

# The fine structure of octahedron-free graphs

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## Abstract

This paper is one of a series of papers in which, for a family  $\mathcal{L}$  of graphs, we describe the typical structure of graphs not containing any  $L \in \mathcal{L}$ . In this paper, we prove sharp results about the case  $\mathcal{L} = \{O_6\}$ , where  $O_6$  is the graph with 6 vertices and 12 edges, given by the edges of an octahedron. Among others, we prove the following results.

(a) The vertex set of almost every  $O_6$ -free graph can be partitioned into two classes of almost equal sizes,  $U_1$  and  $U_2$ , where the graph spanned by  $U_1$  is a  $C_4$ -free and that by  $U_2$  is  $P_3$ -free.

(b) Similar assertions hold when  $\mathcal{L}$  is the family of *all* graphs with 6 vertices and 12 edges.

(c) If  $H$  is a graph with a color-critical edge and  $\chi(H) = p + 1$ , then almost every  $sH$ -free graphs becomes  $p$ -chromatic after the deletion of some  $s - 1$  vertices, where  $sH$  is the graph formed by  $s$  vertex disjoint copies of  $H$ .

These results are natural extensions of theorems of classical extremal graph theory. To show that results like those above do not hold in great generality, we provide examples for which the analogs of our results do not hold.

## 1. Introduction

### 1.1. Notation

Our notation is standard; in particular, the suffix is often the order of the graph in question:  $K_n$  denotes the complete graph,  $C_n$  the cycle and  $P_n$  the path with  $n$  vertices. Also,  $G_n$

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stands for any graph on  $n$  vertices and  $M_{2s}$  is the 1-regular graph, i.e., the complete matching, on  $2s$  vertices. For  $X \subseteq V(G)$  we denote by  $G[X]$  the subgraph of  $G$  spanned by  $X$ .

We define  $U \otimes W$  to be the graph obtained by taking vertex disjoint copies of  $U$  and  $W$  and joining each vertex of  $U$  to each vertex of  $W$ .

Given a family  $\mathcal{L}$ ,  $\mathbf{ex}(n, \mathcal{L})$  denotes the maximum number of edges a graph  $G_n$  can have without containing a graph in  $\mathcal{L}$  as a not necessarily induced subgraph. We call  $\mathcal{L}$  the family of *excluded* or *forbidden* graphs. For  $\mathcal{L} = \{L\}$  we simply write  $\mathbf{ex}(n, L)$ , and use analogous abbreviations elsewhere.  $\mathcal{P}(n, \mathcal{L})$  denotes the set of  $\mathcal{L}$ -free graphs on  $[n] := \{1, \dots, n\}$ . We write  $T_{n,p}$  for the  $p$ -partite Turán graph on  $n$  vertices: this is the complete  $p$ -partite graph of order  $n$  in which the  $p$  classes are as equal as possible. More generally,  $K(n_1, \dots, n_p)$  is the complete  $p$ -partite graph with class sizes  $n_1, \dots, n_p$ . The crucial property of  $T_{n,p}$  is that it is the unique  $p$ -chromatic  $n$ -vertex graph with the maximum number of edges. Also,  $H(n, p, s) := K_{s-1} \otimes T_{n-s+1,p}$ , and let  $\mathcal{A}(n, p, s)$  be the class of graphs  $G_n$  from which one can delete fewer than  $s$  vertices to obtain a graph  $G$  with  $\chi(G) \leq p$ . Note that  $H(n, p, s)$  has the most edges among the  $n$ -vertex graphs having  $s-1$  vertices whose deletion yields a  $p$ -colorable graph.

Denote by  $sL$  the graph obtained by taking  $s$  vertex-disjoint copies of a graph  $L$ , by  $\Gamma(u)$  the neighbourhood of a vertex  $x$ , and write

$$\Gamma^*(X) := \bigcap_{u \in X} \Gamma(u) \tag{1}$$

for the set of common neighbours of a set  $X$ . We shall write  $H(x) = x \log_2 \frac{1}{x} + (1-x) \log_2 \frac{1}{1-x}$  for the binary entropy function; note that

$$\binom{n}{xn} \leq 2^{H(x)n}.$$

This bound is useful because  $H(x) \approx -x \log_2 x \rightarrow 0$  as  $x \rightarrow 0$ .

## 1.2. Erdős–Frankl–Rödl type results

Since all subgraphs of an  $\mathcal{L}$ -free graph are  $\mathcal{L}$ -free, we have

$$|\mathcal{P}(n, \mathcal{L})| \geq 2^{\mathbf{ex}(n, \mathcal{L})}. \tag{2}$$

If  $\mathcal{L}$  consists of a single star:  $\mathcal{L} = \{L\}$ , with  $L = K(1, s)$ , then  $\mathbf{ex}(n, \mathcal{L}) = \lfloor (s-1)n/2 \rfloor$  and

$$|\mathcal{P}(n, L)| = 2^{(1+o(1))(\log_2 n)(s-1)n/2} = 2^{(1+o(1))(\log_2 n)\mathbf{ex}(n, L)},$$

so  $|\mathcal{P}(n, L)|$  is considerably larger than  $2^{\mathbf{ex}(n, L)}$ . However, Erdős conjectured that if  $L$  contains a cycle then

$$|\mathcal{P}(n, L)| = 2^{(1+o(1))\mathbf{ex}(n, L)}. \tag{3}$$

Erdős, Frankl and Rödl [9] proved this conjecture when  $\chi(L) > 2$ . The case when  $\chi(L) = 2$  is still wide open.

The main purpose of this and our earlier papers ([1] and [2]), is to establish sharp forms of Erdős–Frankl–Rödl [9] type results: to prove that for given family  $\mathcal{L}$  of forbidden graphs

almost all  $\mathcal{L}$ -free graphs  $G_n$  look very similar to the subgraphs of  $\mathcal{L}$ -extremal graphs. Of course, in each case we have to specify, what we mean by being similar. It is worth emphasizing that structural results are much deeper than quantitative ones. Instead of going into technicalities, we explain this through an example. Every bipartite graph is triangle-free, but the number of bipartite graphs is larger than the number of the subgraphs of the  $K_3$ -extremal  $T_{n,2}$ , roughly by a factor  $c\sqrt{n}$ . The reason is simple: non-balanced bipartite graphs are not necessarily subgraphs of the extremal graph  $K(n/2, n/2)$ . So the theorem that “almost all triangle-free graphs are bipartite” is more natural and sharper than the assertion that “the number of triangle-free graphs of order  $n$  is  $2^{(1+o(1))n^2/4}$ .”

Throughout this paper, for a given a family  $\mathcal{L}$ , we define

$$p = p(\mathcal{L}) := \min\{\chi(L) - 1 : L \in \mathcal{L}\}. \quad (4)$$

We shall need the notion of the “decomposition family” of  $\mathcal{L}$ , since in extremal graph theory often this governs the finer error terms.

**Definition 1 (Decomposition Family).** Denote by  $I_\nu$  the  $\nu$ -vertex graph with no edges. Given a family  $\mathcal{L}$ , let  $\mathcal{M} := \mathcal{M}(\mathcal{L})$  be the family of minimal graphs  $M$  for which there exist an  $L \in \mathcal{L}$  and a  $t = t_L$  such that  $L \subseteq M' \otimes K_{p-1}(t, \dots, t)$ , where  $M' = M'(t)$  is the graph obtained by adding  $t$  isolated vertices to  $M$ . We call  $\mathcal{M}$  the *decomposition family* of  $\mathcal{L}$ .

Since  $L \subseteq K_{p+1}(t, \dots, t)$  for some  $t \geq 1$  and  $L \in \mathcal{L}$ , the decomposition family  $\mathcal{M}$  always contains some bipartite graphs, here e.g.  $K(t, t)$ .

**Example.** Denote by  $O_6$  the edge-graph of the octahedron; equivalently,  $O_6 = K(2, 2, 2)$ . As  $O_6 = K(2, 2, 2) = C_4 \otimes K_1(2)$  we have that  $\mathcal{M}(O_6) = \{C_4\}$ . Note also that  $\mathcal{M}(C_{2\ell+1}) = \{K_2\}$  showing that for  $\ell > 1$  the role of  $M'$  is important in Definition 1.

In [2] our main result was the following.

**Theorem 2.** *Let  $\mathcal{L}$  be an arbitrary finite family of graphs. Then there exists a constant  $h_{\mathcal{L}}$  such that for almost all  $\mathcal{L}$ -free graphs  $G_n$  we can delete  $h_{\mathcal{L}}$  vertices of  $G_n$  and partition the remaining vertices into  $p$  classes,  $U_1, \dots, U_p$  such that each  $G[U_i]$  is  $\mathcal{M}$ -free.*

**Note.** Here and elsewhere, “almost always” means that all but  $o(|\mathcal{P}(n, \mathcal{L})|)$  of the considered graphs (i.e.  $G_n \in \mathcal{P}(n, \mathcal{L})$ ) have the claimed property.

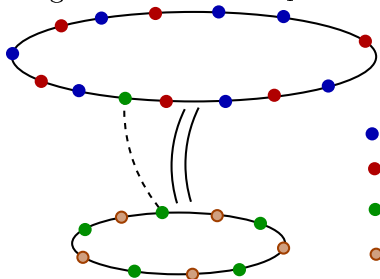
**Remark.** The main motivation for this paper is to investigate to what extent Theorem 2 is sharp. As we shall see, in several instances it is indeed sharp. However, we have to be cautious: as we shall see, we have to avoid certain pitfalls; we shall return to this in Section 6.

## 2. New Results

In this paper we prove several sharp results, and will discuss some of the limitations of our methods.

We say that  $L$  is a *weakly edge-color-critical* graph if there is an edge  $e \in E(L)$  for which  $\chi(L - e) < \chi(L)$ . The edge  $e$  itself is called *critical*. We shall call these graphs shortly *weakly critical*. A graph  $L$  is *edge-colour-critical* if each edge  $e$  of  $L$  is critical. Important

examples of edge-colour-critical graphs are the complete graphs and the odd cycles. In extremal graph theory, if an assertion can be proved for  $K_{p+1}$ , then usually it can be proved for weakly  $(p+1)$ -critical graphs  $L$  as well. To illustrate the differences between the notion of weakly critical and edge-color-critical, consider  $L := C_\ell \otimes C_m$  for  $\ell, m \geq 3$ . If both  $\ell$  and  $m$  are odd, then  $L$  is 6-chromatic and edge-color-critical. If  $\ell$  is odd,  $m$  is even, then  $L$  is 5-chromatic and the edges of the  $C_\ell$  are critical, but the edges of  $C_m$  are not, neither are the cross edges. If both  $\ell$  and  $m$  are even,  $L$  is 4-chromatic and has no critical edges: deleting any edge leaves some  $K_4 \subset L$  untouched.



For every weakly critical graph  $L$  having a critical edge, Prömel and Steger [24] proved that almost all  $L$ -free graphs have chromatic number  $\chi(L) - 1$ . Their result is clearly sharp, since no graph with chromatic number  $\chi(L) - 1$  contains  $L$  as a subgraph. To demonstrate the power of our methods we prove a generalization of their result: We consider the case when the excluded graph is  $L = sH$ , where  $H$  is weakly critical, and  $\chi(H) = p + 1 \geq 3$ . Note that Simonovits [26] proved that for  $n$  sufficiently large, the unique  $L$ -extremal graph is  $H(n, p, s)$ . Observe that if one can delete  $s - 1$  vertices of a graph  $G_n$  to obtain a  $p$ -partite graph, then  $G_n$  is  $L$ -free. We shall prove that almost all  $L$ -free graphs have this property.

**Theorem 3.** *Let  $p$  and  $s$  be positive integers and  $H$  be a weakly edge-color-critical graph of chromatic number  $p + 1$ . Then almost every  $sH$ -free graphs  $G_n$  on  $n$  vertices has a set  $S$  of  $s - 1$  vertices for which  $\chi(G_n - S) = p$ .*

In our main result below we describe the structure of almost all octahedron-free graphs. We say that a graph  $G$  has property  $\mathcal{Q} = \mathcal{Q}(C_3, C_4)$  if its vertices can be partitioned into two sets,  $U_1$  and  $U_2$ , such that  $C_4 \not\subseteq G[U_1]$  and  $P_3 \not\subseteq G[U_2]$ . As we remarked earlier, if  $G \in \mathcal{Q}$  then  $G$  does not contain  $O_6$ . It was proved by Erdős and Simonovits [14] that for  $n$  sufficiently large every  $O_6$ -extremal  $G_n$  has property  $\mathcal{Q}$ . Here we prove the following.

**Theorem 4.** *The vertices of almost every  $O_6$ -free graph can be partitioned into two classes,  $U_1$  and  $U_2$ , so that  $U_1$  spans a  $C_4$ -free graph and  $U_2$  spans a  $P_3$ -free graph.*

A similar, slightly simpler, result is the following. Denote  $\mathcal{P}(n; a, b)$  the family of graphs  $G_n$  for which no  $a$  vertices of  $G_n$  span at least  $b$  edges. In some sense, G. Dirac started investigating such problems [4]. Several results of Erdős and Simonovits are related to this topic, and they became very important for hypergraphs, see e.g., Brown, Erdős and T. Sós [3]. Much later, Griggs, Simonovits and Thomas [18] proved that, for  $n$  sufficiently large, the vertex set of any extremal  $(6, 12)$ -free graph  $G_n$  can be partitioned into  $U_1$  and  $U_2$  so that the induced subgraphs,  $G[U_1]$  is  $\{C_3, C_4\}$ -free and  $G[U_2]$  is an independent set. Note that if  $G_1$  is  $\{C_3, C_4\}$ -free and  $e(G_2) = 0$  then  $G_1 \otimes G_2$  is  $(6, 12)$ -free.

**Theorem 5.** *The vertex set of almost every graph in  $\mathcal{P}(n; 6, 12)$  can be partitioned into two classes,  $U_1$  and  $U_2$ , so that  $U_1$  spans a  $\{C_3, C_4\}$ -free graph and  $U_2$  is an independent set.*

Note that what we actually prove is that almost every  $\mathcal{L}$ -free graph  $G$  can be partitioned into two classes,  $U_1$  and  $U_2$ , so that  $U_1$  spans a  $\{C_3, C_4\}$ -free graph and  $U_2$  is an independent set, where  $\mathcal{L} = \{O_6, C_3 \otimes I_3, P_3 \otimes (P_2 + I_1)\}$ .

Along the lines of the proofs of Theorems 4 and 5, the following can also be proved. We leave the details to the reader.

**Theorem 6.** *Let  $p$  and  $2 \leq a_2 \leq \dots \leq a_p$  be integers. Then for  $L = K(2, 2, a_2, \dots, a_p)$ , almost every  $L$ -free graphs  $G$  has a partition  $(U_1, \dots, U_p)$  where  $G[U_1]$  is  $C_4$ -free, and  $P_3 \not\subseteq G[U_i]$  for  $i > 1$ .*

**Theorem 7.** *For  $p \geq 2$ , almost every  $(3p, 9\binom{p}{2} + 3)$ -free  $G$  has a vertex-partition  $(U_1, \dots, U_p)$  for which  $G[U_1]$  is  $\{C_3, C_4\}$ -free, and  $e(U_i) = 0$  for  $i > 1$ .*

One important difference between the Octahedron problem and the  $(6, 12)$ -problem is that we know much about the  $C_4$ -extremal graphs, including bounds on the extremal number  $\text{ex}(n, C_4)$ , while concerning the  $\{C_3, C_4\}$ -extremal problem there is the following tantalizing unsolved conjecture of Erdős (see [15]).

**Conjecture 8.**

$$\text{ex}(n, \{C_3, C_4\}) = \frac{1}{2\sqrt{2}}n\sqrt{n} + o(n\sqrt{n}).$$

What this conjecture claims is that if we exclude  $C_3$  in addition to  $C_4$ , then we are not far from having excluded all the odd cycles.

In our proofs below we shall make use of the following lower bounds on  $\text{ex}(n, \{C_4\})$  and  $\text{ex}(n, \{C_3, C_4\})$ , see Kővári-T. Sós-Turán [21], Erdős [5] and Erdős-Rényi-T. Sós [13].

**Theorem 9.**

$$\text{ex}(n, \{C_4\}) = \frac{1}{2}n\sqrt{n} + o(n\sqrt{n})$$

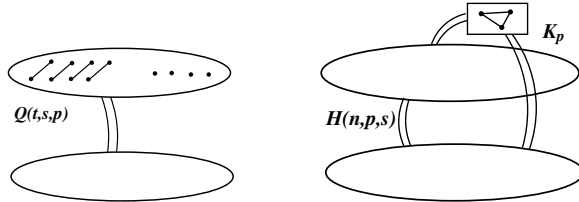
and

$$\text{ex}(n, \{C_3, C_4\}) \geq \frac{1}{2\sqrt{2}}n\sqrt{n} + o(n\sqrt{n}). \quad (5)$$

Our results are, in some sense, pseudo-generalizations of the corresponding results in extremal graph theory: formally they do not imply the theorems: knowing the structure of almost all  $\mathcal{L}$ -free graph yields  $\text{ex}(n, \mathcal{L})$  only asymptotically. However, our results do show that the structural description of the extremal graphs, provided by us, is really the crucial one.

One would think that for every classical theorem of extremal graph theory it would not be too difficult to obtain natural generalizations to counting results. Our previous papers contain several such theorems. However, here we consider finer descriptions of almost all  $\mathcal{L}$ -free graphs. These finer extensions cannot be taken granted: there are cases, where the finer extremal results do not extend to counting versions. This is shown by our next example.

**Definition 10.** Let  $s, p > 0$  be integers. For  $t \geq 2s$  let  $Q(t, p, s)$  be the complete  $p$ -partite graph with  $t$  vertices in each class and with additional  $s$  independent edges, say, in the first class.



Simonovits [31] proved that if  $2s \leq t$ , and  $n$  is sufficiently large, then  $H(n, p, s)$  is the unique extremal graph for  $Q(t, p, s)$ .

Originally we thought that the following conjecture should hold.

**Conjecture 11 (Disproved below).** Fix three integers  $p > 1$  and  $t \geq 2s > 0$ . Let  $L \subset Q(t, p, s)$  with  $\chi(L) = p + 1$ . Then almost all  $L$ -free graphs  $G_n$  contain a vertex set  $S$  with at most  $s - 1$  vertices such that  $G - S$  is  $p$ -chromatic.

We shall see that this conjecture often holds, however, not always. To our surprise, we have found some counterexamples. Conjecture 11 holds for  $s = 1$  by Prömel and Steger [24], since then  $L$  has a color-critical edge. Also, Theorem 3 yields it for  $L = sH$ , if  $H$  is a weakly critical graph. However, for  $s \geq 2$  there are graphs for which Conjecture 11 is false. Below we describe such a counterexample.

Let  $\mathcal{B}(U, V, x)$  be the family of graphs  $G_n$  with vertex set  $[n]$ , and  $x \in [n]$  for which  $G_n - x$  is bipartite with bipartition  $(U, V)$ .

**Example 12.** Let  $t \geq 4$  and  $L = Q(t, 2, 2)$ . Conjecture 11 asserts that almost all  $L$ -free graphs belong to one of the classes  $\mathcal{B}(U, V, x)$ . Since

$$|\mathcal{B}(U, V, x)| \leq 2^{|U||V|+n-1},$$

that would imply the following bounds:

$$|\mathcal{P}(n, \mathcal{L})| \leq (1 + o(1)) \sum_{\{U, V, x\}} 2^{|U||V|+n-1} \approx 2^{n^2/4+3n/2}. \quad (6)$$

Note that in the above summation the main contribution is coming from triplets with  $\|U\| - \|V\| = o(n)$ , which can be assumed when  $|\mathcal{P}(n, \mathcal{L})|$  is estimated.

However, we can generate many more  $L$ -free graphs: Let  $\mathcal{B}(U', V', x, y)$  be the family of graphs  $G_n$  with vertex set  $[n]$ , and  $x, y \in [n]$  for which  $G_n - \{x, y\}$  is bipartite with bipartition  $(U', V')$ , and no vertex  $v \in [n] - \{x, y\}$  joined to both  $x$  and  $y$ . One can check that these graphs are  $L$ -free, and

$$|\mathcal{B}(U', V', x, y)| = 2^{|U'||V'|} 3^{n-2}.$$

Some of  $G_n \in \mathcal{P}(n, \mathcal{L})$  are in more than four families  $\mathcal{B}(U', V', x, y)$ , however, almost all of them uniquely determine  $x, y, U', V'$ , apart from that  $x$  and  $y$  can be switched and  $U'$  and

$V'$  can also be switched. But this results in a loss of a factor at most 4, i.e., we obtain the following lower bound on  $|\mathcal{P}(n, \mathcal{L})|$ :

$$|\mathcal{P}(n, \mathcal{L})| \geq 2^{n^2/4+3n/2-o(n)} (3/(2\sqrt{2}))^n,$$

comparing it with (6) yields a contradiction with Conjecture 11. (Here we used that there are  $2^{(1+o(1))n}$  pairs of  $U', V'$  with  $||U'| - |V'| \leq 1$ ).

**Example 13.** Note that in Example 12 both  $p$  and  $s$  could have been chosen larger, providing counterexamples to Conjecture 11 for many  $p, s \geq 2$ . More importantly, we obtain an example (actually family of examples) which shows that the “condition of deletion of  $h$  vertices” cannot be omitted from Theorem 2. To spell out, fix  $p = 2$  and some  $s > 1$ .

If Theorem 2 were true with  $h = 0$ , then the vertices of almost all  $Q(2s, 2, s)$ -free graphs could be partitioned into two classes, each spanning an  $M_{2s}$ -free graph. Denote  $D(k, s)$  the number of  $M_{2s}$ -free graphs on  $k$  vertices. As an  $M_{2s}$ -free graph cannot contain more than  $s - 1$  vertices with degrees at least  $2s$ , and  $2s - 2$  vertices cover all the edges,

$$2^{(s-1)(k-s)} = 2^{(s-1)k+o(k)} \leq D(k, s) \leq 2^{2s-2} \binom{k}{2s-2} \binom{k}{2s}^s 2^{(s-1)k} = 2^{(s-1)k+o(k)},$$

for fixed  $s$  as  $k$  is tending to infinity. So for a fixed partition  $U, V$  of  $[n]$ , the number of such graphs is

$$D(|U|)D(|V|)2^{|U||V|} = 2^{|U||V|+(s-1)n+o(n)}.$$

However, we can construct for a fixed partition  $U, V$  a larger family of  $Q(2s, 2, s)$ -free graphs. Assume that  $|U| \geq |V|$ , and fix an  $\ell$ -set  $S \subset U$ . We let  $U - S$  and  $V$  to span independent sets, there is no restriction for the edges between  $U - S$  and  $V$ , and each vertex of  $S$  is joined to at most  $s - 1$  vertices of  $U \cup V - S$ . It is easy to check that these graphs are  $Q(2s, 2, s)$ -free, and for a fixed partition  $U, V$  we constructed

$$O(1) \left( \binom{\ell}{0} + \dots + \binom{\ell}{s-1} \right)^n 2^{(|U|-\ell)|V|} \tag{7}$$

graphs. Note that for most of the graphs constructed that way, the partition  $U - S, V, S$  can be reconstructed, a factor of 2 might be lost if  $U - S$  and  $V$  cannot be distinguished.

If we manage to find an  $\ell$  and an  $s$  such that  $\binom{\ell}{0} + \dots + \binom{\ell}{s-1} > 2^{s-1+\ell/2}$  then the second family is exponentially larger than the first, justifying our claim. In general, if  $\ell$  is around  $2s + o(s)$  then this should be true: an example (with the smallest possible  $s$ ) is  $s = 8$  and  $\ell = 19$ .

The organization of the paper is as follows: In Section 3 we lay the groundwork for our proofs, in Section 4 we prove Theorem 3, in Section 5 we prove Theorems 4 and 5, and in Section 6 we make some concluding remarks.

### 3. Notation, parameters, lemmas

In this section we state a sharper version of Theorem 2, needed in many applications.

We shall define a system of parameters. Assume that a finite family  $\mathcal{L}$  is given. We have already defined  $p$  in (4):  $p = p(\mathcal{L}) := \min\{\chi(L) - 1 : L \in \mathcal{L}\}$ .

**Definition 14 (Parameters).** Let  $t := \max\{v(L) : L \in \mathcal{L}\}$ . Fix an  $\varepsilon > 0$ , satisfying

$$H(\varepsilon) < \left(100e^{10^{20}} \cdot 4^{t+1} p^5 t^5\right)^{-1}. \quad (8)$$

This choice of  $\varepsilon$  will make sure that the following relation holds:

$$(511/512)^{10^{-9}/2} (27/\varepsilon^3)^\varepsilon < 1 - 10^{-14}. \quad (9)$$

Now, depending on this  $\varepsilon$  we fix a (small) positive  $\delta$  (this choice depends on Lemma 14 in [2]) and to be sufficiently small to satisfy

$$(1 - 10^{-14})2^{4H(4\delta p)} < 1. \quad (10)$$

Now we define  $\vartheta$  by  $\delta = 2\sqrt{H(\vartheta)}$ . Note that  $\delta$  will be chosen to be much smaller than  $\varepsilon$ , so that we can find appropriate embeddings as in the proof of Claim 20) needed.

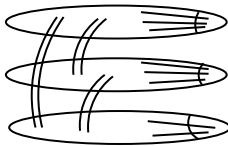
For this  $\varepsilon$  and  $\delta$  we choose a (large) integer  $h$  (again by Lemma 14 in [2]). Note that  $\varepsilon, \delta, \vartheta > 0$  in general are assumed to be smaller than any fixed numerical positive constant (like satisfying (9) and (10).)

Note that we need two upper bound on  $\varepsilon$ : we wanted to (9) to be satisfied, and in [2], from which paper we use several results here, we had  $H(\varepsilon) < (4^{t+1} p^5 t^5)^{-1}$ .

Using these parameters, we define several graph (sub)-classes of  $\mathcal{P}(n, \mathcal{L})$ , whose intersection,  $\mathcal{P}^*(n, \mathcal{L})$ , is the most important for us.

**Definition 15 (Optimal Partition).** Given a graph  $G$ , a vertex partition  $(U_1, \dots, U_p)$  of  $V(G)$  is an *optimal  $p$ -partition* of  $G$ , if  $\sum_i e(G[U_i])$  is the minimum possible. Given  $(U_1, \dots, U_p)$ , we shall call the edges joining vertices in the same  $U_i$  *horizontal*, vertices from different classes *vertical edges*.

Note that the names “horizontal” and “vertical” were motivated by the way the classes are represented on the figure below.



**Definition 16 (GOOD graphs).** Given a graph  $G$  with a vertex partition  $(U_1, \dots, U_p)$ , call an  $r$ -tuple  $X \subset V(G)$  GOOD if, for every  $U_i \subseteq V(G) - X$ ,

$$|\Gamma^*(X) \cap U_i| = \left| \bigcap_{x \in X} \Gamma(x) \cap U_i \right| > \frac{1}{4^{r+1}} |U_i|. \quad (11)$$

An  $r$ -tuple is BAD if it is not GOOD. We say that  $X$  is a BAD  $r$ -tuple for a class  $U_i$ , if (11) is violated.<sup>1</sup>

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<sup>1</sup>We shall use CAPITALS for ordinary words, like GOOD/BAD to emphasize that we use them here in a predefined way.

Note that a set  $X$  may be BAD for several classes in a partition, and whether  $X$  is GOOD or BAD depends on  $(U_1, \dots, U_p)$ .

**Definition 17.**  $\mathcal{P}^*(n, \mathcal{L})$  is the family of graphs  $G_n \in \mathcal{P}(n, \mathcal{L})$  satisfying the following conditions: For every optimal  $p$ -partition  $(U_1, \dots, U_p)$  of  $G_n$

(i)  $\sum_i e(U_i[G_n]) < \vartheta n^2$ .

(ii) For every  $1 \leq i < j \leq p$  and every pair of sets  $A \subset U_i$ ,  $B \subset U_j$  with  $|A| = |B| \geq \lceil \delta n \rceil$  we have

$$e(A, B) > \frac{1}{4}|A| \cdot |B|.$$

(iii) For  $i = 1, \dots, p$ ,

$$\left| |U_i| - \frac{n}{p} \right| < \left( \sqrt{\vartheta} \log \frac{1}{\vartheta} \right) n.$$

(iv) If  $W$  is the set of vertices with horizontal degree  $\geq \varepsilon n$ , then  $G_n - W$  has no BAD  $(\leq t)$ -tuple with respect to this  $(U_1, \dots, U_p)$ . (By Lemma 14 in [2] we know that  $|W| \leq h$ .)<sup>2</sup>

Of course,  $\mathcal{P}^*(n, \mathcal{L})$  strongly depends on the constants fixed in the first part of this paragraph. In [2] we introduced the GOOD graphs in several steps.<sup>3</sup> In a more technical form, our main result in [2] was the following.

**Theorem 18 (Good Graphs).** *Let  $\mathcal{L}$  be a finite family of forbidden graphs. Then almost all  $\mathcal{L}$ -free graphs are in  $\mathcal{P}^*(n, \mathcal{L})$ : there exist two positive constants,  $C$  and  $\omega > 1$  such that*

$$|\mathcal{P}(n, \mathcal{L}) - \mathcal{P}^*(n, \mathcal{L})| \leq \frac{C}{\omega^n} |\mathcal{P}(n, \mathcal{L})|. \quad (12)$$

We shall use the following important lemma that a typical  $\mathcal{L}$ -free graph has not many optimal partition. (The lemma has an easy proof, it is essentially same as Lemmas 6.10-6.11 [1] and Lemma 22 [2].)

**Lemma 19.** *The number of optimal partitions of a  $G_n \in \mathcal{P}^*(n, \mathcal{L})$  is at most  $2^{4H(4\delta p)n}$ .*

## 4. Proof of Theorem 3: $L = sH$ , where $H$ has a critical edge.

**Proof.** We shall deduce Theorem 3 as a simple corollary of the main result of [2], here Theorem 18. The decomposition family for  $sH$  consists of one graph:  $M_{2s} := sK_2$ , a graph of order  $2s$  with  $s$  independent edges. Fix an  $\varepsilon > 0$  and then  $\delta$  and  $\vartheta$  as in Definition 14.

<sup>2</sup>The set of graphs from  $\mathcal{P}(n, \mathcal{L})$  satisfying (i) were called as  $\mathcal{P}_\vartheta(n, \mathcal{L})$ , (i) and (ii)  $\mathcal{P}_{\text{UNIF}}^\delta(n, \mathcal{L})$ , (i) and (iii)  $\mathcal{P}_{\text{WP}}^\vartheta(n, \mathcal{L})$ , and (i) and (iv)  $\mathcal{P}_{\text{GOOD}}^{t,h}(n, \mathcal{L})$ .

<sup>3</sup>There

$$\mathcal{P}^*(n, \mathcal{L}) = \mathcal{P}_{\text{GOOD}}^{t,h}(n, \mathcal{L}) \cap \mathcal{P}_\vartheta(n, \mathcal{L}) \cap \mathcal{P}_{\text{UNIF}}^{\delta, \lambda}(n, \mathcal{L}) \cap \mathcal{P}_{\text{WP}}^\vartheta(n, \mathcal{L}).$$

Let  $m = |V(H)|$ . Fix a  $p$ -coloring of  $H$  which is almost proper, the only “violation” is that the first color class contains the critical edge, badly colored. Denote the sizes of the color classes  $m_1, \dots, m_p$ . We can assume that  $H$  is a complete  $p$ -partite graph with  $m_1, \dots, m_p$  vertices in the classes, with an extra edge in the first class, as this assumption just increases the number of  $sH$ -free graphs, and we still claim that almost all are in property  $\mathcal{A}(n, p, s)$ .

Consider an arbitrary graph  $G_n \in \mathcal{P}^*(n, sH)$ . Fix an optimal partition  $(U_1, \dots, U_p)$ . Let  $W$  be the set of vertices with horizontal degrees higher than  $\varepsilon n$ . Let  $F$  be a maximal set of independent horizontal edges in  $G_n - W$ .

**Claim 20.** *Every graph  $G_n \in \mathcal{P}^*(n, sH)$  contains  $s'H$  as a subgraph, where  $s' := |W| + |F|$ . In particular,  $s' < s$ .*

**Proof.** Write  $\{v_1, \dots, v_{|W|}\} \in W$ . Then for every  $i$  and  $j$ ,  $|N(v_j) \cap U_i| > \varepsilon n$ , and by property (ii) of  $\mathcal{P}^*(n, \mathcal{L})$  (and using  $\varepsilon \gg \delta$ ),  $v$  can be easily extended to a copy of  $H$ ,  $H_j \subseteq G_n$ . Moreover, for each  $v_j \in W$  a new copy of  $H$ ,  $H_j \subseteq G_n$  can be chosen to be vertex disjoint from  $H_{j'}$  for every  $j' < j$ , since the sets  $N(v) \cap U_i - W$  satisfy property (ii) of Definition 17. This way  $|W|$  vertex disjoint copies of  $H$  can be found in  $G_n$ .<sup>4</sup>

Let  $uw \in F$  be a horizontal edge of  $U_1 - W$ . The set  $\{u, w\}$  with any  $m_1 - 2$  additional vertices forming  $H^1$  in  $U_1 - W$  is a GOOD  $m_1$ -tuple. So they have many common neighbors in  $U_2 - W$ . Denote an  $m_2$ -set of them by  $H^2$ . The set  $H^1 \cup H^2$  is a GOOD  $(m_1 + m_2)$ -tuple, so they have many (linear in  $n$ ) common neighbors in  $U_3$ , etc. Observe that during building  $H$  we always had many options to choose the next vertex, therefore the copies of  $H$ 's can be chosen to be pairwise vertex disjoint from each other. This way we find  $|F|$  additional copies of  $H$ , implying  $s'H \subseteq G_n$ . ■

**Claim 21.** *Let  $G_n \in \mathcal{P}^*(n, sH)$ . Given an optimal partition  $(U_1, \dots, U_p)$  of  $G_n$ , set  $\tilde{U}_i := U_i - W$ , where  $W$  is the set of vertices of high horizontal degree. Then  $\{\tilde{U}_1, \dots, \tilde{U}_p\}$  is independent of the optimal partition  $(U_1, \dots, U_p)$ .*

**Proof.** Assume that  $(U'_1, \dots, U'_p)$  is an other optimal partition of  $G_n$ . By relabelling, if necessary, we may assume that  $|U_i \Delta U'_i| \leq 2p\delta n$  for every  $i$ ,  $1 \leq i \leq p$ , otherwise by Definition 17 (ii) there were too many horizontal edges in  $G_n$ . It is sufficient to prove that if  $u \in U_1 - W$  then  $u \in U'_1 - W$  as well. If  $u \in U_1 - W$  then  $|N(u) \cap U_1 - W| \leq \varepsilon n$ , so  $|N(u) \cap U'_1 - W| \leq (\varepsilon + 2p\delta)n$ . However  $u$  is a good 1-tuple with respect to the partition  $(U_1, \dots, U_p)$ , so  $|N(u) \cap U_i - W| \geq 0.02n/p$ , so  $|N(u) \cap U'_2 - W| \geq 0.01n/p$  for every  $2 \leq i \leq p$ . Using  $\varepsilon + 2p\delta \ll 0.01/p$  we obtain that  $u \in U'_1$ . ■

Now we turn to the proof of Theorem 3. For  $s = 1$  we are instantly done by Claim 20, so we shall assume  $s \geq 2$ . For each  $p$ -partite graph  $F$  on  $[n]$  with  $p$ -partition  $(U_1, \dots, U_p)$ , assign a subfamily  $\Phi(F) \subset \mathcal{P}^*(n, \ell)$  of graphs  $G_n \in \mathcal{P}^*(n, \ell)$  with optimal partition  $(U_1, \dots, U_p)$  and vertical (cross)-edges of  $G_n$  spanning  $F$ . By Claim 20, for each  $G_n \in \mathcal{P}^*(n, \ell)$  the set of vertices of high horizontal degree vertices has fewer than  $s$  elements so, by Claim 21, for each  $G_n$  there are at most  $p^{s-1}$  copies of  $F$  with  $G_n \in \Phi(F)$ . This implies that it is sufficient to prove that all but  $2^{-n/20p} |\Phi(F)|$  graphs of  $\Phi(F)$  are in  $\mathcal{A}(n, p, s)$ .

<sup>4</sup>This, or a similar, embedding algorithms can be found in several papers, see for more precise reference [1].

For a given  $F$ , if  $G_n \in \Phi(F)$ , then by Claim 20, in  $G_n$  there are at most  $s' := 2(s-1-|W|)$  vertices covering every horizontal edge. This gives that the number of possible ways the horizontal edges not covered by  $W$  can be placed is at most

$$\binom{n}{s'} \binom{n}{\varepsilon n}^{s'} \leq 2^{s'H(\varepsilon)n+o(n)}.$$

However if  $G_n \notin \mathcal{A}(n, p, s)$  then  $s' > 0$ . Consider  $\Psi(G_n)$ , defined as the subset of  $\Phi(F)$ , that consists of graphs obtained from  $G_n$  by removing all horizontal edges not covered by  $W$ , but to one arbitrary vertex  $x \in [n] - W$  add arbitrarily  $n/18p$  horizontal edges. (We have the upper bound  $n/18p$  on the number of edges added, as in the constructed graphs we would like to keep the same optimal partition.) Then  $\Psi(G_n) \subset \mathcal{A}(n, p, s)$ ,

$$|\Psi(G_n)| > \binom{n/2p}{n/18p} > 2^{n/18p} \quad \text{and} \quad |\Psi^{-1}(G_n)| < n2^{s'H(\varepsilon)n+o(n)}.$$

This implies that all but  $n2^{-n/18p+s'H(\varepsilon)n+o(n)}|\Phi(F)| < 2^{-n/20p}|\Phi(F)|$  graphs from  $\Phi(F)$  are in  $\mathcal{A}(n, p, s)$ , completing the proof.  $\blacksquare$

## 5. Proof of Theorems 4 and 5

The proofs of the two theorems are the same till the very last step; up to that point we use only that  $(6, 12)$ -free graphs are  $O_6$ -free and that our graphs are  $O_6$ -free.

In the first part of the proof we can assume that  $\mathcal{L} = \{O_6\}$  or  $\mathcal{L}$  consists of all graphs with 6 vertices and 12 edges, the arguments are valid in both cases. We shall consider the typical  $\mathcal{L}$ -free graphs  $G_n \in \mathcal{P}^*(n, \mathcal{L})$  with an optimal partition  $(U_1, U_2)$ . Now, the number of high horizontal degree vertices is bounded:  $|W| = O(1)$ . The decomposition family of  $\mathcal{L}$ ,  $\mathcal{M}(\mathcal{L})$ , contains a  $C_4$ , so by Theorem 18, every at most 4-tuple is GOOD inside  $U_i - W$ , so  $U_i - W$  must span a  $C_4$ -free graph.

The difference between the  $O_6$ -free and the  $(6, 12)$ -free cases is that in the  $O_6$ -free case one of the classes (say  $U_1$ ) spans a  $C_4$ -free graph and the other a graph with maximum degree at most 1, while in second case  $U_1$  spans a  $\{C_3, C_4\}$ -free graph, and  $U_2$  should span an independent set. We prove this in several steps. First, in Subsection 5.1, we show that

$$e(U_1) + e(U_2) \geq \frac{n^{3/2}}{20000}.$$

Then we prove that in most  $\mathcal{L}$ -free graphs the horizontal edges are distributed unevenly, most of them are in one of the classes (say in  $U_1$ ). Then we prove in Subsection 5.2 that in any optimal partition of the remaining graphs  $W = \emptyset$ . In the last step we complete the final structural description of the graphs spanned by  $U_2$ . At that point we shall separate the proofs of the two theorems from each other.

One idea used several times is that given the assumed typical graph structure, we fix the graph spanned by  $U_1$  and compare the size of the set of graphs with this  $U_1$  having the “required” structure with the size of the family of graphs not having nice structure. We show that for each fixed partition the number of “bad” graphs is “negligible” among the graphs with that partition, which implies that the total number of “bad” graphs is negligible.

### 5.1. The number of horizontal edges in one class is large and in the other is small

We need a result of Füredi [16].

**Lemma 22.** *For  $T \geq 2n^{4/3}(\log n)^2$  the number of  $C_4$ -free graphs  $G_n$  with  $e(G_n) = T$  is at most*

$$(4n^3/T^2)^T. \quad (13)$$

Note that  $(4n^3/T^2)^T$  is monotone increasing for  $1 \leq T < 0.01n^{3/2}$ . This is used to prove the crucial step in the main result of this subsection.

**Corollary 23.** *The number of  $\mathcal{L}$ -free graphs  $G_n$  having a partition  $(U_1, U_2)$  with  $e(G[U_1]) + e(G[U_2]) \leq n^{3/2}/10000$  is  $o(|\mathcal{P}(n, \mathcal{L})|)$ .*

**Proof.** Indeed, the number of optimal partitions of  $G_n$  is at most  $2^n$ , the number of ways to choose the at most  $h$  vertices of high horizontal degree and the adjacent edges is smaller than  $n^h 2^{hn}$ . The number of ways to add  $T \leq 10^{-4}n^{3/2}$  edges avoiding a  $C_4$  to the rest of the graph is, by Lemma 22, at most

$$\begin{aligned} \sum_{T \leq 2n^{4/3} \log^2 n} \binom{n^2}{T} + \sum_{T \leq 10^{-4}n^{3/2}} \left(\frac{4n^3}{T^2}\right)^T &< n^2[(4 \times 10^8)^{1/10000}]^{n^{3/2}} \\ &< 1.005^{n^{3/2}} < 2^{n^{3/2}/100}, \end{aligned}$$

where the first sum compensates that for small values of  $T$  we do not have Lemma 22, the second one estimates the number of ways to choose  $G[U_i]$  and the number of ways to add the vertical (cross-edges) is at most  $2^{n^2/4}$ . This number,  $2^{n^2/4+n^{3/2}/100+O(n)}$ , is much smaller than the number of  $\mathcal{L}$ -free graphs, which is at least  $2^{n^2/4+((1/4)+o(1))(n/2)^{3/2}}$ . Here we used the lower bound of (5) of Theorem 9, due to Eszter Klein and Erdős, see [5]. ■

From now on we may and shall assume that an optimal partition  $(U_1, U_2)$  of a  $G_n \in \mathcal{P}^*(n, \mathcal{L})$  satisfies

$$e(G[U_1]) \geq e(G_n[U_2]), \quad \text{thus} \quad e(G_n[U_1]) \geq \frac{1}{20000}n^{3/2}. \quad (14)$$

**Lemma 24.** *Let  $G_m$  be a  $C_4$ -free graph with  $e > 10m$  edges. Then  $G_m$  contains at least  $e^2/4m^2$  vertex disjoint  $P_3$ 's, for  $m$  sufficiently large.*

**Proof.** Assume that the maximum number of vertex disjoint  $P_3$ 's in  $G_m$  is  $t$ . Fix  $t$  vertex disjoint  $P_3$ 's in  $G_m$ . The rest of the vertices spans no  $P_3$ . So the  $3t$  vertices of these  $P_3$ 's cover all but at most  $(m - 3t)/2$  edges. Since  $G_m$  is  $C_4$ -free, hence the total number of  $P_3$ 's in  $G_m$  is at most  $\binom{m}{2}$ . On the other hand, the degree sum of these  $3t$  vertices is at least  $e - m$ , so the number of  $P_3$ 's in  $G_m$  is at least

$$3t \binom{\frac{e-m}{3t}}{2}.$$

Putting together, using  $e - m > 9e/10$  we have

$$3t \binom{\frac{e-m}{3t}}{2} < \binom{m}{2},$$

implying

$$t \geq \frac{(e-m)^2}{3m(m-1)} > \frac{e^2}{4m^2}.$$

■

Now we eliminate the case when in an optimal partition of  $G_n$  both classes span at least  $2n(\log n)^2$  edges. The idea is that in this case there are many vertex-disjoint  $P_3$ 's in both classes, hence there are many pairs of  $P_3$ s, yielding restrictions for the cross-edges between  $P_3$ 's in  $U_1$  and  $P_3$ 's in  $U_2$ . Indeed a  $P_3 \otimes P_3$  has 13 edges and contains an octahedron.

**Lemma 25.** *Let  $(U_1, U_2)$  be an optimal partition of a  $G_n \in \mathcal{P}^*(n, \mathcal{L})$ , with*

$$e(G_n[U_1]) > \frac{1}{20000} n^{3/2} \tag{15}$$

and  $n$  large enough.

(i) *The number of graphs  $G_n \in \mathcal{P}^*(n, \mathcal{L})$  with*

$$e(G_n[U_2]) > 2n(\log n)^2 \tag{16}$$

is at most  $2^{-n \log^3 n} |\mathcal{P}^*(n, \mathcal{L})|$ .

(ii) *The number of graphs  $G_n \in \mathcal{P}^*(n, \mathcal{L})$  violating (16) but for which  $G[U_2]$  contains at least  $\log^4 n$  vertex disjoint  $P_3$ s is at most  $2^{-n \log^3 n} |\mathcal{P}^*(n, \mathcal{L})|$ .*

**Proof.** (i) Consider a graph  $G_n \in \mathcal{P}^*(n, \mathcal{L})$ . Fix an optimal partition  $(U_1, U_2)$  of  $G_n$  satisfying (15), and (16) and a graph  $H := G[U_1 - W]$  that is  $C_4$ -free in case of the octahedron case and  $\{C_3, C_4\}$ -free for the (6, 12)-case.

In the proof we compare the sizes of the following two families of graphs:

The first family,  $\mathcal{P}_I(n, \mathcal{L}; H, U_1, W) \subset \mathcal{P}^*(n, \mathcal{L})$ , is the collection of  $\mathcal{L}$ -free graphs  $G_n$ , where  $G_n$  has an optimal partition  $(U_1, U_2)$  with one class spanning<sup>5</sup>  $H$  on  $U_1 - W$  and  $|U_1 \cap W|$  is a set of isolated vertices, the other class,  $U_2$  spans an independent set, and, besides conditions (ii) and (iv) of Definition 17, there is no restriction on the cross-edges. The number of such graphs is at least  $(1 - o(1))2^{|U_1||U_2|}$ , as standard application of Chernoff's inequality implies that only  $o(1)2^{|U_1||U_2|}$  graphs violate these two conditions. (Here  $W \subset V(G_n)$  with  $O(1)$  elements.)

The second set,  $\mathcal{P}_{II}(n, \mathcal{L}; H, U_1, W)$ , is the family of  $\mathcal{L}$ -free graphs  $G_n$ , where in the optimal partition  $(U_1, U_2)$  of  $G_n$ ,  $U_1 - W$  spans  $H$ , and there is no restriction on the edges incident to  $W$ , and  $U_2$  spans any  $C_4$ -free graph on  $U_2 - W$  with  $e(G[U_2]) > 2n(\log n)^2$ .

We give an upper bound on the number of graphs in the second family: The number of ways to choose the horizontal edges adjacent to  $W$  is at most  $2^{|W|n}$ , the number of ways

<sup>5</sup>Here we really mean that  $H$  is spanned, not only the graph spanned is isomorphic to  $H$ .

to add  $e$  edges to  $U_2 - W$  is at most  $\binom{n^2}{e}$ . We estimate the number of possible ways to put edges between  $U_1 - W$  and  $U_2 - W$  more precisely. By Lemma 24, there are at least  $(n^{3/2}/20000)^2/n^2$  vertex disjoint  $P_3$ 's in  $U_1$ , and  $e^2/n^2$  in  $U_2$ . This gives

$$\frac{(n^{3/2}/20000)^2}{n^2} \times \frac{e^2}{n^2} = \frac{e^2}{4 \cdot 10^8 n}$$

pairs of edge-disjoint  $P_3$ 's. Between each pair, to avoid an  $O_6$ , instead of the  $2^9 = 512$  ways of adding the edges, there are only 511 ways (actually fewer). So the number of ways to add the cross edges is at most

$$2^{|U_1||U_2|} \left( \frac{511}{512} \right)^{e^2/(4 \cdot 10^8 n)}$$

This gives

$$\begin{aligned} \frac{|\mathcal{P}_{II}(n, \mathcal{L}, H, U_1, W) \cap \mathcal{P}^*(n, \mathcal{L})|}{|\mathcal{P}_I(n, \mathcal{L}, H, U_1, W)|} &\leq \frac{|\mathcal{P}_{II}(n, \mathcal{L}, H, U_1, W)|}{|\mathcal{P}_I(n, \mathcal{L}, H, U_1, W)|} \\ &\leq (1 + o(1)) 2^{|W|n} \binom{n^2}{e} \left( \frac{511}{512} \right)^{e^2/(4 \cdot 10^8 n)} \\ &\leq 2^{O(n) + e(O(\log n) - c \log^2 n)} \leq 2^{-\epsilon \log n}, \end{aligned} \tag{17}$$

for some positive constant  $c$ , where we used that  $e > n(\log n)^2$  and  $|W| = O(1)$ .

Note that  $\mathcal{P}_I(n, \mathcal{L}, H, U_1, W)$  is not a partition of  $\mathcal{P}^*(n, \mathcal{L})$ , otherwise we would be done, but sufficiently ‘‘close’’. As for any  $G_n \in \mathcal{P}^*(n, \mathcal{L})$  a partition  $(U_1, U_2)$  and a set  $W$  determines  $H$  spanned by  $U_1 - W$ ,  $G_n$  is in at most  $2^n n^h$  sets of  $\mathcal{P}_I(n, \mathcal{L}, H, U_1, W)$ . The number of ways to choose  $e$  is less than  $n^2$ , therefore we proved that for given graph spanned by  $U_1$  there many more  $\mathcal{L}$ -free graphs with  $U_2$  spanning an independent set than graphs with  $e(U_2) > 2n(\log n)^2$ .

The proof of (ii) is exactly the same, the only difference is that in the computation in (17) we have to use that  $e(G[U_2]) < n \log^2 n$  and that the graph spanned by  $U_2$  contains at least  $\log^4 n$  independent  $P_3$ s.  $\blacksquare$

## 5.2. Elimination of vertices with large horizontal degrees

We shall use the following well-known lemma on the maximum number of edges of a  $C_4$ -free bipartite graph.

**Lemma 26.** *Let  $G$  be a bipartite  $C_4$ -free graph with bipartition  $X, Y$ . Then*

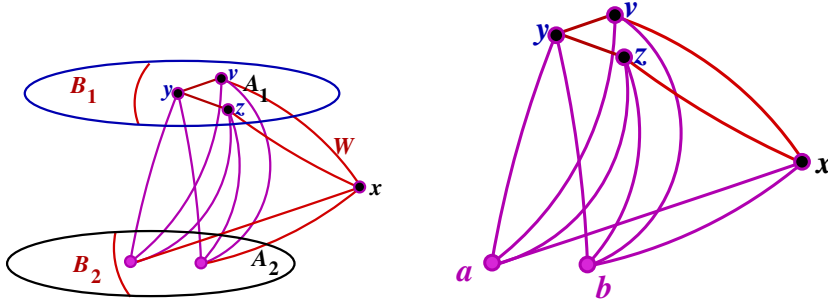
$$e(G) \leq |X| \sqrt{|Y|} + |X| + |Y|. \tag{18}$$

Denote by  $W^*(n, \mathcal{L})$  the family of graphs  $G_n \in \mathcal{P}^*(n, \mathcal{L})$  with an optimal partition  $(U_1, U_2)$ , satisfying (15) but violating (16), also assuming that  $W$ , the set of vertices with high horizontal vertices is non-empty. We shall estimate  $|W^*(n, \mathcal{L})|$ .

**Lemma 27.** *For  $n$  sufficiently large we have*

$$|W^*(n, \mathcal{L})| \leq |\mathcal{P}^*(n, \mathcal{L})| \cdot 2^{-(\epsilon n)^{3/2}/10}.$$

**Proof.** For a  $G_n \in \mathcal{P}^*(n, \mathcal{L})$  fix a vertex  $x \in W$  and denote  $A_i := \Gamma(x) \cap U_i - W$  and  $B_1 := U_1 - A_1 - W$ . (Note that we do not care in which class is  $x$  located.) Let  $vyz$  be a  $P_3$  in  $U_1 - W$  with  $v, z \in A_1$  and  $vy, yz$  edges. The key observation is that if  $|\Gamma^*({v, y, z}) \cap A_2| > 1$  then  $O_6$  is a subgraph in  $G$ :  $x, y, z, v$  form a  $C_4$  and the considered two points,  $a, b \in A_2$  are completely joined to this  $C_4$ . Therefore the number of ways to place edges between  $\{v, y, z\}$  and  $A_2$  is at most  $n7^{|A_2|}$ , instead of  $8^{|A_2|}$ : there is a ‘gain’ of  $n(7/8)^{|A_2|-1} < (7/8)^{(\varepsilon-o(1))n}$ . Similarly to the proof of Lemma 25, from this argument follows that at most  $|\mathcal{P}^*(n, \mathcal{L})| \cdot 2^{-(n)^{3/2}}$  graphs contain more than  $\sqrt{n} \log^2 n$  vertex independent  $P_3$ s like  $vyz$ .



As  $A_1$  spans a  $C_4$ -free graph with at most  $\sqrt{n} \log^2 n$  independent  $P_3$ s, by Lemma 24, we have that  $e(A_1) \leq 2n^{5/4} \log n$ . Let  $t$  denote the maximum number of independent  $P_3$ s with endpoints in  $A_1$  and middle vertices in  $B_1$ . Fix a maximal collection of independent  $P_3$ s of this type, denote by  $A_3$  the set of the endpoints of the paths, and  $B_3$  the set of middle vertices. Note that  $A_3 \subset A_1$  and  $B_3 \subset B_1$ . Using Lemma 26, and  $e(A_1 - A_3, B_1 - B_3) \leq 2|B_1| \leq 2n$ ,  $|A_3| = 2t, |B_3| = t \leq \sqrt{n} \log^2 n$ , we have that

$$\begin{aligned} e(A_1, B_1) &\leq e(A_3, B_3) + e(A_1 - A_3, B_3) + e(A_3, B_1 - B_3) + e(A_1 - A_3, B_1 - B_3) \\ &\leq \sqrt{n}3t + 4n \leq 5n \log^2 n. \end{aligned}$$

The conclusion is that there are only relatively few horizontal edges with at least one of the endpoints in  $A_1$ . This helps us to complete the proof. Indeed, the number of ways to choose an optimal partition, and  $x, A_1, A_2, W$ , and placing the horizontal edges incident to  $W$ , or inside  $U_2$  or  $A_1$  or between  $A_1$  and  $B_1$  is upper bounded by  $2^{n^{5/4} \log^3 n}$ .

Let  $f(m, \mathcal{M})$  denote the number of  $\mathcal{M}$ -free graphs on  $[m]$ . Recall that when  $\mathcal{L} = \{O_6\}$  then  $\mathcal{M} = \{C_4\}$  and when  $\mathcal{L} = \mathcal{P}(6, 12)$  then  $\mathcal{M} = \{C_3, C_4\}$ . Trivially,

$$f(\varepsilon n/2, \mathcal{M}) \geq 2^{((\varepsilon/2+o(1))n)^{3/2}/(2\sqrt{2})} \geq 2^{(\varepsilon n)^{3/2}/9}.$$

Using  $|U_1| < n/2 + o(n) < (1 + \varepsilon)n/2$ ,  $|B_1| \leq |U_1| - \varepsilon n < (1 - \varepsilon)n/2$ , we have

$$f(|B_1|, \mathcal{M})f(\varepsilon n/2, \mathcal{M}) \leq f(|B_1| + \varepsilon n/2, \mathcal{M}) \leq f(n/2, \mathcal{M}).$$

Putting together, we have that

$$\begin{aligned} |W^*(n, \mathcal{L})| &\leq f(|B_1|, \mathcal{M})2^{n^{2/4+n^{5/4} \log^3 n}} \leq 2^{n^{2/4+n^{5/4} \log^3 n}} \frac{f(n/2, \mathcal{M})}{f(\varepsilon n/2, \mathcal{M})} \\ &\leq (1 + o(1))|\mathcal{P}^*(n, \mathcal{L})|2^{n^{5/4} \log^3 n - (\varepsilon n)^{3/2}/9} \leq |\mathcal{P}^*(n, \mathcal{L})|2^{-(\varepsilon n)^{3/2}/10}. \end{aligned}$$

■

### 5.3. Completing the proof of the (6, 12)-theorem

Now it is time to separate the proofs of Theorems 4 and 5. First we prove Theorem 5. For a partition  $(U_1, U_2)$  of  $[n]$  and a graph  $H$  on  $U_1$  we let  $\mathcal{P}^*(n; 6, 12; U_1, H) \subset \mathcal{P}^*(n; 6, 12)$  be the family of graphs  $G_n$ , admitting an optimal partition  $(U_1, U_2)$ , with  $U_1$  spanning  $H$  and  $U_2$  being an independent set, and not having vertices with high horizontal degree. Using Lemmas 25 and 27, we know that in an optimal partition  $(U_1, U_2)$  of a typical (6, 12)-free graph  $G_n$  we have  $e(U_1) > n^{3/2}/20000$  and  $e(U_2) < n(\log n)^2$ , and every vertex of  $G_n$  has horizontal degree at most  $\varepsilon n$ ,  $U_1$  spans a  $(C_3, \mathcal{M})$ -free graph, and in  $U_2$  there are no  $\log^4 n$  independent  $P_3$ .

Assume that the maximum number of independent edges in  $U_2$  is  $t$ . By Lemma 24 there are at least  $(n^{3/2}/20000)^2/(4n^2) > n/(2 \cdot 10^9)$  independent  $P_3$ s in  $U_1$ . If between any pair of vertices spanning an edge in  $U_2$  and a triplet of vertices spanning a  $P_3$  in  $U_1$  there are 6 edges, then, as the triplet is a good 3-tuple in  $U_1$ , taking an extra vertex from their common neighborhood, we obtain 6 vertices spanning at least 12 edges. So not all the 6 cross-edges can be present at the same time, i.e., out of the 64 possibilities there are at most 63 realizable. Therefore we gain on the number of ways of putting the cross-edges a multiplicative factor at least

$$\left(\frac{63}{64}\right)^{tn/(2 \cdot 10^9)} = \left[\left(\frac{63}{64}\right)^{10^{-9}/2}\right]^{nt}. \quad (19)$$

However the number of ways to have a graph in  $U_2$  with maximum  $t$  independent edges and at most  $n(\log n)^2$  edges is much fewer:

Clearly, if  $t > \sqrt{n} \log^2 n$  then (19) is smaller than  $2^{-n^{-3/2} \log n}$  and we are done, as the gain beats the number of choices for the graph spanned by  $U_1$  and  $U_2$ .

Let us count the number of possible graphs  $G_n$  spanned by  $U_2$ , given the graph spanned by  $U_1$  and  $t$ : There are  $2t$  vertices covering all edges in  $U_2$ , each having horizontal degrees at most  $\varepsilon n$ . For each, the number of ways choosing the neighborhood is at most

$$\sum_{i \leq \varepsilon n} \binom{n}{i} \leq 2 \binom{n}{\varepsilon n} \leq \left(\frac{3}{\varepsilon}\right)^{\varepsilon n}.$$

Hence the number of the graphs spanned by  $U_2$  is at most

$$\binom{n}{2t} \left(\frac{3}{\varepsilon}\right)^{2t\varepsilon n} \leq \left(2^{O(\log n/n)} \left(\frac{9}{\varepsilon^2}\right)^\varepsilon\right)^{tn}.$$

Using that for  $\varepsilon$  sufficiently small  $(63/64)^{10^{-9}/2} (9/\varepsilon^2)^\varepsilon < 1 - 10^{-12}$ , we see that for each fixed graph  $H$  spanned by  $U_1$  and  $t$ , the number of (6, 12)-free graphs is at most  $(1 - 10^{-12})^n |\mathcal{P}^*(n; 6, 12; U_1, H)|$ . The number of choices for  $t$  is  $o(n)$ , and more importantly, by Lemma 19 no  $G_n \in \mathcal{P}^*(n; 6, 12)$  has more than  $2^{4H(4\delta p)n}$  optimal partitions, so for each  $G_n$ ,  $U_1$  and  $H$  can be chosen in at most  $2^{4H(4\delta p)n}$  ways, yielding that

$$\sum_{U_1, H} |\mathcal{P}^*(n; 6, 12; U_1, H)| \leq 2^{4H(4\delta p)n} (1 + o(1)) |\mathcal{P}^*(n; 6, 12)|.$$

Here the  $(1 + o(1))$  factor is needed, as the gain is with respect to all possible ways of placing the cross-edges, but only  $1 - o(1)$  fractions of them satisfy the conditions of Definition 17 (ii) and (iv). As  $\delta$  was chosen in Definition 14 satisfying (10), it is small enough to satisfy

$$(1 - 10^{-12})2^{4H(4\delta p)} < 1, \quad (20)$$

implying the theorem.

## 5.4. Completing the proof of the Octahedron Theorem

The proof of Theorem 4 goes along the lines of the previous subsection. For a  $U_1, U_2$  partition of  $[n]$  and a graph  $H$  spanned by  $U_1$  let  $\mathcal{P}^*(n, O_6; U_1, H) \subset \mathcal{P}^*(n, O_6)$  be the family of graphs  $G_n$  with optimal partition  $(U_1, U_2)$ , where  $U_1$  spans  $H$  and  $U_2$  spans a graph with maximum degree at most 1, and having no high horizontal degree. Using Lemmas 25 and 27, we may assume that in an optimal partition  $(U_1, U_2)$  of a typical  $O_6$ -free graph  $G_n$  we have  $e(U_1) > n^{3/2}/20000$  and  $e(U_2) < n(\log n)^2$ , and every vertex of  $G_n$  has horizontal degree at most  $\varepsilon n$ ,  $U_1$  spans a  $C_4$ -free graph, and in  $U_2$  there are no more than  $\log^4 n$  independent paths  $P_3$ . Now we fix the maximum number of independent  $P_3$ s in  $U_2$ , and then the rest of the graph spanned by  $U_2$  is  $P_3$ -free.

Let  $D(k)$  denote the number of labelled  $P_3$ -free graphs on  $[k]$ . Trivially,  $D(k)$  is a monotone increasing function. Let  $t$  be the maximum number of independent  $P_3$ s in  $U_2$ . Like in the (6, 12)-case in the previous subsection we gain a factor

$$\left(\frac{511}{512}\right)^{tn/(2 \cdot 10^9)}$$

on the number of ways of choosing the cross-edges. Now we count the number of ways of choosing the graph spanned by  $U_2$ , given the vertex set  $U_2$ , and  $t$ . There are at most  $\binom{n}{3t}$  ways of choosing  $3t$  vertices spanning  $t$  paths  $P_3$ ; there are at most  $D(|U_2| - 3t)$  ways of choosing the edges in  $U_2$  not incident to these paths; finally, the number of ways of adding the horizontal edges to a vertex of a path is at most

$$\sum_{i \leq \varepsilon n} \binom{n}{i} \leq 2 \binom{n}{\varepsilon n} \leq \left(\frac{3}{\varepsilon}\right)^{\varepsilon n}.$$

To summarize, for given  $H, U_1$  and  $t$ , the number of graphs spanned by  $U_2$  is at most

$$\left(\frac{3}{\varepsilon}\right)^{3\varepsilon tn} \binom{n}{3t} D(|U_2| - 3t) \leq \left[2^{O(\log n/n)} \left(\frac{3^3}{\varepsilon^3}\right)^\varepsilon\right]^{tn} D(|U_2|).$$

Using that the  $\varepsilon$  chosen in Definition 14 is sufficiently small to satisfy

$$(511/512)^{10^{-9}/2} (27/\varepsilon^3)^\varepsilon < 1 - 10^{-14},$$

so for each fixed graph spanned by  $U_1$  and  $t$ , the number of  $O_6$ -free graphs is at most  $(1 - 10^{-14})^n (1 + o(1)) |\mathcal{P}^*(n; O_6; U_1, H)|$ . Here the  $(1 + o(1))$  factor is needed, as the gain is with respect to all possible ways of placing the cross-edges, but only  $1 - o(1)$  fraction of

them satisfy the conditions of Definition 17 (ii) and (iv). The number of choices for  $t$  is  $o(n)$  and, more importantly, by Lemma 19, no  $G_n \in \mathcal{P}^*(n, O_6)$  has more than  $2^{4H(4\delta p)n}$  optimal partitions (so for each  $G_n$  there are no more than  $2^{4H(4\delta p)n}$  choices of  $U_1$  and  $H$ ), yielding

$$\sum_{U_1, H} |\mathcal{P}^*(n; O_6; U_1, H)| \leq 2^{4H(4\delta p)n} |\mathcal{P}^*(n, O_6)|.$$

As  $\delta$  has been chosen small enough to satisfy (10) our theorem follows.

## 6. Comments

Our main motivation to write this paper was to investigate to what extent Theorem 2 is sharp.

(i) For many families  $\mathcal{L}$ , for almost all  $\mathcal{L}$ -free graphs  $G_n$  the vertex set  $[n]$  can be partitioned into  $p$   $\mathcal{M}$ -free classes, i.e. to achieve this we do not have to delete vertices.

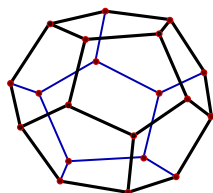
In principle it could happen that for all  $\mathcal{L}$  the deletion is unnecessary. Example 12 disproves this, showing that there exist families  $\mathcal{L}$  for which this vertex deletion is necessary.

(ii) There can also be an other problem with the sharpness, namely, that the conclusion of the theorem is too weak. E.g., in Theorem 4 we do not have to delete vertices and only one  $G[U_i]$  should be  $C_4$ -free, about the other we know a much stronger assertion that it is  $P_3$ -free. We are looking for structural descriptions that are almost necessary and sufficient, in the sense that we wish to have a property  $\mathcal{Q}$  for which all the graphs of property  $\mathcal{Q}$  are  $\mathcal{L}$ -free and almost all  $\mathcal{L}$ -free graphs have the property  $\mathcal{Q}$ . Our theorems below are such statements.

Asserting that each  $G[U_i]$  is  $\mathcal{M}$ -free is not sufficient: there are classes  $\mathcal{L}$  where, if we take  $\mathcal{M}$ -free graphs  $G^{(i)}$ , the product  $G^{(1)} \otimes \dots \otimes G^{(p)}$  is not necessarily  $\mathcal{L}$ -free. For example, for  $\mathcal{L} = \{O_6\}$  the decomposition family is  $\mathcal{M} = \{C_4\}$ , but if for  $i = 1, 2$   $G^{(i)}$  is  $C_4$ -free and contains  $P_3$  then  $G^{(1)} \otimes G^{(2)}$  contains  $O_6$ . On the other hand if  $G^{(1)}$  is  $C_4$ -free and  $G^{(2)}$  is  $P_3$ -free, then  $G^{(1)} \otimes G^{(2)}$  is  $O_6$ -free. We proved that for almost all  $O_6$ -free graphs  $G_n$ ,  $V(G_n)$  can be partitioned into  $U_1$  and  $U_2$  so that  $G[U_1]$  is  $C_4$ -free and  $G[U_2]$  has a more restricted structure, it is  $P_3$ -free.

**Remark 28.** Generally we wish to prove that almost all graphs not containing the considered  $L$  are very similar to subgraphs of the extremal graphs. In many cases, where the extremal graph for  $\mathcal{L}$  is  $H(n, p, s)$ , we wish to prove that from almost all  $\mathcal{L}$ -free graphs on  $n$  vertices belong to  $\mathcal{A}(n, p, s)$ .

To get some insight into this phenomenon, it would be useful to resolve some special cases of Conjecture 11, e.g., when  $L$  is the dodecahedron graph,  $D_{12}$ .



Observe that  $D_{12} \subseteq Q(n, 2, 6)$ , but one cannot delete 5 vertices from  $D_{12}$  to get a bipartite graph. Thus the graphs in  $\mathcal{A}(n, 2, 6)$  do not contain  $D_{12}$ . In 1974 Simonovits [31] proved that there is an  $n_0 = n_0(D_{12})$  such that if  $n > n_0$  then  $H(n, 2, 6)$  is the unique extremal graph for  $D_{12}$ .

**Problem 29.** Is it true that almost all  $D_{12}$ -free graphs we can delete 5 appropriate vertices to get a bipartite graph?

The previous problem is a special case of the next one.

**Problem 30.** Let  $L$  be fixed,  $K_3 \not\subseteq L$ . Is it true that if  $\mathcal{M}(L)$  contains  $s$  independent edges and  $H(n, p, s)$  is an extremal graph for  $L$ , then almost all  $L$ -free graphs are in property  $\mathcal{A}(n, p, s)$ ?

Clearly,  $O_6 = K(2, 2, 2)$ . One could ask that what can be said about the structure of almost all  $K(a_0, a_1, \dots, a_p)$ -free graphs. It was proved by Erdős and Simonovits [14] that if  $a_0 \leq a_1 \leq \dots \leq a_p$ , and  $a_0 = 2, 3$ , and  $n$  is large enough, then every extremal graph  $G_n$  of the  $(p+1)$ -chromatic  $K(a_0, a_1, a_2, \dots, a_p)$  has the following structure:  $V(G_n)$  can be  $p$ -partitioned so that one of the classes spans a  $K(a_0, a_1)$ -free graph, and the others span graphs with maximum degree  $a_1 - 1$ . It can easily be checked that no graph with such a structure contains a  $K(a_0, a_1, a_2, \dots, a_p)$ . This motivates the following conjecture.

**Conjecture 31.** *Let  $p$  and  $2 \leq a_0 \leq \dots \leq a_p$  be fixed integers. Then for  $L = K(a_0, a_1, \dots, a_p)$ , almost every  $L$ -free graph  $G_n$  has a partition  $(U_1, \dots, U_p)$  where  $G[U_1]$  is  $K(a_0, a_1)$ -free, and  $G[U_i]$  is a graph with maximum degree less than  $a_1$  for  $i > 1$ .*

What are the main obstacles to proving Conjecture 31? The first one is that the order of magnitude of the number of edges of the extremal graph of  $K(a_0, a_1)$  is known only if  $a_0 = 2, 3$  or  $a_0 \ll a_1$ . Here, probably it would be sufficient to start our proof if we knew only that

$$\text{ex}(n, K(a_0 - 1, a_1)) = o(\text{ex}(n, K(a_0, a_1))).$$

There is another, more important step missing from our proof. We would need the following statement.

**Conjecture 32.** *If  $\chi(L) = 2$ , then there is a  $c = c(L) > 0$  such that almost all  $L$ -free graphs of order  $n$  have at least  $c \cdot \text{ex}(n, L)$  edges.*

This is known only for  $L = C_4$  and  $C_6$ , (see Kleitman and Wilson [20]). We expect that one could prove results for  $L = C_6 \otimes K(a_2, \dots, a_p)$  that are similar to what we are aiming for in Conjecture 31.

If Conjecture 32 were true for  $H = K(a_0, a_1)$  for some  $a_0 \in \{2, 3\}$  and  $a_1$ , then we expect Conjecture 31 to be true for the same  $a_0, a_1$  and any  $p, a_2, \dots, a_p$  satisfying the conditions.

Finally, we conjecture the following variant of Conjecture 32.

**Conjecture 33.** *If  $\chi(L) = 2$ , then there is a  $c = c(L) > 0$  such that almost all  $L$ -free graphs of order  $n$  have at most  $(1 - c) \cdot \text{ex}(n, L)$  edges.*

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