EDGE-STATISTICS ON LARGE GRAPHS

NOGA ALON, DAN HEFETZ, MICHAEL KRIVELEVICH, AND MYKHAYLO TYOMKYN

Abstract. The inducibility of a graph $H$ measures the maximum number of induced copies of $H$ a large graph $G$ can have. Generalizing this notion, we study how many induced subgraphs of fixed order $k$ and size $\ell$ a large graph $G$ on $n$ vertices can have. Clearly, this number is $\binom{n}{\ell}$ for every $n$, $k$ and $\ell \in \{0, \binom{k}{2}\}$. We conjecture that for every $n$, $k$ and $0 < \ell < \binom{k}{2}$ this number is at most $\left(1/e + o(1)\right)\binom{n}{\ell}$. If true, this would be tight for $\ell \in \{1, k-1\}$.

In support of our ‘Edge-statistics conjecture’ we prove that the corresponding density is bounded away from 1 by an absolute constant. Furthermore, for various ranges of the values of $\ell$ we establish stronger bounds. In particular, we prove that for ‘almost all’ pairs $(k, \ell)$ only a polynomially small fraction of the $k$-subsets of $V(G)$ has exactly $\ell$ edges, and prove an upper bound of $(1/2 + o_k(1))\binom{n}{\ell}$ for $\ell = 1$.

Our proof methods involve probabilistic tools, such as anti-concentration results relying on fourth moment estimates and Brun’s sieve, as well as graph-theoretic and combinatorial arguments such as Zykov’s symmetrization, Sperner’s theorem and various counting techniques.

1. Introduction

Let $k$ be a positive integer and let $G$ be a finite graph of order at least $k$. Let $A$ be chosen uniformly at random from all subsets of $V(G)$ of size $k$ and let $X_{G,k} = e(G[A])$. That is, $X_{G,k}$ is the random variable counting the number of edges of $G$ on $n$ vertices and $\ell$ edges, taken over all graphs of order $n$. A standard averaging argument shows that $I(n, k, \ell)$ is a monotone decreasing function of $n$. Consequently, we define $\text{ind}(k, \ell) := \lim_{n \to \infty} I(n, k, \ell)$ to be the edge-inducibility of $k$ and $\ell$. While this quantity is trivially 1 for $\ell \in \{0, \binom{k}{2}\}$ (simply take $G$ to be a large empty or complete graph, respectively), it is natural to ask how large can $\text{ind}(k, \ell)$ be for $0 < \ell < \binom{k}{2}$.

This question is closely related to the problem of determining the inducibilities of fixed graphs, a concept which was introduced in 1975 by Pippenger and Golumbic [13]. For a graph $H$, let $D_H(G)$ denote the number of induced subgraphs of $G$ that are isomorphic to $H$, and let $I_H(n) = \max\{D_H(G) : |G| = n\}$. Again, the sequence $\{I_H(n)/\binom{n}{|H|}\}_{n=|H|}^{\to \infty}$ is monotone decreasing and thus converges to a limit $\text{ind}(H)$, the inducibility of $H$. Recently there has been a surge of interest in this area (see, e.g., [4, 9, 14, 10]).

Observe that both types of inducibility are invariant under taking complements, that is, $\text{ind}(k, \ell) = \text{ind} \left( k, \binom{k}{2} - \ell \right)$ and $\text{ind}(H) = \text{ind}(\overline{H})$. Note also that $\text{ind}(H) \leq \text{ind}(|H|, e(H))$.

Moreover, if $|H| = k$ and $e(H) \in \left\{1, \binom{k}{2} - 1\right\}$, then $\text{ind}(H) = \text{ind}(k, e(H))$, as $H$ is the unique (up to isomorphism) graph with $k$ vertices and $e(H)$ edges.

Consider a random graph $G \sim G(n, p)$, where $p = (\binom{k}{2})^{-1}$. A straightforward calculation shows that the expected value of the number of $k$-subsets of $V(G)$ which span precisely one edge is about $1/e$. This implies that $\text{ind}(k, 1) \geq 1/e + o_k(1)$. In fact, we will see later that
there are many constructions which achieve \(1/e + o(1)\) as a lower bound for \(\text{ind}(k,1)\). Another construction, achieving the same asymptotic value for \(\ell = k-1\) is the complete bipartite graph with the smaller part of size \(n/k\), so that \(\text{ind}(k,k-1) \geq \text{ind}(K_{1,k-1}) \geq 1/e + o_k(1)\). In fact, it is known [6] that \(\text{ind}(K_{1,k-1}) = 1/e + o(k)\). Note that the \(o(k)\) term is necessary. For example, counting cherries in \(K_{n/2,n/2}\) shows that \(\text{ind}(3,2) = \text{ind}(K_{1,2}) \geq 3/4\) (in fact, it follows from Goodman’s Theorem that \(\text{ind}(3,1) = \text{ind}(3,2) = 3/4\)). Motivated by the aforementioned constructions (as well as some additional data), we conjecture that the lower bound of \(1/e\) is asymptotically tight.

**Conjecture 1.1** (The Edge-statistics Conjecture). For every \(\varepsilon > 0\) there exists \(k_0 = k_0(\varepsilon)\) such that for all integers \(k > k_0\) and \(0 < \ell < \left(\frac{k}{2}\right)\) we have \(\text{ind}(k,\ell) \leq 1/e + \varepsilon\).

For graph-inducibilities we make an analogous conjecture, which would be implied by the Edge-statistics Conjecture.

**Conjecture 1.2** (The Large Inducibility Conjecture).

\[
\limsup \{ \text{ind}(H) : H \notin \{K_{|H|}, \overline{K}_{|H|}\} \} = 1/e.
\]

Our first theorem in this paper constitutes a first step towards proving Conjecture 1.1. It asserts that \(\text{ind}(k,\ell)\) is bounded away from 1 by an absolute constant for every \(k\) and \(0 < \ell < \left(\frac{k}{2}\right)\).

**Theorem 1.3.** There exists an \(\varepsilon > 0\) such that for all positive integers \(k\) and \(\ell\) such that \(0 < \ell < \left(\frac{k}{2}\right)\) we have

\[
\text{ind}(k,\ell) < 1 - \varepsilon.
\]

For clarity of presentation, we do not give explicit bounds on \(\varepsilon\) and refer to Section 6 for a discussion.

Note that it is not hard to prove that for every positive integer \(k\) we have \(\text{ind}(k,\ell) = 1\) if and only if \(\ell \in \{0, \left\lfloor \frac{k}{2} \right\rfloor \}\). Indeed, if \(0 < \ell < \left\lfloor \frac{k}{2} \right\rfloor\), then \(\text{ind}(k,\ell) < 1-4^{-k^2}\) is an easy consequence of Ramsey’s Theorem and the aforementioned monotonicity of \(I(n,k,\ell)\). With a bit more effort, this bound can be improved to \(1 - k^{-2}\). On the other hand, we do not see a simple argument that would upper bound \(\text{ind}(k,\ell)\) away from 1 by an absolute constant as in Theorem 1.3. Note also that the related problem of minimizing graph-inducibilities has been extensively studied. In particular, Pippenger and Golumbic [13] showed that the inducibility of any \(k\)-vertex graph is at least \((1 + o_k(1))k!/k^k\). It follows that \(\text{ind}(H) > 0\) for every graph \(H\) and thus \(\text{ind}(k,\ell) > 0\) for every \(k\) and \(\ell\). We refer the reader to Section 6 for further discussion.

For various ranges of values of \(\ell\) (viewed as a function of \(k\)) we establish much better upper bounds than the one stated in Theorem 1.3. First, for every \(\ell\) satisfying \(\min \left\{ \ell, \left\lfloor \frac{k}{2} \right\rfloor - \ell \right\} = \omega(k)\), we prove an upper bound of \(1/2\).

**Proposition 1.4.** For every \(\varepsilon > 0\) there exist \(C(\varepsilon) > 0\) and \(k_0(\varepsilon) > 0\) such that the following holds. Let \(k\) and \(\ell\) be integers satisfying \(k \geq k_0\) and \(Ck \leq \ell \leq \left(\frac{k}{2}\right) - Ck\). Then

\[
\text{ind}(k,\ell) \leq \frac{1}{2} + \varepsilon.
\]

Next, we prove Conjecture 1.1 ‘almost everywhere’. In fact, we prove a much stronger statement, namely that for every \(\ell\) satisfying \(\min \left\{ \ell, \left(\frac{k}{2}\right) - \ell \right\} = \Omega(k^2)\) the quantity \(\text{ind}(k,\ell)\) is actually polynomially small in \(k\) — the right asymptotic behavior as can be seen by considering the random graph \(G(n,\ell/(\left(\frac{k}{2}\right))\), which gives \(\text{ind}(k,\ell) = \Omega(k^{-1})\).

**Theorem 1.5.** For every positive integers \(k\) and \(\ell\) such that \(\min \{\ell, k^2/2 - \ell\} = \Omega(k^2)\) we have \(\text{ind}(k,\ell) = O\left(\frac{k^{-0.1}}{1}\right)\).

Lastly, we consider the case when \(\ell\) is fixed (i.e., does not depend on \(k\)). Here we prove an upper bound of \(3/4\). In the interesting sub-case \(\ell = 1\), which corresponds to the inducibility of the one-edge graph (equivalently, of \(K_{k-1}\), the complete graph with one edge removed) we prove a yet better bound of \(1/2\).
Theorem 1.6. For every fixed positive integer \( \ell \) we have
\[
\text{ind}(k, \ell) \leq \frac{3}{4} + o_k(1).
\]
Moreover, for \( \ell = 1 \) we have
\[
\text{ind}(k, 1) \leq \frac{1}{2} + o_k(1).
\]
Our results are summarized in the following table. For various ranges of \( \ell \leq k^2/4 \), it states the best known upper bound on \( \text{ind}(k, \ell) \). Note that for \( \ell \geq k^2/4 \) the table can be extended symmetrically.

<table>
<thead>
<tr>
<th>( \ell = \ell(k) )</th>
<th>( \ell(k) )</th>
<th>( \ell/4 )</th>
<th>( \ell/2 )</th>
<th>( \ell/3 )</th>
<th>( \ell/4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{ind}(k, \ell) )</td>
<td>( 1/2 )</td>
<td>( 3/4 )</td>
<td>( 1 - \varepsilon )</td>
<td>( 1/2 )</td>
<td>( O(k^{-0.1}) )</td>
</tr>
</tbody>
</table>

1.1. Notation. Throughout this paper, \( \log \) stands for the natural logarithm, unless explicitly stated otherwise. For positive integers \( n \geq k \) we denote by \( (n)_k \) the falling factorial \( \prod_{i=0}^{k-1} (n-i) \).

The symmetric difference of two sets \( A \) and \( B \), denoted by \( A \Delta B \), is \( (A \setminus B) \cup (B \setminus A) \).

Our graph-theoretic notation is standard and follows that of [5]. In particular, we use the following. For a graph \( G \), let \( V(G) \) and \( E(G) \) denote its sets of vertices and edges respectively, and let \( |G| = |V(G)| \) and \( e(G) = |E(G)| \). The complement of \( G \), denoted by \( \overline{G} \), is the graph with vertex set \( V(G) \) and edge set \( \left(V(G) \right)^c \setminus E(G) \).

For a set \( S \subseteq V(G) \), let \( G[S] \) denote the graph with vertex set \( S \) and edge set \( \{uv \in E(G) : u, v \in S\} \). For disjoint sets \( S,T \subseteq V(G) \), let \( G[S,T] \) denote the bipartite graph with parts \( S \) and \( T \) and edge-set \( \{uv \in E(G) : u \in S, v \in T\} \).

2. Preliminaries

To simplify notation we abbreviate \( X_{G,k} \) to \( X \) whenever there is no risk of confusion. Our first lemma provides a useful global-local criterion for handling edge-inducibilities.

Lemma 2.1. Let \( k \) and \( \ell \) be positive integers satisfying \( 0 < \ell < (\frac{k}{2}) \) and let \( a = \text{ind}(k, \ell) \). Let \( n \) be a sufficiently large integer and let \( G \) be a graph on \( n \) vertices which attains \( I(n,k,\ell) \). Then, for every vertex \( v \in V(G) \), we have \( P(a = X = \ell | v \in A) = (1 + o(1))a \).

Proof. The main idea of the proof is the same as in the proof of Lemma 2.4 from [9]. Double-counting yields
\[
(1 + o(1))a = P(X = \ell) = \frac{1}{k} \sum_{v \in V(G)} P(X = \ell, v \in A) = \frac{1}{k} \sum_{v \in V(G)} P(X = \ell | v \in A) \cdot P(v \in A)
\]
\[
= \frac{1}{k} \cdot \frac{k}{n} \sum_{v \in V(G)} P(X = \ell | v \in A) = \frac{1}{n} \sum_{v \in V(G)} P(X = \ell | v \in A).
\]

Let \( v^+ \) and \( v^- \) be the vertices with the largest and the smallest value of \( P(X = \ell | v \in A) \), respectively. Let the graph \( G' \) be obtained from \( G \) by Żykov’s symmetrization [15], i.e., remove
Suppose that $v^-$ and add a twin copy of $v^+$ instead (say, the two copies of $v^+$ are not connected by an edge in $G'$). Then
\[
\mathbb{P}(X = \ell) \geq \mathbb{P}(X_{G',k} = \ell) \geq \mathbb{P}(X = \ell) - \mathbb{P}(X = \ell, v^- \in A) + \mathbb{P}(X = \ell, v^+ \in A) - \mathbb{P}(X = \ell, v^- \in A, v^+ \in A)
\]
\[
= \mathbb{P}(X = \ell) - \frac{k}{n} \cdot \mathbb{P}(X = \ell | v^- \in A) + \frac{k}{n} \cdot \mathbb{P}(X = \ell | v^+ \in A) - \frac{k(k-1)}{n(n-1)} \cdot \mathbb{P}(X = \ell | v^+, v^- \in A)
\]
\[
= \mathbb{P}(X = \ell) + \frac{k}{n} \cdot (\mathbb{P}(X = \ell | v^+ \in A) - \mathbb{P}(X = \ell | v^- \in A)) - O(n^{-2}),
\]
where the first inequality follows from our assumption that $G$ maximizes $\mathbb{P}(X_{G,k} = \ell)$.

Therefore
\[
\mathbb{P}(X = \ell | v^+ \in A) - \mathbb{P}(X = \ell | v^- \in A) = O(n^{-1}).
\]
Hence,
\[
\mathbb{P}(X = \ell | v^+ \in A) \leq a + O(n^{-1}) \quad \text{and} \quad \mathbb{P}(X = \ell | v^- \in A) \geq a - O(n^{-1}).
\]
Since $a > 0$ (as remarked in the introduction), this concludes the proof of the lemma. \qed

Let now $k, \ell, n, G$ and $a$ be as in Lemma 2.1, and suppose additionally that $a > 1/2$. For two vertices $v, w \in V(G)$ let $B_{vw}$ denote a subset of $V(G) \setminus \{v, w\}$ of size $k - 1$, chosen uniformly at random among all such subsets.

**Lemma 2.2.** For any two vertices $v, w \in V(G)$ we have
\[
\mathbb{P}(e_G(v, B_{vw}) = e_G(w, B_{vw})) > 2a - 1 - o(1).
\]

**Proof.** By Lemma 2.1 we have
\[
\mathbb{P}(X = \ell | v \in A, w \notin A) = \mathbb{P}(X = \ell | v \in A) + o(1) = a + o(1). \tag{2.1}
\]
and, symmetrically,
\[
\mathbb{P}(X = \ell | w \in A, v \notin A) = a + o(1). \tag{2.2}
\]
Setting $G'' = G \setminus \{v, w\}$ and $B = B_{vw}$, identities (2.1) and (2.2) imply that
\[
\mathbb{P}(X_{G'',k-1} + e_G(B, v) = \ell) = a + o(1) \quad \text{and} \quad \mathbb{P}(X_{G'',k-1} + e_G(B, w) = \ell) = a + o(1).
\]
Let $L_v$ (respectively, $L_w$) denote the event $X_{G'',k-1} + e_G(B, v) = \ell$ (respectively, $X_{G'',k-1} + e_G(B, w) = \ell$). Then
\[
\mathbb{P}(e_G(B, v) = e_G(B, w)) \geq \mathbb{P}(L_v \cap L_w) = \mathbb{P}(L_v) + \mathbb{P}(L_w) - \mathbb{P}(L_v \cup L_w) > 2a - 1 - o(1).
\]
\qed

**Lemma 2.3.** In the setting of Lemma 2.2, for any two vertices $v, w \in V(G)$ we have
\[
|N_G(v) \triangle N_G(w)| = O(n/k).
\]
If, additionally, $a = 1 - o(1)$, then for every $v, w \in V(G)$ we have
\[
|N_G(v) \triangle N_G(w)| = o(n/k).
\]

**Proof.** Fix two arbitrary vertices $v, w \in V(G)$. Let
\[
P = N_G(v) \setminus (v \cup N_G(w)), \quad R = N_G(w) \setminus (v \cup N_G(v)) \quad \text{and} \quad Q = V(G) \setminus (\{v, w\} \cup P \cup R),
\]
so that $N_G(v) \triangle N_G(w) = P \cup R$. Let $B = B_{vw}$ be as in Lemma 2.2. It then follows by Lemma 2.2 that
\[
\mathbb{P}(|B \cap P| = |B \cap R|) > 2a - 1 - o(1). \tag{2.3}
\]
Suppose that $|P \cup R| \geq cn/k$ for some absolute constant $c > 0$. Then
\[
\mathbb{P}(B \cap (P \cup R) \neq \emptyset) \geq 1 - (1 + o(1))(1 - c/k)^{k-1} = 1 - e^{-c} + o(1) = \Omega(1). \tag{2.4}
\]
In particular, if $|P \cup R| = \omega(n/k)$, then $\mathbb{P}(B \cap (P \cup R) \neq \emptyset) = 1 - o(1)$. Therefore, using (2.3) we obtain
\[
\mathbb{P}\left( |B \cap P| = |B \cap R| \mid B \cap (P \cup R) \neq \emptyset \right) = \frac{\mathbb{P}(|B \cap P| = |B \cap R| \land B \cap (P \cup R) \neq \emptyset)}{\mathbb{P}(B \cap (P \cup R) \neq \emptyset)} = \frac{2a - 1 - o(1)}{1 - o(1)} = 2a - 1 - o(1).
\] (2.5)

Similarly, if $a = 1 - o(1)$ and $|P \cup R| = \Omega(n/k)$, then (2.3) implies that $\mathbb{P}(|B \cap P| = |B \cap R|) = 1 - o(1)$. Therefore
\[
\mathbb{P}\left( |B \cap P| = |B \cap R| \mid B \cap (P \cup R) \neq \emptyset \right) = \frac{\mathbb{P}(B \cap (P \cup R) \neq \emptyset) - o(1)}{\mathbb{P}(B \cap (P \cup R) \neq \emptyset)} = \frac{2a - 1 - o(1)}{1 - o(1)}.
\] (2.6)

Note that the above argument does not make any use of the graph structure of $G$. Indeed, the situation at hand can be viewed as an urn model, in which we have a large urn filled with $|P|$ pink balls and $|R|$ red balls, and we draw a fixed but otherwise arbitrary number $1 \leq s \leq k - 1$ of balls from the urn uniformly at random, without replacement. We would like to upper bound the probability of drawing equally many pink balls and red balls. To this end, we first prove the following auxiliary claim.

**Claim 2.4.** For every integer $1 \leq t \leq \lfloor (k-1)/2 \rfloor$ we have
\[
\mathbb{P}(|B \cap P| = |B \cap R| = t) \leq \frac{3}{4} \cdot \mathbb{P}(|B \cap (P \cup R)| = 2t).
\]

Moreover, for every $\varepsilon > 0$ there exists $t_0 = t_0(\varepsilon)$ such that for every $t \geq t_0$ we have
\[
\mathbb{P}(|B \cap P| = |B \cap R| = t) \leq \varepsilon \cdot \mathbb{P}(|B \cap (P \cup R)| = 2t).
\]

**Proof.** Fix some $1 \leq t \leq \lfloor (k-1)/2 \rfloor$. By the log-concavity of the binomial coefficients we have
\[
\binom{|P|}{t} \binom{|R|}{t} \leq \left( \frac{|P| + |R|}{2} \right)^2.
\]

Moreover, using the fact that $t$ is much smaller than $|P| + |R|$, straightforward calculations show that
\[
\left( \frac{|P| + |R|}{2} \right)^2 \leq 3 \left( \frac{|P| + |R|}{2t} \right).
\]

We conclude that
\[
\mathbb{P}(|B \cap P| = |B \cap R| = t) = \binom{|P|}{t} \binom{|R|}{t} \binom{n-2-|P|-|R|}{k-1-2t} \leq 3 \cdot \binom{|P| + |R|}{2t} \binom{n-2-|P|-|R|}{k-1-2t} \leq \frac{3}{4} \cdot \mathbb{P}(|B \cap (P \cup R)| = 2t).
\]

The second statement can be proved analogously; we omit the details. $\square$

Coming back to the proof of Lemma 2.3, using Claim 2.4 with $a = 1 - o(1)$ we have
\[
\mathbb{P}(|B \cap P| = |B \cap R| > 0) = \sum_{t=1}^{\lfloor (k-1)/2 \rfloor} \mathbb{P}(|B \cap P| = |B \cap R| = t) \leq \frac{3}{4} \cdot \sum_{t=1}^{\lfloor (k-1)/2 \rfloor} \mathbb{P}(|B \cap (P \cup R)| = 2t) \leq \frac{3}{4} \cdot \mathbb{P}(|B \cap (P \cup R)| > 0).
\]

Therefore
\[
\mathbb{P}\left( |B \cap P| = |B \cap R| \mid B \cap (P \cup R) \neq \emptyset \right) \leq \frac{3}{4}.
\]
contrary to (2.6). Similarly, for any \( a > 1/2 \), if \( |P \cup R| = \omega(n/k) \), we obtain that for some \( t = t(a) \) we have
\[
\mathbb{P} \left( |B \cap P| = |B \cap R| \left| B \cap (P \cup R) > t \right) < \frac{1}{2} \cdot (2a - 1),
\]
contrary to (2.5). This concludes the proof of Lemma 2.3. \( \square \)

Under closer inspection, the statement of Lemma 2.3 can be rephrased more conveniently as follows.

**Lemma 2.5.** Assume the setting of Lemma 2.2, and assume further that \( e(G) \leq \binom{n}{2}/2 \). Then we have \( \Delta(G) = O(n/k) \). If, additionally, \( a = 1 - o(1) \), then \( \Delta(G) = o(n/k) \).

**Proof.** We prove the first statement – the second one can be proven analogously. It follows from Lemma 2.3 that \( |d(v) - d(w)| = O(n/k) \) holds for any \( v, w \in V(G) \). Let \( v \) be a vertex of minimum degree in \( G \). Put \( U := N_G(v) \) and \( W := N_G(v) \). Observe that \( |U| \leq |W| \) since we assumed that \( d(v) = \delta(G) \) and \( e(G) \leq \binom{n}{2}/2 \). Suppose for a contradiction that \( |U| = \omega(n/k) \).

We double-count the edges of the bipartite graph \( G[U, W] \). Applying Lemma 2.3 to \( v \) and \( u \) for every \( u \in U \), we derive that \( d_{G[U, W]}(u) = O(n/k) \). In particular
\[
e(G[U, W]) = O \left( |U| \cdot \frac{n}{k} \right) = O \left( |W| \cdot \frac{n}{k} \right).
\]
On the other hand, applying Lemma 2.3 to \( v \) and \( w \) for every \( w \in W \), yields
\[
d_{G[U, W]}(w) \geq |U| - O \left( \frac{n}{k} \right) \geq \omega \left( \frac{n}{k} \right) - O \left( \frac{n}{k} \right) = \omega \left( \frac{n}{k} \right).
\]
Therefore
\[
|W| \cdot \omega \left( \frac{n}{k} \right) \leq e(G[U, W]) = O \left( |W| \cdot \frac{n}{k} \right),
\]
which is clearly a contradiction, and thus \( \delta(G) = O(n/k) \). Since, moreover, \( |d(v) - d(w)| = O(n/k) \) holds for any \( v, w \in V(G) \) by Lemma 2.3, we conclude that \( \Delta(G) = O(n/k) \) as claimed. \( \square \)

From now on, we denote \( e(G) \) by \( m \). For every \( e \in E(G) \), let \( X_e \) be the indicator random variable for the event \( e \in E(G[A]) \), that is, \( X_e = 1 \) if both endpoints of \( e \) are in \( A \) and \( X_e = 0 \) otherwise. Observe that \( X = \sum_{e \in E(G)} X_e \). Putting \( \mu = \mathbb{E}(X) \) we have
\[
\mu = \sum_{e \in E(G)} \mathbb{E}(X_e) = m \cdot \frac{k(k-1)}{n(n-1)} = m \cdot \frac{(k^2)}{n^2} \cdot (1 + O(1/n)). \quad (2.7)
\]
This has the following consequence (recall that \( a = \text{ind}(k, \ell) \)).

**Lemma 2.6.** \( m \geq (1 - o(1))a\ell \left( n^2/k^2 \right) \). In particular, if \( a = 1 - o(1) \), then \( m \geq (1 - o(1))(n^2/k^2) \).

**Proof.** Suppose for a contradiction that \( m < (1 - \varepsilon) a\ell \left( n^2/k^2 \right) \) for some constant \( \varepsilon > 0 \). It then follows by (2.7) that \( \mu < (1 - \varepsilon/2) a\ell \). On the other hand, since \( X \geq 0 \) and by the choice of \( G \) we have \( \mu \geq \ell \cdot \mathbb{P}(X = \ell) = (1 - o(1)) a\ell \), a contradiction. \( \square \)

Combining the above facts, we can immediately prove Proposition 1.4.

**Proof of Proposition 1.4.** Suppose for a contradiction that there exist \( \varepsilon > 0 \) and an integer \( \ell = \ell(k) \) such that \( Ck \leq \ell \leq \left( \frac{n}{2} \right) - Ck \) for some large \( C > 0 \), and \( \text{ind}(k, \ell) = a > 1/2 + \varepsilon \). Let \( G \) be a graph attaining \( I(n, k, \ell) \), where \( n \) is sufficiently large. By symmetry we may assume that \( e(G) \leq \binom{n}{2}/2 \). Then, on the one hand, by Lemma 2.5 we have \( \Delta(G) = O(n/k) \) entailing \( e(G) = O(n^2/k) \). On the other hand, Lemma 2.6 implies that
\[
e(G) \geq (1/2 - o(1)) \ell \cdot \frac{n^2}{k^2} \geq C \cdot \frac{n^2}{k},
\]
which is a contradiction for large enough \( C \). We conclude that \( a \leq 1/2 + o(1) \) as claimed. \( \square \)
Our next goal is to prove Theorem 1.3. Since, as remarked in the introduction, \( \text{ind}(k, \ell) \) is never identically 1 (assuming \( 0 < \ell < \binom{k}{3} \)), it suffices to prove the theorem for large values of \( k \). Hence, suppose now, for a contradiction, that the assertion of Theorem 1.3 is false for arbitrarily large \( n \).

Lemma 3.1. There exists a constant \( C > 0 \) such that for every \( \ell > C \)

\[
\mathbb{E}(Y) = \mathbb{E}(X) = 0, \quad \text{Var}(Y) = \sigma^2 > 0 \quad \text{and} \quad \text{Var}(X) \leq b^4 \quad \text{for some constant} \quad b > 0.
\]

3. Proof of Theorem 1.3

The aim of this section is to prove the following lemma, which directly implies Theorem 1.3.

Lemma 3.1. There exists a constant \( b > 0 \) such that

\[
\mathbb{E}(Y) = \mathbb{E}(X) = 0, \quad \mathbb{E}(Y^2) = \sigma^2 > 0 \quad \text{and} \quad \mathbb{E}(X^4) \leq b^4 \quad \text{for some constant} \quad b > 0.
\]

Having established this, we conclude the proof Theorem 1.3 as follows. By Lemma 3.1 the random variable \( Y := X - \mu \) satisfies the assumptions of Lemma 2.7. Since the event \( \{X = \ell \} \) is disjoint either from the event \( \{Y > 0\} \) or from the event \( \{Y < 0\} \), using Lemma 2.7 we obtain

\[
\mathbb{P}(X = \ell) \leq 1 - \frac{1}{2^{2/3}b} < 1 - \varepsilon, \quad \text{contrary to our assumption that} \quad \mathbb{P}(X = \ell) > 1 - \varepsilon.
\]

Proof of Lemma 3.1. First let us expand the right hand side of (3.1).

\[
\text{Var}(X)^2 \overset{\text{(2.8)}}{=} (1 + o(1)) \left( m \cdot \frac{k^2}{n^2} + S \cdot \frac{k^3}{n^3} \right)^2 = \Theta \left( m^2 \cdot \frac{k^4}{n^4} + mS \cdot \frac{k^5}{n^5} + S^2 \cdot \frac{k^6}{n^6} \right). \tag{3.2}
\]
Therefore, for every two new vertices, and connecting them by an edge. Let \( t \) by deleting one of its edges (together with any of its endpoints if its degree in \( H \) is 1), adding two new vertices, and connecting them by an edge. Let \( t' \) denote the number of vertices of \( H' \); clearly \( t \leq t' \leq k \). Since \( k \ll n \), a straightforward calculation show that

\[
\mathbb{E}
\left(p \cdot \prod_{a \in E(H_B) \cap E(H'_{B})} X_a\right) = \mathbb{E}
\left(\prod_{a \in E(H_{B})} X_a\right) = O\left(\frac{k'^t}{n^t}\right)
\]

\[
= O\left(\frac{k^t}{n^t}\right) = O\left(\mathbb{E}\left(\prod_{a \in E(H_{B})} X_a\right)\right).
\]

Therefore, for every \( B \subseteq \{e, f, g, h\} \) we have

\[
p^{4-|B|} \cdot \mathbb{E}
\left(\prod_{a \in B} X_a\right) = O(\mathbb{E}(X_eX_fX_gX_h)).
\]

We conclude that

\[
\text{Cov}(e, f, g, h) = O(\mathbb{E}(X_eX_fX_gX_h)),
\]

as claimed. \( \square \)

We now distinguish between several cases, depending on how the four edges \( e, f, g, h \) are arranged. Suppose first that \( e, f, g, h \) are pairwise distinct. Let \( H \) be the four-edge graph spanned by \( e, f, g \) and \( h \). Note that \( H \) is a subgraph of \( G \), but not necessarily an induced one. The options for \( H \) are

(i) \( H = 4K_2 \);
(ii) \( H = 2K_2 + K_{1,2} \);
(iii) \( H = 2K_{1,2} \);
(iv) \( H = K_2 + K_{1,3} \);
(v) \( H = K_2 + P_3 \);
(vi) \( H = K_2 + K_4 \);
(vii) \( H = K_{1,4} \);
(viii) \( H = K_{1,3}^+ \) – a 3-star with one edge subdivided into two;
(ix) \( H = P_3 \);
(x) \( H = C_4 \);
(xi) \( H = K_{3}^+ \) – a triangle with one pendant edge.

There are also several ‘degenerate’ cases, in which two of the edges \( e, f, g, h \) coincide; we will deal with these cases at the end of the proof.

We claim that in each of the above listed cases, after some cancellation, the respective contributions can be bounded from above using the terms appearing on the right hand side of (3.2). As a helpful piece of notation, we denote the number of unlabelled (not necessarily induced) copies of \( H \) in \( G \) by \( N(H) \).
Case (i). $H = 4K_2$.
Given a fixed 4-tuple $(e, f, g, h)$ forming $H$, it follows by (3.4) that
\[
\text{Cov}(e, f, g, h) = \mathbb{E}(X_e X_f X_g X_h) - 4\mathbb{E}(X_e X_f) \mathbb{E}(X_g X_h)p + 6\mathbb{E}(X_e X_f)p^2 - 4\mathbb{E}(X_e)p^3 + p^4
\]
\[
= \frac{1}{n^8} [(k)_8 - 4(k)_6(k)_2 + 6(k)_4((k)_2)^2 - 3((k)_2)^4] + O_k(1/n)
\]
\[
= \frac{1}{n^8} [k^8 - 28k^7 - 4k^8 + 64k^7 + 6k^8 - 48k^7 - 3k^8 + 12k^7 + O(k^6)]
\]
\[
= O\left(\frac{k^6}{n^8}\right).
\]
Taking the sum over all such tuples $(e, f, g, h)$, we obtain an overall contribution of at most
\[
O\left(\frac{m^4k^6}{n^8}\right) = O\left(\frac{m^2 \cdot k^4}{n^4}\right) = O\left(\text{Var}(X)^2\right),
\]
where the penultimate equality holds since $m = O(n^2/k)$ follows from Lemma 2.5 and the last equality holds by (3.2).

Case (ii). $H = 2K_2 + K_{1,2}$.
Let $e$ and $f$ denote the two edges that share a vertex. It follows by (3.4) and a straightforward calculation that
\[
\text{Cov}(e, f, g, h) = \mathbb{E}(X_e X_f X_g X_h) - \mathbb{E}(X_e X_f) \mathbb{E}(X_g X_h)p + \mathbb{E}(X_e X_f)p^2
\]
\[
= \frac{1}{n} \left[(k)_7 - 2(k)_5(k)_2 + (k)_3((k)_2)^2\right] + O_k(1/n)
\]
\[
= \frac{1}{n} \left[k^7 - 21k^6 - 2k^7 + 22k^6 + k^7 - 5k^6 + O(k^5)\right]
\]
\[
= \frac{1}{n} (-4k^6 + O(k^5)) < 0.
\]
Thus, we can ignore such tuples $(e, f, g, h)$ as their contribution is negative.

Case (iii). $H = 2K_{1,2}$.
A straightforward calculation shows that Cov$(e, f, g, h) = (1 + o(1))(\mathbb{E}(X_e X_f X_g X_h)) = O(k^6/n^6)$. Moreover, the total number of such 4-tuples $(e, f, g, h)$ is at most $4! \cdot S^2$. Hence,
\[
\sum_{(e, f, g, h) \in H} \text{Cov}(e, f, g, h) = O\left(S^2 \cdot \frac{k^6}{n^6}\right) = O\left(\text{Var}(X)^2\right),
\]
where the last equality holds by (3.2).

Case (iv). $H = K_2 + K_{1,3}$.
It follows from Claim 3.2 that Cov$(e, f, g, h) = O(k^6/n^6)$. Note that a copy of $K_{1,3}$ in $G$ can be viewed as a copy of $P_3$ with an additional edge attached to its middle vertex. This implies that $N(K_{1,3}) = O(N(P_3) \cdot \Delta(G)) = O(Sn/k)$, where the last equality holds by Lemma 2.5. Therefore,
\[
\sum_{(e, f, g, h) \in H} \text{Cov}(e, f, g, h) = O\left(mS \cdot k^5/n^5\right) = O\left(\text{Var}(X)^2\right),
\]
where the last equality holds by (3.2).

Case (v). $H = K_2 + P_4$.
This case is analogous to Case (iv) with $P_4$ in place of $K_{1,3}$. Since a copy of $P_4$ in $G$ can be viewed as a copy of $P_3$ with another vertex connected by an edge to one of its end vertices, we have $N(P_4) = O(N(P_3) \cdot \Delta(G)) = O(Sn/k)$, where the last equality holds by Lemma 2.5. We conclude that
\[
\sum_{(e, f, g, h) \in H} \text{Cov}(e, f, g, h) = O\left(m \cdot N(P_4) \cdot k^6/n^6\right) = O\left(mS \cdot k^5/n^5\right) = O\left(\text{Var}(X)^2\right),
\]
where the last equality holds by (3.2).
**Case (vi).** $H = K_2 + K_3$. This is similar to cases (iv) and (v). It follows from Claim 3.2 that
\[ \text{Cov}(e, f, g, h) = O(k^5/n^5). \]
Hence,
\[ \sum_{(e, f, g, h) \geq H} \text{Cov}(e, f, g, h) = O \left( m \cdot N(K_3) \cdot \frac{k^5}{n^5} \right) = O \left( mS \cdot \frac{k^5}{n^5} \right) = O \left( \text{Var}(X)^2 \right), \]
where the second equality holds since $N(K_3) = O(S)$ and the last equality holds by (3.2).

**Case (vii).** $H = K_{1,4}$.
It follows from Claim 3.2 that
\[ \sum_{(e, f, g, h) \geq H} \text{Cov}(e, f, g, h) = O \left( N(K_{1,4}) \cdot \frac{k^5}{n^5} \right). \]  
(3.5)
Note that
\[ N(K_{1,4}) = O \left( \sum_{v \in V(G)} d(v)^4 \right) = O \left( \Delta(G)^2 \cdot \sum_{v \in V(G)} d(v)^2 \right) = O \left( \frac{n^2}{k^2} \cdot S \right) = O(mS), \]
where the penultimate equality holds by Lemma 2.5 and the last equality holds by Lemma 2.6. We conclude that
\[ \sum_{(e, f, g, h) \geq H} \text{Cov}(e, f, g, h) = O \left( mS \cdot \frac{k^5}{n^5} \right) = O \left( \text{Var}(X)^2 \right), \]
where the last equality holds by (3.2).

**Case (viii).** $H = K_{1,3}^+.$
This is very similar to Case (vii) with $K_{1,3}^+$ in place of $K_{1,4}$. Since a copy of $K_{1,3}^+$ in $G$ can be viewed as a copy of $P_3$ with two leaves attached to one of its end vertices, it follows that
\[ N \left( K_{1,3}^+ \right) = O \left( S \cdot \Delta(G)^2 \right) = O(mS). \]
Therefore
\[ \sum_{(e, f, g, h) \geq H} \text{Cov}(e, f, g, h) = O \left( N \left( K_{1,3}^+ \right) \cdot \frac{k^5}{n^5} \right) = O \left( mS \cdot \frac{k^5}{n^5} \right) = O \left( \text{Var}(X)^2 \right), \]
where the last equality holds by (3.2).

**Case (ix).** $H = P_5$.
This is again very similar to Case (vii) with $P_5$ in place of $K_{1,4}$. Since a copy of $P_5$ in $G$ can be viewed as a copy of $P_3$ with a leaf attached to each of its end vertices, it follows that
\[ N(P_5) = O \left( S \cdot \Delta(G)^2 \right) = O(mS). \]
Therefore
\[ \sum_{(e, f, g, h) \geq H} \text{Cov}(e, f, g, h) = O \left( N(P_5) \cdot \frac{k^5}{n^5} \right) = O \left( mS \cdot \frac{k^5}{n^5} \right) = O \left( \text{Var}(X)^2 \right), \]
where the last equality holds by (3.2).
Case (x). $H = C_4$. It follows from Claim 3.2 that
\[ \sum_{(e,f,g,h) \in H} \text{Cov}(e,f,g,h) = O \left( N(C_4) \cdot \frac{k^4}{n^4} \right). \]
It is evident that $N(C_4) = O(N(P_4))$. Since, moreover, we can view $P_4$ as $P_3$ with an additional edge appended to one of its leaves, it follows that
\[ N(P_4) = O(N(P_3) \cdot \Delta(G)) = O(S \cdot \Delta(G)) = O(S \cdot \frac{n}{k}), \]
where the last equality holds by Lemma 2.5. Therefore
\[ \sum_{(e,f,g,h) \in H} \text{Cov}(e,f,g,h) = O \left( N(C_4) \cdot \frac{k^4}{n^4} \right) = O \left( S \cdot \frac{k^3}{n^3} \right) = O \left( mS \cdot \frac{k^5}{n^5} \right) = O \left( \text{Var}(X)^2 \right), \]
where the penultimate equality holds by Lemma 2.6 and the last equality holds by (3.2).

Case (xi). $H = K_3^+$. Using the calculations made in Case (x) we obtain
\[ N \left( K_3^+ \right) = O(N(P_4)) = O \left( S \cdot \frac{n}{k} \right). \]
It thus follows by Claim 3.2 that
\[ \sum_{(e,f,g,h) \in H} \text{Cov}(e,f,g,h) = O \left( N(K_3^+) \cdot \frac{k^4}{n^4} \right) = O \left( S \cdot \frac{k^3}{n^3} \right) = O \left( mS \cdot \frac{k^5}{n^5} \right) = O \left( \text{Var}(X)^2 \right), \]
where the last equality holds by (3.2).

The degenerate cases. We now consider the cases where some edge of $\{e, f, g, h\}$ appears more than once. In those cases, the corresponding graph $H$ has at most three edges.

(xii) $H = 3K_2$
(xiii) $H = K_2 + K_{1,2}$
(xiv) $H = K_{1,3}$
(xv) $H = P_4$
(xvi) $H = K_3$
(xvii) $H = K_{1,2}$
(xviii) $H = 2K_2$
(xix) $H = K_2$

Case (xii). $H = 3K_2$. Without loss of generality, suppose that $e, f, g$ are independent and that $h = e$. Since, clearly $X_e^2 = X_e$, we obtain
\[ \text{Cov}(e,f,g,h) = \mathbb{E}((X_e - p)^2(X_f - p)(X_g - p)) = (\mathbb{E}(X_eX_fX_g) - p\mathbb{E}(X_eX_f) - p^2\mathbb{E}(X_e) + p^3\mathbb{E}(X_e)) (1 + O_k(1/n)) \]
\[ = \frac{1}{n^6} \left( (k)_6 - 2(k)_2(k)_4 + ((k)_2)^3 \right) (1 + O_k(1/n)) \]
\[ = -\frac{4k^5 + O(k^4)}{n^6} < 0. \]
Thus, the total contribution of all such tuples is negative.

Case (xiii). $H = K_2 + K_{1,2}$. It follows from Claim 3.2 that
\[ \sum_{(e,f,g,h) \in H} \text{Cov}(e,f,g,h) = O \left( mN(K_{1,2}) \cdot \frac{k^5}{n^5} \right) = O \left( mS \cdot \frac{k^5}{n^5} \right) = O \left( \text{Var}(X)^2 \right), \]
where the last equality holds by (3.2).
Case (xiv). $H = K_{1,3}$.

It follows from Claim 3.2 that

$$
\sum_{(e,f,g,h) \in H} \text{Cov}(e,f,g,h) = O \left( N(K_{1,3}) \cdot \frac{k^4}{n^4} \right) = O \left( \Delta(G) \cdot N(K_{1,2}) \cdot \frac{k^4}{n^4} \right) = O \left( S \cdot \frac{k^3}{n^3} \right) = O \left( mS \cdot \frac{k^5}{n^5} \right) = O \left( \text{Var}(X)^2 \right),
$$

where the third equality holds by Lemma 2.5, the fourth equality holds by Lemma 2.6, and the last equality holds by (3.2).

Case (xv). $H = P_4$.

It follows from Claim 3.2 that

$$
\sum_{(e,f,g,h) \in H} \text{Cov}(e,f,g,h) = O \left( N(P_4) \cdot \frac{k^4}{n^4} \right) = O \left( S \cdot \frac{k^3}{n^3} \right) = O \left( mS \cdot \frac{k^5}{n^5} \right) = O \left( \text{Var}(X)^2 \right),
$$

where the second equality was proved in Case (x) and the last equality holds by (3.2).

Case (xvi). $H = K_3$.

It follows from Claim 3.2 that

$$
\sum_{(e,f,g,h) \in H} \text{Cov}(e,f,g,h) = O \left( N(K_3) \cdot \frac{k^3}{n^3} \right) = O \left( S \cdot \frac{k^3}{n^3} \right) = O \left( mS \cdot \frac{k^5}{n^5} \right) = O \left( \text{Var}(X)^2 \right),
$$

where the last equality holds by (3.2).

Case (xvii). $H = K_{1,2}$.

It follows from Claim 3.2 that

$$
\sum_{(e,f,g,h) \in H} \text{Cov}(e,f,g,h) = O \left( N(K_{1,2}) \cdot \frac{k^3}{n^3} \right) = O \left( S \cdot \frac{k^3}{n^3} \right) = O \left( mS \cdot \frac{k^5}{n^5} \right) = O \left( \text{Var}(X)^2 \right),
$$

where the last equality holds by (3.2).

Case (xviii). $H = 2K_2$.

It follows from Claim 3.2 that

$$
\sum_{(e,f,g,h) \in H} \text{Cov}(e,f,g,h) = O \left( N(2K_2) \cdot \frac{k^3}{n^3} \right) = O \left( m^2 \cdot \frac{k^4}{n^3} \right) = O \left( \text{Var}(X)^2 \right),
$$

where the last equality holds by (3.2).

Case (xix). $H = K_2$.

It follows from Claim 3.2 that

$$
\sum_{(e,f,g,h) \in H} \text{Cov}(e,f,g,h) = O \left( m \cdot \frac{k^2}{n^3} \right) = O \left( m^2 \cdot \frac{k^4}{n^5} \right) = O \left( \text{Var}(X)^2 \right),
$$

where the last equality holds by (3.2).

To conclude, we have considered every possible case and in each one we have shown that its respective contribution to $\mathbb{E}((X - \mu)^4)$ is of order of magnitude $O(\text{Var}(X)^2)$. Since the number of cases is constant, this completes the proof of Lemma 3.1 and thus also of Theorem 1.3. \hfill \Box

4. Very small inducibility for almost all $\ell$

Our aim in this section is to prove Theorem 1.5. Let $k$ and $\ell$ be positive integers for which $\min \left\{ k, \binom{k}{2} - \ell \right\} = \Omega(k^2)$. Since, $\text{ind}(k, \ell)$ is defined as $\lim_{n \to \infty} I(n, k, \ell)$ and the latter sequence is monotone decreasing, it suffices to show that $I(2k, k, \ell) = O(k^{-0.1})$. Suppose then that we have a $2k$-vertex graph $G = (V, E)$, in which we are selecting a $k$-vertex set $A \subseteq V$ uniformly at random. As in the proofs in previous sections, we may assume that $G$ maximizes $\P(X_{G,k} = \ell)$ amongst all $2k$-vertex graphs.

Claim 4.1. $\min \{ e(G), e(\overline{G}) \} = \Omega(k^2)$. 
Proof. Since \(|G| = 2k\) and \(G\) contains an induced subgraph of order \(k\) and size \(\ell = \Omega(k^2)\) (as, clearly, \(I(2k, k, \ell) > 0\)), we have that \(e(G) = \Omega(k^2)\). The statement for \(\overline{G}\) follows analogously.

A pair of distinct vertices \(\{u, v\} \subseteq V\) will be called distinguished if \(|N_G(u) \triangle N_G(v)| = \Theta(k)\). Let \(D = D(G)\) be the set of all distinguished pairs in \(G\).

Claim 4.2. \(|D| = \Theta(k^2)\).

Proof. It is evident that \(|D| = O(k^2)\). To see that \(|D| = \Omega(k^2)\), note that
\[
\sum_{\{u, v\} \in \binom{V}{2}} |N(u) \triangle N(v)| = \sum_{\{u, v\} \in \binom{V}{2}} (d(u) + d(v) - 2|N(u) \cap N(v)|)
\]
\[
= (|V| - 1) \sum_{v \in V} d(v) - 2 \sum_{v \in V} \left(\frac{d(v)}{2}\right)
\]
\[
= 2 \left(2k - 1\right)e(G) - \sum_{v \in V} \left(\frac{d(v)}{2}\right).
\]
By a theorem of Ahlswede and Katona [1], for a graph \(H\) of given order and size the quantity \(\sum_v \left(\frac{d(v)}{2}\right)\), which corresponds to the number of cherries \(K_{1,2}\), is maximized when either \(H\) or its complement is a union of a clique and an independent set. In either case it follows by Claim 4.1 and a straightforward calculation that
\[
\sum_{\{u, v\} \in \binom{V}{2}} |N(u) \triangle N(v)| \geq \sum_{\{u, v\} \in \binom{V}{2}} |N_H(u) \triangle N_H(v)| = \Omega(k^3).
\]
Since the maximum degree of \(G\) is \(O(k)\), we conclude that \(|D| = \Omega(k^2)\), as claimed.

Claim 4.3. For any graph \(F\) with \(2k\) vertices and \(\Omega(k^2)\) edges, and any integer \(t = (1 + o(1))k\), we have
\[
\mathbb{P}\left(X_{F,t} \leq \frac{e(F)}{5}\right) = o(k^{-1}).
\]

Proof. Let \(B \subseteq V(F)\) be a random set of size \(t\) and let \(\overline{B} = V(F) \setminus B\) be its complement. Fix an arbitrary vertex \(v \in V\). It follows by standard tail estimates for the hypergeometric distribution that
\[
\mathbb{P}\left(|d(v, B) - d(v, \overline{B})| > k^{0.9}\right) = o(k^{-2})
\]
(in fact, the right hand side is exponentially small in a positive constant power of \(k\), see for example [11, Theorem 2.10]). Hence, by the union bound, with probability \(1 - o(k^{-1})\), it holds that \(|d(v, B) - d(v, \overline{B})| \leq k^{0.9}\) for every \(v \in V(F)\). Summing over all vertices in \(B\), we obtain
\[
|2e(F[B]) - e(F[B, \overline{B}])| \leq \sum_{v \in B} |d(v, B) - d(v, \overline{B})| \leq 2k^{1.9} = o(e(F)).
\]
Similarly, summing over all vertices in \(\overline{B}\), we obtain
\[
|2e(F[\overline{B}]) - e(F[B, \overline{B}])| = o(e(F)).
\]
Hence, with probability \(1 - o(k^{-1})\) we have
\[
e(F[B]) = e(F[\overline{B}]) + o(e(F)) = \frac{1}{2} \cdot e(F[B, \overline{B}]) + o(e(F))
\]
\[
= (1/4 + o(1)) \cdot e(F).
\]
In particular, \(X_{F,t} = e(F[B]) \geq e(F)/5\) holds with probability \(1 - o(k^{-1})\).

Now, let us sample the set \(A\) in two steps as follows. We first sample a set \(A_0 \subseteq V\) of size \(k - k^{0.2}\) uniformly at random, then we sample a set \(A_1 \subseteq V \setminus A_0\) of size \(k^{0.2}\) in a manner which will be specified later, and finally we set \(A = A_0 \cup A_1\). Note that \(A_1\) will be sampled in a way
which will ensure that the resulting set $A$ will indeed be chosen uniformly amongst all subsets of $V(G)$ of size $k$.

Given $A_0$, a distinguished pair $\{u, v\}$ is said to be bad if $|d(u, A_0) - d(v, A_0)| \leq k^{0.4}$, and good otherwise. Our next claim shows that, with sufficiently high probability, most distinguished pairs are good.

**Claim 4.4.** With probability $1 - O(k^{-0.1})$ there are at most $|D|/6$ bad pairs.

**Proof.** Fix some distinguished pair $\{u, v\}$ and let $X_{uv} = 1$ if $\{u, v\}$ is bad and $X_{uv} = 0$ otherwise. Let $Y_{uv} = |A_0 \cap (N(u) \Delta N(v))|$ and let $s = |N(u) \Delta N(v)|$; recall that $\{u, v\}$ is a distinguished pair and thus $s = \Theta(k)$. Then

$$
\mathbb{P}(X_{uv} = 1) = \sum_{t=0}^{s} \mathbb{P}(X_{uv} = 1|Y_{uv} = t) \cdot \mathbb{P}(Y_{uv} = t) = \sum_{t=0}^{0.9s} \mathbb{P}(X_{uv} = 1|Y_{uv} = t) \cdot \mathbb{P}(Y_{uv} = t) + O(k^{-1}) \, ,
$$

where the first equality holds by the law of total probability and the second equality holds for a sufficiently small constant $\varepsilon > 0$ since, by standard tail estimates for the hypergeometric distribution, we have that $\mathbb{P}(Y_{uv} \leq \varepsilon k) = O(k^{-1})$ and $\mathbb{P}(Y_{uv} \geq 0.9s) = O(k^{-1})$.

Assume without loss of generality that $|N(u) \setminus N(v)| \geq |N(v) \setminus N(u)|$; observe that by the definition of a distinguished pair it thus follows that $r := |N(u) \setminus N(v)| = \Theta(k)$. Let $Z_{uv} = |A_0 \cap (N(u) \setminus N(v))|$. Observe that for any $\varepsilon k \leq t \leq s$ we have

$$
\mathbb{P}(X_{uv} = 1|Y_{uv} = t) \leq \sum_{i=(t-k^{0.4})/2}^{(t+k^{0.4})/2} \mathbb{P}(Z_{uv} = i|Y_{uv} = t). \tag{4.2}
$$

Note that $Z_{uv}|Y_{uv} = t$ is a hypergeometric random variable with parameters $s$, $t$ and $r$. Since, moreover, $\mathbb{E}(Z_{uv}) = rt/s = \Theta(k)$, a straightforward calculation shows that for every $(t-k^{0.4})/2 \leq i \leq (t+k^{0.4})/2$ we have

$$
\mathbb{P}(Z_{uv} = i|Y_{uv} = t) = O\left(k^{-1/2}\right). \tag{4.3}
$$

Combining (4.1), (4.2), and (4.3) we obtain

$$
\mathbb{P}(X_{uv} = 1) = O\left(k^{-0.1}\right). \tag{4.4}
$$

Now, let $X = \sum_{\{u, v\} \in D} X_{uv}$ be the random variable which counts the number of bad pairs in $D$. It follows by (4.4) that

$$
\mathbb{E}(X) = \sum_{\{u, v\} \in D} \mathbb{E}(X_{uv}) = O\left(k^{1.9}\right).
$$

Applying Markov’s inequality to $X$ we conclude that $\mathbb{P}(X \geq |D|/6) = O\left(k^{-0.1}\right)$. \hfill \Box

**Claim 4.5.** With probability $1 - O(k^{-0.1})$ the set $A_0$ will have the following property: there exist disjoint sets $X, Y \subseteq V \setminus A_0$ such that $|X| = |Y| = \Theta(k)$ and $d(x, A_0) - d(y, A_0) \geq k^{0.4}$ holds for every $x \in X$ and $y \in Y$.

**Proof.** Recall that $|D| = \Theta\left(k^2\right)$ holds by Claim 4.2. By considering an auxiliary graph $F$ with $V(F) = V$ and $E(F) = \{uv : \{u, v\} \in D\}$ to which we apply Claim 4.3, we infer that, with probability $1 - o(k^{-1})$, at least $|D|/5$ of the distinguished pairs are disjoint from $A_0$. On the other hand, it follows by Claim 4.4 that, with probability $1 - O\left(k^{-0.1}\right)$, at most $|D|/6$ of the distinguished pairs are bad. We conclude that, with probability $1 - O\left(k^{-0.1}\right)$, there is a set $D' \subseteq D \cap \binom{V \setminus A_0}{2}$ of size $ck^2$, for a constant $c > 0$, such that $|d(u, A_0) - d(v, A_0)| \geq k^{0.4}$ for every $\{u, v\} \in D'$.

Let $(u_1, \ldots, u_{k+k^{0.2}})$ be an ordering of the vertices of $V \setminus A_0$ by non-increasing order of degrees into $A_0$, that is, $d(u_i, A_0) \geq d(u_j, A_0)$ for every $1 \leq i < j \leq k + k^{0.2}$. Let $q = ck/3$, let $X = \{u_1, \ldots, u_q\}$, and let $Y = \{u_{k+k^{0.2} - q + 1}, \ldots, u_{k+k^{0.2}}\}$. Observe that $X \cap Y = \emptyset$ and $|X| = \Theta(k)$. In particular, $d(x, A_0) - d(y, A_0) \geq k^{0.4}$ holds for every $x \in X$ and $y \in Y$. \hfill \Box
\(|Y| = q = \Theta(k)\). It thus remains to prove that \(d(x, A_0) - d(y, A_0) \geq k^{0.4}\) holds for every \(x \in X\) and \(y \in Y\). Suppose for a contradiction that there exist \(x \in X\) and \(y \in Y\) such that \(d(x, A_0) - d(y, A_0) < k^{0.4}\). Since, by definition, \(d(x, A_0) \geq d(u, A_0) \geq d(y, A_0)\) for every \(u \in V \setminus (A_0 \cup X \cup Y)\), it follows that \(\{u, v\} \cap (X \cup Y) \neq \emptyset\) for every \(\{u, v\} \in D'\). Therefore

\[
ck^2 = |D'| \leq \left(\frac{|X \cup Y|}{2}\right) + |X \cup Y| \cdot |V \setminus (A_0 \cup X \cup Y)|
\]

\[
\leq 2q(q + k + k^{0.2} - 2q) \leq 2ck/3 \cdot k < ck^2,
\]

which is clearly a contradiction. \(\square\)

Let \(A_0\) be a set chosen randomly as described above. Let \(X\) and \(Y\) be disjoint subsets of \(V \setminus A_0\) such that \(|X| = |Y| = ck\) for some \(c > 0\), and \(d(x, A_0) - d(y, A_0) \geq k^{0.4}\) holds for every \(x \in X\) and \(y \in Y\); such sets exist with probability \(1 - O(k^{-0.1})\) by Claim 4.5. Now, we choose a random set \(A_1 \subseteq V \setminus A_0\) of size \(k^{0.2}\) as follows. First, we choose \(k^{0.2}\) pairwise-disjoint vertex pairs from \(V \setminus A_0\) uniformly at random. Then, from each such pair, we choose uniformly at random exactly one element to be in \(A_1\); all choices being mutually independent.

**Claim 4.6.** Let \(A_1\) be chosen randomly as described above and let \(A = A_0 \cup A_1\). Then, for any integer \(\ell\), we have \(\Pr(e_G(A) = \ell) = O(k^{-0.1})\).

**Proof.** Let \(M\) denote the set of all \(k^{0.2}\) randomly chosen pairs. Let \(M_{XY}\) denote the set of chosen pairs which have one element in \(X\) and one in \(Y\), and let \(m = |M_{XY}|\). We claim that \(m = \Omega(k^{0.2})\) with probability \(1 - e^{-\Omega(k^{0.2})}\). Indeed, consider choosing the pairs which constitute \(M\) one by one. Suppose that we have already chosen \(j\) pairs for some \(0 \leq j < k^{0.2}\), and now choose the \((j + 1)\)st pair. Let \(M_j\) denote the set of all vertices in the union of these \(j\) pairs; clearly \(|M_j| = O(k^{0.2})\). Let \(T_j + 1 = 1\) if the \((j + 1)\)st pair has one element in \(X\) and one in \(Y\), and \(T_j + 1 = 0\) otherwise. Then

\[
\Pr(T_j + 1 = 1) = \frac{|X \setminus M_j| \cdot |Y \setminus M_j|}{\binom{2m}{2}} \geq \frac{c^2}{3}.
\]

Note that \(m = \sum_{j=1}^{k^{0.2}} T_j\). Let \(Z \sim Bin(k^{0.2}, c^2/3)\) and observe that, by the above calculation, \(m\) stochastically dominates \(Z\). Hence, using standard bounds on the tail of the binomial distribution, we conclude that

\[
\Pr(m < c^2 k^{0.2}/6) \leq \Pr(Z < c^2 k^{0.2}/6) \leq \Pr(Z < E(Z)/2) < e^{-c^2 k^{0.2}/24}.
\]

Let \(\{x_1, y_1\}, \{x_2, y_2\}, \ldots, \{x_m, y_m\}\) be the elements of \(M_{XY}\), where \(\{x_1, \ldots, x_m\} \subseteq X\) and \(\{y_1, \ldots, y_m\} \subseteq Y\). Fix any choice of one element from every pair in \(M \setminus M_{XY}\). With any choice of one element from every pair in \(M_{XY}\), we associate a binary vector \(\vec{z} = (z_1, \ldots, z_m)\) in a natural way, namely, for every \(1 \leq i \leq m\), \(z_i = 1\) if we chose \(x_i\) to be in \(A_1\) and \(z_i = 0\) if we chose \(y_i\). For each such vector \(\vec{z}\), we denote the resulting random \(k\)-subset of \(V(G)\) by \(A_{\vec{z}}\). For two such vectors \(\vec{z}\) and \(\vec{w}\), we say that \(\vec{z} \geq \vec{w}\) if \(z_i \geq w_i\) for every \(1 \leq i \leq m\) and \(\vec{z} \neq \vec{w}\). We claim that \(e_G(A_{\vec{z}}) > e_G(A_{\vec{w}})\) whenever \(\vec{z} > \vec{w}\). Indeed, let \(1 \leq i \leq m\) be an index for which \(z_i = 1\) and \(w_i = 0\). Then

\[
e_G(A_{\vec{z}}) - e_G(A_{\vec{w}}) \geq d(x_i, A_0) - d(y_i, A_0) - e_G(A_{\vec{w}} \setminus A_0) \geq k^{0.4} - \binom{\binom{k^{0.2}}{2}}{2} > 0.
\]

It follows that, for any integer \(\ell\), the elements of \(\{\vec{z} \in \{0, 1\}^m : e_G(A_{\vec{z}}) = \ell\}\) form an anti-chain. Hence, by Sperner’s Theorem we conclude that

\[
\Pr(e_G(A) = \ell) \leq \frac{\binom{m}{\lfloor m/2 \rfloor}}{2^m} = O\left(1/\sqrt{m}\right) = O(k^{-0.1}).
\]

\(\square\)

Claim 4.6 implies that \(I(2k, k, \ell) = O(k^{-0.1})\). Thus indeed \(ind(k, \ell) = O(k^{-0.1})\) and the proof of Theorem 1.5 is complete. Note that the proof of Claim 4.6 resembles (and was inspired by) the Littlewood-Offord problem and its solution by Erdős [7].
Our aim in this section is to show that, under certain natural conditions, ind\(k, \ell\) exhibits a Poisson-like behaviour. The following proposition makes this precise.

**Proposition 5.1.** For every positive integer \(\ell\) there exists an integer \(k_0\) such that the following holds for every \(k \geq k_0\). Let \(G\) be a graph with \(n\) vertices and \(m\) edges, where \(n\) is sufficiently large with respect to \(k\). Suppose that \(m = \Omega\left(n^2/k^2\right)\) and \(\Delta := \Delta(G) = o(mk/n)\). Let \(\mu = \mu(k)\) be a constant satisfying \(\lim_{n \to \infty} m \cdot \frac{k(k-1)}{n(n-1)} = \mu\). Then

\[
\mathbb{P}(X_{G,k} = \ell) = \left(1 + o(1)\right)e^{-\mu} \frac{\mu^\ell}{\ell!}.
\]

**Proof.** By Brun’s Sieve (see, e.g., Theorem 8.3.1 in [2]), in order to prove that \(\mathbb{P}(X_{G,k} = \ell) = (1 + o(1))e^{-\mu} \frac{\mu^\ell}{\ell!}\), it suffices to show that \(\lim_{n \to \infty} \mathbb{E}(X_{G,k}) = \mu\) and that \(\mathbb{E}\left[\binom{\ell}{r}\right] = (1 + o(1)) \frac{k!}{r!}\) holds for every fixed integer \(r\).

Let \(e_1, \ldots, e_m\) be an arbitrary ordering of the edges of \(G\). For every \(1 \leq j \leq m\), let \(X_j = 1\) if both endpoints of \(e_j\) are in the random \(k\)-set \(A\), and \(X_j = 0\) otherwise. Observe that \(X_{G,k} = \sum_{j=1}^m X_j\). In particular,

\[
\mathbb{E}(X_{G,k}) = \sum_{j=1}^m \mathbb{E}(X_j) = m \cdot \frac{n(n-2)}{k(k-2)} = m \cdot \frac{k(k-1)}{n(n-1)}.
\]

It thus follows by the definition of \(\mu\) that \(\lim_{n \to \infty} \mathbb{E}(X_{G,k}) = \mu\).

Now, fix some positive integer \(r\). Let \(1 \leq j_1 < \ldots < j_r \leq m\) be arbitrary indices. Assume first that \(e_{j_1}, \ldots, e_{j_r}\) form a matching in \(G\). Then

\[
\mathbb{P}(X_{j_1} = 1 \land \ldots \land X_{j_r} = 1) = \frac{n(n-2r)}{k(k-2r)} = (1 + o(1)) \left(\frac{k}{n}\right)^{2r}.
\]

Moreover, the number of ways to choose indices \(1 \leq j_1 < \ldots < j_r \leq m\) for which \(e_{j_1}, \ldots, e_{j_r}\) form a matching in \(G\) is \((1 + o(1))\binom{m}{r}\) (trivially, it is at most \(\binom{m}{r}\)). Indeed, by our assumption on \(\Delta\), this number is at least

\[
\frac{1}{r!^\ell} \prod_{t=0}^{\ell-1} (m-t\Delta) \geq \frac{1}{r!^\ell} \prod_{t=0}^{\ell-1} (m-2tmk/n) = \frac{m^{\ell}}{r!} \cdot (1 + o(1)) e^{-2k\binom{\ell}{2}/n} = (1 + o(1)) \binom{m}{r},
\]

where the last equality holds for sufficiently large \(n\).

Next, assume that \(e_{j_1}, \ldots, e_{j_r}\) do not form a matching in \(G\). Let \(H\) be the graph whose edges are \(e_{j_1}, \ldots, e_{j_r}\), and whose vertices are the endpoints of \(e_{j_1}, \ldots, e_{j_r}\). Let \(C_1, \ldots, C_t\) denote the connected components of \(H\), and let \(c_i = |C_i|\) for every \(1 \leq i \leq t\). Then

\[
\mathbb{P}(X_{j_1} = 1 \land \ldots \land X_{j_r} = 1) = \frac{n}{k} - \sum_{i=1}^t c_i \left(\frac{n}{k}\right) = (1 + o(1)) \left(\frac{k}{n}\right) \sum_{i=1}^t c_i.
\]

Assume without loss of generality that \(c_1 \geq \ldots \geq c_t\). Since \(H\) is not a matching, we must have \(c_1 \geq 3\). For every positive integers \(a\) and \(b \geq a - 1\), the number of ways to choose \(b\) edges of \(G\) that form a connected component on \(a\) vertices, is at most

\[
m(a-1)! \Delta^{a-2} \binom{a}{2}^{b-a+1} = m \cdot o\left(\left(\frac{mk}{n}\right)^{a-2}\right).
\]

Indeed, we begin by choosing an arbitrary edge of \(G\) (in \(m\) ways), then, one by one, we choose \(a-2\) additional edges to form a tree on \(a\) vertices (in at most \(2\Delta \Delta^{a-3}\) ways), and then we choose the remaining \(b-a+1\) edges such that their endpoints are among the \(a\) vertices of the tree.
Hence, the total number of ways to choose \( r \) edges of \( G \) that form a graph \( H \) consisting of connected components of orders \( c_1 \geq \ldots \geq c_t \) is at most

\[
\prod_{i=1}^{t} m \cdot o \left[ \left( \frac{mk}{n} \right)^{c_i - 2} \right] = m^t \cdot o \left[ \left( \frac{mk}{n} \right) \sum_{i=1}^{t} c_i - 2r \right].
\]

For every \( 1 \leq t \leq r \), let \( L_t \) denote the set of all integer vectors \((c_1, \ldots, c_t)\) such that \( c_1 \geq \ldots \geq c_t \geq 2, c_1 \geq 3 \), and \( \sum_{i=1}^{t} c_i < 2r \). Combining everything together we conclude that

\[
E \left[ \binom{X}{r} \right] = (1 + o(1)) \left( \frac{m}{r} \right) \cdot (1 + o(1)) \left( \frac{k}{n} \right)^{2r} \sum_{i=1}^{t} \sum_{(c_1, \ldots, c_t) \in L_t} m^t \cdot o \left[ \left( \frac{mk}{n} \right) \sum_{i=1}^{t} c_i - 2r \right] \cdot (1 + o(1)) \left( \frac{k}{n} \right) \sum_{i=1}^{t} c_i \cdot \left( \frac{mk}{n^2} \right)^{r} \sum_{i=1}^{t} \sum_{(c_1, \ldots, c_t) \in L_t} o \left[ \left( \frac{mk}{n^2} \right) \sum_{i=1}^{t} c_i - t \right]
\]

\[
= (1 + o(1)) \left[ \frac{\mu^r}{r!} + o(\mu^r) \right] = (1 + o(1)) \cdot \frac{\mu^r}{r!},
\]

where the penultimate equality holds since \( r \) and \( t \) are fixed, \( \sum_{i=1}^{t} c_i - t \leq r \) and \( \mu = \Omega(1) \) by our assumption on \( m \). □

The first consequence of Proposition 5.1 is that it provides a whole plethora of constructions demonstrating that \( ind(k, 1) \geq 1/e + o(1) \). Indeed, let \( n \) be a sufficiently large integer and let \( G \) be any graph with \( n \) vertices, \( (1 + o(1))(n^2/k^2) \) edges, and maximum degree \( o(n/k) \). Then, \( G \) satisfies the assumptions of Proposition 5.1 with \( \mu = 1 \), implying that \( ind(k, 1) \geq 1/e + o(1) \).

This rich family of constructions includes, in particular, the random graphs \( G \left( n, \frac{k}{n}^{-1}\right) \) (with high probability) which were mentioned in the introduction and the pairwise disjoint union of \( \binom{k}{2} \) cliques, on \( n \binom{k}{2}^{-1} \) vertices each.

Moreover, combining Proposition 5.1 with some of our previous arguments as well as some new ones, we can prove Theorem 1.6.

5.1. The \( 1/2 \)-bound for \( \ell = 1 \). Let \( k \) be a sufficiently large integer, let \( a = ind(k, 1) \), and let \( G \) be a graph on \( n \) vertices, attaining the maximum density of induced one-edged graphs, that is, \( \mathbb{P}(X_{G,k} = 1) = a + o(1) \).

Our aim is to show that either \( a \leq 1/2 + o(1) \), or that the conditions of Proposition 5.1 are satisfied. In the latter case we will be done, as applying Proposition 5.1 would imply \( a \leq 1/e + o(1) \).

Claim 5.2. \( \Delta(G) = O(n/k) \).

Proof. Let \( v \) be a vertex of maximum degree in \( G \) and suppose for a contradiction that \( d(v) = \omega(n/k) \). It follows by Lemma 2.1 that \( \mathbb{P}(X_{G,k} \mid v \in A) = (1 + o(1))a \). However, a straightforward calculation shows that w.h.p. the set \( A \) will contain more than one vertex from \( N_G(v) \). This implies that \( a = o(1) \). Due to the previously established fact that \( a \geq 1/e + o(1) \), this contradicts the maximality of \( G \). □

Assume first that \( \Delta(G) = o(n/k) \). By compactness we may assume that \( e(G)(k)_{2}/(n)_{2} = (1 + o(1))\mu \) holds for some \( \mu = \mu(k) \). Since, moreover, \( e(G) = \Omega(n^2/k^2) \) holds by Lemma 2.6, the conditions of Proposition 5.1 are satisfied. Applying it yields

\[
a + o(1) = \mathbb{P}(X_{G,k} = 1) = (1 + o(1))\mu e^{-\mu} \leq 1/e + o(1).
\]

Hence, by Claim 5.2 we may assume that \( \Delta(G) = cn/k \) for some constant \( c > 0 \). Let \( v \) be a vertex of maximum degree in \( G \), let \( Q = N_G(v) \), and let \( R = V(G) \setminus (Q \cup \{v\}) \). By the Poisson-approximation of the binomial distribution, with probabilities of approximately \( e^{-c} \) and
where the first inequality holds by Claim 5.4 (applied twice), and the second one holds since

Observe that, if in the first step we sampled a set \( A \) of size \( k \) vertices uniformly at random and without replacement, obtaining a \( t \)-edge graph, then the probability to ‘destroy’ it in the second step is at most \( 2t/k \). Therefore

\[
\P(X_{H,k-1} = t) \geq \frac{k-2t}{k} \cdot \P(X_{H,k} = t).
\]

Claim 5.3. For any graph \( H \) and any positive integers \( k \) and \( t \) we have

\[
\P(X_{H,k-1} = t) \geq \frac{k-2t}{k} \cdot \P(X_{H,k} = t).
\]

Proof. Sample uniformly at random a vertex set \( A_{k-1} \subseteq V(H) \) of size \( k-1 \), using the following two steps. First sample \( k \) vertices uniformly at random and without replacement, obtaining a set \( A_k \subseteq V(H) \). Then, choose a vertex \( u \in A_k \) uniformly at random an put \( A_{k-1} = A_k \setminus \{u\} \). Observe that, if in the first step we sampled a \( t \)-edge graph, then the probability to ‘destroy’ it in the second step is at most \( 2t/k \). Therefore

\[
\P(X_{H,k-1} = t) \geq \P(e(G[A_{k-1}]) = t|e(G[A_k]) = t) \cdot \P(e(G[A_k]) = t) \geq \frac{k-2t}{k} \cdot \P(X_{H,k} = t).
\]

Claim 5.4. For any graph \( H \) and any positive integers \( k \) and \( t \) we have

\[
\P(X_{H,k-1} = t) \leq \P(X_{H,k} = t) + \frac{2t + 2}{k}.
\]

Proof. Consider the same two-step sampling as in the proof of Claim 5.3. Note that, if in the first step, the set \( A_k \) contains more than \( t \) edges, then the probability to obtain a \( t \)-edge graph in the second step is at most \( (2t + 2)/k \). Thus,

\[
\P(X_{H,k-1} = t) = \sum_{i=0}^{\binom{k}{2}} \P(X_{H,k} = i) \cdot \P(X_{H,k-1} = t|e(G[A_k]) = i)
\leq \P(X_{H,k} = t) + \sum_{i=t+1}^{\binom{k}{2}} \P(X_{H,k} = i) \cdot \P(X_{H,k-1} = t|e(G[A_k]) = i)
\leq \P(X_{H,k} = t) + \frac{2t + 2}{k} \sum_{i=t+1}^{\binom{k}{2}} \P(X_{H,k} = i)
\leq \P(X_{H,k} = t) + \frac{2t + 2}{k}.
\]

Let \( b \) denote \( \P(X_{G[R],k-2} = 1) \). Then, applying Claim 5.3 to (5.1), we obtain

\[
a \leq (1 + o(k(1)) \cdot (\P(X_{G[R],k-1} = 1) \cdot e^{-c} + \P(X_{G[R],k-2} = 0) \cdot ce^{-c})
\leq (1 + o(k(1)) \cdot (\P(X_{G[R],k-2} = 1) \cdot e^{-c} + \P(X_{G[R],k-2} = 0) \cdot ce^{-c})
\leq (1 + o(k(1)) \cdot (be^{-c} + (1-b)ce^{-c}).
\]

Observe that, if \( c \geq 1 \), then

\[
a \leq (1 + o(1)) \cdot (be^{-c} + (1-b)ce^{-c}) \leq (1 + o(1)) \cdot (bce^{-c} + (1-b)ce^{-c}) = (1 + o(1)) ce^{-c} \leq 1/e + o(1).
\]

Assume then that \( c \leq 1 \). Observe that, in this case, \( bce^{-c} + (1-b)ce^{-c} \) is an increasing function in \( b \). Moreover,

\[
b \leq (1 + o(1)) \P(X_{G[R],k} = 1) \leq (1 + o(1))a,
\]

where the first inequality holds by Claim 5.4 (applied twice), and the second one holds since \( a = ind(k,1) \) and \( R \) is large. Hence,

\[
(1 + o(1))a \leq be^{-c} + (1-b)ce^{-c} \leq ae^{-c} + (1-a)ce^{-c}.
\]
This implies that
\[ a \leq (1 + o(1)) \frac{ce^{-c}}{1 - e^{-c} + ce^{-c}} = (1 + o(1)) \frac{c}{e^c - 1 + c} \leq 1/2 + o(1). \]

5.2. The 3/4-bound for a fixed \( \ell \). We use a similar, but slightly more technical, argument to the one used in the case \( \ell = 1 \). Let \( \ell \) be a positive integer and let \( k \gg \ell \). Let \( a = \text{ind}(k, \ell) \), and note that \( a \) is bounded away from 0 by a constant \( \varepsilon(\ell) \). This can be seen, for instance, by considering an appropriate random graph. Our aim is to prove that \( a \leq 3/4 + o(1) \).

Let \( G \) be a graph on \( n \) vertices, attaining the maximum density of induced \( \ell \)-edged graphs, that is, \( \mathbb{P}(X_{G,k} = \ell) = a + o(1) \). Assume first that \( \Delta(G) = o(n/k) \). By compactness we may assume that \( e(G)(k)_2/(n)_2 = (1 + o(1))\mu \) holds for some \( \mu = \mu(k) \). Since, moreover, \( e(G) = \Omega(n^2/k^2) \) holds by Lemma 2.6, the conditions of Proposition 5.1 are satisfied. Applying it yields
\[ a + o(1) = \mathbb{P}(X_{G,k} = \ell) \leq (1 + o(1))e^{-\mu} \cdot \frac{\mu^\ell}{\ell!} \leq (1 + o(1))e^{-\ell} \cdot \frac{\ell^\ell}{(\ell - 1)!} \leq 1/e + o(1), \]

where the first inequality holds since the function \( f(x) := e^{-x} \cdot x^\ell/\ell! \) attains its maximum when \( x = \ell \).

Hence, using a similar argument to the one used to prove Claim 5.2, we may assume that \( \Delta(G) = cn/k \) for some constant \( c > 0 \). Let \( v \) be a vertex of maximum degree in \( G \), let \( Q = N_G(v) \), and let \( R = V(G) \setminus (Q \cup \{v\}) \). By the Poisson-approximation of the binomial distribution, for each fixed \( t \) with probability of approximately \( e^{-c} \ell^\ell/\ell! \), the set \( A \) will contain exactly \( t \) vertices from \( Q \). Therefore,
\[ (1 + o(1))a = \mathbb{P}(X_{G,k} = \ell | v \in A) \]
\[ = \sum_{t=0}^\ell \mathbb{P}(X_{G,k} = \ell | v \in A \text{ and } |A \cap Q| = t) \cdot \mathbb{P}(|A \cap Q| = t | v \in A) \]
\[ \leq (1 + o_k(1)) \cdot \left( \mathbb{P}(X_{G[R,k-1]} = \ell) \cdot e^{-c} + \sum_{t=1}^\ell \mathbb{P}(X_{G[R,k-1-t]} \leq \ell - t) \cdot \frac{\ell^\ell}{(\ell - 1)!} e^{-c} \right). \tag{5.2} \]

Let \( b \) denote \( \mathbb{P}(X_{G[R,k-\ell-1]} = \ell) \). Then, applying Claim 5.3 to (5.2) a constant number of times, we obtain
\[ a \leq (1 + o_k(1)) \cdot \left( \mathbb{P}(X_{G[R,k-1]} = \ell) \cdot e^{-c} + \sum_{t=1}^\ell \mathbb{P}(X_{G[R,k-1-t]} \leq \ell - t) \cdot \frac{\ell^\ell}{t!} e^{-c} \right) \]
\[ \leq (1 + o_k(1)) \cdot \left( \mathbb{P}(X_{G[R,k-\ell-1]} = \ell) \cdot e^{-c} + \sum_{t=1}^\ell \mathbb{P}(X_{G[R,k-\ell-1]} \leq \ell - t) \cdot \frac{\ell^\ell}{t!} e^{-c} \right) \]
\[ \leq (1 + o_k(1)) \cdot \left( be^{-c} + (1 - b) \sum_{t=1}^\ell \frac{\ell^\ell}{t!} e^{-c} \right). \]

Assume first that \( c < \log 2 \). In this case we have
\[ \sum_{t=1}^\ell \frac{\ell^\ell}{t!} < e^c - 1 < 2 - 1 = 1, \]
which implies that \( be^{-c} + (1 - b) \sum_{t=1}^\ell e^{-c} \ell^\ell/t! \) is an increasing function in \( b \). Now observe that
\[ b \leq (1 + o_k(1)) \mathbb{P}(X_{G[R],k} = \ell) \leq (1 + o_k(1))a, \]
where the first inequality holds by Claim 5.4 (applied \( \ell + 1 \) times), and the second one is due to the facts that \( a = \text{ind}(k, \ell) \) and \( R \) is large. Hence,

\[
(1 + o_k(1)) a \leq be^{-c} + (1 - b) \sum_{t=1}^{\ell} \frac{c^t}{t!} e^{-c} \leq ae^{-c} + (1 - a) \sum_{t=1}^{\ell} \frac{c^t}{t!} e^{-c}.
\]

This implies that

\[
(1 + o_k(1)) a \leq \frac{e^{-c} \sum_{t=1}^{\ell} c^t / t!}{1 - e^{-c} + e^{-c} \sum_{t=1}^{\ell} c^t / t!} = \frac{\sum_{t=1}^{\ell} c^t / t!}{e^c - 1 + \sum_{t=1}^{\ell} c^t / t!} < \frac{\sum_{t=1}^{\ell} c^t / t!}{2 \sum_{t=1}^{\ell} c^t / t!} = \frac{1}{2} < \frac{3}{4}.
\]

It thus remains to consider the case \( c \geq \log 2 \). Recall that \( d_G(v) = \Delta(G) = cn/k \) and let \( w \) be a vertex of minimum degree in \( G \). Let \( B_{cw} \) denote a subset of \( V(G) \setminus \{v, w\} \) of size \( k - 1 \), chosen uniformly at random among all such subsets. We may assume that \( e(G) = O \left( \frac{n^2}{k^2} \right) \), as otherwise the conditions of Proposition 5.1 will be satisfied entailing \( a \leq 1/e + o(1) \). It follows that \( d_G(w) = O \left( \frac{n}{k^2} \right) \). Applying Lemma 2.2 to \( v \) and \( w \), we obtain

\[
\mathbb{P}(e_G(v, B_{cw}) = e_G(w, B_{cw})) > 2a - 1 - o(1).
\]

However, since \( d_G(w) = o(n/k) \) and \( d_G(v) \geq \log 2(n/k) \), a straightforward calculation shows that

\[
\mathbb{P}(e_G(w, B_{cw}) = 0) = 1 - o(1) \quad \text{and} \quad \mathbb{P}(e_G(v, B_{cw}) = 0) \leq (1 + o(1)) e^{-\log 2} = (1 + o(1))1/2.
\]

It follows that \( 1/2 > 2a - 1 + o(1) \), implying \( a \leq 3/4 + o(1) \), as claimed.

6. Concluding remarks

**Bounds on** \( \varepsilon \) **in Theorem 1.3.** While, for clarity of presentation, we did not make an effort to calculate \( \varepsilon \) explicitly, it is not difficult to see that this constant is not too small. When \( k \) is sufficiently large, the value \( \varepsilon = 1/100 \) is certainly sufficient, and with some care, one can improve it to \( \varepsilon = 1/10 \). On the other hand, looking at some of our arguments, it is evident that in order to go below 1/2 for every sufficiently large \( k \) and every \( 0 < \ell < \binom{k}{2} \), one would need new ideas.

**Upper bounds for fixed** \( \ell \). It is not hard to see that our argument in the proof of Theorem 1.6 gives in fact better bounds than \( 1/2 + o(1) \) for \( \ell = 1 \) and \( 3/4 + o(1) \) in the general case. Take for example the case \( \ell = 1 \). For \( \Delta(G) = cn/k \) we obtain

\[
a \leq (1 + o(1)) \frac{c}{e^c - 1 + c},
\]

where the right hand side attains its maximum of 1/2 when \( c \) is close to zero. On the other hand, when \( \Delta(G) = o(n/k) \) Proposition 5.1 (Brun’s sieve) implies that \( a \leq 1/e + o(1) \). Interpolating between these two arguments shows that indeed

\[
\text{ind}(k, 1) < 1/2 - \Omega(1).
\]

**Strengthening Conjecture 1.1 in some ranges.** Theorem 1.5 demonstrates that the assertion of Conjecture 1.1 holds, with room to spare, for almost all values of \( k \) and \( \ell \). In particular, \( \text{ind}(k, \ell) \) tends to 0 with \( k \) as long as \( \ell \) and \( \binom{k}{2} - \ell \) are quadratic in \( k \). We believe that in the above statement ‘quadratic’ can be replaced with ‘super-linear’.

**Conjecture 6.1.** For all pairs \( (k, \ell) \) satisfying \( \min \left\{ \ell, \binom{k}{2} - \ell \right\} = \omega(k) \), we have \( \text{ind}(k, \ell) = o(1) \).

On the other hand, our construction for \( \ell = k - 1 \) can be straightforwardly extended to show that for any fixed integer \( C \) we have \( \text{ind}(k, C(k - C)) = \Omega(1) \).

Note also that the argument appearing in the proof of Theorem 1.5 can be applied in a wider range, namely, it can be used to prove that \( \text{ind}(k, \ell) \) is polynomially small in \( k \) whenever \( \min \left\{ \ell, \binom{k}{2} - \ell \right\} = \Omega(k^{2-\delta}) \) for some explicit constant \( \delta > 0 \).

It would be interesting to determine the ‘correct’ power of \( k \) in various ranges. For instance, when \( \ell \) and \( \binom{k}{2} - \ell \) are quadratic in \( k \), Theorem 1.5 yields \( \text{ind}(k, \ell) = O(k^{-0.1}) \), whereas, for
some values of $\ell = \Theta(k^2)$, we have $\text{ind}(k, \ell) = \Omega(k^{-1/2})$ — take for instance $\ell = k^2/4$ and $G = K_{n/2,n/2}$. We believe that the latter bound is tight.

**Conjecture 6.2.** For all pairs $(k, \ell)$ satisfying $\min \{\ell, \binom{k}{2} - \ell\} = \Omega(k^2)$, we have $\text{ind}(k, \ell) = O(k^{-1/2})$.

**Minimum edge-inducibility.** A natural counterpart to Conjecture 1.1 would be to determine the asymptotic value of

$$
\eta(k) := \min \left\{ \text{ind}(k, \ell) : 0 \leq \ell \leq \binom{k}{2} \right\},
$$

as $k$ tends to $\infty$. Note that this question has been well-studied in the setting of graph-inducibilities [9, 10, 13, 14]. In particular, it is known [13, 14] that

$$
\min \{\text{ind}(H) : |H| = k\} = (1 + o(1)) \frac{k!}{k^k} = e^{-k + o(1)}.
$$

This is in stark contrast with the lower bound of $\eta(k) = \Omega(1/k)$ for edge-inducibilities, achieved by the random graphs $G \left( n, \ell / \binom{k}{2} \right)$.

**3/4 as a general upper bound.** As noted in the introduction, $\text{ind}(k, \ell) < 1$ for every positive integer $k$ and every $0 < \ell < \binom{k}{2}$. It seems plausible that in fact $\text{ind}(k, \ell) \leq 3/4$ for all such pairs $(k, \ell)$. Note that, if true, this bound would be tight since, as noted in the introduction, $\text{ind}(3, 1) = \text{ind}(3, 2) = 3/4$. Such a result would simultaneously improve Theorems 1.3 and 1.6.

**Hypergraphs.** The concepts of both graph- and edge-inducibility extend naturally to $r$-uniform hypergraphs. Since the lower bound constructions of $1/e$ for $r = 1$ and for the star $K_{1,k-1}$ extend to higher uniformities as well, it makes sense to ask if Conjectures 1.1 and 1.2 would also hold in this more general setting. Needless to say that we expect these questions to be difficult.

**Further questions.** The constant of $1/e$, being closely related to the Poisson distribution, makes an appearance in many combinatorial and probabilistic setups. In particular, we would like to draw the reader’s attention to the interesting conjectures of Feige [8] and Rudich (see [12]).

**References**


