Random matrix theory: Lecture 25

Recall: \( T = \bigoplus_{n=0}^{\infty} \mathbb{F} e^{n} \), with \( \mathbb{F} = \mathbb{C}^2 \), basis \( (e_1, e_2) \)
- \( A = \{ a : T \to T \text{ linear bounded operator} \} \)
- \( \varphi(a) = \langle 1, a 1 \rangle \)
- \( a_i, a_i^* \) creation and annihilation operators
- \( A_i = a_i + a_i^* \) distributed according to the semi-circle distribution: \( R_{A_i}(z) = z \)
- \( A_1 \) and \( A_2 \) freely independent

Comment 1

\[ R_{A_1 A_2}(z) = R_{A_1}(z) + R_{A_2}(z) = z + z = 2z \]

ie. \( A_1 A_2 \) is again distributed according to the semi-circle distribution (with a different variance).

ie. the semi-circle distribution plays the same role in free probability as the Gaussian distribution in classical probability. The analogy goes on with the following theorem (turn the page).
Free central limit theorem

Let \( a_1, \ldots, a_n, \ldots \) be a sequence of freely independent random variables, identically distributed and such that
\[
q(a_1) = 0 \quad \text{and} \quad q(a_1^2) = 1.
\]

Let \( \mu_n \) be the distribution of \( \frac{1}{\sqrt{n}} (a_1 + \ldots + a_n) \).

Then \( \mu_n \) converges to the semi-circle distribution as \( n \to \infty \).

(i.e. \( R_{\mu_n}(z) \xrightarrow{n \to \infty} = 2 \quad \forall z \in \mathbb{C} \))

Proof idea:

1) For \( c \) a constant and \( A \) a random variable, \( R_{cA}(z) = c \cdot R_A(cz) \):

\[
\begin{align*}
q_{cA}(z) & = q((cA-2I)^{-1}) = \frac{1}{c} q((A-\frac{2}{c}I)^{-1}) = \frac{1}{c} q_A\left(\frac{2}{c}\right) \\
\Rightarrow q^{-1}_{cA}(z) & = c q^{-1}_A(cz) \quad \text{[} \frac{1}{c} q_A\left(\frac{2}{c}\right) = 5 \Rightarrow c q^{-1}_A(c5) = z \text{]} \\
\text{and} \quad R_{cA}(z) & = q^{-1}_{cA}(-z) - \frac{1}{z} = c \cdot R_A(cz)
\end{align*}
\]

2) \( R_{\frac{1}{\sqrt{n}}(a_1 + \ldots + a_n)}(z) = \frac{1}{\sqrt{n}} R_{a_1 + \ldots + a_n}(\frac{z}{\sqrt{n}}) \) by (1)

(by free indep.) = \( \frac{1}{\sqrt{n}} \sum_{j=1}^{n} R_{a_j}(\frac{z}{\sqrt{n}}) = \sqrt{n} \cdot R_{a_1}(\frac{z}{\sqrt{n}}) \)

3) expansion: \( R_{a_1}(z) = \sum_{k=0}^{\infty} c_k z^k \quad \text{where} \quad c_0 = q(a_1) = 0 \), \( c_1 = q(a_1^2) - q(a_1)^2 = 1 \)

\( \Rightarrow R_{a_1}(z) = 2 + o(z) \)

i.e. \( R_{\frac{1}{\sqrt{n}}(a_1 + \ldots + a_n)}(z) = \sqrt{n} \left( \frac{z}{\sqrt{n}} + o\left(\frac{1}{\sqrt{n}}\right) \right) = z + o(1) \)
Comment 2

The fact that $A_n = a_n * q_n$ is distributed according to the semi-circle distribution can be put in relation with the following:

- Let $A^{(n)} := \frac{1}{n} \sum_{i=1}^{n} (\text{deterministic}) \text{ matrices }$ (with $n \to \infty$)

$$Q(A) := a_{11}^{(n)}$$

$$A^{(n)} := \left( \begin{array}{cccc}
1 & 1 \\
0 & 1 \\
\end{array} \right) \text{ deterministic Toeplitz matrix}$$

Then $\lim_{n \to \infty} Q\left( (A^{(n)})^k \right) = \begin{cases} t e & \text{if } k = 2l \\ 0 & \text{otherwise} \end{cases}$

i.e. as $n \to \infty$, $A^{(n)}$ is distributed according to the semi-circle distribution (with respect to expectation $Q$).

Proof

- $Q\left( (A^{(n)})^k \right) = (A^{(n)})^k \quad \text{# Dyck paths of length } 2^k$

$$\lim_{n \to \infty} Q\left( (A^{(n)})^k \right) = \begin{cases} t e & \text{if } k = 2l \\ 0 & \text{otherwise} \end{cases}$$

Note that with such an expectation $Q$, changing only two entries in the Toeplitz matrix changes drastically the limit.

Proof: use $b_{nm}^{(n)} = \frac{1}{n} \text{Tr}(C^{(n)})$
Free multiplicative convolution and S-transform

Let $A$ be a non-commutative random variable such that $q(A) > 0$.

Let 
\[
\begin{align*}
\Phi_A(z) &= \sum_{k \geq 1} q(A^k) z^k \\
S_A(z) &= \frac{z+1}{z} \Phi_A^{-1}(z) \tag{\text{inverse function}}
\end{align*}
\]

\[\ast\]

**Proposition:**

If $A_1, A_2$ are freely independent and s.t. $q(A_1) > 0, q(A_2) > 0$, then 
\[
S_{A_1 A_2}(z) = S_{A_1}(z) S_{A_2}(z)
\]

and the distribution of $A_1 A_2$ is called the free multiplicative convolution and is denoted as $M_{A_1 A_2} = M_{A_1 \boxtimes M_{A_2}}$.

**Proof idea:**

Same technique as for the R-transform:

- Let $A_1 = (I + a_1) \cdot p(q_1^{-1})$ with $p(x)$ some polynomial s.t. $p(0) > 0$.
- Then $S_{A_1}(z) = \frac{1}{p(z)}$; similarly $S_{A_2}(z) = \frac{1}{q(z)}$.
- and $S_{A_1 A_2}(z) = \frac{1}{p(z) q(z)}$.

\[\ast\]

**Example:** $A$ an "quarter circle", i.e. $2 g_A(z) + 2 g_A(z) + 1 = 0$

\[
\Rightarrow z (g_A(z) + 1)^2 = g_A(z) \Rightarrow S_A(z) = \frac{1}{z+1}
\]
Application to random matrices

- Let \( A^{(n)} \) and \( B^{(n)} \) be \( n \times n \) real symmetric independent random matrices with limiting eigenvalue distributions \( \mu_A, \mu_B \).

- Let \( V^{(n)} \) be orthogonal (Haar dist.) & indep. of both \( A^{(n)} \) and \( B^{(n)} \).

- Then \( A^{(n)} \) and \( V^{(n)} B^{(n)} (V^{(n)})^T \) are asymptotically free, so the limiting eigenvalue distribution of \( A^{(n)} V^{(n)} B^{(n)} (V^{(n)})^T \) is given by \( \mu_{AB} = \mu_A \boxtimes \mu_B \) and can be computed via the S-transform.

\[ (*) \text{ such that } \int_{\mathbb{R}} x \, d\mu_A(x) \neq 0 \text{ and } \int_{\mathbb{R}} x \, d\mu_B(x) \neq 0 \]