Bipartite Subgraphs and Quasi-randomness

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Abstract. We say that a family of graphs $\mathcal{G} = \{G_n : n \geq 1\}$ is p-quasi-random, $0 < p < 1$, if it shares typical properties of the random graph $G(n,p)$; for a definition, see below. We denote by $\mathcal{Q}^{\mathrm{w}}(p)$ the class of all graphs H for which $e(G_n) \geq (1 + o(1))p\binom{n}{2}$ and the number of not necessarily induced labeled copies of H in G_n is at most $(1 + o(1))p^{e(H)}n^{v(H)}$ imply that $\mathcal{G}$ is p-quasi-random. In this note, we show that all complete bipartite graphs $K_{a,b}$, $a, b \geq 2$, belong to $\mathcal{Q}^{\mathrm{w}}(p)$ for all $0 < p < 1$.

1. Notation

We start with fixing notation. For positive integers k, n and a real number x, we set $[n] = \{1, \dots, n\}$ and $(x)_k = x(x-1) \times \cdots \times (x-k+1)$.

Given a graph G with vertex set $V(G)$ and edge set $E(G)$, $v(G)$ stands for $|V(G)|$ and $e(G)$ for $|E(G)|$. Furthermore, for a subset X of $V(G)$, $G[X]$ denotes the subgraph induced by the vertices of X, and $e(X)$ denotes the number of edges of $G[X]$. Given a vertex $x \in V(G)$, $N_G(x)$ is the set of all vertices adjacent to x and, similarly, for a subset X of $V(G)$, $N_G(X)$ denotes the set of all vertices adjacent to every vertex in X. Clearly, $N_G(X) = \bigcap_{x \in X} N_G(x)$. We also put $\deg(x) = \deg_G(x) = \big|N_G(x)\big|$ and $\deg(X) = \deg_G(X) = \big|N_G(X)\big|$.

For a graph $G = G_n$ on n vertices, let $\lambda_1(G), \dots, \lambda_n(G)$,

$$\lambda_1(G) \geq |\lambda_2(G)| \geq \cdots \geq |\lambda_n(G)| ,$$

be the eigenvalues of its adjacency matrix.

Given two graphs G and H, a labeled *induced* copy of H in G is an injection $\psi\colon V(H) \to V(G)$ such that $\{x, x'\} \in E(H)$ if and only if $\{\psi(x), \psi(x')\} \in E(G)$.

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A labeled *weak* (i.e. not necessarily induced) copy of H in G is an injection $\psi\colon V(H) \to V(G)$ such that if $\{x, x'\} \in E(H)$, then $\{\psi(x), \psi(x')\} \in E(G)$. Denote by $\binom{G}{H}$ the set of all labeled induced copies of H in G and by $\binom{G}{H}^{\mathrm{w}}$ the set of all weak labeled copies of H in G.

2. Introduction

The theory of quasi-random graphs deals with properties of graphs, which are equivalent in the sense that a graph satisfying one of the properties must possess them all.

The study of quasi-random graphs was initiated by A.G. Thomason, cf. [11, 12], and systematically studied by Chung, Graham, and Wilson [5]. Their results were later extended to the case of uniform hypergraphs of a constant density, see [3, 2, 4, 6].

Chung, Graham, and Wilson [5] proved the following theorem.

Theorem 1. *Let $0 < p < 1$, $\mathcal{G} = \{G_n : n \in \mathbb{N}\}$ be a family of graphs, $t \geq 4$ be an even integer, $s \geq 4$ be an integer. The following properties $\boldsymbol{P_1}$–$\boldsymbol{P_5}$ are equivalent for the family $\mathcal{G}$:*

$\boldsymbol{P_1(s)}$*: For all graphs H_s on s vertices,*

$$\left|\binom{G_n}{H_s}\right| = (1 + o(1))p^{e(H_s)}(1-p)^{\binom{s}{2}-e(H_s)}n^s\ .$$

$\boldsymbol{P_2(t)}$*: $e(G_n) \geq (1 + o(1))p\binom{n}{2}$ and $\left|\binom{G_n}{C_t}^{\mathrm{w}}\right| \leq (1 + o(1))p^t n^t$, where C_t denotes a t-cycle.*

$\boldsymbol{P_3}$*: $e(G_n) \geq (1 + o(1))p\binom{n}{2}$ and $\lambda_1(G_n) = (1 + o(1))pn$, $\lambda_i(G_n) = o(n)$ for $i \geq 2$.*

$\boldsymbol{P_4}$*: For all $X \subseteq V(G_n)$, $e(X) = \frac{p}{2}|X|^2 + o(n^2)$.*

$\boldsymbol{P_5}$*: For all but at most $o(n)$ vertices $x \in V(G_n)$, $\deg_{G_n}(x) = (1 + o(1))pn$ and for all but at most $o(n^2)$ pairs of vertices $x, x' \in V(G_n)$, $\deg_{G_n}(x, x') = (1 + o(1))p^2 n$.*

The equivalence of these properties is understood in the following sense. For two properties involving $o(1)$ terms $\boldsymbol{P} = \boldsymbol{P}(o(1))$ and $\boldsymbol{P'} = \boldsymbol{P'}(o(1))$, the implication "$\boldsymbol{P} \Rightarrow \boldsymbol{P'}$" means that for every $\varepsilon > 0$ there is a $\delta > 0$ so that any graph G_n satisfying $\boldsymbol{P}(\delta)$ must also satisfy $\boldsymbol{P'}(\varepsilon)$, provided $n > N_0(\varepsilon)$.

The families $\mathcal{G}$ satisfying properties $\boldsymbol{P_1} - \boldsymbol{P_5}$ above are called *p-quasi-random*. We also refer to any property equivalent to any of $\boldsymbol{P_1} - \boldsymbol{P_5}$ as a *p-quasi-random property*.

Since [5], many other p-quasi-random properties have been discovered (e.g. [9, 10]). Given a graph $H = H_t$, let $\boldsymbol{P_w(H)}$ be the following property:

$$\boldsymbol{P_w(H)}:\ e(G_n) \geq (1 + o(1))p\binom{n}{2} \text{ and } \left|\binom{G_n}{H}^{\mathrm{w}}\right| \leq (1 + o(1))p^{e(H)}n^t.$$

One may ask to determine the class $\mathcal{Q}^{\mathrm{w}} = \mathcal{Q}^{\mathrm{w}}(p)$ of all graphs H for which $\boldsymbol{P_w(H)}$ is a p-quasi-random property. By the above theorem, all even cycles belong to this class. Chung, Graham, and Wilson further observed (cf. [5]) that $K_{2,t}$ belong to $\mathcal{Q}^{\mathrm{w}} = \mathcal{Q}^{\mathrm{w}}(p)$, however, odd cycles do not. As remarked in [1] one does not expect $\mathcal{Q}^{\mathrm{w}}$ to be a large class. In this note, we show that all complete bipartite graphs $K_{a,b}$, $a, b \geq 2$, belong to $\mathcal{Q}^{\mathrm{w}}(p)$ for all $0 < p < 1$ (cf. Theorem 2 below).

3. Bipartite Graphs

Our goal is to prove the following theorem. We will use Corollary 1 in its proof. The proof of the corollary is postponed to Section 4.

Theorem 2. *Let $a, b \geq 2$ be integers. For $0 < p < 1$, let $\mathcal{G}_p$ be a family of graphs $\{G_n \colon e(G_n) \geq (1 + o(1))p\binom{n}{2}\}$. If for every $G_n \in \mathcal{G}_p$*

$$\left|\binom{G_n}{K_{a,b}}^{\mathrm{w}}\right| \leq (1 + o(1))p^{ab}n^{a+b}, \tag{1}$$

then $\mathcal{G}_p$ is p-quasi-random.

Proof. Note that adding (or removing) $o(n^2)$ edges to $G_n \in \mathcal{G}$ does not affect whether $\mathcal{G}$ satisfies property $\boldsymbol{P_4}$ and, consequently, whether $\mathcal{G}$ is p-quasi-random or not. Further, it also doesn't change (1).

Hence, we may assume $\deg_{G_n}(x) > A_1$ for every vertex $x \in V(G_n)$, $\deg_{G_n}(x, x') > A_2$ for all pairs of vertices $x, x' \in V(G_n)$, and $\deg_{G_n}(X) > A_a$ for all subsets $X \in [V(G_n)]^a$. Here $[V(G_n)]^a$ stands for the set of all a-element subsets of $V(G_n)$ and A_1, A_2 and A_a are numbers given by Corollary 1. Indeed, let Y be any subset of $V(G_n)$ with $2(A_1+A_2+A_a)$ vertices and set $Z = V(G_n)\setminus Y$. We add to $E(G_n)$ any missing edge between Y and Z and any missing edge within Y. Altogether, we increase the number of edges by at most $2(A_1+A_2+A_a)\times n+4(A_1+A_2+A_a)^2 = o(n^2)$. It is easy to see that every vertex (pair of vertices, or a-element subset, respectively) has more than A_1 (A_2, or A_a respectively) common neighbors in Y.

Then, note that

$$\left|\binom{G_n}{K_{a,b}}^{\mathrm{w}}\right| = \sum_{X\in[V(G_n)]^a} a!b!\binom{\deg_{G_n}(X)}{b}. \tag{2}$$

We use the convexity of $\binom{y}{b}$ [1] for $y \geq 0$, Jensen's inequality, and the fact that $\left|[V(G_n)]^a\right| = \binom{n}{a}$ to estimate the right-hand side of (2). Indeed,

$$\sum_{X\in[V(G_n)]^a} a!b!\binom{\deg_{G_n}(X)}{b} \geq a!b!\binom{n}{a}\binom{\sum_{X\in[V(G_n)]^a}\deg_{G_n}(X)/\binom{n}{a}}{b}. \tag{3}$$

[1] We say that function $\binom{y}{b} = (y)_b/b!$ is convex on interval $[0, \infty)$ if the function

$$g_b(y) = \begin{cases} 0 & \text{for } 0 \leq y \leq b-1, \\ (y)_b/b! & \text{for } y \geq b-1 \end{cases}$$

is convex (in the usual sense) for $y \geq 0$.

Note that, by double counting and the convexity of $\binom{y}{a}$,

$$\sum_{X\in[V(G_n)]^a} \deg_{G_n}(X) = \sum_{x\in V(G_n)} \binom{\deg_{G_n}(x)}{a} \geq n\binom{2e(G_n)/n}{a}.$$

Since $e(G_n) \geq (1+o(1))p\binom{n}{2}$, we obtain

$$\sum_{X\in[V(G_n)]^a} \deg_{G_n}(X) \geq (1+o(1))np^a\binom{n}{a}.$$

We combine this with (2) and (3) and conclude that

$$\left|\binom{G_n}{K_{a,b}}^{\mathrm{w}}\right| \geq (1+o(1))n^a\left((1+o(1))np^a\binom{n}{a}/\binom{n}{a}\right)_b = (1+o(1))p^{ab}n^{a+b}. \quad (4)$$

Comparing (4) with (1), we obtain an asymptotic equality in all inequalities.

Hence, by Corollary 1 (note that $\deg_{G_n}(x) > A_1$ for every vertex $x \in V(G_n)$ is necessary to verify assumption (i) of this proposition), we get that for all but $o(n)$ vertices $x \in V(G_n)$ we have $\deg_{G_n}(x) = (1+o(1))pn$. Similarly, for all but $o(n^a)$ sets $X \in [V(G_n)]^a$, we have $\deg_{G_n}(X) = (1+o(1))p^a n$.

Consequently,

$$\sum_{X\in[V(G_n)]^a} \binom{\deg_{G_n}(X)}{2} = (1+o(1))\binom{n}{a}p^{2a}\binom{n}{2}. \quad (5)$$

On the other hand, by a double counting,

$$\sum_{X\in[V(G_n)]^a} \binom{\deg_{G_n}(X)}{2} = \sum_{\{x,x'\}\in[V(G_n)]^2} \binom{\deg_{G_n}(x,x')}{a}. \quad (6)$$

The right-hand side of (6) can be estimated using Jensen's inequality again:

$$\sum_{\{x,x'\}\in[V(G_n)]^2} \binom{\deg_{G_n}(x,x')}{a} \geq \binom{n}{2}\binom{\sum_{\{x,x'\}\in[V(G_n)]^2}\deg_{G_n}(x,x')/\binom{n}{2}}{a}. \quad (7)$$

Since $\sum_{\{x,x'\}\in[V(G_n)]^2}\deg_{G_n}(x,x') = \sum_{y\in V(G_n)}\binom{\deg_{G_n}(y)}{2} = (1+o(1))p^2n\binom{n}{2}$, we obtain

$$\begin{aligned}\sum_{\{x,x'\}\in[V(G_n)]^2} \binom{\deg_{G_n}(x,x')}{a} &\geq \binom{n}{2}\binom{\sum_{\{x,x'\}\in[V(G_n)]^2}\deg_{G_n}(x,x')/\binom{n}{2}}{a}\\ &\geq \binom{n}{2}\binom{(1+o(1))p^2n\binom{n}{2}/\binom{n}{2}}{a} \quad (8)\\ &= (1+o(1))\binom{n}{a}p^{2a}\binom{n}{2}.\end{aligned}$$

Comparing (5) and (8) yields an asymptotic equality in (7). Consequently, by Corollary 1 (note that $\deg_{G_n}(x,x') > A_2$ for every pair $x, x' \in V(G_n)$ is needed to verify assumption (i) of this corollary), we have $\deg_{G_n}(x, x') = (1 + o(1))p^2 n$ for all but at most $o(n^2)$ pairs x, $x' \in V(G_n)$. Then, $\mathcal{G}_p$ is quasi-random by property $\boldsymbol{P_5}$, Theorem 1. $\square$

We remark that the combined use of convexity and Corollary 1 was already considered in [8,7] to address quasi-randomness for sparse graphs.

4. A Variant of the Cauchy-Schwarz Inequality

Since the function $x^k, k \geq 2$, is a strictly convex function, we have

$$\frac{a_1^k + \cdots + a_n^k}{n} \geq \left(\frac{a_1 + \cdots + a_n}{n}\right)^k \tag{9}$$

by Jensen's inequality with equality iff $a_1 = a_2 = \cdots = a_n$. The proposition below shows that if equality in (9) holds asymptotically, then almost all a_i's are roughly equal to their average.

Proposition 1. *For every $\delta > 0$ and a positive integer $k \geq 2$ there exists $\varepsilon > 0$ such that for non-negative reals $a_1, a_2, \ldots, a_n$ satisfying*

(i) $\sum_{i=1}^n a_i \geq (1 - \varepsilon)na$, *and*
(ii) $\sum_{i=1}^n a_i^k < (1 + \varepsilon)na^k$,

we have $\big|\{i \ : \ |a - a_i| < \delta a\}\big| > (1 - \delta)n$.

Proof. We distinguish two cases: $k = 2$ and $k > 2$.

The first case ($k = 2$) was already considered by Kohayakawa, Rödl, and Sissokho in [7]. We include their proof for the sake of completeness. Given $\delta > 0$ and non-negative reals $a_1, a_2, \ldots, a_n$, we set $\varepsilon = \delta^3/3$ and $B = \big|\{i \ : \ |a - a_i| \geq \delta a\}\big|$. We prove the proposition by showing $|B| < \delta n$.

Indeed, it follows from the definition of B that

$$\sum_{i=1}^{n} (a_i - a)^2 > |B|\delta^2 a^2. \tag{10}$$

By our assumption,

$$\sum_{i=1}^{n} (a_i - a)^2 = \sum_{i=1}^{n} a_i^2 - 2a \sum_{i=1}^{n} a_i + \sum_{i=1}^{n} a^2$$
$$\leq (1 + \varepsilon)a^2 - 2a(1 - \varepsilon)na + na^2 = 3\varepsilon na^2. \tag{11}$$

Combining (10) and (11) yields $|B|\delta^2 a^2 < 3\varepsilon na^2$, which implies $|B| < (3\varepsilon/\delta^2)n = \delta n$.

For the case when $k > 2$, we will use the well-known fact that for $k > 2$, we have

$$\left(\sum_{i=1}^{n} a_i^2/n\right)^{1/2} \leq \left(\sum_{i=1}^{n} a_i^k/n\right)^{1/k}. \tag{12}$$

Set $\varepsilon = \delta^3/3$. Then

$$\sum_{i=1}^{n} a_i^2 \overset{(12)}{\leq} \left(\sum_{i=1}^{n} a_i^k/n\right)^{2/k} n \overset{(ii)}{\leq} \left(\big(1+\delta^3/3\big)a^k\right)^{2/k} n \leq \big(1+\delta^3/3\big)a^2 n$$

because $2/k < 1$. Thus the proof follows from the $k = 2$ case. $\square$

The following corollary is similar to Proposition 1 but we consider function $\binom{x}{k}$ instead of x^k.

Corollary 1. *For every $0 < \delta < 1$ and positive integer $k \geq 2$ there exists $\varepsilon > 0$ and $A_k > 0$ such that for non-negative reals $a_1, a_2, \ldots, a_n, a$ satisfying*

(i) $a > A_k$ and $a_i > A_k$ for all $i \in [n]$,
(ii) $\sum_{i=1}^n a_i \geq (1-\varepsilon)na$, and
(iii) $\sum_{i=1}^n \binom{a_i}{k} < (1+\varepsilon)n\binom{a}{k}$,

we have $\big|\{i \ : \ |a - a_i| < \delta a\}\big| > (1-\delta)n$.

Proof. Set $\varepsilon = \delta^3/12$. Our conclusion follows from the fact that $a_1, \ldots, a_n$ and a satisfy the assumptions of Proposition 1. Since (ii) holds, we must only show that $\sum_{i=1}^n a_i^k \leq \big(1+\delta^3/3\big)na^k$.

Since $\lim_{x\to\infty} x^k/(x)_k = 1$ for every positive integer k, there exists a real number A_k such that $x^k < (1+\varepsilon)(x)_k$ whenever $x > A_k$. By (i)-(iii), we obtain

$$\sum_{i=1}^{n} a_i^k \overset{(i)}{<} (1+\varepsilon)\sum_{i=1}^{n}(a_i)_k = (1+\varepsilon)k!\sum_{i=1}^{n}\binom{a_i}{k} \overset{(iii)}{<} (1+\varepsilon)^2 k! n\binom{a}{k} \leq \big(1+\delta^3/3\big)na^k.$$

$\square$

5. Concluding remarks

In [5], the authors introduced forcing families of graphs. Let $\mathcal{G} = \{G_n : n \geq 1\}$ be a family of graphs. A family $\mathcal{F}$ of graphs is *p-forcing* if $\left|\binom{G_n}{F}^{\mathrm{w}}\right| = (1 + o(1))p^{e(F)}n^{v(F)}$ for all $F \in \mathcal{F}$ and $G_n \in \mathcal{G}$ implies $\mathcal{G}$ is p-quasi-random. Chung, Graham, and Wilson [5] asked what families were p-forcing, and, as an example of p-forcing families, they mentioned $\{P_2, C_{2t}\}$, $t \geq 2$, and $\{P_2, K_{2,t}\}$, $t \geq 2$.

Clearly, if H is any graph for which $\boldsymbol{P_w}(H)$ is p-quasi-random, then $\{P_2, H\}$ is p-forcing. In particular, $\{P_2, K_{a,b}\}$ is a p-forcing family for every a, $b \geq 2$. It would be interesting to decide whether $\{P_2, H\}$ is p-forcing (or $\boldsymbol{P_w}(H)$ is p-quasi-random) for every connected bipartite graph H with at least one cycle. We are not aware of an example of any bipartite graph H with at least one cycle for which $\boldsymbol{P_w}(H)$ is not p-quasi-random.

We also remark that if we consider induced copies instead of weak ones, then we do not obtain p-quasi-random properties. In particular, define the following property:

$$\boldsymbol{P}_{\mathbf{ind}}(H) : e(G_n) \geq (1+o(1))p\binom{n}{2} \quad \text{and}$$
$$\left|\binom{G_n}{H}\right| \leq (1+o(1))p^{e(H)}(1-p)^{\binom{v(H)}{2}-e(H)}n^{v(H)}.$$

Then, for every connected graph H, one can find a non-degenerate interval $I \subset [0,1]$ such that for each $p \in I$ there exists a family $\mathcal{G}_p = \{G_n \colon e(G_n) \geq (1+o(1))p\binom{n}{2}\}$ satisfying $\boldsymbol{P}_{\mathbf{ind}}(H)$ but $\mathcal{G}_p$ is not p-quasi-random. We remark that one can choose all $G_n \in \mathcal{G}_p$ of the form $G_n = 2G(n/2,q)$, where $G(n/2,q)$ is a random graph with edge probability q, and leave the details to the interested reader.

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