Elegantly colored paths and cycles in edge colored random graphs

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Abstract

We first consider the following problem. We are given a fixed perfect matching M of $[n]$ and we add random edges one at a time until there is a Hamilton cycle containing M. We show that w.h.p. the hitting time for this event is the same as that for the first time there are no isolated vertices in the graph induced by the random edges. We then use this result for the following problem. We generate random edges and randomly color them black or white. A path/cycle is said to be *zebraic* if the colors alternate along the path. We show that w.h.p. the hitting time for a zebraic Hamilton cycle coincides with every vertex meeting at least one edge of each color. We then consider some related problems and (partially) extend our results to multiple colors. We also briefly consider directed versions.

1 Introduction

This paper studies the existence of nicely structured objects in (randomly) colored random graphs. Our basic interest will be in what we call *zebraic* paths and cycles. We assume that the edges of a graph G have been colored black or white. A path or cycle will be called *zebraic* if the edges alternate in color along the path. We view this as a variation on the usual theme of *rainbow* paths and cycles that have been well-studied. Rainbow Hamilton cycles in edge colored complete graphs were first studied in Erdős, Nešetřil and Rödl [8]. Colorings were constrained by the number of times, k, that an individual color could be used. Such a coloring is called k-bounded. They showed that allowing k to be any constant, there was always a rainbow Hamilton cycle, provided that the number of vertices n was sufficiently large. Hahn and Thomassen [17] were next to consider this problem and they showed that k could grow as fast as $n^{1/3}$ and there still be a rainbow Hamilton cycle and conjectured that the growth rate of k could in fact be linear. In an unpublished work Rödl and Winkler [22] in 1984 improved this to $n^{1/2}$. Frieze and Reed [16] improved this to $k = O(n/\log n)$ and finally Albert, Frieze and Reed [2] (and Rue) improved the upper bound on k to $n/64$. In another line of research, Cooper and Frieze [5] discussed the existence of rainbow Hamilton cycles in the random graph $G_{n,p}^{(q)}$ which consists of the random graph $G_{n,p}$ where each

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edge is independently and randomly given one of q colors. Here and elsewhere, we use "chosen randomly" to signify "chosen uniformly at random". They showed that if $p \geq \frac{21 \log n}{n}$ and $q \geq 21n$ then with high probability (w.h.p.), i.e. probability $1 - o(1)$, there is a rainbow colored Hamilton cycle. Frieze and Loh [14] improved this to $p \geq \frac{(1+o(1)) \log n}{n}$ and $q \geq n+o(n)$. Ferber and Krivelevich [10] improved it further to $p = \frac{\log n + \log\log n + \omega(n)}{n}$ and $q \geq n + o(n)$. Bal and Frieze [3] considered the case $q = n$ and showed that $p \geq \frac{K \log n}{n}$ suffices for large enough K. Ferber and Krivelevich [10] proved that if $p \gg \frac{\log n}{n}$ and $q = Cn$ colors are used, then w.h.p. $G_{n,p}$ contains $(1 - o(1))np/2$ edge-disjoint rainbow Hamilton cycles, for C large enough.

In this paper we study the existence of other colorings of paths and cycles. Our first result does not at first sight fit into this framework. Let n be even and let M_0 be an arbitrary perfect matching of the complete graph K_n. Now consider the random graph process $\{G_m\} = \{([n], E_m)\}$ where $E_m = \{e_1, e_2, \ldots, e_m\}$ is obtained from E_{m-1} by adding a random edge $e_m \notin E_{m-1}$, for $m = 0, 1, \ldots, N = \binom{n}{2}$.

Let

$$\tau_1 = \min \{m : \delta(G_m) \geq 1\} ,$$

where δ denotes minimum degree. Then let

$$\tau_H = \min \{m : G_m \cup M_0 \text{ contains a Hamilton cycle } H \supseteq M_0\} .$$

Theorem 1 $\tau_1 = \tau_H$ *w.h.p.*

Remark 1 *In actual fact there are two slightly different versions. One where we insist that $M_0 \cap E_m = \emptyset$ and one where E_m is chosen completely independently of M_0. Our proof of the theorem covers both cases. We will first give a proof under the assumption that E_m is chosen independently and then in Remark 17 see how to obtain the other case.*

We note that Robinson and Wormald [21] considered a similar problem with respect to random regular graphs. They showed that one can choose $o(n^{1/2})$ edges at random, orient them and then w.h.p. there will be a Hamilton cycle containing these edges and following the orientations.

Theorem 1 has an easy corollary that fits our initial description. Let $\{G_m^{(r)}\}$ be an r-colored version of the graph process. This means that $G_m^{(r)}$ is obtained from $G_{m-1}^{(r)}$ by adding a random edge and then giving it a random color from $[r]$. Let $E_{m,i}$ denote the edges of color i in $\{G_m^{(r)}\}$ for $i = 1, 2, \ldots, r$. When $r = 2$ denote the colors by *black* and *white* and let $E_{m,b} = E_{m,1}, E_{m,w} = E_{m,2}$. Then let $G_m^{(b)}$ be the subgraph of $G_m^{(2)}$ induced by the black edges and let $G_m^{(w)}$ induced by the white edges. Let

$$\tau_{1,1} = \min \left\{ m : \delta(G_m^{(b)}), \delta(G_m^{(w)}) \geq 1 \right\} ,$$

and let

$$\tau_{ZH} = \min \left\{ m : G_m^{(2)} \text{ contains a zebraic Hamilton cycle} \right\} .$$

Corollary 2 $\tau_{1,1} = \tau_{ZH}$ *w.h.p.*

Our next result is a zebraic analogue of *rainbow connection*. For a connected graph G, its rainbow connection $rc(G)$, is the minimum number r of colors needed for the following to hold: The edges of G can be r-colored so that every pair of vertices is connected by a rainbow path, i.e. a path in which no color is repeated. Recently, there has been interest in estimating this parameter for various classes of graph, including random graphs (see, e.g., [7, 13, 18, 20]). By analogy, we say that a connected graph with a two-coloring of its edges is *zebraicly connected* if there is a zebraic path joining every pair of vertices.

Theorem 2 *At time τ_1, G_{τ_1} with a random black-white coloring of its edges is zebraicly connected, w.h.p.*

We consider now how we can extend our results to more than two colors. Suppose we have r colors $[r]$ and that $r \mid n$. We would like to consider the existence of Hamilton cycles where the ith edge has color $(i \mod r) + 1$. Call such a cycle *r-zebraic*. Our result for this case is not as tight as for the case of two colors. We are not able to prove a hitting time version. We will instead satisfy ourselves with a result for $G_{n,p}^{(r)}$. Let

$$p_r = \frac{r}{\alpha_r} \frac{\log n}{n}$$

where

$$\alpha_r = \left\lceil \frac{r}{2} \right\rceil.$$

Theorem 3 *Let $\varepsilon > 0$ be an arbitrary positive constant and suppose that $r \geq 2$.*

$$\lim_{n\to\infty} \mathbf{Pr}(G_{n,p}^{(r)} \textit{ contains an } r\textit{-zebraic Hamilton cycle}) = \begin{cases} 0 & p \leq (1-\varepsilon)p_r \\ 1 & p \geq (1+\varepsilon)p_r \end{cases}.$$

The proofs of Theorems 1–3 will be given in Sections 4–6.

1.1 Directed Versions

There are some very natural directed versions of these results. With respect to Theorem 1 one can consider the directed graph process where the edges of the complete digraph $\vec{K}_n$ are randomly ordered as $e_1, e_2, \ldots, e_{n(n-1)}$. We can then consider a sequence of digraphs $D_m = ([n], \{e_1, e_2, \ldots, e_m\}), m \geq 1$ and consider hitting times for various properties. For example, suppose in addition one is given a perfect matching $M = \{f_1, f_2, \ldots, f_{n/2}\}$ together with an orientation of each edge in M. One can ask for the likely hitting time for the existence of a directed Hamilton cycle that contains M and respects the given orientation. Assume w.l.o.g. that $f_i = (2i-1, 2i)$ for $i = 1, 2, \ldots, n/2$, so that f_i is oriented from $2i-1$ to $2i$. Let $\vec{\tau}_H$ be the hitting time for the existence of such a cycle. Let $\vec{\tau}_1$ be the hitting time for each $1 \leq i \leq n/2$ to have an in-neighbor in $n/2+1, n/2+2, \ldots, n$ and for each $n/2+1, n/2+2, \ldots, n$ to have an out-neighbor in $1 \leq i \leq n/2$. Clearly $\vec{\tau}_H \geq \vec{\tau}_1$.

Theorem 4 *$\vec{\tau}_1 = \vec{\tau}_H$ w.h.p.*

Our other results will have directed analogs too. Suppose then that $D_{n,p}^{(r)}, m \geq 1$ is an r-colored version of the directed graph $D_{n,p}$. A directed r-zebraic Hamilton cycle is the directed analog what we see in Theorem 3. Then we have

Theorem 5 *Let $\varepsilon > 0$ be an arbitrary positive constant and suppose that $r \geq 2$.*

$$\lim_{n\to\infty} \mathbf{Pr}(D^{(r)}_{n,p} \text{ contains an } r\text{-zebraic directed Hamilton cycle}) = \begin{cases} 0 & p \leq (1-\varepsilon)p_r \\ 1 & p \geq (1+\varepsilon)p_r \end{cases}.$$

Notice that we do not claim a hitting time version for the case $r = 2$. It is unclear what the simple necesary condition should be. We discuss this further in Section 7.

There is a notion of directed zebraic connection when we 2-color a digraph and ask for a directed zebraic path from any vertex to any other vertex. Let $\vec{\tau}_{1,1}$ be the hitting time for D_m to have i-degree and out-degree at least one.

Theorem 6 *At time $\vec{\tau}_{1,1}$, $D_{\vec{\tau}_{1,1}}$ with a random black-white coloring of its edges is directed zebraicly connected, w.h.p.*

We will briefly discuss the proofs of these directed analogs in Section 7.

2 Notation

All logarithms will have base e unless explicitly stated otherwise.

For a graph $G = (V, E)$ and $S, T \subseteq V$ we let $e_G(S)$ denote the number of edges contained in S, $e_G(S, T)$ denote the number of edges with one end in S and the other in T. Let $e_G(S) = e_G(S, S)$ and let $N_G(S)$ denote the set of neighbors of S that are not in S.

We next list certain values and notation that we will use throughout our proofs. They are here for easy reference. The reader is encouraged to skip reading this section and to just refer back as necessary.

$$t_0 = \frac{n}{2}(\log n - 2\log\log n) \text{ and } t_1 = \frac{n}{2}(\log n + 2\log\log n)$$

$$t_2 = \frac{t_0}{10} \text{ and } t_3 = \frac{t_0}{5} \text{ and } t_4 = \frac{9t_0}{10}.$$

$$\zeta_i = t_i - t_{i-1} \text{ for } i = 3, 4.$$

$$p_i = \frac{t_i}{\binom{n}{2}},\ i = 0, 1, 2.$$

$$n_0 = \frac{n}{\log^2 n} \text{ and } n_0' = \frac{n_0}{\log^4 n} \text{ and } n_1 = \frac{n}{10\log n}.$$

$$n_b = \frac{n\log\log\log n}{\log\log n} \text{ and } n_c = \frac{200n}{\log n}.$$

$$L_0 = \frac{\log n}{100} \text{ and } L_1 = \frac{\log n}{\log\log n}.$$

$$\ell_0 = \frac{\log n}{200} \text{ and } \ell_1 = \frac{2\log n}{3\log\log n} \text{ and } \nu_L = \ell_0^{\ell_1} = n^{2/3+o(1)}.$$

The following graphs and sets of vertices are used.

$$\Psi_0 = G_{t_2} \setminus M_0 = ([n], E_{t_2} \setminus M_0).$$
$$V_0 = \{v \in [n] : d_{\Psi_0}(v) \le L_0\}.$$
$$\Psi_1 = \Psi_0 \cup \{e \in E_{\tau_1} \setminus E_{t_2} : e \cap V_0 \neq \emptyset\}.$$
$$V_\lambda = \{v \in [n] : \ v \text{ is large}\}.$$
$$V_\sigma = [n] \setminus V_\lambda.$$
$$E_B = \{e \in E_{t_4} \setminus E_{t_3} : e \cap V_0 = \emptyset\}.$$
$$V_\tau = \left\{v \in [n] \setminus V_0 : \deg_{E_B}(v) \le L_0\right\}.$$

The definition of "large" depends on which theorem we are proving.

Sometimes in what follows we will treat certain values as integer, when they should really be rounded up or down. We do this for conveneience and claim that rounding either way will not affect the validity of what is claimed.

3 Probabilistic Inequalities

We will need standard estimates on the tails of various random variables.

Chernoff Bounds: Let $B(n,p)$ denote the binomial random variable where n is the number of trials and p is the probability of success.

$$\mathbf{Pr}(|B(n,p) - np| \ge \varepsilon np) \le 2e^{-\varepsilon^2 np/3} \qquad \text{for } 0 \le \varepsilon \le 1. \tag{1}$$

$$\mathbf{Pr}(B(n,p) \ge anp) \le \left(\frac{e}{a}\right)^{anp} \qquad \text{for } a > 0. \tag{2}$$

For proofs, see the appendix of Alon and Spencer [1].

McDiarmid's Inequality: Let $Z = Z(Y_1, Y_2, \dots, Y_n)$ be a random variable where $Y_1, Y_2, \dots, Y_n$ are independent for $i = 1, 2, \dots, n$. Suppose that

$$|Z(Y_1, \dots, Y_{i-1}, Y_i, Y_{i+1}, \dots, Y_n) - Z(Y_1, \dots, Y_{i-1}, \widehat{Y}_i, Y_{i+1}, \dots, Y_n)| \le c_i$$

for all $Y_1, Y_2, \dots, Y_n, \widehat{Y}_i$ and $1 \le i \le n$. Then

$$\mathbf{Pr}(|Z - \mathbf{E}(Z)| \ge t) \le 2\exp\left\{-\frac{t^2}{2(c_1^2 + c_2^2 + \dots + c_n^2)}\right\}. \tag{3}$$

For a proof see for example [11](Lemma 21.16) or [19](Remark 2.28).

4 Proof of Theorem 1

4.1 Outline of proof

It is well known (see for example [11](Theorem 4.2) and [19](Section 5.1)) that w.h.p. we have $t_0 \le \tau_1 \le t_1$.

Our strategy for proving Theorem 1 is broadly in line with the 3-phase algorithm described in [6].

(a) We will take the first t_3 edges plus all of the next $\tau_1 - t_3$ edges incident to vertices that have a low degree in G_{t_2}. We argue that w.h.p. this contains a perfect matching M_1 that is disjoint from M_0. The union of M_0, M_1 will then have $O(\log n)$ components w.h.p.

(b) $M_0 \cup M_1$ induces a 2-factor made up of alternating cycles. We then use a selection of about ζ_4 edges from $E_{t_4} \setminus E_{t_3}$ to make the minimum cycle length $\Omega(n/\log n)$. This selection is carefully designed to avoid dependence issues, as is the case of the selection in (c).

(c) We then use a large subset of the final t_2 edges to create a Hamilton cycle containing M_0. This involves a second moment calculation. The edges used to create the cycle here are from $E_{t_0} \setminus E_{t_4}$. It follows that w.h.p. we will have created a Hamilton cycle contained in G_{τ_1}.

We are working in a different model to that in [6] and there are many more conditioning problems to be overcome. For example, in [6], it is very easy to show that the random digraph $D_{3-in,3-out}$ contains a set of $O(\log n)$ vertex disjoint cycles that contain all vertices. Here we have to build a perfect matching M_1 from scratch and to avoid several conditioning problems. The same is true for (b) and (c). The broad strategy is the same, the details are quite different.

4.2 Phase 1: Building M_1

We begin with $\Psi_0 = G_{t_2} \setminus M_0$. Then let V_0 denote the set of vertices that have degree at most $L_0 = \frac{\log n}{100}$ in Ψ_0. Now create $\Psi_1 = ([n], E_1)$ by adding those edges in $E_{\tau_1} \setminus E_{t_2}$ that are incident with V_0 and are disjoint from M_0. We argue that w.h.p. Ψ_1 is a random graph with minimum degree one in which almost all vertices have degree $\Omega(\log n)$. Furthermore, we will show that w.h.p. Ψ_1 is an expander, and then it will not be difficult to show that it contains the required perfect matching M_1.

Let a vertex be *large* if its degree in G_{t_1} is at least L_0 and *small* otherwise. Let V_λ denote the set of large vertices and let V_σ denote the set of small vertices.

The calculations for the next lemma will simplify if we observe the following: Suppose that $m = Np$. It is known that for any monotone property of graphs

$$\mathbf{Pr}(G_m \in \mathcal{P}) \leq 3\,\mathbf{Pr}(G_{n,p} \in \mathcal{P}). \tag{4}$$

In general we have for not necessarily monotone properties:

$$\mathbf{Pr}(G_m \in \mathcal{P}) \leq 3m^{1/2}\,\mathbf{Pr}(G_{n,p} \in \mathcal{P}). \tag{5}$$

For proofs of (4), (5) see Bollobás [4](Theorem 2.2) or Frieze and Karoński [11](Lemmas 1.2 and 1.3) or Janson, Łuczak and Ruciński [19](Lemma 1.10).

We will have reason to deal with a random sequence of multi-graphs defined as follows: Let $x_1, x_2, \ldots, x_t, \ldots,$ be random sequence where for all $i \geq 0$, x_{i+1} is chosen uniformly at random from $[n]$, independently of $x_1, x_2, \ldots, x_i$. For a positive integer t we let Γ_t be the multi-graph with edges $e_1, e_2, \ldots, e_t$ where $e_i = \{x_{2i-1}, x_{2i}\}$ for $i \geq 1$. If after removing the loops and repeats of edges from Γ_t we have τ edges then the graph we obtain has the same distribution as G_τ. Given this, we couple Γ_t with G_τ where $\tau = \tau(\Gamma_t)$ is a random variable.

Let Z_1 denote the number of loops and let Z_2 denote the number of repeated edges in Γ_{t_2}. Now Z_1 is distributed as $\mathrm{Bin}(t_2, 1/n)$ and then the Chernoff bound (2) implies that

$$\mathbf{Pr}(Z_1 \geq \log^2 n) \leq e^{-\log^2 n}. \tag{6}$$

We are doing more than usual here, because we need probability $O(n^{-0.51})$, rather than just probability $o(1)$. We require this in order to enable us to easily handle the case where we have to choose edges disjoint from M_0, as explained in Remark 17. There is one exception to this probabilistic requirement. Let $\mathcal{T}$ be the event that $t_0 \leq \tau_1 \leq t_1$. We do not require that $\mathbf{Pr}(\mathcal{T}) = 1 - O(n^{-0.51})$. A probability of $1 - o(1)$ will suffice.

Now Z_2 is dominated by $\mathrm{Bin}(t_2, t_2/N)$ and then the Chernoff bound (2) implies that

$$\mathbf{Pr}(Z_2 \geq \log^3 n) \leq e^{-\log^3 n}. \tag{7}$$

The properties in the next lemma will be used to show that w.h.p. Ψ_1 is an expander.

Lemma 3 *The following holds with probability* $1 - O(n^{-0.51})$*:*

(a) $|V_0| \leq n^{99/100}$.

(b) *If* $x, y \in V_\sigma$ *then the distance between them in* G_{t_1} *is at least 10.*

(c) *If* $S \subseteq [n]$ *and* $|S| \leq n_0 = \frac{n}{\log^2 n}$ *then* $e_{G_{t_1}}(S) \leq 10|S|$.

(d) *If* $S \subseteq [n]$ *and* $|S| = s \in [n_0' = \frac{n_0}{\log^4 n}, n_1 = \frac{n}{10 \log n}]$ *then* $|N_{\Psi_1}(S)| \geq s \log n/25$.

(e) *No cycle of length 4 in* G_{t_1} *contains a small vertex.*

(f) *No vertex of degree one in* G_{τ_1} *is incident with an edge of* $E_{t_1} \cap M_0$.

(g) *The maximum degree in* $G_{10n \log n}$ *is less than* $100 \log n$. **Crude but easy to verify.**

(h) $\tau_1 \leq 10 n \log n$.

Proof (a) Let V_0' denote the set of vertices of degree at most $L_0 + 1$ in Γ_{t_2}. Then in our coupling $|V_0| \leq Z_1 + 2Z_2 + |V_0'|$. This is because if $v \in V_0 \setminus V_0'$ then it must lie in a loop or a multiple edge. Also, $v \in L_0$ might have degree $L_0 + 1$ in G_{t_2}, but might lose an edge from the deletion of M_0 to create Ψ_1.

Now, applying (1) with $\varepsilon = 4/5$ we get

$$\mathbf{Pr}\left(v \in V_0'\right) \leq \mathbf{Pr}\left(B\left(2t_2, \frac{1}{n}\right) \leq \frac{\log n}{100} + 1\right) \leq n^{-1/99}.$$

It follows, that $\mathbf{E}(|V_0'|) \leq n^{98/99}$. We now use inequality (3) to finish the proof. Indeed, changing one of the x_i's can change $|V_0'|$ by at most one. Hence, for any $u > 0$,

$$\mathbf{Pr}(|V_0'| \geq \mathbf{E}(|V_0'|) + u) \leq \exp\left\{-\frac{u^2}{4t_2}\right\}.$$

Putting $u = n^{2/3}$ into the above and using (6), (7) finishes the proof of (a).

(b) We do not have room to apply (5) here. We need the inequality

$$\frac{\binom{N-a}{t-b}}{\binom{N}{t}} \leq \left(\frac{t}{N}\right)^b \left(\frac{N-t}{N-b}\right)^{a-b} \tag{8}$$

for $b \le a \le t \le N$. Verification of (8) is straightforward and can be found for example in Chapter 21.1 of [11]. We will now and again use the notation $A \le_b B$ in place of $A = O(B)$ when it suits our aesthetic taste. Let $\ell_1 = \frac{2\log n}{3\log\log n}$.

$$\begin{aligned}
\mathbf{Pr}(\exists\, x, y) &\le \sum_{k=2}^{11} \binom{n}{k} k! \sum_{\ell_1,\ell_2=0}^{L_0} \binom{n-k}{\ell_1}\binom{n-k}{\ell_2} \frac{\binom{N-(2n+k-5)}{t_1-(k-1+\ell_1+\ell_2)}}{\binom{N}{t_1}} \\
&\le_b \sum_{k=2}^{11} n^k \sum_{\ell_1,\ell_2=0}^{L_0} \left(\frac{ne}{\ell_1}\right)^{\ell_1} \left(\frac{ne}{\ell_2}\right)^{\ell_2} \left(\frac{t_1}{N}\right)^{\ell_1+\ell_2+k-1} \left(\frac{N-t_1}{N-(\ell_1+\ell_2+k-1)}\right)^{2n-(\ell_1+\ell_2-4)} \\
&\le_b n \sum_{k=2}^{11} \log^{k-1} n \sum_{\ell_1,\ell_2=0}^{L_0} \left(\frac{3\log n}{\ell_1}\right)^{\ell_1} \left(\frac{3\log n}{\ell_2}\right)^{\ell_2} n^{-2+o(1)} \\
&= O(n^{-0.51}).
\end{aligned}$$

(c) We can use (4) here with $p_1 = t_1/N$. If $s = |S|$, then in G_{n,p_1} where $p_1 = t_1/N$ and $N = \binom{n}{2}$,

$$\mathbf{Pr}(e_{G_{t_1}}(S) > 10|S|) \le 3\binom{\binom{s}{2}}{10s} p_1^{10s} \le 3\left(\frac{s^2 e}{20s} \cdot \frac{\log n + 2\log\log n}{n-1}\right)^{10s} \le \left(\frac{s\log n}{n}\right)^{10s}.$$

So,

$$\mathbf{Pr}(\exists\, S) \le \sum_{s=10}^{n_0} \binom{n}{s} \left(\frac{s\log n}{n}\right)^{10s} \le \sum_{s=10}^{n_0} \left(\frac{ne}{s}\right)^{s} \left(\frac{s\log n}{n}\right)^{10s} = \sum_{s=10}^{n_0} \left(e\left(\frac{s}{n}\right)^9 \log^{10} n\right)^s = O(n^{-0.51}).$$

(d) For this we will only use $E_{t_2} \subseteq E(\Psi_1)$. We can use (4) here with $p_2 = t_2/N$. For $v \in V \setminus S$, $\mathbf{Pr}(v \in N_{\Psi_1}(S)) \ge 1 - (1-p_2)^{s-1} \ge \frac{sp_2}{2}$ for $s \le n_1$. Here we have $s-1$ in place of s as we need to exclude the edges of M_0 in this calculation. So $|N_{\Psi_1}(S)|$ stochastically dominates $\mathrm{Bin}(n-s, \frac{sp_2}{2})$. Now $(n-s)\frac{sp_2}{2} \sim \frac{s\log n}{20}$ and so using the Chernoff bound (1) with $\varepsilon \sim 1/5$,

$$\mathbf{Pr}(|N_{\Psi_1}(S)| < s\log n/25) \le e^{-s\log n/1501}.$$

So,

$$\mathbf{Pr}(\exists\, S) \le \sum_{s=n_0'}^{n_1} \binom{n}{s} e^{-s\log n/1501} \le \sum_{s=n_0'}^{n_1} \left(\frac{ne}{s} \cdot n^{-1/1501}\right)^s = O(n^{-0.51}).$$

(e) The expected number of such cycles is bounded by

$$\begin{aligned}
&\binom{n}{4}\frac{3!}{2} \sum_{k=0}^{L_0} 4\binom{n-4}{k} \frac{\binom{N-n-3}{t_1-4-k}}{\binom{N}{t_1}} \\
&\le n^4 \left(\frac{t_1}{N}\right)^4 \left(\frac{N-t_1}{N-4}\right)^{n-1} + n^4 \sum_{k=1}^{L_0} \left(\frac{ne}{k}\right)^k \left(\frac{t_1}{N}\right)^{k+4} \left(\frac{N-t_1}{N-k-4}\right)^{n-k-1} \\
&\le_b \log^4 n \left(1 + \sum_{k=1}^{L_0} \left(\frac{e^{1+o(1)}\log n}{k}\right)^k\right) n^{-1+o(1)} \\
&= O(n^{-0.51}).
\end{aligned}$$

(f) We will first argue that if V_1 is the set of vertices of degree at most one in G_{t_0} then

$$\mathbf{Pr}(|V_1| \geq 2\log^4 n) = O(n^{-0.51}).$$

Indeed, fix a set $U \subseteq V$ of size u. For $v \in U$, let $d(v, V \setminus U)$ denote the number of edges incident with v and $V \setminus U$. Then, the the probability U is a subset of V_1 in G_{n,p_0} is at most

$$\begin{aligned}\mathbf{Pr}(d(v, V \setminus U) \leq 1, \forall v \in U) &= ((1-p_0)^{n-u} + (n-u)p_0(1-p_0)^{n-u-1})^u \\ &< \left(\frac{\log^3 n}{n}\right)^u.\end{aligned}$$

Hence, with $u = \log^4 n$ we have

$$\mathbf{Pr}(|V_1| \geq u) \leq \binom{n}{u}\left(\frac{\log^3 n}{n}\right)^u \leq \left(\frac{ne}{u} \cdot \frac{\log^3 n}{n}\right)^u = o(n^{-2}).$$

We now apply (5) to prove the result for G_{t_0}.

We now consider adding the final $\max\{0, \tau_1 - t_0\}$ edges. (We only know that $\mathbf{Pr}(\tau_1 \geq t_0) = 1 - o(1)$ and not $1 - O(n^{-0.51})$ and so we do not assume that $\tau_1 \geq t_0$ here.) Let $\mathcal{B}$ be the event that any of these edges is (i) incident with V_1 and (ii) lies in M_0. Thus,

$$\mathbf{Pr}(\mathcal{B}) \leq O(n^{-0.51}) + 10n\log n \cdot \frac{4\log^4 n}{n} \cdot \frac{1}{n} = O(n^{-0.51}).$$

Here the first $O(n^{-0.51})$) accounts for the probability that $\tau_1 - t_0 \geq 10n\log n$ or $|V_1| \geq 2\log^4 n$. Note that $\mathbf{Pr}(\tau_1 \geq 10n\log n) = o(n^{-1})$. The proof of this follows from a straigthforward estimate of the expected number of components of size at most $n/2$ at time $10n\log n$, see for example the proof of Theorem 4.1.of [11]. After this, each of the at most $10n\log n$ edges (see (f)) has probability $\frac{4\log^4 n}{n} \cdot \frac{1}{n}$ of being in M_0 and being incident with V_1.

(g) We apply (4) with $p = 10n\log n/N$ and find that the probability of having a vertex of degree exceeding $100\log n$ is at most

$$3n\binom{n-1}{100\log n}\left(\frac{20\log n}{n-1}\right)^{100\log n} \leq 3n\left(\frac{e^{1+o(1)}}{5}\right)^{100\log n} = O(n^{-10}). \tag{9}$$

(h) $\tau_1 > 10n\log n$ implies that $G_{10n\log n}$ contains a component of size at most $n/2$. Thus, with p as in (h),

$$\mathbf{Pr}(\tau_1 > 10n\log n) \leq 3\sum_{k=1}^{n/2}\binom{n}{k}(1-p)^{k(n-k)} \leq 3\sum_{k=1}^{n/2} n^k e^{-5k\log n} = o(1).$$

□

Remark 4 *Because $\mathcal{T}$ occurs w.h.p. we have that the statements in Lemma 3 hold with probability $1-O(n^{-0.51})$ if we condition on $\mathcal{T}$ occuring. This follows from $\mathbf{Pr}(A \mid B) \leq \mathbf{Pr}(A)/\mathbf{Pr}(B)$. Indeed, this is also true for any of the events below that are shown to hold with this probability.*

Lemma 3 implies the following:

Lemma 5 *With probability* $1 - O(n^{-0.51})$,

$$S \subseteq [n] \text{ and } |S| \le n/2000 \text{ implies } |N_{\Psi_1}(S)| \ge |S|. \tag{10}$$

Proof Assume that the conditions described in Lemma 3 hold. Let $N(S) = N_{\Psi_1}(S)$ and $e(S) = e_{\Psi_1}(S)$. We first argue that if $S \subseteq V_\lambda$ and $|S| \le n/2000$ then

$$|N(S)| \ge 4|S|. \tag{11}$$

From Lemma 3(d), we only have to concern ourselves with $|S| \le n_0'$ or $|S| \in [n_1, n/2000]$.

If $|S| \le n_0'$ and $T = N(S)$ then in Ψ_1 we have, using Lemma 3(g),(h), and accounting for the edges in M_0 being forbidden,

$$e(S \cup T) \ge |S| \left(\frac{\log n}{200} - 1 \right) \text{ and } |S \cup T| \le |S| \left(1 + 100 \log n\right) \le n_0. \tag{12}$$

It is important to note that to obtain (12) we use the fact that vertices in $V_0 \setminus V_\sigma$ are given all their edges in Ψ_1.

Equation (12) and Lemma 3(c) imply that $\frac{|S| \log n}{200} \le 10|S \cup T|$ and so (11) holds with room to spare.

If $|S| \in [n_1, n/2000]$ then we choose $S' \subseteq S$ where $|S'| = n_1$ and using Lemma 3(d), see that

$$|N(S)| \ge |N(S')| - |S| \ge \frac{\log n}{25} \cdot \frac{200|S|}{\log n} - |S|.$$

This yields (11), again with room to spare.

Now let $S_0 = S \cap V_\sigma$ and $S_1 = S \setminus S_0$. Then we have

$$|N(S)| \ge |N(S_0)| + |N(S_1)| - |N(S_0) \cap S_1| - |N(S_1) \cap S_0| - |N(S_0) \cap N(S_1)|. \tag{13}$$

But $|N(S_0)| \ge |S_0|$. This follows from (i) Ψ_1 has no isolated vertices (follows from Lemma 3(f)), and (ii) Lemma 3(b) means that S_0 is an independent set and no two vertices in S_0 have a common neighbor. Equation (11) implies that $|N(S_1)| \ge 4|S_1|$. We next observe that trivially, $|N(S_0) \cap S_1| \le |S_1|$. Then we have $|N(S_1) \cap S_0| \le |S_1|$, for otherwise some vertex in S_1 has two neighbors in S_0, contradicting Lemma 3(b). Finally, we also have $|N(S_0) \cap N(S_1)| \le |S_1|$. If for a vertex in S_1 there are two distinct paths of length two to S_0 then we violate one of the conditions – Lemma 3(b) or (e).

So, from (13) we have

$$|N(S)| \ge |S_0| + 4|S_1| - |S_1| - |S_1| - |S_1| = |S|.$$

$\square$

Next let $G = (V, E)$ be a graph with an even number of vertices that does not contain a perfect matching. Let v be a vertex not covered by some maximum matching, and suppose that M is a maximum matching that isolates v. Let $S_0(v,M) = \{u \neq v : M \text{ isolates } u\}$. If $u \in S_0(v,M)$ and $e = \{x,y\} \in M$ and $f = \{u,x\} \in E$ then *flipping* e, f replaces M by $M' = M + f - e$. Here e is *flipped-out*. Note that $y \in S_0(v,M')$.

Now fix a maximum matching M that isolates v and let

$$A(v,M) = \bigcup_{M'} S_0(v,M')$$

where we take the union over M' obtained from M by a sequence of flips.

Lemma 6 *Let G be a graph without a perfect matching and let M be a maximum matching and v be a vertex isolated by M. Then $|N_G(A(v,M))| < |A(v,M)|$.*

Proof Suppose that $x \in N_G(A(v,M))$ and that $f = \{u,x\} \in E$ where $u \in A(v,M)$. Now there exists y such that $e = \{x,y\} \in M$, else $x \in S_0(v,M) \subseteq A(v,M)$. We claim that $y \in A(v,M)$ and this will prove the lemma. Since then, every neighbor of $A(v,M)$ is also a neighbor via an edge of M.

Suppose that $y \notin A(v,M)$. Let M' be a maximum matching that (i) isolates u and (ii) is obtainable from M by a sequence of flips. Now $e \in M'$ because if e has been flipped out then either x or y is placed in $A(v,M)$. But then we can do another flip with M', e and the edge $f = \{u,x\}$, placing $y \in A(v,M)$, contradiction.

□

Define

$$E_A = E_{t_3} \setminus E(\Psi_1) = \{f_1, f_2, \ldots, f_\rho\}$$

where we see from Lemma 3(a),(g),(h) that with probability $1 - O(n^{-0.51})$ we have

$$\zeta_3 \geq \rho \geq \zeta_3 - 100n^{99/100}\log n \sim \frac{n\log n}{20}.$$

Lemma 7 *Given Ψ_1, V_0, ρ where $|V_0| \leq n^{99/100}$, we have that E_A is a uniformly random ρ-subset of $E_2 = \binom{V_1}{2} \setminus E(\Psi_1)$, where $V_1 = [n] \setminus V_0$.*

Proof This follows from the fact that if we remove any f_i and replace it with any other edge from E_2 then V_0 is unaffected. Thus E and $E - f + g$ are equally likely to be E_A, under our conditioning, where $f \in E$ and $g \in E_2 \setminus E$. A sequence of such changes shows that any ρ-subset of E_2 is equally likely to be E_A. □

Now consider the sequence of graphs $H_0 = \Psi_1, H_1, \ldots, H_\rho$ where H_i is obtained from H_{i-1} by adding the edge f_i. We claim that if μ_i denotes the size of a largest matching in H_i that is disjoint from M_0, then

$$\mathbf{Pr}(\mu_i = \mu_{i-1} + 1 \mid \mu_{i-1} < n/2,\ f_1, \ldots, f_{i-1},\ (\Psi_1 \text{ satisfies } (10))) \geq 10^{-7}. \tag{14}$$

To see this, let M_{i-1} be a matching of size μ_{i-1} in H_{i-1}, disjoint from M_0, and suppose that v is a vertex not covered by M_{i-1}. It follows from (10) and Lemma 6 that if $A_{H_{i-1}}(v) = \{g_1, g_2, \ldots g_r\}$

then $r \geq n/2000$. Now consider the pairs (g_j, x), $j = 1, \ldots, r$, $x \in A_{H_{j-1}}(g_j)$. There are at least $\binom{n/2000}{2}$ such pairs and if f_i lies in this collection, then $\mu_i = \mu_{i-1} + 1$. Equation (14) follows from this and Lemma 7. In fact, given Lemma 3(a), the probability in question is at least

$$\frac{\binom{n/2000 - n^{99/100}}{2} - \rho - n/2}{\binom{n}{2}} > 10^{-7},$$

where we have subtracted ρ to account for some edges of E_A having already been checked. And we have subtracted the size of M_0 too.

Now if there is no perfect matching in H_ρ then we will have $\mu_i = \mu_{i-1} + 1$ at most $n/2$ times. But from (14) we see that the probability of this is bounded by $\mathbf{Pr}\left(\mathrm{Bin}\left(\rho, 10^{-7}\right) \leq n/2\right)$. It follows that

$$\mathbf{Pr}(H_\rho \text{ has no perfect matching}) \leq O(n^{-0.51}) + \mathbf{Pr}\left(\mathrm{Bin}\left(\rho, 10^{-7}\right) \leq n/2\right) = O(n^{-0.51}).$$

So with probability $1 - O(n^{-0.51})$, $\Psi_2 = H_\rho$ has a perfect matching. We choose such a matching uniformly at random.

It follows by symmetry that M_1 is uniformly random, conditional only on being disjoint from M_0. This will not be true if we condition on various quantities like Ψ_0, V_0 etc., but we only make an unconditional claim (except for M_0). We will need the following properties of the 2-factor

$$\Pi_0 = M_0 \cup M_1.$$

Lemma 8 *The following hold with probability* $1 - O(n^{-0.51})$*:*

(a) $M_0 \cup M_1$ *has at most* $10 \log_2 n$ *components.*

(b) *There are at most* $n_b = \frac{n \log\log\log n}{\log\log n}$ *vertices in total in components of size at most* $n_c = \frac{200n}{\log n}$*.*

Proof Let

$$\nu(m) = \frac{(2m)!}{2^m m!} = \text{number of perfect matchings of } K_{2m}.$$

We observe that if we choose M_1 completely independently of M_0, then using inclusion-exclusion we see that the probability that $M_0 \cap M_1 = \emptyset$ is

$$\sum_{k=0}^{n/2} (-1)^k \binom{n/2}{k} \frac{\nu(n/2 - k)}{\nu(n/2)}. \tag{15}$$

Now for k constant we see that the summand in (15) is asymptotically equal to $\frac{1}{2^k k!}$. Then by truncating the sum in (15) at a large odd integer and using the Bonferroni inequality we see that the sum in (15) is at least $e^{-1/2} - \delta$ for any positive δ. We will therefore accept that $\mathbf{Pr}(M_0 \cap M_1 = \emptyset) \geq 1/3$ and then we can inflate the probabilities in (17), (18) by 3, at most, to handle the conditioning on $M_0 \cap M_1 = \emptyset$.

(a) We generate a uniform random matching by choosing any unmatched vertex v and pairing it with a random unmtched vertex w. Following the argument in [15] we note that if C is the cycle of $M_0 \cup M_1$ that contains vertex 1 then

$$\mathbf{Pr}(|C| = 2k) < \prod_{i=1}^{k-1} \left(\frac{n - 2i}{n - 2i + 1}\right) \frac{1}{n - 2k + 1} < \frac{1}{n - 2k + 1}. \tag{16}$$

Indeed, consider M_0-edge $\{1 = i_1, i_2\} \in C$ containing vertex 1. Let $\{i_2, i_3\} \in C$ be the M_1-edge containing i_2. Then $\mathbf{Pr}(i_3 \neq 1) = \frac{n-2}{n-1}$. Assume $i_3 \neq 1$ and let $\{i_3, i_4 \neq 1\} \in C$ be the M_0 edge containing i_3. Let $\{i_4, i_5\} \in C$ be the M_1-edge containing i_4. Then $\mathbf{Pr}(i_5 \neq 1) = \frac{n-4}{n-3}$ and so on.

Having chosen C, the remaining cycles come from the union of two (random) matchings on the complete graph $K_{n-|C|}$. It follows from this, by summing (16) over $k \leq n/4$ that

$$\mathbf{Pr}(|C| < n/2) \leq \sum_{k=1}^{n/4} \frac{1}{n-2k+1} \leq \frac{n}{4} \times \frac{2}{n} = \frac{1}{2}.$$

Hence, from (1) with $\varepsilon = 4/5$,

$$\mathbf{Pr}(\neg(a)) \leq \mathbf{Pr}(Bin(10 \log_2 n, 1/2) \leq \log_2 n) \leq 2e^{-10 \log_2 n/3} = O(n^{-0.51}). \tag{17}$$

(b) It follows from (16) that

$$\mathbf{Pr}(|C| \leq n_c) \leq \frac{201}{\log n}.$$

If we generate cycle sizes as in (a) then up until there are fewer than $n_b/2$ vertices left, $\log \nu \sim \log n$ where ν is the number of vertices that need to be partitioned into cycles. It follows that the probability we generate more than $k = \frac{\log\log\log n \times \log n}{1000 \log\log n}$ cycles of size at most n_c up to this time is bounded by

$$O(n^{-0.51}) + \mathbf{Pr}\left(Bin\left(10 \log_2 n, \frac{201}{\log n}\right) \geq k\right) \leq O(n^{-0.51}) + \left(\frac{3000e}{k}\right)^k = O(n^{-0.51}). \tag{18}$$

Thus with probability $1 - O(n^{-0.51})$, we have at most

$$\frac{n_b}{2} + kn_c \leq n_b$$

vertices on cycles of length at most n_b. □

4.3 Phase 2: Increasing minimum cycle length

In this section, we will use the edges in

$$E_B = \{e \in E_{t_4} \setminus E_{t_3} : e \cap V_0 = \emptyset\}$$

to create a 2-factor that contains M_0 and in which each cycle has length at least n_c. Note that

$$E_B \cap \Psi_1 = \emptyset.$$

Note also that

Lemma 9 *Given Ψ_1 and E_{t_3}, E_B is a uniformly random $|E_B|$-subset of $E_3 = \binom{V_1}{2} \setminus (\Psi_1 \cup E_{t_3})$, where $V_1 = [n] \setminus V_0$.*

Proof This follows from the fact that if we remove any edge of E_B and replace it with any other edge from E_3 then V_0 is unaffected. $\square$

We eliminate the small cycles (of length less than n_c) one by one (more or less). Let C be a small cycle. We remove an edge $\{u_0, v_0\} \notin M_0$ of C. We then try to join u_0, v_0 by a sufficiently long M_1 alternating path P that begins and ends with edges not in M_0. This is done in such a way that the resulting 2-factor contains M_0 but has at least one less small cycle. The search for P is done in a breadth first manner from both ends, creating $n^{2/3+o(1)}$ paths that begin at v_0 and another $n^{2/3+o(1)}$ paths that end at u_0. We then argue that with sufficient probability, we can find a pair of paths that can be joined by an edge from E_B to create the required alternating path.

We proceed to a detailed description. Let

$$V_\tau = \left\{v \in [n] \setminus V_0 : \deg_{E_B}(v) \leq L_0\right\},$$

where for a set of edges X and a vertex x, $\deg_X(x)$ is the number of edges in X that are incident with x.

Lemma 10 *The following hold with probability $1 - O(n^{-0.51})$:*

(a) $|V_\tau| \leq n^{2/5}$.

(b) *No vertex has 10 or more G_{t_1} neighbors in V_τ.*

(c) *If C is a cycle with $|C| \leq n_c$ then $|C \cap V_\tau| \leq |C|/200$ in G_{t_1}.*

Proof

(a) Let $p = \frac{|E_B|}{|E_3|} \approx \frac{7 \log n}{n}$, assuming that $|V_0| = o(n)$. Suppose we replace E_B by a subset $X \subseteq E_3$ with edges included independently with probability p. Fix a set $U \subseteq V_1 = V \setminus V_0$ of size μ. For $v \in U$, now let $d(v, V_1 \setminus U)$ denote the number of edges in X incident with v and $V_1 \setminus U$. Then, if $n_1 = |V_1| = n - o(n)$,

$$\begin{aligned}
\mathbf{Pr}(d(v, V_1 \setminus U) \leq L_0, \forall v \in U) &= \left(\sum_{i=0}^{L_0} \binom{n_1}{i} p^i (1-p)^{n_1 - i}\right)^\mu \\
&= (n^{-7/10 + (\log 100)/100 + o(1)})^\mu < n^{-13\mu/20}.
\end{aligned}$$

Hence, applying (5), we have with $\mu = n^{2/5}$,

$$\mathbf{Pr}(|V_\tau| \geq \mu) \leq O(n^{1/2+o(1)}) \binom{n}{\mu} n^{-13\mu/20} \leq O(n^{1/2+o(1)}) \left(\frac{ne}{\mu} \cdot n^{-13/20}\right)^\mu = o(n^{-1}).$$

(b) This time we can condition on $\nu = n - |V_0|$ and $\mu = |\{e \in E_{t_4} \setminus E_{t_3} : e \cap V_0 \neq \emptyset\}| \leq n^{99/100} \times 10 \log n$. We write

$$\mathbf{Pr}(v \text{ violates (b)}) \leq \sum_{S \in \binom{[n-1]}{10}} \mathbf{Pr}(\mathcal{A}(v, S)) \, \mathbf{Pr}(\mathcal{B}(v, S) \mid \mathcal{A}(v, S))$$

where

$$\mathcal{A}(v,S)=\{N(v)\supseteq S,\ \text{in } G_{t_1}\},$$
$$\mathcal{B}(v,S)=\{w \text{ has at most } L_0\ E_B\text{-neighbors in } [n]\setminus(S\cup\{v\}), \forall w\in S\}.$$

Applying (4) we see that $\mathbf{Pr}(\mathcal{A}(v,S))\le 3p_1^{10}$ and then using (4) with

$$p=\frac{t_4-t_3-\mu}{\binom{\nu}{2}}\sim\frac{7\log n}{10n} \tag{19}$$

we see that

$$\mathbf{Pr}(\mathcal{B}(v,S)\mid\mathcal{A}(v,S))\le 3\left(\sum_{k=0}^{L_0}\binom{\nu-11}{k}p^k(1-p)^{\nu-11-k}\right)^{10}$$

and so

$$\begin{aligned}\mathbf{Pr}(v \text{ violates (b)}) &\le_b \binom{n}{10}p_1^{10}\left(\sum_{k=0}^{L_0}\binom{\nu-11}{k}p^k(1-p)^{\nu-11-k}\right)^{10}\\ &\le (e^{o(1)}\log n\cdot n^{1/10-7/10+o(1)})^{10}\\ &= o(n^{-5}).\end{aligned}$$

Now use the Markov inequality.

(c) Let Z denote the number of cycles violating the required property. Using (4) and ν as in (b) and p as in (19), we have

$$\begin{aligned}\mathbf{E}(Z) &\le_b \sum_{k=3}^{n_c}\binom{n}{k}k!p_1^k\binom{k}{\lceil\frac{k}{200}\rceil}\left(\sum_{\ell=0}^{L_0}\binom{\nu-k}{\ell}p^\ell(1-p)^{\nu-\ell}\right)^{\lceil k/200\rceil}\\ &\le \sum_{k=3}^{n_c}(2n)^k\left(\frac{\log n+2\log\log n}{n-1}\right)^k n^{-3\lceil k/200\rceil/5}\\ &= O(n^{-0.51}).\end{aligned}$$

□

Let $\mathcal{E}_0$ denote the intersection of the high probability events of Lemmas 3 and 10.

Lemma 11 *Let $V_1=[n]\setminus V_0$ and let $|E_B|=\mu=\alpha n\log n, \alpha=O(1)$ and $|V_1|=\nu\ge n-n^{99/100}$.*

(a) If $A\subseteq\binom{V_1}{2}$ with $|A|=a=o(n^{1/2})$ and X is a subset of $\binom{V_1}{2}$ with $|X|=O(n^{99/100}\log n)$ and $A\cap X=\emptyset$, then

$$\mathbf{Pr}(E_B\supseteq A\mid\mathcal{E}_0, X\subseteq E_B)=\frac{\binom{\binom{\nu}{2}-a-|X|}{\mu-a-|X|}}{\binom{\binom{\nu}{2}-|X|}{\mu-|X|}} \tag{20}$$
$$=(1+o(1))\left(\frac{2\alpha\log n}{n}\right)^a. \tag{21}$$

(b) $A \subseteq \binom{V_1}{2}$ *with* $|A| = a = o(n^2)$ *then*

$$\mathbf{Pr}(E_B \cap A = \emptyset \mid \mathcal{E}_0) = \frac{\binom{\binom{\nu}{2}-a}{\mu}}{\binom{\binom{\nu}{2}}{\mu}} \tag{22}$$

$$\leq \exp\left\{-\frac{a\mu}{\nu^2}\right\}. \tag{23}$$

Proof (a) Equation (20) follows from Lemma 9. For equation (21), we write

$$\frac{\binom{\binom{\nu}{2}-a-|X|}{\mu-a-|X|}}{\binom{\binom{\nu}{2}-|X|}{\mu-|X|}} = \left(\frac{\mu-|X|}{\binom{\nu}{2}-|X|}\right)^a\left(1+O\left(\frac{a^2}{\mu-|X|}\right)\right) = \left(\frac{\mu}{\binom{\nu}{2}}\right)^a\left(1+O\left(\frac{a^2}{\mu-|X|}\right)+O\left(\frac{a|X|}{\mu}\right)\right).$$

This follows from the fact that in general, if $s^2 = o(N)$ then

$$\frac{\binom{N-s}{M-s}}{\binom{N}{M}} = \left(\frac{M}{N}\right)^s\left(1+O\left(\frac{s^2}{M}\right)\right).$$

(b) Equation (22) follows as for (20), and (23) follows from

$$\frac{\binom{\binom{\nu}{2}-a}{\mu}}{\binom{\binom{\nu}{2}}{\mu}} = \prod_{i=0}^{a-1}\frac{\binom{\nu}{2}-\mu-i}{\binom{\nu}{2}-i}.$$

$\square$

By construction, we can apply this lemma to the graph induced by E_B with

$$\alpha \approx \frac{t_4-t_3}{2n\log n} \approx \frac{7}{20}.$$

Let a cycle C of Π_0 be *small* if its length $|C| < n_c$ and *large* otherwise. Define a near 2-factor to be a graph that is obtained from a 2-factor by removing one edge. A near 2-factor Γ consists of a path $P(\Gamma)$ and a collection of vertex disjoint cycles. A 2-factor or a near 2-factor is *proper* if it contains M_0. We abbreviate proper near 2-factor to PN2F.

We will describe a process of eliminating small cycles. In this process we create intermediate proper 2-factors. Let Γ_0 be a 2-factor and suppose that it contains a small cycle C. To begin the elimination of C we choose an arbitrary edge $\{u_0, v_0\}$ in $C \setminus M_0$, where $u_0, v_0 \notin V_\tau$. This is always possible, since $M_0 \cup M_1$ is the union of disjoint cycles of length at least three and because of Lemma 10(c). We delete it, obtaining a PN2F Γ_1. Here, $P(\Gamma_1) \in \mathcal{P}(v_0, u_0)$, the set of M_1-alternating paths in G from v_0 to u_0. Here an M_1-alternating path must begin and end with an edge of M_1. The initial goal will be to create a large set of PN2Fs such that each Γ in this set has path $P(\Gamma)$ of length at least n_c and the small cycles of Γ are a strict subset of the small cycles of Γ_0. Then we will show that with probability $1 - O(n^{-0.51})$, the endpoints of one of the paths in some such Γ can be joined by an edge to create a proper 2-factor with at least one fewer small cycle than Γ_0.

This process can be divided into two stages. In a generic step of Stage 1, we take a PN2F Γ as above with $P(\Gamma) \in \mathcal{P}(u_0, v)$ and construct a new PN2F with the same starting point u_0 for its path. We do this by considering edges from E_B incident to v. Suppose $\{v, w\} \in E_B$ and that the non-M_0 edge in Γ containing vertex w is $\{w, x\}$. Then $\Gamma' = \Gamma \cup \{v, w\} \setminus \{w, x\}$ is a PN2F with $P(\Gamma') \in \mathcal{P}(u_0, x)$. We say that $\{v, w\}$ is *acceptable* if

(i) $x, w \notin W$ (W defined immediately below).

(ii) $P(\Gamma')$ has length at least n_c and any new cycle created (in Γ' but not Γ) has at least n_c edges.

There is an unlikely technicality to be faced. If Γ has no non-M_0 edge (x, w), then $w = u_0$ and this is accepted if $P(\Gamma')$ has at least n_c edges and it ends the round. When $P(\Gamma')$ has fewer edges we lose one out of $L_0 = \Omega(\log n)$ possible branching choices and this is inconsequential. It is also unlikely, having probability $O(|E_B|/\binom{n}{2}) = O(\log n/n)$. We refer to this as event $\mathcal{C}$ and we remark on it in the proof of Lemma 12 below.

In addition we define a set W of *used* vertices, where

$$W = V_\tau \text{ at the beginning of Phase 2,}$$

and whenever we look at edges $\{v, w\}, \{w, x\}$ (that is, consider using that edge to create a new Γ'), we add v, w, x to W. Additionally, we maintain $|W| = O(n^{99/100})$, or fail if we cannot. Note also that W accumulates as we remove short cycles.

We will build a tree T of PN2Fs, breadth-first, where each non-leaf vertex Γ yields PN2F children Γ' as above. When we stop building T we will have $\nu_L = n^{2/3+o(1)}$ leaves, see (24). This will end Stage 1 for the current cycle C being removed.

We will restrict the set of PN2F's which could be children of Γ in T as follows: We restrict our attention to $w \notin W$ with $\{v, w\} \in E_B$ and $\{v, w\}$ acceptable as defined above. Also, we only construct children from the first $\ell_0 = L_0/2$ acceptable $\{v, w\}$'s at a vertex v. Furthermore we only build the tree down to $\ell_1 = \frac{2\log n}{3\log\log n}$ levels. We denote the nodes in the ith level of the tree by S_i. Thus $S_0 = \{\Gamma_1\}$ and S_{i+1} consists of the PN2F's that are obtained from S_i using acceptable edges. In this way we define a tree of PN2F's with root Γ_1 that has branching factor at most ℓ_0. Thus,

$$|S_{\ell_1}| \le \nu_L = \ell_0^{\ell_1}. \tag{24}$$

Now augment $\mathcal{E}_0$ with the properties claimed in Lemma 8. Then,

Lemma 12 *Conditional on the event $\mathcal{E}_0$,*

$$|S_{\ell_1}| = \nu_L$$

with probability $1 - o(n^{-3})$.

Proof If $P(\Gamma)$ has endpoints u_0, v and $e = \{v, w\} \in E_B$ and e is unacceptable then (i) w lies on $P(\Gamma)$ and is within distance n_c of an endpoint or (ii) $x \in W$ or $w \in W$ or (iii) w lies on a small cycle or (iv) $w \in V_\tau$. Ab initio, there are at least L_0 choices for w and we must bound the number of unacceptable choices.

The probability that at least $L_0/10$ vertices are unacceptable due to (iii) is by Lemmas 8 and 11(a) at most

$$(1+o(1))\binom{n_b}{L_0/10}\left(\frac{7\log n}{(10+o(1))n}\right)^{L_0/10} \le \left(\frac{9en_b\log n}{L_0 n}\right)^{L_0/10}$$
$$\le \left(\frac{900e\log\log\log n}{\log\log n}\right)^{L_0/10} = O(n^{-K})$$

for any constant $K > 0$. In our application of Lemma 11, X is the set of E_B-edges incident with W and A is a possible set of E_B-edges incident with v.

A similar argument deals with conditions (i) and (ii). Lemma 10(b) means that (iv) only requires us to subtract 10.

Thus, with (conditional) probability $1 - o(n^{-4})$,

$$\text{each vertex of } T \text{ is incident with at least } \frac{\log n}{100} - \frac{3\log n}{1000} - 10 - 1 \text{ acceptable edges}$$

$$\text{and so } |S_{t+1}| \geq \frac{\log n}{200}|S_t|,$$

for all t. (The -1 accounts for the possible occurrence of the event $\mathcal{C}$). So with (conditional) probability $1 - o(n^{-3})$ we have

$$|S_{\ell_1}| = \nu_L$$

as desired. (This assumes that $|W|$ remains $O(n^{99/100})$, see Remark 13 below.) $\square$

Having built T, if we have not already made a cycle, we have a tree of PN2Fs and the last level, ℓ_1 has leaves Γ_i, $i = 1, ..., \nu_L$, each with a path $P(\Gamma_i)$ of length at least n_c. (Recall the definition of an acceptable edge.) Now, perform a second stage which will be like executing ν_L-many *Stage 1*'s *in parallel* by constructing trees T_i, $i = 1, ..., \nu_L$ each of depth ℓ_1, where the root of T_i is Γ_i. Suppose for each i, $P(\Gamma_i) \in \mathcal{P}(u_0, v_i)$; we fix the vertex v_i and build paths by first looking at neighbors of u_0, for all i (so in tree T_i, every Γ will have path $P(\Gamma) \in \mathcal{P}(u, v_i)$ for some u).

Construct these ν_L trees in Stage 2 by only enforcing the conditions that $x, w \notin W$. This change will allow the PN2Fs to have small paths and cycles. We will not impose a bound on the branching factor either. As a result of this and the fact that each tree T_i begins by considering edges from E_B incident to u_0, the sets of endpoints of paths (that are not the v_is) of PN2Fs at the same level are the same in each of the trees $T_i, i = 1, 2, \ldots, \nu_L$. That is, for every pair $1 \leq i < j \leq \nu_L$, if Γ_i is a node at level ℓ of tree T_i and $P(\Gamma_i) \in \mathcal{P}(w, v_i)$ for some $w \notin V_\tau$ then there exists a node Γ_j at level ℓ of tree T_j, such that $P(\Gamma_j) \in \mathcal{P}(w, v_j)$. This can be proved by induction, see [5]. Indeed, let $L_{i,\ell}$ denote the set of end vertices, other than v_i, of the paths associated with the nodes at depth ℓ of the tree T_i, $i = 1, 2 \ldots, \nu_L, \ell = 0, 1, \ldots, \ell_1$. Thus $L_{i,0} = \{u_0\}$ for all i. We can see inductively that $L_{i,\ell} = L_{j,\ell}$ for all i, j, ℓ. In fact if $v \in L_{i,\ell} = L_{j,\ell}$ then $\{v, w\} \in E_B$ is acceptable for some i means that $w \notin W$ (at the start of the construction of level $\ell + 1$) and hence if $\{w, x\}$ is the non-M_0 edge for this i then $x \notin W$ and it is the non-M_0 edge for all j. In which case $\{v, w\}$ is acceptable for all i and we have $L_{i,\ell+1} = L_{1,\ell+1}$.

The set of trees $T_i, i = 1, ..., \nu_L$, will be succesfully constructed (i.e. have exactly ν_L leaves) with probability $1 - o(1/n^3)$ and with a similar probability the number of nodes in each tree is at most $(100\log n)^{\ell_1} = n^{2/3+o(1)}$. Here we use the fact that the maximum degree in $G_{t_1} \leq 100\log n$ with this probability, see (9). However, some of the trees may use unacceptable edges, and so we will "prune" the trees by disallowing any node Γ that was constructed in violation of any of those conditions. Call tree T_i GOOD if it still has at least ν_L leaves remaining after pruning and BAD otherwise. Notice that

$$\mathbf{Pr}(\exists\ i : T_i \text{ is BAD} \mid \mathcal{E}_0) = o\left(\frac{\nu_L}{n^3}\right) = o(n^{-2}).$$

Here the $o(1/n^3)$ factor is the one promised in Lemma 12.

Finally, consider the probability that there is no E_B edge from any of the $n^{2/3+o(1)}$ endpoints found in Stage 1 to any of the $n^{2/3+o(1)}$ endpoints found in Stage 2. At this point we will have only exposed the E_B-edges of Π_0 incident with these endpoints. So if for some $k \leq \nu_L$ we examine the (at least) $\log n/100$ edges incident to $v_1, v_2, \ldots, v_k$, then from Lemma 11(b), with X equal to the E_B-edges incident with W and A equal to the set of pairs $(v_i, w), i \leq k$ where w is a leaf of some $T_i, 1 \leq i \leq \nu_L$, we see that the probability we fail to close a cycle and produce a proper 2-factor is at most

$$\exp\left\{-\frac{k \times n^{2/3+o(1)} n \log n}{\binom{\nu}{2}}\right\}.$$

Thus taking $k = n^{1/3+o(1)}$ suffices to make the failure probability $o(n^{-2})$. (If we have n^γ endpoints here, then we need k to be $\omega(n^{1-\gamma})$.) Also, this final part of the construction only contributes $n^{1/3+o(1)}$ to W, viz. $v_1, v_2, \ldots, v_k$ and $O(k \log n)$ of their neighbors. Our choice of $k = n^{1/3+o(1)}$ and $n^{2/3+o(1)}$ for tree size makes this probability small and controls the size of W. There are other choices, this is just one of them.

Therefore, the probability that we fail to eliminate a particular small cycle C is $o(n^{-2})$ and then given $\mathcal{E}_0$, the probability that Phase 2 fails is $o(\log n/n^2) = o(1)$.

Remark 13 *We should check now that w.h.p. $|W| = O(n^{99/100})$ throughout Phase 2. It starts out with at most $n^{99/100} + n^{2/5}$ vertices (see Lemmas 3(a) and 10(a)) and we add $O(n^{2/3+o(1)} \times \log n)$ vertices altogether in this phase.*

So we conclude:

Lemma 14 *The probability that Phase 2 fails to produce a proper 2-factor with minimum cycle length at least n_c is $O(n^{-0.51})$.*

$\square$

4.4 Phase 3: Creating a Hamilton cycle

By the end of Phase 2, we will with probability $1 - O(n^{-0.51})$ have found a proper 2-factor with all cycles of length at least n_c. Call this subgraph Π^*.

In this section, we will use the edges in

$$E_C = \{e \in E_{t_0} \setminus (E_{t_4} \cup E(\Psi_1)) : e \cap V_0 = \emptyset\}$$

to turn Π^* into a Hamilton cycle that contains M_0, w.h.p. It is basically a second moment calculation with a twist to keep the variance under control. We note that Lemma 11 continues to hold if we replace E_B by E_C and α by $\frac{1}{20} + o(1)$.

Arbitrarily assign an orientation to each cycle. Let $C_1, ..., C_k$ be the cycles of Π^* (note that if $k = 1$ we are done) and let $c_i = \lceil |C_i \setminus W|/2 \rceil$. Then $c_i \geq \frac{n_c}{2} - O(n^{99/100}) \geq \frac{99n}{\log n}$ for all i. Let $a = \frac{n}{\log n}$ and

$m_i = 2\lfloor \frac{c_i}{a} \rfloor + 1$ for all i and $m = \sum_{i=1}^{k} m_i$. We arbitrarily orient the cycles $C_1, \ldots, C_k$. Then from each C_i, we will consider choosing m_i edges $\{v, w\}$ such that $v, w \in C_i \setminus W$ and v is the head of a non-M_0 arcs after the arbitrary orientation of the cycles. We then delete these m arcs and replace them with m others to create a proper Hamilton cycle. We use a second moment calculation to show that such a substitution is possible w..h.p.

Given such a deletion of edges, re-label the broken arcs as $(v_j, u_j), j \in [m]$ as follows: in cycle C_i identify the lowest numbered vertex $x_i \in [n]$ which loses a cycle edge directed out of it. Put $v_1 = x_1$ and then go round C_1 defining $v_2, v_3, \ldots v_{m_1}$ in order. Then let $v_{m_1+1} = x_2$ and so on. We thus have m path sections $P_j \in \mathcal{P}(u_{\phi(j)}, v_j)$ in Π^* for some permutation ϕ.

It is our intention to rejoin these path sections of Π^* to make a Hamilton cycle using E_C, if we can. Suppose we can. This defines a permutation ρ on $[m]$ where $\rho(i) = j$ if P_i is joined to P_j by $(v_i, u_{\phi(j)})$, where $\rho \in H_m$, the set of cyclic permutations on $[m]$. We will use the second moment method to show that a suitable ρ exists w.h.p. A technical problem forces a restriction on our choices for ρ. This will produce a variance reduction in a second moment calculation, as explained in (27).

Given ρ define $\lambda = \phi\rho$. In our analysis we will restrict our attention to $\rho \in R_\phi = \{\rho \in H_m : \phi\rho \in H_m\}$. If $\rho \in R_\phi$ then we have not only constructed a Hamilton cycle in $\Pi^* \cup E_C$, but also in the *auxiliary digraph* Λ, whose edges are $(i, \lambda(i))$.

The following lemma is from [6]. The content is in the lower bound. It shows that there are still many choices for ρ and it is needed to show that the expected number of possible re-arrangements of path sections grows with n.

Lemma 15 *$(m-2)! \leq |R_\phi| \leq (m-1)!$*

Let H be the graph induced by the union of Π^* and E_C. In the following lemma we drop the requirement that events occur with probability $1 - O(n^{-0.51})$. This requirement was used to handle issues related to M_0 and the edges chosen. At this point these issues no longer matter and w.h.p. takes its usual meaning.

Lemma 16 *H contains a Hamilton cycle w.h.p.*

Proof Let X be the number of Hamilton cycles in G that can be obtained by removing the edges described above and rearranging the path segments generated by ϕ according to those in $\rho \in R_\phi$ and connecting the path segments using edges in H.

We will use the inequality $\mathbf{Pr}(X > 0) \geq \frac{\mathbb{E}(X)^2}{\mathbb{E}(X^2)}$ to show that such a Hamilton cycle exists with the required probability.

The definition of m_i gives us $\frac{n-|W|}{a} - k \leq m \leq \frac{n-|W|}{a} + k$ and so $1.99 \log n \leq m \leq 2.01 \log n$. Additionally we will use $k \leq \frac{n}{n_c} = \frac{\log n}{200}$, $m_i \geq 199$ and $\frac{c_i}{m_i} \geq \frac{a}{2.01}$ for all i.

From Lemmas 11 and 15, we have, with $\alpha = 1/20 + o(1)$,

$$\mathbb{E}(X) \geq (1-o(1)) \left(\frac{2\alpha \log n}{n}\right)^m (m-2)! \prod_{i=1}^{k} \binom{c_i}{m_i} \tag{25}$$

$$\geq \frac{1-o(1)}{m^{3/2}} \left(\frac{2m\alpha \log n}{en}\right)^m \prod_{i=1}^{k} \left(\left(\frac{c_i e^{1-1/10m_i}}{m_i^{1+(1/2m_i)}}\right)^{m_i} \left(\frac{1-2m_i^2/c_i}{\sqrt{2\pi}}\right)\right) \tag{26}$$

$$= \frac{(1-o(1))e^{-k/10}(2\pi)^{-k/2}}{m^{3/2}} \left(\frac{2m\alpha \log n}{en}\right)^m \prod_{i=1}^{k} \left(\frac{c_i e}{m_i^{1+(1/2m_i)}}\right)^{m_i}$$

where to go from (25) to (26) we have used the approximation $(m-2)! \geq m^{-3/2}(m/e)^m$ and

$$\binom{c_i}{m_i} \geq \frac{c_i^{m_i}(1-2m_i^2/c_i)}{m_i!} \text{ and } m_i! \leq \sqrt{2\pi m_i}\left(\frac{m_i}{e}\right)^{m_i} e^{1/10m_i}.$$

Explanation of (25): We choose the arcs to delete in $\prod_{i=1}^k \binom{c_i}{m_i}$ ways and put them together as explained prior to Lemma 15 in at least $(m-2)!$ ways. The probability that the required edges exist in E_C is $(1+o(1))\left(\frac{2\alpha \log n}{n}\right)^m$, from Lemma 11.

Continuing, we have

$$\begin{aligned}
\mathbb{E}(X) &\geq \frac{(1-o(1))(2\pi)^{-k/2}e^{-k/10}}{m^{3/2}} \left(\frac{2m\alpha \log n}{en}\right)^m \prod_{i=1}^{k} \left(\frac{c_i e}{(1.02)m_i}\right)^{m_i} \\
&\geq \frac{(1-o(1))(2\pi)^{-k/2}}{n^{1/2000}m^{3/2}} \left(\frac{2m\alpha \log n}{en}\right)^m \left(\frac{ea}{2.01 \times 1.02}\right)^m \\
&\geq \frac{1-o(1)}{n^{1/1000}m^{3/2}} \left(\frac{\log n}{30}\right)^m \\
&\to \infty.
\end{aligned}$$

Let M, M' be two sets of selected edges which have been deleted in Π^* and whose path sections have been re-arranged into Hamilton cycles according to ρ, ρ' respectively. Let N, N' be the corresponding sets of edges which have been added to make the Hamilton cycles. Let Ω denote the set of choices for M (and M'.)

Let $s = |M \cap M'|$ and $t = |N \cap N'|$. Now $t \leq s$ since if $(v, u) \in N \cap N'$ then there must be a unique $(\tilde{v}, u) \in M \cap M'$ which is the unique Π^*-edge into u. It is shown in [6] that

$$t = s \text{ implies } t = s = m \text{ and } (M, \rho) = (M', \rho'). \tag{27}$$

(This removes a large term from the second moment calculation). Indeed, suppose then that $t = s$ and $(v_i, u_i) \in M \cap M'$. Now the edge $(v_i, u_{\lambda(i)}) \in N$ and since $t = s$ this edge must also be in N'. But this implies that $(v_{\lambda(i)}, u_{\lambda(i)}) \in M'$ and hence in $M \cap M'$. Repeating the argument we see that $(v_{\lambda^k(i)}, u_{\lambda^k(i)}) \in M \cap M'$ for all $k \geq 0$. But λ is cyclic and so our claim follows.

If $\langle s,t\rangle$ denotes the case where $s=|M\cap M'|$ and $t=|N\cap N'|$, then

$$\begin{aligned}\mathbb{E}(X^2) &\leq \mathbb{E}(X)+(1+o(1))\sum_{M\in\Omega}\left(\frac{2\alpha\log n}{n}\right)^m \sum_{\substack{M'\in\Omega\\ N'\cap N=\emptyset}}\left(\frac{2\alpha\log n}{n}\right)^m \\ &\quad + (1+o(1))\sum_{M\in\Omega}\left(\frac{2\alpha\log n}{n}\right)^m \sum_{s=2}^{m}\sum_{t=1}^{s-1}\sum_{\substack{M'\in\Omega\\ \langle s,t\rangle}}\left(\frac{2\alpha\log n}{n}\right)^{m-t} \\ &= \mathbb{E}(X)+E_1+E_2 \text{ say.}\end{aligned}$$

Note that $E_1\leq(1+o(1))\mathbb{E}(X)^2$.

Now, with σ_i denoting the number of common $M\cap M'$ edges selected from C_i,

$$E_2\leq E(X)^2\sum_{s=2}^{m}\sum_{t=1}^{s-1}\binom{s}{t}\left[\sum_{\sigma_1+\ldots+\sigma_k=s}\prod_{i=1}^{k}\frac{\binom{m_i}{\sigma_i}\binom{c_i-m_i}{m_i-\sigma_i}}{\binom{c_i}{m_i}}\right]\frac{(m-t-1)!}{(m-2)!}\left(\frac{n}{2\alpha\log n}\right)^t.$$

Some explanation: There are $\binom{s}{t}$ choices for $N\cap N'$, given s and t. Given σ_i there are $\binom{m_i}{\sigma_i}$ ways to choose $M\cap M'$ and $\binom{c_i-m_i}{m_i-\sigma_i}$ ways to choose the rest of $M'\cap C_i$. After deleting M' and adding $N\cap N'$ there are at most $(m-t-1)!$ ways of putting the segments together to make a Hamilton cycle.

We see that

$$\frac{\binom{c_i-m_i}{m_i-\sigma_i}}{\binom{c_i}{m_i}}\leq\frac{\binom{c_i}{m_i-\sigma_i}}{\binom{c_i}{m_i}}=\frac{m_i(m_i-1)\cdots(m_i-\sigma_i+1)}{(c_i-m_i+1)\cdots(c_i-m_i+\sigma_i)}\leq(1+o(1))\left(\frac{2.01}{a}\right)^{\sigma_i}\exp\left\{-\frac{\sigma_i(\sigma_i-1)}{2m_i}\right\}.$$

Also, Jensen's inequality, applied twice implies that

$$\sum_{i=1}^{k}\frac{\sigma_i^2}{2m_i}=\left(\sum_{i=1}^{k}\sigma_i^2\right)\cdot\left(\sum_{i=1}^{k}\frac{\sigma_i^2}{\sum_{i=1}^{k}\sigma_i^2}\frac{1}{2m_i}\right)\geq\frac{s^2}{k}\cdot\frac{k}{2m}=\frac{s^2}{2m}\text{ for }\sigma_1+\ldots+\sigma_k=s.$$

Furthermore,

$$\sum_{i=1}^{k}\frac{\sigma_i}{2m_i}\leq\frac{k}{2}\text{ and }\sum_{\sigma_1+\ldots+\sigma_k=s}\prod_{i=1}^{k}\binom{m_i}{\sigma_i}=\binom{m}{s}.$$

Using these approximations, we have

$$\sum_{\sigma_1+\ldots+\sigma_k=s}\prod_{i=1}^{k}\frac{\binom{m_i}{\sigma_i}\binom{c_i-m_i}{m_i-\sigma_i}}{\binom{c_i}{m_i}}\leq e^{(1+o(1))k/2}\exp\left\{-\frac{s^2}{2m}\right\}\left(\frac{2.01}{a}\right)^s\binom{m}{s}.$$

So we can write

$$\frac{E_2}{\mathbb{E}(X)^2}\leq e^{(1+o(1))k/2}\sum_{s=2}^{m}\sum_{t=1}^{s-1}\binom{s}{t}\exp\left\{-\frac{s^2}{2m}\right\}\left(\frac{2.01}{a}\right)^s\binom{m}{s}\frac{(m-t-1)!}{(m-2)!}\left(\frac{n}{2\alpha\log n}\right)^t.$$

We approximate

$$\binom{m}{s}\frac{(m-t-1)!}{(m-2)!}\leq C_1\frac{m^s}{s!}\left(\frac{m-t-1}{e}\right)^{m-t-1}\left(\frac{e}{m-2}\right)^{m-2}\leq C_2\frac{m^s}{s!}\frac{e^t}{m^{t-1}},$$

for some constants $C_1, C_2 > 0$.

Substituting this in, we obtain,

$$\begin{aligned}
\frac{E_2}{\mathbb{E}(X)^2} &\leq_b n^{1/399} m \sum_{s=2}^{m} \left(\frac{2.01}{a}\right)^s \frac{m^s}{s!} \exp\left\{-\frac{s^2}{2m}\right\} \sum_{t=1}^{s-1} \binom{s}{t} \left(\frac{en}{2\alpha m \log n}\right)^t \\
&\leq n^{1/399} m \sum_{s=2}^{m} \left(\frac{2.01}{a}\right)^s \frac{m^s}{s!} \exp\left\{-\frac{s^2}{2m}\right\} \times 2m \left(\frac{en}{2\alpha m \log n}\right)^{s-1} \\
&\leq_b \frac{m^2}{n^{.99}} \sum_{s=2}^{\infty} \left(\frac{(2.01)en\ \exp\{-s/2m\}}{2\alpha a \log n}\right)^s \frac{1}{s!} \\
&\leq \frac{m^2}{n^{.99}} \sum_{s=2}^{\infty} \frac{30^s}{s!} \\
&= O(n^{-9/10}).
\end{aligned}$$

Combining things, we get

$$\mathbb{E}(X^2) \leq \mathbb{E}(X) + \mathbb{E}(X)^2(1+o(1)) + \mathbb{E}(X)^2 n^{-9/10}$$

and so

$$\frac{(\mathbb{E}X)^2}{\mathbb{E}(X^2)} \geq \frac{1}{\frac{1}{\mathbb{E}X} + 1 + o(1) + n^{-9/10}} \longrightarrow 1$$

as $n \to \infty$, as desired. $\square$

Remark 17 *We now consider the case where we are given M_0 and we must choose edges disjoint from M_0.*

(a) If we choose t_1 edges independently of M_0 then the probability they are disjoint from M_0 is, where $N = \binom{n}{2}$,

$$\frac{\binom{N-n/2}{t_1}}{\binom{N}{t_1}} = \prod_{i=0}^{t_1-1}\left(1 - \frac{n}{2(N-i)}\right) \geq \exp\left\{-\sum_{i=0}^{t_1-1} \frac{n}{2(N-i)} + O\left(\frac{t_1 n^2}{N^2}\right)\right\} = n^{-1/2+o(1)}.$$

(b) We have shown that if we generate t_1 edges independent of M_0 then conditional on $t_0 \leq \tau_1 \leq t_1$ we have that with probability $1 - O(n^{-0.51})$ there is a perfect matching in $E_{\tau_1} \setminus M_0$.

(c) If we only choose from edges not in M_0 then the distribution of the edges we choose is the same as simply conditioning on $E_{t_1} \cap M_0 = \emptyset$.

It follows from (a),(b),(c) that if we avoid M_0 then we will still w.h.p. find a perfect matching M_1. Indeed, letting $\mathcal{A} = \{M_1 \text{ exists}\}, \mathcal{B} = \{E_{t_1} \cap M_0 = \emptyset\}$ andn $\mathcal{T} = \{t_0 \leq \tau_1 \leq t_1\}$ as before, we have

$$\mathbf{Pr}(\bar{\mathcal{A}} \mid \mathcal{B}) = \frac{\mathbf{Pr}(\bar{\mathcal{A}}\mathcal{B}\mathcal{T})}{\mathbf{Pr}(\mathcal{B})} + \frac{\mathbf{Pr}(\bar{\mathcal{A}}\mathcal{B}\bar{\mathcal{T}})}{\mathbf{Pr}(\mathcal{B})} \leq \frac{\mathbf{Pr}(\bar{\mathcal{A}} \mid \mathcal{T})}{\mathbf{Pr}(\mathcal{B})\,\mathbf{Pr}(\mathcal{T})} + \mathbf{Pr}(\bar{\mathcal{T}} \mid \mathcal{B}). \tag{28}$$

Now

$$\frac{\mathbf{Pr}(\bar{\mathcal{A}} \mid \mathcal{T})}{\mathbf{Pr}(\mathcal{B})\,\mathbf{Pr}(\mathcal{T})} = \frac{O(n^{-0.51})}{\Omega(n^{-0.5+o(1)})(1-o(1))} = o(1)$$

and this deals with the first term on the RHS of (28)*.*

For the second term on the RHS of (28) *we have*

$$\mathbf{Pr}(\bar{\mathcal{T}} \mid \mathcal{B}) \le n\frac{\binom{\binom{n}{2}-\frac{1}{2}n-(n-2)}{t_1}}{\binom{\binom{n}{2}-\frac{1}{2}n}{t_1}} \le n\left(1-\frac{n-2}{\binom{n}{2}-\frac{1}{2}n}\right)^{t_1} = o(1).$$

It follows that $\mathbf{Pr}(\bar{\mathcal{A}} \mid \mathcal{B}) = o(1)$*. The remainder of the proof that there is a Hamilton cycle containing* M_0 *goes through with minor changes that reflect the fact that we do not choose edges of* M_0*.*

4.5 Proof of Corollary 2

We begin the proof by replacing the sequence $E_0, E_1, \ldots, E_m, \ldots$ by $E_0', E_1', \ldots, E_m', \ldots$, where the edges of $E_m' = \{e_1', e_2', \ldots, e_m'\}$ are randomly chosen *with replacement*. This means in particular that e_m is allowed to be a member of E_{m-1}'. We let G_m' be the graph $([n], E_m')$.

If an edge appears a second time, it will keep its original color. We let R denote the set of edges that get repeated, up to time $\tau_{1,1}$. Note that

$$2t_0 \le \tau_{1,1} \le 2t_1 \text{ } w.h.p. \tag{29}$$

since the Chernoff bounds imply that w.h.p. we there at most $t_0 + O(n^{1/2}\log n)$ edges of each color at time t_0 and at least $t_1 - O(n^{1/2}\log n)$ edges of each color at time t_1. Note that if $e_{\tau_{1,1}} = \{v, w\} \in R$ then v or w is isolated in $G^{(b)}_{\tau_{1,1}-1}$ or $G^{(w)}_{\tau_{1,1}-1}$.

$$\mathbf{Pr}(e_{\tau_{1,1}} \in R) \le 4\,\mathbf{Pr}(\exists e = \{v, w\} \in R : v \text{ has black degree 1 at time } \tau_{1,1}) = o(1). \tag{30}$$

Explanation: The factor 4 comes from v or w having black or white degree one at time $\tau_{1,1}$. Next suppose first that $e_{\tau_{1,1}} = \{v, w\}$ and that v has black degree zero in $G_{\tau_{1,1}-1}$ and w also has black degree zero in $G_{\tau_{1,1}-1}$. Now w.h.p. there is no white edge joining v and w and so $e_{\tau_{1,1}} \notin R$. Indeed, the probability of this event can be bounded by

$$o(1) + \sum_{t=2t_0}^{2t_1}\binom{n}{2}\frac{1}{\binom{n}{2}}\left(\left(1-\frac{n-1}{2\binom{n}{2}}\right)^{t}\left(1-\frac{n-1}{2\binom{n}{2}}\right)^{t-1}\right) \le o(1) + 2t_1\left(\frac{\log^2 n}{n}\right)^2 = o(1).$$

The $o(1)$ accounts for $\tau_{1,1}$ not being in the interval $[2t_0, 2t_1]$. The factor $\binom{n}{2}$ accounts for the choice of v, w. The factor $1/\binom{n}{2}$ is the probability that the tth edge is $\{v, w\}$ and the final product accounts the black degree of both u, v being zero.

Now suppose that $e_{\tau_{1,1}} = \{v, w\}$ and that v has black degree zero in $G_{\tau_{1,1}-1}$ and w has positive black degree in $G_{\tau_{1,1}-1}$. An argument similar to that given for Lemma 3(g) shows that w.h.p. the maximum white degree in G_{2t_1}' is $O(\log n)$. There are $n-1$ choices for w, of which $O(\log n)$ put $e_{\tau_{1,1}}$ into R. So $e_{\tau_{1,1}}$ has an $O(\log n/n)$ chance of being in R. This verifies (30).

At time $m=\tau_{1,1}$ the graphs $G_m^{(b)'}, G_m^{(w)'}$ will w.h.p. contain perfect matchings, see [9]. That paper does not allow repeated edges, but removing them enables one to use the result claimed. Here we use the fact that w.h.p. there are only $O(\log^2 n)$ repeated edges, (as explained below), they are far apart, and are not incident to any low degree vertices. Thus any argument based on expansion goes through without difficulty. We choose perfect matchings M_B, M_W uniformly at random from $G_{\tau_{1,1}}^{(b)'}$, $G_{\tau_{1,1}}^{(w)'}$ respectively. Thus by symmetry, each is a random perfect matching disjoint from its oppositely colored perfect matching.

We couple the sequence $G_1, G_2, \ldots,$ with the sequence $G_1', G_2', \ldots,$ by ignoring repeated edges in the latter. Thus $G_1', G_2', \ldots, G_m'$ is coupled with a sequence $G_1, G_2, \ldots, G_{m'}$ where $m' \leq m$. It follows from (30) that w.h.p. the coupled processes stop with the same edge. Furthermore, they stop with two matchings M_B, M_W, independently chosen. We can then begin analysing Phase 2 and Phase 3 within this context.

We will prove that

$$\mathbf{Pr}(M_B \cap R = \emptyset) \geq n^{-1/2-o(1)}. \tag{31}$$

Corollary 2 follows from this. If $M_B \cap R = \emptyset$ then the white edges are chosen conditional on being disjoint from M_B. It follows from (31) and the fact that Phases 1 and 2 succeed with probability $1-O(n^{-0.51})$ (i.e. when ignoring the conditioning, $M_B \cap R = \emptyset$) that they succeed w.h.p. conditional on $M_B \cap R = \emptyset$.

Phase 3 succeeds w.h.p. even if we avoid using edges in R. We have already carried out calculations with an arbitrary set of $O(n^{99/100}\log n)$ edges that must be avoided. The size of R is dominated by a binomial $Bin(O(n\log n), O(n^{-1}\log n))$ and so $|R| = O(\log^2 n)$ w.h.p. So avoiding R does not change any calculation in any significant way. In other words, we can w.h.p. find a zebraic Hamilton cycle in G_m'.

Finally note that the Hamilton cycle we obtain is zebraic.

Proof of (31)**:** R is a uniformly random set, given its size and it is independent of M_B. Indeed, we can repeat edges arbitrarily without changing M_B. Let t_B be the number of black edges, then

$$\mathbf{Pr}(M_B \cap R = \emptyset \mid t_B) \geq \left(1 - \frac{n/2}{N}\right)^{t_B} \geq \exp\left\{-t_B\left(\frac{1}{n} + O\left(\frac{1}{n^2}\right)\right)\right\}.$$

Explanation of first inequality: Each choice of black edge has at most an $\frac{n/2}{N}$ chance of repeating an edge of M_B, regardless of previously seen edges.

To remove the conditioning, we take expectations and then by convexity

$$\mathbf{E}\left(\exp\left\{-t_B\left(\frac{1}{n} + O\left(\frac{1}{n^2}\right)\right)\right\}\right) \geq \exp\left\{-\,\mathbf{E}(t_B)\left(\frac{1}{n} + O\left(\frac{1}{n^2}\right)\right)\right\} \geq n^{-1/2-o(1)}$$

since $\mathbf{E}(t_B) \sim \frac{1}{2} n \log n$. This proves (31).

5 Proof of Theorem 2

For a vertex $v \in [n]$ we let its *black* degree $d_b(v)$ be the number of black edges incident with v in G_{t_0}. We define its *white* degree $d_w(v)$ analogously. Let a vertex be *large* if $d_b(v), d_w(v) \geq L_0$ and *small* otherwise.

We first show how to construct zebraic paths between a pair x, y of large vertices. We can in fact construct paths, even if we decide on the color of the edges incident with x and y. We do breadth first searches from each vertex, alternately using black and white edges, constructing search trees T_x, T_y. We build trees with $n^{2/3+o(1)}$ leaves and then argue that we can connect the leaves with a correctly colored edge. We then find paths between small vertices and other vertices by piggybacking on the large to large paths.

We will need the following structural properties:

Lemma 18 *The following hold w.h.p.:*

(a) *No set S of at most 10 vertices that is connected in G_{t_1} contains three small vertices.*

(b) *Let a be a positive integer, independent of n. No set of vertices S, with $|S| = s \leq aL_1, L_1 = \frac{\log n}{\log\log n}$, contains more than $s + a$ edges in G_{t_1}.*

(c) *There are at most $n^{2/3}$ small vertices in G_{t_0}.*

(d) *There are at most $\log^3 n$ isolated vertices in G_{t_0}.*

Proof (a) We say that a vertex is a *low color vertex* if it is incident in G_{t_1} to at most $L_\varepsilon = (1+\varepsilon)L_0$ edges of one of the colors, where ε is some sufficiently small positive constant. Furthermore, it follows from (4) that

$$
\begin{aligned}
&\mathbf{Pr}(\exists \text{ a connected } S \text{ in } G_{n,t_1} \text{ with three low color vertices})\\
&\leq \sum_{k=3}^{10} \binom{n}{k} k^{k-2} \frac{\binom{N-k+1}{t_1-k+1}}{\binom{N}{t_1}} \binom{k}{3} \mathbf{Pr}(\text{vertices 1,2,3 are low color } \mid [k] \text{ is a connected set}) \qquad (32)\\
&\leq_b \sum_{k=3}^{10} \binom{n}{k} k^{k-2} \frac{\binom{N-k+1}{t_1-k+1}}{\binom{N}{t_1}} \binom{k}{3} \left(2\sum_{\ell=0}^{L_\varepsilon} \binom{n-k}{\ell} \left(\frac{p_1}{2}\right)^\ell \left(1-\frac{p_1}{2}\right)^{n-k-\ell}\right)^3 \qquad (33)\\
&\leq_b \sum_{k=3}^{10} n^k \left(\frac{t_1}{N}\right)^{k-1} (n^{-0.45})^3\\
&\leq_b \sum_{k=3}^{10} n^k \left(\frac{\log n}{n}\right)^{k-1} (n^{-0.45})^3\\
&= o(1).
\end{aligned}
$$

Explanation of (32)**,**(33)**:** Having chosen our tree, $\frac{\binom{N-k+1}{t_1-k+1}}{\binom{N}{t_1}}$ is the probability that this tree exists in G_{t_1}. Condition on this and choose three vertices. The final $(\cdots)^3$ in (33) bounds the probability of the event that 1,2,3 are low color vertices in G_{n,p_1}. This event is monotone decreasing when restricted to the edges of a fixed color, given the conditioning. So we can use (4) to replace G_{n,t_1} by G_{n,p_1} here.

Now a simple first moment calculation shows that w.h.p. each vertex in $[n]$ is incident with less than $\log n/(\log\log n)^{1/2}$ edges of $E_{t_1} \setminus E_{t_0}$. Indeed, the number of such edges incident with a fixed vertex v is dominated by the binomial $Bin(t_1 - t_0, 2/n) = Bin(2n \log\log n, 2/n)$. And then

$$\mathbf{Pr}(\exists v) \leq n \binom{2n \log\log n}{\log n/(\log\log n)^{1/2}} \left(\frac{2}{n}\right)^{\log n/(\log\log n)^{1/2}} \leq n \left(\frac{4e(\log\log n)^{3/2}}{\log n}\right)^{\log n/(\log\log n)^{1/2}} = o(1).$$

Hence, for (a) to fail, there would have to be a relevant set S with three vertices, each incident in G_{t_1} with at most $(1 + o(1))L_0$ edges of one of the colors, contradicting the above.

(b) We will prove something slightly stronger. Suppose that $p = \frac{K \log n}{n}$ where $K > 0$ is arbitrary. We will show this result for $G_{n,p}$. The result for this lemma follows from when $K = 1 + o(1)$ and from (4). We get

$$\begin{aligned}
\mathbf{Pr}(\exists\ S) &\leq_b \sum_{s \geq 4}^{aL_1} \binom{n}{s} \binom{\binom{s}{2}}{s+a+1} p^{s+a+1} \\
&\leq_b \sum_{s \geq 4}^{aL_1} \left(\frac{ne}{s} \cdot \frac{sep}{2}\right)^s (sep)^{a+1} \\
&\leq_b (Ke^2 \log n)^{aL_1} \left(\frac{\log^2 n}{n}\right)^{a+1} \\
&\leq n^{o(1)} \left(\frac{\log^{3+L_1} n}{n}\right)^a \frac{\log^2 n}{n} \\
&= o(1).
\end{aligned}$$

(c) Using (4) we see that if Z denotes the number of small vertices then

$$\mathbf{E}(Z) \leq_b n \sum_{k=0}^{L_0} \left(\frac{p_0}{2}\right)^k \left(1 - \frac{p_0}{2}\right)^{n-1-k} \leq n^{0.55}.$$

We now use the Markov inequality.

(d) Using (4) we see that the expected number of isolated vertices in G_{t_0} is $O(\log^2 n)$. We now use the Markov inequality. $\square$

Now fix a pair of large vertices $x < y$. We will define sets $S_i^{(b)}(z), S_i^{(w)}(z), i = 0, 1, \ldots, \ell_1,\ z = x, y$.

Assume w.l.o.g. that ℓ_1 is even. We let $S_0^{(b)}(x) = S_0^{(w)}(x) = \{x\}$ and then $S_1^{(b)}(x)$ (resp. $S_1^{(w)}(x)$) is the set consisting of the first ℓ_0 black (resp. white) neighbors of x in G_{t_0}. We will use the notation $S_{\leq i}^{(c)}(x) = \bigcup_{j=1}^i S_j^{(c)}(x)$ for $c = b, w$. We now iteratively define for $i = 0, 1, \ldots, (\ell_1 - 2)/2$.

$$\begin{aligned}
&\hat{S}_{2i+1}^{(b)}(x) = \left\{ v \notin S_{\leq 2i}^{(b)}(x) : v \neq y \text{ is joined by a black } G_{t_0}\text{-edge to a vertex in } S_{2i}^{(b)}(x) \right\}. \\
&S_{2i+1}^{(b)}(x) = \text{the first } \ell_0^i \text{ members of } \hat{S}_{2i+1}^{(b)}(x). \\
&\hat{S}_{2i+2}^{(b)}(x) = \left\{ v \notin S_{\leq 2i+1}^{(b)} : v \neq y \text{ is joined by a white } G_{t_0}\text{-edge to a vertex in } S_{2i+1}^{(b)}(x) \right\}. \\
&S_{2i+2}^{(b)}(x) = \text{the first } \ell_0^i \text{ members of } \hat{S}_{2i+2}^{(b)}(x) :
\end{aligned}$$

We then define, for $i = 0, 1, \ldots, (\ell_1 - 2)/2$.

$\hat{S}^{(w)}_{2i+1}(x) = \left\{ v \notin (S^{(b)}_{\leq \ell_1}(x) \cup S^{(w)}_{\leq 2i}(x)) : v \neq y \text{ is joined by a white } G_{t_0}\text{-edge to a vertex in } S^{(w)}_{2i}(x) \right\}$
$S^{(w)}_{2i+1}(x) = \text{the first } \ell_0^i \text{ members of } \hat{S}^{(w)}_{2i+1}(x).$
$\hat{S}^{(w)}_{2i+2}(x) = \left\{ v \notin (S^{(b)}_{\leq \ell_1}(x) \cup S^{(w)}_{\leq 2i+1}(x)) : v \neq y \text{ s joined by a black } G_{t_0}\text{-edge to a vertex in } S^{(w)}_{2i+1}(x) \right\}$
$S^{(w)}_{2i+2}(x) = \text{the first } \ell_0^i \text{ members of } \hat{S}^{(w)}_{2i+2}(x) :$

Lemma 19 *If $1 \leq i \leq \ell_1$, then in G_{t_0}, for $c = b, w$,*

$$\mathbf{Pr}(|\hat{S}^{(c)}_{i+1}(x)| \leq \ell_0 |S^{(c)}_i(x)| \mid |S^{(c)}_j(x)| = \ell_0^j,\ 0 \leq j \leq i) = O(n^{-K}) \textit{ for any constant } K > 0.$$

Proof This follows easily from (5) and the Chernoff bounds and $\ell_0^{\ell_1} = o(n)$. In G_{n,p_0}, given that $|S^{(c)}_{2i}(x)| = \ell_0^i$, each random variable $\hat{S}^{(c)}_{2i+1}(x)$ is binomially distributed with parameters $n - o(n)$ and $1 - (1 - p_0/2)^{\ell_0^i}$. The mean is therefore asymptotically $\frac{1}{2}\ell_0^i \log n = \Omega(\log^2 n)$ and we are asking for the probability that it is much less than half its mean. $\Box$

It follows from this lemma, that w.h.p., we may define $S^{(b)}_0(x), S^{(b)}_1(x), \ldots, S^{(b)}_{\ell_1}(x)$ where $|S^{(b)}_i(x)| = \ell_0^i$ such that for each j and $z \in S^{(b)}_j(x)$ there is a zebraic path from x to z that starts with a black edge. For $S^{(w)}_{\ell_1}(x)$ we can say the same except that the zebraic path begins with a white edge.

Having defined the $S^{(c)}_i(x)$ etc., we define sets $S^{(c)}_i(y), i = 1, 2 \ldots, \ell_1$, $c = b, w$. We let $S^{(b)}_0(y) = S^{(w)}_0(y) = \{y\}$ and then $S^{(b)}_1(y)$ (resp. $S^{(w)}_1(y)$) is the set consisting of the first ℓ_0 black (resp. white) neighbors of y that are not in $S^{(b)}_{\leq \ell_1}(x) \cup S^{(w)}_{\leq \ell_1}(x)$. We note that for $c = b, w$ we have that w..h.p. $|\hat{S}^{(c)}_1(y)| \geq L_0 - 18 > \ell_0$. This follows from Lemma 18(b). We can appply this lemma because w.h.p. $t_0 \leq \tau_1 \leq t_1$. Indeed, suppose that y has ten neighbors T in $S^{(w)}_{\leq \ell_1}(x)$. Let S be the set of vertices in the paths from T to x in $S^{(w)}_{\leq \ell_1}(x)$. If $|S| = s$ then $S \cup \{y\}$ contains at least $s + 9$ edges. This is because every neighbour after the first adds an additional k vertices and $k + 1$ edges to the subgraph of G_{t_0} spanned by $S \cup \{y\}$, for some $k \leq \ell_1$. Now $s + 1 \leq 10\ell_1 + 1 \leq 7L_1$ and the $s + 9$ edges contradict the condition in the lemma, with $a = 7$.

We make a slight change in the definitions of the $\hat{S}^{(c)}_i(y)$ in that we keep these sets disjoint from the $S^{(c')}_i(x)$. Thus we take for example

$$\hat{S}^{(w)}_{2i+1}(y) = \\ \left\{ v \notin (S^{(w)}_{\leq 2i}(y) \cup S^{(b)}_{\leq \ell_1}(x) \cup S^{(w)}_{\leq \ell_1}(x)) : v \text{ is joined by a white } G_{t_0}\text{-edge to a vertex in } S^{(w)}_{2i}(y) \right\}.$$

Then we note that excluding $o(n)$ extra vertices has little effect on the proof of Lemma 19 which remains true with x replaced by y. We can then define the $S^{(c)}_i(y)$ by taking the first ℓ_0 vertices.

Suppose now that we condition on the sets $S^{(c)}_i(x), S^{(c)}_i(y)$ for $c = b, w$ and $i = 0, 1, \ldots, \ell_1$. The edges between the sets with $c = b$ and $i = \ell_1$ and those with $c = w$ and $i = \ell_1$ are unconditioned. Let

$$\Lambda = \ell_0^{2\ell_1} = n^{4/3 - o(1)}.$$

Then, for example, using (4), (strictly speaking, bounding the probability of monotone events in the context of a hypergeometric distribution by the corresponding probability under a binomial distribution),

$$\mathbf{Pr}(\nexists \text{ a black } G_{t_0} \text{ edge joining } S_{\ell_1}^{(b)}(x), S_{\ell_1}^{(b)}(y)) \leq 3\left(1 - \frac{\log n}{(2+o(1))n}\right)^{\Lambda} = O(n^{-K}),$$

for any positive constant K. □

Thus w.h.p. there is a zebraic path with both terminal edges black between every pair of large vertices. A similar argument using $S_{\ell_1}^{(w)}(x), S_{\ell_1}^{(w)}(y)$ shows that w.h.p. there is a zebraic path with both terminal edges white between every pair of large vertices.

If we want a zebraic path with a black edge incident with x and a white edge incident with y then we argue that there is a black G_{t_0} edge between $S_{\ell_1}^{(b)}(x)$ and $S_{\ell_1-1}^{(w)}(y)$.

We now consider the small vertices. Let V_σ be the set of small vertices that have a large neighbor in G_{τ_1}. The above analysis shows that there is a zebraic path between $v \in V_\sigma$ and $w \in V_\sigma \cup V_\lambda$, where V_λ is the set of large vertices. Indeed if v is joined by a black edge to a vertex $w \in V_\lambda$ then we can continue with a zebraic path that begins with a white edge and we can reach any large vertex and choose the color of the terminating edge to be either black or white. This is useful when we need to continue to another vertex in V_σ.

We now have to deal with small vertices that have no large neighbors at time τ_1. It follows from Lemma 18(a) that such vertices have degree one or two in G_{τ_1} and that every vertex at distance two from such a vertex is large.

Lemma 20 *All vertices of degree at most two in G_{t_0} are w.h.p. at distance greater than 10 in G_{t_1},*

Proof Simpler than Lemma 3(b). We use (5) and then

$$\mathbf{Pr}(\exists \text{ such a pair of vertices}) \leq_b t_1^{1/2} \sum_{k=0}^{9} n^k p_1^{k-1} \left((1-p_0)^{n-k-1} + (n-k)p_0(1-p_0)^{n-k-2}\right)^2 = o(1).$$

□

Let Z_i be the number of vertices of degree $0 \leq i \leq 2$ in G_{t_0} that are adjacent in G_{τ_1} to small vertices that are themselves only incident to edges of one color. Lemma 18(a) implies that

$$Z_2 = 0 \text{ } w.h.p. \tag{34}$$

Now consider the case $i = 1$. Here we let Z_1' be the number of vertices of degree one in G_{t_0} that are adjacent in G_{t_0} to vertices that are themselves only incident to edges of one color. Note that

$Z_1 \leq Z_1'$. Then we have, with the aid of (8),

$$
\begin{aligned}
\mathbf{E}(Z_1') &\leq n\binom{n-1}{1}\frac{\binom{N-n+1}{t_0-1}}{\binom{N}{t_0}}\sum_{k=1}^{n-2}\binom{n-2}{k}\frac{\binom{N-2n+3}{t_0-1-k}}{\binom{N-n+1}{t_0-1}}2^{-(k-1)}. \qquad (35)\\
&\leq_b n^2\frac{t_0}{N}\left(\frac{N-t_0}{N-1}\right)^{n-2}\sum_{k=1}^{n-2}\binom{n-2}{k}2^{-k}\left(\frac{t_0-1}{N-n+1}\right)^k\left(\frac{N-n-t_0+2}{N-n-k+1}\right)^{n-2-k}\\
&\leq_b n\log n\exp\left\{-\frac{(n-2)(t_0-1)}{N-1}\right\}\sum_{k=1}^{n-2}\binom{n-2}{k}\left(\frac{t_0-1}{2(N-n+1)}\right)^k\left(\frac{N-n-t_0+2}{N-n-k+1}\right)^{n-2-k}\\
&\leq n\log n\exp\left\{-\frac{(n-2)(t_0-1)}{N-1}\right\}\sum_{k=1}^{n-2}\binom{n-2}{k}\left(\frac{t_0}{2(N-n)}\right)^k\left(\frac{N-n-2t_0/3}{N-n}\right)^{n-2-k}\\
&\leq_b \log^3 n\left(\frac{t_0}{2(N-n)}+\frac{N-n-2t_0/3}{N-n}\right)^{n-2}\\
&\leq \log^3 n\left(\frac{N-t_0/6}{N-n}\right)^{n-2}\\
&= o(1).
\end{aligned}
$$

Explanation for (35)**:** We choose a vertex v of degree one and its neighbor w in $n\binom{n-1}{1}$ ways. The probability that v has degree one is $\frac{\binom{N-n+1}{t_0-1}}{\binom{N}{t_0}}$. We fix the degree of w to be $k+1$. This now has probability $\frac{\binom{N-2n+3}{t_0-k-1}}{\binom{N-n+1}{t_0-1}}$. The final factor $2^{-(k-1)}$ is the probability that w only sees edges of one color.

Finally, consider Z_0. Condition on G_{t_0} and assume that Properties (c),(d) of Lemma 18 hold. For a given isolated vertex, the first G_{t_0} edge incident with it will have a random endpoint. It follows immediately that

$$\mathbf{Pr}(Z_0 > 0) \leq o(1) + \log^3 n \times \frac{n^{2/3}}{n} = o(1). \qquad (36)$$

Here the $o(1)$ accounts for Properties (c),(d) of Lemma 18 and $\log^3 n \times n^{-1/3}$ bounds the expected number of "first edges" that choose small endpoints.

Equations (34), (35) and (36) show that $Z_0 + Z_1 + Z_2 = 0$ w.h.p. In which case it will be possible to find zebraic paths starting from small vertices. Indeed, we now know that w.h.p. any small vertex v will be adjacent to a vertex w that is incident with edges of both colors and that any other neighbor of w is large.

6 Proof of Theorem 3

The case $r = 2$ is implied by Corollary 2. This follows from Corollary 2 and (29). So we can assume that $r \geq 3$.

6.1 $p \leq (1-\varepsilon)p_r$

For a vertex v, let

$$C_v = \{i : v \text{ is incident with an edge of color } i\}.$$
$$I_v = \{i : \{i, i+1\} \subseteq C_v\}. \qquad (r+1 = 1 \text{ here.})$$

Let v be *bad* if $I_v = \emptyset$. The existence of a bad vertex means that there are no r-zebraic Hamilton cycles. Let Z_B denote the number of bad vertices. Now if r is odd and $C_v \subseteq \{1, 3, \ldots, 2\lfloor r/2 \rfloor - 1\}$ or r is even and $C_v \subseteq \{1, 3, \ldots, r-1\}$ then $I_v = \emptyset$. Hence,

$$\mathbf{E}(Z_B) \geq n\left(1 - \frac{\alpha_r p}{r}\right)^{n-1} = n^{\varepsilon - o(1)} \to \infty.$$

A straightforward second moment calculation shows that $Z_B \neq 0$ w.h.p. and this proves the first part of the theorem.

6.2 $p \geq (1+3\varepsilon)p_r$

Note the replacement of ε by 3ε here, for convenience. Note also that ε is assumed to be sufficiently small for some inequalities below to hold.

Write $1-p = (1-p_1)(1-p_2)^2$ where $p_1 = (1+\varepsilon)p_r$ and $p_2 \sim \varepsilon p_r$. Thus $G_{n,p}$ is the union of G_{n,p_1} and two independent copies of G_{n,p_2}. If an edge appears more than once in $G_{n,p}$, then it retains the color of its first occurence.

Now for a vertex v let $d_i(v)$ denote the number of edges of color i incident with v in G_{n,p_1}. Let

$$J_v = \{i : d_i(v) \geq \eta_0 \log n\}$$

where $\eta_0 = \varepsilon^2/r$.

Let v be *poor* if $|J_v| < \beta_r$ where $\beta_r = \lfloor r/2 \rfloor + 1$. Observe that $\alpha_r + \beta_r = r+1$. Then let Z_P denote the number of poor vertices in G_{n,p_1}. A simple calcluation shows that w.h.p. the minimum degree in G_{n,p_1} is at least L_0 and that the maximum degree is at most $6\log n$. Then

$$\begin{aligned}
\mathbf{Pr}(Z_P > 0) &\leq o(1) + n\sum_{k=L_0}^{6\log n}\binom{n-1}{k}p_1^k(1-p_1)^{n-1-k}\sum_{l=r-\beta_r+1}^{r}\binom{r}{l}\binom{k}{l\eta_0\log n}\left(1-\frac{l}{r}\right)^{k-r\eta_0\log n} \\
&\leq o(1) + n\sum_{k=0}^{6\log n}\binom{n-1}{k}p_1^k(1-p_1)^{n-1-k}2^r\binom{6\log n}{r\eta_0\log n}\left(\frac{\beta_r-1}{r}\right)^k\left(\frac{r}{\beta_r-1}\right)^{r\eta_0\log n} \\
&= o(1) + n2^r\binom{6\log n}{r\eta_0\log n}\left(\frac{r}{\beta_r-1}\right)^{r\eta_0\log n}\sum_{k=0}^{6\log n}(1-p_1)^{n-1}\binom{n-1}{k}\left(\frac{p_1(\beta_r-1)}{r(1-p_1)}\right)^k \\
&\leq o(1) + 2^r n^{1+r\eta_0\log(6e/\eta_0)}(1-p_1)^{n-1}\left(1+\frac{(\beta_r-1)p_1}{r(1-p_1)}\right)^{n-1} \\
&\leq o(1) + 2^r n^{1+r\eta_0\log(6e/\eta_0)}\left(1-\frac{(1+o(1))\alpha_r p_1}{r}\right)^{n-1} \\
&= o(1).
\end{aligned}$$

We can therefore assert that w.h.p. there are no poor vertices. This means that

$$K_v = \{i : d_i(v), d_{i-1}(v) \geq \eta_0 \log n\} \neq \emptyset \text{ for all } v \in [n]. \tag{37}$$

The proof now follows our general 3-phase procedure of (i) finding an r-zebraic 2-factor, (ii) removing small cycles so that we have a 2-factor in which every cycle has length $\Omega(n/\log n)$ and then (iii) using a second moment calculation to show that this 2-factor can be re-arranged into an r-zebraic Hamilton cycle.

6.2.1 Finding an r-zebraic 2-factor

We partition $[n]$ into r sets $V_i = [(i-1)n/r + 1, in]$ of size in/r. Now for each i and each vertex v let

$$N_i(v) = \{w : \{v, w\} \text{ is an edge of } G_{n,p_1} \text{ of color } i\}.$$

$$d_i^+(v) = |V_{i+1} \cap N_i(v)| \text{ and } d_i^-(v) = |V_{i-1} \cap N_{i-1}(v)|.$$

(Here $r + 1$ is interpreted as 1 and 1-1 is interpreted as r).

We now let a vertex $v \in V_i$ be *i-large* if $d_i^+(v), d_i^-(v) \geq \eta \log n$ where $\eta = \min\{\eta_0, \eta_1, \eta_2\}$ and η_1 is the solution to

$$\eta_1 \log\left(\frac{e(1+\varepsilon)}{r\eta_1\alpha_r}\right) = \frac{1}{r\alpha_r}$$

and η_2 is the solution to

$$\eta_2 \log\left(\frac{3er(1+\varepsilon)}{\eta_2\alpha_r}\right) = \frac{1}{3\alpha_r}.$$

Let v be *large* if it is i-large for all i. Let v be *small* otherwise. (Note that $d_i^+(v), d_i^-(v)$ are defined for all v, not just for $v \in V_i$, $i \in [r]$).

Let V_λ, V_σ denote the sets of large and small vertices respectively.

Lemma 21 *W.h.p., in G_{n,p_1},*

(a) $|V_\sigma| \leq n^{1-\theta}$ *where* $\theta = \frac{\varepsilon}{2r\alpha_r}$.

(b) *No connected subset of size at most* $2\log\log n$ *contains more than* $\mu_0 = r\alpha_r$ *members of* V_σ.

(c) *If* $S \subseteq [n]$ *and* $|S| \leq n_0 = n/\log^2 n$ *then* $e(S) \leq 100|S|$.

Proof
(a) If $v \in V_\sigma$ then there exists i such that $d_i^+(v) \leq \eta \log n$ or $d_i^-(v) \leq \eta \log n$. So we have

$$\mathbf{E}(|V_\sigma|) \leq 2rn \sum_{k=0}^{\eta \log n} \binom{n/r}{k} \left(\frac{p_1}{r}\right)^k \left(1 - \frac{p_1}{r}\right)^{n/r-k} \tag{38}$$

$$\leq 3r \left(\frac{(1+\varepsilon)e}{r\eta\alpha_r}\right)^{\eta \log n} n^{1-(1+\varepsilon+o(1))/r\alpha_r} \tag{39}$$

$$\leq n^{1-2\theta+o(1)}.$$

Part (a) follows from the Markov inequality. Note that we can lose the factor 2 in (38) since $d_i^+(v) = d_{i+2}^-(v)$.

(b) The expected number of connected sets S of size at most $2\log\log n$ containing μ_0 members of V_σ can be bounded by

$$\sum_{s=\mu_0}^{2\log\log n} \binom{n}{s} s^{s-2} p_1^{s-1} \binom{s}{\mu_0} \left(r \sum_{k=0}^{\eta\log n} \binom{n/r-s}{k} \left(\frac{p_1}{r}\right)^k \left(1-\frac{p_1}{r}\right)^{n/r-s-k} \right)^{\mu_0}. \tag{40}$$

Explanation: We choose s vertices for S and a tree to connect up the vertices of S. We then choose μ_0 members $A \subseteq S$ to be in V_σ. We multiply by the probability that for each vertex in A, there is at least one j such that v has few neighbors in $V_j \setminus S$ connected to v by edges of color j.

After bounding the the sum in brackets raised to μ_0 as in (39), the sum in (40) can be bounded by

$$n \sum_{s=\mu_0}^{2\log\log n} (4e\log n)^s n^{-\mu_0(1+\varepsilon+o(1))/r\alpha_r} = o(1).$$

(c) This is proved in the same manner as Lemma 3(c). □

For $v \in V_\sigma$ we let $\phi(v) = \min\{i : i \in K_v\}$. Equation (37) implies that $\phi(v)$ exists for all $v \in [n]$. Then let $X_i = \{v \in V_\sigma : \phi(v) = i\}$ for $i \in [r]$ and

$$Y_i = \{w \notin V_\sigma : \exists v \in V_\sigma, s.t.\ (\phi(v) = i-1, w \in N_{i-1}(v)) \text{ or } (\phi(v) = i+1, w \in N_i(v))\}.$$

It is possible that a vertex w lies in more than one Y_i. In which case, delete it from all but one of them. Now let

$$W_i = (V_i \setminus V_\sigma) \cup X_i \cup Y_i, \quad i = 1, 2, \ldots, r.$$

Suppose that $w_i = |W_i| - n/r$ for $i \in [r]$ and let $w_i^+ = \max\{0, w_i\}$ for $i \in [r]$. We now remove w_i^+ randomly chosen large vertices from each W_i and then randomly assign $w_i^- = -\min\{0, w_i\}$ of them to each $W_i, i \in [r]$. Thus we obtain a partition of $[n]$ into r sets $Z_i, i = 1, 2, \ldots, r$, of size n/r for $i \in [r]$.

Let H_i be the bipartite graph induced by Z_i, Z_{i+1} and the edges of color i in G_{n,p_1}. We now argue that

Lemma 22 *H_i has minimum degree at least $\frac{1}{2}\eta\log n$ w.h.p.*

Proof It follows from Lemma 21(b),(d) that no vertex in $Z_i \cap V_i$ loses more than μ_0 neighbors from the deletion of V_σ or from the movement of the vertices in the Y_i's. Also, we move $v \in V_\sigma$ to a Z_i where it has degree at least $\eta\log n - \mu_0$ in V_{i-1} and V_{i+1}. Its neighborhood may have been affected by the deletion of V_σ or the movement of the Y_i's, but only by at most μ_0. Thus for every i and $v \in X_i$, v has at least $\eta\log n - \mu_0$ neighbors in Z_{i-1} connected to v by an edge of color $i-1$ and at least $\eta\log n - \mu_0$ neighbors in Z_{i+1} connected to v by an edge of color i

Now consider the random re-shuffling to get sets of size n/r. Fix a $v \in V_i$. Suppose that it has $d = \Theta(\log n)$ neighbors in Z_{i+1} connected by an edge of color i. Now randomly choose $w_{i+1}^+ = O(|V_\sigma|\log n)$ vertices to delete from Z_{i+1}. The number ν_v of neighbors of v chosen is dominated by Bin $\left(w_{i+1}^+, \frac{d}{n/r}\right)$. This follows from the fact that if we choose these w_{i+1}^+ vertices one by one, then at each step, the chance that the chosen vertex is a neighbor of v is bounded from above by $\frac{d}{n/r}$. So, given the condition in Lemma 21(a) we have

$$\mathbf{Pr}(\nu_v \geq 2/\theta) \leq \binom{n^{1-\theta+o(1)}}{2/\theta}\left(\frac{dr}{n}\right)^{2/\theta} \leq \left(\frac{n^{1-\theta+o(1)}edr\theta}{n}\right)^{2/\theta} = o(n^{-1}).$$

□

We can now verify the existence of perfect matchings w.h.p.

Lemma 23 *W.h.p., each H_i contains a perfect matching $M_i, i = 1, 2, \ldots, r$.*

Proof Fix i. We use Hall's theorem and consider the existence of a set $S \subseteq Z_i$ that has fewer than $|S|$ H_i-neighbors in Z_{i+1}. Let $s = |S|$ and let $T = N_{H_i}(S)$ and $t = |T| < s$. We can rule out $s \leq n_0 = n/2\log^2 n$ through Lemma 21(c). This is because we have $e(S \cup T)/|S \cup T| \geq \frac{1}{4}\eta \log n$ in this case. Let $n_\sigma = |V_\sigma|$ and now consider $n/2\log^2 n \leq s \leq n/2r$. Given such a pair S, T we deduce that there exist $S_1 \subseteq S \subseteq V_i, |S_1| \geq s - n_\sigma$ and $T_1 \subseteq T \subseteq V_{i+1}$ and $U_1 \subseteq V_{i+1}, |U_1| \leq n_\sigma$ such that there are at least $m_s = (s\eta/2 - 6n_\sigma)\log n$ edges between S_1 and T_1 and no edges between S_1 and $V_{i+1} \setminus (T_1 \cup U_1)$. There is no loss of generality in increasing the size of T to s. We can then write

$$\begin{aligned}
\mathbf{Pr}(\exists\, S, T \text{ in } G_{n,p_1}) &\leq \sum_{s=n_0}^{n/2r} \binom{n/r - O(n_\sigma \log n)}{s}^2 \binom{s^2}{m_s} p_1^{m_s}(1-p_1)^{(s-n_\sigma)(n/r-s-n_\sigma)} \\
&\leq \sum_{s=n_0}^{n/2r} \left(\frac{ne}{rs}\right)^{2s} \left(\frac{s^2 p_1 e}{m_s}\right)^{m_s} e^{-(s-n_\sigma)(n/r-s-n_\sigma)p_1} \\
&\leq \sum_{s=n_0}^{n/2r} \left(\left(\frac{s}{n}\right)^{\eta \log n/3} \left(\frac{3er(1+\varepsilon)}{\alpha_r \eta}\right)^{\eta \log n/2} n^{-(1-o(1))/2\alpha_r}\right)^s \\
&= o(1).
\end{aligned}$$

For the case $s \geq n/2r$ we look for subsets of Z_{i+1} with too few neighbors in Z_i. □

It follows from symmetry considerations that the M_i are independent of each other. Indeed, once we condition on the number of edges m_i being colored $i = 1, 2, \ldots, r$, we find that the actual graphs induced by each color are independent of each other. What we have proved implies that for almost all sequences $m_1, m_2, \ldots, m_r$, each H_i has a perfect matching.

Analogously to Lemma 8, we have

Lemma 24 *The following hold w.h.p.:*

(a) *$\bigcup_{i=1}^r M_i$ has at most $10\log n$ components. (Components are r-zebraic cycles of length divisible by r.)*

(b) *There are at most n_b vertices on components of size at most n_c.*

Proof The matchings induce a permutation π on W_1. Suppose that $x \in W_1$. We follow a path via a matching edge to W_2 and then by a matching edge to W_3 and so on until we return to a vertex $\pi(x) \in W_1$. π can be taken to be a random permutation and then the lemma follows from Lemma 8. $\square$

The remaining part of the proof is similar to that described in Sections 4.3, 4.4. We use the edges of the first copy G_{n,p_2} of color 1 to make all cycles have length $\Omega(n/\log n)$ and then we use the edges of the second copy of G_{n,p_2} of color 1 to create an r-zebraic Hamilton cycle. The details are left to the reader.

7 Dealing with the directed analogs

A great deal of the analysis we have seen extends without much comment to the directed case. In particular, in Theorem 1, once we have a shown the existences of a matching M_1 that is independent of M_0, orientation hardly affects the proof. So for Theorem 4 all we really need to argue for is a perfect matching $M_1 = \left\{g_1, g_2, \ldots, g_{n/2}\right\}$ such that if $g_i = \{x_i, y_i\}$ then we can assume that (i) x_i is odd and y_i is even and (ii) g_i is oriented from y_i to x_i. For this we will apply Hall's theorem to the bipartite graph H with bipartition $A = \{2, 4, \ldots, n\}$, $B = \{1, 3, \ldots, n-1\}$. H has an edge $\{a, b\}$ iff (a, b) is an edge of D_m. The stopping time $\vec{\tau}_1$ is for H to have minimum degree one and w.h.p. this will be enough for H to have a perfect matching. After this the proof continues more or less as in the proof of Theorem 1. The "zebraic" corollary to Theorem 4 is not so simple. If we follow the undirected argument then we see that we need to exert control over the orientations of the black and white perfect matchings, they have to be compatible in some sense, and the hitting time for this is not so obvious.

The proof of Theorem 5 is almost identical to that of Theorem 3. We simply change I_v in Section 6 to

$$I_v = \left\{ i : d_-^{(i)} > 0 \text{ and } d_+^{(i+1)} > 0 \right\},$$

where $d_-^{(i)}$ is the number of edges of color i oriented into v and $d_+^{(i+1)}$ is the number of edges of color $i+1$ oriented out of v.

The proof of Theorem 6 follows that of Theorem 2.

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