Asymptotic enumeration of 2-covers and line graphs

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Abstract

In this paper we find asymptotic enumerations for the number of line graphs on n-labelled vertices and for different types of related combinatorial objects called 2-covers.

We find that the number of 2-covers, s_n, and proper 2-covers, t_n, on $[n]$ both have asymptotic growth

$$s_n \sim t_n \sim B_{2n} 2^{-n} \exp\left(-\frac{1}{2}\log(2n/\log n)\right) = B_{2n} 2^{-n} \sqrt{\frac{\log n}{2n}},$$

where B_{2n} is the $2n$th Bell number, while the number of restricted 2-covers, u_n, restricted, proper 2-covers on $[n]$, v_n, and line graphs l_n, all have growth

$$u_n \sim v_n \sim l_n \sim B_{2n} 2^{-n} n^{-1/2} \exp\left(-\left[\frac{1}{2}\log(2n/\log n)\right]^2\right).$$

In our proofs we use probabilistic arguments for the unrestricted types of 2-covers and and generating function methods for the restricted types of 2-covers and line graphs.

KEYWORDS: ASYMPTOTIC ENUMERATION, LINE GRAPHS, SET PARTITIONS

1 Introduction

A k-cover of $[n] := \{1, 2, \ldots n\}$ is a multiset of subsets $\{S_1, S_2, \ldots, S_m\}$, $S_i \subseteq [n]$, (possibly with $S_i = S_j$ for some $i \neq j$), such that for each $d \in [n]$ the number of j such that $d \in S_j$ is exactly k. A k-cover is called *proper* if $S_i \neq S_j$ whenever $i \neq j$. A k-cover is called *restricted* if the intersection of any k of the S_i contains at most one element. These definitions have been taken from [4]. Note that for a proper k-cover $\{S_1, \ldots, S_m\}$ is a set.

The *line graph* $L(G)$ of a simple graph G is the graph whose vertex set is the edge set of G and such that two vertices are adjacent in $L(G)$ if and only if the corresponding edges of G are adjacent.

Let s_n be the number of 2-covers of $[n]$; let t_n be the number of proper 2-covers of $[n]$; let u_n be the number of restricted, proper 2-covers of $[n]$; let v_n be the number of restricted, proper 2-covers of $[n]$; and let l_n be the number of line graphs on n labelled vertices. Let B_n be the nth Bell number. Given sequences a_n and b_n, we write $a_n \sim b_n$ to mean $\lim_{n\to\infty} a_n/b_n = 1$.

Theorem 1 *The number of* 2*-covers and the number of proper* 2*-covers have asymptotic growth*

$$s_n \sim t_n \sim B_{2n} 2^{-n} \exp\left(-\frac{1}{2}\log(2n/\log n)\right) \tag{1}$$

while the number of restricted 2-covers, restricted, proper 2-covers and line graphs all have asymptotic growth

$$u_n \sim v_n \sim l_n \sim B_{2n} 2^{-n} n^{-1/2} \exp\left(-\left[\frac{1}{2}\log(2n/\log n)\right]^2\right). \tag{2}$$

We make some initial observations regarding 2-covers, special graphs and orbits in Section 2. We use a probabilistic method to prove (1) in Section 3. A pair of technical lemmas are proven in Section 3.1, (1) is proven for s_n in Section 3.2 and it is proven for t_n in Section 3.3. We prove (2) in Section 4.

In both probabilistic and generating function proofs we will make use of Lambert's W-function $W(t)$, which is a solution to

$$W(t)e^{W(t)} = t \tag{3}$$

and which has asymptotics (see (3.10) of [6])

$$W(t) = \log t - \log\log t + \frac{\log\log t}{\log t} + o\left(\frac{1}{\log t}\right) \quad \text{as} \quad t \to \infty\,. \tag{4}$$

For each k-cover $S_1, \ldots, S_m$ of $[n]$ we can define an associated $m \times n$ incidence matrix M with entries given by

$$M_{i,j} = \begin{cases} 1 & \text{if } j \in S_i; \\ 0 & \text{if } j \notin S_i. \end{cases}$$

Note that M has exactly k ones in each column and that the rows are unordered. A k-cover is proper if and only if M has no repeated rows. A k-cover is restricted if and only if M has no repeated columns. Therefore, Theorem 1 is equivalent to the asymptotic enumeration of certain 0-1 matrices. The general methods of this paper were used for the asyptotic enumeration of other 0-1 matrices called incidence matrices in [2, 3].

2 2-covers, line graphs and orbits

In this section we establish correspondences between 2-covers, line graphs and orbits of certain permutation groups.

2.1 2-covers and graphs

We define a *special multigraph* to be a multigraph with no isolated vertices or loops. Our first result is

Proposition 1 *There is a bijection between 2-covers on $[n]$ and special multigraphs having unlabelled vertices and n labelled edges, such that*

- *proper 2-covers correspond to multigraphs having no connected component of size 2;*
- *restricted 2-covers correspond to simple graphs.*

Proof Let $S_1, \ldots, S_m$ be a 2-cover of $[n]$. Construct a graph G as follows:

- the vertex set is $[m]$;
- for each $i \in [n]$, there is an edge e_i joining vertices j and k, where S_j and S_k are the two sets of the 2-cover containing i.

The graph G is a multigraph (that is, repeated edges are permitted), but it has no isolated vertices and no loops.

Conversely, given a multigraph without isolated vertices or loops, we can recover a 2-cover: number the edges $e_1, \ldots, e_n$, and let S_i be the set of indices j for which the ith vertex lies on edge e_j. Thus we have the first part of the proposition.

The second part comes from observing that a "repeated set" in a 2-cover corresponds to a pair of vertices lying on the same edges, while a pair of elements lying in two different sets correspond to a pair of edges incident to the same two vertices. ■

2.2 Generating function identities for 2-covers

Recall that s_n, t_n, u_n and v_n denote the numbers of 2-covers, proper 2-covers, restricted 2-covers, and restricted proper 2-covers respectively. Using Proposition 1 in this subsection we will find relationships between these quantities and derive corresponding generating function identities.

Proposition 2 *Let $S(n,k)$ denote the Stirling numbers of the second kind, that is, the number of set partitions of $[n]$ into exactly k nonempty subsets. Then,*

$$\begin{aligned} s_n &= \sum_{k=1}^{n} S(n,k) u_k \\ t_n &= \sum_{k=1}^{n} S(n,k) v_k \\ u_n &= \sum_{k=0}^{n} \binom{n}{k} v_k \end{aligned}$$

Proof We prove these for the corresponding special multigraphs.

Any special multigraph with edges $e_1, \ldots, e_n$ can be described by giving a partition of $[n]$ into, say, k parts, together with a special simple graph with k labelled edges; simply replace the ith edge of the simple graph by the ith set of edges of the partition (where the edges are ordered lexicographically, say). This is clearly a bijection. Moreover, the simple graph has no connected components of size 2 if and only if the same holds for the multigraph. This proves the first two equations.

Given a special simple graph, there is a distinguished subset of $[n]$ (of size $n-k$, say) consisting of isolated edges; the remaining graph has no components of size 2. Again, the correspondence is bijective. So the third equation holds. ■

Proposition 2 can be reformulated in terms of exponential generating functions. Let $S(x) = \sum_{n\geq 0} s_n x^n/n!$, with similar definitions for the others. The proof of Proposition 3 is omitted.

Proposition 3

$$\begin{aligned} S(x) &= U(e^x - 1) \\ T(x) &= V(e^x - 1) \\ U(x) &= V(x)e^x. \end{aligned}$$

It follows from Proposition 3 that $S(x) = T(x)B(x)$, where $B(x) = e^{e^x-1}$ is the exponential generating function for the Bell numbers. This is easily proved directly.

2.3 Unrestricted 2-covers and orbits

Recall the notation $F_n(G)$ for the number of orbits of the oligomorphic group G on ordered n-tuples of distinct elements, and $F_n^*(G)$ for the number of orbits on all n-tuples. Let $S_\infty^{\{2\}}$ denote the group induced by the infinite symmetric group on the set of all 2-element subsets of its domain.

Proposition 4 *$F_n(S_\infty^{\{2\}}) = u_n$ and $F_n^*(S_\infty^{\{2\}}) = s_n$.*

Proof Simply observe that an n-tuple of distinct 2-sets is the edge set of a special simple graph with n labelled edges, while an arbitrary n-tuple of 2-sets is the edge set of a special multigraph with n labelled edges. ■

We note that the relation

$$F^*(G) = \sum_{k=1}^{n} S(n,k)F_k(G)$$

gives an alternative proof of the first equation in Proposition 2. We do not know of a similar interpretation of the other two parameters.

2.4 Generating function identities for line graphs

Let $L(x) = \sum_{n\geq 0} l_n x^n/n!$. We now prove

Proposition 5

$$L(x) = e^{-x^3/3!-6x^4/4!-15x^5/5!-15x^6/6!}U(x) = e^{x-x^3/6-x^4/4-x^5/8-x^6/48}V(x).$$

Proof According to Whitney's Theorem [5], an isomorphism between line graphs $L(G_1)$ and $L(G_2)$ of connected graphs is induced by an isomorphism from G_1 to G_2, except in one case: the line graphs of the triangle K_3 and the star $K_{1,3}$ are isomorphic. Moreover, Sabidussi [8] has shown that if G is a connected graph with at least three vertices, then the automorphism groups of G and $L(G)$ are isomorphic if G is not K_4, K_4 with an edge deleted or K_4 with two adjacent edges deleted, which we shall denote by K_4' and K_4'', respectively.

Now the connected components of line graphs which are triangles contribute a factor $e^{x^3/3!}$ to the exponential generating function $L(x)$ for line graphs on $[n]$; that is, $L(x) = e^{x^3/3!}W'(x)$, where $W'(x)$ is the e.g.f. for line graphs with no such components. Similarly, components which are triangles or stars contribute a factor $(e^{x^3/3!})^2$ to the e.g.f. for special simple graphs with n edges, leading to an overall multiplication by a factor of $e^{-x^3/3!}$

Next, while K_4 has S_4 as an automorpishm group and therefore admits $6!/4! = 30$ different edge labellings, the order of the automorphism group of $L(K_4)$ is $2 \cdot 4!$ and therefore $L(K_4)$ admits 15 different vertex labellings. Similar to above, this leads to a correction by a factor of $e^{-15x^6/6!}$.

Similar arguments hold for K_4' and K_4'', leading to factors $e^{-15x^5/5!}$ and $e^{-6x^4/4!}$, correspondingly.

Proposition 5 now follows by Whitney's Theorem, Sabidussi's result, and Proposition 3. ∎

3 Unrestricted 2-covers: a probabilistic approach

In this section we prove (1) of Theorem 1 by using a probabilistic construction.

3.1 Technical results

We proceed with the following definitions and lemma. Let T_n be the set of proper 2-covers on $[n]$. Let $\mathcal{S}_n$ be the set of set partitions of $[2n]$. Let $E_{1,n} \subset \mathcal{S}_n$ be the subset of set partitions of $[2n]$ such that j and $j+n$ are contained in different blocks for each $j \in [n]$. Define the function ψ from a subset $\tilde{S}$ of $[2n]$ to a subset of $[n]$ by $\psi(\tilde{S}) = \{j : j \in \tilde{S} \text{ or } j+n \in \tilde{S}\}$. Let $E_{2,n} \subset \mathcal{S}_n$ be the subset of set partitions of $[2n]$ with blocks $\{\tilde{S_1}, \ldots, \tilde{S_m}\}$ such that $\psi(\tilde{S}_{i_1}) \neq \psi(\tilde{S}_{i_2})$ for each $i_1 \neq i_2$. Let $C_n = E_{1,n} \cap E_{2,n}$. Let ϕ be the function on $\mathcal{S}_n$ given by

$$\phi(\{\tilde{S_1}, \ldots, \tilde{S_m}\}) = \{\psi(\tilde{S_1}), \ldots, \psi(\tilde{S_m})\}.$$

Lemma 1 *ϕ maps C_n onto T_n and $|\phi^{-1}(\mathbf{a})| = 2^n$ for all $\mathbf{a} \in T_n$.*

Proof Fix $\{\tilde{S_1}, \ldots, \tilde{S_m}\} \in C_n$. Each $j \in [n]$ appears in exactly two blocks of $\phi(\{\tilde{S_1}, \ldots, \tilde{S_m}\})$ because of the definition of $E_{1,n}$ and the blocks of $\{\tilde{S_1}, \ldots, \tilde{S_m}\}$ are unique because of the definition of $E_{2,n}$ so $\phi(\{\tilde{S_1}, \ldots, \tilde{S_m}\}) \in T_n$.

Let $\mathbf{a} = \{S_1, \ldots, S_m\} \in T_n$. For each $j \in [n]$ there are two ways of assigning j, $j+n$ to the appearances of j in $\mathbf{a}$ (think of a fixed ordering of the blocks of $\mathbf{a}$ to see this). The choices made for every $j \in [n]$ determine an *assignment*. Clearly, every element of $\phi^{-1}(\mathbf{a})$ must be of the form $\chi(\mathbf{a})$ for some assignment χ. There are 2^n assignments. We also write $\chi(S_i)$ for the block $\tilde{S_i}$ corresponding to S_i in $\chi(\mathbf{a})$.

We claim that each assignment $\chi(\mathbf{a})$ gives a unique element of C_n. To see this, first note that j and $j+n$ are clearly in different blocks of $\chi(\mathbf{a})$, so $\chi(\mathbf{a}) \in E_{1,n}$. Secondly, $\phi \circ \chi$ is the identity map on T_n. Therefore, $\chi(\mathbf{a}) \in E_{2,n}$ because $\mathbf{a}$ is a proper 2-cover. Moreover, $\chi_1(\mathbf{a}_1) \neq \chi_2(\mathbf{a}_2)$ for all $\mathbf{a}_1, \mathbf{a}_2 \in T_n$ such that $\mathbf{a}_1 \neq \mathbf{a}_2$ and for all assignments χ_1 and χ_2, which gives $\phi^{-1}(\mathbf{a}_1) \cap \phi^{-1}(\mathbf{a}_2) = \emptyset$.

We next prove that if χ_1 and χ_2 are two assignments such that $\chi_1(\mathbf{a}) = \chi_2(\mathbf{a})$, then $\chi_1 = \chi_2$. To see this, let

$$\mathcal{U} = \{j \in [n] : \chi_1 \text{ and } \chi_2 \text{ differ for } j\}.$$

Without loss of generality, assume that $j \in S_1$ and $j \in S_2$. Then, either $j \in \chi_1(S_1)$ and $j \in \chi_2(S_2)$ or $j+n \in \chi_1(S_1)$ and $j+n \in \chi_2(S_2)$ It follows that $\chi_1(S_1) = \chi_2(S_2)$. Therefore, $\phi \circ \chi_1(S_1) = \phi \circ \chi_2(S_2)$ or $S_1 = S_2$ violating the assumption that $\mathbf{a}$ is proper. We conclude that $\mathcal{U} = \emptyset$ and that $\chi_1 = \chi_2$. This implies that $|\phi^{-1}(\mathbf{a})| = 2^n$. ■

Next we generalize Lemma 1 to (possibly) improper covers. Let U_n denote the set of 2-covers of $[n]$.

Lemma 2 *ϕ maps $E_{1,n}$ onto U_n. Let $\mathbf{a} = \{S_1, S_2, \ldots, S_m\}$ be a 2-cover of $[n]$. Let $\mathcal{M}$ be the set of $i \in [m]$ such that there does not exist any $j \in [m]\backslash\{i\}$, $S_j = S_i$. Let*

$$\rho = \frac{m - |\mathcal{M}|}{2}$$

be the number of pairs $\{i, j\}$ such that $S_i = S_j$. Then

$$|\phi^{-1}(\mathbf{a})| = 2^{n-\rho}.$$

Proof Clearly ϕ maps $E_{1,n}$ onto U_n. Let $\mathcal{N} = [n] \setminus \{\cup_{i \in \mathcal{M}} S_i\}$. Then $\{S_i : i \in \mathcal{M}\}$ is a proper cover of $\mathcal{N}$ and Lemma 1 implies that

$$|\phi^{-1}(\{S_i : i \in \mathcal{N}\})| = 2^{|\mathcal{N}|}.$$

For each pair S_{i_1}, S_{i_2} such that $i_1 \neq i_2$ and $S_{i_1} = S_{i_2}$, it must be true that $\phi^{-1}(S_i)$ consists of two sets $\tilde{S}_1$ and $\tilde{S}_2$ such that for each $j \in S_{i_1}$ either $j \in \tilde{S}_{i_1}$ and $j+n \in \tilde{S}_{i_2}$ or $j+n \in \tilde{S}_{i_1}$ and $j \in \tilde{S}_{i_2}$. The number of choosing unordered sets $\tilde{S}_{i_1}$, $\tilde{S}_{i_2}$ is $2^{|S_{i_1}|-1}$. Therefore,

$$|\phi^{-1}(\mathbf{a})| = 2^{|\mathcal{N}|} \prod 2^{|S_{i_1}|-1} = 2^{n-\rho},$$

where the product is over pairs i_1, i_2 such that $i_1 \neq i_2$ and $S_{i_1} = S_{i_2}$. ■

3.2 Asymptotic enumeration of proper 2-covers

From Lemma 1 we conclude that $|C_n| = 2^n t_n$ so

$$t_n = 2^{-n}|C_n| = 2^{-n}\frac{|C_n|}{B_{2n}}B_{2n} \tag{5}$$

where B_{2n} is the $2n$th Bell number.

We will now prove

Lemma 3

$$\frac{|E_{1,n}|}{B_{2n}} \sim \sqrt{\frac{\log n}{2n}} \tag{6}$$

and

$$\frac{|E_{2,n}|}{B_{2n}} = 1 - O\left(\frac{\log^2 n}{n}\right). \tag{7}$$

Proof To prove (6), choose an element of $\mathcal{S}_n$ uniformly at random and let X be the number of $j \in [n]$ for which j and $j+n$ are in the same block. We have

$$\mathbb{P}(X=0) = \frac{|E_{1,n}|}{B_{2n}}. \tag{8}$$

We have $X = \sum_{j=1}^{n} I_j$ where I_j is the indicator random variable that j and $j+n$ are in the same block. The rth falling moment of X_n is

$$\begin{aligned} \mathbb{E}(X)_r &= \mathbb{E}X(X-1)\cdots(X-r+1) \\ &= \sum \mathbb{E}(I_{j_1} I_{j_2} \cdots I_{j_r}) \end{aligned}$$

where the sum is over $(j_1, \ldots, j_r)$ with no repetitions. To find $\mathbb{E}(I_{j_1} I_{j_2} \cdots I_{j_r})$ we take $[2n] \setminus \{j_1, j_2, \ldots, j_r\}$ and form a set partition. We then add j_k to the block containing $j_k + n$ for each $k \in [r]$. This process is uniquely reversible. Therefore,

$$\mathbb{E}(X)_r = \frac{(n)_r B_{2n-r}}{B_{2n}}.$$

We apply the formula in Corollary 13, page 18, of [1] to obtain

$$\mathbb{P}(X=0) = \sum_{r=0}^{\infty} (-1)^r \frac{\mathbb{E}(X)_r}{r!} = \sum_{r=0}^{\infty} \frac{(-1)^r}{r!} \frac{(n)_r B_{2n-r}}{B_{2n}}. \tag{9}$$

To analyze (9) we use the expansion of the Bell numbers [6, 9]

$$\begin{aligned} \log B_n &= e^w(w^2 - w + 1) - \frac{1}{2}\log(1+w) - 1 - \frac{w(2w^2+7w+10)}{24(1+w)^3} e^{-w} \\ &\quad - \frac{w(2w^4 + 12w^3 + 29w^2 + 40w + 36)}{48(1+w)^6} e^{-2w} + O(e^{-3w}), \end{aligned}$$

where $w = W(n)$ is given by (3), (4), from which we obtain (using Maple)

$$\log B_{n-r} - \log B_n = -rw + \frac{rw}{2n}\left(\frac{r}{w+1} + \frac{1}{(w+1)^2}\right) + O\left(\frac{r^3 w}{n^2}\right).$$

In particular,

$$\frac{B_{n-1}}{B_n} \sim \frac{\log n}{n}$$

so there exists a constant $C > 0$ such that

$$\frac{B_{n-r}}{B_n} \leq \frac{(C\log n)^r}{(n)_r}. \tag{10}$$

Moreover,

$$\begin{aligned}
\log B_{2n-r} - \log B_{2n} &= -rv + \frac{rv}{4n}\left(\frac{r}{v+1} + \frac{1}{(v+1)^2}\right) + O\left(\frac{r^3 v}{n^2}\right) \\
&= -r\log n + rc_n + r^2 d_n + +O\left(\frac{r^3 \log n}{n^2}\right),
\end{aligned}$$

where $v = W(2n)$ has the expansion

$$v = \log n - \log\log n + \log 2 + \frac{\log\log n}{\log n} - \frac{\log 2}{\log n} + o\left(\frac{1}{\log n}\right),$$

where

$$\begin{aligned}
c_n &= \log n - v - \frac{rv}{4n(v+1)^2} \\
&= \log\log n - \log 2 - \frac{\log\log n}{\log n} + \frac{\log 2}{\log n} + o\left(\frac{1}{\log n}\right)
\end{aligned}$$

and where

$$d_n = O\left(\frac{1}{n}\right).$$

Using (10) we estimate

$$\begin{aligned}
\left|\sum_{r>\log^{3/2} n} (-1)^r \frac{\mathbb{E}(X)_r}{r!}\right| &\leq \sum_{r>\log^{3/2} n} \frac{(n)_r B_{2n-r}}{r! B_n} \\
&\leq \sum_{r>\log^{3/2} n} \frac{(C\log 2n)^r}{r!} \\
&= (2n)^C \sum_{r>\log^{3/2} n} e^{-C\log 2n} \frac{(C\log 2n)^r}{r!} \\
&= o(1). \qquad (11)
\end{aligned}$$

For $r \leq \log^{3/2} n$, we have

$$\frac{B_{n-r}}{B_n} = n^{-r} \exp\left(rc_n + r^2 d_n + O\left(\frac{\log^9 n}{n^2}\right)\right)$$

and

$$(n)_r = n^r \exp\left(O\left(\frac{r^2}{n}\right)\right),$$

hence

$$\mathbb{E}(X)_r = \exp\left(rc_n + r^2 d_n + O\left(\frac{\log^9 n}{n^2}\right)\right).$$

Therefore,

$$\begin{aligned}
\sum_{0\leq r\leq \log^{3/2} n} (-1)^r \frac{\mathbb{E}(X)_r}{r!} &= \sum_{0\leq r\leq \log^{3/2} n} \frac{(-1)^r}{r!} e^{rc_n + r^2 d_n}\left(1 + O\left(\frac{\log^9 n}{n^2}\right)\right) \\
&= \sum_{0\leq r\leq \log^{3/2} n} \frac{(-1)^r}{r!} e^{rc_n}\left(1 + d_n r^2 + O\left(\frac{\log^9 n}{n^2}\right)\right) \\
&= \sum_{0\leq r\leq \log^{3/2} n} \frac{(-1)^r}{r!} e^{rc_n} + d_n \sum_{0\leq r\leq \log^{3/2} n} \frac{(-1)^r r^2}{r!} e^{rc_n} \\
&\quad + \left(\frac{\log^9 n}{n^2}\right) \sum_{0\leq r\leq \log^{3/2} n} \frac{e^{rc_n}}{r!}. \qquad (12)
\end{aligned}$$

We proceed to approximate the terms in (12). First, we find that

$$\begin{aligned}
\sum_{0\leq r\leq \log^{3/2} n} \frac{(-1)^r}{r!} e^{rc_n} &= \exp\left(-e^{c_n}\right) + O\left(\sum_{\log^{3/2} n\leq r\leq n} \frac{e^{rc_n}}{r!}\right) \\
&= \exp\left(-\frac{\log n}{2}\left[1 - \frac{\log\log n}{\log n} + \frac{\log 2}{\log n} + o\left(\frac{1}{\log n}\right)\right]\right) + o(n^{-1/2}) \\
&\sim \sqrt{\frac{\log n}{2n}}. \qquad (13)
\end{aligned}$$

We estimate

$$\begin{aligned}
& d_n \left| \sum_{0\le r\le \log^{3/2} n} \frac{(-1)^r}{r!} r^2 e^{rc_n} \right| \\
= \; & d_n \left| \sum_{2\le r\le \log^{3/2} n} \frac{(-1)^r}{(r-2)!} e^{rc_n} + \sum_{1\le r\le \log^{3/2} n} \frac{(-1)^r}{(r-1)!} e^{rc_n} \right| \\
= \; & d_n \left| e^{2c_n} \sum_{2\le r\le \log^{3/2} n} \frac{(-1)^r}{(r-2)!} e^{(r-2)c_n} + e^{c_n} \sum_{1\le r\le \log^{3/2} n} \frac{(-1)^r}{(r-1)!} e^{(r-1)c_n} \right| \\
= \; & d_n \left(\exp\left(-e^{c_n} + 2c_n\right) + \exp\left(-e^{c_n} + c_n\right) + O\left(e^{2c_n} \sum_{\log^{3/2} n\le r\le n} \frac{e^{rc_n}}{r!} \right) \right) \\
= \; & o(n^{-1/2}). \qquad (14)
\end{aligned}$$

Finally, we have

$$\begin{aligned}
O\left(\frac{\log^9 n}{n^2}\right) \sum_{0\le r\le \log^{3/2} n} \frac{e^{rc_n}}{r!} \;&\le\; O\left(\frac{\log^9 n}{n^2}\right) e^{c_n} \\
&=\; o(n^{-1/2}). \qquad (15)
\end{aligned}$$

Together, (8), (9), (11), (12), (13), (14) and (15) prove (6).

To show (7), let Y be the number of pairs S_i, S_j in an partition in $\mathcal{S}_n$ chosen uniformly at random for which $\psi(S_i) = \psi(S_j)$. For such S_i, S_j of size $|S_i| = |S_j| = k$, the probability that they are present in the random partition is $B(2n-2k)/B(2n)$. The total number of pairs S_i, S_j of size k is bounded by $\binom{n}{k}2^k$ (the number of ways of choosing a subset J of size k from $[n]$ times a bound on the number of ways of choosing two subsets S_1, S_2 of $[2n]$ of size k such that either $j \in S_1$ and $j+n \in S_2$ or $j+n \in S_1$ and $j \in S_2$ for all

$j \in J$.) Therefore, using (10) we get

$$\begin{aligned}
1 - \frac{|E_{2,n}|}{B_{2n}} &= \mathbb{P}(Y > 0) \\
&\leq \mathbb{E}Y \\
&\leq \sum_{k=1}^{n} \binom{n}{k} 2^k \frac{B_{2n-2k}}{B_{2n}} \\
&\leq \sum_{k=1}^{n} \binom{n}{k} 2^k \frac{(C \log 2n)^{2k}}{(2n)_{2k}} \\
&\leq \sum_{k=1}^{n} \frac{(n)_k (2C^2 \log^2 2n))^k}{(2n)_{2k} k!} \\
&= O\left(\frac{\log^2 n}{n}\right).
\end{aligned}$$

■

Lemma 3 and (5) along with

$$\frac{|C_n|}{B_{2n}} \leq \frac{|E_{1,n}|}{B_{2n}}$$

and

$$\frac{|C_n|}{B_{2n}} \geq \frac{|E_{1,n}| - (B_{2n} - |E_{2,n}|)}{B_{2n}}$$

prove (1) for t_n.

3.3 Asymptotic enumeration of 2-covers

In this subsection we prove (1) for s_n. Recall that U_n denotes the set of 2-covers of $[n]$. Each element of $E_{1,n}$ is mapped to a unique $\mathbf{a} \in U_n$ by ϕ. Given $\omega = \{\tilde{S}_1, \tilde{S}_2, \ldots, \tilde{S}_m\} \in \mathcal{S}_n$, let $Z(\omega)$ be the number of pairs $\{i_1, i_2\}$ such that $\psi(\tilde{S}_{i_1}) = \psi(\tilde{S}_{i_2})$. Note that in the case $\omega \in E_{1,n}$ we have $Z(\omega) = \rho$ with ρ defined with respect to $\mathbf{a} = \phi(\omega)$ in the statement of Lemma 2.

Define $D_{\rho,n}$ for $\rho \in \{0, 1, \ldots, n\}$ to be

$$D_{\rho,n} = \{\omega \in E_{1,n} : Z(\omega) = \rho\}.$$

Note that $D_{0,n} = C_n$. By Lemma 2,

$$\begin{aligned}
u_n &= \sum_{\rho=0}^{n} |D_{\rho,n}| 2^{-n+\rho} \\
&= |C_n| 2^{-n} + \sum_{\rho=1}^{n} |D_{\rho,n}| 2^{\rho} \\
&= B_{2n} 2^{-n} \left(\frac{|C_n|}{B_{2n}} + \sum_{\rho=1}^{n} \frac{|D_{\rho,n}|}{B_{2n}} 2^{\rho} \right).
\end{aligned}$$

We have shown in the previous section that $C_n/B_{2n} \sim \sqrt{\log n/2n}$. Observe that $\sum_{\rho=1}^{n} |D_{\rho,n}| 2^{\rho}/B_{2n} \leq \sum_{\rho=1}^{n} \mathbb{P}(Z=\rho)2^{\rho}$, where Z was defined in the last paragraph and ω is chosen uniformly at random from $\mathcal{S}_n$. In light of these observations, to prove (1) for s_n it suffices to prove that

$$\sum_{\rho=1}^{n} \mathbb{P}(Z=\rho)2^{\rho} = o\left(\sqrt{\frac{\log n}{2n}} \right). \tag{16}$$

The quantity $\mathbb{P}(Z \geq \rho)$ is equal to the probability that the randomly chosen element of $\mathcal{S}_n$ contains at least ρ disjoint pairs of equal sets, therefore,

$$\mathbb{P}(Z \geq \rho) \leq \sum_{s_1=1}^{n} \sum_{s_2=1}^{n} \cdots \sum_{s_\rho=1}^{n} \binom{n}{s_1, s_2, \ldots, s_\rho, n - \sum s_i} \frac{B_{2n-2\sum s_i}}{B_{2n}}$$

Let σ be defined by $\sigma = \sum_{i=1}^{\rho} s_i$. We can assume $\sigma \leq n$. From (10) we have

$$\begin{aligned}
\mathbb{P}(Z \geq \rho) &\leq \sum_{s_1=1}^{n} \sum_{s_2=1}^{n} \cdots \sum_{s_\rho=1}^{n} \binom{n}{s_1, s_2, \ldots, s_\rho, n-\sigma} \frac{(C \log n)^{2\sigma}}{(2n)_{2\sigma}} \\
&= \sum_{s_1=1}^{n} \sum_{s_2=1}^{n} \cdots \sum_{s_\rho=1}^{n} \frac{(n)_\sigma}{\prod_i s_i!} \frac{(C \log n)^{2\sigma}}{(2n)_{2\sigma}}.
\end{aligned}$$

Observing that

$$\frac{(n)_\sigma}{(2n)_{2\sigma}} = \frac{(n)_\sigma}{(2n)_\sigma (2n-\sigma)_\sigma} \leq \frac{1}{(2n)_\sigma} \leq n^{-\sigma},$$

we have

$$\begin{aligned}
\mathbb{P}(Z \geq \rho) &\leq \sum_{\sigma=\rho}^{n} \sum_{\substack{s_1,\ldots,s_\rho: \\ \sum_i s_i = \sigma}} \frac{1}{\prod_i s_i!} \left(\frac{C^2 \log^2 n}{n} \right)^{\sigma} \\
&= \sum_{\sigma=\rho}^{n} \frac{\rho^\sigma}{\sigma!} \left(\frac{C^2 \log^2 n}{n} \right)^{\sigma}
\end{aligned}$$

Therefore,

$$\begin{aligned}
\sum_{\rho=1}^{n} \mathbb{P}(Z = \rho) 2^\rho &\leq \sum_{\rho=1}^{n} \mathbb{P}(Z \geq \rho) 2^\rho \\
&\leq \sum_{\rho=1}^{n} \sum_{\sigma=\rho}^{n} \frac{2^\rho \rho^\sigma}{\sigma!} \left(\frac{C^2 \log^2 n}{n} \right)^{\sigma} \\
&= \sum_{\sigma=1}^{n} \sum_{\rho=1}^{\sigma} \frac{2^\rho \rho^\sigma}{\sigma!} \left(\frac{C^2 \log^2 n}{n} \right)^{\sigma} \\
&\leq \sum_{\sigma=1}^{n} \sum_{\rho=1}^{\sigma} \frac{\rho^\sigma}{\sigma!} \left(\frac{2C^2 \log^2 n}{n} \right)^{\sigma} \\
&\leq \sum_{\sigma=1}^{n} \frac{(\sigma+1)^\sigma}{\sigma!} \left(\frac{2C^2 \log^2 n}{n} \right)^{\sigma} \\
&= O\left(\frac{\log^2 n}{n} \right) \\
&= o\left(\sqrt{\frac{\log n}{2n}} \right).
\end{aligned}$$

The last estimate proves (16). ■

4 Restricted 2-covers and line graphs: an analytic approach

Our proof of (2) will use generating function analysis. Let $a_{n,m}$ be the number of restricted, proper 2-covers on $[n]$ with m blocks. The generating function for restricted, proper 2-covers

$$A(x,y)=\sum_{n=0}^{\infty}\sum_{m=1}^{2n}\frac{a_{n,m}}{n!}x^n y^m$$

equals

$$A(x,y)=\exp\left(-y-\frac{xy^2}{2}\right)\sum_{m\geq 0}\frac{y^m}{m!}(1+x)^{\binom{m}{2}}; \tag{17}$$

see page 203 of [4]. Therefore,

$$V(x)=A(x,1)=e^{-1}\sum_{m=0}^{\infty}\frac{1}{m!}(1+x)^{\binom{m}{2}}e^{-x/2} \tag{18}$$

and

$$v_n=n!e^{-1}\sum_{m=0}^{\infty}\frac{m^{2n}}{m!}\sum_{k=0}^{n}\frac{1}{k!}\left(-\frac{1}{2}\right)^k m^{-2n}\binom{\binom{m}{2}}{n-k}. \tag{19}$$

Note that for $m\geq 2$,

$$\begin{aligned}\left|\sum_{k=0}^{n}\frac{n!}{k!}\left(-\frac{1}{2}\right)^k m^{-2n}\binom{\binom{m}{2}}{n-k}\right| &\leq \sum_{k=0}^{n}\binom{n}{k}\left(\frac{1}{2}\right)^k m^{-2n}\binom{m}{2}^{n-k}\\ &\leq 2^{-n}\sum_{k=0}^{n}\binom{n}{k}m^{-2k}\\ &\leq 2^{-n}\left(\frac{1+m^{-2}}{2}\right)^n=O(2^{-n}). \qquad (20)\end{aligned}$$

We will make use of the asymptotic analysis of the Bell numbers in Example 5.4 of [7], which uses the identity

$$B_n=e^{-1}\sum_{m=0}^{\infty}\frac{m^n}{m!}.$$

Let m_0 be the nearest integer to $\frac{2n}{W(2n)}$, where W is defined by (3). (The choice of m_0 is slightly different here than in [7], but the analysis giving (21) and (22) below remains valid.) In [7] it is proved that

$$\sum_{\substack{1\leq m\leq n\\ |m-m_0|>\sqrt{n}\log n}}\frac{m^{2n}}{m!}=O\left(\frac{m_0^{2n}}{m_0!}\sqrt{n}\exp\left(-(\log n)^3\right)\right) \tag{21}$$

and that

$$\sum_{\substack{1\le m\le n\\ |m-m_0|\le\sqrt{n}\log n}} \frac{m^{2n}}{m!} = \frac{m_0^{2n+1}}{m_0!}\sqrt{\frac{2\pi}{2n+m_0}}\left(1+O\left((\log n)^6 n^{-1/2}\right)\right) \quad (22)$$

$$\sim eB_{2n}. \quad (23)$$

It follows from (20) and (21) that

$$\sum_{\substack{1\le m\le n\\ |m-m_0|>\sqrt{n}\log n}} \frac{m^{2n}}{m!}\sum_{k=0}^{n}\frac{n!}{k!}\left(-\frac{1}{2}\right)^k m^{-2n}\binom{\binom{m}{2}}{n-k} = O\left(\frac{m_0^{2n}}{m_0!}\sqrt{n}2^{-n}\exp\left(-(\log n)^3\right)\right)$$

$$= O\left(B_{2n}2^{-n}\exp\left(-\frac{(\log n)^3}{2}\right)\right). \quad (24)$$

We have

$$\sum_{\substack{1\le m\le n\\ |m-m_0|\le\sqrt{n}\log n}} \frac{m^{2n}}{m!}\sum_{k=0}^{n}\frac{n!}{k!}\left(-\frac{1}{2}\right)^k m^{-2n}\binom{\binom{m}{2}}{n-k} = \sum_{\substack{1\le m\le n\\ |m-m_0|\le\sqrt{n}\log n}} \frac{m^{2n}}{m!}m^{-2n}n!\binom{\binom{m}{2}}{n}+\Delta, \quad (25)$$

where

$$\Delta := \sum_{\substack{1\le m\le n\\ |m-m_0|\le\sqrt{n}\log n}} \frac{m^{2n}}{m!}\sum_{k=1}^{n}\frac{n!}{k!}\left(-\frac{1}{2}\right)^k m^{-2n}\binom{\binom{m}{2}}{n-k}$$

is bounded by

$$|\Delta| \le \sum_{\substack{1\le m\le n\\ |m-m_0|\le\sqrt{n}\log n}} \frac{m^{2n}}{m!}\sum_{k=1}^{n}\frac{n!}{k!}m^{-2n}\binom{\binom{m}{2}}{n}\left(\frac{n}{\binom{m}{2}-n}\right)^k$$

$$= O\left(\frac{\log^2 n}{n}\right)\sum_{\substack{1\le m\le n\\ |m-m_0|\le\sqrt{n}\log n}} \frac{m^{2n}}{m!}m^{-2n}n!\binom{\binom{m}{2}}{n}.$$

One may show that uniformly for m in the range $|m-m_0|\le\sqrt{n}\log n$

$$m^{-2n}\binom{\binom{m}{2}}{n}n! = 2^{-n}\exp\left(-\frac{n}{m_0}-\frac{n^2}{m_0^2}\right)\left(1+O\left(n^{-1/2}\log^6 n\right)\right),$$

hence,

$$|\Delta| = O\left(\frac{\log^2 n}{n}\right) 2^{-n} \exp\left(-\frac{n}{m_0} - \frac{n^2}{m_0^2}\right) B_{2n}. \tag{26}$$

The main term of (25) is

$$\begin{aligned}
\sum_{\substack{1\le m\le n\\ |m-m_0|\le\sqrt{n}\log n}} \frac{m^{2n}}{m!} m^{-2n} n! \binom{\binom{m}{2}}{n} &= 2^{-n} \exp\left(-\frac{n}{m_0} - \frac{n^2}{m_0^2}\right)(1+o(1)) \sum_{\substack{1\le m\le n\\ |m-m_0|\le\sqrt{n}\log n}} \frac{m^{2n}}{m!} \\
&= eB_{2n} 2^{-n} \exp\left(-\frac{n}{m_0} - \frac{n^2}{m_0^2}\right)(1+o(1)) \\
&= eB_{2n} \frac{1}{2^n\sqrt{n}} e^{-\left(\frac{1}{2}\log(2n/\log n)\right)^2}(1+o(1)) \qquad (27)
\end{aligned}$$

where we have used the asymptotic expansion (4) and the definition of m_0 at the last step. Now (19), (24), (26) and (27) prove (2) for v_n.

In the previous argument the result would have been the same if the $e^{-x/2}$ in (18) were replaced by 1 because in the Taylor expansion of $e^{-x/2}$ the constant term 1 corresponds to the main term of (25) and the higher order terms contribute to Δ, which is negligable. The argument for restricted partitions and line graphs are similar, starting from the identities obtained from Proposition 17 and (18)

$$U(x) = e^{-1} \sum_{m=0}^{\infty} \frac{1}{m!} (1+x)^{\binom{m}{2}} e^{x/2}.$$

and

$$L(x) = e^{-1} \sum_{m=0}^{\infty} \frac{1}{m!} (1+x)^{\binom{m}{2}} e^{x/2-x^3/6-x^4/4-x^5/8-x^6/48}.$$

In each case only the contribution of the constant term of the Taylor expansion of the exponential is 1 and the remaining terms contribute to a quantity like Δ which is asymptotically insignificant. ■

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