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Counting rooted spanning forests in complete multipartite graphs

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Abstract

Jin and Liu discovered an elegant formula for the number of rooted spanning forests in the complete bipartite graph K_{a_1,a_2}, with b_1 roots in the first vertex class and b_2 roots in the second vertex class. We give a simple proof to their formula, and a generalization for complete m-partite graphs, using the multivariate Lagrange inverse.

Y. Jin and C. Liu [3] give a formula for $f(m,l;n,k)$, the number of spanning forests of the labelled complete bipartite graph $K_{n,m}$, where in the forest every tree is rooted, there are k roots in the first vertex class (among the n vertices) and l roots in the second vertex class (among the m vertices), and the trees in the forest are not ordered. They discovered the elegant formula

$$f(m,l;n,k) = \binom{m}{l}\binom{n}{k} n^{m-l-1} m^{n-k-1}(km + ln - lk). \tag{1}$$

The goal of the present note is generalization of (1) from complete bipartite to complete multipartite graphs, through a simple proof using the multivariate Lagrange inverse.

Let $f(a_1, b_1; ...; a_m, b_m)$ denote the number of spanning forests of the labelled complete multipartite graph $K_{a_1,a_2,...,a_m}$, where in the forest every tree is rooted, there are b_i roots in the i^{th} vertex class for $i = 1, 2, ..., m$, and the trees in the forest are not ordered. Let $w_i(t_1, ..., t_m)$ denote the multivariate exponential generating function (EGF) of the numbers $f(a_1, 0; ...; a_i, 1; ...; a_m, 0)$ (the number of rooted spanning trees of the complete multipartite graph $K_{a_1,a_2,...,a_m}$, if the root has to be in the i^{th} class), i.e.

$$w_i(t_1, ..., t_m) = \sum_{a_1=0}^{\infty} ... \sum_{a_i=1}^{\infty} ... \sum_{a_m=0}^{\infty} f(a_1, 0; ...; a_i, 1; ...; a_m, 0) \prod_{k=1}^{m} \frac{t_k^{a_k}}{a_k!}. \tag{2}$$

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The key identity for our argument is

$$t_i e^{(w_1+w_2+\ldots+w_m)-w_i} = w_i \quad \text{for} \quad i = 1, 2, ..., m. \tag{3}$$

The proof of formula (3) is based on the following combinatorial decomposition. Given a rooted spanning tree of the complete multipartite graph $K_{a_1,a_2,\ldots,a_m}$, where the root is in the i^{th} class, remove the root vertex from the tree to obtain a spanning forest of $K_{a_1,a_2,\ldots,a_i-1,\ldots,a_m}$, and mark the former neighbors of the eliminated root vertex as roots in the forest. This decomposition establishes a bijection between the following two sets:
the set of rooted spanning trees of the complete multipartite graph $K_{a_1,a_2,\ldots,a_m}$*, where the root is in the* i^{th} *vertex class,*
and
the set of some ordered pairs, where the first entry of the ordered pair is one of the vertices of the i^{th} *vertex class, the second element of the ordered pair is a rooted spanning forest of* $K_{a_1,a_2,\ldots,a_i-1,\ldots,a_m}$*, where the vertex from the first entry is removed from the* i^{th} *vertex class, and the trees of the forest are not ordered.*
Now $t_i e^{(w_1+w_2+\ldots+w_m)-w_i}$ is the EGF of the set of ordered pairs in question, according to the Exponential Formula; and w_i is the same EGF by the bijection. Set $\Phi_i(w_1, w_2, ..., w_m) = e^{(w_1+w_2+\ldots+w_m)-w_i}$.

According to the multiplication rule of EGF's, $\prod_{k=1}^m w_k^{b_k}$ is the multivariate exponential generating function of the number of rooted spanning forests of complete m-partite graphs, with b_k roots in the k^{th} vertex class, where the trees rooted in the same part *are ordered*; hence

$$f(a_1, b_1; ...; a_m, b_m) = \frac{a_1!a_2!\cdots a_m!}{b_1!b_2!\cdots b_m!}[t_1^{a_1}t_2^{a_2}\cdots t_m^{a_m}]\prod_{k=1}^m w_k^{b_k}. \tag{4}$$

According to Part 1 of Theorem 1.2.9 (Multivariate Lagrange Formula) from [2], (3) implies

$$[t_1^{a_1}t_2^{a_2}\cdots t_m^{a_m}]\prod_{k=1}^m w_k^{b_k} = [\lambda_1^{a_1}\cdots\lambda_m^{a_m}]\Bigg\{\det\left|\delta_{ij} - \frac{\lambda_j}{\Phi_i}\cdot\frac{\partial\Phi_i}{\partial\lambda_j}\right| \tag{5}$$

$$\times \quad \lambda_1^{b_1}\cdots\lambda_m^{b_m}\prod_{k=1}^m e^{a_i(w_1+\ldots+w_m)-a_iw_i}\Bigg\}, \tag{6}$$

where Φ_i is a short-hand notation for $\Phi_i(\lambda_1, ..., \lambda_m)$. Observe that $\frac{\lambda_j}{\Phi_i}\cdot\frac{\partial\Phi_i}{\partial\lambda_j} = (1-\delta_{ij})\lambda_j$, and the for the determinant in (5) we have the well-known evaluation

$$\det\left|\delta_{ij} - (1-\delta_{ij})\lambda_j\right| = (\lambda_1+1)\cdots(\lambda_m+1)\left(1 - \frac{\lambda_1}{\lambda_1+1} - \ldots - \frac{\lambda_m}{\lambda_m+1}\right) \tag{7}$$

(see for example Exercise 225 in [1]). Now (7) is easily rewritten as

$$1 - \sum_{j=2}^m (j-1)\sum_{1\le i_1<i_2<\cdots<i_j\le m}\lambda_{i_1}\lambda_{i_2}\cdots\lambda_{i_j}, \tag{8}$$

and (8) is rewritten as

$$\sum_{l_1=0}^{1}\sum_{l_2=0}^{1}\cdots\sum_{l_m=0}^{1}(1-l_1-l_2-\ldots-l_m)(\lambda_1)_{l_1}(\lambda_2)_{l_2}\cdots(\lambda_m)_{l_m}, \qquad (9)$$

where $(x)_t$ stands for the falling factorial, $(x)_0 = 1$ and $(x)_1 = x$. Introducing the notation $A = a_1 + a_2 + \ldots + a_m$ and using (9), we find that (5) and (6) are equal to

$$[\lambda_1^{a_1-b_1}\lambda_2^{a_2-b_2}\cdots\lambda_m^{a_m-b_m}]\sum_{l_1=0}^{1}\sum_{l_2=0}^{1}\cdots\sum_{l_m=0}^{1}(1-l_1-l_2-\ldots-l_m)$$

$$\times(\lambda_1)_{l_1}(\lambda_2)_{l_2}\cdots(\lambda_m)_{l_m}e^{(A-a_1)\lambda_1}e^{(A-a_2)\lambda_2}\cdots e^{(A-a_m)\lambda_m}$$

$$=\left(\prod_{k=1}^{m}\frac{(A-a_k)^{a_k-b_k-1}}{(a_k-b_k)!}\right)\sum_{l_1=0}^{1}\sum_{l_2=0}^{1}\cdots\sum_{l_m=0}^{1}(1-l_1-l_2-\ldots-l_m) \qquad (10)$$

$$\times\left(\prod_{j=1}^{m}(A-a_j)^{1-l_j}(a_j-b_j)_{l_j}\right). \qquad (11)$$

Combining (10), (11), and (4), we obtain the main result:

Theorem 1

$$f(a_1,b_1;\ldots;a_m,b_m)=\left(\prod_{k=1}^{m}\binom{a_k}{b_k}(A-a_k)^{a_k-b_k-1}\right) \qquad (12)$$

$$\times\sum_{l_1=0}^{1}\sum_{l_2=0}^{1}\cdots\sum_{l_m=0}^{1}(1-l_1-l_2-\ldots-l_m)\left(\prod_{j=1}^{m}(A-a_j)^{1-l_j}(a_j-b_j)_{l_j}\right). \qquad (13)$$

For the case $m = 2$, formula (12), (13) specializes to the formula of Jin and Liu (1), and formula (12), (13) yields a closed formula for every fixed m. Note that for the case $m = 2$ we do not even have to evaluate the determinant in general, since for $m = 2$ simply

$$\det\left|\delta_{ij}-(1-\delta_{ij})\lambda_j\right| = 1-\lambda_1\lambda_2.$$

References

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