

Double Turán Problems



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1 Introduction

This thesis focuses on a variation of the *Turán problem* in extremal combinatorics. The fundamental question in extremal hypergraph theory is determining the maximum number of edges in an n -vertex r -uniform graph that does not contain a prescribed r -uniform graph F as a subgraph. These maxima, denoted $\text{ex}(n, F)$, are referred to as the *extremal numbers* or *Turán numbers* for F . One of the cornerstones of extremal graph theory, concerning the case F is a clique, is Turán's Theorem [19]. To state the theorem, we need the *Turán graphs* $T_k(n)$, which denotes a complete multipartite graph with n vertices and k parts of size $\lfloor n/k \rfloor$ or $\lceil n/k \rceil$.

Theorem A (Turán's Theorem). *The maximum number of edges in an n -vertex graph G containing no clique of order $r + 1$ is $e(T_r(n))$, with equality only if $G = T_r(n)$.*

Simonovits [5] observed via the Erdős-Stone Theorem [3] that the asymptotic value of $\text{ex}(n, F)$ may be obtained whenever F is non-bipartite:

Theorem B (Erdős-Stone Theorem, Simonovits' Theorem). *Let F be any graph of chromatic number $r + 1 \geq 3$. Then $\text{ex}(n, F) = (1 + o(1))T_r(n)$ as $n \rightarrow \infty$.*

There are a number of proofs of the Erdős-Stone Theorem. A very general framework involves *Szemerédi's Regularity Lemma*, which may be stated as follows. A pair (U, V) of disjoint sets of vertices in a graph G is called ϵ -regular if for any $X \subseteq U$ and $Y \subseteq V$ of size at least $\epsilon|U|$ and $\epsilon|V|$ respectively,

$$\left| \frac{e(X, Y)}{|X||Y|} - \frac{e(U, V)}{|U||V|} \right| < \epsilon.$$

The following was proved by Szemerédi [18]:

Theorem C (Szemerédi's Regularity Lemma). *For all $\epsilon > 0$, there exist m and M such that for every graph G , there exists a partition (V_1, V_2, \dots, V_k) of $V(G)$ such that $m \leq k \leq M$ and $|V_1| \leq |V_2| \leq \dots \leq |V_k| \leq |V_1| + 1$ and all but at most ϵk^2 pairs (V_i, V_j) are ϵ -regular.*

The value of $\text{ex}(n, F)$ for bipartite F is in general wide open, and the order of magnitude of $\text{ex}(n, K_{4,4})$ or $\text{ex}(n, C_8)$ is not known – see Füredi and Simonovits [8] for a history of the bipartite Turán problem. There is also no analog of the above theorems for r -uniform hypergraphs. The asymptotic value of $\text{ex}(n, K_k^r)$ is not known for any $k > r \geq 3$, where K_k^r denotes the complete r -uniform hypergraph on k vertices. The asymptotic value of $\text{ex}(n, K_4^3)$ was conjectured by Turán [19] to be $\frac{5}{9}\binom{n}{3}$, and this remains open despite decades of intensive research.

1.1 Problem Statement

In this thesis, we investigate closely related problems which we refer to as *double Turán problems*. To describe these problems, let G_1, G_2, \dots, G_m be graphs with the same vertex set $V(G_i) = [n]$ for $i \in [m]$.

Definition 1. For a graph F , we say that G_1, G_2, \dots, G_m is *double F -free* if $E(F) \not\subseteq E(G_i) \cap E(G_j)$ for $1 \leq i < j \leq m$. Moreover, we call a copy of F in $G_i \cap G_j$ a *double F in G_i, G_j* .

The double Turán problem asks for the maximum sum of edges over G_1, G_2, \dots, G_m such that G_1, G_2, \dots, G_m are double F -free.

Definition 2. For a graph F , the *double Turán number* for F , denoted $\phi(m, n, F)$, is the maximum value of $\sum_{i=1}^m e(G_i)$ such that G_1, G_2, \dots, G_m are double F -free.

We would also like to study a special case of the double Turán problem, which we refer to as *induced double Turán problem*.

Definition 3. We call G_1, G_2, \dots, G_m *induced* if for each $i \in [m]$, G_i is an induced subgraph of $\bigcup_{i=1}^m G_i$.

In other words, if $\{u, v\} \in E(G_i)$ and $u, v \in V(G_j)$, then $\{u, v\} \in E(G_j)$.

Definition 4. For a graph F , the *induced double Turán number*, denoted $\phi^*(m, n, F)$, is the maximum value of $\sum_{i=1}^m e(G_i)$ such that G_1, G_2, \dots, G_m are induced and double F -free.

The induced double Turán problem is then to determine $\phi^*(m, n, F)$. Clearly, $\phi(m, n, F) \geq \phi^*(m, n, F)$. Similar to the Turán problem, the induced and non-induced double Turán problems behave differently depending on whether F is bipartite or non-bipartite. Thus we will study these two cases separately in this thesis. We shall see that the study of $\phi(m, n, F)$ and $\phi^*(m, n, F)$ is motivated by certain hypergraph extremal problems.

1.2 Motivation : Link Graphs and Hypergraphs

Apart from the intrinsic interest in investigating $\phi(m, n, F)$, one motivation to study is that $\phi(m, n, F)$ is closely connected to pure hypergraph extremal problems via the notion of *link graphs*. Let H be a triple system, that is, a set of three-element subsets of a finite set $[n]$. We may view H as a 3-uniform hypergraph, where the edges are the three-element subsets of $[n]$.

Definition 5. For $i \in V(H)$, the link graph of i , denoted H_i , is the graph with $V(H_i) = V(H) \setminus \{i\}$ and $E(H_i) = \{\{j, k\} : \{i, j, k\} \in E(H)\}$.

A handy idea in extremal hypergraph theory is to reduce a hypergraph extremal problem to extremal problems for the link graphs. For instance, a triple system H does not contain a tetrahedron, i.e. four triples on four vertices, if and only if all its link graphs are triangle-free.

In the current context, given a graph F , let F^+ denote the triple system with $V(F^+) = V(F) \cup \{x, y\}$ and $E(F^+) = \{e \cup \{x\}, e \cup \{y\} : e \in E(F)\}$. For example, if F is a 4-cycle $K_{2,2}$, then F^+ is the hypergraph for octahedron. We can see that $\phi(n, n, F)$ and $\text{ex}(n, F^+)$ are intimately related: if H is an F^+ -free triple system with vertex set $[n]$, then the link graphs H_1, H_2, \dots, H_n are double F -free, otherwise there exists a double F in some $H_i \cap H_j$ and the vertices i, j along with that copy of F form a F^+ in H , contradiction. Thus, $\text{ex}(n, F^+) \leq \phi(n, n, F)$, and this relates the double Turán problem to hypergraph extremal problems.

On the other hand, the study of the induced double Turán problem is motivated by a special case of the *generalized Turán problem*, which asks for the maximum number $\text{ex}(n, \bar{F}, K_3)$ of triangles in a graph G with vertex set $[n]$ that does not contain some graph \bar{F} . This problem was studied by Alon and Shikhelman [1] and Kostochka, Mubayi and Verstraete [10, 12, 14]. Similar to how link graphs relate to hypergraph extremal problems, the generalized Turán problem is related to $\phi^*(n, n, F)$ as follows: Let \bar{F} be the graph consisting of all pairs contained in triples in F^+ . For example, if $F = K_{2,2}$ then $\bar{F} = K_{2,2,2}$. For $i \in [n]$, define $E(G_i) = \{\{j, k\} : \{i, j\}, \{j, k\}, \{i, k\} \in E(G)\}$. Then G_1, G_2, \dots, G_n are induced and double F -free, so $\phi^*(n, n, F) \geq \text{ex}(n, \bar{F}, K_3)$. This relates the induced double Turán problem to extremal problems for triangles in graphs.

1.3 Main Results : The Induced Case

The determination of $\phi^*(m, n, F)$ turns out to be fairly straightforward when F is a non-bipartite graph: the extremal objects are simply m copies of the same extremal graph for F .

Theorem 1. Let $r, m \geq 3$. There exists $n_0(r)$ such that if $n \geq n_0(r)$ and F is a graph of chromatic number r , then

$$\phi^*(m, n, F) = m \cdot \text{ex}(n, F).$$

Moreover, G_1, \dots, G_m are induced double F -free graphs on $[n]$ that sum up to $m \cdot \text{ex}(n, F)$ edges only if $G_1 = \dots = G_m$ are identical extremal n -vertex F -free graphs.

In the case $F = K_r$, we shall see the theorem is true for all $n \geq 3$:

Theorem 2. *Let $m, n, r \geq 3$. Then*

$$\phi^*(m, n, K_r) = m \cdot e(T_{r-1}(n)).$$

Moreover, G_1, \dots, G_m are induced double K_r -free graphs on $[n]$ that sum up to $m \cdot e(T_{r-1}(n))$ edges only if $G_1 = \dots = G_m = T_{r-1}(n)$.

In the case F is a bipartite graph, even determining the order of magnitude of $\phi^*(m, n, F)$ appears to be difficult. In fact, we do not even know the order of magnitude of $\phi^*(m, n, P)$ when P is a path with two edges. In this thesis, we propose the following very broad conjecture:

Conjecture A. *Let F be any non-empty graph and $m, n \geq 1$. Then*

$$\phi^*(m, n, F) = \Theta(m \cdot \text{ex}(n, F) + n^2).$$

It is clear that a single complete graph K_n does not contain a double F , and neither do identical copies G_1, G_2, \dots, G_m of an extremal n -vertex F -free graph. Thus we have the trivial lower bound

$$\phi^*(m, n, F) \geq \max \left\{ \binom{n}{2}, m \cdot \text{ex}(n, F) \right\}.$$

This conjecture is true when F is non-bipartite, by Theorem 1. If F is bipartite, then the upper bounds on $\phi^*(m, n, F)$ are more difficult to come by, especially when m is large. For instance, from our discussion in the previous section, we know

$$\text{ex}(n, K_{2,2,2}, K_3) \leq \phi^*(n, n, K_{2,2}),$$

and so Conjecture A implies that an n -vertex graph not containing the octahedron graph has $O(n^{5/2})$ triangles. In fact, it is also the case that $\text{ex}(2n, K_{2,2,2}, K_3) \geq \phi^*(n, n, K_{2,2})$: if we have double $K_{2,2}$ -free induced graphs G_1, G_2, \dots, G_n with vertex set $[n]$, then let H be the graph with $V(H) = [2n]$ consisting of all triangles with vertex set $\{i, j, k\}$ such that $n < k \leq 2n$ and $\{i, j\} \in E(G_k)$. The graph H is $K_{2,2,2}$ -free and $|E(H)| = \sum_{i=1}^{n/2} e(G_i)$. This shows that $\text{ex}(n, K_{2,2,2}, K_3)$ and $\phi^*(n, n, K_{2,2})$ are equivalent up to a constant factor. Similarly, we have

$$\text{ex}(n, K_{1,2,2}, K_3) \leq \phi^*(n, n, K_{1,2}),$$

and so Conjecture A implies that an n -vertex graph not containing the wheel graph has $O(n^2)$ triangles, which is conjectured by Mubayi and Verstraete [14]. The conjecture proposes

more generally that if F is a tree, then $\phi^*(n, n, F) = O(n^2)$. In fact, it is possible to prove the following theorem using the *removal lemma* as in [12] as well as a projective plane construction for $\phi(n, n, P)$:

Theorem 3. *Let P be a path with two edges. Then $\phi(n, n, P) = \Omega(n^{5/2})$, whereas $\phi^*(n, n, P) = o(n^{5/2})$, as $n \rightarrow \infty$. In particular,*

$$\lim_{n \rightarrow \infty} \frac{\phi^*(n, n, P)}{\phi(n, n, P)} = 0.$$

Apart from determining the order of magnitude of $\phi^*(m, n, F)$, this above theorem also shows that the order of magnitude of $\phi(n, n, P)$ and $\phi^*(n, n, P)$ can differ significantly. This suggests that the induced and non-induced double Turán problems may be fundamentally different.

A special bipartite case where Conjecture A is true is when F is a matching with two edges. Let M denote a matching with two edges, and let M^+ denote the graph obtained from two copies of K_4 sharing one edge by removing that edge. Then $\text{ex}(n, M^+, K_3) \leq \phi^*(n, n, M)$. If F is the triple system consisting of all four triangles in M^+ , then Füredi [7] showed $\text{ex}(n, M^+) = O(n^2)$, answering a conjecture of Erdős [4]. It is possible to adapt Füredi's proof to give $\phi^*(n, n, M) = O(n^2)$, so in this case Conjecture A is true and $\text{ex}(n, M^+, K_3) = \Theta(\phi^*(n, n, M))$. For improvements of the constant factor, see Mubayi and Verstraete [13] and Pikhurko and Verstraete [15]. We shall see that for some bipartite F , if m is not too large relative to n , then Conjecture A is also true.

1.4 Main Results : The Non-induced Case

Determining $\phi(m, n, F)$ even when F is a complete graph is challenging. The forth theorem we give is well-suited to the case of certain bipartite graphs, and is due to Wilson:

Theorem 4. *Let F be a graph. If there exists an extremal F -free n -vertex graph with maximum degree at most $n^{1/2}/m^2$, then*

$$\phi(m, n, F) = \binom{n}{2} + \binom{m}{2} \text{ex}(n, F).$$

By the Erdős-Stone Theorem, the extremal number for any non-bipartite F is $\Theta(n^2)$, which implies that the maximum degree of an extremal F -free graph exceeds $n^{1/2}$. Thus the condition on the maximum degree in the above theorem can only be satisfied for bipartite graphs, for instance, a path of two edges. An example of a bipartite graph that does not apply

to this theorem would be a matching of two edges, whose extremal graph has a maximum degree of $n - 1$.

Since $\binom{n}{2} + m - 1 \leq \phi^*(m, n, F) \leq \phi(m, n, F)$ for any graph F with at least two edges, Theorem 4 shows $\phi^*(m, n, F) = (1 + o(1))\binom{n}{2}$ whenever the conditions on m in the theorem are satisfied, proving Conjecture A to be true in this case.

Our first theorem on $\phi(m, n, F)$ for non-bipartite graphs F uses the notion of *supersaturation* – see Erdős and Simonovits [6]. We determine the asymptotic value of $\phi(m, n, F)$ as $m \rightarrow \infty$ when F is a non-bipartite graph:

Theorem 5. *Let $n \geq 1$ and let F be a non-bipartite graph. Then as $m \rightarrow \infty$,*

$$\phi(m, n, F) = (1 + o(1))m \cdot \text{ex}(n, F).$$

The next result we present concerns non-bipartite graphs. To state the theorem, we require the notion of the M -color Ramsey number.

Definition 6. *For $M \geq 2$, the M -color Ramsey number, denoted $R_M(r)$, is the smallest integer N such that any coloring of the edges of the complete graph K_N with M colors contains a monochromatic complete subgraph on r vertices.*

Suppose we have a monochromatic K_r -free coloring $c : E(K_N) \rightarrow 2^{[m]}$. For $i \in [m]$, let $H_i = \{\{u, w\} \in E(K_N) : i \in c(u, w)\}$. Then H_1, H_2, \dots, H_m are double K_r -free. If we replace the vertices of K_N with disjoint sets V_1, V_2, \dots, V_N whose sizes add up to n , and then let

$$G_i = \{\{x, y\} : (x, y) \in V_u \times V_w, i \in c(u, w), 1 \leq u < w \leq N\}$$

and make each V_i cliques in G_1 , then G_1, G_2, \dots, G_m is also double K_r -free. We call G_1, G_2, \dots, G_m an (m, n, N) -blowup.

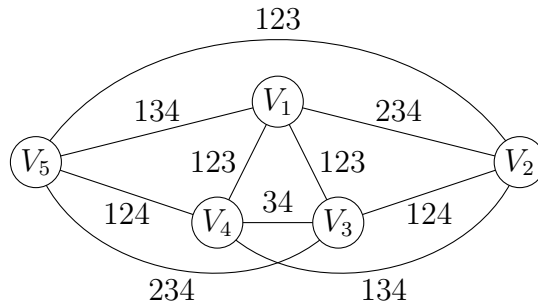


Figure 1: Example of an $(4, n, 5)$ -blowup not containing a double K_3 .

Definition 7. Let $f(m, n, r)$ denote the maximum of $e(G_1) + e(G_2) + \cdots + e(G_m)$ such that G_1, G_2, \dots, G_m is a double K_r -free (m, n, N) -blowup for some $N < R_{\binom{m}{2}}(r)$.

This turns out to be exactly the construction which determines $\phi(m, n, F)$ when F is a complete graph:

Theorem 6. For $m, n, r \geq 3$,

$$\phi(m, n, K_r) = f(m, n, r).$$

While computing $f(m, n, r)$ is a finite calculation, the Ramsey number $R_{\binom{m}{2}}(r)$ unfortunately appears to be intractable in general. It is known that $R_2(3) = 6$ and $R_3(3) = 17$ and $R_2(4) = 18$, but no further multicolor Ramsey numbers are known [2, 11]. In the special case $r = m = 3$, the following holds:

Theorem 7. For $n \geq 1$,

$$\phi(3, n, K_3) = \binom{n}{2} + \left\lfloor \frac{n^2}{2} \right\rfloor.$$

The same problem immediately becomes difficult when m is increased by 1. The blowup construction in Figure 1 shows $\phi(4, n, K_3) - [\binom{n}{2} + 3\text{ex}(n, K_3)] \geq n^2/100$ as $n \rightarrow \infty$. This suggests the actual values of $\phi(m, n, K_r)$ can be significantly larger than our trivial lower bound. We leave it as an open problem to determine $\phi(m, n, K_r)$ for $r, m \geq 3$ and $(r, m) \neq (3, 3)$.

1.5 Definitions and Notations

Denote the set of first n positive integers as $[n] = \{1, 2, \dots, n\}$. Given a set X , we denote 2^X as the power set of X . Let $G = (V, E)$ be a graph. Let $V(G)$ denote the vertex set and $E(G)$ denote the edge set of G . Let $e(G) = |E(G)|$ be the number of edges in G . For vertex $v \in V(G)$, we denote by $N_G(v) = \{u \in V(G) : \{u, v\} \in E(G)\}$ the neighborhood of v . Given two graphs G_1, G_2 , we denote $G_1 \cup G_2$ as the graph on $V(G_1) \cup V(G_2)$ with edge set $E(G_1 \cup G_2) = E(G_1) \cup E(G_2)$. Similarly, we define $G_1 \cap G_2$ as the graph on $V(G_1) \cap V(G_2)$ with edge set $E(G_1 \cap G_2) = E(G_1) \cap E(G_2)$. In this thesis, we reserve n to denote the number of vertices in a graph. We call a n -vertex complete graph K_n , and a complete bipartite graph $K_{a,b}$, where a, b are the sizes of its parts. Given graph G, H , define $G + H$ as the graph fully connecting G, H , i.e. $V(G + H) = V(G) \cup V(H)$ and $E(G + H) = E(G) \cup E(H) \cup \{\{u, v\} : u \in V(G), v \in V(H)\}$. Given graphs G and F , we say that G is F -free if G does not contain F as a subgraph. We denote $\text{ex}(n, F)$ to be the

maximum possible number of edges an F -free graph on n vertices, and we call a F -free graph achieving this maximum an extremal graph for F . Let v be a vertex from G_1, G_2, \dots, G_m . Unless otherwise specified, we denote $d(v)$ as the sum of the degree of v over all G_i .

2 The Induced Double Turán Problem

We prove the theorems for $\phi^*(m, n, F)$ in this chapter. In particular, the main theorem we prove is Theorem 1 for general non-bipartite graphs F and in the special case of cliques. We will first introduce two observations that simplify the problem.

The first observation is that the determination of $\phi^*(m, n, F)$ can be reduced to smaller values of m :

Lemma 8. *Let $n, m, k \geq 2$ with $m \geq k$, and let F be some graph. Then*

$$\phi^*(m, n, F) \leq \frac{m}{k} \cdot \phi^*(k, n, F).$$

Moreover, let G_1, \dots, G_m be induced double F -free graphs on $[n]$ and suppose $\sum_{i=1}^k e(G_i) = \phi^(k, n, F)$ only if $G_1 = \dots = G_k$. Then $\sum_{i=1}^m e(G_i) = \phi^*(m, n, F)$ only if $G_1 = \dots = G_m$.*

Proof. Let G_1, \dots, G_m be induced double F -free graphs on $[n]$. Put $G_{i+m} = G_i$ for all $i \in [m]$. Then

$$\sum_{i=1}^m e(G_i) = \frac{1}{k} \sum_{i=1}^m [e(G_i) + \dots + e(G_{i+k-1})] \leq \frac{1}{k} \sum_{i=1}^m \phi^*(k, n, F) = \frac{m}{k} \cdot \phi^*(k, n, F),$$

which establishes the upper bound. The lower bound follows from the construction with $G_1 = \dots = G_m$ to be n -vertex extremal graphs for F .

Now suppose $\sum_{i=1}^m e(G_i) = (m/k)\phi^*(k, n, F)$ and $G_1 \neq G_2$. By assumption $\sum_{i=1}^k e(G_i) < \phi^*(k, n, F)$. But then $\sum_{i=1}^k e(G_{i+j}) > \phi^*(k, n, F)$ for some $j \geq 1$, contradiction. \square

The second observation shows that the determination of $\phi^*(2, n, F)$ can be reduced to an optimization problem over the number of vertices in the intersection of the two graphs:

Lemma 9. *Let $n \geq 1$. For graph F , define $\mathcal{C}(n, t, F) := \binom{n-t}{2} + (n-t)t + 2\text{ex}(t, F)$. Let G_1, G_2 be induced double F -free graphs on $[n]$. Then*

$$e(G_1) + e(G_2) \leq \max_{0 \leq t \leq n} \mathcal{C}(n, t, F),$$

with equality only if G_2 is an extremal graph for F with t_{\max} vertices and $G_1 = G_2 + K_{n-t}$, where t_{\max} is a maximizer of $\mathcal{C}(n, t, F)$ over $0 \leq t \leq n$.

Proof. Let G_1, G_2 be induced double F -free graphs on $[n]$. Put $T = V(G_1) \cap V(G_2)$, $t = |T|$, $s = |V(G_1) \setminus T|$, and $n - t - s = |V(G_2) \setminus T|$. Note that $t, s \in \mathbb{Z}_{\geq 0}$. Since G_1, G_2 are induced

subgraphs of $G_1 \cup G_2$, we have $G_1[T] = G_2[T] = G_1 \cap G_2$. But then $G_1 \cap G_2$ is F -free, so $e(G_1[T]) = e(G_2[T]) \leq \text{ex}(t, F)$. Notice there can be at most $t(n-t)$ edges between T and $(V(G_1) \cup V(G_2)) \setminus T$. Since $G[V(G_1) \setminus T] \leq \binom{s}{2}$ and $G[V(G_2) \setminus T] \leq \binom{n-t-s}{2}$,

$$e(G_1) + e(G_2) \leq \binom{s}{2} + \binom{n-s-t}{2} + t(n-t) + 2\text{ex}(t, F).$$

But then $\binom{n-t}{2} > \binom{s}{2} + \binom{n-t-s}{2}$ for $0 < s < n-t$, so

$$e(G_1) + e(G_2) \leq \binom{n-t}{2} + (n-t)t + 2\text{ex}(t, F) = \mathcal{C}(n, t, F).$$

This establishes the upper bound. From this we also know that $e(G_1) + e(G_2) = \mathcal{C}(n, t, F)$ only if G_2 is the t -vertex extremal graph for F and $G_1 = G_2 + K_{n-t}$. The result now follows. \square

2.1 Proof of Theorem 2

By Lemma 8, it suffices to prove the theorem for $m = 3$. Let G_1, G_2, G_3 be induced double K_r -free graphs, such that $e(G_1) + e(G_2) + e(G_3) = \phi^*(3, n, K_r)$. We may assume $e(G_1) \geq e(G_2) \geq e(G_3)$, and we already know $\phi^*(3, n, K_r) \geq 3\text{ex}(n, K_r)$. Consequently, we must have $e(G_1) + e(G_2) \geq 2\text{ex}(n, K_r)$. Since G_1, G_2, G_3 are induced and $e(G_1) + e(G_2) + e(G_3) \geq 3\text{ex}(n, K_r)$, it suffices to show that $G_1 = G_2 = T_{r-1}(n)$. In particular, we will use Lemma 9 to show that G_1, G_2 is an extremal configuration without containing a double K_r .

Let $t = |V(G_1 \cap G_2)|$. By Turán's Theorem,

$$\text{ex}(t, K_r) - \text{ex}(t-1, K_r) = e(T_{r-1}(t)) - e(T_{r-1}(t-1)) = t - \left\lceil \frac{t}{r-1} \right\rceil.$$

It immediately follows that

$$\mathcal{C}(n, t, K_r) - \mathcal{C}(n, t-1, K_r) = -t + 1 + 2[\text{ex}(t, K_r) - \text{ex}(t-1, K_r)] = t + 1 - 2 \left\lceil \frac{t}{r-1} \right\rceil. \quad (1)$$

For $r \geq 4$, $\mathcal{C}(n, t, K_r)$ is strictly increasing on t , so by Lemma 9,

$$\phi^*(2, n, K_r) = \mathcal{C}(n, n, K_r) = 2\text{ex}(n, K_r) = e(G_1) + e(G_2)$$

and $G_1 = G_2 = T_{r-1}(n)$, as desired.

Now suppose $r = 3$. Equation (1) shows that $\mathcal{C}(n, t, K_r)$ is non-decreasing on t and

$\mathcal{C}(n, t, K_r) > \mathcal{C}(n, t, K_r)$ for even t . By Lemma 9, we now have

$$\phi^*(2, n, K_r) = \max[\mathcal{C}(n, n, K_r), \mathcal{C}(n, n-1, K_r)] = 2\text{ex}(n, K_r) = e(G_1) + e(G_2),$$

and either $G_1 = G_2 = T_{r-1}(n)$, or $G_2 = T_{r-1}(n-1)$ and $G_1 = G_2 + K_1$. If the latter case is true, then $e(G_3) \geq \text{ex}(n, F) > e(G_2)$, and this contradiction completes the proof. \square

2.2 Proof of Theorem 1

If F is a graph of chromatic number $r+1 \geq 3$, then Theorem B shows $\text{ex}(n, F) = (1 + o(1))\text{ex}(n, K_{r+1})$ as $n \rightarrow \infty$. In this section, we prove Theorem 1 following the same line of reasoning as in the proof of Theorem 2.

Proof of Theorem 1. By Lemma 8, it suffices to prove the theorem for $m = 3$. Let G_1, G_2, G_3 be induced double F -free graphs, such that $e(G_1) + e(G_2) + e(G_3) = \phi^*(3, n, F)$. We may assume $e(G_1) \geq e(G_2) \geq e(G_3)$, and we already know $\phi^*(3, n, F) \geq 3\text{ex}(n, F)$. Consequently, we must have $e(G_1) + e(G_2) \geq 2\text{ex}(n, F)$. Since G_1, G_2, G_3 are induced and $e(G_1) + e(G_2) + e(G_3) \geq 3\text{ex}(n, F)$, it suffices to show that $G_1 = G_2$ are n -vertex F -free extremal graphs. In particular, we will use Lemma 9 to show that G_1, G_2 is an extremal configuration without containing a double F .

Let $t = |V(G_1 \cap G_2)|$. If $t < \sqrt{n}$, then

$$2\text{ex}(n, F) \geq 2e(T_{r-1}(n)) \geq 2 \left\lfloor \frac{n^2}{4} \right\rfloor \geq \binom{n}{2} + \binom{\sqrt{n}}{2} > \mathcal{C}(n, t, F).$$

Thus $t \geq \sqrt{n}$. But then for large enough t , any extremal t -vertex F -free graph contains a spanning complete $(r-1)$ -partite subgraph $T_{r-1}(t)$, so we may add $\text{ex}(t-1, F) - e(T_{r-1}(t-1))$ edges to $T_{r-1}(t)$ and still avoid F as a subgraph. Hence for large enough t , we have $\text{ex}(t, F) \geq \text{ex}(t-1, F) - e(T_{r-1}(t-1)) + e(T_{r-1}(t))$, and so

$$\text{ex}(t, F) - \text{ex}(t-1, F) \geq e(T_{r-1}(t)) - e(T_{r-1}(t-1)) \geq t - \left\lceil \frac{t}{r-1} \right\rceil.$$

It immediately follows that

$$\mathcal{C}(n, t, F) - \mathcal{C}(n, t-1, F) = -t + 1 + 2[\text{ex}(t, F) - \text{ex}(t-1, F)] \geq t + 1 - 2 \left\lceil \frac{t}{r-1} \right\rceil. \quad (2)$$

For $r \geq 4$, $\mathcal{C}(n, t, F)$ is strictly increasing on t , so by Lemma 9,

$$\phi^*(2, n, F) = \mathcal{C}(n, n, F) = 2\text{ex}(n, F) = e(G_1) + e(G_2),$$

and $G_1 = G_2$ are n -vertex F -free extremal graphs, as desired.

Now suppose $r = 3$. Equation (2) shows that $\mathcal{C}(n, t, F)$ is strictly increasing for even t and $\mathcal{C}(n, t, F) \geq \mathcal{C}(n, t-1, F)$ for odd t . By Lemma 9, we now have

$$\phi^*(2, n, F) = \max[\mathcal{C}(n, n, F), \mathcal{C}(n, n-1, F)] = 2\text{ex}(n, F) = e(G_1) + e(G_2),$$

and either $G_1 = G_2$ are n -vertex extremal F -free graphs, or G_2 is an $(n-1)$ -vertex extremal F -free graph and $G_1 = G_2 + K_1$. If the latter case is true, then $e(G_3) \geq \text{ex}(n, F) > e(G_2)$, and this contradiction completes the proof. \square

2.3 Proof of Theorem 3

We need to show that $\phi(n, n, P) = \Omega(n^{5/2})$ and $\phi^*(n, n, P) = o(n^{5/2})$, as $n \rightarrow \infty$.

Claim 1. For $\sqrt{n} < m \leq n$,

$$\phi(n, n, P) = (1/2 + o(1))mn^{3/2},$$

as $n \rightarrow \infty$.

We first show that $\phi(m, n, P) \leq (mn^{3/2} + n^2)/2$. For each vertex $u \in [n]$, define H_u as the $m \times n$ bipartite graph with edge set $E(H_u) := \{\{v, i\} : \{u, v\} \in E(G_i)\}$. If H_u contains a quadrilateral $\{v, i\}, \{v, j\}, \{w, i\}, \{w, j\}$, then $\{u, v\}, \{u, w\}$ form a double P in $G_i \cap G_j$, contradiction. Thus we conclude that H_u is quadrilateral-free, and therefore $e(H_u) \leq m\sqrt{n} + n$, by the Kővari-Sós-Turán Theorem [9]. It now follows that

$$\sum_{i=1}^m e(G_i) = \frac{1}{2} \sum_{u \in V(G)} e(H_u) \leq \frac{1}{2}(mn^{3/2} + n^2).$$

We now show the upperbound is tight asymptotically by giving a finite projective plane construction. Suppose G_1, G_2, \dots, G_n are graphs on $[n]$ containing no double P and $\sum_{i=1}^n e(G_i) \geq (1/2 + o(1))n^{5/2}$, with $e(G_1) \geq e(G_2) \geq \dots \geq e(G_n)$. Then G_1, G_2, \dots, G_m are graphs with no double P and $\sum_{i=1}^m e(G_i) \geq (1/2 + o(1))mn^{3/2}$. Hence, it suffices to prove the case for $m = n$.

Consider a finite projective plane with n points and n lines, with prime q chosen so that $n = (1 + o(1))(q^2 + q + 1)$ as $q \rightarrow \infty$. Let $S_1, \dots, S_n \subseteq [n]$ be the n lines of the projective plane. Note that each line S_i contains $q + 1$ points, and the intersection of any two distinct lines S_i, S_j contains $|S_i \cap S_j| = 1$ point.

Define G_1, \dots, G_n to be graphs on $[n]$, each with edge set

$$E(G_i) := \{\{j, k\} \subseteq [n] : j \neq k, j + k \in S_i \pmod n\}.$$

Note that the intersection of distinct G_i, G_j is P free: since $|S_i \cap S_j| = 1$, if $\{a, b\}, \{a, c\} \in E(G_i) \cap E(G_j)$, then $a + b = a + c$ so $b = c$.

We now count the number of edges in G_1, \dots, G_n . Since $|S_i| = q + 1$, for each point $j \in [n]$, there are $q + 1$ choices for $k \in [n]$ such that $j + k \in S_i$. But then we have to avoid counting the same edge twice and loops, so the number of edges in G_i is

$$e(G_i) = \frac{n(q + 1) - \#\text{loops counted for } G_i}{2}.$$

If $j \in [n]$ is even, then $k = j/2$ is the unique number in $[n]$ such that $k + k = j \pmod n$. If $j \in [n]$ is odd, then $k = (n + j)/2$ is the unique number in $[n]$ such that $k + k = j \pmod n$, as n is even. Hence, for each $j \in S_i$, there exists a unique $k \in [n]$ such that $k + k = j \pmod n$, and thus

$$\#\text{loops counted for } G_i = |S_i| = q + 1.$$

Since $q + 1 = (1 + o(1))n^{1/2}$, the number of edges in G_1, \dots, G_n is

$$\sum_{i=1}^n e(G_i) = n \cdot \frac{n(q + 1) - (q + 1)}{2} = \left(\frac{1}{2} + o(1)\right) n^{5/2},$$

as $n \rightarrow \infty$. This proves the first claim.

Claim 2. $\phi^*(n, n, P) = o(n^{5/2})$, as $n \rightarrow \infty$.

Let G_1, G_2, \dots, G_n be induced and double P -free and let $\epsilon > 0$. Let $d_i(v)$ be the degree of vertex v in the graph G_i . Let I be the set of pairs (i, v) such that $d_i(v) \geq \sqrt{n}/\epsilon + 1$. Since G_1, G_2, \dots, G_n do not contain a double P ,

$$\sum_{(i,v) \in I} \binom{d_i(v)}{2} \leq n^3.$$

The maximum possible value of $\sum_{(i,v) \in I} d_i(v)$ subject to this constraint is when $d_i(v) =$

$\sqrt{n}/\epsilon + 1$ for all (i, v) , in which case $|I| \leq 2\epsilon^2 n^2$ and so

$$\sum_{(i,v) \in I} d_i(v) \leq (2\epsilon^2 n^2) \cdot \left(\frac{\sqrt{n}}{\epsilon} + 1 \right) = 3\epsilon n^{5/2}$$

for large enough n . Remove all edges of G_i on vertex v such that $(i, v) \in I$. The total number of edges removed is at most $3\epsilon n^{5/2}$. Let G'_1, G'_2, \dots, G'_n be the remaining subgraphs of G_1, G_2, \dots, G_n . If $e(G'_i) \leq \epsilon n^{3/2}$, then remove all edges of G'_i . The number of edges removed in this process is at most $\epsilon n^{5/2}$. The remaining graphs $G''_1, G''_2, \dots, G''_m$ have each at least $\epsilon n^{3/2}$ edges and maximum degree at most \sqrt{n}/ϵ . In particular, each G''_i contains a matching M_i of size at least $e(G''_i)/2\Delta(G''_i) = \epsilon^2 n/2$. If $m \leq \epsilon n$, then

$$\sum_{i=1}^n e(G_i) \leq 4\epsilon n^{5/2} + \sum_{i=1}^m e(G''_i) \leq 4\epsilon n^{5/2} + \phi(m, n, P) \leq 5\epsilon n^{5/2}$$

by Claim 1. If $m > \epsilon n$, then we apply Szemerédi's Regularity Lemma to find, for some $\delta > 0$ depending only on ϵ , a matching M_1 in G''_1 such that for some pair of set $X, Y \subseteq V(M_1)$ of size at least δn each, there is a set E of at least $\delta^3 n^2$ edges $\{x, y\}$ of $G''_1 \cup G''_2 \cup \dots \cup G''_m$ such that $x \in X$ and $y \in Y$. Since G''_1 is induced, $E \subseteq E(G_1)$. In particular, there are at least $\delta^5 n^3/4$ copies of P in G_1 . We can repeat the argument in the remaining graphs $G''_i : i \in [2, m]$ to get say M_2 in G''_2 as above, which gives $\delta^5 n^3/4$ copies of P in G_2 . If we do this $4\delta^{-5}$ times, then we have found n^3 copies of P in the first $4\delta^{-5}$ graphs, and two of them have the same edge-set. We conclude $\sum_{i=1}^n e(G_i) \leq 5\epsilon n^{5/2}$ if n is large enough. Since ϵ is arbitrary, this completes the proof. \square

3 The Non-induced Double Turán Problem

In this section, we prove our main theorems on $\phi(m, n, F)$.

3.1 Proof of Theorem 4

We first show that for all $m, n \geq 1$ and graph F ,

$$\phi(m, n, F) \leq \binom{n}{2} + \text{ex}(n, F) \binom{m}{2}.$$

Thereafter, we show that if there is an extremal F -free graph with maximum degree at most $n^{1/2}/m^2$, then the above bound is tight.

Proof of the upper bound. For $S \subseteq [m]$, let E_S denote the set of edges that are contained in exactly $\{G_i\}_{i \in S}$, and note that $E_S \cap E_{S'} = \emptyset$ if $S \neq S'$. Then

$$\sum_{i=1}^m e(G_i) = \sum_{S \subseteq [m]} |S| |E_S| \leq \binom{n}{2} + \sum_{S \subseteq [m], |S| \geq 2} (|S| - 1) |E_S|.$$

Note that $\bigsqcup_{T \supseteq S} E_T$ is the edge set of the intersection of the graphs G_i with $i \in S$, and so for $|S| \geq 2$,

$$\sum_{T \supseteq S} |E_T| \leq \text{ex}(n, F).$$

Hence,

$$\sum_{\substack{S \subseteq [m] \\ |S| \geq 2}} (|S| - 1) |E_S| = \sum_{\substack{S \subseteq [m] \\ |S| = 2}} \sum_{T \supseteq S} \frac{(|T| - 1) |E_T|}{\binom{|T|}{2}} \leq \sum_{\substack{S \subseteq [m] \\ |S| = 2}} \sum_{T \supseteq S} |E_T| \leq \binom{m}{2} \text{ex}(n, F),$$

as each $T \in [m]$ with $|T| \geq 2$ is counted $\binom{|T|}{2}$ times in total and $|T| - 1 \leq \binom{|T|}{2}$. This proves the upper bound.

Proof of the lower bound. We need to show there exists a construction such that the graph with edge set E_S is an extremal F -free graph, for all $S \subseteq [m]$ of size 2. Let $M = \binom{m}{2}$ and H_1, \dots, H_M be copies of an extremal F -free graph on n vertices such that H_i with maximum degree $\Delta \leq n^{1/2}/m^2$ for all $i \in [M]$. It suffices to show that we can embed each H_i onto $[n]$ such that their edge sets are pairwise disjoint. We begin by an arbitrary embedding of each H_i and iteratively decrease the number of intersecting edges. Define a (u, v, i) -swap by swapping the embedding of vertex u and v of H_i , i.e. replacing each edge $\{u, w\} \in E(H_i)$

with the edge $\{u, w\}$ and each edge $\{v, w\} \in E(H_i)$ with the edge $\{v, w\}$. This preserves the type of isomorphism of H_i . Given a vertex v , let $N(v) = N_{H_1}(v) \cup \dots \cup N_{H_M}(v)$. Suppose there exists an intersecting edge $\{u, w\} \in E(H_i) \cap E(H_j)$. Since $|N(u)| \leq M \cdot \Delta \leq n^{1/2}/2$, $|N(u) \cup N(N(u))| \leq \Delta + \Delta(\Delta - 1) \leq n/4$, so there exists a vertex $v \notin N(u) \cup N(N(u))$. Since $N(u) \cap N(v) = \emptyset$, performing a (u, v, i) -swap reduces the number of intersecting edges. The result now follows from iterating this process. \square

3.2 Proof of Theorem 5

We need the following *saturation theorem*, which may be found in [6].

Proposition 10. *Let F be any non-empty graph with k vertices. For all $\epsilon > 0$, there exists $\delta > 0$ such that if G is any n -vertex graph with $\text{ex}(n, F) + \epsilon n^2$ edges, then G contains δn^k copies of F .*

Proof of Theorem 5. Let $k = |V(F)|$ and let $\epsilon > 0$. Let G_1, G_2, \dots, G_m be double F -free. Reorder G_1, G_2, \dots, G_m so that $e(G_i) \geq \text{ex}(n, F) + \epsilon n^2$ for $1 \leq i \leq \ell$ and $e(G_i) < \text{ex}(n, F) + \epsilon n^2$ for $\ell < i \leq m$. Then each $G_i : 1 \leq i \leq \ell$ contains at least δn^k copies of F , by Proposition 10. On the other hand, there are at most n^k copies of F such that $F \subseteq G_i$ for some $i \in [m]$. Therefore $\ell \leq 1/\delta$ and

$$\begin{aligned} \sum_{i=1}^m e(G_i) &= \sum_{i=1}^{\ell} e(G_i) + \sum_{i=\ell+1}^m e(G_i) \\ &\leq \frac{1}{\delta} \binom{n}{2} + (m - \ell) \text{ex}(n, F) + (m - \ell) \epsilon n^2 \\ &\leq m \cdot \text{ex}(n, F) + \epsilon m n^2 + \frac{1}{\delta} \binom{n}{2}. \end{aligned}$$

Since F is not bipartite, $\text{ex}(n, F) = \Theta(n^2)$ and so $\phi(m, n, F) \leq m \cdot \text{ex}(n, F) + (\epsilon + 1/\delta m) m n^2$. Since ϵ was arbitrary and δ is a constant depending only on ϵ , we conclude $\phi(m, n, F) \leq (1 + o(1)) m \cdot \text{ex}(n, F)$ as $m \rightarrow \infty$. \square

Let F be a bipartite graph with $k \geq 2$ vertices and $j \geq 1$ edges. A strong version of a conjecture of Simonovits [16, 17] would suggest that for all $\epsilon > 0$, there exists $\delta > 0$ such that every n -vertex graph G with at least $p\binom{n}{2}(1 + \epsilon)\text{ex}(n, F)$ edges contains at least $\delta p^j n^k$ copies of F . For instance, this is known to be true whenever the asymptotic behavior of $\text{ex}(n, F)$ is known, which includes the case $F = K_{2,t}$. If F is bipartite and $m \cdot \text{ex}(n, F)/n^2 \rightarrow \infty$ as $m, n \rightarrow \infty$, then this conjecture with the same proof as above shows $\phi(m, n, F) = (1 + o(1)) m \cdot \text{ex}(n, F)$. When F contains a cycle, then there exists $\alpha > 0$ such that $\text{ex}(n, F) \geq n^{1+\alpha}$ for

large enough n . Thus, we conclude that if F contains a cycle and the Simonovits conjecture is true for F , then $\phi(m, n, F) = (1 + o(1))m \cdot \text{ex}(n, F)$ for $m \geq n$ and $n \rightarrow \infty$. In particular, this shows $\phi(m, n, K_{2,t}) = (1 + o(1))m \cdot \text{ex}(n, F)$ for $m \geq n$ as $n \rightarrow \infty$.

3.3 Proof of Theorem 6

We now prove Theorem 6. Notice that we trivially have $f(m, n, r) \leq \phi(m, n, K_r)$, so it suffices to show the reverse inequality. That is, we need to show that there exists a blowup construction meeting the desired bound.

Let G_1, G_2, \dots, G_m be graphs on $[n]$ with no double K_r and $\sum_{i=1}^m e(G_i) = \phi(m, n, K_r)$. Observe that any pair $\{i, j\} \subseteq [n]$ must be in some G_i , otherwise, we may add it to G_1 without creating a double K_r .

We call vertices v, v' *clones* if for all $u \in [n] \setminus \{v, v'\}$ and $i \in [m]$, the edge $\{u, v\} \in E(G_i)$ if and only if $\{u, v'\} \in E(G_i)$. Furthermore, we call $\{v, v'\}$ a *light edge* if $\{v, v'\}$ is in exactly one graph G_i .

We now apply Algorithm 1 to G_1, G_2, \dots, G_m .

Algorithm 1 symmetrization algorithm

```

while  $\exists$  a light edge whose endpoints are not clones do
  among all vertices incident to such an edge, select a vertex  $v$  with maximum degree
   $B_v \leftarrow$  collection of vertices sending a light edge to  $v$  that are not clones of  $v$ 
  while  $B_v \neq \emptyset$  do
    pick  $u \in B_v$ 
     $j \leftarrow$  colour of the light edge from  $u$  to  $v$ 
    for  $1 \leq i \leq m$  do
      if  $i \neq j$  then;
         $N_{G_i}(u) \leftarrow N_{G_i}(v)$ 
      else if  $i = j$  then
         $N_{G_i}(u) \leftarrow (N_{G_i}(v) \setminus \{u\}) \cup \{v\}$ 
      end if
    end for
  end while
end while

```

Claim 3. *Algorithm 1 terminates.*

Notice that at the end of the ‘while $B_v \neq \emptyset$ ’ loop, every vertex sending a light edge to v is a clone of v . This implies v along with the set L_v of vertices receiving light edges from v induce a clique of size at least two in some G_i , and an empty graph in every other graph G_j

with $j \neq i$. Moreover, any vertex $w \notin L_v$ sends edges to either all or none of the vertices in L_v , and if w is incident to L_v , then w sends edges to L_v in at least two graphs. It now follows that no light edge incident with a vertex in L_v will be picked again in an iteration of the out most while loop. Thus the algorithm can run through at most $n/2$ such iterations, and so it terminates.

Claim 4. *The resulting graphs G'_1, G'_2, \dots, G'_m do not contain a double K_r and $\sum_{i=1}^m e(G'_i) = \phi(m, n, K_r)$.*

Note that we replace u by a clone of v in the for loop of Algorithm 1. Since $\{u, v\}$ remains a light edge in this step, u and v cannot both belong to a double K_r in the modified graphs. Furthermore, any double K_r containing u after the for loop arises from a double K_r containing v prior to the for loop. But then G_1, G_2, \dots, G_m contained no double K_r to begin with, so G'_1, G'_2, \dots, G'_m do not contain a double K_r .

We now show that the algorithm does not reduce the number of edges. By our choice of v , we know $d(v) \geq d(u)$ for all $u \in B_v$ prior to the for loop. Hence, replacing u with a clone of v does not decrease the number of edge over a complete iteration of the inner while loop. Therefore, $\sum_{i=1}^m e(G'_i) = \phi(m, n, K_r)$. The proof of the claim is now complete.

Hence, the algorithm results in graphs G'_1, G'_2, \dots, G'_m with $\phi(m, n, K_r)$ edges and the additional property that light edges come in ‘clone cliques.’ We may thus partition the vertex set $[n]$ into k disjoint sets V_1, V_2, \dots, V_k , such that each V_i induces a clique of light edges from the same graph. Moreover, for distinct $i, j \in [k]$, define S_{ij} to be the set of all edges between V_i and V_j , and note that any edge in S_{ij} appears in at least two modified graphs. The sets S_{ij} now yield a k -blowup. Notice that if the pattern of the k -blowup contains a double K_r , then the original graphs G_1, G_2, \dots, G_m must have contained a double K_r as well, contradiction. Thus the k -blowup is double K_r -free.

It remains to show that $k < R_M(K_r)$. For each edge $\{i, j\} \subseteq [k]$ in the pattern of the k -blowup, we assign an arbitrary distinct pair $\{a, b\} \subseteq L_{ij} \subseteq [m]$ to $\{i, j\}$. If $k \geq R_M(K_r)$, then there exists K_r in the pattern of the k -blowup colored by some distinct pair $\{a, b\} \subseteq [m]$. But then this implies the pattern of the k -blowup contains a double K_r , contradiction. This completes the proof. \square

3.4 Proof of Theorem 7

It is not hard to see that $\phi(2, n, K_3) = \binom{n}{2} + \lfloor n^2/4 \rfloor$: if G_1, G_2 is double triangle-free, then we have

$$e(G_1) + e(G_2) \leq \binom{n}{2} + e(G_1 \cap G_2) \leq \binom{n}{2} + \text{ex}(n, K_3)$$

and so $\phi(2, n, K_3) \leq \binom{n}{2} + \lfloor n^2/4 \rfloor$. Taking $G_1 = K_n$ and $G_2 = K_{\lfloor n/2 \rfloor, \lceil n/2 \rceil}$ meets this bounds. The main result of this section is to show for all $n \geq 1$,

$$\phi(3, n, K_3) = \binom{n}{2} + \left\lfloor \frac{n^2}{2} \right\rfloor.$$

Let G_1, G_2, G_3 be double triangle-free. Define $H_k \subseteq G$ to be the graph with edges contained in at least k of the G_i 's and note that $e(G_1) + e(G_2) + e(G_3) = e(H_1) + e(H_2) + e(H_3)$. Thus it suffices to show that $e(H_2) + e(H_3) \leq n^2/2$. Notice H_2 must not contain any triangles with two edges in H_3 , so

$$e(H_2) + e(H_3) \leq \binom{n}{2} + e(H_3) - |\{\{u, v\} : u \neq v, N_{H_3}(u) \cap N_{H_3}(v) \neq \emptyset\}|.$$

Let H'_3 be the graph with the same vertex set as H_3 and edge set $\{\{u, v\} : u \neq v, N_{H_3}(u) \cap N_{H_3}(v) \neq \emptyset\}$. It suffices to show that $n/2 \geq e(H_3) - e(H'_3)$.

Let $d_1 \geq d_2 \geq \dots \geq d_n$ and $f_1 \geq f_2 \geq \dots \geq f_n$ each be the degree sequence of H_3 and H'_3 , respectively. We show that $f_i \geq d_i - 1$ for all i . Let v_i denote the vertex in H with degree d_i and u_i be the vertex in H with degree f_i . Let $S_i = |N_{H_3}(v_1) \cup \dots \cup N_{H_3}(v_i)|$. Since

$$\sum_{u \in S_i} d_{H_3}(u) \geq d_1 + \dots + d_i,$$

we have that $|S_i| \geq i$. But then $S_i \setminus \{u_1, \dots, u_{i-1}\}$ is non-empty, and every $u \in S_i$ has degree $d_{H'_3}(u) \geq d_i - 1$. Hence, $f_i \geq d_i - 1$ for all i , which yields

$$e(H'_3) = \frac{1}{2} \sum_{i=1}^n f_i \geq \frac{1}{2} \sum_{i=1}^n (d_i - 1) = e(H_3) - \frac{n}{2}.$$

This proves Theorem 7. □

4 Concluding Remarks

- For Theorem 1, we may not be able to achieve the same result with smaller n . For example, consider F to be the bowtie graph, i.e. the 5-vertex graph with two triangles sharing a vertex. The n -vertex extremal graph for F is given by $K_{\lfloor \frac{n}{2} \rfloor, \lceil \frac{n}{2} \rceil}$ plus an edge when $n \geq 5$, otherwise it is the complete graph. For $n = 5$, the construction $G_1 = K_4, G_2 = K_5$ then shows that $\phi^*(2, 5, F) > 2 \cdot \text{ex}(5, F)$. Fortunately, for non-bipartite F with $|V(F)| = k$, it is not hard to show $n \geq k^2$ is sufficient to avoid this issue.
- We note that Theorem 6 may be generalized to any family of non-bipartite graphs up to asymptotic error via Szemerédi's Regularity lemma
- One could ask for the analogous results for hypergraphs. That is, if F is an r -uniform hypergraph, let $\phi(m, n, F)$ be the maximum number of edges over m double F -free r -uniform hypergraphs on $[n]$. Again, we have $\phi(m, n, F) \geq \binom{n}{r} + (m - 1) \cdot \text{ex}(n, F)$. Another direction of generalization is to relax the constraint to no copies of F contained in the intersection of k of the graphs G_1, G_2, \dots, G_m . Many of the theorems and proofs also hold in this case. For instance, the proof of Theorem 4 applies for this generalization by merely changing the numbers.

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