1. Introduction

First, we recall some definitions.

1.1. Definition. An $N \times N$ matrix $U$ is unitary if $UU^* = I_N$ where $U^*$ is the conjugate transpose of $U$. Then, $U(N)$ is the compact Lie group of all $N \times N$ unitary matrices. Since $U(N - 1) \hookrightarrow U(N)$ via a canonical embedding, we also define

$$U(\infty) := \bigcup_{N=1}^{\infty} U(N)$$

that is, $U(\infty)$ are all infinite $N \times N$ unitary matrices that differ from the identity matrix only in a fixed number of positions.

1.2. Definition. A normalized character of $U(N)$ is a function $\chi : U(N) \to \mathbb{C}$ such that

- (a) $\chi(e) = 1$ (normalized),
- (b) $\chi(ab) = \chi(ba)$ (constant on conjugacy classes),
- (c) $(\sum c_i \chi(a_i))(\sum c_j \chi(a_j)) = \sum c_i c_j \chi(a_i a_j^{-1}) \geq 0$ (nonnegative definite),
- (d) $\chi$ is continuous.

Normalized characters form a convex set since $t\chi_1 + (1 - t)\chi_2$ meets all the axioms of a normalized character for all $t \in [0, 1]$. Then, we can discuss the following notion.

1.3. Definition. An extreme character $\chi : U(N) \to \mathbb{C}$ is a normalized character such that $\chi \neq t\chi_1 + (1 - t)\chi_2$ for any $t \in (0, 1)$ for normalized characters $\chi_1, \chi_2 \neq \chi$.

1.4. Definition. The $N$-dimensional torus is

$$\mathbb{T}^N := \{(x_1, \ldots, x_N) \in \mathbb{C}^N \mid |x_i| = 1\}$$

and lies in $U(N)$ as diagonal matrices. The finitary torus is $\mathbb{T}_{fin}^\infty := \bigcup_{N=1}^{\infty} \mathbb{T}^N$.

Recall one of our main goals is to understand the following theorem.
1.5. **Theorem** (Edrei-Voiculescu). Extreme characters of $U(\infty)$ are functions $\chi: T^\infty_{fin} \to \mathbb{C}$ depending on countably many parameters

\[
\begin{align*}
\alpha^\pm &= (\alpha_1^\pm \geq \alpha_2^\pm \geq \cdots \geq 0); \\
\beta^\pm &= (\beta_1^\pm \geq \beta_2^\pm \geq \cdots \geq 0); \\
\gamma^\pm &\geq 0
\end{align*}
\]

such that

\[
\sum_i \alpha_i^+ + \sum_i \alpha_i^- + \sum_i \beta_i^+ + \sum_i \beta_i^- < \infty, \ \beta_1^+ + \beta_1^- \leq 1
\]

Furthermore, these functions have the form

\[
\chi_{\alpha^\pm, \beta^\pm, \gamma^\pm}(x_1, x_2, \ldots) = \prod_{j=1}^{\infty} \Phi_{\alpha^\pm, \beta^\pm, \gamma^\pm}(x_j)
\]

where $\Phi_{\alpha^\pm, \beta^\pm, \gamma^\pm}: \mathbb{T} \to \mathbb{C}$ is the continuous function

\[
\Phi_{\alpha^\pm, \beta^\pm, \gamma^\pm}(x) := e^{\gamma^+(x-1)+\gamma^-(x^{-1}-1)} \prod_{i=1}^{\infty} \left( \frac{1 + \beta_i^+(x-1)}{1 - \alpha_i^+(x-1)} \cdot \frac{1 + \beta_i^-(x^{-1}-1)}{1 - \alpha_i^-(x^{-1}-1)} \right).
\]

1.6. **Goal.** In this presentation, we will outline two very special examples of this parameterization, namely when

(a) $\beta^+ = (\beta, 0, 0, \ldots), \beta^- = \alpha^\pm = (0, 0, \ldots), \gamma^\pm = 0$ for $\beta \in [0, 1]$ so that

\[
\Phi_{\alpha^\pm, \beta^\pm, \gamma^\pm}(x) = 1 + \beta(x-1) \implies \chi_{\alpha^\pm, \beta^\pm, \gamma^\pm}(x_1, x_2, \ldots) = \prod_{j=1}^{\infty} (1 + \beta(x_j - 1))
\]

(b) $\alpha^+ = (\alpha, 0, 0, \ldots), \beta^\pm = \alpha^\pm = (0, 0, \ldots), \gamma^\pm = 0$ for $\alpha \in [0, 1]$ so that

\[
\Phi_{\alpha^\pm, \beta^\pm, \gamma^\pm}(x) = \frac{1}{1 - \alpha(x-1)} \implies \chi_{\alpha^\pm, \beta^\pm, \gamma^\pm}(x_1, x_2, \ldots) = \prod_{j=1}^{\infty} \frac{1}{1 - \alpha(x_j - 1)}
\]

2. **Symmetric Functions**

In the last lecture, we introduced the following.

2.1. **Definition.** Given a sequence of integers $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_N$, the Schur polynomial is given by

\[
s_\lambda(x_1, \ldots, x_N) = \frac{\det(x_j^{\lambda_i+N-i})_{i,j=1}^{N}}{\det(x_j^{N-i})_{i,j=1}^{N}}
\]

Also, if $\lambda$ has $\lambda_N \geq 0$, we can use “Littlewood’s Combinatorial Description” of Schur functions

2.2. **Proposition.** Given a sequence of integers $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_N \geq 0$, 

\[
s_\lambda(x_1, \ldots, x_N) = \sum_{T \in \text{SSYT}(\lambda)} x^{\text{wt}(T)}
\]
where $x^{\text{wt}(T)} = \prod_{j=1}^{\sum \lambda_i} x_j^{\# \text{ of } j \text{'s in } T}.$

2.3. Example.

\[ s_{(2,1)}(x_1, x_2) = x_1^2 x_2 + x_1 x_2^2 \]

\[
\begin{array}{c c c}
1 & 1 & \text{1 2} \\
2 & & \text{2}
\end{array}
\]

We also proved that

2.4. Theorem. The irreducible representations of $U(N)$ are in one-to-one correspondence with \( \{ \lambda \in \mathbb{Z}^N \mid \lambda_1 \geq \cdots \geq \lambda_N \} \) where the character of representation $T_{\lambda}$ of $U(N)$ corresponding to $\lambda$ has character given by

\[
\text{Tr} \left( T_{\lambda} \begin{pmatrix} x_1 \\ \ddots \\ x_N \end{pmatrix} \right) = s_{\lambda}(x_1, \ldots, x_N)
\]

We will work with two special cases of the Schur polynomials.

2.5. Definition. Let $e_m(x_1, \ldots, x_N) := s_{(1^m)}(x_1, \ldots, x_N)$ be the elementary symmetric polynomials.

2.6. Example. Using the semistandard Young tableaux formula for Schur functions (Littlewood’s combinatorial description), we compute

(a) \[ e_2(x_1, x_2) = x_1 x_2 \]

\[
\begin{array}{c c c}
1 & \text{1} \\
2 & & \text{2}
\end{array}
\]

(b) \[ e_2(x_1, x_2, x_3) = x_1 x_2 + x_1 x_3 + x_2 x_3 \]

\[
\begin{array}{c c c c c c c c c}
1 & & & & & & & & \\
2 & & & & \text{1} & + & \text{1} & & + & \text{2} \\
& & & & & \text{3} & & & & + & \text{3}
\end{array}
\]

(c) \[ e_3(x_1, x_2, x_3) = x_1 x_2 x_3 \]

\[
\begin{array}{c c c c c c c c c}
1 & & & & & & & & \text{1} \\
2 & & & & \text{2} & & & & \text{3}
\end{array}
\]

2.7. Remark. $e_N(x_1, \ldots, x_N)$ encodes character of the “determinant representation” of $U(N)$, that is

\[ T(U)v = (\det U)v = x_1 x_2 \cdots x_N v \]
since the determinant is just the product of the eigenvalues. More generally, 
\( e_m(x_1, \ldots, x_N) \) encodes the representation induced by the \( U(N) \)-action on \( \bigwedge^m \mathbb{C}^N \):

\[
U \cdot (v_1 \wedge \cdots \wedge v_m) = (U v_1 \wedge \cdots \wedge U v_m)
\]

Importantly, we also compute, generalizing our example above

2.8. **Proposition.** For \( 0 < m \leq n \),

\[
e_m(x_1, x_2, \ldots, x_n) = \sum_{T \in \mathrm{SSYT}((1^m))} x^{\text{wt}(T)} = \sum_{I \subseteq \{1, \ldots, n\}, |I| = m} x^I
\]

where \( x^I := \prod_{i \in I} x_i \) and consequently,

\[
e_{m}(1, \ldots, 1) = \binom{n}{m}
\]

**Proof.** To see this, we simply observe that a single column semistandard tableau with \( m \) rows filled with letters \( \{1, \ldots, n\} \) is a choice of \( m \) distinct elements of \( \{1, \ldots, n\} \) since columns must be strictly increasing. \( \square \)

2.9. **Definition.** Let \( h_m(x_1, \ldots, x_N) := s_m(x_1, \ldots, x_N) \) be the complete homogeneous symmetric polynomials.

2.10. **Example.** Using again our tableaux formula for Schur functions, we compute

(a) \( h_2(x_1, x_2) = x_1^2 + x_1x_2 + x_2^2 \)

\[
\begin{array}{cc}
1 & 1 \\
1 & 2 \\
2 & 2 \\
\end{array}
\]

(b) \( h_2(x_1, x_2, x_3) = x_1^2 + x_1x_2 + x_1x_3 + x_2^2 + x_2x_3 + x_3^2 \)

\[
\begin{array}{cccc}
1 & 1 & 1 & 2 \\
1 & 2 & 1 & 3 \\
2 & 2 & 2 & 3 \\
2 & 3 & 3 & 3 \\
\end{array}
\]

2.11. **Proposition.** For \( 0 < m \leq n \),

\[
h_m(x_1, x_2, \ldots, x_n) = \sum_{T \in \mathrm{SSYT}((m))} x^{\text{wt}(T)} = \sum_{I \text{ multiset of } \{1, \ldots, n\}, |I| = m} x^I
\]

where \( x^I := \prod_{i \in I} x_i \) and consequently,

\[
h_{m}(1, \ldots, 1) = \text{Number of ways to choose a multiset of size } m \text{ from } n \text{ things}
\]

\[
= \binom{n + m - 1}{m} = \binom{n + m - 1}{n - 1}
\]
2.12. **Remark.** The combinatorics of the identity above follow by considering a “stars and bars” approach, namely, both expressions are in bijection with the number of ways to place \(n - 1\) bars among \(m\) stars, allowing bars to be consecutive with each other.

\[
\{1, 1, 1, 2, 4, 5\} \rightarrow \ast \ast \ast | \ast | \ast \ast
\]

2.13. **Definition.** Let

\[
\text{(n \choose m)} := \binom{n + m - 1}{m}
\]

be the number of ways to choose a multiset of size \(m\) from \(n\) things.

\section{Two Examples of \(U(\infty)\) characters}

Now, we wish to take a sequence of \(U(N)\) characters to get a character of \(U(\infty)\).

3.1. **Definition.** We say that a sequence of central functions \(f_N\) (i.e. \(f_N\) only depends on the eigenvalues of the input) on \(U(N)\) converge to a central function \(f\) on \(U(\infty)\) if, for every fixed \(K\), we have

\[
f_N(x_1, \ldots, x_K, 1, 1, \ldots) \rightarrow f(x_1, \ldots, x_K, 1, 1, \ldots)
\]

uniformly on the \(K\)-torus \(T^K\) of diagonal matrices.

3.2. **Proposition.** Let \(L: \mathbb{N} \rightarrow \mathbb{N}\) be a sequence such that \(L(N)/N \rightarrow \beta \in [0, 1]\) as \(N \rightarrow \infty\). Then,

\[
e_{L(N)}(x_1, \ldots, x_N) / e_{L(N)}(1, \ldots, 1) \rightarrow \prod_{i=1}^{\infty} (1 + \beta(x_i - 1)), \quad (x_1, x_2, \ldots) \in T_f^\infty
\]

**Proof.** Fix \(K \leq N\). Then,

\[
e_{L(N)}(x_1, \ldots, x_K, 1, \ldots, 1)
\]

\[
= \sum_{\text{T} \in \text{SSYT}(1^{L(N)}) \text{ labelled with } \{1, \ldots, N\}} x^{\text{wt}({\text{T}}_{\leq K})}
\]

\[
= \sum_{\text{binary } K \text{ sequences } \epsilon} \# \{N \text{ sequences with sum } L(N) \text{ that start with } (\epsilon_1, \ldots, \epsilon_K)\} x^{(\epsilon_1, \ldots, \epsilon_K)}
\]

\[
= \sum_{\text{binary } K \text{ sequences } \epsilon} \left( \frac{N - K}{L(N) - \sum_{i=1}^{K} \epsilon_i} \right) x_1^{\epsilon_1} \cdots x_K^{\epsilon_K}
\]

where the last equality comes from considering how to fill tableaux of the form...
3.4. This approach. Derive the proposition directly from this observation. See [Pet12]§4.1.10 for

An astute reader may notice that $(1 - \beta)^{K - \sum_{i=1}^{K} \epsilon_i} \beta^{\sum_{i=1}^{K} \epsilon_i}$ represents the probability of $\sum_{i=1}^{K} \epsilon_i$ successes in $K$ trials where each attempt has probability of success $\beta$. One can use “de Finetti’s theorem” in order to derive the proposition directly from this observation. See [Pet12]§4.1.10 for this approach.

3.3. Remark. An astute reader may notice that $(1 - \beta)^{K - \sum_{i=1}^{K} \epsilon_i} \beta^{\sum_{i=1}^{K} \epsilon_i}$ represents the probability of $\sum_{i=1}^{K} \epsilon_i$ successes in $K$ trials where each attempt has probability of success $\beta$. One can use “de Finetti’s theorem” in order to derive the proposition directly from this observation. See [Pet12]§4.1.10 for this approach.

3.4. Proposition. Let $L : \mathbb{N} \rightarrow \mathbb{N}$ be a sequence such that $L(N)/N \rightarrow \alpha \in [0, 1]$ as $N \rightarrow \infty$. Then,

$$
\frac{h_{L(N)}(x_1, \ldots, x_N)}{h_{L(N)}(1, \ldots, 1)} \rightarrow \prod_{i=1}^{\infty} \frac{1}{1 - \alpha(x_i - 1)}, \quad (x_1, x_2, \ldots) \in \mathbb{T}_{\text{fin}}^\infty
$$

Proof. We proceed much as in the proposition above. For a fixed $K \leq N$, we have

$$
h_{L(N)}(x_1, \ldots, x_K, 1, \ldots, 1)
= \sum_{\epsilon \in \mathbb{N}_0^K} \# \{N \text{ sequences with sum } L(N) \text{ starting with } (\epsilon_1, \ldots, \epsilon_K) \} x_1^{\epsilon_1} \cdots x_K^{\epsilon_K}
= \sum_{\epsilon \in \mathbb{N}_0^K} \left( \frac{N - K}{L(N) - \sum_{i=1}^{K} \epsilon_i} \right) x_1^{\epsilon_1} \cdots x_K^{\epsilon_K}
$$

where the last line comes from thinking about
and so
\[
\frac{h_{L(N)}(x_1, \ldots, x_K, 1, \ldots, 1)}{h_{L(N)}(1, \ldots, 1)} = \sum_{\epsilon \in \mathbb{N}_0^K} \left[ \left( \frac{N - K}{L(N) - \sum_{i=1}^K \epsilon_i} \right) / \left( \frac{N}{L(N)} \right) \right] x_1^{\epsilon_1} \cdots x_K^{\epsilon_K}
\]

Consider that, for fixed \( K \leq N \), we have
\[
\left( \frac{N - K}{L(N) - \sum_{i=1}^K \epsilon_i} \right) / \left( \frac{N}{L(N)} \right) = \left( \frac{N + L(N) - \sum_{i=1}^K \epsilon_i - 1}{(N + L(N) - 1)!} \times \frac{(L(N))!}{(L(N) - \sum_{i=1}^K \epsilon_i)!} \times \frac{(N - 1)!}{(N - K - 1)!} \right)
\]
\[
= \frac{(L(N))^{\sum_{i=1}^K \epsilon_i} N^K}{(N + L(N))^{K + \sum_{i=1}^K \epsilon_i}}
\]
\[
= \left( \frac{L(N)}{N} \right)^{\sum_{i=1}^K \epsilon_i} \left( \frac{1}{1 + \frac{L(N)}{N}} \right)^{K + \sum_{i=1}^K \epsilon_i}
\]
\[
\text{Thus,}
\lim_{N \to \infty} \frac{h_{L(N)}(x_1, \ldots, x_K, 1, \ldots, 1)}{h_{L(N)}(1, \ldots, 1)} = \sum_{\epsilon} \left( \frac{1}{1 + \alpha} \right)^K \left( \frac{\alpha}{1 + \alpha} \right)^{\sum_{i=1}^K \epsilon_i} x_1^{\epsilon_1} \cdots x_K^{\epsilon_K}
\]
\[
= \prod_{i=1}^K \left( \frac{1}{1 + \alpha} \right) \left( 1 + \frac{\alpha}{1 + \alpha} x_i + \left( \frac{\alpha}{1 + \alpha} \right)^2 x_i^2 + \cdots \right)
\]
\[
= \prod_{i=1}^K \frac{1}{1 + \alpha - \alpha x_i}
\]

So, taking \( K \to \infty \) completes the proof. \( \square \)

REFERENCES