

STRONG AMENABILITY AND THE INFINITE CONJUGACY CLASS PROPERTY

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ABSTRACT. A group is said to be strongly amenable if each of its proximal topological actions has a fixed point. We show that a finitely generated group is strongly amenable if and only if it is virtually nilpotent. More generally, a countable discrete group is strongly amenable if and only if none of its quotients have the infinite conjugacy class property.

1. INTRODUCTION

Let $G \curvearrowright X$ be a continuous action of a countable discrete group on a compact Hausdorff space. This action is said to be *proximal* if for any $x, y \in X$ there exists a net $\{g_i\}$ in G such that $\lim_i g_i x = \lim_i g_i y$. G is said to be *strongly amenable* if every such proximal action of G has a fixed point. Glasner introduced these notions in [9], and proved a number of results: he showed that every virtually nilpotent group is strongly amenable, and that non-amenable groups are not strongly amenable. He also gave some examples of amenable groups that are not strongly amenable.¹ Since then, a number of papers have studied strong amenability [2, 8, 10, 12, 15], but none have made significant progress on relating it to other group properties.

Our main result is a characterization of strongly amenable groups. Recall that a group has the infinite conjugacy class property (ICC) if each of its non-trivial elements has an infinite conjugacy class.

Theorem 1. *A countable discrete group is strongly amenable if and only if it has no ICC quotients. In particular, a finitely generated group is strongly amenable if and only if it is virtually nilpotent.*

For example, this implies that the group S_∞ of finite permutations of \mathbb{N} is not strongly amenable. Likewise, the alternating subgroup of S_∞ is not strongly amenable, as is every infinite simple group.

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¹Glasner attributes one of these examples to Furstenberg.

Groups that have no ICC quotients are also known as *hyper-FC-central* [14] or *hyper-FC* [3]. By Theorem 1, these are exactly the strongly amenable groups. This implies that subgroups of strongly amenable countable discrete groups are again strongly amenable. A finitely generated group is hyper-FC if and only if it is virtually nilpotent [4, 14]², from which the second part of the theorem follows.

The case of groups with no ICC quotients is a straightforward consequence of Glasner's work. To prove that groups with ICC quotients are not strongly amenable, we consider an ICC group G , and a certain class of symbolic dynamical systems for G . Using a topological genericity argument, we show that in this class there is a proximal action without a fixed point.

In light of Theorem 1, it is natural to ask whether, in some larger class of topological groups, a group is strongly amenable if and only if each of its quotients has a non-trivial element with a compact (or perhaps precompact) conjugacy class.

The hyper-FC-subgroup, the universal minimal proximal action, and the group von Neumann algebra. One can define the *FC-series* of a group G as

$$1 \leq F_1 \leq F_2 \leq \dots \leq F_\alpha \leq \dots \leq G,$$

where $F_{\alpha+1}/F_\alpha$ is the normal subgroup of G/F_α consisting of the elements of the finite conjugacy classes, and $F_\beta = \cup_{\alpha < \beta} F_\alpha$ for β a limit ordinal [11, 14]. The group $\cup_\alpha F_\alpha$ is called the *hyper-FC-subgroup* of G .

In [9, Section II.4] Glasner defines the universal minimal proximal action of a group G ; this is the unique minimal proximal action of G which has every minimal proximal action as a factor. We denote this action by $G \curvearrowright \partial_p G$. In Proposition 2.12 we show that every ICC group has a minimal proximal faithful action. On the other hand, the proof of Proposition 2.1 shows that the hyper-FC-subgroup of G acts trivially on $\partial_p G$. Combining these gives us:

Corollary 1.1. *For a countable discrete group G , $\ker(G \curvearrowright \partial_p G)$ is equal to the hyper-FC-subgroup of G .*

Glasner also defines the universal minimal *strongly proximal* action of a group G , which is the unique minimal strongly proximal action of G which has every minimal strongly proximal action as a factor³. We

²For a self-contained proof see [5].

³A topological action $G \curvearrowright X$ is *strongly proximal* if for each Borel probability measure μ on X there exists a net $\{g_i\}$ such that $\lim_i g_i \mu$ is a point mass.

denote this action by $G \curvearrowright \partial_s G$. Furman [7, Proposition 7] shows that the kernel of $G \curvearrowright \partial_s G$ is the amenable radical of G .

It is known that the group von Neumann algebra of a group G has a unique tracial state iff G is ICC, and we show that ICC groups are precisely the groups with faithful universal minimal proximal actions. We thus have the following dynamical characterization of the unique trace property of the group von Neumann algebra:

Corollary 1.2. *For a countable discrete group G , the following are equivalent:*

- (1) *The group von Neumann algebra of G has a unique tracial state.*
- (2) *$G \curvearrowright \partial_p G$ is faithful.*

Analogously, it has been recently shown by Breuillard, Kalantar, Kennedy, and Ozawa [1, Corollary 4.3] that the reduced C^* -algebra of G has a unique tracial state if and only if $G \curvearrowright \partial_s G$ is faithful.

Following this analogy raises an interesting question. We know from [13, Theorem 1.5] that simplicity of the reduced C^* -algebra of a group G is equivalent to the freeness of $G \curvearrowright \partial_s G$. We also know from [1, Corollary 4.3] that unique trace property of the reduced C^* -algebra of a group G is equivalent to faithfulness of $G \curvearrowright \partial_s G$. On the other hand, for group von Neumann algebras of discrete groups, simplicity and the unique trace property are equivalent. So it is natural to ask whether freeness of $G \curvearrowright \partial_p G$ is equivalent to its faithfulness.

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2. OVERVIEW OF THE PROOF OF THEOREM 1

That a group with no ICC quotients is strongly amenable follows immediately from the following proposition.

Proposition 2.1. *Let G be a countable discrete group that acts faithfully, minimally and proximally on a compact Hausdorff space X . Then each non-trivial element of G has an infinite conjugacy class.*

Proof. Let g be a non-trivial element of G . Assume by contradiction that g has a finite conjugacy class. Let H be the centralizer of g , so that H has finite index in G . By [9, Lemma 3.2] H acts proximally and minimally on X . Since g is in the center of H , it acts trivially on

X , by [9, Lemma 3.3]. This contradicts the assumption that the action is faithful. \square

Thus, to prove Theorem 1, we consider any G that is ICC, and prove that it has a proximal action that does not have a fixed point. This is without loss of generality, since if G has a proximal action without a fixed point, then so does any group that has G as a quotient.

2.1. Existence by genericity. Our general strategy for the proof of Theorem 1 is to consider a certain space \mathcal{S} of non-trivial actions of G . We show that this space includes a proximal action without a fixed point by showing that, in fact, a *generic* action in this space is minimal and proximal. Genericity here is in the Baire category sense.

To define the space \mathcal{S} , let A be a finite alphabet of size at least 2. The *full shift* A^G , equipped with the product topology, is a space on which G acts continuously by left translations. Enumerate elements of $G = \{g_1, g_2, \dots\}$ and endow A^G with the metric $d(\cdot, \cdot)$ given by $d(s, t) = 1/k$ where $k = \inf\{n : s(g_n) \neq t(g_n)\}$. An element of A^G is called a *configuration*.

The closed, G -invariant non-empty subsets of A^G are called *shifts*. The space of shifts is endowed with the subspace topology of the Hausdorff topology (or Fell topology) on the closed subsets of A^G . This topology is also metrizable: take, for example, the metric that assigns to a pair of shifts $S, T \subseteq A^G$ the distance $1/(n+1)$, where n is the largest index such that S and T agree on $\{g_1, \dots, g_n\}$; by agreement on a finite $X \subseteq G$ we mean that the restriction of the configurations in S to X is equal to the restrictions of the configurations in T to X . Note that for any shift $S \subseteq A^G$, the sets of the form $\{T \subseteq A^G \mid T \text{ agrees with } S \text{ on } X\}$ for different finite subsets $X \subseteq G$ form a basis of the neighborhoods for S .

We define the space \mathcal{S} to be the closure, in the space of shifts, of the strongly irreducible shifts, with the $|A|$ -many trivial (i.e., singleton) shifts removed. Strongly irreducible shifts are defined as follows:

Definition 2.2. A shift $S \subseteq A^G$ is said to be strongly irreducible if there exists a finite $X \subseteq G$ including the identity such that for any two subsets $E_1, E_2 \subseteq G$ with $E_1X \cap E_2X = \emptyset$ and any two configurations $s_1, s_2 \in S$ there is a configuration $s \in S$ such that s restricted to E_1 equals s_1 restricted to E_1 , and s restricted to E_2 equals s_2 restricted to E_2 .

To show that the proximal actions are generic in \mathcal{S} , we define ε -proximal actions; proximal actions will be the actions which are ε -proximal for each $\varepsilon > 0$.

Definition 2.3. An action $G \curvearrowright X$ on a compact metric space with metric $d(\cdot, \cdot)$ is ε -proximal if for all $x, y \in X$ there exists a $g \in G$ such that $d(gx, gy) < \varepsilon$.

To show that minimal actions are generic in \mathcal{S} , we similarly define the notion of ε -minimality.

Definition 2.4. An action $G \curvearrowright X$ on a compact metric space with metric $d(\cdot, \cdot)$ is ε -minimal if for all $x, y \in X$ there exists a $g \in G$ such that $d(gx, y) < \varepsilon$.

A subset of a topological space is generic (in the Baire category sense) if it contains a dense G_δ . To prove our main result, we show that the proximal actions are a dense G_δ in \mathcal{S} . The proof of density is the main challenge of this paper, while proving that this subset is a G_δ is straightforward.

Claim 2.5. *The set of ε -proximal shifts is an open set in \mathcal{S} . Thus the set of proximal shifts is a G_δ set in \mathcal{S} .*

Similarly, the set of ε -minimal shifts is an open set in \mathcal{S} . Thus the set of minimal shifts is a G_δ set in \mathcal{S} .

The Baire Category Theorem guarantees that for well behaved spaces (such as our locally compact space \mathcal{S}), a countable intersection of dense open sets is dense. Thus, to prove that the proximal shifts are dense in the closure of the strongly irreducible shifts, it suffices to show that the ε -proximal shifts are dense in \mathcal{S} for each ε . That is, fixing ε , we must show that for each strongly irreducible shift $S \subseteq A^G$ and each finite subset $X \subseteq G$ there exists a strongly irreducible shift S' that agrees with S on X , and is ε -proximal.

To this end, we construct a class of shifts of $\{0, 1\}^G$ (which we denote by 2^G) which are ε -proximal. Furthermore, for these shifts ε -proximality is witnessed by a particular configuration around the origin: one having a 1 at the origin, and zeros close to it. For a finite symmetric subset $X \subset G$ and $g, h \in G$ we say that g and h are X -*apart* if $g^{-1}h \notin X$.

Definition 2.6. Let X be a finite symmetric subset of G . A non-trivial shift $S \subset 2^G$ is an X -*witness* shift if

- (1) For each $s \in S$, $s(a) = 1$ and $s(b) = 1$ implies that a and b are X -apart.
- (2) For each $s, t \in S$ there exists an $a \in G$ such that $s(a) = t(a) = 1$.

The construction of X -witness shifts in Propositions 2.7 and 2.8 contains the main technical effort of this paper.

2.2. A toy example. To give the reader some intuition and explain the role of ICC in the construction of X -witness shifts, we now explain how to construct a single configuration in 2^G with an X -witness *orbit*, and show that such configurations do not exist for groups that are not ICC. Note that the closure of this orbit is not necessarily an X -witness shift; the construction of X -witness shifts requires more work and a somewhat different approach, which we pursue later, in the formal proofs.

Given a configuration $u \in 2^G$, we denote by $Gu = \{gu : g \in G\}$ the G -orbit of u . Given a finite symmetric $X \subset G$, we say that a configuration $u \in 2^G$ is an *X -witness configuration* if

- (1) For each $s \in Gu$, $s(a) = 1$ and $s(b) = 1$ implies that a and b are X -apart.
- (2) For each $s, t \in Gu$ there exists an $a \in G$ such that $s(a) = t(a) = 1$.

We now informally explain that when G is ICC then for every such X there exist X -witness configurations, and that when G is not ICC then there is a finite symmetric $X \subset G$ for which there are no such configurations.

Suppose first that G is not ICC. Then there cannot exist an X -witness shift for every X . To see this, suppose that $g \in G$ is an element with finitely many conjugates, and let X be a finite symmetric subset of G that contains all the conjugates of g . Assume towards a contradiction that there exists an X -witness configuration u . So, by the second property of X -witness configurations, there exists an $a \in G$, such that $[gu](a) = u(a) = 1$, which means $u(g^{-1}a) = u(a) = 1$. Now, by the first property of u , we need to have that $g^{-1}a$ and a are X -apart, which means $(g^{-1}a)^{-1}a = a^{-1}ga \notin X$. This is a contradiction, since we let X contain all the conjugates of g .

Consider now the case that G is ICC. Given a finite symmetric X , we choose a random configuration $u \in 2^G$ as follows. Assign to each element of G an independent uniform random variable in $[0, 1]$. Let V_a be the random variable corresponding to $a \in G$. For each $a \in G$, let $u(a) = 1$ iff $V_a > V_{ax}$ for all $x \in X \setminus \{e\}$; i.e., $u(a) = 1$ if V_a is maximal in its X -neighborhood. Note that if g and h are X^2 -apart then the event $u(g) = 1$ and the event $u(h) = 1$ are independent.

We claim that u is, with probability one, an X -witness shift. By construction u almost surely satisfies the first property: if $s = g^{-1}u$ and $s(a) = s(b) = 1$ then $u(ga) = u(gb) = 1$, hence ga and gb are X -apart, and so a and b are X -apart. To satisfy the second property, it must hold that for every $g \neq h \in G$ there is some $a \in G$ such that

$u(ga) = u(ha) = 1$. By the ICC property, we can choose an $a \in G$ to make ga and ha arbitrarily far apart, as this corresponds to finding an a such that $a^{-1}(h^{-1}g)a$ is large. For such a choice of a , the events $u(ga) = 1$ and $u(ha) = 1$ are independent, and, since we have infinitely many such a 's that we can use, with probability one at least one of them will give us the desired result.

2.3. Constructing X -witness shifts. We now return to the construction of X -witness shifts, which are the main tool in our proof of Theorem 1. The first step is to construct a single configuration which is an X -witness in a large finite set.

Proposition 2.7. *Let G be an ICC group. For each finite symmetric $X \subset G$ there exists an $s \in 2^G$ and a finite symmetric $Y \supset X$ such that*

- (1) *For every $a, b \in G$, if $s(a) = s(b) = 1$ then a and b are X -apart.*
- (2) *For every $g, h \in Y^{100}$ there exists some $a \in Y$ such that $s(ga) = s(ha) = 1$.*

The proof of this proposition—along with Proposition 2.8 below—contains the main technical effort of this paper. The proof elaborates on the ideas of the informal construction of §2.2: we choose the configuration s at random, and then show that it has the desired properties with positive probability. This stage crucially uses the assumption that the group is ICC, which translates to independence of some events that arise in the analysis of this random choice. This is the only step in the proof of Theorem 1 in which we use the ICC property of G .

We use the configuration constructed in Proposition 2.7 to construct X -witness shifts. These shifts will additionally (and importantly) be strongly irreducible.

Proposition 2.8. *Let G be a group for which, for each finite symmetric $X \subset G$, there exists a configuration that satisfies the conditions of Proposition 2.7. Then for each such X there also exists a strongly irreducible X -witness shift.*

The combination of Propositions 2.7 and 2.8 immediately yields the following.

Proposition 2.9. *Let G be an ICC group. Then for each finite symmetric $X \subset G$ there exists a strongly irreducible X -witness shift $S \subset 2^G$.*

2.4. ε -proximal shifts. Finally, we use these strongly irreducible X -witness shifts to construct approximations to a given strongly irreducible shift S that are both ε -proximal and ε -minimal.

Proposition 2.10. *Let G be a group for which there exists, for each finite symmetric $X \subset G$, a strongly irreducible X -witness shift. Let $T \subseteq A^G$ be a strongly irreducible shift. Then for each ε and finite $X \subset G$ there exists a strongly irreducible shift $T' \subseteq 2^G$ that is ε -proximal, ε -minimal, and agrees with T on X .*

An immediate consequence of Proposition 2.9, Proposition 2.10, and Claim 2.5 is the following.

Proposition 2.11. *Let G be an ICC group. Then there is a dense G_δ set in \mathcal{S} for which the action $G \curvearrowright S$ is minimal and proximal.*

In the next proposition we show that this result can be strengthened to show that a generic shift is additionally faithful.

Proposition 2.12. *Let G be an ICC group. Then there is a dense G_δ set in \mathcal{S} for which the action $G \curvearrowright S$ is faithful, minimal, and proximal.*

Given all this, the proof of our main theorem follows easily.

Proof of Theorem 1. That groups with no ICC quotients are strongly amenable follows immediately from Proposition 2.1. Let G be ICC. By Proposition 2.11 the proximal minimal shifts are a dense G_δ in \mathcal{S} , and in particular exist, since \mathcal{S} is non-empty (e.g., the full shift A^G is strongly irreducible and non-constant). Since there are no trivial shifts in \mathcal{S} , and since non-trivial minimal shifts have no fixed points, we have proved that G is not strongly amenable. \square

3. PROOFS

3.1. Proof of Proposition 2.7. Let G be an ICC group, and let X be a finite, symmetric subset of G . We choose a random configuration $u \in 2^G$ as follows. Assign to each element of G an independent uniform random variable in $[0, 1]$. Let V_a be the random variable corresponding to $a \in G$. For each $a \in G$, let $u(a) = 1$ iff $V_a > V_{ax}$ for all $x \in X \setminus \{e\}$. That is, let $u(a) = 1$ if $V_a > V_b$ whenever $a^{-1}b \in X$ and $b \neq a$. The following claim is an immediate consequence of the definition of u .

Claim 3.1. *If a_1, \dots, a_n are X^2 -apart⁴ for $a_i \in G$, then $\{u(a_i) = 1\}$ are independent events.*

Clearly, for all values of the random configuration, $u(a) = u(b) = 1$ implies that $a^{-1}b \notin X$ for all $a, b \in G$, which means that a and b are X -apart. So the random configuration u almost surely satisfies the

⁴Recall that given a finite symmetric subset $X \subset G$ and $g, h \in G$, we say that g and h are X -apart if $g^{-1}h \notin X$.

first part of the proposition. It thus remains to find a finite symmetric subset $Y \supset X$ such that, with positive probability for the random configuration u , for each $g, h \in Y^{100}$ there exists some $a \in Y$ such that $u(ga) = u(ha) = 1$.

The next lemma claims that there exists a subset Y with certain useful properties. We use this lemma to prove our proposition, and then prove the lemma.

Lemma 3.2. *There exists a $Y \supset X$ with the following properties.*

(1)

$$|Y|^{200}(1 - |X|^{-2})^{|Y|/(20|X^2|+5)} < 1.$$

(2) *For each $g, h \in G$ there exists a subset $Y_{g,h} \subseteq Y$ with the following properties.*

(a) $|Y_{g,h}| \geq |Y|/(20|X^2| + 5)$.

(b) *For $y \in Y_{g,h}$, gy and hy are X^2 -apart.*

(c) *For $y_1 \neq y_2 \in Y_{g,h}$, w_1 and w_2 are X^2 -apart for any $w_1 \in \{gy_1, hy_1\}$ and $w_2 \in \{gy_2, hy_2\}$.*

For $c, d, y \in G$, let E_c be the event that $u(c) = 1$, and let $E_{c,d}^y = E_{cy} \cap E_{dy}$. Now fix $g, h \in G$.

- (1) By the second property of $Y_{g,h}$, gy and hy are X^2 -apart for any $y \in Y_{g,h}$. Hence E_{gy} and E_{hy} are independent, by Claim 3.1.
- (2) $\mathbb{P}[E_c] = 1/|X|$ for all $c \in G$.
- (3) Combining the previous two results: $\mathbb{P}[E_{g,h}^y] = |X|^{-2}$ for all $y \in Y_{g,h}$. So $\mathbb{P}[\neg E_{g,h}^y] = 1 - |X|^{-2}$.
- (4) $E_{g,h}^y$ are independent events for different values of $y \in Y_{g,h}$. This is because (I) gy and hy are X^2 -apart for any $y \in Y_{g,h}$, and (II) w_1 and w_2 are X^2 -apart for any $y_1 \neq y_2 \in Y_{g,h}$, $w_1 \in \{gy_1, hy_1\}$, and $w_2 \in \{gy_2, hy_2\}$, which means $\{E_{gy}, E_{hy} \mid y \in Y_{g,h}\}$ are independent events. And finally, since $E_{g,h}^y = E_{gy} \cap E_{hy}$, we get that $E_{g,h}^y$ are independent events for $y \in Y_{g,h}$.
- (5) We say that the pair (g, h) *fails* if $E_{g,h}^y$ does not happen for any $y \in Y_{g,h}$. So, by the previous two results,

$$\begin{aligned} \mathbb{P}[(g, h) \text{ fails}] &= \mathbb{P}[E_{g,h}^y \text{ for no } y \in Y_{g,h}] \\ &= (1 - |X|^{-2})^{|Y_{g,h}|} \\ &\leq (1 - |X|^{-2})^{|Y|/(20|X^2|+5)}, \end{aligned}$$

where the last inequality follows from the first property of $Y_{g,h}$.

By the last inequality, union bound, and the first property of Y :

$$\begin{aligned} \mathbb{P} [(g, h) \text{ fails for some } g, h \in Y^{100}] &\leq |Y^{100}|^2 (1 - |X|^{-2})^{|Y|/(20|X^2|+5)} \\ &\leq |Y|^{200} (1 - |X|^{-2})^{|Y|/(20|X^2|+5)} < 1. \end{aligned}$$

So, there is at least one configuration, say s , for which no (g, h) fails for $g, h \in Y^{100}$. Therefore, for all $g, h \in Y^{100}$ there is an $a \in Y$ such that $s(ga) = s(ha) = 1$. So this s satisfies the second part of the proposition, which concludes the proof of Proposition 2.7, except the proof of Lemma 3.2, to which we turn now.

Proof of Lemma 3.2. We call an element $g \in G$ *switching* if for all non-identity $x \in X^2$ we have $g^{-1}xg \notin X^2$.

Claim 3.3. *There exists at least one switching element $g_s \in G$.*

Proof. Let C_x be the centralizer of x for each $x \in X^2$. Then there are finitely many cosets of C_x , say $g_1^x C_x, \dots, g_{n_x}^x C_x$, such that $g^{-1}xg \in X^2$ only if $g \in g_i^x C_x$ for some $i \in \{1, \dots, n_x\}$. So, non-switching elements are in the union of finitely many cosets of subgroups with infinite index, i.e. g is non-switching only if $g \in g_i^x C_x$ for some $x \in X^2$ and some $i \in \{1, \dots, n_x\}$. Since G is ICC, each C_x has infinite index in G . By [16, Lemma 4.1] a finite collection of cosets of infinite index does not cover the whole group G , so, there is at least one switching element in G . \square

Let g_s be a switching element. We can choose an arbitrarily large finite subset $Y_1 \subseteq G$ which includes the identity and such that $Y_1 \cap Y_1 g_s = \emptyset$. Choose such a Y_1 that is large enough so that

$$(5|Y_1|)^{200} (1 - |X|^{-2})^{2|Y_1|/(20|X^2|+5)} < 1 \quad \text{and} \quad |Y_1| \geq |X|$$

and let $Y = (Y_1 \cup Y_1 g_s) \cup (Y_1 \cup Y_1 g_s)^{-1} \cup X$. Note that Y is symmetric and $5|Y_1| \geq |Y| \geq 2|Y_1|$, which implies

$$|Y|^{200} (1 - |X|^{-2})^{|Y|/(20|X^2|+5)} < 1.$$

This establishes the first property of Y .

Fix $g, h \in G$ with $g \neq h$. We say $y \in G$ is *distancing* for the pair (g, h) if gy and hy are X^2 -apart.

Claim 3.4. *If $y \in G$ is not distancing for (g, h) then yg_s is distancing for (g, h) .*

Proof. Since y is not distancing for (g, h) , $(gy)^{-1}(hy) = y^{-1}g^{-1}hy \in X^2$. By the definition of a switching element $g_s^{-1}[(gy)^{-1}(hy)]g_s = (gyg_s)^{-1}(hyg_s) \notin X^2$, which means that yg_s is distancing for (g, h) . \square

By this observation, if $y_1 \in Y_1$ is not distancing for (g, h) then $y_1 g_s \in Y_1 g_s$ is distancing for (g, h) . So at least half of the elements in $Y_1 \cup Y_1 g_s$ are distancing for (g, h) and thus at least one fifth of the elements in Y are distancing for (g, h) . Let $Y'_{g,h}$ be the collection of elements in Y that are distancing for (g, h) . We just saw that $|Y'_{g,h}| \geq |Y|/5$.

Now define a graph on $Y'_{g,h}$ by connecting $y_1 \neq y_2 \in Y'_{g,h}$ if w_1 and w_2 are not X^2 -apart for some $w_1 \in \{gy_1, hy_1\}, w_2 \in \{gy_2, hy_2\}$. Call this graph $G'_{g,h}$. Note that the degree of each $y \in Y'_{g,h}$ in $G'_{g,h}$ is at most $4|X^2|$. So, we can find an independent set of size at least $|Y'_{g,h}|/(4|X^2| + 1) \geq |Y|/(20|X^2| + 5)$ in $G'_{g,h}$. Call this independent set $Y_{g,h}$.

Claim 3.5. $|Y_{g,h}| \geq |Y|/(20|X^2| + 5)$, for $y \in Y_{g,h}$, gy and hy are X^2 -apart, and for $y_1 \neq y_2 \in Y_{g,h}$, we have that w_1 and w_2 are X^2 -apart for $w_1 \in \{gy_1, hy_1\}, w_2 \in \{gy_2, hy_2\}$.

Proof. The bound on the size of $Y_{g,h}$ is established in the previous paragraph. Since $Y_{g,h} \subseteq Y'_{g,h}$ and all elements of $Y'_{g,h}$ are distancing for (g, h) , the second property holds. The third property follows from independence of $Y_{g,h}$ in $G'_{g,h}$. \square

This establishes the three properties of $Y_{g,h}$, and thus concludes the proof of the lemma. \square

3.2. Saturated packings. In this section we prove some general claims regarding *saturated packings* (see, e.g., [17]).

Definition 3.6. Let Z_1, \dots, Z_n be distinct non-empty finite subsets of G . A $\{Z_1, \dots, Z_n\}$ -packing is a $p \in \{Z_1, \dots, Z_n, \emptyset\}^G$ with $h p(h) \cap g p(g) = \emptyset$ for all $g \neq h \in G$; note that $h p(h)$ and $g p(g)$ are each a translate, by h and g respectively, of some element of $\{Z_1, \dots, Z_n, \emptyset\}$. When $p(g) \neq \emptyset$, we call the translate $g p(g)$ a *block*.

By an abuse of notation, we use the term Z -packing instead of $\{Z\}$ -packing when we have only one subset.

Definition 3.7. A $\{Z_1, \dots, Z_n\}$ -packing p is *saturated* if there is no $\{Z_1, \dots, Z_n\}$ -packing $p' \neq p$ such that $p(g) \neq \emptyset$ implies $p'(g) = p(g)$.

We say that p is a saturation of q if p is saturated and $q(g) \neq \emptyset$ implies $p(g) = q(g)$.

Saturated packings are packings to which one cannot add any blocks. Note, however, that it may be possible to add more blocks by first removing some. Note also that by Zorn's Lemma there exists for each $\{Z_1, \dots, Z_n\}$ -packing q a $\{Z_1, \dots, Z_n\}$ -packing p that saturates it.

The following claim shows the existence of strongly irreducible saturated packings, which will be useful in the construction of strongly irreducible X -witness shifts. A similar claim with a similar proof appears in [6, Lemma 2.2].

Given two distinct non-empty finite subsets Z_1 and Z_2 of G , we denote by $\pi: \{Z_1, Z_2, \emptyset\}^G \rightarrow \{Z_1, \emptyset\}^G$ the map

$$(\pi(p))(g) = \begin{cases} Z_1 & \text{if } p(g) = Z_1 \\ \emptyset & \text{otherwise.} \end{cases}$$

That is, π transforms a $\{Z_1, Z_2\}$ -packing into a Z_1 -packing by removing all the Z_2 -blocks.

Claim 3.8. *Let Z_1 and Z_2 be two distinct non-empty finite subsets of G . Let P be the collection of all saturated $\{Z_1, Z_2\}$ -packings p such that $\pi(p)$ is a saturated Z_1 -packing. Then P is a non-empty strongly irreducible shift.*

Proof. The proof of the fact that P is a non-empty shift is standard. It thus remains to be shown that it is strongly irreducible.

Let $X = (Z_1 \cup Z_2) \cup (Z_1 \cup Z_2)^{-1}$. Let $F_1, F_2 \subset G$ be any two subsets of G that are X^{14} -apart. To prove the claim, it suffices to show that for any $p_1, p_2 \in P$ there is a $p \in P$ that agrees with p_1 on F_1 and with p_2 on F_2 . We know that $F_1 X^6$ and $F_2 X^6$ are disjoint, and furthermore, if $a_1 \in F_1 X^6$ and $a_2 \in F_2 X^6$ then the blocks $a_1 p_1(a_1)$ and $a_2 p_2(a_2)$ are disjoint.

Let $q_1 = \pi(p_1)$ and $q_2 = \pi(p_2)$. We know that q_1 and q_2 are saturated Z_1 -packings. We also know that if $a_1 \in F_1 X^6$ and $a_2 \in F_2 X^6$ then $a_1 q_1(a_1)$ and $a_2 q_2(a_2)$ are disjoint. Thus there is a Z_1 -packing, say q' , that is equal to q_1 on $F_1 X^6$ and to q_2 on $F_2 X^6$. Let q be a Z_1 -packing that is a saturation of q' . Fix $i \in \{1, 2\}$ and $g \in F_i X^4$. We will show that $q_i(g) = q(g)$.

- If $q_i(g) = Z_1$, we know that $q'(g) = Z_1$, and hence $q(g) = Z_1$.
- If $q_i(g) = \emptyset$, since q_i is a saturated Z_1 -packing, there exists $a \in g Z_1 Z_1^{-1} \subseteq F_i X^6$ with $q_i(a) = Z_1$. So, $q'(a) = Z_1$, and hence $q(a) = Z_1$. Since $g Z_1 \cap a Z_1 \neq \emptyset$, this implies that $q(g) = \emptyset$.

So, q is a saturated Z_1 -packing that agrees with q_1 on $F_1 X^4$ and with q_2 on $F_2 X^4$.

Since q agrees with $q_1 = \pi(p_1)$ on $F_1 X^4$ and with $q_2 = \pi(p_2)$ on $F_2 X^4$, it is easy to see that p' , which is defined as follows, is a well-defined

$\{Z_1, Z_2\}$ -packing:

$$p'(g) = \begin{cases} p_1(g) & \text{if } g \in F_1X^2 \\ p_2(g) & \text{if } g \in F_2X^2 \\ q(g) & \text{otherwise.} \end{cases}$$

So, by definition, p' agrees with p_1 on F_1X^2 and with p_2 on F_2X^2 . Furthermore, $\pi(p') = q$, since $\pi(p_i)$ agrees with q on F_iX^2 .

Let p be a $\{Z_1, Z_2\}$ -packing that is a saturation of p' . Since $\pi(p') = q$ is a saturated Z_1 -packing, we have $\pi(p) = \pi(p') = q$. So, p is a saturated $\{Z_1, Z_2\}$ -packing where $\pi(p)$ is a saturated Z_1 -packing, which means $p \in P$. To complete the proof, we just need to show that p agrees with p_1 on F_1 and with p_2 on F_2 . Fix $i \in \{1, 2\}$ and $g \in F_i$. We will show that $p_i(g) = p(g)$.

- If $p_i(g) \in \{Z_1, Z_2\}$, we know that $p'(g) = p_i(g) \in \{Z_1, Z_2\}$, and hence $p(g) = p_i(g)$.
- If $p_i(g) = \emptyset$, since p_i is a saturated $\{Z_1, Z_2\}$ -packing, for any $j \in \{1, 2\}$ there exist $\ell \in \{1, 2\}$ and $a \in gZ_jZ_\ell^{-1} \subseteq F_iX^2$ with $p_i(a) = Z_\ell$. So, $p'(a) = Z_\ell$, and hence $p(a) = Z_\ell$. Since $gZ_j \cap aZ_\ell \neq \emptyset$, this implies that $p(g) = \emptyset$.

□

3.3. Proof of Proposition 2.8. We can now start the proof of proposition 2.8. Assume that X , a finite symmetric subset of G , is given. We now seek to construct a strongly irreducible X -witness shift T . Since G satisfies proposition 2.7, we can let Y and s be a finite symmetric subset of G and a configuration on G that satisfy the statement of proposition 2.7 for $X \subseteq G$.

Let P be the strongly irreducible shift given by Claim 3.8 for $Z_1 = Y^{100}X$ and $Z_2 = YX$.

Define $\psi : P \rightarrow 2^G$ by

$$[\psi(p)](g) = \begin{cases} s(h^{-1}g) & \text{if } g \in hY^{100} \text{ for some } h \in G \\ & \text{with } p(h) = Y^{100}X \\ s(h^{-1}g) & \text{if } g \in hY \text{ for some } h \in G \\ & \text{with } p(h) = YX \\ 0 & \text{otherwise.} \end{cases}$$

What ψ does is produce a configuration which is 0 outside of the X -interior⁵ of blocks, and is equal to translates of $s|_{Y^{100}}$ and $s|_Y$ inside the interior of blocks.

⁵The X -interiors of $Y^{100}X$ and YX are Y^{100} and Y .

It is again easy to see that ψ is continuous and equivariant, so $T = \psi(P)$ is a strongly irreducible shift. The following claim completes the proof of proposition 2.8.

Claim 3.9. *T is an X -witness shift.*

The claim follows immediately from the following two lemmas. The first of the lemmas is straightforward from our construction, while the second is less immediate.

Lemma 3.10. *For all $t \in T$, the 1's in t are X -apart.*

Proof. Let $t \in T$ and $a, b \in G$ with $t(a) = t(b) = 1$. Since $t \in T$, there is a $p \in P$ with $\psi(p) = t$. By the definition of ψ , since $[\psi(p)](a) = [\psi(p)](b) = 1$, we get that $a \in hp(h)$ and $b \in gp(g)$ for some $h, g \in G$. If $g = h$, i.e. a and b are in the same block of p , then $s(h^{-1}a) = t(a) = 1$ and $s(h^{-1}b) = t(b) = 1$. But, since s satisfies proposition 2.7 (in particular, the 1's in s are X -apart), $h^{-1}a$ and $h^{-1}b$ are X -apart, which implies a and b are X -apart. If $g \neq h$, then $hp(h)$ and $gp(g)$ are disjoint, so the X -interior of $hp(h)$ and the X -interior of $gp(g)$ are X -apart. We also know that a is in the X -interior of $hp(h)$ and b is in the X -interior of $gp(g)$. Therefore, a and b are X -apart. \square

Lemma 3.11. *For any $t_1, t_2 \in T$ there is an $a \in G$ with $t_1(a) = t_2(a) = 1$.*

Proof. We essentially prove this lemma by a series of reductions.

Let $t_1, t_2 \in T$. So there are $p_1, p_2 \in P$ with $\psi(p_1) = t_1$ and $\psi(p_2) = t_2$. Pick an $a_1 \in G$ with $p_1(a_1) = Y^{100}X$. This means that $a_1^{-1}p_1$ has a block of shape $Y^{100}X$ centered at the identity. Let $p'_1 = a_1^{-1}p_1$, $p'_2 = a_1^{-1}p_2$, and let $t'_1 = \psi(p'_1)$, $t'_2 = \psi(p'_2)$. So, p'_1 has a block of shape $Y^{100}X$ centered at the identity.

Since p'_2 is saturated, we know there is an $a_2 \in Y^4$ such that either (I) a_2 is in the YX -interior of a block of shape $Y^{100}X$ in p'_2 , or (II) a_2 is the center of a block of shape YX in p'_2 . Let $p''_1 = a_2^{-1}p'_1$, $p''_2 = a_2^{-1}p'_2$, and let $t''_1 = \psi(p''_1)$, $t''_2 = \psi(p''_2)$. Observe that in p''_1 the identity is in the YX -interior of a block of shape $Y^{100}X$, say $e \in k_1Y^{99}$ for some $k_1 \in G$ with $p''_1(k_1) = Y^{100}X$. Moreover, in p''_2 the identity is either (I) in the YX -interior of a block of shape $Y^{100}X$ or (II) in the center of a block of shape YX .

In case (I), since in p''_2 the identity is in the YX -interior of a block of shape $Y^{100}X$, $e \in k_2Y^{99}$ for some $k_2 \in G$ with $p''_2(k_2) = Y^{100}X$. So $k_2^{-1} \in Y^{99}$. By the second part of proposition 2.7 applied to $g = k_1^{-1}$ and $h = k_2^{-1}$, we know that there is an $a_3 \in Y$ such that $s(k_1^{-1}a_3) = s(k_2^{-1}a_3) = 1$. So, by the definition of ψ , the fact that $k_1^{-1}a_3 \in Y^{100}$,

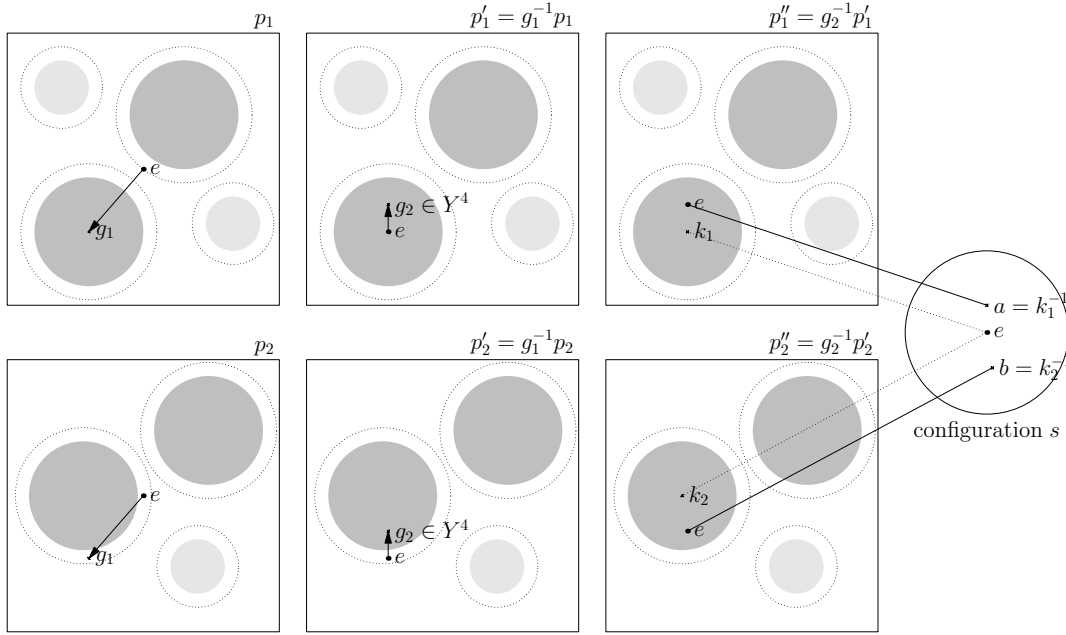


FIGURE 1. Case (I).

and the fact that $p''_1(k_1) = Y^{100}X$, we get $t''_1(a_3) = s(k_1^{-1}a_3) = 1$, and similarly, we get $t''_2(a_3) = s(k_2^{-1}a_3) = 1$. Therefore, $t_1(a_1a_2a_3) = t''_1(a_3) = 1$ and $t_2(a_1a_2a_3) = t''_2(a_3) = 1$. Case (I) is schematically depicted in Figure 1.

In case (II), $p''_2(e) = YX$. Again, if we apply the second part of proposition 2.7 to $g = k_1^{-1}$ and $h = e$, we get that there is an $a_3 \in Y$ such that $s(k_1^{-1}a_3) = s(a_3) = 1$. So, by the definition of ψ , the fact that $k_1^{-1}a_3 \in Y^{100}$, and the fact that $p''_1(k_1) = Y^{100}X$, we get $t''_1(a_3) = s(k_1^{-1}a_3) = 1$. Also, by the definition of ψ , the fact that $a_3 \in Y$, and the fact that $p''_2(e) = YX$, we get $t''_2(a_3) = s(a_3) = 1$. Therefore, $t_1(a_1a_2a_3) = t''_1(a_3) = 1$ and $t_2(a_1a_2a_3) = t''_2(a_3) = 1$. Case (II) is schematically depicted in Figure 2.

In both cases we showed there is an $a \in G$ with $t_1(a) = t_2(a) = 1$. This completes the proof. \square

3.4. Proof of Proposition 2.10. Fix $\epsilon > 0$ and X a finite symmetric subset of G . Without loss of generality, we may assume that X includes the identity, and is large enough so that any two configurations that agree on X have distance less than ϵ .

Since $T \subseteq A^G$ is a strongly irreducible shift, there is a finite symmetric $U \subseteq G$ including the identity such that for any two subsets $E_1, E_2 \subseteq G$ with $E_1U \cap E_2U = \emptyset$ and any two configurations $t_1, t_2 \in T$

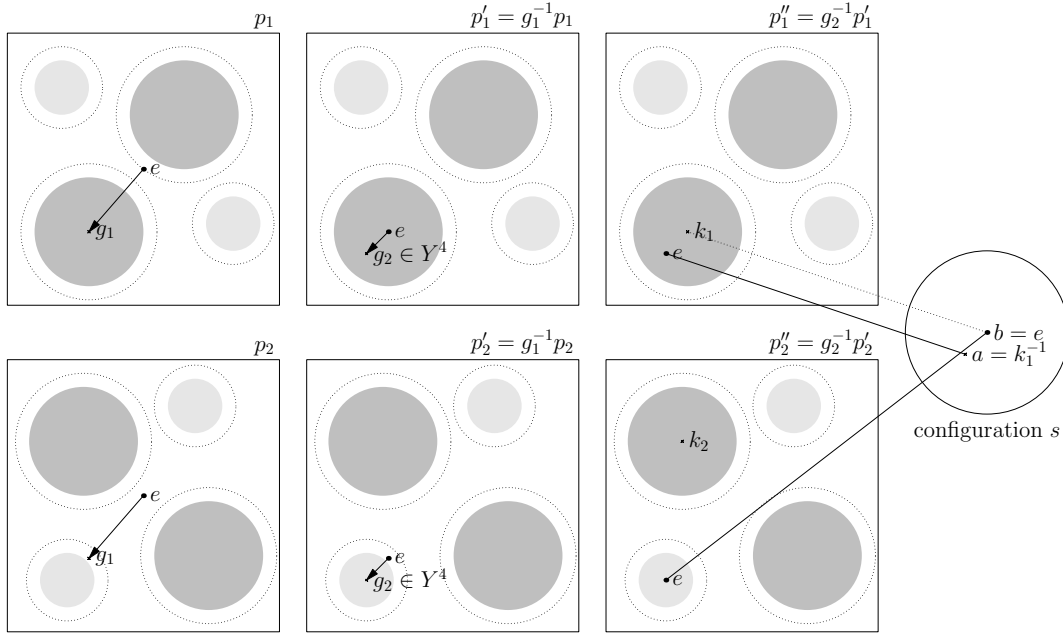


FIGURE 2. Case (II).

there is a configuration $t \in T$ such that t restricted to E_1 equals t_1 restricted to E_1 , and t restricted to E_2 equals t_2 restricted to E_2

Given a shift $S \subseteq A^G$ and a finite $Y \subset G$, we call a map $p: Y \rightarrow A$ a Y -*pattern* of S if it is equal to $s|_Y$, the restriction of some $s \in S$ to Y . In this case we say that s contains the Y -pattern p .

By strong irreducibility of T , we can find a $u \in T$ whose orbit $\{gu : g \in G\}$ contains all the X -patterns of T . Furthermore, since there are only finitely many X -patterns in T , there must be a finite $V \subset G$ (which we assume w.l.o.g. to be symmetric and contain the identity) such that $\{gu : g \in \text{the } X\text{-interior of } V\}$ contains all the X -patterns of T . By making V even larger, we can assume that $d(t, t') < \varepsilon$ for any two configurations $t, t' \in T$ that agree on V , where $d(\cdot, \cdot)$ is the metric on T .

Let $Z = (VU^2X)(VU^2X)^{-1}$. By the assumption in the statement, there is a strongly irreducible Z -witness shift for G . Call this shift S .

Now, define a continuous equivariant function $\phi: S \times T \rightarrow A^G$. Let $t' = \phi(s, t)$ be defined as follows, in the following cases:

- (1) $g = kh$ for some $k \in G$ with $s(k) = 1$ and some $h \in V$:
In this case, let $t'(g) = u(h)$.
- (2) $g = kh$ for some $k \in G$ with $s(k) = 1$ and some $h \in VU^2 \setminus V$:

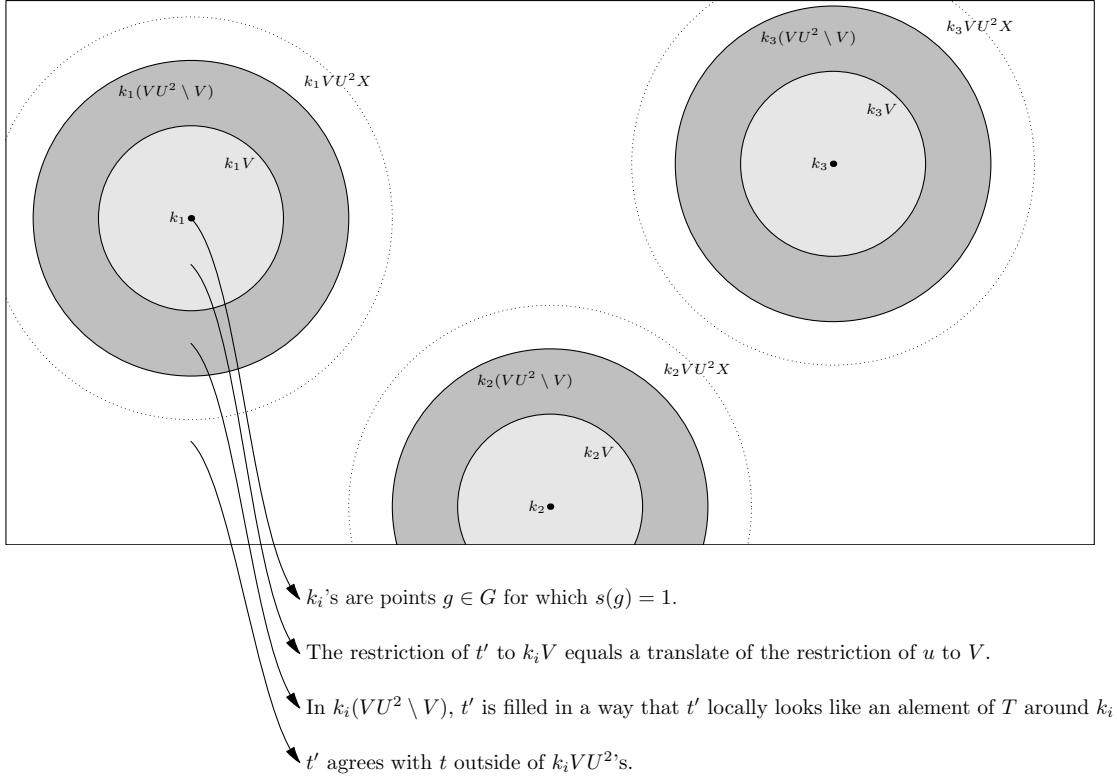


FIGURE 3. $t' = \phi(s, t)$ for $s \in S$ and $t \in T$.

In this case let $E_1 = kV$ and $E_2 = kVU^2X^2 \setminus kVU^2$. Since $E_1U \cap E_2U = \emptyset$, there is a $v \in T$ with $v|_{E_1} = (ku)|_{E_1}$ and $v|_{E_2} = t|_{E_2}$. If there are multiple choices for v , choose the v such that the restriction of $k^{-1}v$ to $F = VU^2X^2 \setminus VU^2$ is lexicographically least for a fixed ordering of F and a fixed ordering of A . Let $t'(g) = v(kh)$.

- (3) $g \neq kh$ for $s(k) = 1$ and $h \in VU^2$:

In this case, let $t'(g) = t(g)$.

Since the 1's in S are Z -apart, this leads to a well-defined definition for t' . Informally, t' is constructed from t as follows: the configuration t' mostly agrees with t . The first exceptions are the V -neighborhoods of any $k \in G$ such that $s(k) = 1$, where we set t' to equal the pattern that appears around the origin in u . The second exceptions are the borders of these V -neighborhoods, where some adjustments need to be made so that—as we explain below— t' and t agree on any translate of X . This construction is schematically depicted in Figure 3.

The following hold:

- ϕ is continuous and equivariant. So $T' = \phi(S \times T)$ is a shift.
- Since strong irreducibility is closed under taking products and factors, we see that T' is strongly irreducible.
- Let $t'_1 = \phi(s_1, t_1), t'_2 = \phi(s_2, t_2) \in T'$. Since S is a $(VU^2X)(VU^2X)^{-1}$ -witness shift, there is a $g \in G$ with $s_1(g) = s_2(g) = 1$. So, $t'_1|_{gV}$ and $t'_2|_{gV}$ are both translates of $u|_V$, which means $(g^{-1}t'_1)|_V = (g^{-1}t'_2)|_V$. So from the definition of V , we get $d(g^{-1}t'_1, g^{-1}t'_2) < \epsilon$. Hence T' is ϵ -proximal.
- Now we claim that the set of X -patterns of T' and T are equal.
 First note that since $u|_V$ has all the X -patterns in T , and $u|_V$ appears in T' , we get that all the X -patterns of T appear in T' .
 Now let $t' = \phi(s, t) \in T'$ and fix an X -pattern in t' , located at gX . If gX does not meet any $k(VU^2)$ for $s(k) = 1$, then $t'|_{gX} = t|_{gX}$ and so the pattern appears in T . If, on the other hand, gX intersects $k(VU^2)$ for some k with $s(k) = 1$ (note that there is at most one such k), we have $gX \subseteq k(VU^2X^2)$, and by the definition of t' around k , we again see that the pattern in gX appears in T .
- To see ϵ -minimality of T' , let $t'_1, t'_2 \in T'$. We know that $t'_2|_X$ is one of the X -patterns in T , so it appears somewhere in t'_1 , i.e. there exists a $g \in G$ such that $(gt'_1)|_X$ agrees with $t'_2|_X$. We assumed that any two configurations that agree on X have distance less than ϵ . So, $d(gt'_1, t'_2) < \epsilon$.

This concludes the proof of Proposition 2.10.

3.5. Proof of Claim 2.5. First we prove proximal shifts are a G_δ . Given a shift S , an $\epsilon > 0$ and a $g \in G$, let $P_g \subset S \times S$ be the set of pairs of configurations s_1, s_2 such that $d(gs_1, gs_2) < \epsilon$. Since P_g is the preimage of an open set under a continuous map P_g is open. Thus, whenever S is ϵ -proximal the collection $\{P_g : g \in G\}$ forms an open cover of $S \times S$ and thus, by compactness, whenever a shift is ϵ -proximal there is a finite subset $X \subset G$ which suffice to demonstrate this. For each $X \subset G$, whether X demonstrates ϵ -proximality is determined by the restriction of S to a finite set of elements of G . But this is exactly the definition of a clopen set in the topology on the space of shifts. Thus the set of ϵ -proximal shifts is the union of a collection of clopen sets and is therefore open.

Now we prove minimal shifts are a G_δ . To do this, since minimal shifts are exactly the shifts that are ϵ -minimal for all $\epsilon > 0$, it is enough to show that the set of ϵ -minimal shifts is open. Note that by compactness of X , a shift is ϵ -minimal iff its ϵ -minimality is demonstrated by a finite set. Thus ϵ -minimality is determined by the set of Z -patterns

for a finite large enough $Z \subseteq G$. So, as above, the set of ε -minimal shifts is a union of clopen sets, so it is open.

3.6. Proof of Proposition 2.12. By Proposition 2.11 the minimal proximal shifts are a dense G_δ in \mathcal{S} . It thus remains to be shown that faithfulness is also generic. Given an element $g \in G$ call a shift g -faithful if g acts non-trivially on the shift. It is easy to see that g -faithfulness is an open condition, and so the intersection over all non-trivial $g \in G$, which is faithfulness of the action of G , is a G_δ set. It remains to show that it is dense. To do this we show that each non-trivial $g \in G$ acts non-trivially on every non-trivial strongly irreducible shift. Suppose g is not the identity and acts trivially on a shift S . Then all conjugates of g also act trivially on S , so that $hs = s$ for every h a conjugate of g and $s \in S$. In particular, $s(h^{-1})$ must be the same for every h a conjugate of g and every $s \in S$. Since g has an infinite conjugacy class this holds for infinitely many such h . But if S is strongly irreducible and non-trivial, then there is some finite $X \subset G$ such that, if $h \notin X$ then there is an $s \in S$ such that $s(h) \neq s(e)$. Thus g must act non-trivially on every non-trivial strongly irreducible shift, and so we have proved the claim.

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