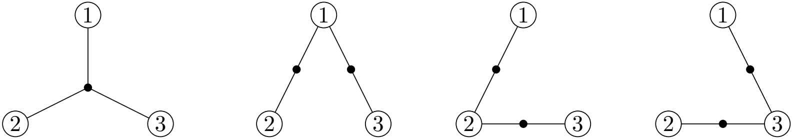

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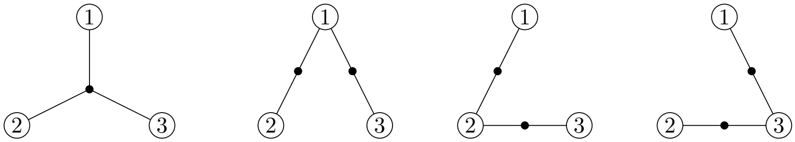

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Remarks $\Rightarrow$ The sums of the RHS of

$$M_n(x_1,\ldots,x_n)=\sum_{r_1,\ldots,r_n\geq 0}\ \sum_{T\in\mathcal{G}_{0,n}(\mathbf{r}+1)}\left(\prod_{i=1}^n \mathrm{O}_{r_i}(w_i)\right)\prod_{I\in\mathcal{I}(T)}' C_{\#I}(w_I)$$

are finite.

Example: $n = 3$

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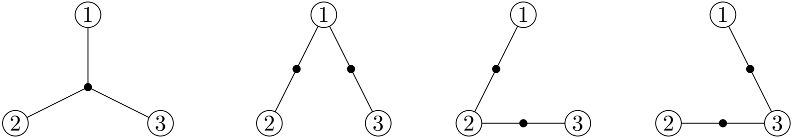

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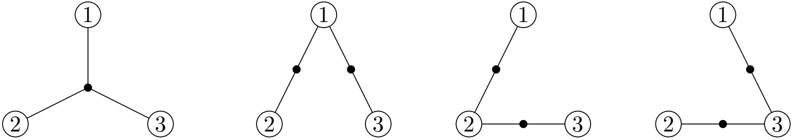

$$\begin{aligned}
\mathcal{W}(T_0) &= C_3(w_1, w_2, w_3), \\
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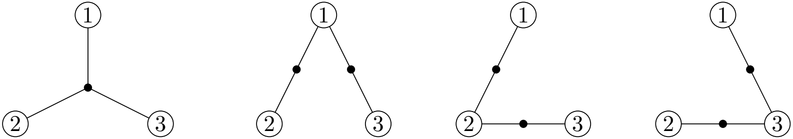
&\vdots
\end{aligned}$$

Example: $n = 3$

$$T_0 = T_{0,0,0}, \qquad T^{(1)} = T_{1,0,0}, \qquad T^{(2)} = T_{0,1,0}, \qquad T^{(3)} = T_{0,0,1}.$$



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$$\mathsf{O}_r(w) := \sum_{m \geq 0} \left(\frac{w}{C(w)x'(w)}\partial_w\right)^m \frac{1}{C(w)x'(w)}[v^m] \left(\partial_y + \frac{v}{y}\right)^r \cdot 1\Big|_{y=C(w)}$$

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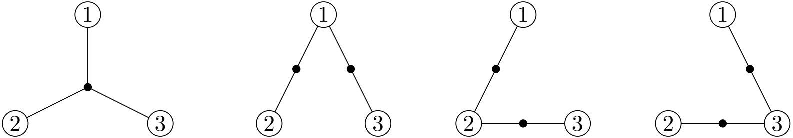

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$$M_n(x_1, \ldots, x_n) = \textstyle\sum_{r_1,\ldots,r_n \geq 0} \sum_{T \in \mathcal{G}_{0,n}(\mathbf{r}+1)} \left(\prod_{i=1}^n \mathrm{O}_{r_i}(w_i)\right)\mathcal{W}(T)$$

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Master relation in the Fock space

- $Z\mathbb{C}[\mathfrak{S}_d] \rightsquigarrow$ center of the group algebra of the symmetric group $\mathfrak{S}_d$.
- Basis (indexed by partitions $\lambda \vdash d$): $\hat{C}_\lambda = \sum_{\gamma \in C_\lambda} \gamma$.
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$$e_k(X_1, \ldots, X_n) = \sum_{1 \leq j_1 < j_2 < \cdots < j_k \leq n} X_{j_1} \cdots X_{j_k}$$ elementary symmetric polynomials.

$$\mathsf{D} := \prod_{k \geq 2} (1 + \hbar J_k) = \sum_{k \geq 0} \hbar^k e_k(J_2, J_3, \ldots) = \sum_{k \geq 0} \sum_{\substack{\tau_1, \ldots, \tau_k \\ (\max \tau_i)_{i=1}^k \\ \text{strictly increasing}}} \tau_1 \cdots \tau_k$$

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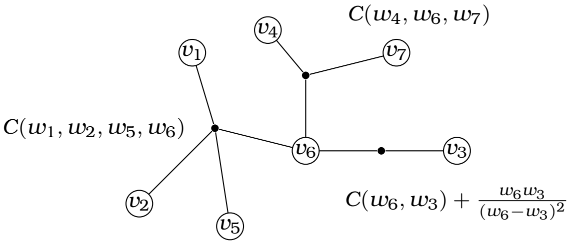
Under the identification Ψ, D acts on $\mathcal{F}_{\mathbb{C},\hbar}$:

Master relation: $Z(\lambda) = z(\lambda) \sum_{\nu \vdash d} H^<(\lambda,\nu) Z^\vee(\nu) \Leftrightarrow Z = \mathrm{D}Z^\vee$

Outline

Future and ongoing work

- Combinatorial proof of the functional relations?
- Master relation simplifies maps; for constellations it forgets one color (from $(m+1)$-constellations to m-constellations). Studying these towers of problems related by the master relation (also from TR and free probability). Other meaningful towers?
- **Conjecture:** If we have TR for $G_{g,n}$, we have TR for $G^{\vee}_{g,n}$ with a symplectically transformed spectral curve.
- Symplectic invariance of TR?



Merci beaucoup pour votre attention !