Sharp thresholds for constraint satisfaction problems and homomorphisms

Hamed Hatami *and* Michael Molloy
Department of Computer Science
University of Toronto
Toronto, Canada
{hamed,molloy}@cs.toronto.edu

October 24, 2018

Abstract

We determine under which conditions certain natural models of random constraint satisfaction problems have sharp thresholds of satisfiability. These models include graph and hypergraph homomorphism, the (d, k, t)-model, and binary constraint satisfaction problems with domain size three.

1 Introduction

Random 3-SAT and its generalizations have been studied intensively for the past decade or so (see e.g. [1, 5, 7, 16, 27, 2, 6, 12, 15, 34, 8]). One of the most interesting things about these models, and arguably the main reason that most people study them, is that many of them exhibit what is called a *sharp threshold of satisfiability*[1], a critical clause-density at which the random problem suddenly moves from being almost surely[1] satisfiable to almost surely unsatisfiable. Most of the work on these problems is, at least implicitly, an attempt to determine the precise locations of their thresholds. At this point, these locations are known only for a handful of the problems, such as [2, 6, 12, 15, 34, 8]. Just proving the existence of a sharp threshold for random 3-SAT was considered a major breakthrough by Friedgut[16]. The vast majority of these generalizations appear to have sharp thresholds, but there are exceptions which are said to have coarse thresholds[1].

The ultimate goal of the present line of enquiry is to determine precisely which of these models have sharp thresholds, but this appears to be quite difficult; in Section 2 we show that it is at least as difficult as determining the location of the threshold for 3-colourability, something that has been sought after for more than 50 years (see e.g. [13, 30, 11]). A more fundamental goal is to obtain a better understanding of what can cause some problems to have coarse thresholds rather than sharp ones.

Molloy[31] and independently Creignou and Daudé[9] introduced a wide family of models for random constraint satisfaction problems which includes 3-SAT and many of its generalizations. This permits us to study them under a common umbrella, rather than one-at-a-time. Molloy determined precisely which models from this family have any threshold at all ([9] provides the same result for those models with domain[1] size 2). But he left open the much more important question of which models have sharp thresholds. In this paper, we begin to address this question. We answer it for two of the most natural subfamilies - the so-called (d, k, t)-family[1] (Theorem 3), and the family of graph and hypergraph

[1] Defined formally below.

homomorphism problems (Theorem 5). We also study binary constraint satisfaction problems with domain size 3.

The standard example of a problem with a coarse threshold is 2-colourability. Here, there is a coarse threshold precisely because unsatisfiability (i.e. non-2-colourability) can be caused only by the presence of odd cycles. Roughly speaking, Friedgut's theorem[16] implies that a problem exhibits a coarse threshold iff unsatisfiability is *approximately* equivalent to having one of a set of unicyclic[1] subproblems. It is not hard to see that if there are unsatisfiable unicyclic instances of a problem then that problem exhibits a coarse threshold (or exhibits no threshold at all). This makes it quite natural to pose the following rule-of-thumb:

Hypothesis A: *If a random model from the family in [31] is such that: (a) it exhibits a threshold, and (b) every unicyclic instance is satisfiable, then that threshold is sharp.*

However, reality is not that simple. [31] presents a counterexample to Hypothesis A; others are presented in this paper. Nevertheless, the hypothesis holds for certain subfamilies of models. Creignou and Daudé[9] conjectured that Hypothesis A holds for problems with domain-size two. Special cases of this conjecture were proven by Istrate[25] and independently Creignou and Daudé[10]; the proofs of each paper can be extended to cover the entire conjecture. Theorems 3 and 5 in this paper show that Hypothesis A holds for the (d, k, t)-models and for homomorphisms to connected graphs.

In general, coarse thresholds can be caused by much more subtle and insidious reasons than unsatisfiable unicyclic instances. In this paper we begin to understand some of these reasons by focusing on the case where the constraint size is two and the domain size is three (a natural next step after the well-understood domain-size-two case). In this paper, we identify a particular subtle property that must hold whenever Hypothesis A fails (Theorem 17). If we permit either greater domain sizes or greater constraint sizes then this is no longer true.

1.1 The random models

In our setting, the variables of a constraint satisfaction problem (CSP) all have the same domain of permissable values, $\{1, ..., d\}$, and all constraints will have size k, for some fixed integers d, k. Given a k-tuple of variables, $(x_1, ..., x_k)$, a *restriction* on $(x_1, ..., x_k)$ is a k-tuple of values $R = (\delta_1, ...\delta_k)$ where $1 \leq \delta_i \leq d$ for each i. For each k-tuple $(x_1, ..., x_k)$, the set of restrictions on that k-tuple is called a *constraint*. The *empty constraint* is the constraint which contains no restrictions. We say that an assignment of values to the variables of a constraint C *satisfies* C if that assignment is not one of the restrictions in C. An assignment of values to all variables in a CSP *satisfies* that CSP if every constraint is simultaneously satisfied. A CSP is *satisfiable* if it has such a satisfying assignment.

It will be convenient to consider a set of canonical variables $X_1, ..., X_k$ which are used only to describe the "pattern" of a constraint. These canonical variables are not variables of the actual CSP. For any d, k there are d^k possible restrictions and 2^{d^k} possible constraints over the k canonical variables. We denote this set of constraints as $\mathcal{C}^{d,k}$. For our random model, one begins by specifying a particular probability distribution, $\mathcal{P}$ over $\mathcal{C}^{d,k}$. We use $\mathbf{supp}(\mathcal{P})$ to denote the support of $\mathcal{P}$; i.e. the set of constraints C with $\mathcal{P}(C) > 0$. Different choices of $\mathcal{P}$ give rise to different instances of the model.

We now define our random models. The "$G_{n,M}$" model, where the number of constraints is fixed to be M, is the most common. But in this paper, it will be much more convenient to focus on the "$G_{n,p}$" model where each k-tuple of variables is chosen independently with probability $p = c/n^{k-1}$ to receive a constraint. The two models are, in most respects, equivalent when $M = (c/k!)n$. In particular, it is straightforward to show that one exhibits a sharp threshold iff the other does.

The $CSP_{n,p}(\mathcal{P})$ Model: Specify n, p and $\mathcal{P}$ (typically $p = c/n^{k-1}$ for some constant c; note that $\mathcal{P}$ implicitly specifies d, k). First choose a random k-uniform hypergraph on n variables where each of the $\binom{n}{k}$ potential hyperedges is selected with probability p. Next, for each hyperedge e, we choose a constraint on the k variables of e as follows: we take a random permutation from the k variables onto

$\{X_1, ..., X_k\}$ and then we select a random constraint according to $\mathcal{P}$ and map it onto the k variables.

A property holds *almost surely* (a.s) if the limit as $n \to \infty$ of it holding is 1. In [9, 31] it was shown that for every $\mathcal{P}$, either: (i) $CSP_{n,p}(\mathcal{P})$ is a.s. satisfiable for every $c \geq 0$, (ii) $CSP_{n,p}(\mathcal{P})$ is a.s. unsatisfiable for every $c > 0$, or (iii) there is some $c_1 < c_2$ such that $CSP_{n,p}(\mathcal{P})$ is a.s. satisfiable for every $0 \leq c \leq c_1$ and $CSP_{n,p}(\mathcal{P})$ is a.s. unsatisfiable for every $c > c_2$. We say that $CSP_{n,p}(\mathcal{P})$ has a *sharp threshold of satisfiability* if there is some positive-valued function $c(n) = \Theta(1)$ such that for every $\epsilon > 0$, if $p = (1-\epsilon)c(n)/n^{k-1}$ then $CSP_{n,p}(\mathcal{P})$ is a.s. satisfiable and if $p = (1+\epsilon)c(n)/n^{k-1}$ then $CSP_{n,p}(\mathcal{P})$ is a.s. unsatisfiable. This is often abbreviated to just *sharp threshold*. We say that $CSP_{n,p}(\mathcal{P})$ has a *coarse threshold* if for all c in some interval $c_1(n) < c < c_2(n)$, $CSP_{n,p}(\mathcal{P})$ is neither a.s. satisfiable nor a.s. unsatisfiable. It is easy to see that every $\mathcal{P}$ satisfying case (iii) above must have either a coarse threshold or a sharp threshold.

Each k-tuple of vertices can have at most one constraint in $CSP_{n,p}(\mathcal{P})$. When applying Friedgut's theorem, it will be convenient to relax this condition, and allow k-tuples to possibly receive multiple constraints. Thus up to $k! \times |\mathbf{supp}(\mathcal{P})|$ constraints can appear on a k-tuple of variables.

The $\widehat{CSP}_{n,p}(\mathcal{P})$ Model: Specify n, p and $\mathcal{P}$. For each of the $n(n-1)...(n-k+1)$ *ordered* k-tuples of variables and each constraint $C \in \mathbf{supp}(\mathcal{P})$, we assign C to the ordered k-tuple with probability $\mathcal{P}(C) \times p/k!$.

Note that the expected total number of constraints is the same under each model. Furthermore, it is easy to calculate that the probability of at least one k-tuple receiving more than one constraint in $\widehat{CSP}_{n,p}(\mathcal{P})$ is for $k \geq 3$, $o(1)$ and for $k = 2$, an absolute constant $0 < \alpha < 1$. It follows that if a property holds a.s. in $\widehat{CSP}_{n,p}(\mathcal{P})$ then it holds a.s. in $CSP_{n,p}(\mathcal{P})$. As a corollary, we have:

Lemma 1 *If $\widehat{CSP}_{n,p}(\mathcal{P})$ has a sharp threshold then so does $CSP_{n,p}(\mathcal{P})$. The reverse is true for $k \geq 3$.*

So for the remainder of the paper, whenever we wish to prove that $CSP_{n,p}(\mathcal{P})$ has a sharp threshold, we will work in the $\widehat{CSP}_{n,p}(\mathcal{P})$ model.

We often focus on the *constraint hypergraph* of a CSP; i.e. the hypergraph whose vertices are the variables and whose edges are the tuples of variables that have constraints. A *tree-CSP* is a CSP whose constraint hypergraph is a hypertree. A CSP is *unicyclic* if its constraint hypergraph is unicylic; i.e. has exactly one cycle. (Hypertree and cycle are defined below).

F_1 is said to be a *sub-CSP* of F_2 if every variable of F_1 is a variable of F_2 and every constraint of F_1 is a constraint of F_2.

We close this subsection with some hypergraph definitions. A hypergraph consists of a set of vertices and a set of *hyperedges*, where each hyperedge is a collection of vertices. If every hyperedge has size exactly k then the hypergraph is *k-uniform*. In a *simple* hypergraph, no vertex appears twice in any one hyperedge, and no two edges are identical. So, for example, the constraint hypergraph of $CSP_{n,p}(\mathcal{P})$ is simple, but the constraint hypergraph of $\widehat{CSP}_{n,p}(\mathcal{P})$ may have multiple edges. Neither model permits multiple copies of a vertex in a single edge, but such edges are possible when we discuss hypergraph homomorphism problems. The edge $(v, v, ..., v)$ is called a *loop*.

A walk P of length r is a sequence of r hyperedges and $r+1$ vertices $(v_0, e_1, v_1, e_2, v_2 \ldots, e_r, v_r)$ such that e_i contains both v_{i-1} and v_i. A walk is a *path* if the v_i are distinct. A walk is a *cycle* of size r if for $i = 1, \ldots, r$ the v_i and e_i are distinct, and $v_0 = v_r$. The *distance* from a vertex u to a vertex v is the minimum r such that there exists a walk of length r, $(v, e_1, v_1, \ldots, e_r, u)$; the distance of a vertex from itself is defined to be 0. The distance from a vertex v to a set of vertices is the minimum distance from v to any vertex in the set. A hypergraph is a *hypertree* if it has no cycles and it is connected.

By *contracting* two vertices u and v into a new vertex w, we mean (i) adding a new vertex w to the set of the vertices, (ii) replacing u and v in every hyperedge by w, and (iii) removing u and v. Note that this may result in a hyperedge containing multiple copies of w.

1.2 Two special families

The ultimate goal of this research is to characterize all distributions $\mathcal{P}$ for which $CSP_{n,p}(\mathcal{P})$ exhibits a sharp threshold. However, in section 2, we will show that this is very difficult by proving the following:

Observation 2 *If one can determine which distributions $\mathcal{P}$ yield sharp thresholds for $CSP_{n,p}(\mathcal{P})$ then one can determine the locations of each of those thresholds.*

Determining the locations of some of these thresholds, eg the 3-SAT threshold or the 3-colourability threshold, is notoriously difficult (see [30] for a survey on those two thresholds). So Observation 2 suggests that we should set our sights lower and focus on some important classes of distributions.

Perhaps the most natural choice for $\mathcal{P}$ is the distribution obtained by selecting each of the d^k possible restrictions independently with probability q for some constant q. However, as noted in [4], every such choice of $\mathcal{P}$ yields a model that is a.s. unsatisfiable for any non-trivial choice of p. So this is a rather uninteresting family of models, particularly as far as the study of thresholds goes.

The next most natural choice for $\mathcal{P}$ is to fix t, the number of restrictions per clause, and to make every constraint with exactly t restrictions equally likely. (Note that for $d = 2, t = 1$ this yields random k-SAT.) This is often called the (d, k, t)-model and has received a great deal of study, both from a theoretical perspective [28, 32] and from experimentalists (see [19] for a survey of many such studies). In [4] it is shown that when $t \geq d^{k-1}$, this model is problematic in the same way as the previously mentioned one, as it is a.s. unsatisfiable even for values of $p = o(1/n^{k-1})$ (i.e. when the number of constraints is $o(n)$). However, it was proven in [19] that for every $1 \leq t < d^{k-1}$, the (d, k, t)-model does not have that problem. One of the main contributions of this paper is to show that for this case, the model exhibits a sharp threshold:

Theorem 3 *For every $d, k \geq 2$ and every $1 \leq t < d^{k-1}$, the (d, k, t)-model has a sharp threshold.*

Note that this generalizes the well-known result that k-SAT has a sharp threshold ([6, 20] for $k = 2$; [16] for $k \geq 3$), as can be seen by setting $d = 2, t = 1$.

From a different perspective, it is quite natural to consider the case where every constraint is identical, i.e. $|\mathbf{supp}(\mathcal{P})| = 1$. It is not hard to see that every such problem is equivalent to a hypergraph homomorphism problem, as defined below:

For two k-uniform hypergraphs, G, H, a *homomorphism* from G to H is a mapping h from $V(G)$ to $V(H)$ such that for each edge $(v_1, v_2, \ldots, v_k)$ of G, $(h(v_1), h(v_2), \ldots, h(v_k))$ is an edge of H. We say that G is *homomorphic* to H, if there exists such a homomorphism. When $k = 2$ and H is the complete graph with no loops, we are simply asking whether G has a $|H|$-colouring. Homomorphisms are an important generalization of graph colouring (see e.g. [24]). They are often also referred to as H-colourings (e.g. [23, 21]).

Suppose that H is a fixed undirected k-uniform hypergraph, and G is a random k-uniform hypergraph on n vertices where each of the $\binom{n}{k}$ potential hyperedges is selected with probability p. Set d to be equal to the number of vertices in H and define a constraint C with domain size d and constraint size k by saying that C permits $X_1 = \delta_1, ..., X_k = \delta_k$ iff $(\delta_1, ..., \delta_k)$ is a hyperedge of H. Treat each vertex of G as a variable with domain $\{1, .., d\}$ and assign C to each hyperedge of G. We call this the *H-homomorphism problem.*

Thus we have an instance of $CSP_{n,p}(\mathcal{P})$ where C is the only constraint in $\mathbf{supp}(\mathcal{P})$ and furthermore C is symmetric under permutations of the canonical variables; in other words, all constraints are identical even under permutations of variables. It is easy to see that every such $\mathcal{P}$ corresponds to a homomorphism problem; just take H to be the hypergraph where $(\delta_1, ..., \delta_k)$ is a hyperedge iff C permits $X_1 = \delta_1, ..., X_k = \delta_k$. Note that here a hyperedge in H may contain multiple copies of a vertex.

Thus, these H-homomorphism problems are not only important as a fundamental graph problem, but also because they form a very natural subclass of our family of random CSP models. In this paper, we prove that Hypothesis A holds for every connected undirected H.

It is easy to see that if H has a loop $(\delta, \delta, ..., \delta)$ then every hypergraph is trivially homomorphic to H (just map every vertex to δ); so the H-homomorphism problem has no threshold at all. The other trivial case is where H has no hyperedges at all and so no non-trivial hypergraph has an H-homomorphism.

Lemma 4 *Suppose that H is a nontrivial k-uniform hypergraph with no loops. We have the following:*

(a) For $k \geq 3$, every unicylic k-uniform hypergraph is homomorphic to a single hyperedge, and hence to H.

(b) For $k = 2$: if the triangle is homomorphic to H, then so is every unicyclic graph; and the triangle is homomorphic to H iff H contains a triangle.

Proof. To prove part (1), let $(v_0, e_1, v_1, e_2, v_2 \ldots, e_r, v_0)$ be the unique cycle of the hypergraph, and let $(w_0, \ldots, w_{k-1})$ be a single hyperedge. Define $h(v_i) = w_{(i \bmod 2)}$, for every $0 \leq i \leq r-2$ and $h(v_{r-1}) = w_2$. It is easy to see that one can extend h to a homomorphism from the unicyclic hypergraph to H.

Part (2) easily follows from the easy and well-known fact that every cycle is homomorphic to the triangle, and the triangle is not homomorphic to any cycle of size greater that 3. ■

From Lemma 4 we conclude that proving that Hypothesis A holds whenever H is connected and undirected is equivalent to proving:

Theorem 5 *If H is a connected undirected loopless k-uniform hypergraph with at least one edge, then the H-homomorphism problem has a sharp threshold iff (a) $k \geq 3$ or (b) $k = 2$ and H contains a triangle.*

Note that this generalizes the well-known result that c-colourability has a sharp threshold for $c \geq 3$[3], as can be seen by setting $k = 2$ and taking $H = K_c$.

We do not have a strong feeling as to whether the "connected" condition is necessary here; we discuss the possibility of extending Theorem 5 to disconnected graphs in Section 3. In section 3.2, we provide a disconnected directed graph H for which the H-homomorphism problem is a counterexample to the analogue of Hypothesis A in the $\widehat{CSP}_{n,p}(\mathcal{P})$ model but not in the $CSP_{n,p}(\mathcal{P})$ model.

1.3 Tools

Our main tool is distilled from Friedgut's main theorem in [16]. Friedgut reported to us[private communication] that his proof can be adapted to the setting of this paper; for completeness, the first author worked out the details of such an extension in [22] as they did not appear in print. To provide Friedgut's theorem for CSP's in its full power instead of being restricted to the unsatisfiability property, we consider, as Friedgut did, properties that are preserved under constraint addition; such properties are called *monotone*. A property on CSP's is called *monotone symmetric* if it is monotone and invariant under CSP automorphisms. For a property A, A_n denotes the restriction of A on CSP's with exactly n variables. Roughly speaking, Friedgut's theorem says that for a value of p that is "within" the coarse threshold, there is a constant sized instance M such that $\tau < \Pr[M \subseteq \widehat{CSP}_{n,p}(\mathcal{P})] < 1 - \tau$ for some constant τ which does not depend on n, and adding M to our random CSP boosts the probability of being in A by at least $2\alpha > 0$, whereas adding a linear number of new random constraints only boosts it by at most α. First, we must formalize what we mean by "adding M". Given two CSP's M, F where M has r variables, and F has at least r variables, we define $F \oplus M$ to be the CSP obtained by choosing a random r-tuple of variables in F and then adding M on those r variables. Now we can formally state an adaptation of Friedgut's theorem to the setting of this paper. A proof can be found in [22]:

Theorem 6 *Let A be a monotone symmetric property in $\widehat{CSP}_{n,p}(\mathcal{P})$ which has a coarse threshold. There exist $p = p(n)$, $\tau, \alpha, \epsilon > 0$, and a CSP M whose constraints are chosen from $\mathbf{supp}(\mathcal{P})$ such that for an infinite number of n:*

(a) $\alpha < \Pr[\widehat{CSP}_{n,p}(\mathcal{P}) \in A] < 1 - 2\alpha$.

(b) $\Pr[\widehat{CSP}_{n,(1+\epsilon)p}(\mathcal{P}) \in A] < 1 - 2\alpha$.

(c) $\Pr[\widehat{CSP}_{n,p}(\mathcal{P}) \oplus M \in A] > 1 - \alpha$.

(d) $\tau < \Pr[M \subseteq \widehat{CSP}_{n,p}(\mathcal{P})] < 1 - \tau$.

Since in our setting $p(n) = c(n)/n^{k-1}$ where $c(n) = \theta(1)$, Theorem 6(d) implies that M has exactly one cycle.

Corollary 7 *For any $\mathcal{P}$, if $\widehat{CSP}_{n,p}(\mathcal{P})$ has a coarse threshold of satisfiability then there exist $p = p(n)$, $\alpha, \epsilon > 0$, and a unicyclic CSP M on a constant number of variables whose constraints are chosen from $\mathbf{supp}(\mathcal{P})$ such that:*

(a) $\alpha < \Pr[\widehat{CSP}_{n,p}(\mathcal{P}) \text{ is unsatisfiable}] < 1 - 2\alpha$.

(b) $\Pr[\widehat{CSP}_{n,(1+\epsilon)p}(\mathcal{P}) \text{ is unsatisfiable}] < 1 - 2\alpha$.

(c) $\Pr[\widehat{CSP}_{n,p}(\mathcal{P}) \oplus M \text{ is unsatisfiable}] > 1 - \alpha$.

Our next tool proves some properties for local parts of a random CSP.

Lemma 8 *Suppose that $p < cn^{1-k}$ for some positive constant c, and let G be an instance of $\widehat{CSP}_{n,p}(\mathcal{P})$. Let t be a positive constant integer and choose a set T of t random variables. Then for every $\epsilon > 0$, and integer $r > 0$ there exists an integer $L(c, t, r, \epsilon)$ such that with probability at least $1 - \epsilon$:*

(i): No constraint of G contains more than one variable of T.

(ii): G induces a forest on the set of the variables that are of distance at most r from T.

(iii): There are at most L variables that are of distance at most r from T.

Proof. Let E_1, E_2, and E_3 denote the events (i), (ii), and (iii) respectively. Trivially

$$\Pr[E_1] \geq 1 - \sum_{i=2}^{k} n^{k-i} \binom{t}{i} k! p = 1 - o(1). \tag{1}$$

The expected number of the cycles of size at most $2r$ which contain at least one variable in T is at most $t \sum_{i=2}^{2r} n^{ik-i-1} p^i$. Thus

$$\Pr[E_2] \geq 1 - t \sum_{i=2}^{2r} n^{ik-i-1} p^i \geq 1 - \frac{2tr(1+c)^{2r}}{n} = 1 - o(1). \tag{2}$$

The expected number of the variables in a distance of at most r from T is at most $t\sum_{i=1}^{r} n^{ik-i}p^i$. So by Chebychev's inequality, for sufficiently large L:

$$\Pr[E_3] \geq 1 - \frac{t\sum_{i=1}^{r} n^{ik-i}p^i}{L} \geq 1 - \frac{\epsilon}{2}. \tag{3}$$

The lemma follows from (1), (2), and (3). ■

Our third tool is easily proven with a straightforward first moment calculation and concentration argument (via e.g. the second moment method or Talagrand's inequality); we omit the details.

Lemma 9 *Let T be a tree-CSP whose constraints are in* $\mathbf{supp}(\mathcal{P})$*. There exists $z = o(n^{1-k})$ such that a.s. $\widehat{CSP}_{n,z}(\mathcal{P})$ contains T as a sub-CSP.*

2 Difficulty

Here we prove Observation 2, thus showing that characterizing those distributions $\mathcal{P}$ for which $CSP_{n,p}(\mathcal{P})$ has a sharp threshold is at least as difficult as determining the location of all such thresholds.

Suppose, for example, that one wanted to know the 3-colourability threshold; i.e. the value $c = c(n)$ such that for all $\epsilon > 0$, $\chi(G_{n,p=c(n)-\epsilon})$ is a.s. 3-colourable and $\chi(G_{n,p=c(n)+\epsilon})$ is a.s. not 3-colourable. (The existence of this threshold was proven in [3].) We will construct a family of distributions $\mathcal{P}$ such that determining which of those distributions have sharp thresholds is sufficient to determine the 3-colourability threshold.

We set $d = 5$ and $k = 2$, and define two constraints by listing their pairs of forbidden values:

$$\begin{aligned} C_1 &= \{(4,4),(5,5)\} \cup (\{1,2,3\} \times \{4,5\}) \cup (\{4,5\} \times \{1,2,3\}), \\ C_2 &= \{(1,1),(2,2),(3,3)\} \cup (\{1,2,3\} \times \{4,5\}) \cup (\{4,5\} \times \{1,2,3\}). \end{aligned}$$

Note that each constraint forces the endpoints of every edge to take values that are either both in $\{1,2,3\}$ or both in $\{4,5\}$. A C_1 constraint says that they have to be different values if they are both in $\{4,5\}$. A C_2 constraint says that they have to be different values if they are both in $\{1,2,3\}$.

We let C_1 occur with probability q and C_2 occur with probability $1-q$ in $\mathcal{P}$. Set $c(q) = (1-q)/q$.

Fact 10 *(a) If $G_{n,p=c(q)/n}$ is a.s. 3-colourable, then $CSP_{n,p}(\mathcal{P})$ has a sharp threshold.*

(b) If there is some $\epsilon > 0$ such that $G_{n,p=(c(q)-\epsilon)/n}$ is a.s. not 3-colourable, then $CSP_{n,p}(\mathcal{P})$ has a coarse threshold.

Thus, determining the type of the threshold for all such models $CSP_{n,p}(\mathcal{P})$ requires the knowledge of for which values of c, $G(n, \frac{c}{n})$ is a.s. 3-colourable, and for which values it is a.s. not 3-colourable.

Proof Choose our $CSP_{n,p}(\mathcal{P})$ by first taking $G_{n,p=c/n}$ and then setting each edge to be C_1 with probability q and C_2 otherwise. Let G_1, G_2 be the subgraphs formed by the edges chosen to be C_1, C_2 respectively. If $c < 1$ then all components of $G_{n,p=c/n}$ are trees or unicycles and the CSP is trivially satisfiable. So we can focus on the range $c > 1$ and we let T denote the giant component of $G_{n,p=c/n}$. Note that the variables of T must either all take values from $\{1,2,3\}$ or all take values from $\{4,5\}$.

Case 1: $c > \frac{1}{q}$. Then G_1 is equivalent to $G_{n,p=c_1/n}$ for $c_1 = cq > 1$ and it follows easily that a.s. G_1 contains a giant component which is not 2-colourable. This giant component is a subgraph of T and so the variables of T must all take values from $\{1,2,3\}$. It follows that the CSP is satisfiable iff G_2 is 3-colourable. Note that G_2 is equivalent to $G_{n,p=c_2/n}$ for $c_2 = c \times (1-q) > c(q)$.

Case 2: $c < \frac{1}{q}$. Then G_1 is equivalent to $G_{n,p=c_1/n}$ for $c_1 = cq < 1$ and G_2 is equivalent to $G_{n,p=c_2/n}$ for $c_2 = c \times (1-q) < c(q)$. If G_2 is a.s. 3-colourable then the CSP is a.s. satisfiable. If G_2 is a.s.

not 3-colourable then the CSP is satisfiable iff T is 2-colourable; i.e., if G_1 does not have an odd cycle lying within T. Since $c_1 < 1$, G_1 is a random graph with edge-density below the critical point. So with probability at least some positive constant, it has no odd cycle at all, let alone one lying within T. On the other hand, the distribution of the number of triangles in G_1 is asymptotically Poisson with mean $c_1^3/6$ (see, eg Section 3.3 of [26]), and so the probability of containing at least one triangle tends to $1 - \epsilon^{-c_1^3/6}$. If we condition on u, v, w forming a triangle in G_1, then the probability that they are all in the giant component T is easily seen to not increase, and so is at least $(|T|/n)^3$ which tends to a positive constant. Therefore, the probability that G_1 has an odd cycle in T is at least some positive constant. This implies that the CSP is neither a.s. satisfiable nor a.s. unsatisfiable.

Fact 10 now follows. If $G_{n,p=c(q)/n}$ is a.s. 3-colourable, then $CSP_{n,p}(\mathcal{P})$ has a sharp threshold which lies somewhere above $\frac{1}{q}$. If there is some $\epsilon > 0$ such that $G_{n,p=(c(q)-\epsilon)/n}$ is a.s. not 3-colourable, then for all $\frac{1}{q} - \frac{\epsilon}{1-q} < c < \frac{1}{q}$, we are in Case 2 where $c_2 > c(q) - \epsilon$ and so G_2 is a.s. not 3-colourable. In that range of c, $CSP_{n,p=c/n}(\mathcal{P})$ is neither a.s. satisfiable nor a.s. unsatisfiable. So $CSP_{n,p}(\mathcal{P})$ has a coarse threshold running from $\frac{1}{q} - \delta$ to $\frac{1}{q}$ for some $\delta > \epsilon/(1-q)$. □

It is straightforward to adapt this example so that, instead of 3-colourability, we use any model $CSP_{n,p}(\mathcal{P})$ which has a sharp threshold. Suppose that $\mathcal{P}$ is over constraints of size k with domain-size d. We will create a distribution $\mathcal{P}'$ over constraints of size k and with domain-size $d+2$. All constraints will enforce:

(1) All k variables take values in $\{1, ..., d\}$ or all k variables take values in $\{d+1, d+2\}$.

Constraint C^* also enforces:

(2) The first two variables cannot both be $d+1$ and they cannot both be $d+2$

For each constraint $C_i \in \mathbf{supp}(\mathcal{P})$ we have a constraint C'_i which has the same restrictions as C_i, and also enforces (1). We set $\mathcal{P}'(C'_i) = (1-q)\mathcal{P}(C_i)$ and we set $\mathcal{P}'(C^*) = q$.

Note that if $\mathcal{P}$ is simply the 3-colouring CSP then this yields the example from above. Similar reasoning to that above shows that we cannot know which values of q yield a sharp threshold for $\mathcal{P}'$ without knowing the location of the threshold for $\mathcal{P}$. This yields Observation 2.

3 Homomorphisms

In this section, we prove Theorem 5 which concerns H-homomorphisms. Let $G_{n,p}^k$ denote the random k-uniform hypergraph on n vertices where each k-tuple is present as a hyperedge with probability p.

We begin with a technical lemma:

Lemma 11 *Let H be a connected graph which contains a triangle. Let u be a vertex of H and M be a unicyclic graph with unique cycle C. Denote the vertices of M in a distance of exactly $r \geq |V(H)| + 3$ from C by U. There is a homomorphism from M to H such that all vertices in U are mapped to u.*

Proof. Let h be a homomorphism from C to the triangle (v_1, v_2, v_3) of H. Observe that for $i = 1, 2, 3$, there exist walks $(v_i =)v_{i,0}, \ldots, v_{i,r}(= u)$ of length exactly r in H. Let w be a vertex in M in the distance of $j \leq r$ from C, and w' be the vertex of C which has the distance j from w. Extend h by assigning $h(w) = v_{ij}$ where $h(w') = v_i$. Observe that h is a partial homomorphism from M to H which maps every vertex in U to u. Trivially h can be extended to a homomorphism from M to H. ■

Proof of Theorem 5. Let H be some k-uniform hypergraph, and assume that the H-homomorphism problem has a coarse threshold. Let M, p, α, ϵ be as guaranteed by Corollary 7. In this setting, M is a k-uniform unicyclic hypergraph, such that adding M to $G^k_{n,p}$ boosts the probability of not having a homomorphism to H by at least 2α.

Our strategy will be to show that adding M to $G^k_{n,p}$ does not increase the probability of not having a homomorphism to H by more than adding a copy of $G^k_{n,z}$ for some $z(n) = o(n^{1-k})$. We are assuming that the former boosts that probability to at least $1 - \alpha$ and thus so must the latter. But that will contradict Corollary 7(b). To show this, we will construct a hypertree T such that the probability that $G^k_{n,p} \oplus M$ has no homomorphism to H is at most the probability that $G^k_{n,p} \oplus T$ has no homomorphism to H. Then we simply apply Lemma 9 to obtain our desired z.

We begin with the case $k \geq 3$.

Consider $G = G^k_{n,p} \oplus M$. Let M^+ be the subgraph of G consisting of all hyperedges that contain at least one vertex of M (and, of course all vertices in those hyperedges); in other words, M^+ is the subhypergraph induced by the vertices of M and all their neighbours. Lemma 8 implies that there is some constant L such that, defining E to be the event that "M^+ is unicyclic and has at most L vertices, no hyperedge of $G^k_{n,p}$ contains more than one vertex of M, and the vertices of distance at most 2 from M^+ induce a forest", we have $\mathbf{Pr}(E) \geq 1 - \frac{\alpha}{2}$.

Since M is unicylic and $k \geq 3$, by Lemma 4(a) there exists a homomorphism h from M to a single edge, say $(v_1, \ldots, v_k)$. Let h_i be the set of the vertices in M that are mapped by h to v_i. Obtain the hypergraph G' from G by (i) removing all edges in M; (ii) contracting all of the vertices in h_i into one single new vertex u_i, for each $1 \leq i \leq k$; (iii) adding the single hyperedge $(u_1, \ldots, u_k)$.

Suppose that h' is a homomorphism from G' to H. Then a mapping from the vertices of G to the vertices of H which maps every vertex v in $G - M$ to $h'(v)$, and every vertex in h_i to $h'(u_i)$ is a homomorphism from G to H. Thus, if G' is homomorphic to H then so is G.

We define our hypertree T as follows: T has a hyperedge $(t_1, ..., t_k)$, and each t_i lies in L other hyperedges. Only $t_1, ..., t_k$ lie in more than one edge of T. Thus, T has $k + k(k-1)L$ vertices and $kL+1$ hyperedges. If E holds, then the subgraph of G' induced by all edges containing $\{u_1, \ldots, u_k\}$ forms a tree; note that it is a subtree of T. It follows that $G^k_{n,p} \oplus T$ is at least as likely to be non-homomorphic to H as G' is, so:

$$\begin{aligned}
\Pr[G^k_{n,p} \oplus M \text{ is not homomorphic to } H] &\leq \Pr[G^k_{n,p} \oplus M \text{ is not homomorphic to } H|E] + \mathbf{Pr}(\overline{E}) \\
&\leq \Pr[G^k_{n,p} \oplus T \text{ is not homomorphic to } H] + \frac{\alpha}{2}.
\end{aligned}$$

By Lemma 9, there is some $z = o(n)$ such that increasing p by an additional z a.s. results in the addition of a copy of T. Thus for every $\epsilon > 0$:

$$\Pr[G^k_{n,p} \oplus T \text{ is not homomorphic to } H] \leq \Pr[G^k_{n,(1+\epsilon)p} \text{ is not homomorphic to } H]$$

which yields a contradiction to Corollary 7(b).

This proves the case where $k \geq 3$, so we now turn to the case $k = 2$. If H contains no triangle, then K_3 is not homomorphic to H. Thus, K_3 forms a unicyclic unsatisfiable CSP using the H-colouring constraints and so we do not have a sharp threshold, since for any $0 < c < \frac{1}{2}$:(i) with probability at least some positive constant, $G_{n,p=c/n}$ is a forest, and hence has a homomorphism to H; and (ii) with probability at least some positive constant, $G_{n,p=c/n}$ contains a triangle and hence has no homomorphism to H. So we will focus on graphs H that contain a triangle. Our proof follows along the same lines as the case $k \geq 3$, but is complicated a bit since we can no longer assume that M is homomorphic to a single edge. We only highlight the differences.

Define M^+ to be the subgraph of $G = G^k_{n,p} \oplus M$ induced by all vertices within distance $r = |V(H)| + |V(M)| + 3$ of the unique cycle of M. By Lemma 8 there is some constant L such that with probability at least $1 - \frac{\alpha}{2}$: M^+ is unicyclic and has at most L vertices, no hyperedge of $G^k_{n,p}$ contains more than one vertex of M, and the vertices of distance at most 2 from M^+ induce a forest.

Define U to be the set of vertices of G that are of distance exactly $r = |V(H)| + |V(M)| + 3$ from the unique cycle of M. Consider any vertex $u \in H$. By Lemma 11, if M^+ is unicyclic then there is a homomorphism from M^+ to H such that all vertices in U are mapped to u.

Obtain the graph G' from G by (i) removing all of the vertices of distance less than r from the unique cycle of M, and (ii) contracting U into a single new vertex u. Suppose that h' is a homomorphism from G' to H. Then by the previous paragraph, h' can be extended to a homomorphism from G to H where each vertex $v \in V(G') - u$ is mapped to $h'(v)$, and every vertex in U is mapped to $h'(u)$. Thus, if G' is homomorphic to H then so is G.

We now define T to be the tree which consists of a vertex adjacent to L leaves. Since the degree of u in G' is at most L, and using the fact that all vertices of M are deleted when forming G' (here is where we require $r > |M|$), the rest now follows as in the $k \geq 3$ case. $\square$

3.1 Disconnected Graphs

In this subsection we discuss the possibilities of extending Theorem 5 to the case where H is disconnected. We will focus on graphs, i.e. the $k = 2$ case.

When considering disconnected graphs, it is helpful to note that if the H'-homomorphism problem has a sharp threshold for every component H' of H, then the H-homomorphism problem has a sharp threshold. In fact, it is simply the smallest of the thresholds for its components. To see this, note first that for each component H', since the H'-homomorphism problem has a sharp threshold, every tree or unicyclic graph must have a homomorphism to H'. $G_{n,p=c/n}$ a.s. has at most one component with more than one cycle (i.e. a giant component). So a.s. $G_{n,p}$ is homomorphic to H iff either (i) there is no giant component or (ii) the giant component is homomorphic to H. Since the giant component is connected, it is homomorphic to H iff it is homomorphic to at least one component of H. That giant component will a.s. be homomorphic to at least one component of H iff it is a.s. homomorphic to the one with the smallest satisfiability threshold.

We now show that if there is at least one graph H such that Hypothesis A does not hold for the H-homomorphism problem, then there must be such a graph with two components: a triangle and a graph that is triangle-free and not 3-colourable.

Assume that Hypothesis A does not hold for H. That is, every unicyclic graph has a homomorphism to H, and the H-homomorphism problem has a coarse threshold.

First note that a triangle is not homomorphic to any triangle-free graph. Also, Lemma 4(b) says that every unicyclic graph is homomorphic to a triangle. So "every unicyclic graph has a homomorphism to H" is equivalent to "H contains a triangle".

Since the H-homomorphism problem has a coarse threshold, there is some component H_i of H, such that the H_i-homomorphism problem has a coarse threshold. By Theorem 5, H_i has no triangle.

Let H^1 be the subgraph of H which consists of all triangle-free components and H^2 be the subgraph consisting of the remaining components of H; we have argued that neither H^1 nor H^2 is empty. Since each component H_i of H^2 has a triangle, Theorem 5 implies that the H_i-homomorphism problem has a sharp threshold. Therefore, the H^2-homomorphism problem has a sharp threshold.

Suppose that H^1 is 3-colourable. Then every graph homomorphic to H^1 is also homomorphic to a triangle, and hence is homomorphic to H^2. It follows that being homomorphic to H is equivalent to being homomorphic to H^2. But this contradicts the facts that H-homomorphism has a coarse threshold and H^2-homomorphism has a sharp threshold. Therefore $\chi(H^1) > 3$.

Also, we know that H^1-homomorphism has a coarse threshold since H^1 is triangle-free.

Let $c_3(n)$ denote the 3-colourability threshold, and let $c'(n)$ be the H^2-homomorphism threshold. Every 3-colourable graph is homomorphic to a triangle and thus is homomorphic to H^2. Therefore $c'(n) \geq c_3(n)$. For every $c < c'(n)$, $G_{n,p=c/n}$ a.s. has a homomorphism to H^2 and hence to H. Since

H-homomorphism has a coarse threshold, there must be some $c = c(n) > c'(n)$ for which $G_{n,p=c/n}$ is not a.s. non-H-homomorphic. With probability bounded away from zero, the non-giant components of $G_{n,p=c/n}$ are trees and hence are homomorphic to H^1 and H^2. Therefore a.s. the giant component of $G_{n,p=c/n}$ is not H^2-homomorphic as otherwise $G_{n,p=c/n}$ would not be a.s. non-H^2-homomorphic. Therefore the giant component must not be a.s. non H^1-homomorphic as otherwise $G_{n,p=c/n}$ would be a.s. non-H-homomorphic. Therefore $G_{n,p=c/n}$ is not a.s. non-H^1-homomorphic.

Replacing H^2 by a triangle has the effect of replacing $c'(n)$ by $c_3(n)$. Since this does not increase $c'(n)$, we still have some $c^* = c^*(n) > c'(n)$ for which $G_{n,p=c^*/n}$ is not a.s. non-H^1-homomorphic. If H^1 is disconnected, add some edges so that it is connected but remains triangle-free; call the resulting subgraph $(H^1)'$, and call the resulting graph, i.e. $(H^1)'$ plus a triangle component, H'. Any graph that is H^1-homomorphic is $(H^1)'$-homomorphic and so $G_{n,p=c^*/n}$ is not a.s. non-$(H^1)'$-homomorphic. Since H^1 is triangle-free, Theorem 5 implies that $(H^1)'$-homomorphism has a coarse threshold. The range of this threshold either includes $c^*(n)$ or lies higher than $c^*(n)$; either way, it contains a range of values that is higher than $c_3(n)$. In that range of values of c, $G_{n,p=c^*/n}$ a.s. has no homomorphism to the triangle component of H'. It follows that that range of values lies within the range of a coarse threshold for H'.

Therefore, H' has a triangle but H'-homomorphism has a coarse threshold and so violates Hypothesis A.

So the question of whether there is any undirected graph H for which the H-homomorphism problem violates Hypothesis A is equivalent to the following:

Question 12 *Is there any triangle-free graph H_1 with $\chi(H_1) > 3$ such that for some values of n and some $c > c_3(n)$, $G_{n,p=c/n}$ is not a.s. non-H_1-homomorphic, where $c_3(n)$ is the threshold value of 3-colorability?*

3.2 Directed Graphs

Earlier in this section, we discussed whether there exist any connected graphs H for which the H-homomorphism problem violates Hypothesis A. Now we turn our attention to directed graphs. We provide an example of a disconnected directed graph H which comes close to violating Hypothesis A. It has the properties:

1. every unicyclic digraph has a homomorphism to H, and
2. the H-homomorphism problem under the $\widehat{CSP}_{n,p}(\mathcal{P})$ model has a coarse threshold.

This does not actually violate Hypothesis A. The coarse threshold is under the $\widehat{CSP}_{n,p}(\mathcal{P})$ model rather than the $CSP_{n,p}(\mathcal{P})$ model.

For a directed graph D, let $\tilde{D}$ denote the undirected graph that is obtained from D by removing the directions from the edges and then replacing each double edge by a single edge. We define $D_{n,p}$ to be the random digraph on n vertices where each of the $n(n-1)$ potential directed edges is present with probability p. Thus $D_{n,p}$ possibly contains both edges uv and vu for some pair of vertices v, u, i.e. a 2-cycle; in fact, if $p = c/n$ for a constant c, then it is straightforward to show that the probability that D contains at least one 2-cycle is $\zeta + o(1)$ for some constant $\zeta = \zeta(c) < 1$. This is the reason that we need to use the $\widehat{CSP}_{n,p}(\mathcal{P})$ model rather than the $CSP_{n,p}(\mathcal{P})$ model; the digraphs formed by the $CSP_{n,p}(\mathcal{P})$ model cannot have any 2-cycles since they cannot have more than one constraint on the same pair of variables.

H consists of a specific connected digraph H_1, defined below, and a pair of vertices u_1, u_2, where the edges u_1, u_2 and u_2, u_1 are both present. There are no edges between $\{u_1, u_2\}$ and H_1. H_1 has the following properties:

(i): every unicyclic digraph which does not contain a 2-cycle a.s. has a homomorphism to H_1; and

(ii): For some $c_1 > 1/2$, $D_{n,p=c_1/n}$ is not a.s. non-H_1-homomorphic.

It is easy to see that any unicyclic digraph, whose cycle is a 2-cycle, has a homomorphism to the 2-cycle. By (i), every other unicyclic digraph has a homomorphism to H_1. Thus, every unicyclic digraph has an H-homomorphism, as claimed. We will show that, for every $1/2 < c < c_1$, $D_{n,p=c/n}$ is neither a.s. H-homomorphic nor a.s. non-H-homomorphic. Thus, we have a coarse threshold. Condition (ii) above implies the latter, so we just need to prove the former.

The graph $\tilde{D}$ for $D = D_{n,p}$, a.s. has a giant component, since it is equivalent to $G_{n,p}$ where $p = 1-(1-\frac{c}{n})^2 = \frac{2c}{n} - o(\frac{1}{n})$ and $2c > 1$. The number of 2-cycles in D are easily shown to have a Poisson distribution with constant mean, using the same analysis as in, eg., Section 3.3 of [26]. Also, each edge of $\tilde{D}$ is equally likely to correspond to a 2-cycle in D. Therefore, with probability bounded away from zero, D has a 2-cycle which lies in the giant component of $\tilde{D}$. It is not hard to see that a.s. if D has such a 2-cycle then there is no H-homomorphism: That 2-cycle must be mapped onto u_1, u_2. Since H has no edges between H_1 and $\{u_1, u_2\}$, any vertex that can be reached in $\tilde{D}$ from that 2-cycle must also be mapped onto u_1 or u_2. So the entire giant component must be mapped onto $\{u_1, u_2\}$. It is well-known that a.s. a giant component is not 2-colourable and hence has an odd cycle. (This follows, eg. from the facts that: (i) $\tilde{D}$ is a.s. not 2-colourable and (ii) with probability at least some positive constant, all components of $\tilde{D}$ other than the giant one are trees and hence 2-colourable.) Thus a.s. $\tilde{D}$ has an odd cycle and no odd cycle can be mapped onto a 2-cycle. Therefore, D is not a.s. H-homomorphic.

It remains only to prove the existence of some H_1 satisfying (i), (ii). We will choose H_1 to be a tournament (i.e. for every pair of vertices, exactly one of the possible edges between them is present) which contains every loopless 2-cycle-free directed graph on k_0 vertices as a subgraph where k_0 is a constant defined below. This can be done trivially if $|H_1| \geq k_0 2^{\binom{k_0}{2}}$; simply place each tournament on k_0 vertices on a different set of vertices of H_1.

For an undirected graph G which does not contain any multiple edges, the *oriented chromatic number* χ_o of G is the minimum number k such that every loopless 2-cycle-free directed graph D satisfying $\tilde{D} = G$ is homomorphic to a loopless 2-cycle-free directed graph H with at most k vertices. The *acyclic chromatic number* of a graph G is the least integer k for which there is a proper coloring of the vertices of G with k colors in such a way that every cycle of G contains at least 3 different colors. It was proved in [33] that if the acyclic chromatic number of a graph G is at most k, then its oriented chromatic number is at most $k \times 2^{k-1}$. We also need the following:

Lemma 13 *There exists a number $c > 1$ such that a.s. the acyclic chromatic of $G_{n,p=c/n}$ is at most 5.*

Proof. Let $G = G_{n,p}$. A *pendant* path in G is a path in which no vertices other than the endpoints lie in any edge of the graph off the path. It was proven in [29] (see the proof of Lemma 6) that there exists $c > 1$ such that a.s. after removing the internal vertices of pendant paths of length at least 4 from G every component is either a tree or it is unicyclic. One can use 3 colors to color the vertices in these components and then use 2 other colors to color the removed vertices such that every cycle in G is colored by at least 3 colors. ■

When $D = D_{n,p=c_1/n}$ every edge is present in $\tilde{D}$ with probability $2p - p^2$ and independent of the other edges. Thus, if $c_1 = c/2$, where c is the constant obtained from Lemma 13, a.s. the acyclic chromatic number of $\tilde{D}$ is at most 5 and so $\chi_o(\tilde{D}) \leq 5 \times 2^4 = k_0$. Therefore, a.s. if D is 2-cycle-free then D is homomorphic to some loopless 2-cycle-free digraph H on at most k_0 vertices. Since every such H is a subgraph of H_1, this would mean D is homomorphic to H_1. Since D does not a.s. have a 2-cycle, this establishes that H_1 satisfies (ii).

4 The (d,k,t)-model

In this section, we prove Theorem 3 which says that the (d,k,t)-model has a sharp threshold whenever $d,k \geq 2$ and $1 \leq t < d^{k-1}$; i.e. whenever d,k,t are not such that the model is a.s. unsatisfiable for all $c > 0$.

Proof of Theorem 3 Suppose that the (d,k,t)-model exhibits a coarse threshold. Then consider p,α,ϵ and M as guaranteed by Corollary 7. As in the proof of Theorem 5, we will find some hypertree T such that adding T to the random CSP increases the probability of unsatisfiability by a constant. This time, adding T may not boost the probability as much as M does; but it will boost it by a small constant, and that will be enough.

Gent et.al.[19] proved that for $k=2$: if $t < d^{k-1}$ and M is unicyclic, then M is satisfiable (see their Theorem 1 and Corollaries 1 and 2). Their argument easily extends to the case where $k \geq 3$. So we can assume that M is satisfiable. Suppose that $V(M) = u_1,...,u_r$ and let a_i be the value of u_i in some particular satisfying assignment A of M. Given a CSP F on at least r variables, we define $F \oplus A$ to be the CSP formed by choosing a random ordered r-tuple of variables $v_1,...,v_r$ in F and for each $1 \leq i \leq r$, forcing v_i to take the value a_i by adding a one-variable constraint on v_i. Clearly the probability that $\widehat{CSP}_{n,p}(\mathcal{P}) \oplus A$ is unsatisfiable is at least as high as the probability that $\widehat{CSP}_{n,p}(\mathcal{P}) \oplus M$ is unsatisfiable.

Lemma 8 implies that there exists some constant L such that, defining E_1 to be the event that "every v_i has at most L neighbours and no hyperedge contains two v_i, v_j", $\mathbf{Pr}(E_1) \geq 1 - \frac{\alpha}{2}$. Suppose that E_1 holds.

Consider a particular v_i and expose the $\ell \leq L$ edges containing it, $e_1,...,e_\ell$ and the corresponding constraints $C_1,...,C_\ell$. For each C_j, let C'_j be the $(k-1)$-variable constraint obtained by restricting v_i to be a_i; i.e. a $(k-1)$-tuple of values is permitted for C'_j iff C_j permits that same $(k-1)$-tuple along with $v_i = a_i$. Thus, we can remove C_j and add the constraint C'_j on the $k-1$ other variables. After doing so for every C_j, we can remove the restriction that $v_i = a_i$, since v_i no longer lies in any constraints. (Note that, since E_1 holds, no constraint will contain some pair v_i, v_j and thus be reduced twice.)

It is useful now to consider choosing $\widehat{CSP}_{n,p}(\mathcal{P}) \oplus A$ by first selecting the random variables $v_1,...,v_r$ and then choosing $\widehat{CSP}_{n,p}(\mathcal{P})$. Thus, carrying out the operation described in the previous paragraph is equivalent to, for each v_i: expose ℓ, choose ℓ random $(k-1)$-tuples of variables from $V - \{v_1,...,v_r\}$; for each selected $(k-1)$-tuple, choose a random C_j with exactly t restrictions and place C'_j on the $(k-1)$-tuple; then remove v_i. Note that since C_j has t restrictions, C'_j has at most t restrictions.

For convenience, we modify the experiment in a manner that increases the probability of unsatisfiability. For each v_i, instead of randomly exposing ℓ, we simply assume $\ell = L$; i.e. we choose L random $(k-1)$-tuples. Next, if C'_j has fewer than t restrictions, we add more restrictions to it so that it has exactly t restrictions. Our final modification is that instead of picking a random $(k-1)$-tuple and randomly selecting C'_j as described above, we choose $\binom{d^{k-1}}{t}$ random $(k-1)$-tuples and place each of the $\binom{d^{k-1}}{t}$ possible constraints on $k-1$ variables and with t restrictions on one of the $(k-1)$-tuples. The last modification may appear to be a bit of an overkill, but it has the (minor) convenience that the added constraints are not randomly selected. Finally, we wish to do without the fact that $v_1,...,v_r$ are not permitted to be selected as members of the $(k-1)$-tuples. So we choose the $(k-1)$ tuples randomly from amongst all vertices and let E_2 be the event that none of them use any of the vertices in $v_1,...,v_r$. Since $r = O(1)$ and we are choosing a total of $O(1)$ $(k-1)$-tuples, $\mathbf{Pr}(E_2) = 1 - O(n^{-1})$.

So we let G be a random CSP formed as follows: start with a random $\widehat{CSP}_{n,p}(\mathcal{P})$ and then for each of the $\binom{d^{k-1}}{t}$ possible constraints on $k-1$ variables and with t restrictions, choose rL random ordered $(k-1)$-tuples of variables and place that constraint on them. $\mathbf{Pr}(G \text{ is unsatisfiable} | E_2) \geq \mathbf{Pr}(\widehat{CSP}_{n,p}(\mathcal{P}) \oplus A$ is unsatisfiable , as described in the preceding paragraph. Since $\mathbf{Pr}(E_2) = 1 - o(1)$, this implies that adding those $\binom{d^{k-1}}{t} rL$ constraints boosts the probability of unsatisfiability by at least

$2\alpha - o(1)$. We say that a collection of $\binom{d^{k-1}}{t} rL$ $(k-1)$-tuples is *bad* if adding the constraints to that set results in an unsatisfiable CSP. So, consider the following random experiment: pick a random $\widehat{CSP}_{n,p}(\mathcal{P})$ and then pick $\binom{d^{k-1}}{t} rL$ ordered $(k-1)$-tuples of the variables. The probability that we pick a bad collection is at least 2α. Since $\binom{d^{k-1}}{t} rL = O(1)$, a simple first moment calculation shows that a.s. the choice of $(k-1)$-tuples will be vertex disjoint. Thus, the probability of picking a bad collection is at least $2\alpha - o(1)$ even if we condition on the $(k-1)$-tuples being vertex-disjoint.

Now we are finally ready to define our hypertree T as follows: (i) take the hypergraph consisting of a vertex v lying in $rL\binom{d^k}{t}$ edges where no other vertex lies in more than one of the edges (i.e. a star), and (ii) place each of the $\binom{d^k}{t}$ possible (d,k,t)-constraints on rL of the edges. This, of course, is where we take advantage of the fact that we are using the (d,k,t)-model.

Now consider adding a copy of T to $\widehat{CSP}_{n,p}(\mathcal{P})$. For each $1 \le \delta \le d$, let T_δ denote the collection of $(k-1)$-tuples obtained by removing v from every edge of T that contains a constraint in which every restriction has $v = \delta$; note that T_δ consists of rL copies of every constraint on $k-1$ variables with exactly t restrictions and so $|T_\delta| = \binom{d^{k-1}}{t} rL$. The probability that for each $1 \le \delta \le d$, T_δ is a bad set is at least $(2\alpha - o(1))^d$. Note that if every T_δ is a bad set, then the resulting CSP is unsatisfiable because setting $v = \delta$ requires the set of $(k-1)$-constraints on T_δ to be enforced.

So by Lemma 9, there is some $z = o(n^{1-k})$ such that the probability that $\widehat{CSP}_{n,p=p+z}(\mathcal{P})$ is unsatisfiable is at least $(2\alpha - o(1))^d$. By considering adding x copies of T, we see that the probability that $\widehat{CSP}_{n,p=p+xz}(\mathcal{P})$ is satisfiable is at most $(1-(2\alpha - o(1))^d)^x$ which is less than α for some sufficiently large constant x. Since $z = o(n^{1-k})$, this implies that $\mathbf{Pr}(\widehat{CSP}_{n,(1+\epsilon)p}(\mathcal{P})$ is unsatisfiable$) > 1-\alpha$ which contradicts Corollary 7(b). □

5 Binary CSP's with domain size 3

Recall that the arguments from Istrate[25] and from Creignou and Daudé[10] can show that when the domain size $d = 2$, then Hypothesis A holds; i.e. if every unicyclic CSP is satisfiable, then $CSP_{n,p}(\mathcal{P})$ has a sharp threshold. This result does not extend to $d = 3$. Consider the following example, with $d = 3, k = 2$:

Example 14 *We have two constraints. C_1 says that either both variables are equal to 1, or neither is equal to 1. C_2 says that the variables cannot both have the same value. $\mathcal{P}(C_1) = \frac{2}{3}, \mathcal{P}(C_2) = \frac{1}{3}$.*

Observe that every unicyclic CSP that uses only constraints C_1, C_2 is satisfiable.

Consider any $\frac{3}{2} < c < 3$. Thus, a.s. the sub-CSP formed by the C_1 constraints has a giant component, and the sub-CSP formed by the C_2 constraints does not. We will show that $CSP_{n,p}(\mathcal{P})$ is neither a.s. satisfiable nor a.s. unsatisfiable.

To see that it is not a.s. unsatisfiable, note that the subgraph induced by the C_2 constraints is 2-colourable with probability at least some positive constant. This follows from the well known fact[13] that for $c < 1$ the random graph $G(n, \frac{c}{n})$ is a forest with probability at least some positive constant. If it is 2-colourable, then we can satisfy all the C_2 constraints by assigning every variable either 2 or 3; this will not violate any C_1 constraints.

To see that it is not a.s. satisfiable, note that the subgraph formed by the C_1 constraints has a giant component T. So either every variable in T is assigned 1 or none of them are. A.s. at least one C_2 constraint has both variables in T, and so they cannot both be assigned 1. Thus, a.s. no variables in T can be assigned 1. This implies that if the C_2 constraints form an odd cycle using variables of T then the CSP is not satisfiable. That event occurs with probability at least some positive constant, because the graph formed by the C_2 constraints that use only variables of T is $G_{n',\frac{1/3}{n'}}$ where $n' = |T| = \Theta(n)$ and so it is not 2-colourable with probability at least some positive constant.

It is instructive to look at this example in light of Corollary 7. Here, the subgraph M is a triangle whose edges are all C_2 constraints. If M appears, then at least one of its variables must be assigned the value 1. However, with probability at least some $\zeta > 0$, the remainder of the CSP has a structure implying that if at least one of those variables has the value 1 then some specific set of $\Theta(n)$ other variables all must be assigned the value 1. But a.s. there is a C_2 constraint between at least two of those variables and thus they can't all be assigned 1. This enables the appearance of M to boost the probability of unsatisfiability by at least some positive constant.

The main result of this section shows that when $d = 3$ and $k = 2$, if Hypothesis A fails on some model, then there must be an M as in Corollary 7 whose presence boosts the probability of unsatisfiability for essentially the same reason as that in Example 14.

Before presenting our theorem, we begin with a few preliminaries. To simplify, we will take $k = 2$.

Consider a CSP where every constraint is on 2 variables. Suppose there is some constraint on variables v, u which implies that if v is assigned δ then u must be assigned γ; we say that $v : \delta \to u : \gamma$. Moreover if there is a sequence of variables $v_1, \ldots, v_r$ and values $\delta_1, \ldots, \delta_r$ such that $v_i : \delta_i \to v_{i+1} : \delta_{i+1}$ for $i = 1, \ldots, r-1$ then we say that $v_1 : \delta_1 \to v_r : \delta_r$.

For each variable v and each pair of (possibly equal) values δ, γ we define $F_{\delta,\gamma}(v)$ to be the set of variables u such that $v : \delta \to u : \gamma$, and we define $F_\delta(v) = \cup_{1 \le \gamma \le d} F_{\delta,\gamma}(v)$. Thus $F_\delta(v)$ is the set of variables u such that if v is assigned δ then there is *a path of constraints* which imply that u must be assigned a particular value. Assigning δ to v may force assignments to other variables w via a combination of more than one path of constraints. But the locally tree-like nature of $CSP_{n,p}(\mathcal{P})$ will imply that such variables are not a significant concern.

In $CSP_{n,p}(\mathcal{P})$, we can expose $F_\delta(v)$ by using a simple breadth-first search from v. This allows us to analyze the distribution of the size of $F_\delta(v)$ and $F_{\delta,\gamma}(v)$ using a standard branching-process analysis (see e.g. Chapter 5 of [26]). Straightforward branching-process arguments yield:

Lemma 15 *With the exception of at most d^2 constants c, if $p = (c + o(1))/n$ then for every pair δ, γ, one of these cases holds:*

(a) $\mathbf{Exp}(|F_{\delta,\gamma}(v)|) = O(1)$*; or*

(b) $\mathbf{Exp}(|F_{\delta,\gamma}(v)|) = \Theta(n)$.

We omit the standard proofs. We remark only that those d^2 constants are the so-called *critical points* for each $F_{\delta,\gamma}$.

We say that $F_{\delta,\gamma}$ is *subcritical* if case (a) holds and *supercritical* if case (b) holds. We say that F_δ is *supercritical* if $F_{\delta,\gamma}$ percolates for at least one γ, and is *subcritical* otherwise. Markov's Inequality immediately implies:

Lemma 16 *(a) If $F_{\delta,\gamma}$ is subcritical, then for every $\xi > 0$ there is a constant L such that* $\mathbf{Pr}(|F_{\delta,\gamma}(v)| \le L) > 1 - \xi$.

(b) If $F_{\delta,\gamma}$ is supercritical, then there are constants $\zeta, \beta > 0$ such that $\mathbf{Pr}(|F_{\delta,\gamma}(v)| \ge \beta n) > \zeta$.

We can now state the main result of this section:

Theorem 17 *Consider some $\mathcal{P}$ with $d = 2, k = 3$ such that $CSP_{n,p}(\mathcal{P})$ has a coarse threshold and every unicyclic CSP formed from* $\mathbf{supp}(\mathcal{P})$ *is satisfiable. Then there exist p, α, ϵ, M as in Corollary 7 such that for some value $1 \le \delta \le 3$ we have:*

(a) *M cannot be satisfied using only the two values other than δ; and*

(b) *$F_{\delta,\delta}$ is supercritical.*

E.g., in Example 14 we can take M to be a triangle of C_2 constraints and $\delta = 1$.

This theorem does not extend to $d = 4, k = 2$ nor $d = 3, k = 3$; in each of these cases, we have counterexamples. Before proving our theorem, we start with a helpful lemma.

Lemma 18 *Suppose $p = (c + o(1))/n$ where c is not one of the 9 exceptional constants from Lemma 15. If F_δ is supercritical then either (i) $F_{\delta,\delta}$ is supercritical or (ii) there is some μ such that $F_{\mu,\mu}$ is supercritical and there is a sequence of constraints in* $\mathbf{supp}(\mathcal{P})$ *through which $v : \delta \to u : \mu$.*

Proof: If $F_{\delta,\delta}$ is supercritical then (i) holds; so assume otherwise. Thus there is some $\gamma \neq \delta$ such that $F_{\delta,\gamma}$ is supercritical. Thus there is a sequence of constraints in $\mathbf{supp}(\mathcal{P})$ through which $v : \delta \to u : \gamma$. So if $F_{\gamma,\gamma}$ is supercritical then (ii) holds with $\mu = \gamma$; so assume otherwise.

Let α be the third value. Consider any vertex v and any constant $\zeta > 0$.

Case 1: there is no sequence of constraints in $\mathbf{supp}(\mathcal{P})$ *through which $v : \delta \to u : \alpha$.* Thus $F_{\delta,\alpha}(v) = \emptyset$. By Lemma 16(a) there is some constant L_1 such that with probability at least $1 - \zeta/3$, $|F_{\delta,\delta}(v)| \leq L_1$. If that bound holds, then by Lemma 8, there is a constant L_2 such that with probability at least $1 - \zeta/3$, the set of variables u such that there is some $w \in F_{\delta,\delta}(v)$ and some constraint implying $w : \delta \to u : \gamma$ has size at most L_2; call the set of such variables X. If that second bound holds, then applying Lemma 16(a) again, there is a constant L_3 such that with probability at least $1 - \zeta/3$, $| \cup_{x \in X} F_{\gamma,\gamma}(x)| < L_3$. Therefore, with probability at least $1 - \zeta$, $|F_{\delta,\gamma}(v)| < L_3$; since this holds for every $\zeta > 0$, this contradicts Lemma 16(b) and the fact that $F_{\delta,\gamma}$ is supercritical.

Case 2: there is a sequence of constraints in $\mathbf{supp}(\mathcal{P})$ *through which $v : \delta \to u : \alpha$.* Then the same argument that showed $F_{\gamma,\gamma}$ is subcritical shows that $F_{\alpha,\alpha}$ is also subcritical. We proceed as in Case 1:

By Lemma 16(a) there is some constant L_1 such that with probability at least $1 - \zeta/5$, $|X| \leq L_1$. If that bound holds, then by Lemma 8, there is a constant L_2 such that with probability at least $1 - \zeta/5$, the set of variables u such that there is some $w \in F_{\delta,\delta}(v)$ and some constraint implying $w : \delta \to u : \alpha$ has size at most L_2; call the set of such variables X_1. If that second bound holds, then applying Lemma 16(a) again, there is a constant L_3 such that with probability at least $1 - \zeta/5$, $| \cup_{x \in X_1} F_{\alpha,\alpha}(x)| < L_3$. If that bound holds, then again by Lemma 8, there is a constant L_4 such that with probability at least $1 - \zeta/5$, the set of variables u such that either (i) there is some $w \in F_{\delta,\delta}(v)$ and some constraint implying $w : \delta \to u : \gamma$ or (ii) there is some $w \in \cup(\cup_{x \in X_1} F_{\alpha,\alpha}(x))$ and some constraint implying $w : \alpha \to u : \gamma$ has size at most L_4; call the set of such variables X_2. Finally, if all those bounds hold, then applying Lemma 16(a) again, there is a constant L_5 such that with probability at least $1 - \zeta/5$, $| \cup_{x \in X_2} F_{\gamma,\gamma}(x)| < L_5$. Therefore, with probability at least $1 - \zeta$, $|F_{\delta,\gamma}(v)| < L_5$; since this holds for every $\zeta > 0$, this contradicts Lemma 16(b) and the fact that $F_{\delta,\gamma}$ is supercritical. □

We are now ready to prove our theorem.

Proof of Theorem 17: Suppose that $\widehat{CSP}_{n,p}(\mathcal{P})$ has a coarse threshold and consider $M, \epsilon, \alpha, p = p(n)$ from Corollary 7. If $p = (c + o(1))/n$ where c is one of the 9 exceptional constants from Lemma 15, then we can increase p by some small ϵ'/n, and decrease ϵ slightly, so that the conditions of Corollary 7 still hold. This allows us to apply Lemmas 15, 18.

As defined in [31], a value $1 \leq \delta \leq 3$ is *bad* if there is a constraint in $\mathbf{supp}(\mathcal{P})$ which forbids a variable from receiving δ; i.e. if there is a constraint C which contains the restrictions $(\delta, 1), (\delta, 2), (\delta, 3)$ or the restrictions $(1, \delta), (2, \delta), (3, \delta)$. A value δ is also said to be bad if there is a sequence of constraints in $\mathbf{supp}(\mathcal{P})$ joining variables u, v for which $v : \delta \to u : \gamma$ where γ is a bad value. It is easy to see that if there is a unicyclic CSP M formed from the constraints of $\mathbf{supp}(\mathcal{P})$ such that every satisfying assignment to M uses at least one bad value, then M can be modified to an unsatisfiable unicyclic CSP

M' formed from $\mathbf{supp}(\mathcal{P})$: we simply attach paths of constraints to each variable of M which forbid those variables from receiving any bad values. (See [31] for the details.) Therefore, if every unicyclic CSP formed from $\mathbf{supp}(\mathcal{P})$ is satisfiable, then every such CSP can be satisfied without using any bad values. Thus, M can be satisfied without using any bad values.

Case 1: There is a value δ such that (i) every satisfying assignment of M must use δ or a bad value on at least one variable and (ii) F_δ is supercritical.

If there are any bad values, then the above construction produces a unicyclic $M' \supset M$ such that every satisfying assignment of M' must use δ on at least one variable. (Otherwise, set $M' = M$.) If $F_{\delta,\delta}$ is supercritical then M', δ satisfy Theorem 17. Otherwise, by Lemma 18, there is a value $\mu \neq \delta$ such that $F_{\mu,\mu}$ is supercritical and there is a sequence of constraints so that $v : \delta \to u : \mu$. Attaching that sequence to every variable of M' yields a unicyclic CSP M'' for which every satisfying assignment must use μ on at least one variable. Thus M'', μ satisfy Theorem 17.

Case 2: There is a satisfying assignment A of M in which every value δ used is such that δ is not bad and F_δ is not supercritical. Suppose that M has r variables $x_1, ..., x_r$ and that A assigns a_i to x_i. Recall from Section 4 that $CSP_{n,p}(\mathcal{P}) \oplus A$ is formed by taking $CSP_{n,p}(\mathcal{P})$ and then choosing r random variables $v_1, ..., v_i$ and adding one-variable constraints that force v_i to take a_i. Clearly $\mathbf{Pr}(CSP_{n,p}(\mathcal{P}) \oplus A$ is unsatisfiable$) \geq \mathbf{Pr}(CSP_{n,p}(\mathcal{P}) \oplus M$ is unsatisfiable$)$.

Expose $F = \cup_{i=1}^r F_{a_i}(v_i)$, and U, the set of variables outside of F that lie in a constraint with a variable in F. Since all of the F_{a_i} are subcritical, Lemmas 8 and 16(a) imply that there is some L such that with probability at least $1 - \alpha/2$, $|U| < L$ and $F \cup U$ is a forest with r trees, one containing each a_i. Since adding M to $\widehat{CSP}_{n,p}(\mathcal{P})$ increases the probability of unsatisfiability by at least α, it must be that the probability that $\widehat{CSP}_{n,p}(\mathcal{P})$ is satisfiable, $|U| \leq L$, $\Phi \cup U$ is such a forest and $\widehat{CSP}_{n,p}(\mathcal{P}) \oplus A$ is unsatisfiable is at least $\alpha/2$.

Suppose that $\widehat{CSP}_{n,p}(\mathcal{P})$ is satisfiable, $|U| \leq L$ and $F \cup L$ is a forest of r treees, one for each a_i. Note that the forest structure of $F \cup U$ implies that every variable whose value is determined by the assignment A lies in F. Consider some $u \in U$ sharing a constraint with $w \in F$ where A forces w to take the value μ. Let $\Omega = \Omega(u)$ be the set of values which can be assigned to u which, in conjunction with assigning μ to w do not violate their constraint. We know that $|\Omega| \neq 0$ since otherwise μ is a bad value and hence some a_i is a bad value. We know that $|\Omega| \neq 1$ since otherwise $u \in F$. So $|\Omega(u)| \geq 2$ for each $u \in U$. Suppose that $u_1, ..., u_\ell$ are the variables in U with $|\Omega| = 2$, and let δ_i be the value not in $\Omega(u_i)$. Consider taking a random CSP formed as follows: first take a $\widehat{CSP}_{n,p}(\mathcal{P})$ and then choose ℓ random variables $u_1, ..., u_\ell$ and force u_i to not take value δ_i using a one-variable constraint. We have proved that the one-variable constraints boost the probability of unsatisfiability by at least $\alpha/2$.

We have now reached a stage where the rest of the proof is by now standard. We can use the techniques in any of [16, 3, 18] to show that if ℓ 1-variable constraints, each of the form "v_i cannot receive δ_i" boost the probability of unsatisfiability by at least $\alpha/2$, then so does the addition of some constant number of additional random constraints. This will lead to a contradicton of Corollary 7(c). We will take the most concise of these techniques, the one from [18] (which was proposed by Alon). The main tool is a variant of a theorem of Erdős and Simonovits [14], as stated in [17]:

Lemma 19 *For all positive integers k, ℓ and real $0 < \gamma \leq 1$, there exists $\gamma' > 0$ such that for sufficiently large n, if $H \subseteq [n]^\ell$ is such that $|H| \geq \gamma n^\ell$ then with probability at least γ' a random choice of ℓ k-tuples of integers between 1 and n: $(v_1^1, ..., v_1^k), ..., (v_\ell^1, ..., v_\ell^k)$ yields a complete ℓ-partite system of elements of H; i.e. for every function $f : [\ell] \to [k]$, the ℓ-tuple $(v_1^{f(1)}, ..., v_\ell^{f(\ell)}) \in H$.*

To apply this lemma, we set $k = 2$ and we let H be the set of *bad* ℓ-tuples of variables in $CSP_{n,p}(\mathcal{P})$; i.e. those ℓ-tuples $v_1, ..., v_\ell$ such that if we forbid each v_1 from receiving δ_i then the CSP will be unsatisfiable. We have shown that choosing a random ℓ-tuple $v_1, ..., v_\ell$ and forbidding each v_i from receiving δ_i boosts the probability of unsatisfiability by at least $\alpha/2$. That random choice will only make the CSP unsatisfiable if we choose a bad t-tuple of variables. Therefore, $|H| \geq (\alpha/2)n^\ell$, and so Lemma 19 applies to H.

Now suppose that instead of adding those ℓ 1-variable constraints to $CSP_{n,p}(\mathcal{P})$, we instead add ℓ new random constraints selected according to $\mathcal{P}$; call these constraints $C_1, ..., C_\ell$. For each value δ, there is at least one constraint $C_\delta \in \mathbf{supp}(\mathcal{P})$ which does not allow both variables to recieve δ; otherwise $CSP_{n,p}(\mathcal{P})$ would be trivially satisfiable by setting every variable equal to δ. The probability that for each $1 \leq i \leq \ell$, $C_i = C_{\delta_i}$ is $\prod_{i=1}^{\ell} \mathcal{P}(C_{\delta_i}) = \zeta > 0$. If this event occurs, then we can treat each C_i as a pair (i.e. 2-tuple) of variables at least one of which cannot take the value δ_i. By Lemma 19, with probability at least some $\gamma' > 0$ this collection of ℓ pairs forms a complete ℓ-partite system of elements of H. If so, then the resulting CSP is unsatisfiable: To see this, consider any satisfying assignment and for each $1 \leq i \leq \ell$, set $\phi(i)$ to be a variable of C_i which does not have the value δ_i. Then the ℓ-tuple $(\phi(1), ..., \phi(\ell))$ is a member of H and hence is bad. Thus there is no satisfying assignment in which each $\phi(i)$ does not receive δ_i.

Therefore, adding ℓ random constraints increases the probability of unsatisfiability by at least $\zeta\gamma' > 0$. So adding a sufficiently large constant number of additional random constraints will boost it by arbitarily close to 1. Increasing p by ϵ/n will a.s. result in at least that many extra constraints. So this contradicts Corollary 7(c). This establishes Claim 4 and hence our Lemma. □

We close this section by noting why this proof cannot be extended to general d. The problem is that possibly some of the variables in U would have their domain sizes reduced by two instead of one and so some of the 1-variable constraints would be of the form "v_i cannot receive δ_i or γ_i". This would prevent us from using Lemma 19 and any of the other known techniques for establishing sharp thresholds.

6 Future Directions

There is clearly much work still to be done along these lines of research. The big problem still remains - determine precisely which models from [31] have a sharp threshold. Of course, Section 2 indicates that this may be overly ambitious. In the example of Section 2, $\mathbf{supp}(\mathcal{P})$ is *disconnected* in that the values can be partitioned into two parts (namely $\{1, 2, 3\}$ and $\{4, 5\}$ such that no constraint permits its variables to take members of different parts. In [29], it was noted that when $\mathbf{supp}(\mathcal{P})$ is disconnected $CSP_{n,p}(\mathcal{P})$ can behave strangely. So perhaps it is more feasible to determine precisely which models with $\mathbf{supp}(\mathcal{P})$ connected have sharp thresholds. An important subgoal would be to do this for binary CSP's, i.e. the case where $k = 2$. Another reasonable goal to pursue would be the $d = 3$ case.

As far as more specific classes of models go, one should try to extend the work in Section 3 and examine whether Hypothesis A holds for H-homomorphism problems when H is a *directed* hypergraph. Such homomorphism problems are equivalent to CSP's in which every constraint is identical under some permutation of the variables. Of course, we showed in Section 3.2 that this is not always true in the $\widehat{CSP}_{n,p}(\mathcal{P})$ model. But there is a chance that it is true for the $CSP_{n,p}(\mathcal{P})$ model. Also, the example in Section 3.2 is not connected. So perhaps Hypothesis A holds for H-homomorphism problems whenever H is a connected directed hypergraph. Or perhaps one needs to require that H is strongly connected. And of course, it would be good to determine whether the "connected" condition can be removed from Theorem 5 by answering Question 12.

References

[1] Dimitris Achlioptas, Paul Beame, and Michael Molloy. A sharp threshold in proof complexity. In *STOC '01: Proceedings of the 33rd Annual ACM Symposium on Theory of Computing*, pages 337–346 (electronic), New York, 2001. ACM.

[2] Dimitris Achlioptas, Arthur Chtcherba, Gabriel Istrate, and Cristopher Moore. The phase transition in 1-in-k SAT and NAE 3-SAT. In *SODA '01: Proceedings of the twelfth annual ACM-SIAM symposium on Discrete algorithms*, pages 721–722, Philadelphia, PA, USA, 2001. Society for Industrial and Applied Mathematics.

[3] Dimitris Achlioptas and Ehud Friedgut. A sharp threshold for k-colorability. *Random Structures Algorithms*, 14(1):63–70, 1999.

[4] Dimitris Achlioptas, Michael S. O. Molloy, Lefteris M. Kirousis, Yannis C. Stamatiou, Evangelos Kranakis, and Danny Krizanc. Random constraint satisfaction: A more accurate picture. *Constraints*, 6(4):329–344, 2001.

[5] Dimitris Achlioptas and Cristopher Moore. The asymptotic order of the random k -SAT threshold. In *FOCS '02: Proceedings of the 43rd Symposium on Foundations of Computer Science*, pages 779–788, Washington, DC, USA, 2002. IEEE Computer Society.

[6] Vašek Chvátal and Bruce Reed. Mick gets some (the odds are on his side). In *FOCS '92: Proceedings of the 33rd Symposium on Foundations of Computer Science*, pages 620–627, Washington, DC, USA, 1992. IEEE Computer Society.

[7] Vašek Chvátal and Endre Szemerédi. Many hard examples for resolution. *J. Assoc. Comput. Mach.*, 35(4):759–768, 1988.

[8] Harold Connamacher and Michael Molloy. The exact satisfiability threshold for a potentially intractible random constraint satisfaction problem. In *FOCS '04: Proceedings of the 45th Annual IEEE Symposium on Foundations of Computer Science (FOCS'04)*, pages 590–599, Washington, DC, USA, 2004. IEEE Computer Society.

[9] Nadia Creignou and Hervé Daudé. Generalized satisfiability problems: minimal elements and phase transitions. *Theor. Comput. Sci.*, 302(1-3):417–430, 2003.

[10] Nadia Creignou and Hervé Daudé. Combinatorial sharpness criterion and phase transition classification for random CSPs. *Inform. and Comput.*, 190(2):220–238, 2004.

[11] O. Dubois and J. Mandler. On the non-3-colourability of random graphs. *ArXiv Mathematics e-prints*, math/0209087, 2002.

[12] Olivier Dubois and Jacques Mandler. The 3-XORSAT threshold. In *FOCS '02: Proceedings of the 43rd Symposium on Foundations of Computer Science*, pages 769–778, Washington, DC, USA, 2002. IEEE Computer Society.

[13] P. Erdős and A. Rényi. On random graphs. I. *Publ. Math. Debrecen*, 6:290–297, 1959.

[14] Paul Erdős and Miklós Simonovits. Supersaturated graphs and hypergraphs. *Combinatorica*, 3(2):181–192, 1983.

[15] Abraham D. Flaxman. A sharp threshold for a random constraint satisfaction problem. *Discrete Math.*, 285(1-3):301–305, 2004.

[16] Ehud Friedgut. Sharp thresholds of graph properties, and the k-sat problem. *J. Amer. Math. Soc.*, 12(4):1017–1054, 1999. With an appendix by Jean Bourgain.

[17] Ehud Friedgut. Hunting for sharp thresholds. *Random Structures Algorithms*, 26(1-2):37–51, 2005.

[18] Ehud Friedgut and Michael Krivelevich. Sharp thresholds for certain Ramsey properties of random graphs. *Random Structures Algorithms*, 17(1):1–19, 2000.

[19] Ian P. Gent, Ewan Macintyre, Patrick Prosser, Barbara M. Smith, and Toby Walsh. Random constraint satisfaction: Flaws and structure. *Constraints*, 6(4):345–372, 2001.

[20] Andreas Goerdt. A threshold for unsatisfiability. *J. Comput. System Sci.*, 53(3):469–486, 1996. 1994 ACM Symposium on Parallel Algorithms and Architectures (Cape May, NJ, 1994).

[21] Leslie Ann Goldberg, Steven Kelk, and Mike Paterson. The complexity of choosing an H-coloring (nearly) uniformly at random. *SIAM J. Comput.*, 33(2):416–432, 2004.

[22] Hamed Hatami. Technical report. in prepration.

[23] Pavol Hell and Jaroslav Nešetřil. On the complexity of H-coloring. *J. Combin. Theory Ser. B*, 48(1):92–110, 1990.

[24] Pavol Hell and Jaroslav Nešetřil. *Graphs and homomorphisms*, volume 28 of *Oxford Lecture Series in Mathematics and its Applications*. Oxford University Press, Oxford, 2004.

[25] Gabriel Istrate. Coarse and sharp thresholds of boolean constraint satisfaction problems. *Discrete Applied Mathematics*, to appear.

[26] Svante Janson, Tomasz Łuczak, and Andrzej Rucinski. *Random graphs*. Wiley-Interscience Series in Discrete Mathematics and Optimization. Wiley-Interscience, New York, 2000.

[27] Svante Janson, Yannis C. Stamatiou, and Malvina Vamvakari. Bounding the unsatisfiability threshold of random 3-SAT. *Random Structures Algorithms*, 17(2):103–116, 2000.

[28] David G. Mitchell. Resolution complexity of random constraints. In *CP '02: Proceedings of the 8th International Conference on Principles and Practice of Constraint Programming*, pages 295–309, London, UK, 2002. Springer-Verlag.

[29] Michael Molloy. When does the giant component bring unsatisfiability? *Combinatorica*, to appear.

[30] Michael Molloy. Thresholds for colourability and satisfiability in random graphs and Boolean formulae. In *Surveys in combinatorics, 2001 (Sussex)*, volume 288 of *London Math. Soc. Lecture Note Ser.*, pages 165–197. Cambridge Univ. Press, Cambridge, 2001.

[31] Michael Molloy. Models and thresholds for random constraint satisfaction problems. In *STOC '02: Proceedings of the thiry-fourth annual ACM symposium on Theory of computing*, pages 209–217, New York, NY, USA, 2002. ACM Press.

[32] Michael Molloy and Mohammad Reza Salavatipour. The resolution complexity of random constraint satisfaction problems. *SIAM J. Comp.*, to appear. Preliminary version in Proceedings of FOCS 2003.

[33] André Raspaud and Eric Sopena. Good and semi-strong colorings of oriented planar graphs. *Inform. Process. Lett.*, 51(4):171–174, 1994.

[34] Ke Xu and Wei Li. Exact phase transitions in random constraint satisfaction problems. *J. Artificial Intelligence Res.*, 12:93–103 (electronic), 2000.