

On Folkman Numbers

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Abstract

This survey contains a comprehensive overview of the results relating to Folkman numbers, a topic in general Ramsey Theory. We present data which, to the best of our knowledge, includes all known nontrivial values and bounds for definite Folkman numbers of arbitrary forms. In particular, we present results, with complete citations, for general edge and vertex Folkman numbers of the form $F(a_1, \dots, a_r; q) = \min\{|V(G)| : G \rightarrow (a_1, \dots, a_r; q) \text{ and } \omega(G) < q\}$, where the edge and vertex Folkman numbers consist of edge and vertex colorings satisfying this property.

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Chapter 1

Introduction

1.1 Scope and Notation

Folkman numbers, first introduced by Folkman in 1970 [13], are a branch of Ramsey theory concerned with the graphs in which a monochromatic copy of a particular subgraph exists for all (edge or vertex) colorings. We write $G \rightarrow (a_1, \dots, a_k; p)^e$ iff for every edge coloring of an undirected simple graph G not containing K_q , there exists a monochromatic K_{a_i} in color i for some $i \in \{1, \dots, k\}$. The edge Folkman number is defined as $F_e(a_1, \dots, a_k) = \min\{|V(G)| : G \rightarrow (a_1, \dots, a_k; q)^e\}$. Similarly, the vertex Folkman number is defined as $F_v(a_1, \dots, a_k) = \min\{|V(G)| : G \rightarrow (a_1, \dots, a_k; q)^v\}$. In 1970 Folkman proved that for all $k > \max(s, t)$, edge- and vertex-Folkman numbers $F_e(s, t; k)$ and $F_v(s, t; k)$ exist. The sets $\mathcal{F}_v(s, t; q) = \{G : G \rightarrow (s, t)^v \wedge \omega(G) < q\}$ and $\mathcal{F}_e(s, t; q) = \{G : G \rightarrow (s, t)^e \wedge \omega(G) < q\}$ are the *vertex* and *edge Folkman graphs*, respectively.

In this survey we only consider finite, simple graphs (i.e. those without loops and multiple edges). We denote the vertex and edge set of a graph G using $V(G)$ and $E(G)$, respectively. $N(v)$ is the open neighborhood of vertex $v \in V(G)$, consisting of all vertices adjacent to v . $G[V], V \subset V(G)$ denotes the subgraph induced by the vertices V . Also, $\alpha(G)$ and $\omega(G)$ denote the cardinality of a maximum independent set of G (i.e. a set for which all pairwise vertices are not adjacent in G) and the cardinality of the largest clique in G (i.e. a set for which all pairwise vertices are adjacent in G). The chromatic number of G , which is the minimal number of colors required to a vertex two-coloring of G , is denoted as $\chi(G)$. The girth of a graph G , denoted as $g(G)$, is the length of the shortest cycle in G . Finally, we denote the complement of a graph G as G^c .

We denote $G - v = G[V(G) \setminus v]$. We also denote $G - e$ as the subgraph of G such that $V(G - e) = V(G)$ and $E(G - e) = E(G) \setminus \{e\}$. Similarly, we denote $G + e$ as the supergraph of G such that $V(G + e) = V(G)$ and $E(G + e) = E(G) \cup \{e\}$. Finally, we denote the union of two graphs G_1 and G_2 as $G_1 + G_2$, where $V(G_1 + G_2) = V(G_1) \cup V(G_2)$ and $E(G_1 + G_2) = E(G_1) \cup E(G_2) \cup \{(u, v) : u \in V(G_1) \text{ and } v \in V(G_2)\}$. From this definition, it is clear that $\omega(G_1 + G_2) = \omega(G_1) + \omega(G_2)$. As a special case, we denote $K_n - C_m$, $m \leq n$, as the induced subgraph of K_n obtained by removing all edges on some cycle C_m . The k th power of a graph G , denoted as G^k , is the graph $(V(G), E(G) \cup \{(u, v) : d(u, v) < k\})$.

A *hypergraph* G is the pair $(V(G), E(G))$ where $V(G)$ is the set of vertices and $E(G) = 2^{V(G)}$ is the set of hyperedges. Traditional definitions for graph order and clique sizes apply to hypergraphs. A hypergraph is *k-uniform* if every edge $e \in E(G)$ appears exactly k times in the set (i.e. it has cardinality k).

Classical Ramsey numbers $R(s, t)$ are pivotal in the study of Folkman numbers. We define $R(s, t)$ as the smallest integer n such that every 2-coloring of the edges of K_n there exists a monochromatic K_s in the first color or K_t in the second color. In other words, $R(s, t) = \min\{n | K_n \rightarrow (s, t)^e\}$. We often generalize the arrowing property to graphs G and H such that $R(G, H) = \min\{n | K_n \rightarrow (G, H)^e\}$. Radziszowski [58] maintains a regularly updated survey containing the most recent results with known bounds and exact values for small Ramsey numbers.

We begin our exploration of finite Folkman numbers in Chapter 2.2.1 with a discussion of

classical Folkman numbers - those edge and vertex numbers of the form $F(s, t; q)$. We then discuss multicolor Folkman numbers in Chapter 3.4. Asymptotic results are then presented in Chapter 4.0.1, followed by a discussion of the complexity theoretical results regarding Folkman numbers and their computations in Chapter 5

Chapter 2

Classical Folkman Numbers

In this section we present results for edge and vertex Folkman numbers. In some cases there is an important connection between these two values. For example, Piwakowski et al. showed that $G \rightarrow (3, 3; 4)^v$ implies $G + x \rightarrow (3, 3; 5)^e$ for some additional vertex x [56]. Such relations have been important in the computation of various Folkman numbers, as we will describe in the following sections.

2.1 Edge Folkman Numbers $F_e(s, t; q)$

It is clear that $G \rightarrow (s, t; q)^e$ implies that $\omega(G) \geq \max\{s, t\}$ [13], which means that $F_e(s, t; q)$ exists if and only if $q > \max\{s, t\}$. It is well known that as q decreases, the difficulty in computing $F_e(s, t; q)$ increases. For this reason, exact values for $F_e(s, t; 4)$ and $F_e(s, t; 5)$ have been among the most well-studied problems. We present all known values of these two numbers in Tables 2.2 and 2.2.

Table 2.1: Values and Bounds for Edge Folkman numbers of the type $F_e(s, t; 7)$.

(s, t)	2	3	4	5	6	7	8	9	10	11	12	13
2												
3		6 [15]										
4												
5												
6												
7												
8												

Table 2.2: Values and Bounds for Edge Folkman numbers of the type $F_e(s, t; 6)$.

(s, t)	2	3	4	5	6	7	8	9	10	11	12	13
2												
3		8 [15]										
4												
5												
6												
7												
8												

Table 2.3: Values and Bounds for Edge Folkman numbers of the type $F_e(s, t; 5)$.

(s, t)	2	3	4	5	6	7	8	9	10	11	12	13
2												
3		15 [56]		≤ 21 [28]								
4												
5												
6												
7												
8												

Table 2.4: Values and Bounds for Edge Folkman numbers of the type $F_e(s, t; 4)$.

(s, t)	2	3	4	5	6	7	8	9	10	11	12	13
2												
3		≥ 19 [57], ≤ 786 [32]										
4												
5												
6												
7												
8												

2.1.1 Triangle-Free Graphs

It is a well-known result that if $k > R(s, t) \rightarrow F_e(s, t; k) = R(s, t)$. Conversely, when $k \leq R(s, t)$, very little is known about the bounds of $F_e(s, t; k)$. Table 2.5 shows that as the value of k decreases, the problem of finding $F_e(s, t; k)$ becomes increasingly difficult.

$F_e(3, 3; 4)$ History

The number $F_e(3, 3; 4)$ has a particular intriguing history, starting with the question first posed by Erdős in [11]:

What is the order of the smallest K_4 -free graph for which any 2-coloring of its edges must contain at least one monochromatic triangle?

This question is equivalent to finding the smallest K_4 -free graph that is not the union of two triangle-free graphs. Folkman first proved the existence of such graphs in 1970, showing that for all $k > \max\{s, t\}$, $F_e(s, t; k)$ must exist [13].

Erdős followed this result by offering a \$100 prize (equivalent to 300 Swiss francs at the time) for determining if $F_e(3, 3; 4) < 10^{10}$. In 1988, Spencer [60] presented the first proof of graphs below this bound using a probabilistic approach, which was shown to contain an error by Hovey in 1989, who adjusted the bound to $F_e(3, 3; 4) < 3 \times 10^9$. More than twenty years passed before Dudek and Rödl [6] proposed a construction technique for Folkman graphs based on the

Table 2.5: Folkman number bounds for small values of k . Note that $R(3, 3) = 6$.

k	$F_e(3, 3; k)$	graphs	reference
≤ 7	6	K_6	folklore
6	8	$C_5 + K_3$	[15]
5	15	659 graphs	[56]
4	≤ 786	G_{786}	[32]

Table 2.6: History of $F_e(3, 3; 4)$

Year	Bounds	Who	Ref.
1967	any?	Erdős-Hajnal	[11]
1970	exist	Folkman	[13]
1972	≥ 10	Lin	[33]
1975	$\leq 10^{10}?$	Erdős offers \$100 for proof	
1986	$\leq 8 \times 10^{11}$	Frankl-Rödl	[14]
1988	$\leq 3 \times 10^9$	Spencer	[60]
1999	≥ 16	Piwakowski et al. (implicit)	[56]
2007	$\geq 19, \leq 127?$	Radziszowski-Xu	[57]
2008	≤ 9697	Lu	[34]
2008	≤ 941	Dudek-Rödl	[6]
2012	≤ 786	Lange et al.	[32]
2012	$\leq 100?$	Graham offers \$100 for proof	

maximum cut of a related graph that was used to improve the bound to $F_e(3, 3; 4) \leq 941$. Lange et al. [32] further improved this bound to $F_e(3, 3; 4) \leq 786$ with the same technique using the Geomans-Williamson MAX-CUT approximation algorithm. The conjecture that $F_e(3, 3; 4) \leq 127$ proposed by Radziszowski et al. [57] is still an open problem, and is motivated by the intuition that $G_{127} = (\mathbb{Z}_{127}, \{(x, y) | x - y \equiv \alpha^3 \pmod{127}\})$ contains many triangles and small dense subgraphs. Following in the footsteps in Erdős, Graham offered a \$100 prize for proving that $F_e(3, 3; 4) \leq 100$.

Open Problem: $F_e(3, 3; 4) \leq 100?$

The lower bound of $F_e(3, 3; 4) \geq 10$ was first proved by Lin in 1972 [33]. Piwakowski et al. [56] improved this bound to $F_e(3, 3; 4) \geq 16$ by enumerating all graphs in $\mathcal{F}_e(3, 3; 5)$ and proving that all of them contain K_4 's. In 2007, Radziszowski et al. [57] pushed this bound to $F_e(3, 3; 4) \geq 19$ with a construction technique that relied on the fact that $G \rightarrow (3, 3; 4)^v$ implies $G + x \rightarrow (3, 3; 5)^e$ and $F_e(3, 3; 5) = 15$. Table 2.7 enumerates these developments leads us to the current state of the field.

$F_e(3, 3; 5)$ History

This number also has a dated history, starting with the existential question posed by Erdős et al. in 1967 [11]. However, the first proof of the existence of this number predates Erdős in an unpublished manuscript by Pösa. A viable upper bound was first proven by Schöuble [] in 1969, shortly after the proposition by Erdős et al., in which it was shown that $F_e(3, 3; 5) \leq 42$. Graham and Spencer [16] improved this bound to $F_e(3, 3; 5) \leq 23$ in 1971, and further conjectured that $F_e(3, 3; 5) = 23$ without supporting reasoning. This bound was subsequently reduced by Irving [22] in 1973. At this point, work on the upper bound diverged. Hadziivanov and Nenov [19] were able to construct a 16-vertex graph in $\mathcal{F}_e(3, 3; 5)$, and Nenov [41] further improved this bound with a 15-vertex graph in $\mathcal{F}_e(3, 3; 5)$, thus proving that $F_e(3, 3; 5) \leq 15$. Hadziivanov and Nenov [20] found another such graph on 15 vertices in 1984. Years later, Erickson [12] found a 17-vertex graph in $\mathcal{F}_e(3, 3; 5)$ and subsequently conjecture that $F_e(3, 3; 5) = 17$. However, Bukor [2] disproved this conjecture by showing the same 16-vertex construction presented in [19]. In 1996, the upper bound of 15 was verified once more by Urbański [61] with a different construction of the 15-vertex graph in [41]. The lower bound of $F_e(3, 3; 5)$ has much less history. In 1972 Lin [33] proved that $F_e(3, 3; 5) \geq 10$, which was subsequently improved by Nenov [40] to $F_e(3, 3; 5) \geq 11$, and then by Hadziivanov and Nenov [21] to $F_e(3, 3; 5) \geq 12$. The final value of $F_e(3, 3; 5) = 15$, proven by Piwakowski et al. [56] in 1999, was shown by constructing all 659 15-vertex graphs in $\mathcal{F}_e(3, 3; 5; 15)$, where each such graph has a K_4 .

CAW: fill in the table with the paragraph contents

Table 2.7: History of $F_e(3, 3; 5)$

Year	Bounds	Who	Ref.
1967	any?	Erdős-Hajnal	[11]

2.1.2 $F_e(a_1, \dots, a_r; R(a_1, \dots, a_r))$

Folkman numbers of the form $F_e(a_1, \dots, a_r; R(a_1, \dots, a_r))$ are very difficult to find. To date, only a few results are known, as shown below.

- $F_e(3, 3; 6) = 8$ [15]. This was shown with the graph $G = K_8 - C_5 = K_3 + C_5 \rightarrow (3, 3)^e$.
- $F_e(3, 4; 9) = 14$ [46].
- $F_e(3, 5; 14) = 16$ [33].
- $F_e(4, 4; 18) = 20$ [33].
- $F_e(3, 3, 3; 17) = 19$ [33].

2.1.3 Special Cases

Other special cases of edge Folkman numbers exist which do not fall under the typical two-color form. We present these results below.

- $F_e(3, 4; \leq 10) = 9$ (K_9 since $R(3, 4) = 9$ [58])
- $F_e(3, 4; 9) = 14$ shown by the critical graph $K_4 + C_5 + C_5$ [46]
- $F_e(3, 4; 8) = 16$ shown by the critical graph $K_4 + C_5 + C_5 + C_5$ [24]
- $F_e(3, 5; 14) = 16$

Need citation

- $F_e(4, 4; 18) = 20$

Need citation

- $F_e(3, 7; 22) \geq 27$

Need citation

- $F_e(3, 5; 8) \leq 21$ [28], shown with the distinguishing graph $G = K_8 + Q$ (where Q is the graph shown in Figure 3.2), which improved the upper bound of $F_e(3, 5; 8) \leq 24$ proven by Kolev and Nenov in 2008 [28]. Since $\omega(K_8 + Q) = \omega(K_8) + \omega(Q)$ and $\omega(Q) = 4$ [17], we have that $\omega(G) = 12$. Thus, since $|V(G)| = 21$ and $G \rightarrow (3, 5)^e$, $F_e(3, 5; 13) \leq 21$ [28]. The best known lower bound for this number, $F_e(3, 5; 13) \geq 18$, was shown by Lin [33] in 1972. Nenov [43] showed that the equality $F_e(3, 5; 13) = 18$ is only possible by proving the arrowing $K_8 + C_5 + C_5 \rightarrow (3, 5)^e$, but no one has been able to check this yet.
- $F_e(4, 4; 17) \leq 25$ [31]. This was the first result on the upper bound of this number, as previously the only known fact was that the number existed, as proved by Folkman.

Open Problem: $F_e(3, 4; 7) = ?$ **Open Problem:** $F_e(3, 5; 13) = 18?$

2.2 Vertex Folkman Numbers $F_v(s, t; q)$

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$F_v(2, 2; 3) = 5$ using the graph $C_5 \rightarrow (2, 2)$ [30]

Table 2.8: Values and Bounds for Vertex Folkman numbers of the type $F_v(s, t; 6)$.

(s, t)	2	3	4	5	6	7	8	9	10	11	12	13
2												
3												
4												
5												
6												
7												
8												

Table 2.9: Values and Bounds for Vertex Folkman numbers of the type $F_v(s, t; 5)$.

(s, t)	2	3	4	5	6	7	8	9	10	11	12	13
2												
3												
4			≥ 16 [54] ≤ 25 [30]									
5												
6												
7												
8												

Table 2.10: Values and Bounds for Vertex Folkman numbers of the type $F_v(s, t; 4)$.

(s, t)	2	3	4	5	6	7	8	9	10	11	12	13
2	13 [49]											
3		14 [56]										
4												
5												
6												
7												
8												

2.2.1 Special Cases

CAW: TODO

Chapter 3

General Folkman Numbers

General Folkman numbers are typically unconstrained in the number of r colorings used in their specification. Variations of these general, or multicolor, Folkman numbers vary either the number of colors r or the colors (a_i) themselves. Many interesting results have been derived for these types of problems. Research for general Folkman numbers is targeted at finding bounds for a variety of Folkman number classes, often times leading to explicit values for such classes. We will discuss all related results in the following sections. First, however, we define some important terms and notation that will be used in this discussion.

For Folkman numbers $F(a_1, \dots, a_r; q)$ we define $m = \sum_{i=1}^r (a_i - 1) + 1$ and $p = \max\{a_1, \dots, a_r\}$, as was first done by Luczak et al. in [35]. Many results make use of these values. It is clear that $K_m \rightarrow (a_1, \dots, a_r)^v$ and $K_{m-1} \not\rightarrow (a_1, \dots, a_r)^v$, so if $q \geq m + 1$ then $F_v(a_1, \dots, a_r; q) = m$. An (a_1, \dots, a_r) -vertex minimal graph G is one such that $G \in \mathcal{F}_v(a_1, \dots, a_r; q)$ and $G - v \notin \mathcal{F}_v(a_1, \dots, a_r; q)$ for all $v \in V(G)$. Similarly, an (a_1, \dots, a_r) -edge minimal graph G is one such that $G \in \mathcal{F}_e(a_1, \dots, a_r; q)$ and $G - e \notin \mathcal{F}_e(a_1, \dots, a_r; q)$ for all $e \in E(G)$. Finally, since it is well known that if $F_v(a_1, a_2, \dots, a_r; q) = F_v(a_2, \dots, a_r; q)$ if $a_1 = 1$, we assume $a_i \geq 2$ for all $1 \leq i \leq r$ unless otherwise stated.

3.1 Multicolor Edge Folkman Numbers

In 1983, Nenov [43] showed that for integer colors a_1, \dots, a_r , where $a_i \geq 2$ for all $1, \dots, r$, $r \geq 2$, then $F_e(a_1, \dots, a_r; R(a_1, \dots, a_r) - 2) \geq R(a_1, \dots, a_r) + 6$. The Folkman number $F_e(3, 3, 3; 15) = 23$ is one such number of this kind [42]. Since $a_i \geq 3$ and $r \geq 2$, $R(a_1, \dots, a_r) > 2 + \max\{a_1, \dots, a_r\}$, which implies that such Folkman numbers exist. The exact value of $F_e(a_1, \dots, a_r; R(a_1, \dots, a_r) - 2) = R(a_1, \dots, a_r) + 6$ was shown to be true if and only if $K_{R-7} + Q \rightarrow (a_1, \dots, a_r)^e$ or $K_{R-9} + C_5 + C_5 + C_5 \rightarrow (a_1, \dots, a_r)^e$, where $R = R(a_1, \dots, a_r)$. In this case, Q is the graph shown in Figure 3.2. Based on this result, Nenov showed that $F_e(3, 5; 12) \geq 12$ and $F_e(4, 4; 16) \geq 24$. In combination with the bound $F_e(3, 4; 7) \geq 15$ and $F_e(3, 4; 8) = 16$ (found in [24]), the bound $F_e(3, 4; 7) \geq 17$ emerges. Of further interest, the Folkman number $F_e(3, 3, 3; 15) = 23$ proves that $K_8 + C_5 + C_5 + C_5 \rightarrow (3, 3, 3)^e$ [55].

General upper bounds for edge Folkman numbers have been found to be closely related to certain Ramsey numbers. In particular, Kolev [31] considered the following relationship. Let $a, \alpha \in \mathbb{Z} \cup \{0\}$, such that $R(3, a) = R(3, a - 1) + a - \alpha$, $\alpha \geq 4$. Under these conditions, given the

existence of a graph U such that $\omega(U) = a - 1$, $U \rightarrow (a - 1, a - 2)^v$, and $U \rightarrow (3, \overbrace{a - 3, \dots, a - 3}^r)^v$, and $R(3, a) - 3a + \alpha + 5 \geq R(3, a - 2)$, then $F_e(3, a; R - a + \alpha + 4) \leq R(3, a) - 2a + \alpha + 4 + |V(U)|$. Searching for such graphs U is very much a nontrivial problem, and to date there have been no such graphs that serve as appropriate candidates for this theorem.

- $F_e(3, 3, 3; 17) = 19$

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- $F_e(3, 3, 3; 16) = 21$

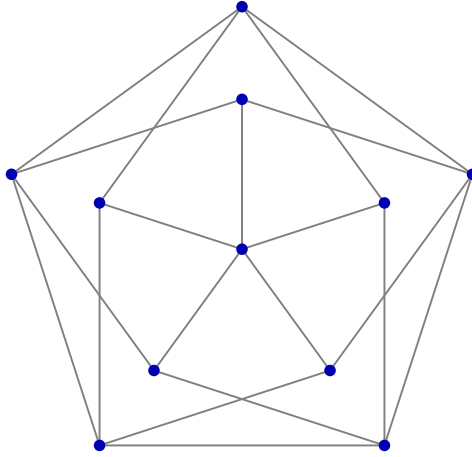


Figure 3.1: The Grötzsch graph showing that $F_e(2, 2, 2; 3) = 11$.

Need citation

3.2 Vertex Folkman Numbers

Folkman [13] showed that $F_v(a_1, \dots, a_k; q) = m$ for $q > m$ and $F_v(a_1, \dots, a_k; q) = a + m$ for $q = m$. To date, few exact values for $F_v(a_1, \dots, a_r; m - 1)$, are known. For this reason, we enumerate those known values below.

- $F_v(2, 3, 3; 5) = 12$

Need citation

- $F_v(3, 3; 4) = 14$. The inequality $F_v(3, 3; 4) \leq 14$ was proven by Nenov [41] in 1981 with a Ramsey graph $R(3, 3)$ that does not contain a clique of size 4, and the inequality $F_v(3, 3; 4) \geq 14$ was proven by Piwakowski et al. [56] in 1999 using computations to exhaustively check all possible Folkman graphs containing less than 14 vertices.
- $F_v(2, 2, 2; 3) = 11$, shown by the graph in Figure 3.1 []
- $F_v(2, 2, 2, 2; 4) = 11$, indicating the smallest 5-chromatic K_4 -free graph has 11 vertices [44]
- $F_v(2, 2, 2, 2; 3) = 22$, indicating the smallest 5-chromatic K_4 -free graph has 22 vertices [23]

In [53], Nenov proved a very interesting result for Folkman numbers of the form $F_v(3, \dots, 3) = \min\{|V(G)| : G \rightarrow \underbrace{(3, \dots, 3)}_r \text{ and } \omega(G) < 2r\}$, showing that $F_v(3, \dots, 3; 2r) = 2r + 7, r \geq 3$. This

was an improvement on the bounds of $2r + 5 \leq F_v(3, \dots, 3; 2r) \leq 2r + 10, r \geq 4$, proven by Luczak et al. [36]. A similar bound of $2r + 6 \leq F_v(3, \dots, 3) \leq 2r + 8, r \geq 3$, was proven by Nenov et al. in [48].

In 2001, Luczak et al. [36] showed that Vertex Folkman numbers of the form $F_v(a_1, \dots, a_r; m \geq p + 1)$, where $r \geq 2$, are equal to $m + p$. Furthermore it was shown that if $G \rightarrow (a_1, \dots, a_r)$, $\omega(G) < m$, and $|V(G)| = m + p$, then $G = K_{m+p} - C_{2p+1}$. Nenov provided a similar proof for this result in [48], in which he also showed that for $a_1, \dots, a_r, r \geq 2$, and positive integers m and p such that $m \geq p + 2$, $F_v(a_1, \dots, a_r; m - 1) \geq m + p + 2$.

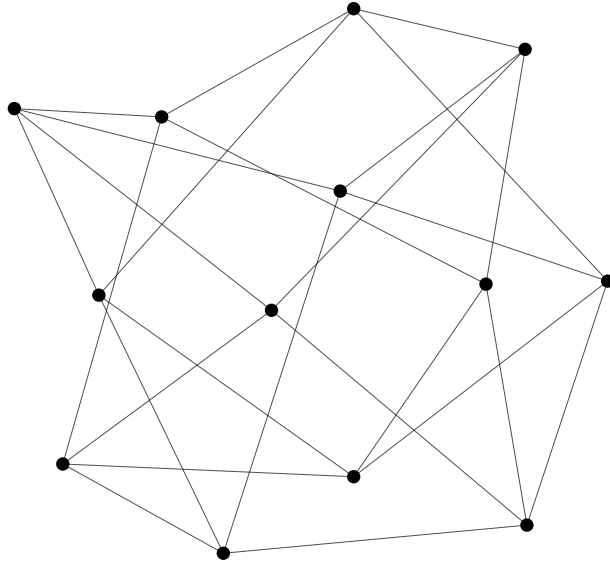


Figure 3.2: The Nenov graph from [55].

3.2.1 $F_v(a_1, \dots, a_r; q = m)$

In 2001, Luczak et al. [36] proved that $F_v(a_1, \dots, a_r; q) \geq 2m - q + 1$. Computing the vertex Folkman number becomes very interesting when $q = m$, and Luczak went on to construct very large classes, and in certain cases, infinitely many graphs that satisfy this property. Let $k \in \{a_r, a_r + 1, \dots, m - 1\}$, n an integer such that $n > 2k$, $s = \gcd\{s, k\}$, and $t = k/s$. Using the graph $G = G(n, k) = C_n^{k-1} + K_{m-k-1}$, Luczak et al. showed that $G \in \mathcal{F}_v(a_1, \dots, a_r; q = m)$ if and only if $\sum_{i=1}^r \lfloor (a_i - 1)/t \rfloor < s$. Recall that $\omega(G) = m - 1$ because $\omega(C_n^{k-1}) + \omega(K_{m-k-1}) = m - k - 1 + k = m - 1$, so G is K_m -free. This construction is unique in that it enables the construction of infinitely many vertex Folkman graphs. In particular, if $\gcd\{n, k\} = 1$, then $s = 1$ and $t = k$, so $\sum_{i=1}^r \lfloor (a_i - 1)/t \rfloor = 0 < s = 1$, which means that $G \in \mathcal{F}_v(a_1, \dots, a_r; q = m)$ [36]. Since there exists infinitely many integers n, k that satisfy this construction criteria, clearly an infinite number of graphs can be produced.

It is interesting to note that not all such graphs are minimal with respect to their membership in $\mathcal{F}_v(a_1, \dots, a_r; q = m)$. In fact, G is only (a_1, \dots, a_r) -vertex minimal if $k = p$, $n \geq 2k + 1$, and of course, if $\gcd\{n, k\} = 1$.

Would a separate section on classes of Folkman graphs and their constructions be better?

Luczak et al. [35] showed that $F_v(a_1, \dots, a_r; m) = m + p$. A looser bound of $F_v(a_1, \dots, a_r; m) \leq m + p$ still holds with the exception of the unique distinguishing graph $G = K_{m-p-1} + \bar{C}_{2p+1}$ in $\mathcal{F}_v(a_1, \dots, a_r; m)$ with vertex order $m + p$.

3.2.2 $F_v(a_1, \dots, a_r; m - 1)$

It is well known that $F_v(a_1, \dots, a_r; m) < F_v(a_1, \dots, a_r; m - 1)$, and furthermore, that $\mathcal{F}_v(a_1, \dots, a_r; m - 1)$ is non-empty if and only if $m \geq p + 2$. To date, there are few vertex Folkman numbers of the form $F_v(a_1, \dots, a_r; m - 1)$. In 1955 Mycielski [37] found an 11-vertex graph G such that $G \rightarrow (2, 2, 2)^v$ and $\omega(G) = 2$. This proved that $F_v(2, 2, 2; 3) \leq 11$. The lower bound of $F_v(2, 2, 2; 3) = 11$ was shown to be exact by Chavátal in 1974 [3].

$F_v(2, 2, 2, 2; 4) = 11$ was proven disjointly by Nenov in 1984 [44], who showed that $F_v(2, 2, 2, 2; 4) \geq 11$, and Nenov in 1983 [43, 39], who showed that $F_v(2, 2, 2, 2; 4) \leq 11$ (see [47] as well).

For $a_1 = \dots = a_r = 2$, Nenov et al. [52] showed that

$$F_v(\underbrace{2, \dots, 2}_r) = \begin{cases} 11 & : r = 3, 4, \\ r + 5 & : r \geq 5 \end{cases}$$

The exact value of $F_v(\underbrace{2, \dots, 2}_r) = r + 5, r \geq 5$ was proved in [43, 39, ?].

Few other numbers of the form $F_v(a_1, \dots, a_r; m - 1)$ are known. One particularly interesting case is the number $F_v(3, 3; 4) = 14$, which was proved over the span of almost two decades by Nenov [41] and Piwakowski et al. [56]. Nenov showed that $F_v(3, 3; 4) \leq 14$ using constructions, and Piwakowski et al. showed that $F_v(3, 3; 4) \geq 14$ using computational techniques.

Other numbers of this form include $F_v(3, 4; 5) = 13$ [50], $F_v(2, 2, 4; 5) = 13$ [48], but which is also shown by the following Lemma, and $F_v(4, 4; 6) = 14$ [38].

The lemma, stated inline below, would go here. Is this even worth including?

In 2002, Nenov [52] showed that $F_v(2, 2, 2, 4; 6) = F_v(2, 3, 4; 6) = 14$. To do this, he also showed that if $G \rightarrow (a_1, \dots, a_r)^v$ and there exists one $a_i \geq 2$, then $G \rightarrow (a_1, \dots, a_{i-1}, 2, a_i - 1, a_{i+1}, \dots, a_r)$. Thus, if $G \rightarrow (2, 3, 4)^v$, for example, then by this fact we also have that $G \rightarrow (2, 2, 2, 4)^v$.

In 2006, Kolev and Nenov [25] found an upper bound for a similar class of vertex Folkman numbers where $p \geq 3$. In particular, they showed that $F_v(a_1, \dots, a_r; m - 1) \leq m + 3p$ for $p \geq 3$, which improved the upper bound of $F_v(a_1, \dots, a_r; m - 1) \leq p^2 + m$ when $m \geq 2p + 2$ shown by Luczak et al. [?]. This bound is exact for $F_v(2, 2, 3; 4) = 14$ [4] (though a looser bound of $10 \leq F_v(2, 2, 3; 4) \leq 14$ was proved by Nenov in 2000 [48]) and $F_v(3, 3; 4) = 14$ [56]. Coles et al. obtained this result by constructing all Folkman graphs G on 14 vertices from three-vertex extensions of smaller K_4 -free graphs G' on 11 vertices, and for all such graphs G checking to see if $G - v \in \mathcal{F}_v(2, 2, 3; 4; 13)$. Large-scale computations were used to exhaustively show that no such graphs on 13 vertices exist, and thus the exact value of $F_v(2, 2, 3; 4) = 14$ holds. Luczak et al. also claimed that $F_v(a_1, \dots, a_r; m - 1) \leq 3p^2 + p - mp + 2m - 3$, for $p + 3 \leq m \leq 2p + 1$, without proof.

Luczak states that the lower bound of $F_v(a_1, a, \dots, a_r; m - 1)$ is $m + p + 1$ in 2001. Is this true?

A general lower bound for $F_v(a_1, \dots, a_r; m - 1) \geq m + p + 2, p \geq 2$ was proved by Nenov [48] in 2000. Equality of $F_v(a_1, \dots, a_r; m - 1) = m + p + 2, p \geq 2$ only occurs when $p = 2$ and $m \geq 5$ [18, 36, 43].

In 2001, Nenov [51] proved that $F_v(2, 3, 3; 5) = 12$.

3.2.3 Avoiding Smaller Cliques

Obtaining bounds on Folkman numbers becomes much more difficult as the forbidden clique size decreases. Luczak et al. [36] obtained the bound of $F_v(\underbrace{2, \dots, 2}_r; r + 1 - k) \leq r + 2k + 3$ when

$0 \leq k \leq (r - 2)/3$. This bound is exact when $k = 0, 1$.

What about proposition 7 that was used to enumerate graphs with clique number $m - s$ for $1 \leq s \leq m/3$?

For a graph G with girth $g(G) \geq 2p$ and $|V(G)| \geq 2m - 1$, Luczak observed that $G^c \rightarrow (a_1, \dots, a_r)^v$. Since any r -coloring of G will yield a vertex set S of $2a_i - 1$ vertices for some $i \in \{1, \dots, r\}$. Since $g(G) \geq 2p$, it is clear that $G^c[S]$ does not contain a cycle, and thus is bipartite, meaning that $\alpha(G^c[S]) \leq \lceil |S|/s \rceil = a_i$. Therefore, if $\alpha(G^c[S]) < w$, then G does not contain a clique of size w , and therefore $G \in \mathcal{F}_v(a_1, \dots, a_r; w)$ [36]. This observation led to the theorem by Luczak et al. [36] stating that if G is a graph such that $g(G) \geq 2p$, $\alpha(G) < l$, $w \geq l$, and $w - l + \frac{1}{2}|V(G)| \geq m$, then $G = K_{w-l} + G^c \in \mathcal{F}_v(a_1, \dots, a_r; w)$.

Theorem 1 ([36]) *Let $q = 2m - w \geq e^{e^2}$ and $B = 2q(\log \log q)/\log q + 2 \log \log q(\log q)^{2p-1}$. If $w \geq B$ and $p \leq \log q / \log \log q$, then $F_v(a_1, \dots, a_r; w) \leq q + B$.*

Remark 2 This bound was obtained using a probabilistic construction with the Galois circulant graph $G(n, r)$.

Given that $F_v(a_1, \dots, a_r; m) < F_v(a_1, \dots, a_r; m-1)$, it might be intuitive to attempt to prove the existence of Folkman numbers using a construction based on recurrence relation between these two Folkman numbers. In fact, this is exactly what Łuczak et al. [36] did to study the most restrictive case of the vertex Folkman numbers (when $w = p + 1$), as shown in the following Theorem.

Theorem 3 ([36]) For all $r \geq 2$ and $2 \leq a_1 \leq \dots \leq a_r$, the following recurrence inequality holds:

$$F_v(a_1, \dots, a_r; p+1) \leq 1 + (1 + (r-1)(F_2 - 1)) \cdot F_1 + \binom{1 + (r-1)(F_2 - 1)}{F_2} F_2,$$

where $F_1 = F_v(a_1 - 1, \dots, a_r - 1; p)$ and $F_2 = F_v(a_2, \dots, a_r; p+1)$.

Remark 4 This type of construction is actually a modification of Folkman's original existential proof [13].

Corollary 5 ([36]) $F_v(k, l; l+1) \leq 2 \sum_{i=0}^{k-1} \frac{l!}{(l-i)!} - 1$.

Remark 6 This was proved by induction on k using the fact that $F_v(a_1, \dots, a_r; m) \leq p + m$, which implies that $F_v(2, l; l+1) \leq 2l + 1 = 2 \sum_{i=0}^1 \frac{l!}{(l-i)!} - 1$ for all $l \geq 2$. When $k = l$, the upper bound of $2 \sum_{i=0}^{k-1} \frac{l!}{(l-i)!} - 1$ collapses to $\lfloor 2k!(e-1) \rfloor - 1$, where e is the number of edges in the graph G . Also, this bound implies that $F_v(3, 3; 4) \leq 19$, which supports the result from Piwakowski et al. [56] that $F_v(3, 3; 4) = 14$.

CAW: What is e ? It is unclear from the context of the paper...

3.2.4 Multiplicative Vertex Folkman Numbers

Few results in this topic are known. In 2007, Kolev [30] considered the product of two vertex Folkman numbers $F_v(a_1, \dots, a_r; s+1)$ and $F_v(b_1, \dots, b_r; t+1)$, for positive integers s and t . The product of these numbers was shown to bound $F_v(a_1, \dots, a_r; st+1)$, meaning that $F_v(a_1, \dots, a_r; st+1) \leq F_v(a_1, \dots, a_r; s+1) \times F_v(b_1, \dots, b_r; t+1)$. This result can be generalized to $F_v(\underbrace{kl, \dots, kl}_r; kl+1) \leq F_v(\underbrace{k, \dots, k}_r; k+1) \times F_v(\underbrace{l, \dots, l}_r; l+1)$ if we let $a_i = s = k$, $b_i = t = l$.

Nenov [54, 26] also showed that $F_v(p+1, p+1; p+2) \leq (p+1)F_v(p, p; p+1)$. Using the fact that $F_v(4, 4; 5) \leq 25$ [27], Kolev [30] showed that $F_v(p, p; p+1) \leq \frac{25}{24}p!$, where $p \geq 4$, which improved the upper bound of $F_v(p, p; p+1) \leq \lfloor 2p!(e-1) \rfloor - 1$ that was presented by Łuczak et al. in 2001 [36]. This result is obtained by induction on p .

3.3 Edge and Vertex Folkman Number Connections

Given the Ramsey number $R(a_1, \dots, a_r)$, it is clear that $F_e(a_1, \dots, a_r; q)$ for all $q > R(a_1, \dots, a_r)$, simply because the Ramsey number already attains this lower bound on the size of the graph n .

CAW: look at #5 and #10 from luczak paper for proofs of this result to be more specific

Given this relation, the following lemma emerges.

Lemma 7 ([36]) Let $R_i = R(a_1, \dots, a_{i-1}, a_i - 1, a_{i+1}, \dots, a_r)$ for all $i \in \{1, 2, \dots, r\}$. If $H \in \mathcal{F}_v(R_1, R_2, \dots, R_r; w)$, then $H + v \in \mathcal{F}_v(a_1, \dots, a_r; w+1)$.

Remark 8 Clearly, this enables one to derive bounds on edge Folkman numbers using known bounds on related vertex Folkman numbers that are increased by one.

Corollary 9 ([36]) For $k, l \geq 3$, let $M = \max\{R(k-1, l), R(k, l-1)\}$ and $m = \min\{R(k-1, l), R(k, l-1)\}$, then it is true that $F_e(k, l; M+2) \leq 2 \sum_{i=0}^{m-1} \frac{M!}{(M-i)!}$.

Remark 10 This bound collapses to $F_e(k, k; M+2) \leq \lfloor 2M!(e-1) \rfloor$ when $k = l$. Furthermore, this is a very loose upper bound. The bound obtained when $k = l = 3$ is $F_e(3, 3; 5) \leq 20$ is close to the true value of 15, but other values for k and l are much farther off. However, it is still very useful for closing the gap between the original existential question and true values.

3.4 Relationship with the Chromatic Number

If a graph G satisfies the condition that $\chi(G) = k$ and $\omega(G) \leq r$, then G is k -chromatic and K_{r+1} -free. It is well known that if $G \rightarrow (a_1, \dots, a_r)^v$ then $\chi(G) \geq m$. A graph G is called an edge-critical k -chromatic graph if $\chi(G) = k$ and $\chi(G') < k$ for each proper subgraph G' of G (i.e. $G' = G - v$ or $G' = G - e$). All edge critical k -chromatic graphs must be connected, $\chi(G) = k$, and $\chi(G - e) < k$ for all $e \in E(G)$. Similarly, a graph G is a vertex-critical k -chromatic if $\chi(G) = k$ and $\chi(G - v) < k$ for all $v \in V(G)$.

By whom?

It has been proven that if $G \rightarrow (a_1, \dots, a_r)$ then $\chi(G) \leq m$, where $m = \sum_{i=1}^r (a_i - 1) + 1$. In 1972, Lin [33] showed that $G \rightarrow (a_1, \dots, a_r)^3 \Rightarrow \chi(G) \geq R(a_1, \dots, a_r)$.

Chapter 4

Asymptotic Bounds for Folkman Numbers

Dudek et al. [7] asked the general question of determining $F_v(r, \mathcal{G})$, the minimal order of a graph H such that $\omega(H) = \omega(\mathcal{G})$ and for every r -coloring of the vertices of H there exists a monochromatic, induced copy of \mathcal{G} . This is equivalent to finding a minimal graph $H \xrightarrow[\text{ind}]{\rightarrow} (G)_b^r$.

Clearly, the induced subgraph requirement places a tighter constraint on the structure of H . Preliminary results are captured in the following theorems.

Theorem 11 [7] $F_v(r, n, q = n + 1) = F_v(n, K_n) \leq cn^2(\log n)^4$ for some constant $c = C(r)$. Therefore, $F_v(r, n, q = n + 1) = F_v(n, K_n) = \mathcal{O}(n^2(\log n)^4)$.

Remark 12 This was proven with a construction for graphs H of order $Cn^2 \log^4 n$, $C = C(\alpha)$, such that $\omega(H) = n$ and for all induced subgraphs $H[V]$, where $V \subset V(H)$ and $|V| = \lfloor \alpha |V(H)| \rfloor$, $H[V]$ contains a copy of K_n , and thus avoids a clique of size $n + 1$. These graphs were randomly constructed from the vertex set \mathcal{V} of projected planes $PG(2, q)$, where q is prime.

Theorem 13 [7] $F_v(r, n[(2 + \epsilon)n]) \leq Cn$ for a $r \in \mathbb{N}$, some arbitrarily small constant $\epsilon > 0$ and constant $C = C(r, \epsilon)$.

Remark 14 This is a direct result of Theorem 11, which arises when cliques of size bigger than $q = (2 + o(1))$ are forbidden. This result is also complementary to the results obtained by Luczak et al. [36] and Kolev et al. [25], who found that $F_v(r, n, r(n - 1)) \leq r(n - 1) + n^2 + 1$ and $F_v(r, n, r(n - 1)) \leq r(n - 1) + 3n + 1$, respectively. The bound obtained by Kolev et al. is significantly tighter than that of Luczak et al. as n tends towards infinity.

The special two-color case of this vertex Folkman number, $F_v(2, n, n + 1)$ was shown to be equal to $\mathcal{O}(n!)$ by Nenov [45]. This was an improvement on the upper bound obtained by Folkman [13], which was proven using an iterated power function.

Efforts to improve Folkman's theorem using the induced subgraph constraint and without controlling the forbidden clique size were started in 1991 by Brown et al. [1], in which they proved the following theorem.

Theorem 15 For every $r \in \mathbb{N}$ there exists constants C and c such that for every graph G of order n ,

$$cn^2 \leq \max_G \left\{ \min_H \left\{ |V(H)| : H \xrightarrow[\text{ind}]{\rightarrow} (G)_r^v \right\} \right\} \leq Cn^2 \log^2 n.$$

Remark 16 Note that all logarithms are base e unless otherwise explicitly stated.

The order of graphs satisfying this induced arrow property was further constrained by Dudek et al. [7], who adding the additional constraint that $\omega(H) = \omega(G)$. In doing so, they were only able to achieve an upper bound of $Cn^3 \log^3 n$, for some constant C , as shown in the following theorem.

Theorem 17 *For a given $r \in \mathbb{N}$, there exists a constant $C = C(r)$ such that for every graph G of order n ,*

$$\min \left\{ |V(H)| : H \xrightarrow[\text{ind}]{(G)_r^v} \text{ and } \omega(H) = \omega(G) \right\} \leq Cn^3 \log^3 n.$$

Theorem 18 [8] $F(r, \mathcal{G}) \leq \frac{cn^3}{\omega(\mathcal{G})} (\log n)^5$ for some constant $c = \mathcal{O}(r)$.

Remark 19 *CAW: print and read paper for more details*

4.0.1 Asymptotic Results for Hypergraphs

The induced Folkman number $F(r, \mathcal{G})$ of a k -uniform hypergraph \mathcal{G} of order n is the minimum order of a k -uniform hypergraph H such that $\omega(H) = \omega(\mathcal{G})$ and that for every r -coloring of the vertices of H there exists a monochromatic, induced copy of \mathcal{G} . Dudek et al. [9] showed that $F(r, \mathcal{G})$ for hypergraphs \mathcal{G} is *almost* quadratic, with the bound $F(r, \mathcal{G}) \leq cn^2 (\log n)^2$ for any k -uniform hypergraph \mathcal{G} on n vertices. In doing so, Dudek et al. also showed that for every pair of positive integers k, n there exists a constant c such that $F(r, \mathcal{G}) \leq cr^2$ for a hypergraph \mathcal{G} on n vertices and any non-negative number of colors r . Dudek et al. [10] showed a special case of this bound with $\mathcal{G} = \mathcal{K}_n^k$, the complete hypergraph on n vertices which is k -uniform, shown in the following theorem.

Theorem 20 [10] $F(r, \mathcal{K}_n^k) \leq cr (\log r)^{\frac{1}{k-2}}$ for some constant $c = \mathcal{O}(k, n)$.

Chapter 5

Complexity Connections

TODO

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