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Computing the number of $h$-edge spanning forests in complete bipartite graphs

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Let $f_{m,n,h}$ be the number of spanning forests with $h$ edges in the complete bipartite graph $K_{m,n}$. Kirchhoff’s Matrix Tree Theorem implies $f_{m,n,m} + n - 1 = m^n - 1 - n^m - 1$ when $m \geq 1$ and $n \geq 1$, since $f_{m,n,m} + n - 1$ is the number of spanning trees in $K_{m,n}$. In this paper, we give an algorithm for computing $f_{m,n,h}$ for general $m, n, h$. We implement this algorithm and use it to compute all non-zero $f_{m,n,h}$ when $m \leq 50$ and $n \leq 50$ in under 2 days.

MSC 2010: 68R10, 05C85, 05C30, 05C38, 05C05

Keywords: complete bipartite graph, spanning forest

1 Introduction

A consequence of Kirchhoff’s Matrix Tree Theorem is that the number of spanning trees in the complete bipartite graph $K_{m,n}$ is $m^n - 1 - n^m - 1$ when $m \geq 1$ and $n \geq 1$. In this paper, we consider a generalisation of this counting problem: the number $f_{m,n,h}$ of $h$-edge spanning forests in $K_{m,n}$. The number of spanning trees in $K_{m,n}$ is $f_{m,n,m} + n - 1$ when $m \geq 1$ and $n \geq 1$, since spanning trees of $K_{m,n}$ have $m + n - 1$ edges.

The numbers $f_{m,n,h}$ arise in relation to the Tutte polynomial of $K_{m,n}$. For a general graph $G = (V,E)$, the Tutte polynomial is

$$T_G(x,y) = \sum_{A \subseteq E} (x - 1)^{k(A) - k(E)} (y - 1)^{k(A) + |A| - |V|}$$

where $k(A)$ is the number of connected components in the graph $(V,A)$. Importantly, for the Tutte polynomial, we take $0^0 = 1$. Thus, the number of spanning forests of $G$ is given by

$$T_G(2,1) = \sum_{A \subseteq E} 0^{k(A) + |A| - |V|}$$

$$= \# \{ A \subseteq E : k(A) + |A| = |V| \}$$

$$= \text{number of spanning forests of } G \quad (1)$$

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since \( k(A) + |A| = |V| \) if and only if \( A \) is a spanning forest.

In the present paper, we are interested in the case of when \( G = K_{m,n} \), and will look for \( h \)-edge spanning forests. In this situation,

\[
T_{K_{m,n}}(2, 1) = \sum_{h \geq 0} f_{m,n,h}.
\]

For general graphs \( G = (V, E) \), Myrvold [10] gave an algorithm for computing the number of \( k \)-component spanning forests of \( G \). Björklund et al. [4] described an algorithm that could compute \( T_G(2, 1) \) in time \( 2^{|V|}|V|^{O(1)} \) by using Kirchhoff’s Matrix Tree Theorem for each of the \( 2^{|V|} \) subsets of \( V \), then combining the results together with Inclusion-Exclusion. Other relevant work for the enumeration of spanning forests includes [9]. Porter [11] gave an algorithm for generating the spanning trees of \( K_{m,n} \).

Farr and McDiarmid [5] showed that computing the number of circuits in \( G \) is \#P-complete \(^{(i)} \).

Bounds for the number of spanning forests in graphs were given by Teranishi [13], from which we can deduce

\[
T_{K_{m,n}}(2, 1) \geq \sum_{k \geq 0} \binom{\min(m, n)}{2}^{m+n-k} \binom{m+n}{k}
\]

for all \( m \geq 0 \) and \( n \geq 0 \). Jin and Liu [8] gave a simple formula for the number of rooted spanning forests in \( K_{m,n} \) (see also [7] and [12]).

This paper instead heads in a different direction to previous work: we derive algorithms for enumerating \( h \)-edge spanning forests in \( K_{m,n} \).

2 Basic results

To be clear, all forests in this paper will be labelled. Let \( \mathbb{N} = \{0, 1, 2, \ldots\} \). The following lemma gives the boundary conditions on \( f_{m,n,h} \).

\textbf{Lemma 1} Suppose \( m, n, h \in \mathbb{N} \). Then

\begin{itemize}
  \item \( f_{m,n,0} = 1 \),
  \item if \( h \geq 1 \), then \( f_{0,n,h} = f_{m,0,h} = 0 \),
  \item if \( m \geq 1 \) and \( n \geq 1 \), then \( f_{m,n,h} > 0 \) if and only if \( 0 \leq h \leq m + n - 1 \),
  \item if \( m \geq 1 \) and \( n \geq 1 \), then \( f_{m,n,m+n-1} = m^{n-1} n^{m-1} \).
\end{itemize}

\textbf{Proof:} If \( h = 0 \), then there is exactly one subgraph of \( K_{m,n} \) with no edges (and it is a spanning forest), so \( f_{m,n,0} = 1 \). If \( m = 0 \) or \( n = 0 \), then \( K_{m,n} \) has no edges, and thus we obtain the second bulleted item.

Now assume \( m \geq 1 \) and \( n \geq 1 \). Since \( K_{m,n} \) is connected, it has a spanning tree, which must have exactly \( m + n - 1 \) edges. By deleting edges from this spanning tree, we find \( h \)-edge forests in \( K_{m,n} \) for all \( 0 \leq h \leq m + n - 1 \). Hence \( f_{m,n,h} > 0 \) when \( 0 \leq h \leq m + n - 1 \).

Now assume \( A \) is an \( h \)-subset of the edges in \( K_{m,n} \), where \( m \geq 1 \) and \( n \geq 1 \) and \( h \geq m + n \). To be a spanning forest, we need \( k(A) + h = m + n \) as per \([1] \), but if \( h \geq m + n \), then \( k(A) \leq 0 \), giving a contradiction.

\(^{(i)} \#P \) is the set of counting problems which ask for the number of “yes” instances for decision problems in NP. A \#P problem is in \#P-complete whenever any other problem in \#P can be reduced to it by a polynomial-time counting reduction.
The number of $h$-edge spanning forests in $K_{m,n}$

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Fig. 1: Small non-zero values of $f_{m,n,h}$.

The fourth bulleted item is from Kirchhoff’s Matrix Tree Theorem (already mentioned).

The following lemma is an important (but basic) consequence of the symmetry of the problem.

**Lemma 2** For all $m, n, h \in \mathbb{N}$, we have $f_{m,n,h} = f_{n,m,h}$.

In Figure 1 we list the non-zero values of $f_{m,n,h}$ when $0 \leq m \leq n \leq 6$. These values were generated using a straightforward backtracking algorithm.

### 3 Combinatorial equivalence

In this section, we will describe some combinatorial objects that are equivalent to $h$-edge spanning forests of $K_{m,n}$.

Let $M$ be an $m \times n (0,1)$-matrix. We define a cycle in $M$ to be a set $\{e_1,e_2,\ldots,e_t\}$ of entries of $M$, such that:

- each $e_i$ contains the symbol 1, and
- for $i \in \{1,2,\ldots,t\}$, we have that (a) $e_{2i-1}$ belongs to the same row as $e_{2i}$ and (b) $e_{2i}$ belongs to the same column as $e_{2i+1}$ (where we take $e_{2t+1} = e_1$).

For example, the matrix

$$
\begin{array}{cccccc}
0 & 1 & 0 & 1 & 1 \\
0 & 0 & 1 & 0 & 1 \\
1 & 0 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 \\
\end{array}
$$
Rebecca J. Stones has a cycle (consisting of the circled 1’s), whereas the matrices

\[
\begin{bmatrix}
0 & 1 & 1 \\
0 & 0 & 0
\end{bmatrix}
\quad \text{and} \quad 
\begin{bmatrix}
0 & 1 & 1 & 0 & 1 \\
1 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 & 0
\end{bmatrix}
\]
do not have cycles.

Let \( A_{m,n,h} \) be the set of \((0,1)\)-matrices with exactly \( h \) elements equal to 1. Let \( p_{m,n,h} \) be the probability that an element of \( A_{m,n,h} \) chosen uniformly at random contains a cycle. An anonymous user of math.stackexchange.com asked for a formula for \( p_{m,n,h} \). In fact, this was the original motivation for the author to study this problem.

**Lemma 3** For all \( m, n, h \in \mathbb{N} \), we have \( f_{m,n,h} \) is the number of \( m \times n \) \((0,1)\)-matrices with \( h \) 1’s that do not contain a cycle, and hence

\[
f_{m,n,h} = (1 - p_{m,n,h}) \binom{mn}{h}.
\]

**Proof:** A matrix \( M \in A_{m,n,h} \) can be interpreted as the biadjacency matrix of an \( h \)-edge subgraph \( G = G(M) \) of \( K_{m,n} \). A cycle in \( M \in A_{m,n,h} \) corresponds to a cycle in \( G \). Hence

\[
f_{m,n,h} = (1 - p_{m,n,h}) |A_{m,n,h}| = (1 - p_{m,n,h}) \binom{mn}{h}.
\]

▫

A problem related to the \((0,1)\)-matrix problem above comes from the study of \((0,1)\)-matrices that do not have a submatrix which is the incidence matrix of any cycle of length at least 3; these are called “totally balanced matrices” (see e.g. [2]).

Another interpretation of matrices in \( A_{m,n,h} \) is as induced subgraphs of \( K_m \square K_n \), where \( \square \) represents the Cartesian product of graphs. The graph \( K_m \square K_n \) is sometimes called the “rook’s graph”, since the edges represent the legal moves of a rook on an \( m \times n \) chess board. The vertices in \( K_m \square K_n \) are \( \{(i,j) : 1 \leq i \leq m \text{ and } 1 \leq j \leq n\} \) and there is an edge between distinct vertices \((i,j) \) and \((i',j')\) whenever \( i = i' \) or \( j = j' \). The graph \( K_m \square K_n \) is also the line graph of \( K_{m,n} \).

There is a bijection between induced subgraphs \( H = H(M) \) of \( K_m \square K_n \) and \((0,1)\)-matrices \( M = (m_{ij}) \in A_{m,n,h} \): we include the vertex \((i,j)\) in \( H \) if and only if \( m_{ij} = 1 \). For example, if we ignore the vertices marked 0 in

\[
\begin{array}{cccccc}
0 & 1 & 1 & 0 & 1 \\
1 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 & 0
\end{array}
\]

(ii) Full URL: [http://math.stackexchange.com/q/24800](http://math.stackexchange.com/q/24800)

(iii) The biadjacency matrix of a bipartite graph \( G \) on the vertex set \( \{u_i\}_{1 \leq i \leq m} \cup \{v_j\}_{1 \leq j \leq n} \) is the \( m \times n \) \((0,1)\)-matrix \( M = (m_{ij}) \) with \( m_{ij} = 1 \) if and only if \( u_i v_j \) is an edge in \( G \).
The number of $h$-edge spanning forests in $K_{m,n}$

we obtain an induced subgraph $H(M)$ of $K_3 \square K_5$, corresponding to the matrix

$$M = \begin{pmatrix} 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 \end{pmatrix}$$

in $A_{3,5,6}$. We see that cycles in $M$ map from cycles $C_k$ in $H$ for some $k \in \{4, 6, 8, \ldots\}$ (an example of a 6-cycle is highlighted). There are other cycles in $H$ (e.g. $C_3$ in the above example; in fact, if $M$ above had a row of 1's, then $H$ would have a $K_5$ subgraph). However, induced cycles $C_k$ in $H(M)$ of length $k \in \{4, 6, 8, \ldots\}$ are in one-to-one correspondence with cycles in $M$ via the above bijection.

**Lemma 4** For all $m, n, h \in \mathbb{N}$, we have that $f_{m,n,h}$ is the number of $h$-vertex induced subgraphs of $K_{m,n}$ that do not contain an induced $C_k$ for any $k \in \{4, 6, 8, \ldots\}$.

4 Simplifying the equation

4.1 A formula for $f_{m,n,h}$

We will look at two related ways of simplifying $f_{m,n,h}$. Let $K_{m,n}$ have the vertex bipartition $M \cup N$, where $M = \{u_1, u_2, \ldots, u_m\}$ and $N = \{v_1, v_2, \ldots, v_n\}$. Let $B_{m,n,h}$ be the set of $h$-edge spanning forests of $K_{m,n}$. Hence $f_{m,n,h} = |B_{m,n,h}|$. Define

$$W_{m,n,h} = \{G \in B_{m,n,h} : G \text{ has no isolated vertices}\}$$

and $w_{m,n,h} = |W_{m,n,h}|$. We observe the following:

- Given any spanning forest in $B_{m,n,h}$ we can delete the isolated vertices to obtain a spanning forest in $W_{i,j,h}$ for some $i \leq m$ and $j \leq n$.
- Conversely, given any spanning forest in $W_{i,j,h}$, we can add isolated vertices to it in $\binom{m}{m-i} \binom{n}{n-j}$ ways to obtain a spanning forest in $B_{m,n,h}$.

In both of the operations above, we need to relabel the vertices, but we preserve the order of the indices of the non-isolated vertices within $M$ and $N$.

Hence

$$f_{m,n,h} = \sum_{i=0}^{m} \sum_{j=0}^{n} \binom{m}{i} \binom{n}{j} w_{i,j,h}. \quad (2)$$

This formula eliminates the need to further account for isolated vertices.

We can decompose any $G \in W_{m,n,h}$ into disjoint components, each of which belong to $W_{i,j,k}$ for some $i \leq m$ and $j \leq n$ and $k \leq h$. Hence any $G \in W_{m,n,h}$ decomposes into the following.

- A partition $P$ of $M$ where $x, y \in M$ belong to the same part if there is a path from $x$ to $y$ in $G$.
- A partition $Q$ of $N$ where $x', y' \in N$ belong to the same part if there is a path from $x'$ to $y'$ in $G$.
- A bijection $\alpha : P \rightarrow Q$ such that every edge $ab$ in $G$ has $a \in p$ and $b \in \alpha(p)$ for some $p \in P$. Hence we have $|P| = |Q|$.
For each $p \in P$, a subgraph in $W_{|p|,|\alpha(p)|,|p|+|\alpha(p)|-1}$ induced by the vertices in $p \cup \alpha(p)$.

Regarding the final bulleted item, we observe that the subgraph induced by $p \cup \alpha(p)$ for some $p \in P$ must be a spanning tree on $K_{|p|,|\alpha(p)|}$. Any more edges would cause a cycle, while fewer edges would cause disjoint components (in which case $G$ could be further decomposed).

We give an example of a graph $G$ in $W_{3,5,6}$ below.

Here, the partitions $P$ and $Q$ are given by $P = \{\{u_1, u_2\}, \{u_3\}\}$ and $Q = \{\{v_1, v_2\}, \{v_3, v_4, v_5\}\}$ and we have the bijection $\alpha$ such that

$\{u_1, u_2\} \mapsto \{v_1, v_2\}$

$\{u_3\} \mapsto \{v_3, v_4, v_5\}$.

We see that $G$ decomposes into a graph in $W_{2,2,3}$ and a graph in $W_{1,3,3}$.

In general, for any $p \in P$, we must have exactly $|p| + |\alpha(p)| - 1$ edges in $p \cup \alpha(p)$. Summing this over all $p \in P$ gives $h = m + n - |P|$. We conclude that

$|P| = m + n - h$

(and thus $|Q| = m + n - h$).

We will now describe how to construct any graph in $W_{m,n,h}$ via its decomposition. Let $P$ be the set of partitions of $M$ and let $Q$ be the set of partitions of $N$. Given (a) a partition $P \in P$ of size $|P| = m + n - h$, (b) a partition $Q \in Q$ and (c) a bijection $\alpha : P \rightarrow Q$, we can construct $\prod_{p \in P} W_{|p|,|\alpha(p)|,|p|+|\alpha(p)|-1}$ distinct graphs $G \in W_{m,n,h}$ by the following steps:

1. Start with $G$ as the graph with vertex set $M \cup N$ and no edges.

2. For each $p \in P$ add one of the subgraphs in $W_{|p|,|\alpha(p)|,|p|+|\alpha(p)|-1}$ on the vertices $p \cup \alpha(p)$.

Since all graphs in $W_{m,n,h}$ can be constructed uniquely by the above steps we have the following theorem.

**Theorem 1** For $m$, $n$, $h \in \mathbb{N}$,

$\sum_{i=0}^{m} \sum_{j=0}^{n} \binom{m}{i} \binom{n}{j} w_{i,j,h}$
The number of \( h \)-edge spanning forests in \( K_{m,n} \)

where

\[
w_{m,n,h} = \sum_{P \in \mathcal{P}} \sum_{Q \in \mathcal{Q}} \sum_{\alpha : P \to Q} \prod_{p \in P} \omega[p,|\alpha(p)|,|p|+|\alpha(p)|-1]
\]

where

\[
\omega[p,|\alpha(p)|,|p|+|\alpha(p)|-1] = |p|^{\alpha(p)-1} |\alpha(p)|^{p-1}.
\]

4.2 An improved formula for \( f_{m,n,h} \)

We will derive two further equations for \( f_{m,n,h} \) (in Theorems 2 and 3, which are related to Theorem 1). They result in a slightly more complicated algorithm, but will allow us to compute \( f_{m,n,h} \) faster than (2).

For all \( m, n, h \in \mathbb{N}, \) define

\[
W'_{m,n,h} = \{ G \in W_{m,n,h} : \text{the vertices in } N \text{ have degree } \geq 2 \}.
\]

Given any \( G \in B_{m,n,h} \) we can delete the isolated vertices and the leaves (vertices of degree 1) in \( N \) to obtain a spanning forest in \( W'_{i,j,h-k} \) for some \( i \leq m \) and \( j \leq n \) and \( k \in \mathbb{N} \). Conversely, given any \( G \in W'_{i,j,h-k} \), we can add:

- \( m-i \) isolated vertices to \( M \) in \( \binom{m}{m-i} \) ways, so as to increase \( |M| \) to \( m \), then
- \( n-j \) isolated vertices to \( N \) in \( \binom{n}{n-j} \) ways, so as to increase \( |N| \) to \( n \), then
- \( k \) edges to \( G \) in \( \binom{n-j}{k} \) ways, so as to increase the number of leaves in \( N \) by \( k \), therefore obtaining a spanning forest in \( B_{m,n,h} \).

Similar to the derivation of (2), we need to relabel the vertices so as to preserve the order of the indices of the non-isolated vertices within \( M \) and the non-isolated non-leaf vertices within \( N \). Hence

\[
f_{m,n,h} = \sum_{i=0}^{m} \sum_{j=0}^{n} \sum_{k=0}^{\min(n-j,h)} \binom{m}{i} \binom{n}{j, k, n-j-k} m^k w'_{i,j,h-k}.
\]

All of the steps involved for finding the formula (3) for \( w_{m,n,h} \) are still valid for \( w'_{m,n,h} \). Hence (3) remains true if we replace \( w \) with \( w' \). However, we can no longer make use of the simple formula for \( w[p,|\alpha(p)|,|p|+|\alpha(p)|-1] \). Nevertheless, we will be able to find a formula for \( w'_{i,j,h-k} \) via Inclusion-Exclusion.

For \( I \subseteq N \), define

\[
A_I = \{ G \in W_{m,n,m+n-1} : \text{vertices in } I \text{ are leaves} \}.
\]

Note that spanning forests in \( A_I \) might also have leaves outside of \( I \). Hence \( |A_\emptyset| = |W_{m,n,m+n-1}| = m^{n-1}n^{m-1} \). By symmetry, if \( I, J \subseteq N \) and \( |I| = |J| \) then \( |A_I| = |A_J| \). So we will assume \( I = \{ n-i+1, n-i+2, \ldots, n \} \). We can construct the graphs in \( A_I \) by adding \( i \) leaves to the graphs in \( W_{m,n-|I|,m+n-|I|-1} \) (i.e., the set of spanning trees of \( K_{m,n-|I|} \)), and these leaves can be added in \( m^i \) ways. Hence

\[
|A_I| = m^i \cdot \text{number of spanning trees of } K_{m,n-i} = m^i m^{n-i-1}(n-i)^{m-1} = m^{n-1}(n-i)^{m-1}.
\]
when \( m \geq 1 \) and \( n \geq 1 \). Here we take \( 0^0 = 1 \), since we want to account for \( K_{1,0} \in W_{1,0,0} \). Hence, by Inclusion-Exclusion, we find

\[
w'_{m,n,m+n-1} = |A_0| - \left| \bigcup_{I \subseteq N \atop I \neq \emptyset} A_I \right|
\]

\[
= m^{n-1}n^{m-1} - \sum_{i=1}^{n} (-1)^{i-1} \binom{n}{i} m^{n-1}(n-i)^{m-1}
\]

\[
= m^{n-1} \sum_{i=0}^{n} (-1)^{i} \binom{n}{i} (n-i)^{m-1}
\]

when \( m \geq 1 \) and \( n \geq 1 \). By definition, we also have \( w'_{m,n,m+n-1} = 0 \) when either \( m = 0 \) or \( n = 0 \) (and \( w'_{m,n,m+n-1} \) is not defined when \( m = 0 \) and \( n = 0 \)).

Before identifying formulae for \( w_{m,n,h} \) and \( w'_{m,n,h} \) in the next section, we make the following observation.

**Lemma 5** For all \( m, n, h \in \mathbb{N} \), we have \( n! \) divides \( w'_{m,n,h} \).

**Proof:** The symmetric group on \( N \) acts on \( W'_{m,n,h} \) by permuting the vertices in \( N \). Suppose a graph \( G \in W'_{m,n,h} \) has a non-trivial stabiliser subgroup under this action. Then there exists a non-identity permutation \( \alpha \) such that \( \alpha G = G \), and distinct vertices \( v, v' \in N \) for which \( \alpha(v) = v' \). Since \( G \in W'_{m,n,h} \), the degree of \( v \) is 2 or more, so assume \( v \) has distinct neighbours \( a, b \in M \). Then, since \( \alpha G = G \), we find that \( v' = \alpha(v) \) has the neighbours \( a \) and \( b \) too. Thus, \( \{v, v', a, b\} \) induces a 4-cycle, giving a contradiction. Hence, all stabiliser subgroups are trivial, and by the Orbit-Stabiliser Theorem, all orbits have size \( n! \). Hence \( n! \) divides \( w'_{m,n,h} \). \( \Box \)

### 4.3 Formulae for \( w_{m,n,h} \) and \( w'_{m,n,h} \)

Now we will simplify (3), noting that our simplifications remain valid when we replace \( w \) with \( w' \).

For \( a \geq 1 \) and \( t \geq 1 \), let \( S_{a,t} \) be the set of (number) partitions of \( a \) into \( t \) non-zero parts. We will interpret elements of \( S_{a,t} \) as multisets; for example \( \{4,3,3,1,1\} \in S_{12,5} \). We will require \( S_{a,0} = \emptyset \) when \( t < 0 \), and \( S_{0,0} = \{\emptyset\} \) and \( S_{0,t} = \emptyset \) when \( t > 0 \). For \( z \in S_{a,t} \), let \( T[z] \) be the set of partitions of \( \{1,2,\ldots,a\} \) whose part sizes induce the number partition \( z \). For \( z \in S_{a,t} \), let \( \hat{z} \) denote an arbitrary element of \( T[z] \). If \( P \in T[x] \) and \( Q \in T[z] \), then any bijection \( \alpha : P \rightarrow Q \) induces a bijection \( \beta : x \rightarrow z \).
The number of $h$-edge spanning forests in $K_{m,n}$

Hence

$$w_{m,n,h} = \sum_{x,z \in S_{m,m+n-h}} \sum_{P \in T[x]} \sum_{Q \in T[z]} \sum_{\alpha: P \rightarrow Q \text{ is a bijection}} \prod_{p \in P} w_{\|p|,|\alpha(p)|,|p|+|\alpha(p)|-1}$$

$$= \sum_{x,z \in S_{m,m+n-h}} \sum_{P \in T[x]} \sum_{Q \in T[z]} \sum_{\alpha: \tilde{z} \rightarrow \tilde{z} \text{ is a bijection}} \prod_{p \in \tilde{z}} w_{\|p|,|\alpha(p)|,|p|+|\alpha(p)|-1}$$

$$= \sum_{x,z \in S_{m,m+n-h}} |T[x]| \cdot |T[z]| \sum_{\alpha: \tilde{z} \rightarrow \tilde{z} \text{ is a bijection}} \prod_{p \in \tilde{z}} w_{\|p|,|\alpha(p)|,|p|+|\alpha(p)|-1}$$

$$= \sum_{x,z \in S_{m,m+n-h}} |T[x]| \cdot |T[z]| \sum_{\beta: x \rightarrow z, \beta \text{ is a bijection}} \prod_{\gamma \in \tilde{z}} w_{r,\beta(r),r+\beta(r)-1}.$$

If $z \in S_{a,t}$, then

$$|T[z]| = \frac{a!}{\prod_{i \geq 1} i^{s_i(z)} s_i(z)!}$$

where $s_i(z)$ denotes the number of parts $i$ in $z$ (see e.g. [1] Theorem 13.2]). Hence we have the following theorems.

**Theorem 2** For $m, n, h \in \mathbb{N},$

$$f_{m,n,h} = \sum_{i=0}^{m} \sum_{j=0}^{n} \binom{m}{i} \binom{n}{j} w_{i,j,h}$$

where

$$w_{m,n,h} = \sum_{x,z \in S_{m,m+n-h}} \sum_{\beta: x \rightarrow z \text{ is a bijection}} m! \prod_{i \geq 1} i^{s_i(z)} s_i(z)! \prod_{i \geq 1} n_i! \prod_{r \in \tilde{z}} w_{r,\beta(r),r+\beta(r)-1}.$$  \hspace{1cm} (4)

**Theorem 3** For $m, n, h \in \mathbb{N},$

$$f_{m,n,h} = \sum_{i=0}^{m} \sum_{j=0}^{n} \sum_{k=0}^{\min(n-j,h)} \binom{m}{i} \binom{n}{j,k,n-j-k} m^k w_{i,j,h-k}.$$ 

where

$$w'_{m,n,h} = \sum_{x,z \in S_{m,m+n-h}} \sum_{\beta: x \rightarrow z \text{ is a bijection}} m! \prod_{i \geq 1} i^{s_i(z)} s_i(z)! \prod_{i \geq 1} n_i! \prod_{r \in \tilde{z}} w'_{r,\beta(r),r+\beta(r)-1}$$

where

$$w'_{m,n,m+n-1} = m^{n-1} \sum_{i=0}^{n} (-1)^i \binom{n}{i} (n-i)^{m-1}.$$ 

The main advantage of Theorems 2 and 3 over Theorem 1 is the summation is over number partitions (rather than set partitions).
5 Implementation

The author has implemented the two formulae for \( f_{m,n,h} \), described in the preceding section, along with a simple backtracking algorithm. The results between all three implementations concur, giving confidence in the accuracy of the code. The C source code is available as supplementary material to this document. The GMP library was used for arbitrary precision arithmetic [6].

The formula involving \( w_{m,n,h}' \) instead of \( w_{m,n,h} \) was (unsurprisingly) much faster, largely because many values of \( w_{m,n,h} \) equal 0, such as when \( m \leq n \), which can be used to drastically reduce the search tree.

5.1 Symmetry breaking

The run-time of the program was also improved through the use of symmetry breaking, which we will now describe. For \( x \in S_{m,m+n−h} \) and \( z \in S_{n,m+n−h} \), there are often many bijections \( \beta : x \rightarrow z \) which map the same elements to the same elements (since both \( x \) and \( z \) are multisets). In these instances, a naïve algorithm would repeat the same computation unnecessarily. Let \( x \) and \( z \) be the multisets \( x = \{x_1, x_2, \ldots, x_{m+n−h}\} \) and \( z = \{z_1, z_2, \ldots, z_{m+n−h}\} \). We define the condition:

*Symmetry breaking condition 1:* We say \( \beta : x \rightarrow z \) is half-canonical if \( \beta^{-1}(z_{i−1}) < \beta^{-1}(z_i) \) whenever \( z_{i−1} = z_i \).

We need to add a multiplicative factor to adjust for the restriction to half-canonical bijections. Hence

\[
w_{m,n,h} = \sum_{x,z \in S_{m,m+n−h}} \sum_{\beta : x \rightarrow z, \beta \text{ is a bijection}} \left( \prod_{i \geq 1} i^{s_i(z)} \right) \prod_{i \geq 1} \frac{m!}{i^{s_i(x)} s_i(x)!} \prod_{r \in x} w_{r, \beta(r), r+\beta(r)-1}
\]

and similarly with \( w' \) in place of \( w \). Using this assumption, we reduce the number of bijections by a factor of \( \prod_{i \geq 1} i^{s_i(z)} \), which results in a substantial time saving.

Instead of the single symmetry breaking assumption, it is possible to utilise symmetry breaking using an additional condition:

*Symmetry breaking condition 2:* We say \( \beta : x \rightarrow z \) is canonical if it is half-canonical and \( \beta(x_{i−1}) < \beta(x_i) \) whenever \( x_i = x_{i−1} \).

Again, we find

\[
w_{m,n,h} = \sum_{x,z \in S_{m,m+n−h}} \sum_{\beta : x \rightarrow z, \beta \text{ is a bijection}} \Gamma_{x,z,\beta} \prod_{i \geq 1} \frac{m!}{i^{s_i(x)} s_i(x)!} \prod_{r \in x} w_{r,\beta(r),r+\beta(r)-1}
\]

and similarly with \( w' \) in place of \( w \), where \( \Gamma_{x,z,\beta} \) is the number of bijections between the multisets \( x \) and \( z \) which map the same elements to the same elements (as \( \beta \)). A formula for \( \Gamma_{x,z,\beta} \) was given by e.g. [3], namely

\[
\Gamma_{x,z,\beta} = \prod_{i \geq 1} \frac{s_i(x)!}{i^{s_i(z)}} \prod_{j \geq 1} \frac{s_j(z)!}{i^{s_j(x)}} \prod_{r \in x} w_{r,\beta(r),r+\beta(r)-1}
\]

where
The number of $h$-edge spanning forests in $K_{m,n}$

- $s_i(z)$ denotes the number of parts $i$ in $z$ (as before), and
- $s_{i,j}(x,\beta)$ is the number of elements $(i,j)$ in the multiset $\{(r,\beta(r)) : r \in x\}$.

The author has implemented both of these symmetry breaking schemes in order to compare their performance (see Section 5.3).

5.2 Pseudo-code

Algorithm 1 gives a pseudo-code version of the C code used to implement the algorithm described by Theorem 3 using the half-canonical symmetry breaking condition. The partitions of $m$ and $n$ into $k$ parts were computed whenever needed and stored in memory. Iterating through the half-canonical bijections was performed “on the fly” using a backtracking algorithm.

While Theorems 2 and 3 are valid for all $m, n, h \in \mathbb{N}$, we need to set $f_{m,n,0} = 1$ separately in the C code.

5.3 Performance

The C code was run on a $2 \times 2.66$ GHz processor (although the code itself is not parallelised). The following table gives the run-times (in seconds) for the two algorithms under the two symmetry breaking schemes when computing all non-zero $f_{m,n,h}$ with $m, n \leq 19$.

<table>
<thead>
<tr>
<th></th>
<th>half-canonical</th>
<th>canonical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theorem 2</td>
<td>27.1</td>
<td>6.8</td>
</tr>
<tr>
<td>Theorem 3</td>
<td>4.1</td>
<td>4.5</td>
</tr>
</tbody>
</table>

The fastest version is Theorem 3 using half-canonical symmetry breaking. Under these conditions, the code had the following run-times to find all non-zero values of $f_{m,n,h}$ with $m, n \leq t$:

<table>
<thead>
<tr>
<th>$t$</th>
<th>time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>20.5</td>
</tr>
<tr>
<td>26</td>
<td>27.7</td>
</tr>
<tr>
<td>27</td>
<td>35.4</td>
</tr>
<tr>
<td>28</td>
<td>46.0</td>
</tr>
<tr>
<td>29</td>
<td>62.2</td>
</tr>
<tr>
<td>30</td>
<td>83.0</td>
</tr>
</tbody>
</table>

This table indicates the scalability of the program, which is not overwhelming for these values of $t$. The author also ran the program to compute $f_{m,n,h}$ with $m, n \leq t$ where $t = 50$, which took under 2 days (to be precise, it took 1 day 15 hours and 17 minutes). The largest number encountered was $f_{50,50,101}$, which has 167 digits, and is equal to the number of spanning trees of $K_{50,50}$, which is $50^{50-1} \cdot 50^{50-1} = 50^{98}$.

5.4 Complexity

In the worst case, $x = z = \{1,2,3,\ldots,t\}$, where $\min(m,n) = 1 + 2 + \cdots + t = \frac{1}{2}t(t + 1)$ (so $t = O(\sqrt{\min(m,n)})$, in which case the program must iterate through all $t!$ bijections from $x$ to $z$. So, for a worst case analysis, we assume $m = n$ and $m + n - h = \lfloor \sqrt{m} \rfloor$.
Algorithm 1 Implementation of Theorem 3 using half-canonical symmetry breaking

\begin{algorithm}
\begin{algorithmic}
\State $f_{m,n,m+n-1} := 0; ~\text{for all}~ m, n, h$
\State $w'_{m,n,m+n-1} := 0; ~\text{for all}~ m, n, h$
\State $w'_{0,0,0} := 1;$
\For{$m = 0, 1, \ldots, \text{MAX}(m)$}
\For{$n = 0, 1, \ldots, \text{MAX}(n)$}
\If{$m > n$ and $m > 0$ and $n > 0$} // Other values of $w'_{m,n,h}$ are 0
\For{$i = 0, 1, \ldots, n$}
\State // Using the Inclusion-Exclusion formula
\State $w'_{m,n,m+n-1} := w'_{m,n,m+n-1} + (-1)^i \binom{n}{i} (n-i)^{-1};$
\EndFor
\EndIf
\EndFor
\EndFor
\EndFor
\State Compute all partitions of $m$ into $m+n-h$ parts and store in memory.
\State Compute all partitions of $n$ into $m+n-h$ parts and store in memory.
\For{partitions $x$ of $m$ into $m+n-h$ parts}
\For{partitions $z$ of $n$ into $m+n-h$ parts} // via backtracking algorithm
\State $\Gamma := \prod_{i \geq 1} i^{s_i(x)};$
\State $w'_{m,n,h} := w'_{m,n,h} + \Gamma \cdot m! \prod_{i \geq 1} i^{s_i(x)} \prod_{i \geq 1} i^{s_i(z)} \prod_{r \in x} w'_{r, \beta(r), r+\beta(r)-1};$
\EndFor
\EndFor
\EndFor
\EndIf
\State $f_{m,n,0} = 1;$
\For{$h = 1, 2, \ldots, m+n-1$}
\For{$i = 0, 1, \ldots, m$}
\For{$j = 0, 1, \ldots, n$}
\For{$k = 0, 1, \ldots, \text{min}(n-j, h)$}
\State $f_{m,n,h} := f_{m,n,h} + \binom{m}{i} \binom{n}{j} k!^{m} w'_{i,j,h-k};$
\EndFor
\EndFor
\EndFor
\EndFor
\For{$h = 0, 1, \ldots, m+n-1$}
\State Print $f_{m,n,h};$
\EndFor
\EndFor
\EndAlgorithm
\end{algorithm}

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Hence, given \( x, z \in S_{m,m+n-h} \), there can be \( O(\sqrt{m}!) \) canonical bijections from \( x \) to \( z \). Hardy and Ramanujan’s asymptotic formula for the number of partitions of \( m \), namely

\[
\frac{1}{4m\sqrt{3}} e^{\pi \sqrt{2m/3}},
\]
gives a crude asymptotic upper bound on \( |S_{m,\sqrt{m}}|^2 \), specifically

\[
|S_{m,\sqrt{m}}|^2 = O \left( \frac{e^{\text{const}-m}}{m^2} \right)
\]
as the number of ways of choosing \( x \) and \( z \). Hence, \([4]\) has

\[
O \left( e^{\text{const}-\sqrt{m}m/2+\text{const}} \right)
\]
terms, by Stirling’s Approximation. In contrast, a backtracking algorithm would need to generate and check around \( (\frac{m^2}{\sqrt{m}})^2 \leq \frac{1}{\sqrt{m}!}m^2\sqrt{m} \) graphs, which, when \( m = n \) and \( h = 2m - \sqrt{m} \), is

\[
O(e^{\sqrt{m}m^1.5+\text{const}})
\]
iterations, by Stirling’s Approximation. Of course, when implementing these algorithms, we use pruning whenever possible to reduce the search space, which makes a drastic difference not accounted for in these approximations.

5.4.1 When \( h \) is fixed

We conclude this paper with the observation that, when \( h \) is fixed, computing \( f_{m,n,h} \) is asymptotically “easy”. The underlying reason is that, for sufficiently large \( m \) or \( n \), we must have isolated vertices in graphs in \( B_{m,n,h} \). Thus, \([2]\) only contains a finite number of non-zero terms.

**Theorem 4** For fixed \( h \), computing \( f_{m,n,h} \) can be performed in time \( O(\log(mn)) \).

**Proof:** If \( i > h \) or \( j > h \), then \( w_{i,j,h} = 0 \) (since any graph in \( B_{i,j,h} \) must have an isolated vertex). Hence, \([2]\) is equivalent to

\[
f_{m,n,h} = \sum_{i=0}^{h} \sum_{j=0}^{h} \binom{m}{i} \binom{n}{j} w_{i,j,h}.
\]

For fixed \( h \), there is a finite number of terms in this sum. Thus, for fixed \( h \), we could write a program in which:

- we store a list of the pairs \((i, j)\) for which \( w_{i,j,h} \) is non-zero, along with the value of \( w_{i,j,h} \),
- we iterate through this list, computing \( \binom{m}{i} \binom{n}{j} \), and add it to a running total.

We can compute \( \binom{m}{i} = \frac{1}{i!}m(m-1)\cdots(m-i+1) \) using \( O(h) \) multiplications (since \( i \leq h \)), each of which takes time \( O(\log m) \), and one division. Hence, \( \binom{m}{i} \) can be computed in time \( O(\log m) \) time (since \( h \) is fixed). Similarly \( \binom{n}{j} \) can be computed in \( O(\log n) \) time. We conclude that the whole summation can be performed in time \( O(\log(mn)) \). \( \square \)
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