Multicolor Ramsey Numbers for Complete Bipartite Versus Complete Graphs

John Lenz [*]

University of Illinois at Chicago

lenz@math.uic.edu

Dhruv Mubayi [†]

University of Illinois at Chicago

mubayi@math.uic.edu

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Abstract

Let $H_1, \ldots, H_k$ be graphs. The multicolor Ramsey number $r(H_1, \ldots, H_k)$ is the minimum integer r such that in every edge-coloring of K_r by k colors, there is a monochromatic copy of H_i in color i for some $1 \leq i \leq k$. In this paper, we investigate the multicolor Ramsey number $r(K_{2,t}, \ldots, K_{2,t}, K_m)$, determining the asymptotic behavior up to a polylogarithmic factor for almost all ranges of t and m. Several different constructions are used for the lower bounds, including the random graph and explicit graphs built from finite fields. A technique of Alon and Rödl using the probabilistic method and spectral arguments is employed to supply tight lower bounds. A sample result is

$$c_1 \frac{m^2 t}{\log^4(mt)} \leq r(K_{2,t}, K_{2,t}, K_m) \leq c_2 \frac{m^2 t}{\log^2 m}$$

for any t and m, where c_1 and c_2 are absolute constants.

Keywords: Ramsey Theory, Graph Eigenvalues, Graph Spectrum

1 Introduction

The multicolor Ramsey number $r(H_1, \ldots, H_k)$ is the minimum integer r such that in every edge-coloring of K_r by k colors, there is a monochromatic copy of H_i in color i for some $1 \leq i \leq k$. Ramsey's famous theorem [18] states that $r(K_s, K_t) < \infty$ for all s and t. Determining these numbers is usually a very difficult problem. Even determining the asymptotic behavior is difficult; there are only a few infinite families of graphs where the order of magnitude is known. A famous example is $r(K_3, K_m) = \Theta(m^2/\log m)$, where the upper bound was proved by Ajtai, Komlós, and Szemerédi [1] and the lower bound by Kim [13].

H	$k = 2$	$k \geq 3$
K_3	$\dfrac{m^3}{\log^{4+\delta} m} \ll r_2(K_3; K_m) \ll \dfrac{m^3 \log\log m}{\log^2 m}$	$\dfrac{m^{k+1}}{\log^{2k+\delta} m} \ll r_k(K_3; K_m) \ll \dfrac{m^{k+1}(\log\log m)^{k-1}}{\log^k m}$
C_4	$\dfrac{m^2}{\log^4 m} \ll r_2(C_4; K_m) \ll \dfrac{m^2}{\log^2 m}$	$r_k(C_4; K_m) = \Theta\left(\dfrac{m^2}{\log^2 m}\right)$
C_6	$\dfrac{m^{3/2}}{\log^3 m} \ll r_2(C_6; K_m) \ll \dfrac{m^{3/2}}{\log^{3/2} m}$	$r_k(C_6; K_m) = \Theta\left(\dfrac{m^{3/2}}{\log^{3/2} m}\right)$
C_{10}	$\dfrac{m^{5/4}}{\log^{5/2} m} \ll r_2(C_{10}; K_m) \ll \dfrac{m^{5/4}}{\log^{5/4} m}$	$r_k(C_{10}; K_m) = \Theta\left(\dfrac{m^{5/4}}{\log^{5/4} m}\right)$
$K_{s,t}$	$\dfrac{m^s}{\log^{2s} m} \ll r_2(K_{s,t}; K_m) \ll \dfrac{m^s}{\log^s m}$	$r_k(K_{s,t}; K_m) = \Theta\left(\dfrac{m^s}{\log^s m}\right)$

Table 1: Results on $r_k(H; K_m)$ proved by Alon and Rödl [2].

For more colors, in 1980 Erdős and Sós [9] conjectured that $r(K_3, K_3, K_m)/r(K_3, K_m) \to \infty$ as $m \to \infty$. This conjecture was open for 25 years until it was proved true by Alon and Rödl [2]. In their paper, they provided a general technique using graph eigenvalues and the probabilistic method which provides good estimates on multicolor Ramsey numbers. This breakthrough provided the first sharp asymptotic (up to a poly-log factor) bounds on infinite families of multicolor Ramsey numbers with at least three colors.

The exact results proved by Alon and Rödl [2] are shown in Table 1. For $k \geq 1$, define $r_k(H; G)$ to be $r(H, \ldots, H, G)$, where H is repeated k times. In other words, $r_k(H; G)$ is the minimum integer r such that in every edge-coloring of K_r by $k + 1$ colors, there is a monochromatic copy of H in one of the first k colors or a copy of G in the $k + 1$st color. In Table 1, s and t are fixed with $t \geq (s-1)! + 1$, $\delta > 0$ is any positive constant, and m is going to infinity. Also, in the tables below, $a \ll b$ means there exists some positive constant c such that $a \leq cb$. All logarithms in this paper are base e.

One surprising aspect of Alon and Rödl's [2] techniques is that they prove very good upper and lower bounds for multicolor Ramsey numbers in cases where the two-color Ramsey number is not as well understood. For example, Erdős [8] conjectured that $r(C_4, K_m) = O(m^{2-\epsilon})$ for some absolute constant $\epsilon > 0$, and this conjecture is still open. The current best upper bound is an unpublished result of Szemerédi which was reproved by Caro, Rousseau, and Zhang [7] where they showed that $r(C_4, K_m) = O(m^2/\log^2 m)$ and the current best lower bound is $\Omega(m^{3/2}/\log m)$ by Bohman and Keevash [5]. In sharp contrast, for three colors Alon and Rödl [2] determined $r(C_4, C_4, K_m)$ up to a poly-log factor and found the order of magnitude of $r_k(C_4; K_m)$ for $k \geq 3$. A similar situation occurs for the other graphs in Table 1 besides K_3.

2 Results

We focus on the problem of determining $r_k(K_{2,t}; K_m)$ when k is fixed and t is no longer a constant. Our results can be summarized by the following table; more precise statements

are given later.

	$m \ll \log^2 t$	$\log^2 t \ll m \ll 2^t$	$2^t \ll m$
$k = 1$	$mt \ll r \ll \frac{m^2 t}{\log^2 m}$	$\frac{m^2 t}{\log^2(mt)} \ll r \ll \frac{m^2 t}{\log^2 m}$	$r \ll \frac{m^2 t}{\log^2 m}$
$k = 2$	$mt \ll r \ll \frac{m^2 t}{\log^2 m}$	$\frac{m^2 t}{\log^2(mt)} \ll r \ll \frac{m^2 t}{\log^2 m}$	$\frac{m^2 t}{\log^4(mt)} \ll r \ll \frac{m^2 t}{\log^2 m}$
$k \geq 3$	$mt \ll r \ll \frac{m^2 t}{\log^2 m}$	$\frac{m^2 t}{\log^2(mt)} \ll r \ll \frac{m^2 t}{\log^2 m}$	$\frac{m^2 t}{\log^2(mt)} \ll r \ll \frac{m^2 t}{\log^2 m}$

Table 2: Results on $r = r_k(K_{2,t}; K_m)$ in this paper.

We are able to find the order of magnitude of $r_k(K_{2,t}; K_m)$ up to a ploy-log factor for all ranges of m and t except the upper right table cell where m is much larger than t and $k = 1$. This is similar to the fact that the order of magnitude of $r(C_4, K_m)$ is unknown but Alon and Rödl [2] found the order of magnitude up to a poly-log factor when $k \geq 2$. So the only remaining case is $r(K_{2,t}, K_m)$ when m is much larger than t. The best known lower bound is $r(K_{2,t}, K_m) \geq c_t(m/\log m)^{\rho(K_{2,t})}$, where $\rho(K_{2,t}) = 2 - \frac{2}{t}$ (see [3, 15].) Unfortunately, this lower bound has a constant c_t depending on t when we would like to know the exact order of magnitude.

The upper bound in Table 2 is a straightforward counting argument using the extremal number of $K_{2,t}$. Szemerédi (unpublished) and Caro, Rousseau, and Zhang [7] proved the following proposition for two colors; we extend it for all k using a related but slightly different technique.

Proposition 1. *For $k \geq 1$, $t \geq 2$, and $m \geq 3$ integers, there exists a constant c depending only on k such that*

$$r_k(K_{2,t}; K_m) \leq c \frac{m^2 t}{\log^2 m}.$$

The main contribution in this paper is the various lower bounds given in the table. One simple lower bound is to take $m - 1$ vertex sets $X_1, \ldots, X_{m-1}$, each of size $t + 1$. Color edges inside each X_i with one color and color all edges between X_is in the other color. This proves $r(K_{2,t}, K_m) > (m - 1)(t + 1)$. In fact, this proves the following proposition.

Proposition 2. *Let $k \geq 1$, $t \geq 2$, and $m \geq 3$ be integers. Then $r_k(K_{2,t}; K_m) > (m-1)(t+1)$.*

Note that being slightly more clever for $k \geq 2$ and making each X_i of size $r_k(K_{2,t}) - 1$ does not give a large improvement. A theorem of Lazebnik and Mubayi [16] proves that $r_k(K_{2,t}) > k^2(t - 1)$ when k and t are prime powers and $r_k(K_{2,t}) \leq k^2(t - 1) + k + 2$ for all k and t. Therefore the size of each X_i could be increased to roughly $k^2 t$ but that implies only a constant improvement in Proposition 2.

Another lower bound comes from the random graph $G(n, p)$. Consider a coloring of $E(K_n)$ obtained by taking k random graphs $G(n, p)$ as the first k colors and letting the

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last color be the remaining edges. Depending on the choice of n and p, this construction avoids $K_{2,t}$ in the first k colors and K_m in the last color. In Proposition 3, we show that when $\log^2 t \ll m \ll 2^t$ it is possible to choose p so that $G(m^2 t / \log^2(mt), p)$ avoids $K_{2,t}$ and has independence number at most m. When $m \gg 2^t$, the number of vertices must be reduced to roughly $m^{2-2/t}$ which does not provide a good lower bound on the Ramsey number. Most likely, when $m \ll \log^2 t$ a more detailed analysis shows that one can choose p so that $G(m^2 t / \log^2(mt), p)$ avoids $K_{2,t}$ and has independence number at most m. We skip this analysis and only investigate Proposition 3 for $m \gg \log^2 t$ because when $m \ll \log^2 t$, the lower bound of mt from Proposition 2 is better than $m^2 t / \log^2(mt)$. The precise statement of this lower bound is given in the following proposition.

Proposition 3. *Let $k \geq 1$, $t \geq 2$. For all constants $c_1, c_2 > 0$, there exists a constant $d > 0$ depending only on k and c_1, c_2 such that if $c_1 \log^2 t \leq m \leq c_2 2^t$ then $r_k(K_{2,t}; K_m) \geq d \frac{m^2 t}{\log^2(mt)}$.*

Proposition 2 and Proposition 3 take care of the left two columns in Table 2. Proposition 2 works in both columns and most likely Proposition 3 also works in both columns, although we do not prove that since Proposition 2 is better when $m \ll \log^2 t$. What about the range $m \gg 2^t$? As mentioned, an extension of Proposition 3 using the random graph $G(n, p)$ gives a lower bound of $c_t m^{2-2/t}$ for some constant c_t depending on t. When t is constant, Alon and Rödl's [2] result from Table 1 shows lower bounds of $m^2 / \log^4 m$ and $m^2 / \log^2 m$ depending on k. If t is not fixed but still much smaller than m, we can prove the following precise lower bounds. This is our main theorem.

Theorem 4. *Let $t \geq 2$ and $k \geq 3$. There exists a constant $\rho > 0$ depending only on k such that the following holds.*

(i) *If $m \geq 128 \log^2 t$, then $r(K_{2,t}, K_{2,t}, K_m) \geq \rho \frac{m^2 t}{\log^4(mt)}$.*

(ii) *If $m \geq 16k \log t$, then $r_k(K_{2,t}; K_m) \geq \rho \frac{m^2 t}{\log^2(mt)}$.*

The construction in the above theorem works for $k \geq 2$ and (roughly) the rightmost two columns in Table 2. When $k = 2$, it is slightly worse than the random graph construction from Proposition 3 and matches it when $k \geq 3$. But it has the advantage over the random graph of working in the rightmost column of Table 2, where m is much larger than t. Also, the construction only works for $k \geq 2$, which is the reason for the missing lower bound in the upper right cell of Table 2.

This construction is an algebraic graph construction using finite fields and is similar to a construction by Lazebnik and Mubayi [16], which in turn was based on constructions of Axenovich, Füredi, and Mubayi [4] and Füredi [11]. A theorem of Alon and Rödl [2] which relates the second largest eigenvalue of a graph with the number of the independent sets is then used to show the construction is a good choice for a $K_{2,t}$-free graph with small independence number. The properties of the construction are stated in the following theorem.

Theorem 5. *For any prime power q and any integer $t \geq 2$ such that $q \equiv 0 \pmod{t}$ or $q \equiv 1 \pmod{t}$, there exists a graph G with the following properties:*

- *G has $q(q-1)/t$ vertices,*
- *G has no multiple edges but some vertices have loops,*
- *G is regular of degree $q-1$ (loops contribute one to the degree),*
- *G is $K_{2,t+1}$-free,*
- *the second largest eigenvalue of the adjacency matrix of G is $\sqrt{q}$.*

Several open problems remain: in Table 2 are the upper or lower bounds correct? The upper and lower bounds are very close; we are fighting against a poly-log term. But it would still be interesting to know which bounds are correct. One of the differences is a $\log^2 m$ versus a $\log^2(mt)$ in the denominator. If m is much larger than t then $\log^2 m \sim \log^2(mt)$, but in the left two columns the gap starts to widen. As m gets smaller relative to t, the $m^2 t/\log^2(mt)$ lower bound eventually becomes worse than a really simple mt lower bound.

Other open problems include $r(K_{2,t}, K_m)$ when m is much larger than t and $r_k(K_{s,t}; K_m)$ when s is larger than two. Using ideas from the projective norm graphs, the construction in Section 4 can be extended to use norms to forbid $K_{s,t}$ for s fixed, at the expense of more complexity in the proof of the spectrum. Thus the remaining problem on $r_k(K_{s,t}; K_m)$ is to investigate when s, t, and m are all going to infinity. In other words, how do the constants (implicit) in Table 2 depend on s? Comments about these and other open problems are discussed in Section 5.

3   The Ramsey Numbers $r_k(K_{2,t}; K_m)$

In this section we prove all the upper and lower bounds given in Table 2: Proposition 1 in Section 3.1, Proposition 3 in Section 3.2, and Theorem 4 in Section 3.3.

3.1   An upper bound

In this section, we prove Proposition 1. For two colors, the proposition was first proved in the 1980s by Szemerédi but he never published a proof. Caro, Rousseau, and Zhang [7] published a proof in 2000 and Jiang and Salerno [12] gave another more general proof but still for two colors. We use a slightly different (but closely related) proof technique inspired by Alon and Rödl [2] to extend the upper bound to three or more colors. First, we need the following two theorems. If F is a graph and n is an integer, define $ex(n, F)$ to be the maximum number of edges in an n-vertex graph which does not contain F as a subgraph.

Theorem 6. *(Kővari, Sós, Turán [14]) For $2 \le t \le n$, $ex(n, K_{2,t}) \le \frac{1}{2}\sqrt{t-1}n^{3/2} + \frac{n}{2} \le \sqrt{t}n^{3/2}$.*

The following theorem is a corollary of the famous result of Ajtai, Komlós, and Szemerédi [1] on $r(K_3, K_m)$ (see also [6, Lemma 12.16].)

Theorem 7. *There exists an absolute constant c such that the following holds. Let G be an n-vertex graph with average degree d and let s be the number of triangles in G. Then*

$$\alpha(G) \geq \frac{cn}{d}\left(\log d - \frac{1}{2}\log\left(\frac{s}{n}\right)\right).$$

We will apply this theorem in a graph where we can bound the average degree and know a bound on the number of edges in any neighborhood; using standard tricks the theorem can be changed to use average degree.

Corollary 8. *There exists an absolute constant c such that the following holds. Let G be an n-vertex graph with average degree at most d, where for every vertex $v \in V(G)$, every $2d$-subset of $N(v)$ spans at most d^2/f edges. Then the independence number of G is at least $\frac{cn\log f}{d}$.*

Proof. Let H be the subgraph of G formed by deleting all vertices with degree bigger than $2d$. H has at least half the vertices of G since G has average degree at most d; in addition H has maximum degree $2d$. Also, H has at most $s = nd^2/f$ triangles since each neighborhood of a vertex in H spans at most d^2/f edges. Thus Theorem 7 implies there exists a constant c so that

$$\alpha(G) \geq \frac{cn}{d}\left(\log d - \frac{1}{2}\log\left(\frac{d^2}{f}\right)\right) = \frac{cn}{d}\left(\log d - \log\left(\frac{d}{\sqrt{f}}\right)\right) = \frac{cn}{2d}\log f.$$

$\square$

Proof of Proposition 1. Let c_1 be the constant from Corollary 8; note that we can assume $c_1 \leq 1$. Define $c_2 = \frac{256k^2}{c_1^2}$ and assume $n > \frac{c_2 m^2 t}{\log^2 m}$. Consider a $(k+1)$-coloring of $E(K_n)$ and let C_i be the graph whose edges are the ith color class for $i = 1, \ldots, k$. Assume C_i is $K_{2,t}$-free for all $1 \leq i \leq k$. We will show that the independence number of $C_1 \cup \cdots \cup C_k$ is at least m, which will imply the $(k+1)$-st color class contains a copy of K_m; i.e. $r_k(K_{2,t}; K_m) \leq \frac{c_2 m^2 t}{\log^2 m}$.

Since $C_1, \ldots, C_k$ are $K_{2,t}$-free, they each have at most $\sqrt{t}n^{3/2}$ edges by Theorem 6. Let $G = C_1 \cup \cdots \cup C_k$ so $|E(G)| \leq k\sqrt{t}n^{3/2}$. Let $d = 2k\sqrt{tn}$, so that G has average degree at most d. Consider some vertex $v \in V(G)$ and let $A \subseteq N(v)$ with $|A| = 2d$. Then $C_i[A]$ is $K_{2,t}$-free for $1 \leq i \leq k$ so $|E(G[A])| \leq k \cdot ex(2d, K_{2,t}) \leq 4k\sqrt{t}d^{3/2}$. To apply Corollary 8, we need to solve the following for f:

$$4k\sqrt{t}d^{3/2} = \frac{d^2}{f}.$$

The solution is $f = \frac{1}{4k}\sqrt{d/t}$ so Corollary 8 implies G contains an independent set of size $\frac{c_1 n\log f}{d}$. To complete the proof, we just need to show this is at least m. Use the definitions of $d = 2k\sqrt{tn}$ and $f = \frac{1}{4k}\sqrt{d/t}$ to obtain

$$\alpha(G) \geq \frac{c_1 n}{d}\log f = \frac{c_1 n}{2k\sqrt{tn}}\log\left(\frac{1}{4k}\frac{\sqrt{2k}\sqrt[4]{tn}}{\sqrt{t}}\right) = \frac{c_1}{2k}\sqrt{\frac{n}{t}}\log\left(\frac{1}{2\sqrt{2k}}\sqrt[4]{\frac{n}{t}}\right).$$

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Recall that we assumed $n > \frac{c_2 m^2 t}{\log^2 m}$, so

$$\alpha(G) \geq \frac{c_1}{2k} \sqrt{\frac{c_2 m^2}{\log^2 m}} \log \left(\frac{1}{2\sqrt{2k}} \sqrt[4]{\frac{c_2 m^2}{\log^2 m}} \right).$$

Use that $c_2 = \frac{256 k^2}{c_1^2}$ and simplify to obtain

$$\alpha(G) \geq \frac{8m}{\log m} \log \left(\sqrt{\frac{\sqrt{c_2}}{8k}} \cdot \frac{m}{\log m} \right) = \frac{4m}{\log m} \log \left(\frac{2}{c_1} \frac{m}{\log m} \right).$$

Since $c_1 \leq 1$,

$$\alpha(G) \geq \frac{4m}{\log m} \log \left(\frac{m}{\log m} \right) = \frac{4m}{\log m} (\log m - \log \log m) \geq m.$$

The last inequality uses $\log m \geq \frac{4}{3} \log \log m$ which is true for $m \geq 3$. $\qquad\square$

3.2   The Random Graph

In this section, we prove Proposition 3 by using the random graph $G(n, p)$.

Lemma 9. *For all constants c_1, c_2, there exists a constant c_3 such that the following holds. Given two integers t and m with $c_1 \log^2 t \leq m \leq c_2 2^t$, let $n = c_3 \frac{m^2 t}{\log^2 (mt)}$ and $p = \sqrt{\frac{t}{e^8 n}}$. Then with probability tending to 1 as m tends to infinity ($m \to \infty$ implies $t, n \to \infty$ as well), $G(n, p)$ is $K_{2,t}$-free and has independence number at most m.*

Proof. Let $c_3 = \min\{\frac{1}{c_2^2}, \frac{1}{400 e^8}\}$. The expected number of $K_{2,t}$s is upper bounded by

$$n^2 \binom{n}{t} p^{2t} \leq n^2 \left(\frac{en}{t} \right)^t \left(\frac{t}{e^8 n} \right)^t = n^2 e^{-7t}. \tag{1}$$

We want this to go to zero as $m \to \infty$, so it suffices to show that t is bigger than roughly $\log n$. Using the definition of n, upper bound $\log n$ by

$$\log n = \log \left(c_3 \frac{m^2 t}{\log^2 (mt)} \right) \leq 2 \log m + \log t + \log c_3$$

But since $m \leq c_2 2^t \leq c_2 e^t$,

$$\log n \leq 2(\log c_2 + t) + \log t + \log c_3 \leq 2t + \log t + 2 \log c_2 + \log c_3.$$

Since $c_3 \leq \frac{1}{c_2^2}$, $2 \log c_2 + \log c_3 \leq 0$. Using that $\log t \leq t$, we obtain $\log n \leq 3t$, which when combined with (1) shows the expected number of $K_{2,t}$s is upper bounded by

$$n^2 e^{-7t} = e^{2 \log n - 7t} \leq e^{-t}.$$

Since $m \to \infty$ implies $t \to \infty$, the expected number of $K_{2,t}$s goes to zero as $m \to \infty$.

Let $d = pn$. When $d = o(n)$, the independence number of $G(n,p)$ is concentrated around $\frac{2n}{d} \log d$. More precisely, Frieze [10] (see also [3, 6]) proved that for fixed $\epsilon > 0$ and $d = o(n)$, with probability going to one as $n \to \infty$, the independence number of $G(n,p)$ is within $\frac{\epsilon n}{d}$ of $\frac{2n}{d}(\log d - \log\log d - \log 2 + 1)$. First, note that since $c_1 \log^2 t \le m$, $m^2 t / \log^2(mt) \to \infty$ as $m \to \infty$. This implies $n/t \to \infty$ which implies $d = pn = o(n)$, so the result of Frieze [10] can be applied. Therefore, w.h.p.

$$\alpha(G(n,p)) < 10\frac{2n}{pn} \log(pn) = 20e^4 \sqrt{\frac{n}{t}} \log\left(\sqrt{\frac{nt}{e^8}}\right) \le 10e^4 \sqrt{\frac{n}{t}} \log(nt).$$

The next step is to show that when the definition of n is inserted, the expression is at most m showing w.h.p. the independence number of $G(n,p)$ is at most m. The computations are very similar to the end of the proof of Proposition 1 in Section 3.1.

$$\alpha(G(n,p)) < 10e^4 \sqrt{c_3} \frac{m}{\log(mt)} \log\left(\frac{c_3 m^2 t^2}{\log^2(mt)}\right) \le 20e^4 \sqrt{c_3} m \le m.$$

Therefore, as m tends to infinity, the probability that $G(n,p)$ contains a copy of $K_{2,t}$ or has independence number at least m tends to zero, completing the proof. $\square$

Proof of Proposition 3. Color $E(K_n)$ by $k+1$ colors as follows: let the first color correspond to $G(n,p)$ with $p = \sqrt{t/(e^8 n)}$, do not assign any edges to colors $2, \ldots, k$, and let the $(k+1)$st color be the remaining edges (complement of the first color). Lemma 9 shows w.h.p. the first color is $K_{2,t}$-free (since k is fixed) and the $(k+1)$st color has clique number at most m. $\square$

3.3 An algebraic lower bound

In this subsection, we prove Theorem 4. Our main tool is the following very general theorem from Alon and Rödl [2]. Their idea is to take an H-free graph G and construct k graphs $G_1, \ldots, G_k$ by taking k random copies of G. In other words, fix some set W of size $|V(G)|$ and let G_i be the graph obtained by a random bijection between $V(G)$ and W. We now have a $k+1$ coloring of the edges of the complete graph on vertex set W: let the first k colors be $G_1, \ldots, G_k$ and let the $k+1$st color be the edges outside any G_i. Alon and Rödl's key insight is that if we know the second largest eigenvalue of G, then G is an expander graph which implies some knowledge about the independent sets in G. This is then used to bound the independence number of $G_1 \cup \cdots \cup G_k$, in other words obtain an estimate of m.

Theorem 10. *(Alon and Rödl, Theorem 2.1 and Lemma 3.1 from [2]) Let G be an n-vertex, H-free, d-regular graph where G has no multiple edges but some vertices have loops and let $k \ge 2$ be any integer. Let λ be the second largest eigenvalue in absolute value of the adjacency matrix of G. If $m \ge \frac{2n}{d} \log n$ and*

$$\left(\frac{emd^2}{4\lambda n \log n}\right)^{\frac{2kn \log n}{d}} \left(\frac{2e\lambda n}{md}\right)^{km} \left(\frac{m}{n}\right)^{m(k-1)} < 1 \tag{2}$$

then $r_k(H; K_m) > n$.

A combination of Theorem 10 and Theorem 5 plus the density of the prime numbers proves Theorem 4. To be able to apply Theorem 5, we need to find a prime power q which is congruent to zero or one modulo t and is in the required range. Recall that we are targeting a bound of $\frac{m^2 t}{\log^4(mt)}$ or $\frac{m^2 t}{\log^2(mt)}$ and the number of vertices from Theorem 5 is $q(q-1)/t$. Given inputs m and t, we therefore want to find a prime power q so that $q \equiv 0 \pmod{t}$ or $q \equiv 1 \pmod{t}$ and $q(q-1)/t$ is near $\frac{m^2 t}{\log^{2s}(mt)}$ where s is one or two. This can be accomplished using the Prime Number Theorem.

Lemma 11. *Fix integers $s, L \geq 1$. There exists a constant $\delta > 0$ depending only on s and L such that the following holds. For every $t \geq 2$ and $m \geq 4^s L \log^s t$, either $\frac{\delta m^2 t}{L^2 \log^{2s}(mt)} \leq 2$ or there is a prime power q so that $q \equiv 1 \pmod{t}$ and*

$$\delta \frac{m^2 t}{L^2 \log^{2s}(mt)} \leq \frac{q(q-1)}{t} \leq \frac{m^2 t}{L^2 \log^{2s}(mt)}.$$

The proof of this lemma appears online. Now a combination of Lemma 11, Theorem 5, and Theorem 10 plus some computations proves Theorem 4 *(i)*.

Proof of Theorem 4 (i). Suppose $t \geq 2$, $k = 2$, and $m \geq 128 \log^2 t$ are given. Fix $s = 2$ and $L = 8$ so that the conditions of Lemma 11 are satisfied. Choose q and δ according to Lemma 11. Note that if $\frac{\delta m^2 t}{L^2 \log^4(mt)} \leq 2$, then trivially $r(K_{2,t}, K_{2,t}, K_m) \geq 2 \geq \frac{\delta m^2 t}{L^2 \log^4(mt)}$. Therefore, assume that

$$\delta \frac{m^2 t}{64 \log^4(mt)} \leq \frac{q(q-1)}{t} \leq \frac{m^2 t}{64 \log^4(mt)}. \tag{3}$$

Let G be the graph from Theorem 5. Then d (the average degree) is $q - 1$, λ (the second largest eigenvalue in absolute value) is $\sqrt{q}$, and $n = q(q-1)/t$.

To apply Theorem 10, we need to show that $m \geq \frac{2n}{d} \log n$ and also show k, m, λ, n, and d satisfy the inequality (2). We break this into two steps: first we show that $m \geq \frac{n}{d} \log^2 n \geq \frac{2n}{d} \log n$ using the choice of q from Lemma 11. Next, we let $m' = \frac{n}{d} \log^2 n$ and check the inequality (2) with k, m', λ, n, and d. This shows $r_k(K_{2,t}; K_{m'}) > n$, and since $m \geq m'$, this implies $r_k(K_{2,t}; K_m) > n$. Using that $n = q(q-1)/t$, equation (3) shows $n > \frac{1}{64} \delta m^2 t / \log^4(mt)$. If $\rho \leq \frac{\delta}{64}$, we have proved $r(K_{2,t}, K_{2,t}, K_m) \geq \rho m^2 t / \log^4(mt)$. Also, note that we can assume $n > n_0$ for some constant n_0 by choosing $\rho = \frac{\delta}{64 n_0}$ (since then $n \leq n_0$ implies $\rho m^2 t / \log^4(mt) \leq 1$.)

Step 1 We want to show $m \geq \frac{n}{d} \log^2 n$. Start with (3):

$$n \leq \frac{m^2 t}{64 \log^4(mt)}$$

$$64 n \log^4(mt) \leq m^2 t. \tag{4}$$

Take the log of both sides, to obtain

$$\log 64 + \log n + \log \log^4(mt) \leq 2 \log m + \log t \leq 2 \log(mt)$$

$$\log n \leq 2 \log(mt).$$

Combining this with (4) yields

$$n \log^4 n \le 16n \log^4(mt) \le \frac{1}{4}m^2 t$$

$$\Rightarrow \quad m^2 \ge \frac{4n}{t} \log^4 n$$

$$\Rightarrow \quad m \ge 2\sqrt{\frac{n}{t}} \log^2 n = \frac{2\sqrt{q(q-1)}}{t} \log^2 n \ge \frac{q}{t} \log^2 n = \frac{n}{d} \log^2 n.$$

Step 2 Let $m' = \frac{n}{d} \log^2 n$. We need to verify that

$$\left(\frac{em'd^2}{4\lambda n \log n}\right)^{\frac{2kn \log n}{d}} \left(\frac{2e\lambda n}{m'd}\right)^{km'} \left(\frac{m'}{n}\right)^{m'(k-1)} < 1.$$

Substitute in $k = 2$ and $m' = \frac{n}{d} \log^2 n$ in the exponent of the LHS and then take the m'th-root to obtain

$$\Lambda := \left(\frac{em'd^2}{4\lambda n \log n}\right)^{\frac{4}{\log n}} \left(\frac{2e\lambda n}{m'd}\right)^{2} \left(\frac{m'}{n}\right).$$

We must show $\Lambda < 1$. Substitute in $m' = \frac{n}{d} \log^2 n$ and simplify to obtain

$$\Lambda = \left(\frac{ed \log n}{4\lambda}\right)^{\frac{4}{\log n}} \left(\frac{4e^2\lambda^2}{\log^4 n}\right) \left(\frac{\log^2 n}{d}\right) = \left(\frac{e^4 d^4 \log^4 n}{256\lambda^4}\right)^{\frac{1}{\log n}} \left(\frac{4e^2\lambda^2}{d \log^2 n}\right). \tag{5}$$

Now $d = q - 1$, $\lambda = \sqrt{q}$, and $n = q(q-1)/t$ so $\lambda^2/d = q/(q-1) \le 2$ and

$$\frac{d^4}{\lambda^4} = \frac{(q-1)^4}{q^2} < q(q-1) = nt < n^2.$$

Insert these inequalities into (5) to obtain

$$\Lambda < \left(\frac{e^4 n^2 \log^4 n}{256}\right)^{\frac{1}{\log n}} \left(\frac{8e^2}{\log^2 n}\right).$$

Since $n^2 = e^{2 \log n}$ raised to the power $1/\log n$ is a constant, when n gets big the above expression drops below 1 (as mentioned above, we can assume $n > n_0$.) Therefore, Theorem 10 implies that $r(K_{2,t}, K_{2,t}, K_{m'}) > n$. In Step 1, we showed that $m \ge m'$ so $r(K_{2,t}, K_{2,t}, K_m) > n$. Since $n = q(q-1)/t$, equation (3) shows that $n > \frac{1}{64}\delta \frac{m^2 t}{\log^4 mt}$, completing the proof. $\qquad \square$

Proof sketch of Theorem 4 (ii). Given m, t, and $k \ge 3$, fix $s = 1$ (instead of 2) and $L = 4k$ and choose q and δ according to Lemma 11. The proof is mostly the same as the above proof, except we choose $m' = 2k\frac{n}{d} \log n$ (the difference is that the log is not squared plus now there is a $2k$ out front.) The proof then proceeds in two steps: show that $m \ge 2k\frac{n}{d} \log n = m'$ and then show that k, m', λ, n, and d satisfy the inequality (2). Showing $m \ge m'$ is almost identical to Step 1 in the previous proof. Showing k, m', λ, n, and d satisfy inequality (2) in Theorem 10 is tedious; the details are online. $\qquad \square$

4 An algebraic $K_{2,t+1}$-free construction

To prove Theorem 5, we construct two different graphs for the two cases: one graph G^+ for $q \equiv 0 \pmod{t}$ and one graph $G^\times$ for $q \equiv 1 \pmod{t}$. The two graphs are closely related; they are built from finite fields. Fix a prime p and an integer a, and let $q = p^a$. Let $\mathbb{F}_q$ be the finite field of order q and let $\mathbb{F}_q^*$ be the finite field of order q without the zero element.

When $q \equiv 0 \pmod{t}$, let H be an additive subgroup of $\mathbb{F}_q$ of order t. Such a subgroup exists since t divides q so $t = p^b$ for some $b \leq a$. Define a graph G^+ as follows. Let $V(G^+) = (\mathbb{F}_q/H) \times \mathbb{F}_q^*$. We will write elements of $\mathbb{F}_q/H$ as $\bar{a}$, where $\bar{a}$ as the additive coset of H generated by a. That is, $\bar{a} = \{h + a : h \in H\}$. For $\bar{a}, \bar{b} \in \mathbb{F}_q/H$ and $x, y \in \mathbb{F}_q^*$, make $(\bar{a}, x)$ adjacent to $(\bar{b}, y)$ if $xy \in \overline{a + b}$. Since H is a normal subgroup the coset $\overline{a + b}$ is well-defined, so by $xy \in \overline{a + b}$ we mean there exists some $h \in H$ such that $xy = h + a + b$. [1]

When $q \equiv 1 \pmod{t}$, let H be a multiplicative subgroup of $\mathbb{F}_q^*$ of order t. Such a subgroup exists since t divides the order of $\mathbb{F}_q^*$ and $\mathbb{F}_q^*$ is a cyclic multiplicative group. Define a graph $G^\times$ as follows. Let $V(G^\times) = (\mathbb{F}_q^*/H) \times \mathbb{F}_q$. For $\bar{a}, \bar{b} \in \mathbb{F}_q^*/H$ and $x, y \in \mathbb{F}_q$, make $(\bar{a}, x)$ adjacent to $(\bar{b}, y)$ if $x + y \in \overline{ab}$. [2]

4.1 Simple properties of G^+ and $G^\times$

Lemma 12. *G^+ and $G^\times$ are regular of degree $q - 1$.*

Proof. First, consider G^+. Fix some vertex $(\bar{a}, x) \in V(G^+)$ and pick $y \in \mathbb{F}_q^*$ ($q - 1$ choices.) The element xy is now in some coset $\bar{c}$. Since the cosets form a group, the coset $\overline{c - a}$ is well-defined. Thus $(\bar{a}, x)$ is adjacent to $(\bar{d}, y)$ in G^+ if and only if $\bar{d} = \overline{xy - a}$.

Now consider $G^\times$. Fix some vertex $(\bar{a}, x) \in V(G^\times)$ and pick $y \in \mathbb{F}_q$. If $x \neq -y$, then there is a coset $\bar{c}$ containing $x + y$. Since the cosets form a group, the coset $\overline{ca^{-1}}$ is well defined. If $x = -y$, then there is no coset which contains zero. Thus $(\bar{a}, x)$ is adjacent to $(\bar{d}, y)$ if and only if $x \neq -y$ and $\bar{d} = \overline{(x + y)a^{-1}}$. Therefore $(\bar{a}, x)$ is adjacent to $q - 1$ vertices, since there are $q - 1$ choices for $y \in \mathbb{F}_q$ with $x \neq -y$. $\square$

Lemma 13. *The common neighborhood of any two vertices in G^+ has size exactly t.*

Proof. The proof is similar to the proofs given in [11, 16]. Fix $\bar{a}, \bar{b} \in \mathbb{F}_q/H$ and $x, y \in \mathbb{F}_q^*$ and consider the common neighborhood of the vertices $(\bar{a}, x)$ and $(\bar{b}, y)$. A vertex $(\bar{c}, z)$ will be adjacent to both of $(\bar{a}, x)$ and $(\bar{b}, y)$ if

$$xz \in \overline{a + c}$$
$$yz \in \overline{b + c}.$$

---

[1] In finite fields, additive subgroups of a given order are isomorphic as groups. Each element of $\mathbb{F}_q$ has additive order the characteristic, so H decomposes into p^{b-1} orbits of size p and one can obtain a group isomorphism by mapping orbits to orbits. Therefore, G^+ is uniquely defined up to isomorphism.

[2] In finite fields, multiplicative subgroups of a given order are isomorphic as groups since $\mathbb{F}_q^*$ is cyclic. Therefore, $G^\times$ is uniquely defined up to isomorphism.

In other words, there exists some $h_1, h_2 \in H$ such that

$$xz = a + c + h_1$$
$$yz = b + c + h_2.$$

So fix $h_1, h_2 \in H$ and count how many choices there are for c and z so that $(\bar{c}, z)$ is adjacent to both $(\bar{a}, x)$ and $(\bar{b}, y)$ using h_1 and h_2. We show there is a unique c and z. Say we had c, c', z, z' such that

$$xz = a + c + h_1 \tag{6}$$
$$yz = b + c + h_2 \tag{7}$$
$$xz' = a + c' + h_1 \tag{8}$$
$$yz' = b + c' + h_2. \tag{9}$$

Add (6) to (9); this equals (7) plus (8).

$$xz + yz' = a + b + c + c' + h_1 + h_2 = yz + xz'$$
$$(x - y)(z - z') = 0. \tag{10}$$

If $x = y$, then subtracting (6) from (7) gives $a - b \in H$ which means $\bar{a} = \bar{b}$. But now $(\bar{a}, x)$ and $(\bar{b}, y)$ are the same vertex. Thus (10) implies $z = z'$. Then subtracting (6) and (8) we get $c = c'$, showing there is a unique c, z such that $(\bar{c}, z)$ is adjacent to both $(\bar{a}, x)$ and $(\bar{b}, y)$ using h_1, h_2. (Note that not only is there a unique $(\bar{c}, z)$, but the choice of the representative c for the coset $\bar{c}$ is unique.)

There are now t^2 choices for h_1 and h_2 and each provides a unique c, z. But each coset $\bar{c}$ has t elements so there are exactly $t^2/t = t$ common neighbors of $(\bar{a}, x)$ and $(\bar{b}, y)$. □

Lemma 14. *The common neighborhood of any two vertices in $G^\times$ has size exactly t.*

Proof. Fix $\bar{a}, \bar{b} \in \mathbb{F}_q^*/H$ and $x, y \in \mathbb{F}_q$ and consider the common neighborhood of the vertices $(\bar{a}, x)$ and $(\bar{b}, y)$. A vertex $(\bar{c}, z)$ will be adjacent to both $(\bar{a}, x)$ and $(\bar{b}, y)$ if

$$x + z \in \overline{ac}$$
$$y + z \in \overline{bc}.$$

In other words, there exists some $h_1, h_2 \in H$ such that

$$x + z = h_1 ac$$
$$y + z = h_2 bc.$$

So fix some $h_1, h_2 \in H$ and count how many choices there are for c and z so that $(\bar{c}, z)$ is adjacent to both $(\bar{a}, x)$ and $(\bar{b}, y)$ using h_1 and h_2. We show there is a unique such c and z. Say there existed c, c', z, z' such that

$$x + z = h_1 ac \tag{11}$$
$$y + z = h_2 bc \tag{12}$$
$$x + z' = h_1 ac' \tag{13}$$
$$y + z' = h_2 bc'. \tag{14}$$

Multiply (11) by (14), which equals (12) times (13).

$$(x + z)(y + z') = h_1 h_2 abcc' = (y + z)(x + z')$$
$$xy + xz' + yz + zz' = xy + yz' + xz + zz'$$
$$xz' + yz = xz + yz'$$
$$(x - y)(z' - z) = 0 \tag{15}$$

If $x = y$, then (11) and (12) show

$$h_1 ac = x + z = y + z = h_2 bc$$
$$ab^{-1} = h_1^{-1} h_2 \in H$$

which shows $\bar{a} = \bar{b}$. But now $(\bar{a}, x)$ and $(\bar{b}, y)$ are the same vertex. Thus (15) implies $z = z'$. But now (11) and (13) show $c = c'$.

Thus for every choice of $h_1, h_2 \in H$ there is a unique c, z such that $(\bar{c}, z)$ is adjacent to both $(\bar{a}, x)$ and $(\bar{b}, y)$ using h_1, h_2. Note that not only is there a unique $(\bar{c}, z)$, but the choice of the representative c for the coset $\bar{c}$ is unique. There are now t^2 choices for h_1 and h_2 and each provides a unique c, z. But each coset $\bar{c}$ has t elements so there are exactly $t^2/t = t$ common neighbors of $(\bar{a}, x)$ and $(\bar{b}, y)$. $\square$

4.2 The Spectrum of G^+ and $G^\times$

Lemma 15. *The eigenvalues of G^+ are $q - 1$, $\pm\sqrt{q}$, ± 1, and 0. If p is an odd prime, they have the following multiplicities: $q - 1$ has multiplicity 1, $\sqrt{q}$ and $-\sqrt{q}$ each have multiplicity $\frac{1}{2}(q/t - 1)(q - 2)$, 1 and -1 both have multiplicity $\frac{1}{2}(q/t - 1)$, and 0 has multiplicity $q - 2$.*

Lemma 16. *The eigenvalues of $G^\times$ are $q - 1$, $\pm\sqrt{q}$, ± 1, and 0. If p is an odd prime, they have the following multiplicities: $q - 1$ has multiplicity 1, $\sqrt{q}$ and $-\sqrt{q}$ each have multiplicity $\frac{1}{2}((q - 1)/t - 1)(q - 1)$, 1 and -1 both have multiplicity $\frac{1}{2}(q - 1)$, and 0 has multiplicity $(q - 1)/t - 1$.*

The proof of these lemmas are similar to proofs by Alon and Rödl [2, Lemma 3.6] and Szabó [19]. In addition, the two proofs given below are almost the same but there are several subtle issues involving the fact that G^+ and $G^\times$ switch between $\mathbb{F}_q$ and $\mathbb{F}_q^*$. There are small but crucial differences in how the proofs below handle the zero element. Therefore, we give both proofs and caution the reader to pay attention to how the zero element is handled when reading the proofs.

Proof of Lemma 15. Let M be the adjacency matrix of G^+. Let χ be an arbitrary additive character of $\mathbb{F}_q/H$ and let ϕ be an arbitrary multiplicative character of $\mathbb{F}_q^*$. This means that

$$\chi : \mathbb{F}_q/H \to \mathbb{C} \qquad \phi : \mathbb{F}_q^* \to \mathbb{C}$$

where χ is an additive group homomorphism (if $\bar{a}, \bar{b}$ are cosets in $\mathbb{F}_q/H$ then $\chi(\bar{a} + \bar{b}) = \chi(\bar{a})\chi(\bar{b})$, $\chi(\bar{0}) = 1$, and $\chi(-\bar{a}) = \chi(\bar{a})^{-1}$) and ϕ is a multiplicative group homomorphism (if

$a, b \in \mathbb{F}^*/q$ then $\phi(ab) = \phi(a)\phi(b)$, $\phi(1) = 1$, $\phi(a^{-1}) = \phi(a)^{-1}$.) Note that since $\phi(1) = 1$ and $x^q = 1$ for any $x \in \mathbb{F}_q^*$, $\phi(x)$ must be a root of unity in $\mathbb{C}$. Thus $\phi(x^{-1}) = \phi(x)^{-1} = \overline{\phi(x)}$ where $\overline{\phi(x)}$ is the complex conjugate of $\phi(x)$. Similarly, $\chi(-\bar{a}) = \overline{\chi(\bar{a})}$, the complex conjugate of χ applied to the coset $\bar{a}$.

Let $\langle \chi, \phi \rangle$ denote the column vector whose coordinates are labeled by the elements of $V(G^+)$ and whose entry at the coordinate $(\bar{a}, x)$ is $\chi(\bar{a})\phi(x)$. We now show that $\langle \chi, \phi \rangle$ is an eigenvector of M and compute its eigenvalue. The following expression is the entry of the vector $M \langle \chi, \phi \rangle$ at the coordinate $(\bar{a}, x)$.

$$\sum_{\substack{(\bar{b},y) \text{ is a vertex} \\ (\bar{a},x) \leftrightarrow (\bar{b},y)}} \chi(\bar{b})\phi(y) = \sum_{\substack{\bar{b} \in \mathbb{F}_q/H \\ y \in \mathbb{F}_q^* \\ xy \in \overline{a+b}}} \chi(\bar{b})\phi(y)$$

First, we make two changes of variables in this sum. The first change is to switch $\bar{b}$ to $\bar{c}$ by the transformation $\bar{c} = \overline{a+b} = \bar{a} + \bar{b}$.

$$\sum_{\substack{\bar{c} \in \mathbb{F}_q/H \\ y \in \mathbb{F}_q^* \\ xy \in \bar{c}}} \chi(\overline{c-a})\phi(y)$$

Next, switch y to z by the transformation $z = xy$.

$$\sum_{\substack{\bar{c} \in \mathbb{F}_q/H \\ z \in \mathbb{F}_q^* \\ z \in \bar{c}}} \chi(\overline{c-a})\phi\left(\frac{z}{x}\right).$$

Using that χ and ϕ are characters (homomorphisms), this transforms to

$$(\chi(\bar{a})\phi(x))^{-1} \sum_{\substack{\bar{c} \in \mathbb{F}_q/H \\ z \in \mathbb{F}_q^* \\ z \in \bar{c}}} \chi(\bar{c})\phi(z) = \overline{\chi(\bar{a})\phi(x)} \sum_{\left\{(\bar{c},z): \bar{c} \in \mathbb{F}_q/H, z \in \mathbb{F}_q^*, z \in \bar{c}\right\}} \chi(\bar{c})\phi(z)$$

There is an obvious bijection between the set $\left\{(\bar{c}, z) : \bar{c} \in \mathbb{F}_q/H, z \in \mathbb{F}_q^*, z \in \bar{c}\right\}$ and the set $\left\{z : z \in \mathbb{F}_q^*\right\}$, since once z is picked, there is a unique coset containing z. Thus the above sum can be simplified to

$$\overline{\chi(\bar{a})\phi(x)} \sum_{z \in \mathbb{F}_q^*} \chi(\bar{z})\phi(z).$$

Define $\Gamma_{\chi,\phi} = \sum_{z \in \mathbb{F}_q^*} \chi(\bar{z})\phi(z)$ so that $\Gamma_{\chi,\phi}$ is some constant depending only on χ and ϕ. Then the vector $M \langle \chi, \phi \rangle$ is $\Gamma_{\chi,\phi} \langle \overline{\chi}, \overline{\phi} \rangle$. Thus $M^2 \langle \chi, \phi \rangle = \Gamma_{\chi,\phi}\overline{\Gamma_{\chi,\phi}} \langle \chi, \phi \rangle$, so $\Gamma_{\chi,\phi}\overline{\Gamma_{\chi,\phi}}$ is an eigenvalue of M^2.

Lemma 17. *Let A be a finite group. There are $|A|$ characters of A and if $\tau : A \to \mathbb{C}$ is a non-principal character then $\sum_{a \in A} \tau(a) = 0$.*

The above lemma shows there are $|\mathbb{F}_q/H| \cdot |\mathbb{F}_q^*| = q(q-1)/t = |V(G^+)|$ vectors $\langle \chi, \phi \rangle$. Secondly, the lemma shows $\langle \chi, \phi \rangle$ is orthogonal to $\langle \chi', \phi' \rangle$ if $\chi \neq \chi'$ or $\phi \neq \phi'$ (the dot product of $\langle \chi, \phi \rangle$ with $\langle \chi', \phi' \rangle$ is a sum which can be rearranged to apply Lemma 17.)

Since $\{ \langle \chi, \phi \rangle : \chi, \phi \text{ characters } \}$ is a linearly independent set of $|V(G^+)|$ eigenvectors of M^2 and M^2 has $|V(G^+)|$ columns, all eigenvalues of M^2 are of the form $\Gamma_{\chi,\phi}\overline{\Gamma_{\chi,\phi}}$. The eigenvalues of M^2 are the squares of the eigenvalues of M. Since M is symmetric, these eigenvalues are real so all eigenvalues of M are of the form $\pm |\Gamma_{\chi,\phi}|$.

When χ and ϕ are principal characters of their respective groups (this means χ and ϕ map everything to 1), the corresponding eigenvalue is $q-1$ since there are $q-1$ terms in the sum defining $\Gamma_{\chi,\phi}$. This eigenvalue has multiplicity one. When χ is principal but ϕ is not principal, the eigenvalues are

$$\Gamma_{\chi,\phi} = \sum_{z \in \mathbb{F}_q^*} \phi(z) = 0.$$

There are $q-1$ possible characters ϕ, but one of them is principal so 0 will have multiplicity $q-2$ as an eigenvalue. When ϕ is principal but χ is not, we obtain

$$\Gamma_{\chi,\phi} = \sum_{z \in \mathbb{F}_q^*} \chi(\bar{z}) = t \sum_{\bar{z} \in \mathbb{F}_q/H} \chi(\bar{z}) - \chi(\bar{0}) = -\chi(\bar{0}) = -1.$$

($\chi(\bar{0})$ is subtracted since the sum over $\mathbb{F}_q^*$ will have $t = |H|$ terms for each coset, except the zero coset will only appear $t-1$ times.) Thus the eignevalues when ϕ is principal and χ is not are ± 1. For the multiplicities, there are $q/t - 1$ non-principal characters χ. They come in pairs, since if χ is a character, the complex conjugate $\overline{\chi}$ is a character as well. Also, note that $\langle \chi, \phi \rangle + \langle \bar{\chi}, \phi \rangle$ has eigenvalue 1 and $\langle \chi, \phi \rangle - \langle \bar{\chi}, \phi \rangle$ has eigenvalue -1 (when ϕ is principal.) Thus if p is an odd prime, 1 and -1 will each have multiplicity $\frac{1}{2}(q/t - 1)$.

When neither χ nor ϕ is a principal character, we apply a theorem on Gaussian sums of characters.

Theorem 18. *If χ' and ϕ are additive and multiplicative non-principal characters of $\mathbb{F}_q$ and $\mathbb{F}_q^*$ respectively, then $\left| \sum_{x \in \mathbb{F}_q^*} \chi'(x)\phi(x) \right| = \sqrt{q}$.*

While we can't apply this theorem directly since χ is not a character on $\mathbb{F}_q$, define a new additive character χ' on $\mathbb{F}_q$ as follows: for $x \in \mathbb{F}_q$ let $\chi'(x) = \chi(\bar{x})$. This is an additive character because $\chi'(0) = \chi(\bar{0}) = 1$, $\chi'(x + y) = \chi(\overline{x+y}) = \chi(\bar{x} + \bar{y}) = \chi(\bar{x})\chi(\bar{y}) = \chi'(x)\chi'(y)$, and $\chi'(-x) = \chi(\overline{-x}) = \chi(\bar{x})^{-1} = \chi'(x)^{-1}$. We can now rewrite $\Gamma_{\chi,\phi}$ as

$$\Gamma_{\chi,\phi} = \sum_{z \in \mathbb{F}_q^*} \chi'(x)\phi(x).$$

Theorem 18 shows that when χ and ϕ are both non-principal, the corresponding eigenvalue is $\pm\sqrt{q}$. $\qquad\square$

Proof of Lemma 16. Let M be the adjacency matrix of $G^\times$. Let χ be an arbitrary multiplicative character of $\mathbb{F}_q^*/H$ and let ϕ be an arbitrary additive character of $\mathbb{F}_q$.

Let $\langle \chi, \phi \rangle$ denote the column vector whose coordinates are labeled by the elements of $V(G^\times)$ and whose entry at the coordinate $(\bar{a}, x)$ is $\chi(\bar{a})\phi(x)$. We now show that $\langle \chi, \phi \rangle$ is an eigenvector of M and compute its eigenvalue. The following expression is the entry of the vector $M \langle \chi, \phi \rangle$ at the coordinate $(\bar{a}, x)$.

$$\sum_{\substack{(\bar{b}, y) \text{ is a vertex} \\ (\bar{a}, x) \leftrightarrow (\bar{b}, y)}} \chi(\bar{b})\phi(y) = \sum_{\substack{\bar{b} \in \mathbb{F}_q^*/H \\ y \in \mathbb{F}_q \\ x + y \in \overline{ab}}} \chi(\bar{b})\phi(y)$$

First, we make two changes of variables in this sum. The first change is to switch $\bar{b}$ to $\bar{c}$ by the transformation $\bar{c} = \overline{ab} = \bar{a} \cdot \bar{b}$.

$$\sum_{\substack{\bar{c} \in \mathbb{F}_q^*/H \\ y \in \mathbb{F}_q \\ x + y \in \bar{c}}} \chi(\overline{ca^{-1}})\phi(y)$$

Next, switch y to z by the transformation $z = x + y$.

$$\sum_{\substack{\bar{c} \in \mathbb{F}_q^*/H \\ z \in \mathbb{F}_q \\ z \in \bar{c}}} \chi(\overline{ca^{-1}})\phi(z - x).$$

Using that χ and ϕ are characters (homomorphisms), this transforms to

$$(\chi(\bar{a})\phi(x))^{-1} \sum_{\substack{\bar{c} \in \mathbb{F}_q^*/H \\ z \in \mathbb{F}_q \\ z \in \bar{c}}} \chi(\bar{c})\phi(z) = \overline{\chi(\bar{a})\phi(x)} \sum_{\left\{ (\bar{c}, z) : \bar{c} \in \mathbb{F}_q^*/H, z \in \mathbb{F}_q, z \in \bar{c} \right\}} \chi(\bar{c})\phi(z)$$

There is an obvious bijection between the set $\left\{ (\bar{c}, z) : \bar{c} \in \mathbb{F}_q^*/H, z \in \mathbb{F}_q, z \in \bar{c} \right\}$ and the set $\left\{ z : z \in \mathbb{F}_q^* \right\}$, since once a non-zero z is picked, there is a unique coset containing z. (When $z = 0$, there is no coset containing z.) Thus the above sum can be simplified to

$$\overline{\chi(\bar{a})\phi(x)} \sum_{z \in \mathbb{F}_q^*} \chi(\bar{z})\phi(z).$$

Define $\Gamma_{\chi, \phi} = \sum_{z \in \mathbb{F}_q^*} \chi(\bar{z})\phi(z)$ so that $\Gamma_{\chi, \phi}$ is some constant depending only on χ and ϕ. Then the vector $M \langle \chi, \phi \rangle$ is $\Gamma_{\chi, \phi} \langle \overline{\chi}, \overline{\phi} \rangle$. Thus $M^2 \langle \chi, \phi \rangle = \Gamma_{\chi, \phi} \overline{\Gamma_{\chi, \phi}} \langle \chi, \phi \rangle$ so $\Gamma_{\chi, \phi} \overline{\Gamma_{\chi, \phi}}$ is an eigenvalue of M^2. Like the last proof, Lemma 17 shows all eigenvalues of M^2 are of the form $\Gamma_{\chi, \phi} \overline{\Gamma_{\chi, \phi}}$ so all eigenvalues of M are of the form $\pm |\Gamma_{\chi, \phi}|$.

When χ and ϕ are principal characters of their respective groups, the corresponding eigenvalue is $q - 1$ since there are $q - 1$ terms in the sum. This eigenvalue has multiplicity one. When ϕ is principal but χ is not principal, the eigenvalues are

$$\Gamma_{\chi, \phi} = \sum_{z \in \mathbb{F}_q^*} \chi(\bar{z}) = t \sum_{\bar{z} \in \mathbb{F}_q^*/H} \chi(\bar{z}) = 0.$$

There are $(q-1)/t$ possible characters χ, but one of them is principal so 0 will have multiplicity $(q-1)/t - 1$ as an eigenvalue. When χ is principal but ϕ is not, we obtain

$$\Gamma_{\chi,\phi} = \sum_{z \in \mathbb{F}_q^*} \phi(z) = \sum_{z \in \mathbb{F}_q} \phi(z) - \phi(0) = -\phi(0) = -1.$$

Thus the eignevalues when χ is principal and ϕ is not are ± 1. For the multiplicities, there are $q-1$ non-principal characters ϕ. They come in pairs, since if ϕ is a character, the complex conjugate $\overline{\phi}$ is a character as well. Also, note that $\langle \chi, \phi \rangle + \langle \chi, \overline{\phi} \rangle$ has eigenvalue 1 and $\langle \chi, \phi \rangle - \langle \chi, \overline{\phi} \rangle$ has eigenvalue -1 (when χ is principal.) Thus if p is an odd prime, 1 and -1 will each have multiplicity $\frac{1}{2}(q-1)$.

When neither χ or ϕ is a principal character, we apply Theorem 18. While we can't apply this theorem directly since χ is not a multiplicative character on $\mathbb{F}_q^*$, define a new multiplicatve character χ' on $\mathbb{F}_q^*$ as follows: for $x \in \mathbb{F}_q^*$ let $\chi'(x) = \chi(\bar{x})$. This is a multiplicative character because $\chi'(1) = \chi(\bar{1}) = 1$, $\chi'(xy) = \chi(\overline{xy}) = \chi(\bar{x} \cdot \bar{y}) = \chi(\bar{x})\chi(\bar{y}) = \chi'(x)\chi'(y)$, and $\chi'(x^{-1}) = \chi(\overline{x^{-1}}) = \chi(\bar{x})^{-1} = \chi'(x)^{-1}$. We can now rewrite $\Gamma_{\chi,\phi}$ as

$$\Gamma_{\chi,\phi} = \sum_{z \in \mathbb{F}_q^*} \chi'(x)\phi(x).$$

Theorem 18 shows that when χ and ϕ are both non-principal, the corresponding eigenvalue is $\pm\sqrt{q}$. $\qquad\square$

4.3 Independence number

In Table 2, there is no lower bound in the upper right cell; that is, when m is much larger than t the only lower bound we know is the bound of $c_t m^{2-1/t}$ from the random graph. What about using G^+ or $G^\times$ as the first color in a construction for the lower bound? In other words, what is the independence number of G^+ and $G^\times$? This is related to the conjecture that Paley Graphs are Ramsey Graphs (see [17] and its references.) While we aren't able to determine exactly the independence number, computation suggests that G^+ and $G^\times$ have independent sets of size roughly $\sqrt{n}$, where n is the number of vertices. In particular, computation suggests the following conjecture for G^+.

Conjecture 19. *Let $G^+(q, t)$ be the graph constructed at the beginning of this section for the parameters q and t. Recall that $G^+(q, t)$ has $q(q-1)/t$ vertices which is regular of degree $q-1$ so $G^+(2^a, 2^{a-1})$ is an n-vertex graph where every degree is about $n/2$ and any pair of vertices have about $n/4$ common neighbors. For $a \geq 6$,*

$$\alpha(G^+(2^a, 2^{a-1})) = \begin{cases} 2^{a/2} & \text{if a is even} \\ 2^{(a-1)/2} + 1 & \text{if a is odd} \end{cases}$$
$$\alpha(G^+(p^2, p)) = p^2 - 1 \qquad \text{if p is odd}$$

Note that $\alpha(G^+(2^3, 2^2)) = 4$ and $\alpha(G^+(2^4, 2^3)) = 5$, which don't quite match the conjecture. For $\alpha(G^+(2^a, 2^{a-1})$, the conjecture is true for $a = 6, 7, 8, 9, 10$. For $G^+(p^2, p)$, the conjectured value is $p^2 - 1$; we can prove a lower bound of $\frac{1}{2}p^2$. First, we need the following simple lemma about finite fields and field extensions.

Lemma 20. *Let p be a prime and let $x \in \mathbb{F}_{p^a}^*$ with x a generator for the cyclic multiplicative group $\mathbb{F}_{p^a}^*$. Then*

$$\{1, 2, \ldots, p-1\} = \left\{ x^{t(p^a-1)/(p-1)} : 0 \le t < p-1 \right\}$$

Proof. The Frobenius automorphism $\phi(z) = z^p$ has fixed points exactly the elements in $\mathbb{Z}_p$. Thus

$$\phi(x^{t(p^a-1)/(p-1)}) = x^{tp(p^a-1)/(p-1)} = x^{t(p^a-1)} x^{t(p^a-1)/(p-1)}.$$

Since $x^{q-1} = 1$, $x^{t(p^a-1)/(p-1)}$ is a fixed point so it is in $\mathbb{Z}_p$. Also, since the multiplicative group of $\mathbb{F}_q$ is cyclic, the elements $x^{t(p^a-1)/(p-1)}$ are distinct and there are $p-1$ of them. $\square$

Lemma 21. *If p is an odd prime, then $\alpha(G^+(p^2, p)) \ge \lfloor p^2/2 \rfloor$.*

Proof. $q = p^2$, $t = p$, so $n = p^2(p-1)$. Thus $\frac{1}{2}n^{2/3} \le \frac{1}{2}p^2 = \frac{1}{2}q$.

The field $\mathbb{F}_q$ is $\mathbb{Z}_p[x]/(f(x))$, where $f(x)$ is some irreducible polynomial of degree 2. Thus elements of $\mathbb{F}_q$ can be written as $\alpha x + \beta$ for $\alpha, \beta \in \mathbb{Z}_p$. Since $t = p$, we need H to be an additive subgroup of $\mathbb{F}_q$ of order p. The additive subgroup generated by x has order p, so let $H = \{0, x, 2x, 3x, \ldots, (p-1)x\}$. We now claim the following set is an independent set:

$$\left\{ (\bar{0}, x^{2k}) : 0 \le k < q/2 \right\}.$$

Consider two vertices in this set: $(\bar{0}, x^{2j})$ and $(\bar{0}, x^{2k})$. These will be adjacent if $x^{2j+2k} \in \bar{0} = H$, in other words $x^{2j+2k-1} \in \mathbb{Z}_p$. But from Lemma 20, the powers of x which give elements in $\mathbb{Z}_p$ are of the form $t(p+1)$ for some t. Since p is an odd prime, $p+1$ is even. Thus $x^{2j+2k-1} \notin \mathbb{Z}_p$. $\square$

Most likely, the above proof can be extended to $G^+(p^a, p^b)$ when b divides a as follows. Let $q = p^a$ and view the field $\mathbb{F}_q$ as an extension field over $\mathbb{F}_p$; the Galois group $Gal(\mathbb{F}_q/\mathbb{F}_p)$ is cyclic of order a with generator the Frobenius automorphism used in Lemma 20. Since b divides a, there is a subgroup of $Gal(\mathbb{F}_q/\mathbb{F}_p)$ of order a/b. By the fundamental theorem of Galois theory, this corresponds to an intermediate field extension of order p^b. Thus we have a subfield of $\mathbb{F}_q$ of order p^b and an automorphism ϕ which fixes this subfield. Replace the Frobenius automorphism in the above proof by this ϕ, investigate which powers of x are fixed by ϕ, and find a set whose sums avoid these powers of x to construct an independent set in $G^+(p^a, p^b)$.

5   Conclusion and open problems

- Looking at Table 2, it is somewhat strange that when m is around $\log^2 t$ the best lower bound switches from a simple construction (the Turán Graph) to the random graph. Perhaps some combination of these two constructions could provide a good lower bound when m is around $\log^2 t$. Unfortunately, the two simple ideas do not work. One option is to take ℓ random graphs forbidding $K_{2,t}$ and independence number m/ℓ as one color and all edges between the random graphs as the second color. Another option is to take ℓ cliques in red (of some size smaller than $t+1$) and put a random graph between cliques. We are unable to make either of these two constructions beat the bounds in Table 2, even for a restricted range of m.

- The ideas in this paper can be extended to $r_k(K_{s,t}; K_m)$ when s is fixed using field norms, similar to the projective norm graphs. Let $N : \mathbb{F}_{q^s} \to \mathbb{F}_q$ be the field norm of the extension of $\mathbb{F}_{q^s}$ over $\mathbb{F}_q$. (When q is prime $N(x) = x^{(q^s-1)/(q-1)}$ and when q is a prime-power the field norm is more complicated.) Given q, t, and s, let H be an additive subgroup of $\mathbb{F}_q$ of order t and form a graph G^+ as follows. The vertex set is $(\mathbb{F}_q/H) \times \mathbb{F}_{q^s}^*$ and two vertices $(\bar{a}, x)$ and $(\bar{b}, y)$ are adjacent if $N(xy) \in \overline{a+b}$. The graph $G^\times$ can be similarly extended using norms. These constructions will now avoid $K_{s,t}$ when $t \geq (s-1)! + 1$. Using ideas from [19], the computations in Section 4.2 can be extended to find the spectrum of G^+ and $G^\times$. Theorem 10 can then be used to prove a lower bound on $r_k(K_{s,t}; K_m)$ when $k \geq 2$ and s is fixed.

  Extending to s not fixed, somehow the vertex set should be taken as $(\mathbb{F}_q/H) \times (\mathbb{F}_q^*/J)$ where H is an additive subgroup of order t and J is a multiplicative subgroup of order s. But if $(\bar{a}, \bar{x})$ and $(\bar{b}, \bar{y})$ are vertices, it is not clear what the relation between $\overline{a+b}$ and $\overline{xy}$ is. Perhaps if H and J are taken not as arbitrary subgroups but specific subgroups with certain properties, the coset $\overline{a+b}$ would be completely contained in or disjoint from $\overline{xy}$.

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