

Functions without influential coalitions

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Abstract

We give counterexamples to a conjecture of Benny Chor and another of the second author, both from the late 80s, by exhibiting functions for which the influences of large coalitions are unexpectedly small relative to the expectations of the functions.

1 Introduction

For a set T we use $\Omega(T)$ for the discrete cube $\{0, 1\}^T$ and μ_T for the uniform probability measure on $\Omega(T)$. In this paper f will always be a Boolean function on $\Omega([n])$ (that is, $f : \Omega([n]) \rightarrow \{0, 1\}$, where, as usual, $[n] = \{1, \dots, n\}$), and we will write μ for $\mu_{[n]}$. We reserve x, y for elements of $\Omega([n])$ and set $|x| = \sum x_i$.

Following Ben-Or and Linial [2] we define, for a given f and $S \subset [n]$, the *influence of S toward one* to be

$$I_S^+(f) = \mu_{[n] \setminus S}(\{u \in \Omega([n] \setminus S) : \exists v \in \Omega(S), f(u, v) = 1\}) - \mu(f). \quad (1)$$

Similarly, the influence of S toward zero is

$$I_S^-(f) = \mu_{[n] \setminus S}(\{u \in \Omega([n] \setminus S) : \exists v \in \Omega(S), f(u, v) = 0\}) - (1 - \mu(f)) \quad (2)$$

and the (total) influence of S is

$$I_S(f) = I_S^+(f) + I_S^-(f).$$

Suppose $\mu(f) = 1/2$. It then follows from a theorem of Kahn, Kalai and Linial [10] (Theorem 2.2 below, henceforth “KKL”) that for every $a > 0$

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there is an $S \subset [n]$ of size an with $I_S^+(f) \geq 1/2 - n^{-c}$, where $c > 0$ depends on a . (See Theorem 2.3.) Benny Chor conjectured in 1989 that one can in fact achieve $I_S^+(f) \geq 1/2 - c^n$ (where, again, $c < 1$ depends on a). The conjecture has been “in the air” since that time, though as far as we know it has appeared in print only in [11, 13].

In this note we disprove Chor’s conjecture and another, similar conjecture from the same period.

For our purposes the subtracted terms in (1) and (2) are mostly a distraction, and it sometimes seems clearer to speak of $J_S^+(f) := I_S^+(f) + \mu(f)$ and $J_S^-(f) := I_S^-(f) + (1 - \mu(f))$. Thus, for example, $J_S^+(f)$ is the probability that a uniform setting of the variables in $[n] \setminus S$ doesn’t force $f = 0$, and Chor’s conjecture predicts an S with $J_S^+(f) \geq 1 - c^n$. The following statement shows that this need not be the case.

Theorem 1.1. *For any fixed $\alpha, \delta \in (0, 1)$ there are a C and an f with $\mu(f) = \alpha$ and $J_S^+(f) < 1 - n^{-C}$ for every $S \subseteq [n]$ of size $(1/2 - \delta)n$.*

We should note that one cannot expect to go much beyond $|S| = (1/2 - \delta)n$; for example if $\mu(f) = 1/2$, then it follows from the “Sauer-Shelah Theorem” (Theorem 2.5) that there is an S of size $n/2$ with $J_S^+(f) = 1$.

Another consequence of KKL (see Theorem 2.4 below) is that there is a $\beta > 0$ such that for any f with $\mu(f) > n^{-\beta}$ there is an S of size (say) $0.1n$ with influence $1 - o(1)$. A conjecture of the second author, again from the late 80s, asserts that the same conclusion holds even assuming only $\mu(f) > (1 - \varepsilon)^n$ for sufficiently small ε . This conjecture turns out to be false as well:

Theorem 1.2. *For any fixed $\varepsilon, \delta > 0$ there are an $\alpha > 0$ and Boolean functions f such that $\mu(f) > (1 - \varepsilon)^n$ and no set of size $(1/2 - \delta)n$ has influence to 1 more than $\exp[-n^\alpha]$.*

(This can be strengthened a bit to require $\mu(f) > \exp[-n^{1-c}]$ for some fixed $c = c_\delta > 0$.)

It would be interesting to see how close one can come to the positive result (i.e. Theorem 2.4) mentioned before Theorem 1.2. For example, could it be that there is some fixed β for which one can find f ’s with $\mu(f) \approx n^{-\beta}$ for which no S of size $0.1n$ has influence $\Omega(1)$? We will discuss this question further in the next section.

Each of our examples is of the form $f = \bigwedge_{i=1}^m C_i$, where the C_i ’s are random \vee ’s of k literals using k distinct variables (henceforth “ k -clauses”). These f ’s, which may be thought of as variants of the “tribes” construction

of Ben-Or and Linial (see below), were inspired by a paper of Ajtai and Linial [1] and share with it the following curious feature. It's easy to see that any f can be converted to a *monotone* (i.e. increasing) f' with $\mu(f') = \mu(f)$ and each influence (I_S^+ and so on) for f' no larger than the corresponding influence for f ; thus it's natural to look for f 's with small influences among the increasing functions. But the present random examples, like those of [1], do not do this, and it's not easy to see what one gets by monotonizing them.

2 Background and perspective

Influence

We write $I_\ell(f)$ for $I_{\{\ell\}}(f)$. A form of the classic edge isoperimetric inequality for Boolean functions is

Theorem 2.1. *For any (Boolean function) f with $\mu(f) = t$,*

$$I(f) := \sum_{k=1}^n I_k(f) \geq 2t \log_2(1/t). \quad (3)$$

(This convenient version is easily derived from the precise statement, due to Hart [7]; see also [9, Sec. 7] for a simple inductive proof.)

While (3) is exact or close to exact (depending on t), it typically gives only a weak lower bound on the maximum of the $I_\ell(f)$'s, namely

$$\max_{\ell} I_\ell(f) \geq 2t \log_2(1/t)/n. \quad (4)$$

For t not too close to 0 or 1, the following statement from [10] gives better information.

Theorem 2.2 (KKL). *There is a fixed $c > 0$ such that for any f with $\mu(f) = t$, there is a $k \in [n]$ with*

$$I_k(f) \geq ct(1-t) \log n/n. \quad (5)$$

Recall that $J_\ell(f) = \mu(f) + I_\ell(f)$. Repeated application of Theorem 2.2 gives the following two corollaries.

Theorem 2.3. *For all $a, t \in (0, 1)$ there is a c such that for any f with $\mu(f) = t$ there is an $S \subseteq [n]$ with $|S| \leq an$ and*

$$J_S^+(f) \geq 1 - n^{-c}$$

(that is, $I_S^+(f) \geq (1-t) - n^{-c}$).

Similarly (either by the same argument or by applying Theorem 2.3 to the function $1 - f(x)$) there is a small S' with $J_{S'}^-(f) \geq 1 - n^{-c}$ (i.e. $I_{S'}^-(f) \geq t - n^{-c}$), and combining these observations we find that there is in fact a small S'' (e.g. $S \cup S'$) with $I_{S''}(f) \geq 1 - n^{-c}$.

Theorem 2.4. *For every $\delta, \epsilon > 0$, there is an $\alpha > 0$ such that for large enough n and any f with $\mu(f) \geq n^{-\alpha}$, there is an $S \subseteq [n]$ with $|S| = \delta n$ and*

$$J_S^+(f) \geq 1 - \epsilon.$$

The conjecture of Chor stated in Section 1 asserts that the n^{-c} in Theorem 2.3 can be replaced by something exponential in n , and the conjecture stated before Theorem 1.2 proposes a similar weakening of the $n^{-\alpha}$ lower bound on $\mu(f)$ in Theorem 2.4. As already noted, we will show below that these conjectures are incorrect.

Tribes

The original “tribes” examples of Ben-Or and Linial [2] are Boolean functions of the form $f = \bigvee_{i=1}^m C_i$, where the “tribes” C_i are \wedge ’s of k (distinct) variables and each variable belongs to exactly one tribe. The dual of such an f (so “dual tribes”) is $g = \bigwedge_{i=1}^m D_i$, where D_i is the \vee of the variables in C_i (so again, each variable belongs to exactly one D_i).

When $k = \log n - \log \log n - \log \ln(1/t)$, we have $1 - \mu(f) = \mu(g) \approx t$ (where $\log = \log_2$ and f, g are as above). For fixed $t \in (0, 1)$ both constructions show that Theorem 2.2 is sharp (up to the value of c).

On the other hand, when $t = O(n^{-c})$ for a fixed $c > 0$, f shows that (4) is tight up to a multiplicative constant, depending on c ; for example, $k = 2 \log n - \log \log n$ gives $\mu(f) \approx 1/(2n)$ and $I_\ell(f) \approx 2 \log n / n^2 = \Theta(\mu(f) \log(1/\mu(f))/n)$ for each ℓ . (In contrast, for $\mu(g) \approx 1/n$, we should take $k = \log n - 2 \log \log n - 1$, in which case $I_\ell(g) = \Theta(\log^2 n / n^2)$ and (4) is off by a \log .)

For f (again, as above) with $\mu(f) \in (\Omega(1), 1 - \Omega(1))$, there are sets of size $\log n$ with large influence towards 1, while no set of size $o(n/\log n)$ has influence $\Omega(1)$ towards 0. (The corresponding statement with the roles of 0 and 1 reversed holds for g .) The Ajtai-Linial construction mentioned in the introduction shows that there are Boolean functions h with $\mu(h) \approx 1/2$ and $I_S(h) < o(1)$ for every S of size $o(n/\log^2 n)$.

Trace

We now briefly consider influences from a different point of view. For a set X let $2^X = \{S : S \subset X\}$, $\binom{X}{k} = \{S \subset X : |S| = k\}$ and $\binom{X}{<k} = \{S \subset X : |S| < k\}$. For $\mathcal{F} \subset 2^X$ and $Y \subset X$, the *trace* of \mathcal{F} on Y is

$$\mathcal{F}|_Y = \{S \cap Y : S \in \mathcal{F}\}.$$

Let $X = [n]$. The following ‘‘Sauer-Shelah Theorem’’ determines, for every n and m , the minimum T such that for each $\mathcal{F} \subseteq 2^X$ of size T there is some $Y \in \binom{X}{m}$ on which the trace of \mathcal{F} is *complete*, meaning $\mathcal{F}|_Y = 2^Y$. Such a Y is said to be *shattered* by \mathcal{F} .

Theorem 2.5 (The Sauer-Shelah Theorem). *If $\mathcal{F} \subset 2^X$ and $|\mathcal{F}| > \binom{n}{<r}$, then \mathcal{F} shatters some $Y \in \binom{X}{r}$.*

That this is sharp is shown by $\mathcal{F} = \binom{X}{<r}$, the *Hamming ball* of radius $r - 1$ about \emptyset with respect to the usual Hamming metric on $2^X \equiv \Omega(X)$.

Theorem 2.5 was proved around the same time by Sauer [14], Shelah and Perles [15], and Vapnik and Chervonenkis [16]. It has many connections, applications and extensions in combinatorics, probability theory, model theory, analysis, statistics and other areas.

The connection between traces and influences is as follows. Let f be a Boolean function on $\Omega([n])$ and $\mathcal{F} = f^{-1}(1)$. It is easy to see (identifying $\Omega([n])$ and $2^{[n]}$ as usual) that for $S \subseteq [n]$ and $T = [n] \setminus S$,

$$J_S^+(f) = 2^{-|T|} |\mathcal{F}|_T.$$

Thus, in the language of traces, we are interested in the effect of relaxing ‘‘ \mathcal{F} shatters Y ’’ to require only that $\mathcal{F}|_Y$ contain a large fraction of 2^Y .

The following arrow notation (e.g. [4, 6]) is convenient. Write $(N, n) \rightarrow (M, r)$ if every $\mathcal{F} \subseteq 2^{[n]}$ of size N has a trace of size at least M on some $S \in \binom{[n]}{r}$; for example the Sauer-Shelah Theorem says $(\binom{n}{<r} + 1, n) \rightarrow (2^r, r)$.

One might hope that Hamming balls would again give the best examples in our relaxed setting, which would say, for example, that for $m \leq n$,

$$(\binom{n}{<r} + 1, n) \rightarrow (\binom{m}{<r} + 1, m). \quad (6)$$

But (6), which was first considered by Bollobás and Radcliffe [3] and would have implied both of the conjectures disproved here, was shown in [3] to be false for fixed k and (large) $m = n/2$. (For $r = n/2$ and $m = n - 1$, it fails for the original tribes example discussed above.)

A consequence of (6) is that for fixed $\delta, \epsilon > 0$ and large r ,

$$((\binom{n}{\leq (1+\epsilon)r/2}), n) \rightarrow ((1-\delta)2^r, r),$$

which would imply our second conjecture from the introduction. Here a counterexample with $n \gg r$ was given by Kalai and Shelah [12], but this seems not very relevant to present concerns, for which the regime of interest has n a little smaller than $2r$.

A problem

Question 2.6. *For fixed $\alpha, \delta > 0$, what is the largest $t \in (0, 1/2)$ for which one can find Boolean functions f with $\mu(f) = t$ and $I_S^+(f) < \alpha$ for every $S \subseteq [n]$ of size $(1/2 - \delta)n$?*

As far as we know $t > n^{-\beta}$ (with β depending on α, δ) is possible.

3 Examples

In each construction we consider, for suitable k and m , $f = \bigwedge_{i=1}^m C_i$, where the C_i 's are random \vee 's of k literals using k distinct variables (henceforth “ k -clauses”) and show that f is likely to have the desired properties. We use g_i for the specification associated with C_i , and write $C_i \sim x$ if some entry of x agrees with g_i . We say C_i *misses* $S \subseteq [n]$ if the indices of all variables in C_i lie in $[n] \setminus S$.

Let $s = (1/2 - \delta)n$. We will always use S for an s -subset of $[n]$ and (for such an S) set $m_S = |\{i : C_i \text{ misses } S\}|$. (Following common practice we omit irrelevant floor and ceiling symbols, pretending all large numbers are integers. As in the case of k, m and s , parameters not declared to be constants are assumed to be functions of n .) We use \log for \log_2 .

Both constructions will make use of the next two observations, with Theorem 1.1 following immediately from these and Theorem 1.2 requiring a little more work.

Lemma 3.1. *If $k = o(\sqrt{n})$ and $(1/2 + \delta)^k m = \omega(n)$ then w.h.p.*

$$m_S \sim (1/2 + \delta)^k m \quad \forall S \in \binom{[n]}{s}. \quad (7)$$

(where, as usual, $a_n \sim b_n$ means $a_n/b_n \rightarrow 1$ and *with high probability* (w.h.p.) means with probability tending to 1, both as $n \rightarrow \infty$).

Proof. For a given S , m_S has the binomial distribution $B(m, p)$, with $p = \binom{n-s}{k} / \binom{n}{k} \sim (1/2 + \delta)^k$ (using $k = o(\sqrt{n})$ for the “ \sim ”). Thus $\mathbb{E}m_S = mp$ and, by “Chernoff’s Inequality” (e.g. [8, Theorem 2.1]),

$$\Pr(m_S \notin ((1 - \zeta)mp, (1 + \zeta)mp)) < \exp[-\Omega(\zeta^2 mp)],$$

for $\zeta \in (0, 1)$. Applying this with a ζ which is both $\omega(\sqrt{n/(mp)})$ and $o(1)$ gives $\Pr(m_S \not\sim mp) < 2^{-\omega(n)}$, and the union bound then gives (7). ■

The next lemma is stated to cover both applications, though nothing so precise is needed for Theorem 1.1.

Lemma 3.2. *If there is a ξ for which*

$$\exp[-\xi^2 n] = o((1 - 2^{-k})^m) \tag{8}$$

and

$$[(1 + 2\xi)/4]^k = o(1/m), \tag{9}$$

then w.h.p.

$$\mu(f) \sim (1 - 2^{-k})^m. \tag{10}$$

Proof. This is a simple second moment method calculation (similar to what’s done in [1], though described differently there).

Recalling that x, y always denote elements of $\{0, 1\}^n$, write A_x for the event $\{f(x) = 1\}$ and $\mathbf{1}_x$ for its indicator, and set $X = \sum \mathbf{1}_x = 2^n \mu(f)$. Then $\Pr(A_x) = (1 - 2^{-k})^m$ and $\mathbb{E}X = (1 - 2^{-k})^m 2^n$; so we just need to show $\mathbb{E}X^2 \sim \mathbb{E}^2 X$ (equivalently, $\mathbb{E}X^2 < (1 + o(1))\mathbb{E}^2 X$), since Chebyshev’s Inequality then gives $\Pr(|X - \mathbb{E}X| > \zeta \mathbb{E}X) = o(1)$ for any fixed $\zeta > 0$.

We have

$$\mathbb{E}X^2 = \sum_x \sum_y \mathbb{E}\mathbf{1}_x \mathbf{1}_y = \sum_x \Pr(A_x) \sum_y \Pr(A_y | A_x),$$

so will be done if we show that for a fixed x ,

$$\sum_y \Pr(A_y | A_x) < (1 + o(1))(1 - 2^{-k})^m 2^n.$$

Since the sum is the same for all x , it’s enough to prove this when $x = \underline{0}$. Set $Z = \{y : |y| < (1/2 - \xi)n\}$ and recall that by Chernoff’s Inequality, $|Z| < \exp[-2\xi^2 n] 2^n$. It is thus enough to show that (for $x = \underline{0}$)

$$y \notin Z \Rightarrow \Pr(A_y | A_x) < (1 + o(1))(1 - 2^{-k})^m, \tag{11}$$

since then, using (8), we have

$$\sum_y \Pr(A_y|A_x) < |Z| + \sum_{y \notin Z} \Pr(A_y|A_x) < (1 + o(1))(1 - 2^{-k})^m 2^n.$$

Now since $x = \underline{0}$, we have $A_x = \{g_i \neq \underline{1} \ \forall i\}$; so if, for a given $y \notin Z$, we set $\beta = \beta_y = \Pr(C_i \sim y | g_i \neq \underline{1})$ (a function of $|y|$), then $\Pr(A_y|A_x) = \beta^m$. Aiming for a bound on β , we have

$$\begin{aligned} 1 - 2^{-k} &= \Pr(C_i \sim y) \\ &= \Pr(g_i = \underline{1}) \Pr(C_i \sim y | g_i = \underline{1}) + \Pr(g_i \neq \underline{1}) \Pr(C_i \sim y | g_i \neq \underline{1}) \\ &= 2^{-k} \Pr(C_i \sim y | g_i = \underline{1}) + (1 - 2^{-k})\beta \end{aligned}$$

and

$$\Pr(C_i \sim y | g_i = \underline{1}) > 1 - (1 - |y|/n)^k \geq 1 - (1/2 + \xi)^k =: 1 - \nu$$

(using the fact that if $g_i = \underline{1}$, then $g_i \not\sim y$ iff all indices of variables in C_i belong to $\{j : y_j = 0\}$). Combining, we have

$$\beta < (1 - 2^{-k})^{-1} [1 - 2^{-k} - 2^{-k}(1 - \nu)] = (1 - 2^{-k}) \left[1 + \frac{2^{-k}(\nu - 2^{-k})}{(1 - 2^{-k})^2} \right],$$

which with (9) gives $\beta^m < (1 + o(1))(1 - 2^{-k})^m$ (which is (11)).

■

Proof of Theorem 1.1. Notice that it's enough to prove this with $\mu(f) \sim \alpha$ (rather than “ $= \alpha$ ”); for then, since $f^{-1}(1) \subseteq g^{-1}(1)$ trivially implies $J_S^+(f) \leq J_S^+(g)$ for all S , we can choose $\beta \in (\alpha, 1)$ and a g with $\mu(g) \sim \beta$ possessing the desired small influences, and shrink $g^{-1}(1)$ to produce f .

Let $k = C \log n$, with $C = C_\delta$ chosen so that $(1 + 2\delta)^k = \omega(n)$ (e.g. $C = 1/\delta$ does this), and $m = 2^k \ln(1/\alpha) = n^C \ln(1/\alpha)$. Here all we use from Lemma 3.1 (whose hypotheses are satisfied for our choice of k and m) is the fact that w.h.p. $m_S \neq 0$ for all S , whence each $J_S^+(f)$ is at most $1 - 2^{-k} = 1 - n^{-C}$. On the other hand, by Lemma 3.2 (with, for example, $\xi = 0.1$), we have $\mu(f) \sim \alpha$ w.h.p. So w.h.p. f meets our requirements.

■

Proof of Theorem 1.2. Here, intending to recycle n , m and f , we rename these quantities **n**, **m** and **f**. We may of course assume δ is fairly small. Let

(for example) $\xi = \delta/3$, fix ε with $0 < \varepsilon < \xi^2$, and set $k = (1 + \delta) \log \mathbf{n}$ and $\mathbf{m} = \varepsilon 2^k \mathbf{n}$. These values are easily seen to give the hypotheses of Lemmas 3.1 and 3.2. In particular, we can say that w.h.p. the supports of the C_i 's are chosen so (7) holds (note this says nothing about the values specified by the g_i 's) and

$$\mu(\mathbf{f}) \sim (1 - 2^{-k})^{\mathbf{m}} \sim e^{-\varepsilon \mathbf{n}}. \quad (12)$$

Set $n = (1/2 + \delta) \mathbf{n}$. Fix $S \in \binom{[n]}{s}$, set $m = m_S$, and let $f = f_S$ be the \wedge of the m C_i 's—w.l.o.g. C_1, \dots, C_m —that miss S . Thus f is the \wedge of $m \sim (1/2 + \delta)^k \mathbf{m} = \varepsilon(1 + 2\delta)^k \mathbf{n}$ random k -clauses from a universe of n variables. Theorem 1.2 (with $\alpha = \delta$) thus follows from

Claim A. $\Pr(\mu(f) > \exp[-n^\delta]) < o(2^{-n})$

(since then w.h.p. we have $\mu(f_S) \leq \exp[-n^\delta]$ for every S).

Remarks. The actual bound in Claim A will be $\exp[-\Omega(m)]$, so much smaller than 2^{-n} . Note that here it doesn't matter whether we take μ to be our original measure (i.e. μ uniform on $\{0, 1\}^{\mathbf{n}}$) or uniform measure on $Q := \{0, 1\}^n$; but it's now more natural to think of the latter—and we will do so in what follows—since our original universe plays no further role in this discussion. It may also be worth noting that, unlike in the proof of Lemma 3.2, the second moment method is not strong enough to give the exponential bound in Claim A.

Claim B. If $X \subseteq Q$, $\mu(X) = \beta > \exp[-o(n/\log^2 n)]$ and $\zeta = o(2^{-k})$, then for a random k -clause C ,

$$\Pr(\mu(C \wedge X) > (1 - \zeta)\mu(X)) < 1/2$$

(where $C \wedge X = \{x \in X : C \sim x\}$).

Remark. This is probably true for β greater than something like $\exp[-n/k]$. The bound in the claim is just what the proof gives, and is more than enough for us since we're really interested in much larger β .

To see that Claim B implies Claim A, set $f_j = \wedge_{i=1}^j C_i$ and notice that $\mu(f) \geq \beta$ implies (for example)

$$|\{i : \mu(f_i) < (1 - \frac{5 \ln(1/\beta)}{m})\mu(f_{i-1})\}| < m/5 \quad (13)$$

(and, of course, $\mu(f_i) \geq \beta \forall i$). But if we take $\beta = \exp[-n^\delta]$ then our choice of parameters gives

$$\zeta := 5m^{-1} \ln(1/\beta) = o(2^{-k})$$

(using $m/\ln(1/\beta) = \Theta(n^{(1+\delta)\log(1+2\delta)+1-\delta})$ and $2^k = n^{1+\delta}$), so Claim B bounds the probability of (13) by

$$\binom{m}{m/5} 2^{-4m/5} = o(2^{-n}).$$

■

Proof of Claim B. Let G be the bipartite graph on $Q \cup W$, where W is the set of $(n-k)$ -dimensional subcubes of Q and, for $(x, D) \in Q \times W$, we take $x \sim D$ if $x \in D$. (So we've gone to complements: for a clause C the corresponding subcube is $D = \{y : C \not\models y\}$, so $C \wedge X = X \setminus D$.)

Assuming Claim B fails at X , fix $T \subseteq W$ with $|T| = |W|/2$ and

$$D \in T \Rightarrow \mu(D \cap X) < \zeta \mu(X),$$

and set $R = W \setminus T$.

Consider the experiment: (i) choose x uniformly from X ; (ii) choose D uniformly from the members of W containing x ; (iii) choose y uniformly from D .

Claim C. $\Pr(y \in X) > (2 - o(1))\beta$.

Proof. Since each triple (x, D, y) with $x \in X$ and $x, y \in D$ is produced by (i)-(iii) with probability $|X|^{-1} \cdot 2^k |W|^{-1} \cdot 2^{k-n}$, we just need to show that the number of such triples with $y \in X$ is at least

$$(2 - o(1))\beta |X| |W| 2^n 2^{-2k} = (2 - o(1)) |X|^2 |W| 2^{-2k}.$$

Writing d for degree in G , we have

$$\sum_{x \in X} d_T(x) = \sum_{D \in T} d_X(D) < |T| \zeta |X|,$$

implying

$$\begin{aligned} \sum_{D \in R} d_X(D) &= \sum_{x \in X} (d(x) - d_T(x)) \\ &> |X| |W| 2^{-k} - \zeta |T| |X| = (1 - o(1)) |X| |W| 2^{-k}. \end{aligned}$$

The number of (x, D, y) 's as above is thus

$$\begin{aligned} \sum_{D \in W} d_X^2(D) &\geq \sum_{D \in R} d_X^2(D) \geq (\sum_{D \in R} d_X(D))^2 / |R| \\ &> (1 - o(1)) |X|^2 |W|^2 |R|^{-1} 2^{-2k} = (2 - o(1)) |X|^2 |W| 2^{-2k}. \end{aligned}$$

■

Let $T(x)$ be the random element of Q gotten from x by choosing K uniformly from $\binom{[n]}{k}$ and randomly (uniformly, independently) revising the x_i 's with $i \notin K$. Then y gotten from x by (ii) and (iii) above is just $T(x)$, so the next assertion contradicts Claim C, completing the proof of Claim B (and Theorem 1.2).

Claim D. If $\mu(X) > \exp[-o(n/\log^2 n)]$ and x is uniform from X , then $\Pr(T(x) \in X) < (1 + o(1))\mu(X)$.

Remark. If X is a subcube of codimension n/k , say $X = \{x : x \equiv 0 \text{ on } L\}$ with $|L| = n/k$, then for any $x \in X$,

$$\Pr(T(x) \in X) = \sum_t \Pr(|K \cap L| = t) 2^{-(|L|-t)} = \mu(X) \sum_t \Pr(|K \cap L| = t) 2^t,$$

and, since $|K \cap L|$ is essentially Poisson with mean 1, the sum is approximately $e^{-1} \sum_t 2^t/t! = e$. So Claim D fails for $\mu(X) = 2^{-n/k}$ and, as earlier, it's natural to guess that it holds if $\mu(X)$ is much bigger than this.

Proof of Claim D. Let $Q_r = \{y \in Q : |y| \leq r\}$. The assumption on $\mu(X)$ implies that $\mu(Q_{r-1}) < \mu(X) \leq \mu(Q_r)$ for some $r > (1/2 - o(1/k))n$, so Claim D follows from

Claim E. If $\varphi = o(1/k)$ and $r > (1/2 - \varphi)n$, then for any $x \in Q$ and $X \subseteq Q$ with

$$\mu(X) \leq \mu(Q_r), \tag{14}$$

$$\Pr(T(x) \in X) < (1 + o(1))\mu(Q_r). \tag{15}$$

Proof. We may assume $x = \underline{0}$, so that $\Pr(T(x) = y)$ is a decreasing function of $|y|$. We thus maximize $\Pr(T(x) \in X)$ subject to (14) by taking $X = Q_r$, and (15) is then a routine calculation using

$$\mu(X) = \Pr(\text{Bin}(n, 1/2) \leq r)$$

and

$$\Pr(T(x) \in X) = \Pr(\text{Bin}(n - k, 1/2) \leq r)$$

(where $\text{Bin}(\cdot, \cdot)$ denotes a binomially distributed r.v.).

■

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