Making K_{r+1}-Free Graphs r-partite

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Abstract

The Erdős–Simonovits stability theorem states that for all $\varepsilon > 0$ there exists $\alpha > 0$ such that if G is a K_{r+1}-free graph on n vertices with $e(G) > \mathrm{ex}(n, K_{r+1}) - \alpha n^2$, then one can remove εn^2 edges from G to obtain an r-partite graph. Füredi gave a short proof that one can choose $\alpha = \varepsilon$. We give a bound for the relationship of α and ε which is asymptotically sharp as $\varepsilon \to 0$.

1 Introduction

Erdős asked how many edges need to be removed in a triangle-free graph on n vertices in order to make it bipartite. He conjectured that the balanced blow-up of C_5 with class sizes $n/5$ is the worst case, and hence $1/25n^2$ edges would always be sufficient. Together with Faudree, Pach and Spencer [5], he proved that one can remove at most $1/18n^2$ edges to make a triangle-free graph bipartite.

Further, Erdős, Győri and Simonovits [6] proved that for graphs with at least $n^2/5$

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Research is partially supported by NSF Grant DMS-1764123, Arnold O. Beckman Research Award (UIUC Campus Research Board RB 18132) and the Langan Scholar Fund (UIUC).

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edges, an unbalanced C_5 blow-up is the worst case. For $r \in \mathbb{N}$, denote $D_r(G)$ the minimum number of edges which need to be removed to make G r-partite.

Theorem 1.1 (Erdős, Győri and Simonovits [6]). *Let G be a K_3-free graph on n vertices with at least $n^2/5$ edges. There exists an unbalanced C_5 blow-up of H with $e(H) \geq e(G)$ such that*

$$D_2(G) \leq D_2(H).$$

This proved the Erdős conjecture for graphs with at least $n^2/5$ edges. A simple probabilistic argument (e.g. [6]) settles the conjecture for graphs with at most $2/25n^2$ edges.

A related question was studied by Sudakov; he determined the maximum number of edges in a K_4-free graph which need to be removed in order to make it bipartite [13]. This problem for K_6-free graphs was solved by Hu, Lidický, Martins, Norin and Volec [10].

We will study the question of how many edges in a K_{r+1}-free graph need at most to be removed to make it r-partite. For $n \in \mathbb{N}$ and a graph H, $\mathrm{ex}(n, H)$ denote the Turán number, i.e. the maximum number of edges of an H-free graph. The Erdős–Simonovits theorem [7] for cliques states that for every $\varepsilon > 0$ there exists $\alpha > 0$ such that if G is a K_{r+1}-free graph on n vertices with $e(G) > \mathrm{ex}(n, K_{r+1}) - \alpha n^2$, then $D_r(G) \leq \varepsilon n^2$.

Füredi [8] gave a nice short proof of the statement that a K_{r+1}-free graph G on n vertices with at least $\mathrm{ex}(n, K_{r+1}) - t$ edges satisfies $D_r(G) \leq t$; thus providing a quantitative version of the Erdős–Simonovits theorem. In [10] Füredi's result was strengthened for some values of r. For small t, we will determine asymptotically how many edges are needed. For very small t, it is already known [3] that G has to be r-partite.

Theorem 1.2 (Brouwer [3]). *Let $r \geq 2$ and $n \geq 2r + 1$ be integers. Let G be a K_{r+1}-free graph on n vertices with $e(G) \geq \mathrm{ex}(n, K_{r+1}) - \lfloor \frac{n}{r} \rfloor + 2$. Then*

$$D_r(G) = 0.$$

This result was rediscovered in [1,9,11,15]. We will study K_{r+1}-free graphs on fewer edges.

Theorem 1.3. *Let $r \geq 2$ be an integer. Then for all $n \geq 3r^2$ and for all $0 \leq \alpha \leq 10^{-7} r^{-12}$ the following holds. Let G be a K_{r+1}-free graph on n vertices with*

$$e(G) \geq \mathrm{ex}(n, K_{r+1}) - t,$$

where $t = \alpha n^2$, then

$$D_r(G) \leq \left(\frac{2r}{3\sqrt{3}} + 30 r^3 \alpha^{1/6} \right) \alpha^{3/2} n^2.$$

Note that we did not try to optimize our bounds on n and α in the theorem. One could hope for a slightly better error term of $30r^3\alpha^{5/3}$ in Theorem 1.3, but the next natural step would be to prove a structural version.
To state this structural version we introduce some definitions. The blow-up of a graph G is obtained by replacing every vertex $v \in V(G)$ with finitely many copies so that the copies of two vertices are adjacent if and only if the originals are.
For two graphs G and H, we define $G \otimes H$ to be the graph on the vertex set $V(G) \cup V(H)$ with $gg' \in E(G \otimes H)$ iff $gg' \in E(G)$, $hh' \in E(G \otimes H)$ iff $hh' \in E(H)$ and $gh \in E(G \otimes H)$ for all $g \in V(G)$, $h \in V(H)$.

Conjecture 1.4. *Let $r \geq 2$ be an integer and n sufficiently large. Then there exists $\alpha_0 > 0$ such that for all $0 \leq \alpha \leq \alpha_0$ the following holds. For every K_{r+1}-free graph G on n vertices there exists an unbalanced $K_{r-2} \otimes C_5$ blow-up H on n vertices with $e(H) \geq e(G)$ such that*

$$D_r(G) \leq D_r(H).$$

This conjecture can be seen as a generalization of Theorem 1.1. We will prove that Theorem 1.3 is asymptotically sharp by describing an unbalanced blow-up of $K_{r-2} \otimes C_5$ that needs at least that many edges to be removed to make it r-partite. This gives us a strong evidence that Conjecture 1.4 is true.

Theorem 1.5. *Let $r, n \in \mathbb{N}$ and $0 < \alpha < \frac{1}{4r^4}$. Then there exists a K_{r+1}-free graph on n vertices with*

$$e(G) \geq \operatorname{ex}(n, K_{r+1}) - \alpha n^2 + \frac{4r}{3\sqrt{3}}\alpha^{3/2}n^2 - \frac{2r(r-3)}{9}\alpha^2 n^2$$

and

$$D_r(G) \geq \frac{2r}{3\sqrt{3}}\alpha^{3/2}n^2.$$

In Kang-Pikhurko's proof [11] of Theorem 1.2 the case $e(G) = \operatorname{ex}(n, K_{r+1}) - \lfloor n/r \rfloor + 1$ is studied. In this case they constructed a family of K_{r+1}-free non-r-partite graphs, which includes our extremal graph, for that number of edges.
We recommend the interested reader to read the excellent survey [12] by Nikiforov. He gives a good overview on further related stability results, for example on guaranteeing large induced r-partite subgraphs of K_{r+1}-free graphs.
We organize the paper as follows. In Section 2 we prove Theorem 1.3 and in Section 3 we give the sharpness example, i.e. we prove Theorem 1.5.

2 Proof of Theorem 1.3

Let G be an n-vertex K_{r+1}-free graph with $e(G) \geq \operatorname{ex}(n, K_{r+1}) - t$, where $t = \alpha n^2$. We will assume that n is sufficiently large. Furthermore, by Theorem 1.2 we can assume that

$$\alpha \geq \frac{\lfloor \frac{n}{r} \rfloor - 2}{n^2} \geq \frac{1}{2rn}.$$

This also implies that $t \geq r$ because $n \geq 3r^2$. During our proof we will make use of Turán's theorem and a version of Turán's theorem for r-partite graphs multiple time. Turán's theorem [14] determines the maximum number of edges in a K_{r+1}-free graph.

Theorem 2.1 (Turán [14]). *Let $r \geq 2$ and $n \in \mathbb{N}$. Then,*

$$\frac{n^2}{2}\left(1 - \frac{1}{r}\right) - \frac{r}{2} \leq ex(n, K_{r+1}) \leq \frac{n^2}{2}\left(1 - \frac{1}{r}\right).$$

Denote $K(n_1, \ldots, n_r)$ the complete r-partite graph whose r color classes have sizes $n_1, \ldots, n_r$, respectively. Turanś theorem for r-partite graphs states the following.

Theorem 2.2 (folklore). *Let $r \geq 2$ and $n_1, \ldots, n_r \in \mathbb{N}$ satisfying $n_1 \leq \ldots \leq n_r$. For a K_r-free subgraph H of $K(n_1, \ldots, n_r)$, we have*

$$e(H) \leq e(K(n_1, ..., n_r)) - n_1 n_2.$$

For a proof of this folklore result see for example [2, Lemma 3.3].

We denote the maximum degree of G by $\Delta(G)$. For two disjoint subsets U, W of $V(G)$, write $e(U, W)$ for the number of edges in G with one endpoint in U and the other endpoint in W. We write $e^c(U, W)$ for the number of non-edges between U and W, i.e. $e^c(U, W) = |U||W| - e(U, W)$.

Füredi [8] used Erdős' degree majorization algorithm [4] to find a vertex partition with some useful properties. We include a proof for completeness.

Lemma 2.3 (Füredi [8]). *Let $t, r, n \in \mathbb{N}$ and G be an n-vertex K_{r+1}-free graph with $e(G) \geq \mathrm{ex}(n, K_{r+1}) - t$. Then there exists a vertex partition $V(G) = V_1 \cup \ldots \cup V_r$ such that*

$$\sum_{i=1}^{r} e(G[V_i]) \leq t, \quad \Delta(G) = \sum_{i=2}^{r} |V_i| \quad \text{and} \quad \sum_{1 \leq i < j \leq r} e^c(V_i, V_j) \leq 2t. \tag{1}$$

Proof. Let $x_1 \in V(G)$ be a vertex of maximum degree. Define $V_1 := V(G) \setminus N(x_1)$ and $V_1^+ = N(x_1)$. Iteratively, let x_i be a vertex of maximum degree in $G[V_{i-1}^+]$. Let $V_i := V_{i-1}^+ \setminus N(x_i)$ and $V_i^+ = V_{i-1}^+ \cap N(x_i)$. Since G is K_{r+1}-free this process stops at $i \leq r$ and thus gives a vertex partition $V(G) = V_1 \cup \ldots \cup V_r$.

In the proof of [8, Theorem 2], it is shown that the partition obtained from this algorithm satisfies

$$\sum_{i=1}^{r} e(G[V_i]) \leq t.$$

By construction,

$$\sum_{i=2}^{r} |V_i| = |V_1^+| = |N(x_1)| = \Delta(G).$$

Let H be the complete r-partite graph with vertex set $V(G)$ and all edges between V_i and V_j for $1 \leq i < j \leq r$. The graph H is r-partite and thus has at most $\mathrm{ex}(n, K_{r+1})$ edges. Finally, since G has at most t edges not in H and at least $\mathrm{ex}(n, K_{r+1}) - t$ edges total, at most $2t$ edges of H can be missing from G, giving us

$$\sum_{1 \leq i < j \leq r} e^c(V_i, V_j) \leq 2t$$

and proving the last inequality. □

For this vertex partition we can get bounds on the class sizes.

Lemma 2.4. *For all $i \in [r]$, $|V_i| \in \{\frac{n}{r} - \frac{5}{2}\sqrt{\alpha}n, \frac{n}{r} + \frac{5}{2}\sqrt{\alpha}n\}$ and thus also*

$$\Delta(G) \leq \frac{r-1}{r}n + \frac{5}{2}\sqrt{\alpha}n.$$

Proof. We know that

$$\sum_{1 \leq i < j \leq r} |V_i||V_j| \geq e(G) - \sum_{i=1}^{r} e(G[V_i]) \geq \left(1 - \frac{1}{r}\right)\frac{n^2}{2} - \frac{r}{2} - 2t.$$

Also,

$$\sum_{1 \leq i < j \leq r} |V_i||V_j| = \frac{1}{2}\sum_{i=1}^{r} |V_i|(n - |V_i|) = \frac{n^2}{2} - \frac{1}{2}\sum_{i=1}^{r} |V_i|^2.$$

Thus, we can conclude that

$$\sum_{i=1}^{r} |V_i|^2 \leq \frac{n^2}{r} + r + 4t. \tag{2}$$

Now, let $x = |V_1| - n/r$. Then,

$$\begin{aligned}\sum_{i=1}^{r} |V_i|^2 &= \left(\frac{n}{r} + x\right)^2 + \sum_{i=2}^{r} |V_i|^2 \geq \left(\frac{n}{r} + x\right)^2 + \frac{(\sum_{i=2}^{r} |V_i|)^2}{r-1} \\ &\geq \left(\frac{n}{r} + x\right)^2 + \frac{\left(n\left(1 - \frac{1}{r}\right) - x\right)^2}{r-1} \geq \frac{n^2}{r} + x^2.\end{aligned}$$

Combining this with (2), we get $|x| \leq \sqrt{r + 4t} \leq \frac{5}{2}\sqrt{t} = \frac{5}{2}\sqrt{\alpha}n$, and thus

$$\frac{n}{r} - \frac{5}{2}\sqrt{\alpha}n \leq |V_1| \leq \frac{n}{r} + \frac{5}{2}\sqrt{\alpha}n.$$

In a similar way we get the bounds on the sizes of the other classes. □

Lemma 2.5. *The graph G contains r vertices $x_1 \in V_1, \dots, x_r \in V_r$ which form a K_r and for every i*

$$\deg(x_i) \geq n - |V_i| - 5r\alpha n.$$

Proof. Let $V_i^c := V(G) \setminus V_i$. We call a vertex $v_i \in V_i$ *small* if $|N(v_i) \cap V_i^c| < |V_i^c| - 5r\alpha n$ and *big* otherwise. For $1 \leq i \leq r$, denote B_i the set of big vertices inside class V_i. There are at most

$$\frac{4t}{5r\alpha n} = \frac{4}{5r} n$$

small vertices in total as otherwise (1) is violated. Thus, in each class there are at least $n/10r$ big vertices, i.e. $|B_i| \geq n/10r$. The number of missing edges between the sets $B_1, \dots, B_r$ is at most $2t < \frac{1}{100r^2} n^2$. Thus, using Theorem 2.2 we can find a K_r with one vertex from each B_i. □

Lemma 2.6. *There exists a vertex partition $V(G) = X_1 \cup \ldots \cup X_r \cup X$ such that all X_is are independent sets, $|X| \leq 5r^2\alpha n$ and*

$$\frac{n}{r} - 3\sqrt{\alpha} n \leq |X_i| \leq \frac{n}{r} + 3r\sqrt{\alpha} n$$

for all $1 \leq i \leq r$.

Proof. By Lemma 2.5 we can find vertices $x_1, \dots, x_r$ forming a K_r and having $\deg(x_i) \geq n - |V_i| - 5r\alpha n$. Define X_i to be the common neighborhood of $x_1, \dots, x_{i-1}$, $x_{i+1}, \dots, x_r$ and $X = V(G) \setminus (X_1 \cup \dots \cup X_r)$. Since G is K_{r+1}-free, the X_is are independent sets. Now we bound the size of X_i using the bounds on the V_is. Since every x_j has at most $|V_j| + 5r\alpha n$ non-neighbors, we get

$$|X_i| \geq n - \sum_{\substack{1 \leq j \leq r \\ j \neq i}} (|V_j| + 5r\alpha n) \geq |V_i| - 5r^2\alpha n \geq \frac{n}{r} - 3\sqrt{\alpha} n.$$

and

$$\sum_{i=1}^{r} \deg(x_i) \geq n(r-1) - 5r^2\alpha n. \tag{3}$$

A vertex $v \in V(G)$ cannot be incident to all of the vertices $x_1, \dots, x_r$, because G is K_{r+1}-free. Further, every vertex from X is not incident to at least two of the vertices $x_1, \dots, x_r$. Thus,

$$\sum_{i=1}^{r} \deg(x_i) \leq n(r-1) - |X|. \tag{4}$$

Combining (3) with (4), we conclude that

$$|X| \leq 5r^2\alpha n.$$

For the upper bound on the sizes of the sets X_i we get

$$|X_i| \leq n - \sum_{\substack{1\leq j\leq r\\ j\neq i}} |X_j| \leq n - \frac{r-1}{r}n + 3r\sqrt{\alpha}n = \frac{n}{r} + 3r\sqrt{\alpha}n.$$

□

We now bound the number of non-edges between $X_1, \ldots, X_r$.

Lemma 2.7.

$$\sum_{1\leq i<j\leq r} e^c(X_i, X_j) \leq t + e(X, X^c) + |X|^2 - \left(1 - \frac{1}{r}\right) n|X| + r.$$

Proof.

$$\begin{aligned} \frac{n^2}{2}\left(1-\frac{1}{r}\right) - \frac{r}{2} - t \leq e(G) &= e(X, X^c) + e(X) + \sum_{1\leq i<j\leq r} e(X_i, X_j) \\ \leq e(X, X^c) + \frac{|X|^2}{2} &+ \left(1 - \frac{1}{r}\right)\left(\frac{(n-|X|)^2}{2}\right) - \sum_{1\leq i<j\leq r} e^c(X_i, X_j). \end{aligned}$$

This gives the statement of the lemma. □

Let

$$\bar{X} = \left\{ v \in X \,\middle|\, \deg_{X_1\cup\cdots\cup X_r}(v) \geq \frac{r-2}{r}n + 3\alpha^{1/3}n \right\} \quad \text{and} \quad \hat{X} := X \setminus \bar{X}.$$

Let $d \in [0,1]$ such that $|\bar{X}| = d|X|$. Further, let $k \in [0, 5r^2]$ such that $|X| = k\alpha n$. Now we shall give an upper bound the number of non-edges between $X_1, \ldots, X_r$.

Lemma 2.8.

$$\sum_{1\leq i<j\leq r} e^c(X_i, X_j) \leq 20r^2\alpha^{4/3}n^2 + \left(1 - (1-d)\frac{1}{r}k\right)\alpha n^2.$$

Proof. By Lemma 2.7,

$$\sum_{1\le i<j\le r} e^c(X_i,X_j) \le t + e(X,X^c) + |X|^2 - \left(1-\frac{1}{r}\right) n|X| + r$$
$$\le t + d|X|\Delta(G) + (1-d)|X|\left(\frac{r-2}{r}n + 3\alpha^{1/3}n\right) + |X|^2 - \left(1-\frac{1}{r}\right) n|X| + r$$
$$\le t + d|X|\left(n\frac{r-1}{r} + \frac{5}{2}\sqrt{\alpha}n\right) + (1-d)|X|\left(\frac{r-2}{r}n + 3\alpha^{1/3}n\right)$$
$$+ |X|^2 - \left(1-\frac{1}{r}\right) n|X| + r$$
$$\le \frac{5}{2}d|X|\sqrt{\alpha}n + 3(1-d)|X|\alpha^{1/3}n + |X|^2 + t + n|X|\frac{d-1}{r} + r$$
$$\le \frac{5}{2}k\alpha^{3/2}n^2 + 3k\alpha^{4/3}n^2 + |X|^2 + \left(1-(1-d)\frac{1}{r}k\right)\alpha n^2 + r$$
$$\le \frac{25}{2}r^2\alpha^{3/2}n^2 + 15r^2\alpha^{4/3}n^2 + 25r^4\alpha^2n^2 + \left(1-(1-d)\frac{1}{r}k\right)\alpha n^2 + r$$
$$\le 20r^2\alpha^{4/3}n^2 + \left(1-(1-d)\frac{1}{r}k\right)\alpha n^2.$$

□

Let

$$C(\alpha) := 20r^2\alpha^{4/3} + \left(1-(1-d)\frac{1}{r}k\right)\alpha.$$

For every vertex $u \in X$ there is no K_r in $N_{X_1}(u) \cup \cdots \cup N_{X_r}(u)$. Thus, by applying Theorem 2.2 and Lemma 2.8, we get

$$\min_{i\neq j} |N_{X_i}(u)||N_{X_j}(u)| \le \sum_{1\le i<j\le r} e^c(X_i,X_j) \le C(\alpha)n^2. \tag{5}$$

Bound (5) implies in particular that every vertex $u \in X$ has degree at most $\sqrt{C(\alpha)}n$ to one of the sets $X_1,\ldots,X_r$, i.e.

$$\min_i |N_{X_i}(u)| \le \sqrt{C(\alpha)}n. \tag{6}$$

Therefore, we can partition $\hat{X} = A_1 \cup \ldots \cup A_r$ such that every vertex $u \in A_i$ has at most $\sqrt{C(\alpha)}n$ neighbors in X_i.
By the following calculation, for every vertex $u \in \bar{X}$ the second smallest neighborhood to the X_i's has size at least $\alpha^{1/3}n$.

$$\min_{i\neq j} |N_{X_i}(u)| + |N_{X_j}(u)| \ge \frac{r-2}{r}n + 3\alpha^{1/3}n - (r-2)\left(\frac{n}{r} + 3r\sqrt{\alpha}n\right) \ge 2\alpha^{1/3}n,$$

where we used the definition of $\bar{X}$ and Lemma 2.6. Combining the lower bound on the second smallest neighborhood with (5) we can conclude that for every $u \in \bar{X}$

$$\min_i |N_{X_i}(u)| \le \frac{C(\alpha)}{\alpha^{1/3}} n. \tag{7}$$

Hence, we can partition $\bar{X} = B_1 \cup \ldots \cup B_r$ such that every vertex $u \in B_i$ has at most $C(\alpha)\alpha^{-1/3}n$ neighbors in X_i. Consider the partition $A_1 \cup B_1 \cup X_1, A_2 \cup B_2 \cup X_2, \ldots, A_r \cup B_r \cup X_r$. By removing all edges inside the classes we end up with an r-partite graph. We have to remove at most

$$e(X) + d|X|\frac{C(\alpha)}{\alpha^{1/3}}n + (1-d)|X|\sqrt{C(\alpha)}n \le 6r^2\alpha^{5/3}n^2 + (1-d)k\sqrt{C(\alpha)}\alpha n^2$$
$$\le 6r^2\alpha^{5/3}n^2 + (1-d)k\left(\sqrt{20r^2\alpha^{4/3}} + \sqrt{\left(1-(1-d)\frac{1}{r}k\right)\alpha}\right)\alpha n^2$$
$$\le \left(\frac{2r}{3\sqrt{3}} + 30r^3\alpha^{1/6}\right)\alpha^{3/2}n^2$$

edges. We have used (6), (7) and the fact that

$$(1-d)k\sqrt{1-(1-d)\frac{k}{r}} \le \frac{2r}{3\sqrt{3}},$$

which can be seen by setting $z = (1-d)k$ and finding the maximum of $f(z) := z\sqrt{1-\frac{z}{r}}$ which is obtained at $z = 2r/3$.

3 Sharpness Example

In this section we will prove Theorem 1.5, i.e. that the leading term from Theorem 1.3 is best possible.

Proof of Theorem 1.5. Let G be the graph with vertex set $V(G) = A \cup X \cup B \cup C \cup D \cup X_1 \cdots \cup X_{r-2}$, where all classes $A, X, B, C, D, X_1, \ldots, X_{r-2}$ form independent sets; A, X, B, C, D form a complete blow-up of a C_5, where the classes are named in cyclic order; and for each $1 \le i \le r-2$, every vertex from X_i is incident to all vertices from $V(G) \setminus X_i$.

The sizes of the classes are

$$|X| = \frac{2r}{3}\alpha n, \quad |A| = |B| = \sqrt{\frac{\alpha}{3}}n, \quad |C| = |D| = \frac{1-\frac{2r}{3}\alpha}{r}n - \sqrt{\frac{\alpha}{3}}n, \quad |X_i| = \frac{1-\frac{2r}{3}\alpha}{r}n.$$

The smallest class is X and the second smallest are A and B. By deleting all edges between X and A ($|X||A| = \frac{2r}{3\sqrt{3}}\alpha^{3/2}n^2$) we get an r-partite graph. Since the classes A

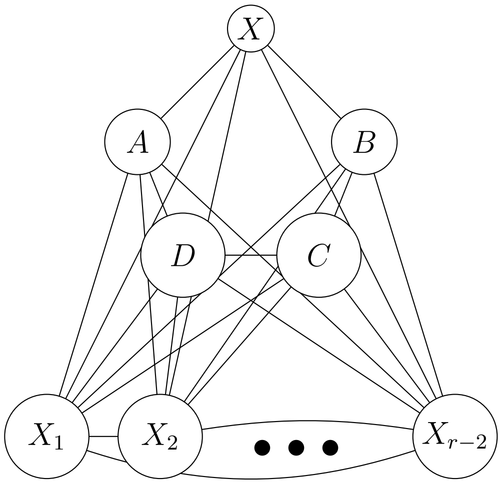

Figure 1: Graph G

and X are the two smallest class sizes, one cannot do better as observed in [6, Theorem 7]. Hence

$$D_r(G) \geq \frac{2r}{3\sqrt{3}}\alpha^{3/2}n^2.$$

Let us now count the number of edges of G. The number of edges incident to X is

$$\begin{aligned} e(X, X^c) &= \left(\frac{2r}{3}\alpha\right)\left(2\sqrt{\frac{\alpha}{3}}\right)n^2 + \left(\frac{2r}{3}\alpha\right)\left(\frac{1-\frac{2r}{3}\alpha}{r}(r-2)\right)n^2 \\ &= \left(\frac{2}{3}(r-2)\alpha + \frac{4r}{3\sqrt{3}}\alpha^{3/2} - \frac{4r(r-2)}{9}\alpha^2\right)n^2. \end{aligned}$$

Using that $|A| + |C| = |B| + |D| = |X_1|$, we have that the number of edges inside $A \cup B \cup C \cup D \cup X_1 \cup \cdots \cup X_{r-2}$ is

$$\begin{aligned} e(X^c) = |X_1|^2\binom{r}{2} - |A||B| &= \left(\frac{1-\frac{2r}{3}\alpha}{r}n\right)^2\binom{r}{2} - \frac{1}{3}\alpha n^2 \\ &= \frac{1}{r^2}\binom{r}{2}n^2 - \frac{4r}{3}\frac{1}{r^2}\alpha\binom{r}{2}n^2 + \frac{4}{9}\alpha^2\binom{r}{2}n^2 - \frac{1}{3}\alpha n^2 \\ &= \left(1-\frac{1}{r}\right)\frac{n^2}{2} - \frac{2}{3}(r-1)\alpha n^2 - \frac{1}{3}\alpha n^2 + \frac{4}{9}\alpha^2\binom{r}{2}n^2. \end{aligned}$$

Thus, the number of edges of G is

$$\begin{aligned} e(G) = e(X^c) + e(X, X^c) &= \left(1 - \frac{1}{r}\right)\frac{n^2}{2} - \alpha n^2 + \frac{4r}{3\sqrt{3}}\alpha^{3/2}n^2 - \frac{2r(r-3)}{9}\alpha^2 n^2 \\ &\geq \mathrm{ex}(n, K_{r+1}) - \alpha n^2 + \frac{4r}{3\sqrt{3}}\alpha^{3/2}n^2 - \frac{2r(r-3)}{9}\alpha^2 n^2, \end{aligned}$$

where we applied Turán's theorem in the last step. □

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