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THE RANGE OF THRESHOLDS FOR DIAMETER 2 IN RANDOM CAYLEY GRAPHS

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ABSTRACT. Given a group G , the model $\mathcal{G}(G, p)$ denotes the probability space of all Cayley graphs of G where each element of the generating set is chosen independently at random with probability p .

Given a family of groups (G_k) and a $c \in \mathbb{R}_+$ we say that c is the threshold for diameter 2 for (G_k) if for any $\varepsilon > 0$ with high probability $\Gamma \in \mathcal{G}(G_k, p)$ has diameter greater than 2 if $p \leq \sqrt{(c - \varepsilon) \frac{\log n}{n}}$ and diameter at most 2 if $p \geq \sqrt{(c + \varepsilon) \frac{\log n}{n}}$. In [5] we proved that if c is a threshold for diameter 2 for a family of groups (G_k) then $c \in [1/4, 2]$ and provided two families of groups with thresholds 1/4 and 2 respectively.

In this paper we study the question of whether every $c \in [1/4, 2]$ is the threshold for diameter 2 for some family of groups. Rather surprisingly it turns out that the answer to this question is negative. We show that every $c \in [1/4, 4/3]$ is a threshold but a $c \in (4/3, 2]$ is a threshold if and only if it is of the form $4n/(3n - 1)$ for some positive integer n .

1. INTRODUCTION

Let us begin by recalling that given a group G and a subset S of G , the Cayley graph $\Gamma = \Gamma(G; S)$ of G with respect to S has the elements of G as its vertex set and g and h are neighbours if and only if $hg^{-1} \in S$ or $gh^{-1} \in S$. We ignore any loops, so in particular, whether $1 \in S$ or not is immaterial. Observe for example that Γ is connected if and only if the set S generates the group G . Throughout the paper, we will often refer to the set S as the generating set of the graph Γ irrespectively of whether it is a generating set for the group G or not.

The model $\mathcal{G}(G, p)$ is the probability space of all graphs $\Gamma(G; S)$ in which every element of G is assigned to the set S independently at random with probability p . We refer the reader to [5] for a discussion of some similarities and differences between this model and various other models of random graphs.

In this paper we continue the study of the diameter of random Cayley graphs that was initiated in [5]. Given a family of groups (G_k) of orders n_k with $n_k \rightarrow \infty$ as $k \rightarrow \infty$ and a $c \in \mathbb{R}_+$ we say that c is the threshold for diameter 2 for (G_k) if for any $\varepsilon > 0$ with high probability $\Gamma \in \mathcal{G}(G_k, p)$ has diameter greater than 2 if $p \leq \sqrt{(c - \varepsilon) \frac{\log n}{n}}$ and diameter at most 2 if $p \geq \sqrt{(c + \varepsilon) \frac{\log n}{n}}$. In [5] we proved that if c is a threshold for diameter 2 for a family of groups (G_k) then $c \in [1/4, 2]$. Moreover this is best possible as 1/4 is the threshold for the family of symmetric groups S_n while 2 is the threshold for the family of products of two-cycles $(C_2)^n$. Here we can also mention that for a model for random Cayley digraphs the probability of having diameter 2 was studied in [7].

Given the above result it is natural to ask whether for every $c \in [1/4, 2]$ there is a family of groups for which it is a threshold for diameter 2. Rather surprisingly, it turns out that the answer is negative. The aim of this paper is to give a characterisation of the values of c that can appear as thresholds.

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Theorem 1.1. *Let $c \in [1/4, 2]$. Then c is the threshold for diameter 2 for a family of groups (G_k) if and only if $c \in [1/4, 4/3] \cup \{\frac{4n}{3n-1} : n \in \mathbb{N}\}$.*

We break the proof of Theorem 1.1 into the following results.

Theorem 1.2. *Let $c \in [1/4, 1/2)$. Then c is the threshold for diameter 2 for the family $S_n \times C_m$, where $m = \lfloor n!^{\frac{2c}{1-2c}} \rfloor$.*

Theorem 1.3. *Let $c \in [1/2, 1)$. Then c is the threshold for diameter 2 for the family $G = (C_2)^n \times (C_m)$ where $m = \lfloor 2^{\frac{(1-c)n}{c}} \rfloor$.*

Theorem 1.4. *Let $c \in [1, 4/3)$. Then c is the threshold for diameter 2 for the family $G = (C_2)^n \times (D_{2m})$ where $m = \lfloor 2^{\frac{(4-3c)n}{3c}} \rfloor$ and D_{2m} is the dihedral group of order $2m$.*

Theorem 1.5. *Suppose $c > 4/3$ is the threshold for diameter 2 for some family of groups. Then $c \in \{\frac{4n}{3n-1} : n \in \mathbb{N}\}$. Moreover, given a positive integer n , $\frac{4n}{3n-1}$ is the threshold for diameter 2 for the family $((C_2)^k \times D_{4n})_k$.*

It is evident that Theorem 1.1 follows from Theorems 1.2-1.5. These results will be consequences of the more general Theorem 2.1 which enables us to determine the threshold for diameter 2 for a family of groups provided we have enough information about some specific structure of the groups of this family.

As we mentioned this looks like a surprising result as one would expect that by taking ‘suitable combinations’ of groups with different thresholds, one should be able to interpolate to get all possible values between the two thresholds. This is exactly what happens in Theorem 1.2. Symmetric groups have threshold $1/4$, cyclic groups have threshold $1/2$, and by taking a suitable direct product we can get any threshold in the interval $[1/4, 1/2]$. However there is a natural reason why this result is not so surprising after all. As one would expect the result depends on various group properties and there are many such properties for which you cannot interpolate. We are thinking here of properties which say that when the group is ‘too close to being abelian’ then it actually is abelian. For example it is a trivial observation that if more than half of the elements of a group are central (i.e. they commute with every other element) then the group is abelian and so all elements are central. (In fact the same holds even when more than a quarter of the elements are central.) In a similar manner, if more than $5/8$ of pairs of elements commute then all pairs commute [6, 9] and if less than $7|G|/4$ pairs of elements are conjugate then no pair of distinct elements are conjugate [2]. In our situation the important group theoretic property which affects the final outcome is the percentage of involutions (i.e. elements which square to the identity) of a finite group. It turns out that in the interval $[1/2, 1]$ there are only finitely many values which can appear as proportion of involutions [8] and this is exactly what causes the set of thresholds in the interval $(4/3, 2]$ to be discrete.

The plan of the paper is as follows. In Section 2 we define certain dependency graphs of a group G . Their structure and more specifically the number of their edges will be the key factor to decide whether c is the threshold for a family of groups or not. This is formulated precisely in Theorem 2.1. The proof of this theorem will naturally split into two cases. The case where p is below the threshold in which we show that the diameter of the random Cayley graph is with high probability greater than 2, and the case where p is above the threshold in which we show that the diameter of the random Cayley graph is with high probability at most 2. We consider these cases in Sections 3 and 4 respectively. Finally in Section 5 we apply Theorem 2.1 to prove Theorems 1.2-1.5.

2. THE DEPENDENCY GRAPHS FOR DISTANCE GREATER THAN 2 FROM THE IDENTITY

Let G be a finite group and let us denote its identity element by 1. For each non-identity element x of a group G , we define the graph Γ_x whose vertices are the elements of G and where

g is adjacent to h if and only if $h \in \{xg, xg^{-1}, x^{-1}g, x^{-1}g^{-1}, gx, gx^{-1}, g^{-1}x, g^{-1}x^{-1}\}$. Here we do allow loops but we ignore multiple edges.

The reason for the definition of this graph is the following: If S is a subset of G then x is at distance greater than 2 from the identity in $\Gamma(G; S)$ precisely when $x, x^{-1} \notin S$ and $\Gamma_x[S]$ is independent. Indeed, x is a neighbour of the identity if and only if $x \in S$ or $x^{-1} \in S$ and x is at distance 2 from the identity if and only if $x, x^{-1} \notin S$ and furthermore there is a y such that 1 is a neighbour of y and y is a neighbour of x in $\Gamma(G; S)$. The latter happens if and only if at least one of y, y^{-1} and at least one of yx^{-1}, xy^{-1} belong to S . Setting g to be equal to one of these four expressions and setting h to be equal to one of the other two we get that this happens if and only if $h \in \{xg, xg^{-1}, x^{-1}g, x^{-1}g^{-1}, gx, gx^{-1}, g^{-1}x, g^{-1}x^{-1}\}$.

We now make a few simple observations about these dependency graphs

- (O1) Γ_x has maximum degree at most 8.
- (O2) Every vertex of Γ_x is incident to an edge which is not a loop.
- (O3) Γ_x has a loop at y if and only if $x = y^2$ or $x = y^{-2}$.
- (O4) For every two distinct elements g, h of G there are at most eight distinct Γ_x 's in which g and h are adjacent.

Given a graph Γ with loops but no multiple edges we write $L(\Gamma)$ for the set of loops of Γ and $E(\Gamma)$ for the set of edges of Γ which are not loops. We also write $\ell(\Gamma)$ and $e(\Gamma)$ for the sizes of the corresponding sets.

For a group G , and an element x of G distinct from the identity we write

$$g_G(x) = |G|^{-\frac{e(\Gamma_x)}{|G|}}.$$

Also, if $x^2 = 1$ then we set

$$h_G(x) = e^{-\sqrt{\frac{\log n}{n}} \ell(\Gamma_x)}$$

while if $x^2 \neq 1$ then we set

$$h_G(x) = e^{-2\sqrt{\frac{\log n}{n}} \ell(\Gamma_x)}.$$

Given a positive real number c we write

$$f_G(x; c) = g_G(x)^c h_G(x)^{\sqrt{c}}.$$

Finally, for a graph G and a positive real number c we write

$$f_G(c) = \sum_{x \in G \setminus \{1\}} f_G(x; c).$$

As the group G will usually be understood from the context, we will often ignore the dependence of G and write $g(x), h(x), f(x; c)$ and $f(c)$ instead. It turns out that this last quantity is the one which determines the threshold for diameter 2 in random Cayley graphs.

Theorem 2.1. *Let c be a positive real number and let (G_k) be a family of groups whose orders tend to infinity. Then c is the threshold for diameter 2 for this family if and only if for every $\varepsilon > 0$ we have that $f_{G_k}(c - \varepsilon) \rightarrow \infty$ and $f_{G_k}(c + \varepsilon) \rightarrow 0$ as $k \rightarrow \infty$.*

This is a direct consequence of the following two results.

Theorem 2.2. *Let c be a positive real number and let (G_k) be a family of groups whose orders tend to infinity. Suppose that for every $\varepsilon > 0$ we have that $f_{G_k}(c - \varepsilon) \rightarrow \infty$ as $k \rightarrow \infty$. Then for every $\varepsilon > 0$, with high probability the diameter of $\Gamma \in \mathcal{G}\left(G_k, \sqrt{\frac{(c - \varepsilon) \log |G_k|}{|G_k|}}\right)$, is greater than 2.*

Theorem 2.3. *Let c be a positive real number and let (G_k) be a family of groups whose orders tend to infinity. Suppose that for every $\varepsilon > 0$ we have that $f_{G_k}(c + \varepsilon) \rightarrow 0$ as $k \rightarrow \infty$. Then for every $\varepsilon > 0$, with high probability the diameter of $\Gamma \in \mathcal{G}\left(G_k, \sqrt{\frac{(c + \varepsilon) \log |G_k|}{|G_k|}}\right)$, is at most 2.*

We proceed in the next two sections to prove these two theorems. The main ideas of the two proofs already appear in [5] and more specifically in the proofs of Theorems 1.3 and 1.6 respectively.

3. PROOF OF THEOREM 2.2

In the proof we will use the following corollary of Kleitman's Inequality, which we state using the notation of Janson's inequality, as that will be used later.

Theorem 3.1 (Kleitman's Inequality). *Let Ω be a finite set and let $\{F_i\}_{i \in I}$ be a family subsets of Ω , where I is a finite index set. Let R be a random subset of Ω and for each $i \in I$ let E_i be the event that $F_i \subseteq R$. Then*

$$\Pr\left(\bigcap_{i \in I} \overline{E_i}\right) \geq \prod_{i \in I} \Pr(\overline{E_i}).$$

We refer the reader to [1] for a proof of the inequality (they give the full form of Kleitman's inequality as Proposition 6.3.1 and provide the proof for the version stated here in the proof of Theorem 8.1.1) and continue with the proof of Theorem 2.2.

Let $G = G_k$ where k is large enough so that all of the following calculations hold. We write n for the order of G .

For any element x of G , let us write B_x for the event that x has distance greater than 2 from the identity. Suppose first that $x^2 \neq 1$. Then we have that

$$\Pr(B_x) \geq (1-p)^2(1-p)^{2\ell(\Gamma_x)}(1-p^2)^{e(\Gamma_x)}$$

This follows directly from Kleitman's Inequality since

$$B_x = \overline{E_x} \cap \overline{E_{x^{-1}}} \bigcap_{\{y: y^2=x\}} (\overline{E_y} \cap \overline{E_{y^{-1}}}) \bigcap_{e \in E(\Gamma_x)} \overline{E_e},$$

where for an element z of G , E_z denotes the event that z appears in the generating set and for an edge e of Γ_x , E_e denotes the event that both of its incident vertices appear in the generating set. Thus, provided k and therefore n is large enough, we have

$$\begin{aligned} \Pr(B_x) &\geq \frac{1}{2} \exp\left\{-\frac{2p\ell(\Gamma_x)}{1-p}\right\} \exp\left\{-\frac{p^2 e(\Gamma_x)}{1-p^2}\right\} \\ &= \frac{1}{2} h(x)^{\frac{\sqrt{c-\varepsilon}}{1-p}} g(x)^{\frac{c-\varepsilon}{1-p^2}} \\ &\geq \frac{1}{2} h(x) \sqrt{c-\varepsilon/2} g(x)^{c-\varepsilon/2} = \frac{1}{2} f(x; c-\varepsilon/2). \end{aligned}$$

Here we have made use of the inequality $(1-x) \geq e^{-\frac{x}{1-x}}$ which holds for all $x \in [0, 1)$.

If $x^2 = 1$, then for each y with $y^2 = x$ we have $y^{-2} = x^{-1} = x$ as well, so

$$\bigcap_{\{y: y^2=x\}} (\overline{E_y} \cap \overline{E_{y^{-1}}}) = \bigcap_{\{y: y^2=x\}} \overline{E_y}.$$

So in this case we again have

$$\begin{aligned} \Pr(B_x) &\geq \frac{1}{2} \exp\left\{-\frac{p\ell(\Gamma_x)}{1-p}\right\} \exp\left\{-\frac{p^2 e(\Gamma_x)}{1-p^2}\right\} \\ &= \frac{1}{2} h(x)^{\frac{\sqrt{c-\varepsilon}}{1-p}} g(x)^{\frac{c-\varepsilon}{1-p^2}} \\ &\geq \frac{1}{2} h(x) \sqrt{c-\varepsilon/2} g(x)^{c-\varepsilon/2} = \frac{1}{2} f(x; c-\varepsilon/2) \end{aligned}$$

Let us now write X for the number of vertices of G which are at distance greater than 2 from the identity. Then

$$\mathbb{E}X = \sum_{x \neq 1} \Pr(B_x) \geq \frac{1}{2} f_G(c - \varepsilon/2) \rightarrow \infty.$$

However this is not enough to show that $X > 0$ with high probability. The reason is that some pairs of these events are highly correlated. For this reason, in general we will have $\text{Var}(X) \gg (\mathbb{E}X)^2$ and so the second moment method cannot be used directly. To overcome this difficulty, we will give a quantitative result of the fact that if B_x and B_y are highly correlated then the graphs Γ_x and Γ_y have many common edges. Having proved this result, the next task will be to cleverly choose a subset I of the elements of G such that the events $(B_x)_{x \in I}$ are ‘almost’ independent and furthermore it is still the case that $\sum_{x \in I} \Pr(B_x) \rightarrow \infty$.

Lemma 3.2. *Let x, y be distinct elements of G such that the graphs Γ_x and Γ_y have exactly r common edges. Suppose furthermore that either $\ell(\Gamma_x) = o(\frac{n}{\log n})$ or $\ell(\Gamma_y) = o(\frac{n}{\log n})$. Then*

$$\Pr(B_x \cap B_y) \leq (1 + o(1)) \Pr(B_x) \Pr(B_y) (1 - p^2)^{-r}.$$

Proof. We may assume that $\ell(\Gamma_y) = o(\frac{n}{\log n})$. Let us write e_1, \dots, e_r for the common edges of Γ_x and Γ_y and let e_{r+1}, \dots, e_s be all other edges of Γ_y . By (O3) at most two of e_1, \dots, e_r are loops. For each $1 \leq i \leq s$, let C_i be the event that not both vertices incident to e_i appear in the generating set and let $D_i = \cap_{j=1}^i C_j$. Since $D_s = B_y$ then

$$\Pr(B_x \cap B_y) = \Pr(B_x) \Pr(B_y) \frac{\Pr(B_x | B_y)}{\Pr(B_x)} = \Pr(B_x) \Pr(B_y) \prod_{i=1}^s \frac{\Pr(B_x | D_i)}{\Pr(B_x | D_{i-1})}$$

where by convention $\Pr(B_x | D_0) := \Pr(B_x)$.

By the law of total probability, for each $1 \leq i \leq s$ we have

$$\begin{aligned} \Pr(B_x | D_{i-1}) &= \frac{\Pr(B_x \cap D_{i-1})}{\Pr(D_{i-1})} = \frac{\Pr(B_x \cap D_{i-1} \cap C_i) + \Pr(B_x \cap D_{i-1} \cap \overline{C_i})}{\Pr(D_{i-1})} \\ &= \frac{\Pr(B_x | D_{i-1} \cap C_i) \Pr(D_{i-1} \cap C_i)}{\Pr(D_{i-1})} + \frac{\Pr(B_x \cap D_{i-1} \cap \overline{C_i})}{\Pr(D_{i-1})} \\ &= \Pr(B_x | D_i) \Pr(C_i | D_{i-1}) + \frac{\Pr(B_x \cap D_{i-1} \cap \overline{C_i})}{\Pr(D_{i-1})}. \end{aligned}$$

To bound the first term, we use Kleitman’s Inequality to the events $\overline{C_i}$ and $\overline{D_{i-1}}$ to get

$$\begin{aligned} \Pr(B_x | D_i) \Pr(C_i | D_{i-1}) &\geq \Pr(B_x | D_i) \Pr(C_i) \\ &= \begin{cases} (1 - p) \Pr(B_x | D_i) & \text{if } e_i \text{ is a loop,} \\ (1 - p^2) \Pr(B_x | D_i) & \text{otherwise.} \end{cases} \end{aligned}$$

To bound the second term, observe first that if $1 \leq i \leq r$ then $B_x \subseteq C_i$ and so $\Pr(B_x \cap D_{i-1} \cap \overline{C_i}) = 0$. If $r + 1 \leq i \leq s$, let X_i denote the event that no vertex adjacent to a vertex of e_i in Γ_x appears in the generating set and Y_i the event that for each $j < i$ if e_j meets e_i then the vertex incident to e_j but not e_i is not in the generating set. Then, $B_x \cap D_{i-1} \cap \overline{C_i} = B_x \cap D_{i-1} \cap \overline{C_i} \cap X_i \cap Y_i$. Observe now that whether the two vertices incident to the edge e_i appear in the generating set or not does not affect the outcome of the event $B_x \cap D_{i-1} \cap X_i \cap Y_i$, i.e. the events $B_x \cap D_{i-1} \cap X_i \cap Y_i$ and $\overline{C_i}$ are independent. Applying now Kleitman’s Inequality

to the events $\overline{B_x} \cup \overline{D_{i-1}}, \overline{X_i}$ and $\overline{Y_i}$ we get

$$\begin{aligned} \Pr(B_x \cap D_{i-1} \cap \overline{C_i}) &= \Pr(\overline{C_i}) \Pr(B_x \cap D_{i-1} \cap X_i \cap Y_i) \\ &\geq \Pr(\overline{C_i}) \Pr(X_i) \Pr(Y_i) \Pr(B_x \cap D_{i-1}) \\ &\geq \begin{cases} p(1-p)^{28} \Pr(B_x|D_{i-1}) \Pr(D_{i-1}) & \text{if } e_i \text{ is a loop,} \\ p^2(1-p)^{28} \Pr(B_x|D_{i-1}) \Pr(D_{i-1}) & \text{otherwise.} \end{cases} \end{aligned}$$

To see the last inequality, recall that by (O1) Γ_x and Γ_y have maximum degree at most 8 and so each of the events X_i and Y_i says that at most 14 elements of G (at most seven for each vertex incident to e_i) do not appear in the generating set.

It follows that if $1 \leq i \leq r$ then $\Pr(B_x|D_i) \leq \Pr(B_x|D_{i-1})/(1-p^2)$ unless e_i is a loop in which case we have $\Pr(B_x|D_i) \leq \Pr(B_x|D_{i-1})/(1-p)$. Also if $r+1 \leq i \leq s$ then

$$\frac{\Pr(B_x|D_i)}{\Pr(B_x|D_{i-1})} \leq \frac{1-p^2(1-p)^{28}}{1-p^2} \leq 1+29p^3$$

provided that n is large enough unless e_i is a loop in which case we have

$$\frac{\Pr(B_x|D_i)}{\Pr(B_x|D_{i-1})} \leq \frac{1-p(1-p)^{28}}{1-p} \leq 1+29p^2$$

provided n is large enough. So recalling that at most two edges e_i with $1 \leq i \leq r$ are loops and at most $o(\frac{n}{\log n})$ edges are loops in general we get

$$\begin{aligned} \Pr(B_x \cap B_y) &\leq \Pr(B_x) \Pr(B_y) (1-p)^{-2} (1-p^2)^{-r} (1+29p^2)^{\ell(\Gamma_y)} (1+29p^3)^{4n} \\ &= (1+o(1)) \Pr(B_x) \Pr(B_y) (1-p^2)^{-r} \end{aligned}$$

as $p^2 \ell(\Gamma_y) = o(1)$ and $p^3 n = o(1)$. \square

The next task is to choose a ‘large’ set I such that the events B_x for $x \in I$ are ‘almost independent’ in the sense of Lemma 3.2. To this end we define a new graph H with vertex set the elements of G excluding the identity in which x and y are adjacent if and only if Γ_x and Γ_y have at least $n^{1-\delta}$ common edges. (Later, we will set $\delta = \varepsilon/8$.) Since by (O1) Γ_x has at most $4n$ edges and by (O4) every edge of Γ_x belongs to at most 7 other Γ_y ’s, the degree of x in H is at most $28n^\delta$. Let us now write x_1, \dots, x_{n-1} for the vertices of H . We may assume that

$$f(x_1; c - \varepsilon/2) \geq \dots \geq f(x_{n-1}; c - \varepsilon/2).$$

Now going through this order, we greedily pick an independent set I of H and let Y be the number of vertices $y \in I$ which are at distance greater than 2 from the identity and furthermore they satisfy $\ell(\Gamma_y) = o(\frac{n}{\log n})$. Using (O3) we see that the number of y ’s which do not satisfy $\ell(\Gamma_y) = o(\frac{n}{\log n})$ is $O(\log n)$. For each such y , using (O2) we see that Γ_y contains a matching of size at least $n/8$. Indeed if M is a maximal matching of size m , then by (O2) every vertex outside M has at least one neighbour inside M and so there are at least $n-m$ edges with exactly one incident vertex inside M . On the other hand by (O1) every vertex inside M has at most seven neighbours outside M so there are at most $7m$ edges with exactly one incident vertex inside M . So $n-m \leq 7m$ which gives the claimed bound. Therefore, $P(B_y) \leq (1-p^2)^{n/8}$. In particular the sum over all such y is $o(1)$.

So since the maximum degree of H is at most $28n^\delta$ this way of picking the elements of I guarantees that

$$\mathbb{E}Y \geq \frac{1}{2(28n^\delta + 1)} f_G(c - \varepsilon/2) - o(1) \geq \frac{n^{-\delta}}{60} f_G(c - \varepsilon/2) - o(1)$$

But for each x we have

$$n^{-\delta} g(x)^{c-\varepsilon/2} = n^{-\delta-(c-\varepsilon/2)\frac{e(\Gamma_x)}{n}} \geq n^{-(c+2\delta-\varepsilon/2)\frac{e(\Gamma_x)}{n}}$$

since by (O2) we have $e(\Gamma_x) \geq n/2$. Thus, by taking $\delta = \varepsilon/8$ we obtain

$$n^{-\delta} g(x)^{c-\varepsilon/2} \geq g(x)^{c-\varepsilon/4}$$

and so

$$n^{-\delta} f(x, c - \varepsilon/2) \geq f(x, c - \varepsilon/4).$$

Therefore we get that

$$\mathbb{E}Y \geq \frac{1}{60} f_G(c - \varepsilon/4) \rightarrow \infty.$$

Since also $\mathbb{E}Y(Y - 1) \leq (1 + o(1))(\mathbb{E}Y)^2$ by Chebyshev's inequality we get

$$\Pr(Y = 0) \leq \frac{\text{Var}(Y)}{(\mathbb{E}Y)^2} = \frac{\mathbb{E}Y(Y - 1)}{(\mathbb{E}Y)^2} - 1 + \frac{1}{\mathbb{E}Y} = o(1),$$

from which we deduce that with high probability there are vertices of Γ which are at distance greater than 2 from the identity, thus completing the proof of Theorem 2.2.

4. PROOF OF THEOREM 2.3

Let G be a group from the family (G_k) and let us write 1 for its identity element and n for its order. Since the graph Γ is vertex-transitive it is enough to show that with high probability every element of G is at distance at most 2 from the identity. Now fix a non-identity element x of G and for each $y \neq 1, x$ let us denote by $A_y := A_y(1, x)$ the event that the edges between 1 and y and between x and y both appear in Γ . So we have

$$\Pr(d(1, x) > 2) \leq \Pr\left(\bigcap_{y \neq 1, x} \overline{A_y}\right).$$

The events A_y are not independent and so to estimate the right hand side of the above inequality we will make use of the following inequality of Janson. We refer the reader to [1] for its proof.

Theorem 4.1 (Janson's Inequality). *Let Ω be a finite set and let $\{F_i\}_{i \in I}$ be a family of subsets of Ω , where I is a finite index set. Let R be a random subset of Ω and for each $i \in I$ let E_i be the event that $F_i \subseteq R$. Suppose also that $\Pr(E_i) \leq \varepsilon$ for each $i \in I$. Then*

$$\Pr\left(\bigcap_{i \in I} \overline{E_i}\right) \leq \exp\left(-\sum_{i \in I} \Pr(E_i) + \frac{1}{1 - \varepsilon} \sum_{i \in I} \sum_{\{j \neq i: F_i \cap F_j \neq \emptyset\}} \Pr(E_i \cap E_j)\right).$$

We will not apply this result directly to all of the events A_y but only to a specially chosen subset of them.

We start by defining an equivalence relation on G by letting y be equivalent to z if and only if $y = z$ or $y = z^{-1}$. We write $[y]$ for the equivalence class of y and we let Ω be the set of all equivalence classes. We let R be a random subset of Ω where each equivalence class is chosen independently with probability p or $2p - p^2$ depending on whether the equivalence class contains one or two elements, so to match the corresponding edge probabilities. For each element i of G we let $F_i = F_i(x) = \{[i], [xi^{-1}]\}$ and we let E_i be the event that $F_i \subseteq R$.

Observe that the edge between g and h belongs to Γ precisely when at least one of the elements gh^{-1} and hg^{-1} belongs to S . This happens with probability p if $[gh^{-1}]$ has size 1 and with probability $2p - p^2$ if it has size 2. So by thinking of $[y] \in R$ as happening precisely when at least one of y, y^{-1} belongs to S then we can translate events concerning edges of Γ to events concerning elements of R . Having this correspondence in mind, one can now check that the event E_i occurs exactly when the event A_i occurs. So for any $I \subseteq V(G) \setminus \{1, x\}$ we have

$$\Pr(d(1, x) > 2) \leq \Pr\left(\bigcap_{y \neq 1, x} \overline{A_y}\right) \leq \Pr\left(\bigcap_{i \in I} \overline{E_i}\right).$$

Now let $I = J \cup I_0 \cup I_1 \cup I_2$ be any subset of $V(G) \setminus \{1, x\}$ with the following properties.

- (P1) For each $i \in J$ we have $|F_i| = 1$.
- (P2) For each $i \in I_0 \cup I_1 \cup I_2$ we have $|F_i| = 2$. Furthermore exactly t of the equivalence classes in F_i have size 2 if and only if $i \in I_t$.
- (P3) For each $j \in J$ and $i \in I_0 \cup I_1 \cup I_2$ we have that $F_i \cap F_j = \emptyset$.
- (P4) For each distinct $i, j \in I_0 \cup I_1 \cup I_2$ we have $F_i \neq F_j$.

Here the sets I, J, I_0, I_1, I_2 depend on x and later we will have such sets for each x . In order to distinguish between them, we will sometimes write $I(x), J(x), I_0(x), I_1(x)$ and $I_2(x)$ instead. However if we feel that there is no danger of confusion we will choose to drop the dependence on x .

Suppose now that we are given such sets satisfying properties (P1)-(P4). Observe that for each $i \in J$ we have $i^2 = x$, so $i \neq i^{-1}$ and therefore $\Pr(E_i) = 2p - p^2$. Observe also that for each $i \in I_0$ we have $\Pr(E_i) = p^2$, for each $i \in I_1$ we have $\Pr(E_i) = p(2p - p^2)$ and for each $i \in I_2$ we have $\Pr(E_i) = (2p - p^2)^2$. In particular for each $t \in \{0, 1, 2\}$ and each $i \in I_t$ we have $\Pr(E_i) = 2^t p^2 + O(p^3)$. Finally observe that for each i there are at most 6 other j 's for which $F_i \cap F_j \neq \emptyset$. Indeed $F_i \cap F_j \neq \emptyset$ if and only if $[j] = [i]$ or $[j] = [xi^{-1}]$ or $[xj^{-1}] = [i]$ or $[xj^{-1}] = [xi^{-1}]$ which (for $j \neq i$) happens if and only if $j \in \{i^{-1}, xi^{-1}, ix^{-1}, ix, ix^{-1}, xi^{-1}x\}$.

So applying Janson's inequality with this set I we get

$$\Pr(d(1, x) > 2) \leq \exp(-2p|J| + p^2|J| - p^2|I_0| - 2p^2|I_1| - 4p^2|I_2| + O(np^3)).$$

We continue by choosing the sets $J(x)$ that we are going to use. To this end let $K(x) = \{i \in G : i^2 = x\}$ and observe that for (P1) to hold we must have $J(x) \subseteq K(x)$. If $x^2 \neq 1$ we set $J(x) = K(x)$, while if $x^2 = 1$ then we choose $J(x)$ such that it contains exactly one element from each pair $\{i, i^{-1}\}$ contained in K . Note that all these pairs really have size two since if it was the case that $i = i^{-1}$ then we would have $i^2 = 1 \neq x$ and so $i \notin K(x)$. So with this definition, in the first case we have $|J(x)| = \ell(\Gamma_x)$ while in the second case we have $|J(x)| = \ell(\Gamma_x)/2$. In particular, in both cases we get

$$\Pr(d(1, x) > 2) \leq (1 + o(1))h(x)^{\sqrt{c+\varepsilon}}n^{-(c+\varepsilon)(|I_0|+2|I_1|+4|I_2|-|J|)/n}.$$

Suppose now that for each x we could find $I_0(x), I_1(x), I_2(x)$ such that properties (P2)-(P4) are satisfied and furthermore we have that

$$|I_0(x)| + 2|I_1(x)| + 4|I_2(x)| - |J(x)| \geq (1 + o(1))e(\Gamma_x). \quad (1)$$

Then we would get

$$\Pr(d(1, x) > 2) \leq (1 + o(1))f(x; c + \varepsilon/2)$$

and so the probability that there is an x with distance greater than 2 from the identity would be at most

$$\sum_x \Pr(d(1, x) > 2) \leq (1 + o(1))f(c + \varepsilon/2) \rightarrow 0$$

and therefore with high probability the diameter of Γ would be at most 2.

In fact, because for each x for which $|J(x)| \geq n^{2/3}$ we have that

$$\Pr(d(1, x) > 2) \leq (1 + o(1))\exp\{-(2p - p^2)|J(x)|\} \leq (1 + o(1))e^{-p|J(x)|} = o(1/n)$$

it is enough to find sets $I_0(x), I_1(x), I_2(x)$ satisfying properties (P2)-(P4) and (1) only for those x for which $|J(x)| < n^{2/3}$. Furthermore in this case we don't even need to satisfy property (P3). Indeed as we observed earlier, for each $j \in J(x)$ there are at most six other i 's with $F_i \cap F_j \neq \emptyset$. So having found sets $I_0(x), I_1(x), I_2(x)$ satisfying properties (P2), (P4) and (1) by removing at most $6|J| = o(n)$ elements from each of them we will get sets $I'_0(x), I'_1(x), I'_2(x)$ satisfying (P2)-(P4) and since $e(\Gamma_x) \geq n/2$, the inequality (1) will still be satisfied.

So pick an element x of G which is different from the identity and assume that $|J(x)| < n^{2/3}$. Let us pick an element y of G distinct from the identity for which $y^2 \neq x$ and $y^{-2} \neq x$. The condition $|J(x)| < n^{2/3}$ guarantees that all but $o(n)$ elements y satisfy these properties. Our first task is to understand how many neighbours does y have in the graph Γ_x . Recall that $N(y) = \{xy, xy^{-1}, x^{-1}y, x^{-1}y^{-1}, yx, y^{-1}x, yx^{-1}, y^{-1}x^{-1}\}$. So we want to find the size of this set

and this of course depends on certain relations that x and/or y may satisfy. All the information required is conveyed in Table 1.

R1	$x^2 = 1$	1, 3	2, 4	5, 7	6, 8	B, E	$B = E$
R2	$y^2 = 1$	1, 2	3, 4	5, 6	7, 8	*	$B = C$
R3	$xy = yx$	1, 5	2, 6	3, 7	4, 8	C, D	$C = D$
R4	$(xy)^2 = x^2$	1, 6	2, 5	3, 8	4, 7	B, D	$B = D$
R5	$(xy)^2 = y^2$	1, 7	2, 8	3, 5	4, 6	A, F	$A = F$
R6	$(xy)^2 = 1$	1, 8	4, 5				
R7	$(xy^{-1})^2 = 1$	2, 7	3, 6			*	$D = E$
R8	$x^2 = y^2$	2, 3	6, 7			C, E	$C = E$
R9	$x^2 = y^{-2}$	1, 4	5, 8				

TABLE 1.

We can use Table 1 to interpret in which instances the possible neighbours of y are actually equal. Here we list the possible neighbours in the order $xy, xy^{-1}, x^{-1}y, x^{-1}y^{-1}, yx, y^{-1}x, yx^{-1}, y^{-1}x^{-1}$. For example, the first row of the table says that whenever $x^2 = 1$ then the first expression xy is equal to the third expression $x^{-1}y$, the second is equal to the fourth and so on. The last two columns of Table 1 will be explained later. We can now use Table 1 to construct Table 2.

1	R1,R2,R3	12345678	**	$BCDE$
2	R1,R2	1234 5678	*	BCE
3	R1,R3	1357 2468		$AF BE CD$
4	R1,R4	1368 2457	*	BDE
5	R1	13 24 56 78		BE
6	R2,R3	1256 3478	*	BCD
7	R2,R5	1278 3456	**	
8	R2	12 34 56 78	*	
9	R3,R6,R7	1458 2367	*	CDE
10	R3,R6	1458 26 37		CD
11	R3,R7	15 48 2367	*	CDE
12	R3	15 26 37 48		CD
13	R4,R5	1467 2358		$AF BD CE$
14	R4	16 25 38 47		BD
15	R5	17 28 35 46		AF
16	R6,R7	18 27 36 45	*	
17	R6,R8	18 23 45 67		CE
18	R6	18 45 2 3 6 7		
19	R7,R9	14 27 36 58	*	
20	R7	1 4 5 8 27 36	*	
21	R8,R9	14 23 58 67		CE
22	R8	1 4 5 8 23 67		CE
23	R9	14 58 2 3 6 7		
24		1 2 3 4 5 6 7 8		

TABLE 2.

From Table 2 we can read how many neighbours each y has depending on which relations x and y satisfy. For example the third row says that if x and y satisfy the relations in rows 1 and 3 of Table 1 and all the relations that can be deduced by them but no relation from

any other row, then y has exactly two neighbours. This is because the first, third, fifth and seventh expression in the above list are all equal and also the second, fourth, sixth and eighth relation are again all equal but distinct from the others (as no other relation holds). The last two columns of Table 2 will be discussed later. We now explain how the second of Table 2 is constructed. (The construction of the third column from the second is obvious.) In principle, Table T2 should have 2^9 rows, one for each subset of relations that appear in Table 1. However since some of these relations together imply some others we can cut this down a lot. We start by setting all relations one by one to be true until they force all other relations to be true. For example, once the relations in rows R1-R3 of Table 1 are true, then so are all the other. This creates the (second column of the) first row of Table 2. Having constructed the k -th row of Table 2 we construct its $(k+1)$ -th row as follows: If in the second column of the k -th row we have the elements Ri_1, \dots, Ri_s with $i_1 < \dots < i_s$, then for the $(k+1)$ -th row we set the relations Ri_1, \dots, Ri_{s-1} as true, all other relations Ri_t with $t \leq s$ as false and then we continue by setting all other relations one by one as true until these force the rest to be either true or false.

Recall that we do the above calculations only for elements y for which $x \neq y^2, y^{-2}$. So when computing $E(\Gamma_x)$ we will miss all neighbours of such y 's. However we already observed that there are at most $2|J(x)| < 2n^{2/3} = o(n)$ such y so the total contribution that we miss is only $o(E(\Gamma_x))$.

Our second task now is for each y with $y \neq 1, x, x^{-1}$ and $y^2, y^{-2} \neq x$ to understand the sizes of the equivalence classes of F_y and also how many distinct z 's are there for which $F_y \neq F_z$. We begin by recalling that $F_y \cap F_z$ is not empty only in the cases where $z = y^{-1}, yx, y^{-1}x, xy^{-1}, yx^{-1}, xy^{-1}x$ in which cases we have $F_{y^{-1}} = \{[y], [xy]\}$, $F_{yx} = \{[y], [yx]\}$, $F_{y^{-1}x} = \{[y], [y^{-1}x]\}$, $F_{xy^{-1}} = \{[xyx^{-1}], [xy^{-1}]\}$, $F_{yx^{-1}} = \{[x^2y^{-1}], [xy^{-1}]\}$ and $F_{xy^{-1}x} = \{[xy^{-1}x], [xy^{-1}]\}$. Let us write $A = y^{-1}, B = yx, \dots, F = xy^{-1}x$. Now let us go back to Table 1. The last column denotes equalities between A, B, \dots, F . For example the first row says that whenever $x^2 = 1$ then $B = E$ (i.e. $yx = yx^{-1}$) and no other relation must necessarily hold. The second to last column says for which z we actually have $F_y = F_z$. For example again from the first row we read that if $x^2 = 1$ then we must have $F_y = F_B = F_E$ but no other equality must necessarily hold. The stars in the second and seventh row denote the fact that some of the equivalence classes of F_y will have size one instead of two. For example if $y^2 = 1$ then the class $[y]$ of F_y has size one.

We now discuss the last two columns of Table 2. The second to last column denotes how many equivalence classes of F_y have size one. The number of them is the number of stars appearing in this column. The last column denotes which F_z 's are neighbours to F_y . For example in the first row we have that all F_B, F_C, F_D, F_E are equal to F_y and moreover we actually have $B = C = D = E$. While in the third row we see that all F_A, \dots, F_F are equal to F_y but in fact the only equalities between A, B, \dots, F are $A = F, B = E$ and $C = D$.

Let us now define a graph $R(x)$ on the set of all y with $y \neq 1, x, x^{-1}$ and $x \neq y^2, y^{-2}$ in which we join y to z if and only if $F_y = F_z$. We see from Table 2 that this graph is a union of disjoint K_2 's and K_4 's. To satisfy conditions (P2) and (P4) it is necessary and sufficient the the elements we pick to form $I_0(x) \cup I_1(x) \cup I_2(x)$ are an independent set of $R(x)$. We now go through each K_2 and K_4 and pick one element at random. We calculate $\mathbb{E}(|I_0(x)| + 2|I_1(x)| + 4|I_2(x)|)$. The first row of Table 2 says that each y of this type contributes $\frac{1}{2} \cdot 1 = \frac{1}{2}$ to this expectation. Here the $1/2$ comes from the fact that this element is chosen with probability $1/2$, while the 1 comes from the fact that this element will belong to $I_0(x)$. Because every such y has exactly one neighbours, it also contributes $1/2$ to the count of $E(\Gamma_x) = \sum_y |N_{\Gamma_x}(y)|/2$. We now go through each row and we discover that the contribution to $\mathbb{E}(|I_0(x)| + 2|I_1(x)| + 4|I_2(x)|)$ in each one of them is equal to the contribution to $E(\Gamma_x)$ unless in the following instances:

- In row 10 we get a contribution of 2 instead of $3/2$.
- In row 11 we get a contribution of 1 instead of $3/2$.

- In row 18 we get a contribution of 4 instead of 3.
- In row 20 we get a contribution of 2 instead of 3.
- In row 22 we get a contribution of 2 instead of 3.
- In row 23 we get a contribution of 4 instead of 3.

However, the number of y 's which satisfy the relations of row 10 is equal to the number of y 's which satisfy the relations of row 11. Indeed one can check that y satisfies the relations of row 10 if and only if y^{-1} satisfies the relations of row 11. Similarly, again under the transformation $y \mapsto y^{-1}$, we see that the number of y 's which satisfy the relations of row 18 is the same as those which satisfy the relations of row 20 and the same happens with rows 22 and 23. So we have

$$\mathbb{E}(|I_0(x)| + 2|I_1(x)| + 4|I_2(x)|) \geq (1 + o(1))e(\Gamma_x)$$

where the $1 + o(1)$ factor comes from the fact that we did not consider y 's with $x = y^2$ or $x = y^{-2}$. In particular there is a choice of y 's for which

$$|I_0(x)| + 2|I_1(x)| + 4|I_2(x)| \geq (1 + o(1))e(\Gamma_x).$$

This completes the proof of Theorem 2.3.

5. PROOFS OF THEOREMS 1.2-1.5

We begin with the proof of Theorem 1.3 which is the simplest of the four. To avoid unnecessary repetitions both in this and the proofs that follow, whenever we refer to the neighbours of a vertex in a graph we will mean the neighbours of this vertex in the underlying simple graph.

Proof of Theorem 1.3. Let $G = (C_2)^n \times (C_m)$ where $m = \lfloor 2^{\frac{(1-c)n}{c}} \rfloor$ and let us write N for the order of G . So $2^n \sim N^c$ and $m \sim N^{1-c}$. We now compute $f(x; c')$ for each $x \in G$.

- If x is of the form $(x', 1)$ where 1 is the identity in C_m , then $x^2 = 1$, Γ_x has no loops, and each y has exactly two neighbours in Γ_x , namely xy and xy^{-1} unless $y^2 = 1$. Since there are at most $2^{n+1} = o(N)$ such y 's we have $e(\Gamma_x) = (1 + o(1))N$ and so $f(x, c') = N^{-c'+o(1)}$. Since there are $2^n \sim N^c$ such elements x the total contribution of these elements to $f(c')$ is $N^{c-c'+o(1)}$ which tends to infinity if $c' < c$ and tends to 0 if $c' > c$.
- If x is not as in (a) but still satisfies $x^2 = 1$, then each y has exactly two neighbours in Γ_x , namely xy and xy^{-1} unless $y^2 \in \{1, x\}$. Since there are at most $o(N)$ such y 's we have $e(\Gamma_x) = (1 + o(1))N$ and so $f(x, c') = N^{-c'+o(1)}$. Since there are at most $2^n \sim N^c$ such elements x the total contribution of these elements to $f(c')$ is $N^{c-c'+o(1)}$ which tends to 0 if $c' > c$.
- If x is not as in (a) or (b) then all but $o(N)$ y 's have exactly four neighbours in Γ_x , namely $xy, xy^{-1}, x^{-1}y, x^{-1}y^{-1}$. Therefore $e(\Gamma_x) = (2 + o(1))N$ and so $f(x, c') \leq N^{-2c'+o(1)}$. In particular the total contribution of such elements to $f(c')$ is at most $N^{1-2c'+o(1)}$ which (since $c \geq 1/2$) tends to 0 if $c' > c$.

Combining the calculations in (a)-(c) we see that $f(c')$ tends to infinity if $c' < c$ and to 0 if $c' > c$ as required. \square

We now proceed with the proof of Theorem 1.2. In the proof we will repeatedly make use of the facts that for each element x of S_n there are at most $(n!)^{1/2+o(1)}$ elements y with $y^2 = x$ and (unless x is the identity) at most $(n-2)!$ elements which commute with x . (The second assertion is a simple exercise. To prove the first assertion, it is enough by [10, Exercise 7.69.c] to prove it when x is the identity. A proof of this is included in [5].) In particular for each element x of S_n there are at most $o(n!)$ elements y for which the set $\{xy, xy^{-1}, x^{-1}y, x^{-1}y^{-1}, yx, y^{-1}x, yx^{-1}, y^{-1}x^{-1}\}$ has size less than 8. The only case where this might not be immediately obvious is that for each x there are at most $o(n)$ elements y with $(xy)^2 = y^2$. But if there is a z with $(xz)^2 = z^2$ then $z^{-1}xz = x^{-1}$. So x^{-1} belongs to the equivalence class of x and so the number of y 's with

$(xy)^2 = y^2$ is the same as the number of y 's for which $y^{-1}xy = x$, i.e. it is the same as the number of elements which commute with x .

Proof of Theorem 1.2. Let $G = S_n \times C_m$ where $m = \lfloor n!^{\frac{2c}{1-2c}} \rfloor$ and let us write N for the order of G . So $n! \sim N^{1-2c}$ and $m \sim N^{2c}$.

We begin by computing $h(x)$ for each $x \in G$. Since for each $x \in C_m$ there are at most two y 's in C_m with $y^2 = x$ and for each $x \in S_n$ there are at most $n!^{1/2+o(1)}$ y 's in S_n with $y^2 = x$ then for each element $x \in G$ there are at most $N^{1/2-c+o(1)}$ elements y with $y^2 = x$. In particular $\ell(\Gamma_x) = O(N^{1/2-c+o(1)})$ and so $h(x) = (1 + o(1))$.

We continue by computing $g(x)$ and thus $f(x; c')$ for each $x \in G$.

- (a) There is at most one (non-identity) element x of the form $(1, x')$, where 1 is the identity of S_n , with $x^2 = 1$. It contributes $o(1)$ to $f(c')$.
- (b) Suppose x is of the form $(1, x')$ where 1 is the identity of S_n and $x^2 \neq 1$. Then all but $o(N)$ elements y have exactly four neighbours in Γ_x , namely $xy, xy^{-1}, x^{-1}y$ and $x^{-1}y^{-1}$. Therefore $e(\Gamma_x) = (1 + o(1))N$ and so $f(x, c') = N^{-2c'+o(1)}$. Since there are either m or $m - 1$ such elements, the total contribution of these elements to $f(c')$ is $N^{2c-2c'+o(1)}$ which tends to infinity if $c' < c$ and tends to 0 if $c' > c$.
- (c) If x is not of the above forms but $x^2 = 1$, then all but $o(N)$ elements y have exactly four neighbours in Γ_x , namely xy, xy^{-1}, yx and $y^{-1}x$. Therefore $e(\Gamma_x) = (2 + o(1))N$ and so $f(x, c') = N^{-2c'+o(1)}$. Since there are (at most) $n!^{1/2+o(1)} = N^{1/2-c+o(1)}$ such elements the total contribution of these elements to $f(c')$ is at most $N^{1/2-c-2c'}$ which (since $c \geq 1/4$) tends to 0 if $c' > c$.
- (d) If x is not of the above forms then all but $o(N)$ elements y have exactly eight neighbours in Γ_x . Therefore $e(\Gamma_x) = (4 + o(1))N$ and so $f(x, c') = N^{-4c'+o(1)}$. In particular the total contribution of these elements to $f(c')$ is at most $N^{1-4c'+o(1)}$ which (since $c \geq 1/4$) tends to 0 if $c' > c$.

Combining the calculations in (a)-(d) we see that $f(c')$ tends to infinity if $c' < c$ and to 0 if $c' > c$ as required. \square

Proof of Theorem 1.4. Let $G = (C_2)^n \times (D_{2m})$ where $m = \lfloor 2^{\frac{(4-3c)n}{3c}} \rfloor$ and D_{2m} is the dihedral group of order $2m$ and let us write N for the order of G . So $2^n = \Theta(N^{3c/4})$ and $2m = \Theta(N^{1-3c/4})$. We now compute $f(x; c')$ for each $x \in G$.

- (a) Suppose x is of the form $(x', 1)$ where 1 is the identity element of D_{2m} and x' is a non-identity element of C_2^n . Since no element of G squares to x then Γ_x has no loops and so $h(x) = 1$. Note that x is central satisfying $x^2 = 1$ and therefore every y has at most two neighbours in Γ_x , namely xy and xy^{-1} . Moreover it has exactly one neighbour if and only if y is an involution. Since D_{2m} has either $m + 1$ or $m + 2$ involutions depending on the parity of m we have that G has $\Theta(N/2)$ involutions and so $e(\Gamma_x) = (3/4 + o(1))N$ and $f(x; c') = N^{-3/4c'+o(1)}$. Since there are $2^n = \Theta(N^{3c/4})$ such elements, the total contribution of these elements to $f(c')$ is $N^{3c/4-3c'/4+o(1)}$ which tends to infinity if $c' < c$ and tends to 0 if $c' > c$.
- (b) Suppose x is of the form $(1, x')$ where 1 is the identity in $(C_2)^n$ and x' is a non-identity element of D_{2m} representing a rotation of the regular m -gon. Then the equation $y^2 = x$ has at least $2^n = \Theta(N^{3c/4})$ solutions. Since $c > 1$, we deduce that $h(x) = e^{-\Omega(n^{1/4})}$ and so $f(x; c') = o(1/N)$. So the total contribution of these elements to $f(c')$ is $o(1)$.
- (c) For every other element x we have that Γ_x contains no loops. Moreover, either we have that x is not an involution, in which case every y has at least two neighbours in Γ_x , namely xy and $x^{-1}y$, or x is an involution in which case all but at most $O(2^n) = O(N^{3/4})$ elements y commute with x with the rest having at least two neighbours in Γ_x , namely xy and yx . So in both cases we have $e(\Gamma_x) \geq (1 + o(1))N$, and therefore

$f(x, c') = 1/N^{c'} = o(1/N)$. So the total contribution of these elements to $f(c')$ is also $o(1)$.

Combining the calculations in (a)-(d) we see that $f(c')$ tends to infinity if $c' < c$ and to 0 if $c' > c$ as required. \square

As we mentioned in the introduction the proof of Theorem 1.5 is based on the fact that there are finitely many values that can appear as the proportion of involutions of a finite group in the interval $[1/2, 1]$. The earliest reference we could locate for this result is [8]. Here, we will make use of the following theorem of Wall [11] which classifies all groups for which more than half of their elements are involutions.

Theorem 5.1. *Let G be a group having exactly $(1/2 + c)|G|$ involutions, where $c > 0$. Then there is a positive integer n such that $c = 1/2n$. Moreover, G is the direct product of copies of C_2 together with a group H which has one of the following forms:*

- (I) H contains an abelian subgroup H_1 of index 2 and an element g with $gh = h^{-1}g$ for every $h \in H$. Moreover C_2 does not appear as a factor in the decomposition of H_1 as products of cyclic groups of prime power orders.
- (II) $H = D_8 \times D_8$.
- (III) H is generated by involutions $c, x_1, y_1, \dots, x_r, y_r$ for which all of them commute with each other apart from the pairs $\{x_i, y_i\}$ for $1 \leq i \leq r$ which satisfy $(x_i y_i)^2 = c$.
- (IV) H is generated by involutions $c, x_1, y_1, \dots, x_r, y_r$ for which all of them commute with each other apart from the pairs $\{c, x_i\}$ for $1 \leq i \leq r$ which satisfy $(c x_i)^2 = y_i$.

In particular, for each $d > 0$, there is a finite set $S(d)$ of groups such that every group G with more than $(1/2 + d)|G|$ involutions is a direct product of copies of C_2 together with a group from $S(d)$.

Armed with this result we can move on to the proof of Theorem 1.5.

Proof of Theorem 1.5. Suppose there is a family (G_k) of groups for which $c > 4/3$ is a threshold for diameter 2. Let $c' = (c + 4/3)/2$. By Theorem 2.1 we have that $f_{G_k}(c') \rightarrow \infty$. Let G be a group from the family (G_k) for which $f_G(c')$ is sufficiently large and let us write N for its order and αN for the number of its involutions. We now compute $f(x; c')$ for each $x \in G$. We may assume that the equation $x = y^2$ has at most $N^{1/2}$ solutions as otherwise $\ell(\Gamma_x) \geq N^{1/2}$ which implies that $f(x, c') = o(1/N)$ and the total contribution of such elements to $f(c')$ is $o(1)$.

- (a) Suppose that x is not an involution. Then each y has at least two neighbours in Γ_x , namely xy and $x^{-1}y$ and so $e(\Gamma_x) \geq N$. It follows that $f(x; c') \leq 1/N^{c'} = o(1/N)$ and so the total contribution of these elements to $f(c')$ is $o(1)$.
- (b) Suppose that x is an involution which is not central. Let $C(x) = \{y \in G : yx = xy\}$ be the centraliser of x and suppose that it has size βN . Since $C(x)$ is a subgroup of G and since x is not central we must have $\beta \leq 1/2$. The only y 's which have exactly one neighbour in Γ_x must belong to $C(x)$ so

$$e(\Gamma_x) \geq (\beta + 2(1 - \beta) + o(1))n/2 = (1 - \beta/2 + o(1))N \geq (3/4 + o(1))N.$$

It follows that $f(x; c') \leq N^{-3c'/4 + o(1)} = o(1/N)$. So again the total contribution of these elements to $f(c')$ is $o(1)$.

- (c) If now x is a central involution, then each y which does not satisfy $y^2 = x$ has either one or two neighbours in Γ_x depending on whether y is an involution or not. So $e(\Gamma_x) = (1 - \alpha/2 + o(1))N$. In particular, if $\alpha \leq 1/2 + d$, then the total contribution of these elements to $f(c')$ is at most $N^{1 - c'(3/4 - d/2 + o(1))}$ which is $o(1)$ if $d > 0$ is sufficiently small.

Combining the calculations in (a)-(c) we see that unless the proportion of involutions in G is at least $1/2 + d$ for some sufficiently small but fixed d , then $f(c')$ tends to 0, a contradiction.

So we can now use Theorem 5.1 to see that G must be a direct product of copies of C_2 together with a group H from a finite set $S(d)$ of groups. In particular, if $M(d)$ is the largest cardinality

of a group in $S(d)$ then we have that G contains at least $N/M(d)$ central involutions, namely all elements of the form $(x, 1)$ where x belongs to the direct product of the C_2 's and 1 is the identity element of H . In particular, it contains at least $\Theta(N)$ central involutions x for which the equation $y^2 = x$ has at least $n^{1/3}$ solutions. For each such x we have $g(x) = (1 + o(1))$ and so by (c) the total contribution of these elements to $f(c')$ is $\Theta(N^{1-c'(1-\alpha/2)})$. This tends to infinity if $c' < \frac{2}{2-\alpha}$ and tends to 0 if $c' > \frac{2}{2-\alpha}$. So $c = \frac{2}{2-\alpha}$ which is equal to $\frac{4n}{3n-1}$ if $\alpha = 1/2 + 1/2n$. To complete the proof of the theorem, we just observe that the given family has a proportion of $1/2 + 1/2n$ involutions as so does D_{4n} . \square

6. CONCLUSION AND OPEN PROBLEMS

Even though we stated the results with fixed ε , the same proofs work to show the following

Theorem 6.1. *Let c be a positive real number and let (G_k) be a family of groups of order n_k with n_k tending to infinity. Then c is the threshold for diameter 2 for this family if and only if $f_{G_k}(c_k) \rightarrow \infty$ whenever $c - c_k = \omega(\frac{\log \log n_k}{\log n_k})$ and $f_{G_k}(c_k) \rightarrow 0$ whenever $c_k - c = \omega(\frac{1}{\log n_k})$.*

As in the case of the diameter of random graphs (see e.g. [3, Theorem 10.10]) one cannot expect to improve the $\omega(\frac{1}{\log n_k})$ term. Note however that for achieving diameter greater than 2 we needed an $\omega(\frac{\log \log n_k}{\log n_k})$ term rather than an $\omega(\frac{1}{\log n_k})$ term. It would be interesting to check whether this can be improved.

It would be also interesting to check whether loops in Γ_x really do make a difference or whether the same results hold if $f_G(c)$ is replaced by $\tilde{f}_G(c) = \sum_{x \in G \setminus \{1\}} g_G(x)^c$.

Finally we mention a related group theoretic problem that arises. As we have already mentioned the problem of which numbers in $(1/2, 1]$ can appear as proportions of involutions of a finite group has been well studied and the groups with these proportions have been characterised. But what about numbers in the interval $[0, 1/2]$? Is it true that for every number in this interval there are finite groups whose proportion of involutions is sufficiently close to this number, or are there other gaps in this interval as well? We haven't been able to locate this problem in the literature but we believe it is an interesting one to investigate.

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