

Independence in uniform linear triangle-free hypergraphs



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ABSTRACT

The independence number $\alpha(H)$ of a hypergraph H is the maximum cardinality of a set of vertices of H that does not contain an edge of H . Generalizing Shearer's classical lower bound on the independence number of triangle-free graphs Shearer (1991), and considerably improving recent results of Li and Zang (2006) and Chishti et al. (2014), we show that

$$\alpha(H) \geq \sum_{u \in V(H)} f_r(d_H(u))$$

for an r -uniform linear triangle-free hypergraph H with $r \geq 2$, where

$$f_r(0) = 1, \quad \text{and}$$

$$f_r(d) = \frac{1 + ((r-1)d^2 - d)f_r(d-1)}{1 + (r-1)d^2} \quad \text{for } d \geq 1.$$

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1. Introduction

We consider finite hypergraphs H , which are ordered pairs $(V(H), E(H))$ of two sets, where $V(H)$ is the finite set of vertices of H and $E(H)$ is the set of edges of H , which are subsets of $V(H)$. The order $n(H)$ of H is the cardinality of $V(H)$. The degree $d_H(u)$ of a vertex u of H is the number of edges of H that contain u . The average degree $d(H)$ of H is the arithmetic mean of the degrees of its vertices. Two distinct vertices of H are adjacent or neighbors if some edge of H contains both. The neighborhood $N_H(u)$ of a vertex u of H is the set of vertices of H that are adjacent to u . For a set X of vertices of H , the hypergraph $H - X$ arises from H by removing from $V(H)$ all vertices in X and removing from $E(H)$ all edges that intersect X . If every two distinct edges of H share at most one vertex, then H is linear. If H is linear and for every two distinct non-adjacent vertices u and v of H , every edge of H that contains u contains at most one neighbor of v , then H is double linear. If there are not three distinct vertices u_1, u_2 , and u_3 of H and three distinct edges e_1, e_2 , and e_3 of H such that $\{u_1, u_2, u_3\} \setminus \{u_i\} \subseteq e_i$ for $i \in \{1, 2, 3\}$, then H is triangle-free. A set I of vertices of H is a (weak) independent set of H if no edge of H is contained in I . The (weak) independence number $\alpha(H)$ of H is the maximum cardinality of an independent set of H . If all edges of H have cardinality r , then H is r -uniform. If H is 2-uniform, then H is referred to as a graph.

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The independence number of (hyper)graphs is a well studied computationally hard parameter. Caro [4] and Wei [14] proved a classical lower bound on the independence number of graphs, which was extended to hypergraphs by Caro and Tuza [5]. Specifically, for an r -uniform hypergraph H , Caro and Tuza [5] proved

$$\alpha(H) \geq \sum_{u \in V(H)} f_{CT(r)}(d_H(u)),$$

where $f_{CT(r)}(d) = \left(\frac{d+\frac{1}{r-1}}{d}\right)^{-1}$. Thiele [13] generalized Caro and Tuza's bound to general hypergraphs; see [3] for a very simple probabilistic proof of Thiele's bound. Originally motivated by Ramsey theory, Ajtai et al. [2] showed that $\alpha(G) = \Omega\left(\frac{\ln d(G)}{d(G)}n(G)\right)$ for every triangle-free graph G . Confirming a conjecture from [2] concerning the implicit constant, Shearer [11] improved this bound to $\alpha(H) \geq f_{S_1}(d(G))n(G)$, where $f_{S_1}(d) = \frac{d \ln d - d + 1}{(d-1)^2}$. In [11] the function f_{S_1} arises as a solution of the differential equation

$$(d + 1)f(d) = 1 + (d - d^2)f'(d) \quad \text{and} \quad f(0) = 1.$$

In [12] Shearer showed that

$$\alpha(G) \geq \sum_{u \in V(G)} f_{S_2}(d_G(u))$$

for every triangle-free graph G , where f_{S_2} solves the difference equation

$$(d + 1)f(d) = 1 + (d - d^2)(f(d) - f(d - 1)) \quad \text{and} \quad f(0) = 1.$$

Since $f_{S_1}(d) \leq f_{S_2}(d)$ for every non-negative integer d , and f_{S_1} is convex, Shearer's bound from [12] is stronger than his bound from [11].

Li and Zang [10] adapted Shearer's approach to hypergraphs and obtained the following.

Theorem 1 (Li and Zang [10]). *Let r and m be positive integers with $r \geq 2$.*

If H is an r -uniform double linear hypergraph such that the maximum degree of every subhypergraph of H induced by the neighborhood of a vertex of H is less than m , then

$$\alpha(H) \geq \sum_{u \in V(H)} f_{LZ(r,m)}(d_H(u)),$$

where

$$f_{LZ(r,m)}(x) = \frac{m}{B} \int_0^1 \frac{(1-t)^{\frac{a}{m}}}{t^b(m - (x-m)t)} dt,$$

$$a = \frac{1}{(r-1)^2}, \quad b = \frac{r-2}{r-1}, \quad \text{and} \quad B = \int_0^1 (1-t)^{\left(\frac{a}{m}-1\right)} t^{-b} dt.$$

Note that for $r \geq 2$, an r -uniform linear hypergraph H is triangle-free if and only if it is double linear and the maximum degree of every subhypergraph of H induced by the neighborhood of a vertex of H is less than 1. Therefore, since $f_{S_1} = f_{LZ(2,1)}$ and f_{S_1} is convex, Theorem 1 implies Shearer's bound from [11]. Nevertheless, since $f_{S_1}(d) < f_{S_2}(d)$ for every integer d with $d \geq 2$, Shearer's bound from [12] does not quite follow from Theorem 1.

In [6] Chishti et al. presented another version of Shearer's bound from [11] for hypergraphs.

Theorem 2 (Chishti et al. [6]). *Let r be an integer with $r \geq 2$.*

If H is an r -uniform linear triangle-free hypergraph, then

$$\alpha(H) \geq f_{CZPI(r)}(d(H))n(H),$$

where

$$f_{CZPI(r)}(x) = \frac{1}{r-1} \int_0^1 \frac{1-t}{t^b(1 - ((r-1)x-1)t)} dt$$

$$\text{and } b = \frac{r-2}{r-1}.$$

Since $f_{S_1} = f_{CZPI(2)}$, for $r = 2$, the last result coincides with Shearer's bound from [11].

A drawback of the bounds in Theorems 1 and 2 is that they are very often weaker than Caro and Tuza's bound [5], which holds for a more general class of hypergraphs. See Fig. 1 for an illustration.

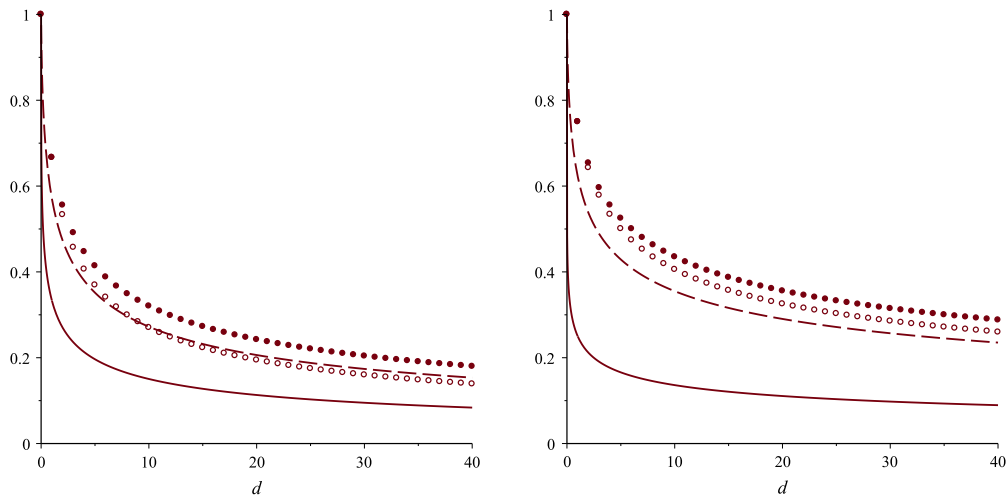


Fig. 1. The values of $f_{LZ(r,1)}(d)$ (line), $f_{CZP(r)}(d)$ (dashed line), $f_{CT(r)}(d)$ (empty circles), and $f_r(d)$ (solid circles) for $0 \leq d \leq 40$ and $r = 3$ (left) and $r = 4$ (right).

In the present paper we extend Shearer’s approach from [12] and establish a lower bound on the independence number of a uniform linear triangle-free hypergraph that considerably improves Theorems 1 and 2 and is systematically better than Caro and Tuza’s bound.

For further related results we refer to Ajtai et al. [1], Duke et al. [7], Dutta et al. [8] and Kostochka et al. [9]. Note that our main result provides explicit values when applied to a specific hypergraph but that we do not completely understand its asymptotics. In contrast to that, results as in [1,7,8] are essentially asymptotic statements but are of limited value when applied to a specific hypergraph.

2. Results

For an integer r with $r \geq 2$, let $f_r : \mathbb{N}_0 \rightarrow \mathbb{R}_0$ be such that

$$f_r(0) = 1 \quad \text{and}$$

$$f_r(d) = \frac{1 + ((r - 1)d^2 - d)f_r(d - 1)}{1 + (r - 1)d^2}$$

for every positive integer d .

Lemma 3. *If r and d are integers with $r \geq 2$ and $d \geq 0$, then $f_r(d) - f_r(d + 1) \geq f_r(d + 1) - f_r(d + 2)$.*

Proof. Substituting within the inequality $f_r(d) - 2f_r(d + 1) + f_r(d + 2) \geq 0$ first $f_r(d + 2)$ with

$$\frac{1 + ((r - 1)(d + 2)^2 - (d + 2))f_r(d + 1)}{1 + (r - 1)(d + 2)^2}$$

and then $f_r(d + 1)$ with

$$\frac{1 + ((r - 1)(d + 1)^2 - (d + 1))f_r(d)}{1 + (r - 1)(d + 1)^2},$$

and solving it for $f_r(d)$, it is straightforward but tedious to verify that it is equivalent to $f_r(d) \geq L(r, d)$ where

$$L(r, d) = \frac{(2r - 1)d + 3r}{r(d^2 + 5d + 5)}.$$

Therefore, in order to complete the proof, it suffices to show $f_r(d) \geq L(r, d)$. For $d = 0$, we have $f_r(0) = 1 > \frac{3}{5} = L(r, 0)$. Now, let $f(d) \geq L(r, d)$ for some non-negative integer d . Since $(r - 1)(d + 1)^2 - (d + 1) \geq 0$, we obtain by a straightforward yet tedious calculation

$$f(d + 1) - L(r, d + 1) = \frac{1 + ((r - 1)(d + 1)^2 - (d + 1))f(d)}{1 + (r - 1)(d + 1)^2} - L(r, d + 1)$$

$$\begin{aligned} &\geq \frac{(1 + ((r - 1)(d + 1)^2 - (d + 1))L(r, d)}{1 + (r - 1)(d + 1)^2} - L(r, d + 1) \\ &= \frac{2(1 + (r - 1)(d + 2)^2)}{r(d^2 + 7d + 11)(d^2 + 5d + 5)}, \end{aligned}$$

which is positive for $r \geq 2$. Therefore, $f(d + 1) \geq L(r, d + 1)$, which completes the proof by an inductive argument. \square

The following is our main result.

Theorem 4. Let r be an integer with $r \geq 2$.

If H is an r -uniform linear triangle-free hypergraph, then

$$\alpha(H) \geq \sum_{u \in V(H)} f_r(d_H(u)).$$

Before we proceed to the proof, we compare our bound to the bounds of Caro and Tuza [5], Li and Zang [10], and Chishti et al. [6]. Fig. 1 illustrates some specific values. An inspection of Li and Zang’s proof in [10] reveals that they actually prove a lower bound on the so-called *strong independence number*, which is defined as the maximum cardinality of a set of vertices that does not contain two adjacent vertices. Therefore, especially for large values of r , Theorem 1 is much weaker than Theorem 2. In fact, it is quite natural that it is worse by a factor of about $r - 1$.

As we show now, our bound is systematically better than Caro and Tuza’s bound [5].

Lemma 5. If r and d are integers with $r \geq 3$ and $d \geq 2$, then $f_r(d) > f_{CT(r)}(d)$.

Proof. Note that $f_r(0) = f_{CT(r)}(0) = 1$, $f_r(1) = f_{CT(r)}(1) = \frac{r-1}{r}$, and $f_{CT(r)}(d) = \frac{d}{d+r-1} f_{CT(r)}(d-1)$ for $d \in \mathbb{N}$, which immediately implies that $f_{CT(r)}(d) < \frac{r-1}{r}$ for $d \geq 2$. Now, if $f_r(d-1) \geq f_{CT(r)}(d-1)$ for some $d \geq 2$, then

$$\begin{aligned} f_r(d) - f_{CT(r)}(d) &= \frac{1 + ((r - 1)d^2 - d)f_r(d - 1)}{1 + (r - 1)d^2} - f_{CT(r)}(d) \\ &\geq \frac{1 + ((r - 1)d^2 - d)f_{CT(r)}(d - 1)}{1 + (r - 1)d^2} - f_{CT(r)}(d) \\ &= \frac{1 + ((r - 1)d^2 - d)\frac{1+(r-1)d}{(r-1)d}f_{CT(r)}(d)}{1 + (r - 1)d^2} - f_{CT(r)}(d) \\ &= \frac{1 - \frac{r}{r-1}f_{CT(r)}(d)}{1 + (r - 1)d^2} \\ &> 0, \end{aligned}$$

that is, $f_r(d) > f_{CT(r)}(d)$, which completes the proof by an inductive argument. \square

For $r = 2$, Lemma 5 would state that Shearer’s bound [12] is better than Caro [4] and Wei’s bound [14], which is known. We proceed to the proof of Theorem 4.

Proof of Theorem 4. We prove the statement by induction on $n(H)$. If H has no edge, then $\alpha(H) = n(H)$, which implies the desired result for $n(H) \leq r - 1$. Now let $n(H) \geq r$. If H has a vertex x with $d_H(x) = 0$, then $f_r(d_H(x)) = 1$ and, by induction,

$$\alpha(H) \geq 1 + \alpha(H - x) \geq f_r(d_H(x)) + \sum_{u \in V(H) \setminus \{x\}} f_r(d_{H-x}(u)) = \sum_{u \in V(H)} f_r(d_H(u)).$$

Hence we may assume that H has no vertex of degree 0.

Since H is r -uniform and linear, for every two edges e_1 and e_2 with $e_1 \cap e_2 = \{u\}$ for some vertex u of H , the sets $e_1 \setminus \{u\}$ and $e_2 \setminus \{u\}$ are disjoint and of order $r - 1$. Therefore, for every vertex u of H , there is a set $\mathcal{R}(u)$ of $r - 1$ sets of neighbors of u such that every neighbor of u belongs to exactly one of the sets in $\mathcal{R}(u)$, and $|e \cap R| = 1$ for every edge e of H with $u \in e$ and every $R \in \mathcal{R}(u)$.

If x is a vertex of H and $R \in \mathcal{R}(x)$ is such that

$$1 + \sum_{u \in V(H) \setminus (\{x\} \cup R)} f_r(d_{H - (\{x\} \cup R)}(u)) \geq \sum_{u \in V(H)} f_r(d_H(u)),$$

then the statement follows by induction, because $\alpha(H) \geq 1 + \alpha(H - (\{x\} \cup R))$. Therefore, in order to complete the proof, it suffices to show that the following term is non-negative:

$$P = \sum_{x \in V(H)} \sum_{R \in \mathcal{R}(x)} \left(1 + \sum_{u \in V(H) \setminus (\{x\} \cup R)} f_r(d_{H - (\{x\} \cup R)}(u)) - \sum_{u \in V(H)} f_r(d_H(u)) \right).$$

Since H is linear and triangle-free, we have $d_{H - (\{x\} \cup R)}(z) = d_H(z) - |N_H(z) \cap R|$ for every vertex z in $V(H) \setminus (\{x\} \cup R)$. Trivially, $d_{H - (\{x\} \cup R)}(z) = d_H(z)$ for $z \notin N_H(R)$, and hence P equals $P_1 + P_2$, where

$$P_1 = \sum_{x \in V(H)} \sum_{R \in \mathcal{R}(x)} \left(1 - f_r(d_H(x)) - \sum_{y \in R} f_r(d_H(y)) \right) \quad \text{and}$$

$$P_2 = \sum_{x \in V(H)} \sum_{R \in \mathcal{R}(x)} \sum_{z \in N_H(R) \setminus \{x\}} \left(f_r(d_H(z) - |N_H(z) \cap R|) - f_r(d_H(z)) \right).$$

Since for every vertex u of H , there are exactly $(r - 1)d_H(u)$ many vertices v of H such that u belongs to exactly one of the sets in $\mathcal{R}(v)$, we have

$$P_1 = \sum_{x \in V(H)} \left((r - 1) - (r - 1)(d_H(x) + 1)f_r(d_H(x)) \right).$$

Since $f_r(d - 1) - f_r(d)$ is decreasing by Lemma 3, we have $f_r(d - n) - f_r(d) \geq n(f_r(d - 1) - f_r(d))$ for all positive integers d and n with $n < d$. Therefore,

$$\begin{aligned} P_2 &\geq \sum_{x \in V(H)} \sum_{R \in \mathcal{R}(x)} \sum_{z \in N_H(R) \setminus \{x\}} |N_H(z) \cap R| \left(f_r(d_H(z) - 1) - f_r(d_H(z)) \right) \\ &= \sum_{x \in V(H)} \sum_{R \in \mathcal{R}(x)} \sum_{z \in N_H(R) \setminus \{x\}} \sum_{y \in R} |N_H(z) \cap \{y\}| \left(f_r(d_H(z) - 1) - f_r(d_H(z)) \right) \\ &= \sum_{x \in V(H)} \sum_{R \in \mathcal{R}(x)} \sum_{y \in R} \sum_{z \in N_H(R) \setminus \{x\}} |N_H(z) \cap \{y\}| \left(f_r(d_H(z) - 1) - f_r(d_H(z)) \right) \\ &= \sum_{x \in V(H)} \sum_{R \in \mathcal{R}(x)} \sum_{y \in R} \sum_{z \in N_H(y) \setminus \{x\}} \left(f_r(d_H(z) - 1) - f_r(d_H(z)) \right). \end{aligned}$$

Let T be the set of all 4-tuples (x, R, y, z) with $x \in V(H)$, $R \in \mathcal{R}(x)$, $y \in R$, and $z \in N_H(y) \setminus \{x\}$. Note that $y \in N_H(z)$ for every (x, R, y, z) in T . Since H is linear, for a given vertex z of H and a given neighbor y of z , there are $(r - 1)d_H(y) - 1$ many vertices x of H with $y \in R$ for some R in $\mathcal{R}(x)$ and $z \in N_H(y) \setminus \{x\}$. Furthermore, by the properties of $\mathcal{R}(x)$, given x and y , the set R in $\mathcal{R}(x)$ with $y \in R$ is unique. Therefore,

$$\begin{aligned} P_2 &\geq \sum_{x \in V(H)} \sum_{R \in \mathcal{R}(x)} \sum_{y \in R} \sum_{z \in N_H(y) \setminus \{x\}} \left(f_r(d_H(z) - 1) - f_r(d_H(z)) \right) \\ &= \sum_{z \in V(H)} \sum_{y \in N_H(z)} \left((r - 1)d_H(y) - 1 \right) \left(f_r(d_H(z) - 1) - f_r(d_H(z)) \right). \end{aligned}$$

Let \mathcal{E} be the edge set of the graph that arises from H by replacing every edge of H by a clique, that is, \mathcal{E} is the set of all sets containing exactly two adjacent vertices of H .

We obtain

$$\begin{aligned} P_2 &\geq \sum_{z \in V(H)} \sum_{y \in N_H(z)} \left((r - 1)d_H(y) - 1 \right) \left(f_r(d_H(z) - 1) - f_r(d_H(z)) \right) \\ &= \sum_{\{y,z\} \in \mathcal{E}} \left(h_1(y)h_2(z) + h_1(z)h_2(y) \right), \quad \text{where} \end{aligned}$$

$$h_1(x) = (r - 1)d_H(x) - 1 \quad \text{and}$$

$$h_2(x) = f_r(d_H(x) - 1) - f_r(d_H(x)).$$

If $d_H(y) \geq d_H(z)$, then $h_1(y) \geq h_1(z)$ and, by Lemma 3, $h_2(z) \geq h_2(y)$, which implies

$$\left(h_1(y) - h_1(z) \right) \left(h_2(z) - h_2(y) \right) \geq 0.$$

Therefore, $h_1(y)h_2(z) + h_1(z)h_2(y) \geq h_1(y)h_2(y) + h_1(z)h_2(z)$.

Since, for every vertex y of H , there are exactly $(r - 1)d_H(y)$ many vertices z of H with $\{y, z\} \in \mathcal{E}$, we obtain

$$\begin{aligned} P_2 &\geq \sum_{\{y,z\} \in \mathcal{E}} \left(h_1(y)h_2(z) + h_1(z)h_2(y) \right) \\ &\geq \sum_{\{y,z\} \in \mathcal{E}} \left(h_1(y)h_2(y) + h_1(z)h_2(z) \right) \\ &= \sum_{x \in V(H)} (r - 1)d_H(x)h_1(x)h_2(x) \\ &= \sum_{x \in V(H)} (r - 1)d_H(x) \left((r - 1)d_H(x) - 1 \right) \left(f_r(d_H(x) - 1) - f_r(d_H(x)) \right). \end{aligned}$$

Combining these estimates, we see that

$$\begin{aligned} P &= P_1 + P_2 \\ &\geq \sum_{x \in V(H)} \left((r - 1) - (r - 1)(d_H(x) + 1)f_r(d_H(x)) \right. \\ &\quad \left. + (r - 1)d_H(x) \left((r - 1)d_H(x) - 1 \right) \left(f_r(d_H(x) - 1) - f_r(d_H(x)) \right) \right), \end{aligned}$$

which is 0 by the definition of f_r . This completes the proof. \square

It seems a challenging task to extend the presented results to non-uniform and/or non-linear triangle-free hypergraphs.

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