

Codegree Turán density of complete r -uniform hypergraphs

Lo, Allan; Zhao, Yi

DOI:
[10.1137/18M1163956](https://doi.org/10.1137/18M1163956)

Document Version
Peer reviewed version

Citation for published version (Harvard):
Lo, A & Zhao, Y 2018, 'Codegree Turán density of complete r -uniform hypergraphs', *SIAM Journal on Discrete Mathematics*, vol. 32, no. 2, pp. 1154-1158. <https://doi.org/10.1137/18M1163956>

[Link to publication on Research at Birmingham portal](#)

Publisher Rights Statement:
Checked for eligibility: 20/04/2018

First Published in SIAM Journal on Discrete Mathematics in Vol 32, 2018, published by the Society for Industrial and Applied Mathematics (SIAM)
Version of record available at: <https://doi.org/10.1137/18M1163956>

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

CODEGREE TURÁN DENSITY OF COMPLETE r -UNIFORM HYPERGRAPHS

ALLAN LO AND YI ZHAO

ABSTRACT. Let $r \geq 3$. Given an r -graph H , the minimum codegree $\delta_{r-1}(H)$ is the largest integer t such that every $(r-1)$ -subset of $V(H)$ is contained in at least t edges of H . Given an r -graph F , the codegree Turán density $\gamma(F)$ is the smallest $\gamma > 0$ such that every r -graph on n vertices with $\delta_{r-1}(H) \geq (\gamma + o(1))n$ contains F as a subhypergraph. Using results on the independence number of hypergraphs, we show that there are constants $c_1, c_2 > 0$ depending only on r such that

$$1 - c_2 \frac{\ln t}{t^{r-1}} \leq \gamma(K_t^r) \leq 1 - c_1 \frac{\ln t}{t^{r-1}},$$

where K_t^r is the complete r -graph on t vertices. This gives the best general bounds for $\gamma(K_t^r)$.

1. INTRODUCTION

An r -uniform hypergraph (r -graph) H consists of a vertex set $V(H)$ and an edge set $E(H)$, which is a family of r -subsets of $V(H)$. A fundamental problem in extremal combinatorics is to determine the Turán number $\text{ex}(n, F)$, which is the largest number of edges in an r -graph on n vertices not containing a given r -graph F as a subhypergraph (namely, F -free). When $r \geq 3$, we only know $\text{ex}(n, F)$, or its asymptotics $\pi(F) := \lim_{n \rightarrow \infty} \text{ex}(n, F) / \binom{n}{r}$ for very few F . Let K_t^r denote the complete r -graph on t vertices. Determining $\pi(K_t^r)$ for any $t > r \geq 3$ is a well known open problem, in particular, Turán [18] conjectured in 1941 that $\pi(K_4^3) = 5/9$. The best (general) bounds for $\pi(K_t^r)$ are due to Sidorenko [17] and de Caen [1]

$$1 - \left(\frac{r-1}{t-1} \right)^{r-1} \leq \pi(K_t^r) \leq 1 - \frac{1}{\binom{t-1}{r-1}}. \quad (1.1)$$

For more Turán-type results on hypergraphs, see surveys [7, 9].

A natural variation on the Turán problem is to ask how large the minimum ℓ -degree can be in an F -free r -graph. Given an r -graph H , the *degree* $\deg(S)$ of a set $S \subset V(H)$ is the number of the edges that contain S . Given $1 \leq \ell < r$, the minimum ℓ -degree $\delta_\ell(H)$ is the minimum $\deg(S)$ over all $S \subset V(H)$ of size ℓ . Mubayi and Zhao [14] introduced the *codegree Turán number* $\text{ex}_{r-1}(n, F)$, which is the largest $\delta_{r-1}(H)$ among all F -free r -graphs on n vertices, and *codegree (Turán) density* $\pi_{r-1}(F) := \lim_{n \rightarrow \infty} \text{ex}_{r-1}(n, F)/n$ (it was shown [14] that this limit exists). The corresponding ℓ -degree Turán number $\text{ex}_\ell(n, F)$ and density $\pi_\ell(F)$ were defined similarly and studied by Lo and Markström [12].¹

Most codegree Turán problems do not seem easier than the original Turán problems. We only know the codegree densities of the following r -graphs. Let Fano denote the Fano plane (a 3-graph on seven vertices and seven edges). Mubayi [13] showed that $\pi_2(\text{Fano}) = 1/2$ and Keevash [8] later showed that $\text{ex}_2(n, \text{Fano}) = \lfloor n/2 \rfloor$ for sufficiently large n (DeBiasio and Jiang [2] gave another proof). Keevash and Zhao [10] studied the codegree density for other projective geometries and constructed a family of 3-graphs whose codegree densities are $1 - 1/t$ for all integers $t \geq 1$. Falgas-Ravry, Marchant, Pikhurko, and Vaughan [5] determined $\text{ex}_2(F_{3,2})$ for sufficiently large n , where $F_{3,2}$ is the 3-graph on $\{1, 2, 3, 4, 5\}$ with edges $123, 124, 125, 345$.

Date: April 5, 2018.

The first author is supported by EPSRC grant EP/P002420/1. The second author is partially supported by NSF grants DMS-1400073 and 1700622.

¹A simple averaging argument shows that $\pi_1(F) = \pi(F)$ for every F .

Falgas-Ravry, Pikhurko, Vaughan and Volec [6] also proved that $\pi_2(K_4^{3-}) = 1/4$, where K_4^{3-} is the (unique) 3-graphs on four vertices with three edges.

In this note we obtain asymptotically matching bounds for $\pi_{r-1}(K_t^r)$ for any fixed $r \geq 3$ and sufficiently large t . Since its value is close to one, it is more convenient to write $\pi_{r-1}(K_t^r)$ in the complementary form. Given an r -graph H and $\ell < r$, let $\Delta_\ell(H)$ denote the *maximum ℓ -degree* of H and $\alpha(H)$ denote the *independence number* (the largest size of a set of vertices containing no edge) of H . Define

$$T_\ell(n, t, r) = \min \{ \Delta_\ell(H) : H \text{ is an } r\text{-graph on } n \text{ vertices with } \alpha(H) < t \}$$

and $\tau_\ell(t, r) = \lim_{n \rightarrow \infty} T_\ell(n, t, r) / \binom{n-\ell}{r-\ell}$. It is clear that $T_\ell(n, t, r) = \binom{n-\ell}{r-\ell} - \text{ex}_\ell(n, K_t^r)$ and $\tau_\ell(t, r) = 1 - \pi_\ell(K_t^r)$. Falgas-Ravry [4] showed that $\tau_2(t, 3) \leq 1/(t-2)$ for $t \geq 4$ while Lo and Markström [12] showed that $\tau_{r-1}(t, r) \leq 1/(t-r+1)$ for $t > r \geq 3$. Recently Sidorenko [16] used zero-sum-free sequences in \mathbb{Z}_3^d to get $\tau_2(t, 3) \leq O(\frac{1}{t \ln t})$.

We show that $\tau_{r-1}(t, r) = \Theta(\ln t / t^{r-1})$ as $t \rightarrow \infty$.

Theorem 1.1. *For all $r \geq 3$, there exist $c_1, c_2 > 0$ such that*

$$c_1 \ln t / t^{r-1} \leq \tau_{r-1}(t, r) \leq c_2 \ln t / t^{r-1}.$$

In fact, the upper bound immediately follows from a construction of Kostochka, Mubayi and Verstraëte [11] (see Construction 2.1). The lower bound can be deduced from either the main result of [11] or a result of Duke, Lefmann, and Rödl [3]. However, since both results require $\Delta_{r-1}(H) = o(n)$, we need to extend them slightly by allowing $\Delta_{r-1}(H)$ to be a linear function of n (see Theorem 2.2).

We prove Theorem 1.1 in the next section and give concluding remarks and open questions in the last section.

2. PROOF OF THEOREM 1.1

A *partial Steiner (n, r, ℓ) -system* is an r -graph on n vertices in which every set of ℓ vertices is contained in at most one edge. Rödl and Šinajová [15] showed that there exists $a_2 > 0$ such that for every m , there is a partial Steiner $(m, r, r-1)$ -system S with $\alpha(S) \leq a_2(m \ln m)^{1/(r-1)}$. Kostochka, Mubayi and Verstraëte [11, Section 3.1] used the blowup of this Steiner system to obtain the following construction. A similar construction (but not using the result of [15]) was given in [4].

Construction 2.1. [11] *Let S be the partial Steiner $(m, r, r-1)$ -system given by Rödl and Šinajová. Let V be a union of disjoint sets V_1, \dots, V_m each of size d . For each edge $e = \{i_1, \dots, i_r\}$ of S , let $E_e := \{v_1 v_2 \dots v_r : v_j \in V_{i_j} \text{ for } j \in [r]\}$. Let H be the r -graph with vertex set V and edge set $\bigcup_{i \in [m]} \binom{V_i}{r} \cup \bigcup_{e \in S} E_e$. It is easy to see that*

$$\Delta_{r-1}(H) = d \quad \text{and} \quad \alpha(H) = (r-1)\alpha(S) \leq a_2(r-1)(m \ln m)^{\frac{1}{r-1}}.$$

Construction 2.1 will be used to prove the upper bound of Theorem 1.1. The lower bound of Theorem 1.1 follows from the following theorem, which will be proved at the end of the section.

Theorem 2.2. *For all $r \geq 3$, there exist $c_0, \delta_0 > 0$ such that for every $0 < \delta \leq \delta_0$, the following holds for sufficiently large n . Every r -graph on n vertices with $\Delta_{r-1}(H) \leq \delta n$ satisfies $\alpha(H) \geq c_0 \left(\frac{1}{\delta} \ln \frac{1}{\delta} \right)^{1/(r-1)}$.*

Proof of Theorem 1.1. Fix $r \geq 3$. Without loss of generality, we assume that t is sufficiently large. We first prove the upper bound with $c_2 = (r-1)^r a_2^{r-1}$, where a_2 is from Construction 2.1. Our goal is to construct r -graphs H on n vertices (for infinitely many n) with $\alpha(H) < t$ and $\Delta_{r-1}(H) \leq c_2 n \ln t / t^{r-1}$. To achieve this, we apply Construction 2.1 with $m = \lceil t^{r-1} / (c_2 \ln t) \rceil$ and $d = n/m \leq c_2 n \ln t / t^{r-1}$ obtaining an r -graph H on n vertices with $\Delta_{r-1}(H) = d$ and

$\alpha(H) \leq a_2(r-1)(m \ln m)^{1/(r-1)}$. Since t is sufficiently large, it follows that $\ln \left\lceil \frac{t^{r-1}}{c_2 \ln t} \right\rceil < \ln t^{r-1} - 1$ and

$$m \ln m = \left\lceil \frac{t^{r-1}}{c_2 \ln t} \right\rceil \ln \left\lceil \frac{t^{r-1}}{c_2 \ln t} \right\rceil < \left(\frac{t^{r-1}}{c_2 \ln t} + 1 \right) (\ln t^{r-1} - 1) < \frac{(r-1)t^{r-1}}{c_2}.$$

Consequently $\alpha(H) < a_2(r-1)(\frac{(r-1)t^{r-1}}{c_2})^{1/(r-1)} = t$ by the choice of c_2 .

We now prove the lower bound. Suppose c_0, δ_0 are as in Theorem 2.2. Let $c_1 = (r-1)c_0^{r-1}/2$ and $\delta = c_1 \ln t / t^{r-1}$. Since t is large, we have $\delta \leq \delta_0$. Let n be sufficiently large. We need to show that every r -graph H on n vertices with $\alpha(H) < t$ satisfies $\Delta_{r-1}(H) \geq \delta n$. Indeed, by Theorem 2.2, any r -graph H on n vertices with $\Delta_{r-1}(H) = d \leq \delta n$ satisfies

$$\alpha(H) \geq c_0 \left(\frac{1}{\delta} \ln \frac{1}{\delta} \right)^{1/(r-1)} > c_0 \left(\frac{t^{r-1}}{2c_1 \ln t} \ln t^{r-1} \right)^{1/(r-1)} = t$$

because t is large and $c_1 = (r-1)c_0^{r-1}/2$. \square

The rest of the section is devoted to the proof of Theorem 2.2. We need [11, Theorem 1] of Kostochka, Mubayi, Verstraëte and [14, Lemma 2.1] of Mubayi and Zhao.²

Theorem 2.3. [11] *For all $r \geq 3$, there exists $b_1 > 0$ such that every r -graph with $\Delta_{r-1}(H) \leq d$ for some $0 < d < n/(\ln n)^{3(r-1)^2}$ satisfies $\alpha(H) \geq b_1 \left(\frac{n}{d} \ln \frac{n}{d} \right)^{1/(r-1)}$.*

Lemma 2.4. [14] *Let $r \geq 2$ and $\varepsilon > 0$. Let m be the positive integer such that $m \geq 2(r-1)/\varepsilon$ and $\binom{m}{r-1} e^{-\varepsilon^2(m-r+1)/12} \leq 1/2$. Every r -graph H on $n \geq m$ vertices contains an induced sub- r -graph H' on m vertices with $\Delta_{r-1}(H')/m \leq \Delta_{r-1}(H)/n + \varepsilon$.*

Proof of Theorem 2.2. Fix $r \geq 3$. Let $0 < \delta_0 < 1/4$ such that

$$24(r-1) \ln \left(\left\lceil \frac{1}{\delta^4} \right\rceil \right) \leq \frac{1}{\delta^2} \quad \text{and} \quad \frac{1}{\delta^4} \leq \exp \left(\left(\frac{1}{2\delta} \right)^{\frac{1}{3(r-1)^2}} \right) - 1 \quad (2.1)$$

for all $0 < \delta \leq \delta_0$. Let $m = \lceil 1/\delta^4 \rceil$. We claim that m satisfies the assumption of Lemma 2.4 when $\varepsilon = \delta$. Indeed, it follows from the first inequality of (2.1) that

$$m \geq \frac{24(r-1) \ln m}{\delta^2} > \frac{2(r-1)}{\delta},$$

which further implies that

$$\binom{m}{r-1} e^{-\delta^2(m-r+1)/12} \leq \frac{1}{2} m^{r-1} e^{-\frac{m\delta^2}{24}} \leq \frac{1}{2}.$$

Let $c_0 = 4^{-1/(r-1)} b_1$, where b_1 is defined in Theorem 2.3. Suppose H is an r -graph on $n \geq m$ vertices with $\Delta_{r-1}(H) \leq \delta n$. By Lemma 2.4, there exists an induced subhypergraph H' on m vertices such that

$$\Delta_{r-1}(H') \leq 2\delta m < \frac{m}{(\ln m)^{3(r-1)^2}},$$

which follows from the second inequality of (2.1) and $m = \lceil 1/\delta^4 \rceil$. We now apply Theorem 2.3 to H' with $d = 2\delta m$ and obtain that

$$\alpha(H) \geq \alpha(H') \geq b_1 \left(\frac{1}{2\delta} \ln \frac{1}{2\delta} \right)^{1/(r-1)} \geq b_1 \left(\frac{1}{4\delta} \ln \frac{1}{\delta} \right)^{1/(r-1)} = c_0 \left(\frac{1}{\delta} \ln \frac{1}{\delta} \right)^{1/(r-1)}$$

by the choice of c_0 and the assumption that $\delta \leq 1/4$. \square

²Alternatively we could apply [3, Theorem 3] of Duke, Lefmann, and Rödl – we choose [11, Theorem 1] because it provides a better constant.

3. CONCLUDING REMARKS

Theorem 1.1 shows that $c_1 \ln t/t^{r-1} \leq \tau_{r-1}(t, r) \leq c_2 \ln t/t^{r-1}$. Our proofs of Theorems 1.1 and 2.2 together give that $c_1 = (r-1)b_1^{r-1}/8$, where b_1 comes from Theorem 2.3. A slightly more careful calculation allows us to take $c_1 = (1 + o_t(1))(r-1)b_1^{r-1}$ (where $o_t(1) \rightarrow 0$ as $t \rightarrow \infty$). The equation (7) in [11] shows that $b_1^{r-1} = (1 + o_r(1))(r-3)!/3$ and thus

$$c_1 = (1 + o_r(1)) \frac{r-1}{3} (r-3)!.$$

On the other hand, our proof of Theorem 1.1 gives $c_2 = (r-1)^r a_2^{r-1}$, where a_2 comes from Construction 2.1. Unfortunately, we do not know the smallest a_2 such that there is a partial Steiner $(m, r, r-1)$ -system S with $\alpha(S) \leq a_2(m \ln m)^{1/(r-1)}$ for every m . However, the random construction in [11, Section 3.2] yields a constant that asymptotically equals b_1 but requires $\ln \Delta_{r-1}(H) = o(\ln n)$. Nevertheless, we can use the blowup of this construction and add some additional edges when $r \geq 4$ to derive that³

$$c_2 = \begin{cases} (1 + o_t(1))r \cdot r! & \text{if } r \text{ is even,} \\ (1 + o_t(1))2^{r-1}r \cdot r! & \text{if } r \text{ is odd.} \end{cases}$$

When r is even, above refined values of c_1 and c_2 differ by a factor of $3r^3$ asymptotically. We tend to believe that $\tau_{r-1}(t, r) \sim r \cdot r! \ln t/t^{r-1}$ when $t \gg r \gg 1$.

Given any r -graph H on n vertices, $\Delta_\ell(H)/\binom{n-\ell}{r-\ell}$ is an increasing function of ℓ . As a result, $\tau_\ell(t, r)$ is an increasing function of ℓ . When $t \rightarrow \infty$, we have $\tau_1(t, r) = 1 - \pi(K_t^r) = \Theta(1/t^{r-1})$ from (1.1) and $\tau_{r-1}(t, r) = \Theta(\ln t/t^{r-1})$ from Theorem 1.1. Putting these together, we have

$$\Theta\left(\frac{1}{t^{r-1}}\right) = \tau_1(t, r) \leq \tau_2(t, r) \leq \cdots \leq \tau_{r-1}(t, r) = \Theta\left(\frac{\ln t}{t^{r-1}}\right).$$

It is interesting to know if $\tau_\ell(t, r) = \Theta(\ln t/t^{r-1})$ for all $\ell \geq 2$.

ACKNOWLEDGMENT

The authors would like to thank Sidorenko and two referees for their valuable comments.

REFERENCES

- [1] D. de Caen. Extension of a theorem of Moon and Moser on complete subgraphs. *Ars Combin.*, 16:5–10, 1983.
- [2] L. DeBiasio and T. Jiang. On the co-degree threshold for the Fano plane. *European J. Combin.*, 36:151–158, 2014.
- [3] R. A. Duke, H. Lefmann, and V. Rödl. On uncrowded hypergraphs. In *Proceedings of the Sixth International Seminar on Random Graphs and Probabilistic Methods in Combinatorics and Computer Science, “Random Graphs ’93” (Poznań, 1993)*, volume 6, pages 209–212, 1995.
- [4] V. Falgas-Ravry. On the codegree density of complete 3-graphs and related problems. *Electron. J. Combin.*, 20(4):Paper 28, 14, 2013.
- [5] V. Falgas-Ravry, E. Marchant, O. Pikhurko, and E. R. Vaughan. The codegree threshold for 3-graphs with independent neighborhoods. *SIAM J. Discrete Math.*, 29(3):1504–1539, 2015.
- [6] V. Falgas-Ravry, O. Pikhurko, E. R. Vaughan, and J. Volec. The codegree threshold of K_4^- . *Electron. Notes Discrete Math*, 61:407–413, 2017.
- [7] Z. Füredi. Turán type problems. In *Surveys in combinatorics, 1991 (Guildford, 1991)*, volume 166 of *London Math. Soc. Lecture Note Ser.*, pages 253–300. Cambridge Univ. Press, Cambridge, 1991.
- [8] P. Keevash. A hypergraph regularity method for generalized Turán problems. *Random Structures Algorithms*, 34(1):123–164, 2009.
- [9] P. Keevash. Hypergraph Turán problems. In *Surveys in combinatorics 2011*, volume 392 of *London Math. Soc. Lecture Note Ser.*, pages 83–139. Cambridge Univ. Press, Cambridge, 2011.
- [10] P. Keevash and Y. Zhao. Codegree problems for projective geometries. *J. Combin. Theory Ser. B*, 97(6):919–928, 2007.

³For example, when r is even, we add all the r -sets that lie inside one vertex class and the r -sets that intersect $r/2$ vertex classes each with exactly two vertices.

- [11] A. Kostochka, D. Mubayi, and J. Verstraëte. On independent sets in hypergraphs. *Random Structures Algorithms*, 44(2):224–239, 2014.
- [12] A. Lo and K. Markström. ℓ -degree Turán density. *SIAM J. Discrete Math.*, 28(3):1214–1225, 2014.
- [13] D. Mubayi. The co-degree density of the Fano plane. *J. Combin. Theory Ser. B*, 95(2):333–337, 2005.
- [14] D. Mubayi and Y. Zhao. Co-degree density of hypergraphs. *J. Combin. Theory Ser. A*, 114(6):1118–1132, 2007.
- [15] V. Rödl and E. Šiňajová. Note on independent sets in Steiner systems. In *Proceedings of the Fifth International Seminar on Random Graphs and Probabilistic Methods in Combinatorics and Computer Science (Poznań, 1991)*, volume 5, pages 183–190, 1994.
- [16] A. Sidorenko. Extremal problems on the hypercube and the codegree Turán density of complete r -graphs. *ArXiv e-prints*, October 2017.
- [17] A. F. Sidorenko. Systems of sets that have the T -property. *Vestnik Moskov. Univ. Ser. I Mat. Mekh.*, (5):19–22, 1981.
- [18] P. Turán. Eine Extremalaufgabe aus der Graphentheorie. *Mat. Fiz. Lapok*, 48:436–452, 1941.

SCHOOL OF MATHEMATICS, UNIVERSITY OF BIRMINGHAM, BIRMINGHAM, B15 2TT, UK
Email address: `s.a.lo@bham.ac.uk`

DEPARTMENT OF MATHEMATICS AND STATISTICS, GEORGIA STATE UNIVERSITY, ATLANTA, GA 30303
Email address: `yzhao6@gsu.edu`