PARTIAL DYNAMICAL SYSTEMS AND $C^*$-ALGEBRAS GENERATED BY PARTIAL ISOMETRIES

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Abstract. A collection of partial isometries whose range and initial projections satisfy a specified set of conditions often gives rise to a partial representation of a group. The $C^*$-algebra generated by the partial isometries is thus a quotient of the universal $C^*$-algebra for partial representations of the group, from which it inherits a crossed product structure, of an abelian $C^*$-algebra by a partial action of the group. Questions of faithfulness of representations, simplicity, and ideal structure of these $C^*$-algebras can then be addressed in a unified manner from within the theory of partial actions. We do this here, focusing on two key properties of partial dynamical systems, namely amenability and topological freeness; they are the essential ingredients of our main results in which we characterize faithful representations, simplicity and the ideal structure of crossed products. As applications we consider three situations involving $C^*$-algebras generated by partial isometries: partial representations of groups, Toeplitz algebras of quasi-lattice ordered groups, and Cuntz-Krieger algebras. These $C^*$-algebras share a crossed product structure which we give here explicitly and which we use to study them in terms of the underlying partial actions.

Introduction

In this paper we develop tools to analyze partial dynamical systems and use them in our general approach to $C^*$-algebras generated by partial isometries. We realize the universal $C^*$-algebra for partial representations of a group subject to relations as the crossed product by a partial action of the group on a commutative $C^*$-algebra. A key feature of our method is the explicit description of the spectrum of this commutative $C^*$-algebra in terms of the specified relations. Our work builds upon [8], where a certain crossed product is shown to be universal for the partial representations of a group.

We begin by reviewing the definition and basic construction of crossed products by partial actions in Section 1; we also establish the one-to-one correspondence between covariant representations of a partial dynamical system and representations of the associated crossed product.

In Section 2 we adapt the notion of topological freeness for group actions [1] to the context of partial actions on abelian $C^*$-algebras. The main technical result is Theorem 2.6, where we show that for a locally compact Hausdorff space $X$ the ideals in the reduced crossed product of $C_0(X)$ by a topologically free partial action of a discrete group $G$ necessarily intersect $C_0(X)$ nontrivially; hence a representation of the reduced crossed product is faithful if and only if it

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is faithful on $C_0(X)$. This leads to a sufficient condition for simplicity of the reduced crossed product in Corollary 2.9.

In Section 3, we consider invariant ideals of a partial action and the ideals they generate in the crossed product. In Proposition 3.1, we give a general short exact sequence relating an invariant ideal of a partial action, the corresponding ideal of the crossed product, and the crossed product by the quotient partial action. After discussing the approximation property introduced in [9], which implies amenability of a partial action and hence equality of the full and reduced crossed products, we prove Theorem 3.2, the main result of the section. Specifically, the result is that if a partial action has the approximation property and is topologically free on closed invariant subsets, then the ideals of the crossed product are in one-to-one correspondence with the invariant ideals, and hence with invariant open subsets under the partial action.

We begin Section 4 by introducing a class of partial dynamical systems arising from partial representations whose range projections satisfy a given set of relations. In Proposition 4.1, we describe the spectrum associated to the relations and give a canonical partial action of the group on this spectrum. The resulting crossed product has a universal property with respect to partial representations of the group satisfying the relations, this is proved in Theorem 4.4, the main result of the section. It is through this that the results of the first three sections become available to study the C*-algebras generated by partial representations subject to relations.

In the final three sections, we apply the main results to three concrete situations. In Section 5, we show that the partial dynamical system canonically associated to a discrete group in [8] is topologically free if and only if the group is infinite. Since the reduced partial C*-algebra of such a group is a crossed product by a partial action, we are able to characterize its faithful representations. In Section 6, we realize the Toeplitz C*-algebras associated by Nica in [16] to quasi-lattice ordered groups as crossed products by partial actions. We show that the corresponding partial dynamical systems are topologically free, and from this we strengthen a result from [14] by showing that a representation of the generalized Toeplitz algebra is faithful if and only if it is faithful on the diagonal.

In Section 7, we realize the Cuntz-Krieger algebra $O_A$ associated to a $\{0,1\}$-valued $n \times n$ matrix $A$ as a crossed product by a partial action of the free group on $n$ generators. We relate the properties of the spectrum of the Cuntz-Krieger relations to properties of the matrix $A$. In particular, we show that the condition (I) of Cuntz and Krieger [5] corresponds to topological freeness, and this enables us to deduce the Cuntz-Krieger uniqueness theorem from the results of Section 6 and an amenability result from [9]. Our description of the crossed product realizations of the Toeplitz and the Cuntz-Krieger algebras will be explicit, as opposed to the indirect method of [20].

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1. Crossed products by partial actions.

Let $\alpha$ be a partial action of the discrete group $G$ on the C*-algebra $A$ in the sense of [5, 13, 8, 20]. We denote by $D_t$ the range of $\alpha_t$ for each $t \in G$, and we say that the triple $(A, G, \alpha)$ is a partial dynamical system. There are two C*-algebras associated with a partial dynamical system: the full crossed product and the reduced crossed product, cf. [1, 13]. These are defined, in analogy with the crossed products of group actions, as certain C*-completions
of the convolution ∗-algebra of $A$-valued $\ell^1$-functions on the group. As such, they contain the collection of finite sums $\{\sum_i a_i \delta_t : a_i \in D_t\}$ as a dense ∗-subalgebra. It is also possible to view the full crossed product as a universal $C^*$-algebra for covariant representations as in [20]. Since we will exploit this point of view, we briefly review some definitions and basic facts.

**Definition 1.1.** [8 Definition 6.2] A partial representation of a group $G$ on a Hilbert space $H$ is a map $u$ from $G$ into the bounded linear operators on $H$ such that

(i) $u(e) = 1$,
(ii) $u(t^{-1}) = u(t)^*$ and
(iii) $u(s)u(t)u(t^{-1}) = u(st)u(t^{-1})$ for $s, t \in G$.

Note that these conditions imply that the $u_t$ are partial isometries on $H$. An equivalent definition which is sometimes easier to verify is given in [20, Definition 1.7], where one only requires that the $u_t$ be partial isometries with commuting range projections, satisfying $u(e)u(e)^* = 1$, $u(s)^*u(s) = u(s^{-1})u(s^{-1})^*$, and that $u(st)$ extends $u(s)u(t)$ in the sense of [20, Lemma 1.6]. The equivalence is proved in [20, Lemma 1.8].

We will use the following definition of covariant representations of partial actions.

**Definition 1.2.** A covariant representation of the partial dynamical system $(A, G, \alpha)$ on a Hilbert space $H$ is a pair $(\pi, u)$ in which $\pi$ is a nondegenerate representation of $A$ on $H$ and $u$ is a partial representation of $G$ on $H$ such that for each $t \in G$ we have that $u_t u_t^*$ is the projection onto the subspace $\text{span}_t \pi(D_t)H$ and

$$\pi(\alpha_t(a)) = u_t \pi(a) u_{t^{-1}}^{-1}, \quad a \in D_{t^{-1}}.$$  

As in the case of actions of groups, covariant representations of a partial action correspond to representations of the associated crossed product. This correspondence was first proved in [3, Propositions 5.5 and 5.6] in the case of a single partial automorphism, and it was generalized to partial actions of discrete groups in [13, Propositions 2.7 and 2.8]. Our definition of covariant representations is slightly different from those of [3, 13], but this poses no problem because the various definitions have been shown to be equivalent [20, Remark 1.12], see also [20, Section 3]. We state the results in the following Proposition and Theorem, and include proofs based on our Definition of covariant representations for the convenience of the reader.

**Proposition 1.3.** Let $(\pi, u)$ be a covariant representation of $(A, G, \alpha)$ on $H$. Then there exists a (necessarily unique) representation, denoted $\pi \times u$, of $A \rtimes_{\alpha} G$ on $H$, such that

$$\pi \times u(a \delta_t) = \pi(a) u_t,$$

for all $t$ in $G$ and all $a$ in $D_{t^{-1}}$.

**Proof.** Let $\ell^1(G, A)$ be the $\ell^1$-algebra associated to the partial dynamical system $(A, G, \alpha)$. If $b \in \ell^1(G, A)$, i.e., if $b = \sum_{t \in G} a_t \delta_t$, where each $a_t \in D_t$ and $\|b\|_1 = \sum_{t \in G} \|a_t\| < \infty$, then put

$$\rho(b) = \sum_{t \in G} \pi(a_t) u_t.$$

Clearly, $\rho$ is a bounded linear map under the $\ell^1$-norm. We claim that $\rho$ is a representation of $\ell^1(G, A)$. To prove this claim suppose that $a \in D_t$ and $b \in D_s$. Then

$$\rho(a \delta_t) \rho(b \delta_s) = \pi(a) u_t \pi(b) u_s = u_t u_{t^{-1}} \pi(a) u_t \pi(b) u_s,$$

because $u_t u_{t^{-1}}$ is the orthogonal projection onto $H_t$, which contains the range of $\pi(a)$. Also, $u_{t^{-1}} u_t$, being the projection onto $H_{t^{-1}}$, will commute with any $\pi(b)$, since the latter leaves
$H_{t-1}$ invariant. Therefore, the above equals
\[ u_t u_{t-1} \pi(a) u_t u_{t-1} u_t \pi(b) u_s = u_t u_{t-1} \pi(a) u_t \pi(b) u_{t-1} u_t u_s = u_t \pi(\alpha_{t-1}(a)) \pi(b) u_{t-1} u_{ts} = \pi(\alpha_t(\alpha_{t-1}(a)b)) u_{ts}. \]

By definition, the product in $A \rtimes_\alpha G$ is given by
\[ (a \delta_t)(b \delta_s) = \alpha_t(\alpha_{t-1}(a)b) \delta_{ts}, \]

hence $\rho$ is multiplicative. We leave for the reader to complete the proof of the claim by verifying that $\rho$ also preserves the star operation. Since the crossed product is the enveloping $C^*$-algebra of $\ell^1(G, A)$, the *-homomorphism $\rho$ extends to the desired representation of $A \rtimes_\alpha G$. \hfill \Box

**Theorem 1.4.** Let $\alpha$ be a partial action of the group $G$ on the $C^*$-algebra $A$, and let $H$ be a Hilbert space. Then the map
\[ (\pi, a) \mapsto \pi \times a \]

is a one-to-one correspondence between covariant representations of $(A, G, \alpha)$ on $H$ and non-degenerate representations of $A \rtimes_\alpha G$ on $H$.

**Proof.** Let $\rho$ be a non-degenerate representation of $A \rtimes_\alpha G$ on $H$. Identify $A$ with its isomorphic copy $A \delta_e$ within $A \rtimes_\alpha G$ and denote by $\pi$ the restriction of $\rho$ to $A$.

For each $t \in G$ let $H_{t-1}$ be the closure of the linear space consisting of the vectors of the form $\eta = \sum_{i=1}^n \pi(a_i) \xi_i$, with $a_i \in D_{t-1}$ and $\xi_i \in H$. For each such $\eta$ define
\[ u_t(\eta) = \sum_{i=1}^n \rho(\alpha_t(a_i)) \delta_t \xi_i. \]

We claim that $u_t$ extends to an isometry $H_{t-1} \to H_t$. To see this let us study the norm of the right hand side of (1.1). We have
\[ \left\| \sum_{i=1}^n \rho(\alpha_t(a_i)) \delta_t \xi_i \right\|^2 = \left\langle \sum_{i,j=1}^n \rho((\alpha_t(a_j)) \delta_t^* \alpha_t(a_i)) \delta_t \xi_i, \xi_j \right\rangle. \]

It is easy to see that $(\alpha_t(a_j)) \delta_t^* \alpha_t(a_i) \delta_t = a_j^* a_i \delta_e$, and hence the above equals
\[ \left\langle \sum_{i,j=1}^n \pi(\alpha_t(a_i)) \xi_i, \xi_j \right\rangle = \left\| \pi(\alpha_t(a_i)) \xi_i \right\|^2 = \left\| \eta \right\|^2. \]

It follows easily that $u_t$ is a well-defined linear isometry on its domain of definition $\text{span}\{\pi(a) \xi : a \in D_{t-1}, \xi \in H\}$. Hence $u_t$ extends to an isometry, also denoted by $u_t$, on $H_{t-1} = \overline{\text{span}\{\pi(a) \xi : a \in D_{t-1}, \xi \in H\}}$. Next we show that the range of $u_t$ is precisely $H_t$.

If $\{e_\lambda\}$ is an approximate unit for $D_t$, we have, for all $a \in D_{t-1}$, and $\xi \in H$, that
\[ \rho(\alpha_t(a)) \xi = \lim_\lambda \rho(e_\lambda a \alpha_t(a)) \delta_t \xi = \lim_\lambda \pi(e_\lambda) \rho(\alpha_t(a)) \delta_t \xi, \]

which shows that $\rho(\alpha_t(a)) \xi \in H_t$ and hence that the range of $u_t$ is a subset of $H_t$. Conversely, given $a \in D_t$, observe that
\[ a = \lim_\lambda a e_\lambda = \lim_\lambda (a \delta_t) (\alpha_{t-1}(e_\lambda) \delta_{t-1}), \]

and hence, for all $\xi \in H$, we have
\[ \pi(a) \xi = \lim_\lambda \rho(a \delta_t) \rho(\alpha_{t-1}(e_\lambda) \delta_{t-1}) \xi = \lim_\lambda u_t \left( \pi(\alpha_{t-1}(a)) \rho(\alpha_{t-1}(e_\lambda) \delta_{t-1}) \xi \right), \]
proving that $H_t$ is contained in the range of $u_t$.

Consider next the extension of $u_t$ to all of $H$ defined by setting $u_t = 0$ on the orthogonal complement of $H_{t-1}$. In this way, $u_t$ becomes a partial isometry on $H$, and it is clear that its range projection, namely $u_t u_t^*$, coincides with the orthogonal projection onto $H_t$.

We claim that the map $t \mapsto u_t$ is a partial representation of $G$.

We prove $u_{t-1} = u_t^*$ first. For this purpose, let $a \in D_{t-1}$ and $\xi \in H$. We then have that

$$u_{t-1} u_t (\pi(a) \xi) = u_{t-1} \rho(a_\lambda(a) \delta_t) \xi.$$ 

Choose an approximate unit $\{e_\lambda\}$ for $D_t$, so that the above equals

$$\lim_\lambda u_{t-1} \rho(a_\lambda(a)e_\lambda \delta_t) \xi = \lim_\lambda u_{t-1} \pi(a_\lambda(a)) \rho(e_\lambda \delta_t) \xi$$

$$= \lim_\lambda \rho(a_\delta_{t-1}) \rho(e_\lambda \delta_t) \xi = \lim_\lambda \rho(a_\delta_{t-1} e_\lambda \delta_t) \xi$$

$$= \lim_\lambda \pi(\alpha_{\delta_{t-1}}(e_\lambda)) \xi = \pi(a) \xi,$$

where the last equality holds because $\{\alpha_{\delta_{t-1}}(e_\lambda)\}$ is an approximate unit for $D_{t-1}$. This shows that $u_{t-1} u_t$ coincides with the orthogonal projection onto $H_{t-1}$, which is precisely the initial space of $u_t$. In other words

$$u_{t-1} u_t = u_t^* u_t.$$ 

Is is evident that the initial space of $u_{t-1}$ is $H_t$, which is also the final space of $u_t$, that is,

$$u_{t-1}^* u_{t-1} = u_t u_t^*.$$ 

So, employing the last two formulas we obtain

$$u_{t-1} = u_{t-1} u_{t-1} u_{t-1} = u_{t-1} u_t u_t^* = u_t^* u_t u_t^* = u_t^*.$$ 

Since $\rho$ was supposed non-degenerate, it follows that $\pi$ is also non-degenerate (because any approximate unit for $A$ is also an approximate unit for $A \rtimes_\alpha G$). Therefore $H_{e} = \pi(A) H = H$ and it is not hard to see that $u_e$ is the identity operator on $H$.

The last axiom of partial representations to be checked is

$$\rho = \pi(A) H = H$$

$$u_t u_s u_{s-1} = u_t u_s u_{s-1},$$

which we now set out to prove. A crucial observation in this respect is that for each $t$ in $G$, the orthogonal projection onto $H_t$, which we shall henceforth denote by $p_t$, lies in the center of the von Neumann subalgebra of $B(H)$ generated by $\pi(A)$. In particular this implies that the projections $p_{t} = u_t u_{t-1}$ commute with each other.

Since the left hand side of (1.2) satisfies

$$u_t u_s u_{s-1} = u_t u_s u_{s-1} u_t u_s u_{s-1} = u_t p_{t-1} p_s,$$

we see that it vanishes on the orthogonal complement of $H_{t-1} \cap H_s$. Incidentally, it is not hard to see that $H_{t-1} \cap H_s = \pi(D_{t-1} \cap D_s) H$.

Let $\xi \in \pi(D_{t-1} \cap D_s) H$ and suppose that $\xi$ has the form $\xi = \pi(ab)\eta$, where $a$ and $b$ are in $D_{t-1} \cap D_s$ and $\eta \in H$. It is clear that the closed linear span of the set of all such $\xi$'s is equal to $H_{t-1} \cap H_s$. We have

$$u_{ts} u_{s-1} \xi = u_{ts} u_{s-1} \pi(ab) \eta = u_{ts} \rho(\alpha_{s-1}(ab) \delta_{s-1}) \eta$$

$$= u_{ts} \pi(\alpha_{s-1}(a)) \rho(\alpha_{s-1}(b) \delta_{s-1}) \eta$$

$$= \rho(\alpha_{ts}(\alpha_{s-1}(a)) \delta_s) \rho(\alpha_{s-1}(b) \delta_{s-1}) \eta$$

$$= \rho(\alpha_t(a) \delta_s \alpha_{s-1}(b) \delta_{s-1}) \eta = \rho(\alpha_t(a) \alpha_t(b) \delta_t) \eta = u_t \xi.$$
This shows that \( u_{ts}u_{s^{-1}} \) coincides with \( u_t \) on \( H_{t^{-1}} \cap H_s \). This can be expressed by saying that
\[
(1.3) \quad u_{ts}u_{s^{-1}}p_{t^{-1}}p_s = u_tp_{t^{-1}}p_s,
\]
which is easily seen to imply that
\[
(1.4) \quad u_{ts} = u_t p_{t^{-1}}.
\]
Taking adjoints, we get
\[
(1.5) \quad p_s u_{t^{-1}} = p_{t^{-1}} u_s u_{(ts)^{-1}},
\]
and, replacing \( s \) by \((ts)^{-1}\) and \( t \) by \( s \), we have
\[
(1.6) \quad p_{(ts)^{-1}} u_s^{-1} = p_{s^{-1}} u_{(ts)^{-1}} u_t
\]
Next, observe that the right hand side of (1.2) satisfies
\[
(1.7) \quad u_{ts}u_{s^{-1}} = u_{ts} p_{(ts)^{-1}} u_{s^{-1}},
\]
hence, using (1.5) on the right-hand-side,
\[
(1.8) \quad u_{ts}u_{s^{-1}} = u_{ts} p_{s^{-1}} u_{(ts)^{-1}} u_t.
\]
The precise form of this last identity is not absolutely crucial, except for the fact that \( u_t \)
appears as the last factor in the right hand side. Since \( u_t = u_t p_{t^{-1}} \), we conclude that \( u_{ts}u_{s^{-1}} \)
is likewise not affected by right multiplication by \( p_{t^{-1}} \). Using (1.3), we see that
\[
(1.9) \quad u_{ts}u_{s^{-1}} = u_{ts}u_{s^{-1}}p_{t^{-1}} = u_{tp} = u_{ts}u_{s^{-1}},
\]
proving (1.2).

Thus \( u \) is a partial representation of \( G \) on \( H \). To see that it satisfies the covariance equation
\[
(1.6) \quad u_t \pi(a)u_{t^{-1}} = \pi(\alpha_t(a)), \quad a \in D_{t^{-1}},
\]
observe that both sides of this equation represent operators vanishing on the orthogonal complement of \( H_t \). Thus it suffices to prove that they coincide when applied to vectors of the form
\[
\pi(b)\xi, \quad b \in D_t
\]
We have
\[
u_t \pi(a)u_{t^{-1}} \pi(b)\xi = \rho(\alpha_t(a)\delta_t)\rho(\alpha_{t^{-1}}(b)\delta_{t^{-1}})\xi
= \rho(\alpha_t(a)b)\xi = \pi(\alpha_t(a))\pi(b)\xi,
\]
finishing the proof of (1.6).

We claim next that the representation \( \pi \times u \) associated to the covariant representation \( (\pi, u) \) coincides with \( \rho \). To prove this suppose \( \eta = \pi(b)\xi, \) with \( b \in A \), and recall that \( \pi \) is non-degenerate, so the set of these \( \eta \)'s is dense in \( H \). Then for all \( a \in D_t \)
\[
\rho(\alpha\delta_t)\eta = \rho(\alpha\delta_t)\pi(b)\xi = \rho(\alpha\delta_t b\delta_e)\xi = \rho(\alpha\alpha_{t^{-1}}(a)\delta_t)\xi
= \lim_\lambda \rho(\alpha\alpha_{t^{-1}}(a)e_\lambda b\delta_t)\xi,
\]
where \( \{e_\lambda\} \) is an approximate unit for \( D_{t^{-1}} \). The above then equals
\[
\lim_\lambda \rho(\alpha\alpha_{t^{-1}}(e_\lambda b)\delta_t)\xi = \lim_\lambda \rho(a)\rho(\alpha_{t^{-1}}(e_\lambda b)\delta_t)\xi = \lim_\lambda \rho(a)u_t\pi(e_\lambda b)\xi
= \lim_\lambda \pi(a)u_{t^{-1}}\pi(e_\lambda)\pi(b)\xi = \pi(a)u_t\pi(b)\xi,
\]
where the last step follows from the fact that \( \pi(e_\lambda) \) converges, in the weak operator topology, to the projection onto \( H_{t^{-1}} \), which is the initial space of \( u_t \). This shows that \( \pi \times u = \rho \).

To conclude we must prove that \( (\pi, u) \) is the unique covariant representation such that \( \pi \times u = \rho \). Since we want \( \rho(\alpha\delta_e) = \pi(a)u_e, \) then clearly \( \pi \) is uniquely determined. Assuming
that \((\pi,v)\) is another covariant representation such that \(\pi \times v = \rho\), we have, for \(a,b \in D_{t-1}\) and \(\xi \in H\), that
\[
v_t \pi(ab) \xi = v_t \pi(a) v_{t-1} v_t \pi(b) \xi = \pi(\alpha_t(a)) v_t \pi(b) \xi = \rho(\alpha_t(a)) \delta_t \pi(b) \xi = u_t \pi(ab) \xi.
\]
Since the collection of vectors of the form \(\pi(ab) \xi\), as above, is dense in \(H_{t-1}\), we conclude that \(v_t = u_t\). 

\[\square\]

2. Topologically free partial actions.

We will mostly be concerned with partial actions arising from partial homeomorphisms of a locally compact space \(X\), so that for every \(t \in G\) there is an open subset \(U_t\) of \(X\) and a homeomorphism \(\theta_t : U_{t-1} \to U_t\) such that \(\theta_{st}\) extends \(\theta_s \theta_t\). The partial action \(\alpha\) of \(G\) on \(C_0(X)\) corresponding to \(\theta\) is given by
\[\alpha_t(f)(x) := f(\theta_{t-1}(x)), \quad f \in C_0(U_{t-1}).\]
So, here the ideals are \(D_t = C_0(U_t)\). We will talk about the partial action at either the topological or the \(C^*\)-algebraic level, according to convenience.

**Definition 2.1** (cf. [1]). The partial action \(\theta\) is topologically free if for every \(t \in G \setminus \{e\}\) the set \(F_t := \{x \in U_{t-1} : \theta_t(x) = x\}\) has empty interior.

We point out that although the set \(F_t\) need not be closed in \(X\), it is relatively closed in the domain \(U_{t-1}\) of \(\theta_t\). A standard argument gives the following equivalent version of topological freeness which is more appropriate for our purposes.

**Lemma 2.2.** The partial action \(\theta\) on \(X\) is topologically free if and only if for every finite subset \(\{t_1, t_2, \ldots, t_n\}\) of \(G \setminus \{e\}\), the set \(\bigcup_{t=1}^n F_{t}\) has empty interior.

**Proof.** It suffices to show that for every \(t \in G \setminus \{e\}\), the fixed point set \(F_t\) is nowhere dense (i.e., its closure in \(X\) has empty interior), and then use the fact that a finite union of nowhere dense sets is nowhere dense.

Since \(F_t\) is closed relative to \(U_t\) we can write \(F_t = C \cap U_t\) with \(C\) closed in \(X\). Suppose \(V \subset F_t\) is open. Since the set \(V \cap U_t\) is contained in \(C \cap U_t = F_t\), it must be empty, by the assumption of topological freeness. Thus \(V\) and \(U_t\) are disjoint open sets, so each one is disjoint from the other’s closure. But \(V \subset C \cap U_t \subset C \cap U_t \subset U_t\), so \(V\) itself is empty and hence \(F_t\) is nowhere dense. \(\square\)

**Lemma 2.3.** Let \(t \in G \setminus \{e\}\), \(f \in D_t\), and \(x_0 \notin F_t\). For every \(\epsilon > 0\) there exists \(h \in C_0(X)\) such that
\[
\begin{align*}
(i) & \quad h(x_0) = 1, \\
(ii) & \quad \|h(f \delta_t)h\| \leq \epsilon, \text{ and} \\
(iii) & \quad 0 \leq h \leq 1.
\end{align*}
\]

**Proof.** We separate the proof into two cases according to \(x_0\) being in the domain \(U_t\) of \(\theta_{t-1}\) or not. If \(x_0 \notin U_t\), let \(K := \{x \in U_t : |f(x)| \geq \epsilon\}\). Then \(K\) is a compact subset of \(D_t\) and \(x_0 \notin K\), so there is \(h \in C_0(X)\) such that \(0 \leq h \leq 1, h(x_0) = 1\) and \(h(K) = 0\). Since \(f\) is bounded by \(\epsilon\) off \(K\), it follows that \(\|hf\| \leq \epsilon\), so (ii) holds too.

If \(x_0 \in U_t\) then \(\theta_{t-1}(x_0)\) is defined and not equal to \(x_0\). Take disjoint open sets \(V_1\) and \(V_2\) such that \(x_0 \in V_1\) and \(\theta_{t-1}(x_0) \in V_2\). We may assume that \(V_1 \subset U_t\) and \(V_2 \subset U_{t-1}\).
Letting $V := V_1 \cap \theta_t(V_2)$, we have that $x_0 \in V \subset V_1$ and $\theta_{t-1}(V) \subset V_2$, from which it follows that $\theta_{t-1}(V) \cap V = \emptyset$. Take now $h \in C_0(X)$ such that $0 \leq h \leq 1$, $h(x_0) = 1$ and $h(X \setminus V) = 0$. It remains to prove that $h$ satisfies (ii). In fact, the product $hf_h \cdot h = \alpha_h(\alpha_{t-1}(hf_h))\delta_t$ vanishes because the support of $\alpha_{t-1}(hf)$ is contained in $\theta_{t-1}(V)$ and the support of $h$ is in $V$. \[\square\]

The reduced crossed product associated to a partial dynamical system in [15, \S3] can also be obtained as the reduced cross-sectional algebra of the Fell bundle determined by the partial action \[\square\] Definition 2.3.

This reduced crossed product is a topologically graded algebra and the conditional expectation, denoted by $E_r$, from $C_0(X) \rtimes_r G$ onto $C_0(X)$ is a faithful positive map \[\square\] Proposition 2.12] (see also \[18, Corollary 3.9 and Lemma 1.4\] and \[20, Corollary 3.8\]).

**Proposition 2.4.** If $(C_0(X), G, \alpha)$ is a topologically free partial action then for every $c \in C_0(X) \rtimes_r G$ and every $\epsilon > 0$ there exists $h \in C_0(X)$ such that:

(i) $\|hE_r(c)\| = \|E_r(c)\| - \epsilon$

(ii) $\|hE_r(c)h - hch\| \leq \epsilon$, and

(iii) $0 \leq h \leq 1$.

**Proof.** Assume first $c$ is a finite linear combination of the form $\sum_{t \in T} a_t \delta_t$, where $T$ denotes a finite subset of $G$, in which case $E_r(c) = a_e$ (where we put $a_e = 0$ if $e \notin T$). Let $V = \{x \in X : |a_e(x)| > \|a_e\| - \epsilon\}$, which is clearly open and nonempty. By Lemma 2.2 there exist $x_0 \in V$ such that $x_0 \notin F_t$ for every $t \in T \setminus \{e\}$, and by Lemma 2.3 there exist functions $h_t$ satisfying

$$h_t(x_0) = 1, \quad \|h_t(a_t \delta_t)h_t\| \leq \frac{\epsilon}{|T|}, \quad 0 \leq h_t \leq 1.$$ 

Let $h := \prod_{t \in T \setminus \{e\}} h_t$. Then (iii) is immediate, and (i) also holds because $x_0 \in V$ so $\|ha_e h\| \geq |a_e(x_0)| > \|a_e\| - \epsilon$. For (ii), we have

$$\|ha_e h - hah\| = \|\sum_{t \in T \setminus \{e\}} ha_t \delta_t h\|$$

$$\leq \sum_{t \in T \setminus \{e\}} \|ha_t \delta_t h\|$$

$$\leq \sum_{t \in T \setminus \{e\}} \|h_t a_t \delta_t h_t\|$$

$$< \epsilon.$$ 

Since the elements of the form $\sum_{t \in T} a_t \delta_t$ are dense in the crossed product and the conditional expectation $E_r$ is contractive, a standard approximation argument gives the general case. \[\square\]

**Remark 2.5.** It is easy to see that the Proposition also holds with the full crossed product replacing the reduced one.

**Theorem 2.6.** Suppose $(C_0(X), G, \alpha)$ is a topologically free partial action. If $I$ is an ideal in $C_0(X) \rtimes_r G$ with $I \cap C_0(X) = \{0\}$, then $I = \{0\}$. A representation of the reduced crossed product $C_0(X) \rtimes_r G$ is faithful if and only if it is faithful on $C_0(X)$.

**Proof.** Denote by $\pi : C_0(X) \rtimes_r G \to (C_0(X) \rtimes_r G)/I$ the quotient map, and let $a \in I$ with $a \geq 0$, so that $\pi(a) = 0$. Given $\epsilon > 0$ take $h \in C_0(X)$ satisfying conditions (i), (ii) and (iii) of Proposition 2.4. Then

$$\|\pi(hE_r(a)h)\| = \|\pi(h(E_r(a) - a)h)\| \leq \epsilon,$$
because $\pi(a) = 0$. Since $\pi$ is isometric on $C_0(X)$, because $I \cap C_0(X) = \{0\}$, it follows that $\|hE_r(a)h\| \leq \epsilon$. By Proposition 2.4 (i), $\|E_r(a)\| - \epsilon \leq \|hE_r(a)h\|$, so $\|E_r(a)\| \leq 2\epsilon$, and $E_r(a)$ has to vanish. Since the conditional expectation $E_r$ is faithful on the reduced crossed product this implies that $a = 0$ and hence that $I = \{0\}$. This proves the first assertion, which, applied to the kernel of a representation, gives the second one. \hfill \Box

**Definition 2.7.** A subset $V$ of $X$ is invariant under the partial action $\theta$ on $X$ if $\theta_s(V \cap U_{s-1}) \subset V$ for every $s \in G$.

An ideal $J$ in $C_0(X)$ is invariant under the corresponding partial action $\alpha$ on $C_0(X)$ if $\alpha_t(J \cap D_{t-1}) \subset J$ for every $t \in G$.

It is easy to see that if $U$ is an invariant open set then the associated ideal $C_0(U)$ is invariant and, conversely, every invariant ideal corresponds to an invariant open set.

**Definition 2.8.** The partial action $\theta$ on $X$ is minimal if there are no $\theta$-invariant open subsets of $X$ other than $\emptyset$ and $X$ or, equivalently, if the partial action $\alpha$ on $C_0(X)$ has no nontrivial proper invariant ideals.

The complement of an invariant set is invariant too, so the partial action is minimal if and only if it has no nontrivial proper closed invariant subsets.

**Corollary 2.9.** If a partial action is topologically free and minimal then the associated reduced crossed product is simple.

**Proof.** Suppose $J$ is the kernel of a representation $\rho$ of $C_0(X) \rtimes_r G$, and write $\rho = \pi \times \nu$ by Theorem 2.4. Then $J \cap C_0(X)$ is an ideal in $C_0(X)$ which is invariant under $\alpha$ because for every $f \in J \cap D_{t-1}$, we have, by covariance, that $\pi(\alpha_t(f)) = \nu_t(\pi(f))\nu_t^* = 0$, and hence that $\alpha_t(f) \in J$.

By assumption $\alpha$ is minimal, so either $J \cap C_0(X) = C_0(X)$, in which case $\pi = 0$, hence $\rho = 0$ by Proposition 1.3, or else $J \cap C_0(X) = \{0\}$, in which case the representation $\pi$ is faithful by Theorem 2.6. This proves that the crossed product is simple. \hfill \Box

3. **Invariant ideals and the approximation property.**

Let $\alpha$ be a partial action on the $C^*$-algebra $A$. For each invariant ideal $I$ of $A$ there is a restriction of $\alpha$ to a partial action on $I$, with ideals $D_t \cap I$ as domains of the restricted partial automorphisms, and there is also a quotient partial action $\hat{\alpha}_t$ of $G$ on $A/I$, defined by composition with the quotient map $a \in A \mapsto a + I \in A/I$: the domain of $\hat{\alpha}_t$ is the ideal $\hat{D}_{t-1} := \{a + I \in A/I : a \in D_{t-1}\}$ and $\hat{\alpha}_t(a + I) = \alpha_t(a) + I$.

We will show that the quotient of the crossed product $A \rtimes G$ modulo the ideal generated by $I$ is isomorphic to the crossed product of the quotient partial action modulo $I$. This result generalizes [14, Proposition 3.4], which proves the case $G = \mathbb{Z}$, and extends part of [14, Proposition 5.1], which only concerns ideals. The original argument, for group actions, is from [14, Lemma 1]. We will denote by $\langle S \rangle$ the ideal generated by a subset $S$ of a $C^*$-algebra $B$.

**Proposition 3.1.** Suppose $\alpha$ is a partial action on $A$ and assume $I$ is an $\alpha$-invariant ideal of $A$. Then the map $a\delta_t \in I \rtimes G \mapsto a\delta_t \in A \rtimes G$ extends to an injection of $I \rtimes G$ onto the ideal $\langle I \rangle$ generated by $I$ in $A \rtimes G$, and $\langle I \rangle \cap A = I$.

The map $a\delta_t \in A \rtimes G \mapsto (a + I)\delta_t \in (A/I) \rtimes G$ extends to a surjective homomorphism, giving the short exact sequence

$$0 \to I \rtimes G \to A \rtimes G \to (A/I) \rtimes G \to 0.$$
Proof. The assertion that \( I \times G \) injects as an ideal in \( A \times G \) is proved in [13, Proposition 5.1 and Corollary 5.2] and, as done there, we identify \( I \times G \) with \( \text{span}\{\delta_t : a \in D_t \cap I, t \in G\} \); we also identify \( I \) with its canonical image \( I \delta_t \) in \( A \times G \). It is clear that \( \langle I \rangle \) is contained in \( I \times G \). To prove the reverse inclusion it suffices to show that \( a \delta_t \in \langle I \rangle \) for every \( a \in D_t \cap I \) and \( t \in G \). Assume \( a \in D_t \cap I \) and let \( b_\lambda \) be an approximate unit for the ideal \( D_t \). Then \( a b_\lambda \delta_t = (a b_\lambda)(b_\lambda \delta_t) \in \langle I \rangle \) so \( a \delta_t = \lim \lambda a b_\lambda \delta_t \in \langle I \rangle \). This proves that \( I \times G = \langle I \rangle \), from which it is obvious that \( I = \langle I \rangle \cap A \).

The map \( a \delta_t \mapsto (a + I)\delta_t \) induces a \( * \)-homomorphism from \( \ell^1(G, A) \) onto \( \ell^1(G, A/I) \). Since \( A \rtimes G \) is the enveloping \( C^* \)-algebra of \( \ell^1(G, A) \), there is \( C^* \)-homomorphism \( \phi \) of \( A \rtimes G \) onto \( (A/I) \rtimes G \) which sends \( a \delta_t \) to \((a + I)\delta_t\) for every \( a \in D_t \) and every \( t \in G \). To finish the proof we need to show that \( \ker \phi = \langle I \rangle \).

It is clear that \( \ker \phi \) contains the ideal \( \langle I \rangle \) generated by \( I \) in \( A \rtimes G \). It remains to prove that \( \ker \phi \subset \langle I \rangle \). Let \( \pi \times u \) be a representation of \( A \rtimes G \) with kernel \( \langle I \rangle \). Since the kernel of \( \pi \) contains \( I \), \( \pi \) factors through the quotient map \( A \to A/I \); denote by \( \tilde{\pi} \) the corresponding representation of \( A/I \). The pair \( (\tilde{\pi}, u) \) is covariant and determines a representation \( \tilde{\pi} \times u \) of \( (A/I) \rtimes G \). Then \( \pi \times u = (\tilde{\pi} \times u) \circ \phi \), so \( \ker \phi \subset \ker (\pi \times u) \).

Remark 3.2. We point out that, at the level of reduced crossed products, it is always true that \( I \rtimes_r G \) injects as an ideal in \( A \rtimes_r G \) [13, Proposition 5.1], but whether the quotient is the reduced crossed product \( (A/I) \rtimes_r G \) is a subtler question. We refer to the discussion at the end of [3, §4] for related considerations.

When \( A = C_0(X) \) the \( \alpha \)-invariant ideals are in one to one correspondence with invariant open sets; the corresponding quotients are naturally identified with the continuous functions on the complements of these invariant open sets. Specifically, if \( \alpha \) is a partial action on \( C_0(X) \) and \( U \) is an invariant open subset of \( X \) then \( C_0(U) \) is an invariant ideal in \( C_0(X) \), and every invariant ideal is of this form. Moreover, \( C_0(X)/C_0(U) \cong C_0(\Omega) \) with \( \Omega = X \setminus U \), the quotient map being simply restriction. The quotient partial action \( \alpha \) of \( C_0(\Omega) \) is given by \( \alpha_t(f|_\Omega) = \alpha_t(f)|_\Omega \) for \( f \in D_{t^{-1}} \) (the domain of \( \alpha_t \) consists of the restrictions to \( \Omega \) of functions in \( D_{t^{-1}} \)).

In general there may be more ideals in a crossed product than those of the form \( \langle I \rangle \) with \( I \) an invariant ideal in \( A \). Easy examples abound even for full actions; for instance write \( C^*(G) = C \rtimes G \) (with the trivial action). If \( G \) has more than one element, then the kernel of the trivial homomorphism \( s \mapsto 1 \) from \( C^*(G) \) to \( C \) is a proper nontrivial ideal which is not generated by an ideal in \( C \).

The quotient system \((C_0(\Omega), G, \alpha)\), obtained by restricting the partial action \( \alpha \) to a closed invariant subset \( \Omega \) of \( X \), need not be topologically free even if \((C_0(X), G, \alpha)\) is. An easy example of this phenomenon is obtained by restricting the action of \( \mathbb{Z} \) by translation on \( C(\mathbb{Z} \cup \{\pm \infty\}) \) to the subset \( \{\pm \infty\} \). However, we will see that if topological freeness holds on quotients of a partial action having the approximation property introduced in [3], then all the ideals of the crossed product are obtained from their intersections with \( C_0(X) \), via the map \( I \mapsto \langle I \rangle \). Before we prove this we briefly review some basic facts about amenability and the approximation property.

A partial dynamical system \((C_0(X), G, \alpha)\) is amenable if the canonical homomorphism from the full crossed product to the reduced one is faithful. Amenability is equivalent to faithfulness (as a positive map) of the conditional expectation from the full crossed product \( C_0(X) \rtimes G \) onto \( C_0(X) \) [3, Proposition 4.2]; it is also equivalent to normality of the dual coaction in the
Theorem 3.5. Let every closed invariant subset of $X$ is, if there exists a net $(a_i)$ of finitely supported functions $a_i : G \to C_0(X)$ such that
\[ \sup_i \| \sum_{t \in G} a_i(t)a_i(t) \| < \infty \]
and
\[ \lim_{t \in G} \sum_{i} a_i(st)f\delta_s a_i(t) = f\delta_s \quad s \in G, f \in D_s. \]

This approximation property implies amenability [1, Theorem 4.6], over which it has the advantage of being inherited by graded quotients of Fell bundles in the sense specified in the next proposition. We do not know at present whether the approximation property is actually equivalent to amenability.

Although we will only need the following result in the special situation of crossed products by partial actions, it is more convenient to formulate it for the topologically graded algebras studied in [3].

Proposition 3.4. Suppose the $C^*$-algebra $B$ is topologically graded over $G$, and assume the associated Fell bundle has the approximation property. Let $J \subset B$ be such that $J = (J \cap B_e)$. Then the quotient $B/J$ is topologically graded over $G$ and its associated Fell bundle also has the approximation property.

Proof. Let $\pi : B \to B/J$ be the quotient map. That $B/J$ is topologically graded is proved in [3, Proposition 3.1]. To prove the second claim, suppose that the $a_i$ are the approximating functions for $B$. Then the collection of functions $t \mapsto \pi(a_i(t))$ can be used to show that the approximation property holds for $B/J$. \qed

Theorem 3.5. Let $(C_0(X), G, \alpha)$ be a partial dynamical system which is topologically free on every closed invariant subset of $X$ and which satisfies the approximation property. Then the map
\[ U \mapsto \langle C_0(U) \rangle \]
is a lattice isomorphism of the invariant open subsets of $X$ onto the ideals of $C_0(X) \rtimes G$.

Proof. It is clear that the map $U \mapsto \langle C_0(U) \rangle$ maps invariant open subsets of $X$ to ideals in $C_0(X) \rtimes G$, and that if $U_1 \subset U_2$ then $\langle C_0(U_1) \rangle \subset \langle C_0(U_2) \rangle$. Since $C_0(U) = \langle C_0(U) \rangle \cap C_0(X)$ by Proposition 3.1, the map is one-to-one. Next we show that every ideal in $C_0(X) \rtimes G$ is of this form; this will prove that $U \mapsto \langle C_0(U) \rangle$ is an order preserving bijection, hence a lattice isomorphism.

Suppose $J$ is an ideal of $C_0(X) \rtimes G$, and let $I := J \cap C_0(X)$. Then $I = C_0(U)$ for an open invariant subset $U \subset X$, and it is clear that $\langle C_0(U) \rangle \subset J$; we will show that in fact $\langle C_0(U) \rangle = J$.

The set $\Omega := X \setminus U$ is closed and invariant, so $\langle C_0(U) \rangle$ is the kernel of the homomorphism
\[ \phi : C_0(X) \rtimes G \to C_0(\Omega) \rtimes G \]
by the preceding proposition. Let $b \in \phi(J) \cap C_0(\Omega)$, so that $b = \phi(a)$ for some $a \in J$ and $b = \phi(a_1)$ for some $a_1 \in C_0(X)$. Thus $a - a_1 \in \ker \phi$, and since $\ker \phi = \langle C_0(U) \rangle \subset J$ it follows...
that \( a_1 \) itself is in \( J \). But then \( a_1 \in J \cap C_0(X) = C_0(U) \), so \( b = \phi(a_1) = 0 \). This shows that the ideal \( \phi(J) \) of \( C_0(\Omega) \rtimes G \) has trivial intersection with \( C_0(\Omega) \).

By Proposition 4.3 the partial action on the quotient \( C_0(\Omega) \) satisfies the approximation property, so it is amenable and the reduced and full crossed products coincide, by [4, Proposition 4.2].

Since by assumption \( \alpha \) is topologically free on \( \Omega \), \( \phi(J) \) is trivial by Proposition 2.3, and thus \( J \subset \ker \phi = \left( C_0(U) \right) \) as required.

4. Partial representations subject to conditions.

We begin by reviewing some of the main ideas from [8]. Consider the compact Hausdorff space \( \{0,1\}^G \), and let \( e \) denote the identity element in \( G \). The subset

\[ X_G := \{ \omega \in \{0,1\}^G : e \in \omega \} \]

is a compact Hausdorff space with the relative topology inherited from \( \{0,1\}^G \).

The sets \( X_t := \{ \omega \in X_G : t \in \omega \} \) are clopen, and we define a partial homeomorphism \( \theta_t \) on \( X_{t^{-1}} \) by \( \theta_t(\omega) = t\omega \), where \( t\omega = \{tx : x \in \omega\} \). This gives a partial action \((\{X_t\}, \{\theta_t\})_{t \in G}\) canonically associated to the group \( G \).

At the algebra level, denote by \( 1_t \) the characteristic function of \( X_t \); then \( C(X_G) \) is the closed linear span of the projections \( \{1_s : s \in G\} \). The domain of the partial automorphism \( \alpha_t \) is \( C_0(X_{t^{-1}}) = \text{span} \{1_s1_{t^{-1}} : s \in G\} \), and \( \alpha_t \) is determined by

\[ \alpha_t(1_s1_{t^{-1}}) = 1_t1_t. \]

The crossed product \( C(X_G) \rtimes \alpha G \) has the following universal property:

(U1) For every partial representation \( u \) of \( G \) there is a unique representation \( \rho_u \) of \( C(X_G) \) satisfying \( \rho_u(1_t) = u_tu_t^* \), and \( (\rho_u, u) \) is a covariant representation of \( (C(X_G), G, \alpha) \);

(U2) every representation of \( C(X_G) \rtimes \alpha G \) is of the form \( \rho_u \times u \) with \( (\rho_u, u) \) as above.

Since \( C^*\{u_t : t \in G\} \) coincides with the \( C^* \)-algebra generated by the range of \( \rho \times u \), this justifies referring to the crossed product \( C(X_G) \rtimes \alpha G \) as the universal \( C^* \)-algebra for partial representations of \( G \) or, simply, as the partial group algebra of \( G \) [8, Definition 6.4].

Notice that since \( X_t \) is clopen the partial isometries themselves belong to the crossed product and, indeed, they generate it. We will denote by \( [t] \) the partial isometry corresponding to the group element \( t \) in the universal partial representation of \( G \), and, by abuse of notation, we will also write \( 1_t = [t][t]^* \). When \( u \) is a partial representation of \( G \) we will denote the range projections \( u_tu_{t^{-1}} = u tu_t^* \) by \( e^u(t) \) or simply by \( e(t) \). Notice that the initial projection of \( u_t \) is the range projection of \( u_{t^{-1}} \), so we only need to mention range projections.

We are interested here in partial representations whose range projections satisfy a set of relations of the form

\[ \sum_i \prod_j \lambda_{ij} e(t_{ij}) = 0, \]

where the \( \lambda_{ij} \) are scalars and the sums and products are over finite sets. More generally, given a collection of functions \( \mathcal{R} \) in \( C(X_G) \) we will say that the partial representation \( u \) of \( G \) satisfies the relations \( \mathcal{R} \) if the representation \( \rho_u \) of \( C(X_G) \) obtained by extending the map \( 1_t \mapsto u_tu_t^* \) vanishes on every \( f \in \mathcal{R} \). When the relations in \( \mathcal{R} \) are of the form specified above, this amounts to saying that the generating partial isometries satisfy \( \sum_i \prod_j \lambda_{ij} u_{t_{ij}}u_{t_{ij}}^* = 0 \).
Proposition 4.1. Let \( \mathcal{R} \) be a collection of functions in \( C(X_G) \). Then the smallest \( \alpha \)-invariant (closed, two-sided) ideal of \( C(X_G) \) containing \( \mathcal{R} \) is the ideal, denoted \( I \), generated by the set \( \{ \alpha_t(f_{1_t^{-1}}) : t \in G, f \in \mathcal{R} \} \). Moreover,

\[
\Omega_\mathcal{R} := \{ \omega \in X_G : f(t^{-1}\omega) = 0 \text{ for all } t \in \omega, f \in \mathcal{R} \}
\]
is a compact invariant subset of \( X_G \) such that \( I = C_0(X_G \setminus \Omega_\mathcal{R}) \), and the quotient \( C(X_G)/I \) is canonically isomorphic to \( C(\Omega_\mathcal{R}) \).

Proof. Notice first that for every \( f \in C(X_G) \) the function \( f_{1_t^{-1}} \) is in \( D_{t^{-1}} \) so that it makes sense to talk about \( \alpha_t(f_{1_t^{-1}}) \). Moreover, identifying \( C(X_G) \) with its image in the crossed product and using covariance, we have \( \alpha_t(f_{1_t^{-1}}) = [tf[t^{-1}] \mathcal{R} \mathcal{R}] \). Let \( I \) be the ideal generated by \( \{ \alpha_t(f_{1_t^{-1}}) : t \in G, f \in \mathcal{R} \} \). Since any invariant ideal which contains \( f \) must contain \( \alpha_t(f_{1_t^{-1}}) = [tf[t^{-1}] \mathcal{R} \mathcal{R}] \), the smallest invariant ideal containing \( \mathcal{R} \) must contain \( I \). The reverse inclusion will follow once we show that \( I \) is invariant, i.e., that \( \alpha_t(I \cap D_{t^{-1}}) \subset I \) for every \( t \in G \). Since \( I \cap D_{1_t^{-1}} = 1_t^{-1}I \), we need to show that \( \alpha_t(f_{1_t^{-1}}) \in I \) for every \( f \in I \) and \( t \in G \).

For \( g \in C(X_G), f \in \mathcal{R} \) and \( s, t \in G \), we have

\[
[s] \alpha_t(f_{1_t^{-1}})g[s^{-1}] = [s][tf[t^{-1}]g][s^{-1}] = [st][t^{-1}][tf[t^{-1}]g][s^{-1}][s][s^{-1}] = [st]f[t^{-1}][s^{-1}]g[s^{-1}] = [st]f((st)^{-1}g')
\]

with \( g' = [s]g[s^{-1}] \). Since the linear span of the elements \( \alpha_t(f_{1_t^{-1}})g \) is dense in \( I \) and \( \alpha_t(f_{1_t^{-1}}) = [tf[t^{-1}] \mathcal{R} \mathcal{R}] \), invariance follows.

Let \( U \subset X_G \) be the invariant open set such that \( I = C_0(U) \). Then the quotient \( C_0(X_G)/I \) is isomorphic to \( C(X_G \setminus U) \) and it only remains to prove that \( U = X_G \setminus \Omega_\mathcal{R} \).

Since \( \alpha_t(f_{1_t^{-1}})(\omega) \) is equal to \( f(t^{-1}\omega) \) when \( t \in \omega \), and 0 otherwise, the characterization of \( I \) given in the first part implies that \( f(t^{-1}\omega) = 0 \) for every \( t \in \omega \) and \( f \in \mathcal{R} \) if and only if \( F(\omega) = 0 \) for every \( F \in I \). This proves that \( \Omega_\mathcal{R} = X_G \setminus U \), finishing the proof.

Definition 4.2. The set \( \Omega_\mathcal{R} \) is called the spectrum of the relations \( \mathcal{R} \).

The spectrum of a set of relations is invariant under the partial action \( \alpha \) on \( C(X_G) \) so there is a quotient partial action (also denoted \( \alpha \)) on \( C(\Omega_\mathcal{R}) \) obtained by restricting the partial homeomorphisms to \( \Omega_\mathcal{R} \). The restricted partial homeomorphisms have compact open (relative to \( \Omega_\mathcal{R} \)) sets as domains and ranges so for each group element \( t \) the partial isometry \( v_t = (v_tv_t^*)v_t \) belongs to the crossed product. We will show that the crossed product \( C(\Omega_\mathcal{R}) \rtimes G \) has a universal property with respect to partial representations of \( G \) subject to the relations \( \mathcal{R} \).

Definition 4.3. Suppose \( G \) is a group and let \( \mathcal{R} \subset C_0(X_G) \) be a set of relations. A partial representation \( v \) of \( G \) is universal for the relations \( \mathcal{R} \) if

(i) \( v \) satisfies \( \mathcal{R} \), i.e., \( \rho_v(\mathcal{R}) = \{0\} \), and
(ii) for every partial representation \( V \) of \( G \) satisfying \( \mathcal{R} \) the map \( v_t \mapsto V_t \) extends to a \( C^* \)-algebra homomorphism from \( C^*(\{v_t : t \in G\}) \) onto \( C^*(\{V_t : t \in G\}) \).

The \( C^* \)-algebra generated by a universal partial representation for \( \mathcal{R} \) (which is clearly unique up to canonical isomorphism) will be called the universal \( C^* \)-algebra for partial representations of \( G \) subject to the relations \( \mathcal{R} \) and denoted \( C_p^*(G; \mathcal{R}) \).
The existence of universal representations subject to relations, and of the universal $C^*$-algebra for $R$, could be derived from an abstract argument, cf. [3]; we choose instead to give a concrete realization as a crossed product.

**Theorem 4.4.** Suppose $R$ is a collection of relations in $C(X_G)$ with spectrum

$$\Omega_R = \{ \omega \in X_G : f(t^{-1}\omega) = 0 \text{ for all } t \in \omega, f \in R \}.$$ 

(i) If $\rho \times V$ is a representation of $C(\Omega_R) \rtimes G$ then $V$ is a partial representation of $G$ satisfying the relations $R$.

(ii) Conversely, if $V$ is a partial representation of $G$ satisfying the relations $R$, then $1_t \mapsto V(t)V(t)^*$ extends uniquely to a representation $\rho_V$ of $C(\Omega_R)$, and the pair $(\rho_V, V)$ is covariant.

(iii) The universal $C^*$-algebra $C_p^*(G; R)$ for partial representations of $G$ subject to the relations $R$ exists and is canonically isomorphic to $C(\Omega_R) \rtimes G$.

**Proof.** (i) holds because the range projections of the partial isometries $v_t$ are in $C(\Omega_R)$, which was defined precisely so that the relations $R$ be satisfied.

Next we prove (ii). If $V$ is a partial representation satisfying the relations, then the representation of $C(X_G)$ determined by the range projections $1_t \mapsto V_tV_t^*$ factors through $C(\Omega_R)$, and hence gives a covariant representation of $(C(\Omega_R), G, \alpha)$.

By (i) and (ii) there is a bijection between partial representations satisfying the relations and covariant representations of $(C(\Omega_R), G, \alpha)$. Furthermore, the range of a partial representation generates the same $C^*$-algebra as the range of the corresponding covariant representation. Since $C_p^*(G; R)$ and $C(\Omega_R) \rtimes G$ are both generated by the ranges of universal representations, $C(\Omega_R) \rtimes G$ is a realization of $C_p^*(G; R)$.

In the remaining sections we consider several situations that fall naturally into the framework of partial representations with relations.

5. **No relations: the partial group algebra $C_p^*(G)$.**

Let $R$ be the empty set of relations and consider all partial representations of a group $G$, subject to no restrictions. This is the situation considered in [2] and mentioned at the beginning of Section 4. The spectrum $\Omega_\emptyset$ is $X_G := \{ \omega \subset 2^G : e \in \omega \}$ and the canonical partial action $\theta$ is given by $\theta_t(\omega) = t\omega$ for $\omega \ni t^{-1}$. By Theorem 4.4, the crossed product $C(X_G) \rtimes_\alpha G$ is the universal $C^*$-algebra $C_p^*(G) := C_p^*(G; \emptyset)$ for partial representations of $G$.

**Proposition 5.1.** The canonical partial action of a group $G$ on $X_G$ is topologically free if and only if $G$ is infinite.

**Proof.** When the group $G$ is finite, the spectrum $X_G$ has the discrete topology. Since the point $G \in X_G$ is fixed by every group element, the partial action associated to partial representations of a finite group is never topologically free.

Assume now that $G$ is infinite and let

$$U := \{ \chi \in X_G : a_i \in \chi \text{ and } b_j \notin \chi \text{ for } 1 \leq i \leq m \text{ and } 1 \leq j \leq n \}$$

be a typical basic (nonempty) open set in $X_G$ where $a_i, b_j \in G$. It suffices to show that for every element $t \in G \setminus \{ e \}$ there is some $\omega_0 \in U$ which is not fixed by $t$. We may restrict our attention to the intersection of $U$ with the domain of $\theta_t$, by assuming that one of the $a_i$’s (and none of the $b_j$’s) is equal to $t^{-1}$. 

Since \( G \) is infinite there exists an element \( c \in G \) different from the \( a_i \) and the \( b_j \) and such that \( tc \) is different from the \( a_i \). Then \( \omega_0 := \{e,a_1,a_2,\ldots,a_m,c\} \) is in \( U \) and \( \theta_t(\omega_0) = \{t,ta_1,ta_2,\ldots,ta_m,tc\} \) is different from \( \omega_0 \) because \( tc \) is not in \( \omega_0 \). Thus \( \omega_0 \) is not fixed by \( t \), finishing the proof.

**Corollary 5.2.** For infinite \( G \), a representation of \( C(X_G) \times_r G \) is faithful if and only if its restriction to \( C(X_G) \) is faithful.

**Proof.** Direct application of Theorem 2.6.

**Remark 5.3.** The singleton \( \{G\} \subset X_G \) is always closed and invariant under the partial action, so topological freeness fails at least for the restriction to \( \{G\} \). Because of this the situation of Theorem 3.5 never arises for the empty set of relations, and a characterization of the ideals in \( C^*_p(G) \) lies beyond the present techniques.

**Theorem 5.4.** The canonical partial action of \( G \) on \( C(X_G) \) has the approximation property if and only if \( G \) is amenable.

**Proof.** That the partial action of an amenable group \( G \) on \( X_G \) satisfies the approximation property is an easy consequence of [1, Theorem 4.7]. To prove the converse suppose the action of \( G \) on \( X_G \) satisfies the approximation property. Then by Proposition 3.4 the (trivial) action on the closed invariant singleton products coincide. Since they correspond to the reduced and full group approximation property. Hence this trivial action is amenable and the reduced and full crossed it itself must be an amenable group.

**Remark 5.5.** Since we do not know whether amenability itself is inherited by quotients, we do not know whether amenability of the partial action of \( G \) on \( C(X_G) \) entails amenability of \( G \).

6. **Nica covariance: the Toeplitz algebras of quasi-lattice groups.**

Let \( (G,P) \) be a quasi-lattice ordered group, as defined by Nica in [16, §2]. The semigroup \( P \) induces a partial order in \( G \) via \( x \leq y \) if and only if \( x^{-1}y \in P \). The quasi-lattice condition says that if for \( x,y \in G \) the set \( \{z \in P : x \leq z, y \leq z\} \) is nonempty, then it has a unique minimal element, denoted \( x \lor y \), and referred to as the least common upper bound in \( P \) of \( x \) and \( y \), (if there is no common upper bound, we write \( x \lor y = \infty \)). It is easy to see that \( x \) has an upper bound in \( P \) if and only if \( x \in PP^{-1} \).

An isometric representation of \( P \) on \( H \) is a map \( V : P \rightarrow B(H) \) such that \( V_x^*V_x = 1 \) and \( V_xV_y = V_{xy} \). The isometric representation \( V \) is covariant if it satisfies

\[
V_xV_x^*V_y = V_{x\lor y}V_{x\lor y}^* \quad x,y \in P,
\]

here we use the convention that \( V_\infty = 0 \), so that if \( x \) and \( y \) do not have a common upper bound in \( P \) then the corresponding isometries have orthogonal ranges.

The Toeplitz (or Wiener-Hopf) algebra \( T(G,P) \) is the \( C^* \)-algebra generated by the left regular representation \( T \) of \( P \) on \( \ell^2(P) \) [16], which is easily seen to be covariant. The universal \( C^* \)-algebra \( C^*(G,P) \) is the \( C^* \)-algebra generated by a universal covariant semigroup of isometries. When \( (G,P) \) is amenable, the canonical homomorphism \( C^*(G,P) \rightarrow T(G,P) \) is an isomorphism [16, 14].
Every \( x \in PP^{-1} \) can be written in a “most efficient way” as \( x = \sigma(x)\tau(x)^{-1} \), where \( \sigma(x) := x \vee e \) is the smallest upper bound of \( x \) in \( P \) and \( \tau(x) := \sigma(x^{-1}) = x^{-1}\sigma(x) \). Using this factorization Raeburn and the third author have shown in \cite{RaeburnLacaQuigg2004} Theorem 6.6] that \( \mathcal{T}(G, P) \) is a crossed product by a partial action on its diagonal subalgebra. Their proof involves extending isometric covariant representations of \( P \) to partial representations of \( G \), and can be pushed further to describe the class of such extensions in terms of relations satisfied by the range projections, which we do next.

**Proposition 6.1.** Let \( (G, P) \) be a quasi-lattice ordered group.

1. If \( V \) is a covariant isometric representation of \( P \) then

\[
(6.1) \quad u_x = \begin{cases} 
V_{\sigma(x)}V_{\tau(x)}^* & \text{if } x \in PP^{-1} \\
0 & \text{if } x \notin PP^{-1}.
\end{cases}
\]

is a partial representation of \( G \) satisfying the relations

\[ (N_1) \quad u_t^*u_t = 1 \quad \text{for } t \in P, \text{ and} \]

\[ (N_2) \quad u_xu_y^*u_yu_x^* = u_{x \vee y}u_{x \vee y}^* \quad \text{for } x, y \in G, \]

which we denote collectively by \( (N) \).

2. Conversely, every partial representation \( u_t \) of \( G \) satisfying the relations \( (N) \) arises this way from a covariant isometric representation of \( P \).

**Proof.** (1.) That \( u_x \) is a partial representation is proved in \cite{RaeburnLacaQuigg2004}, Theorem 6.6] and that it satisfies \((N_1)\) is obvious. We prove \((N_2)\) next. Let \( x, y \in G \) and assume both are in \( PP^{-1} \), for otherwise both sides are zero and there is nothing to prove. Notice first that

\[
u_xu_x^*vu_y^* = V_{\sigma(x)}V_{\tau(x)}^*V_{\sigma(y)}^*V_{\sigma(y)} = V_{\sigma(x)\vee\sigma(y)}V_{\sigma(x)\vee\sigma(y)}^*.
\]

Since \( x \vee y = x \vee e \vee y = \sigma(x) \vee \sigma(y) \) this proves \((N_2)\).

(2.) Assume now that \( u_x \) is a partial representation of \( G \) satisfying \((N)\). Then \( u_t \) is an isometry for every \( t \in P \), and property (iii) in the Definition [1] of partial representation gives

\[ u_xu_t = u_{x\vee t}u_{t}^*u_t = u_{st}u_{t}^*u_t = u_{st}. \]

Thus the restriction of \( u \) to \( P \) is an isometric representation, which is covariant by \((N_2)\).

It only remains to check that \( u \) arises from its restriction \( V \) to \( P \) as in \((6.1)\). Let \( x \in G \). Then

\[ u_xu_x^* = u_xu_x^*u_xu_x^* = u_{\sigma(x)}u_{\sigma(x)}^* \]

by \((N_2)\). If \( x \notin PP^{-1} \), then \( \sigma(x) = \infty \) and \( u_xu_x^* \) vanishes. If \( x \in PP^{-1} \), then

\[ u_x = u_xu_x^*u_x = u_{\sigma(x)}u_{\sigma(x)}^*u_x. \]

The last two factors can be combined using property (iii) of Definition [1], and since \( \sigma(x)^{-1}x = \tau(x)^{-1} \) we conclude that \( u_x = u_{\sigma(x)}u_{\tau(x)}^* \).

**Definition 6.2.** A subset \( \omega \) of \( G \) is hereditary if \( \omega P^{-1} \subseteq \omega \) for every \( x \in \omega \). It is directed if for every \( x, y \in \omega \) there exists \( z \in \omega \cap P \) with \( x \leq z \) and \( y \leq z \).

Notice that a hereditary subset \( \omega \) is directed if and only if the least upper bound of any two of its elements exists and is in \( \omega \); in particular, hereditary, directed subsets are contained in the set \( PP^{-1} \).

**Lemma 6.3.** The set of hereditary, directed subsets of \( G \) containing \( e \) is invariant under the partial action \( \theta \) on \( X_G \).
Proof. Suppose \( \omega \in X_G \) is hereditary and directed and let \( z^{-1} \in \omega \). In order to see that \( z\omega \) is hereditary, suppose \( zx \in z\omega \) with \( x \in \omega \) and let \( t \in P \). Then \( xt^{-1} \in \omega \) and \( xzt^{-1} \in z\omega \).

Next we show that \( z\omega \) is directed. Assume \( zx \) and \( zy \) are elements of \( z\omega \). Since \( \omega \) is directed and contains \( x, y, \) and \( z^{-1} \), it follows that \( (x \vee y \vee z^{-1}) \in P \cap \omega \). It is easy to see using the definition that \( z(x \vee y \vee z^{-1}) \in P \cap z\omega \) is a common upper bound for \( zx \) and \( zy \). Thus \( zx \vee zy \leq z(x \vee y \vee z^{-1}) \) and, since \( z\omega \) is hereditary, \( zx \vee zy \in z\omega \). \( \square \)

Theorem 6.4. The spectrum \( \Omega_N \) of the relations \((N)\) is the set of hereditary, directed subsets of \( G \) which contain the identity element.

The crossed product \( C(\Omega_N) \rtimes_{\alpha} G \) is canonically isomorphic to the universal \( C^*\)-algebra \( C^*(G, P) \) for covariant isometric representations of \( P \).

Proof. Let \( H \) be the set of hereditary, directed subsets of \( G \) containing the identity element. Then clearly \( H \subset X_G \).

First we show that every \( \omega \in \Omega_N \) is hereditary and directed; that \( e \in \omega \) is obvious because \( \Omega_N \subset X_G \). If \( x \in \omega \) then \( \omega \) is in the domain of the partial homeomorphism \( \theta_{x^{-1}} \), and since \( \Omega_N \) is invariant we have \( x^{-1}\omega = \theta_{x^{-1}}(\omega) \in \Omega_N \). By the relation \((N_1)\), for \( t \in P \) we obtain \([t^*t](x^{-1}\omega) = 1\), which means that \( t^{-1} \in x^{-1}\omega \). Since \( xt^{-1} \in \omega \) for every \( t \in P \) and every \( x \in \omega \), \( \omega \) is hereditary.

If \( x \) and \( y \) are elements of \( \omega \), then \( 1 = [x][x^*[y][y]^*(\omega)] = [x \vee y][x \vee y]^*(\omega) \) by \((N_2)\). Thus \( x \vee y \in \omega \) and \( \omega \) is directed.

Conversely, by the preceding lemma, if \( \omega \in X_G \) is hereditary and directed, and if \( z^{-1} \in \omega \), then \( z\omega \) is also hereditary and directed, so it suffices to show that the relations \((N)\) hold at every hereditary, directed \( \omega \in X_G \).

It is trivial to verify \((N_1)\), since \( e \in \omega \) implies \( et^{-1} \in \omega \) for every \( t \in P \) by hereditariness of \( \omega \). For \((N_2)\) we need to show that \( [x][x^*[y][y]^*(\omega)] = [x \vee y][x \vee y]^*(\omega) \), or, equivalently, that \( x \) and \( y \) are in \( \omega \) if and only if \( x \vee y \in \omega \). The “only if” holds because \( \omega \) is directed, and the “if” holds because it is hereditary, since \((x \vee y)^{-1}x \in P \) and \( x = (x \vee y)(y)^{-1}x \).

The crossed product is isomorphic to \( C^*(G, P) \) because of Proposition 6.1. \( \square \)

Remark 6.5. Hereditary directed subsets of the semigroup \( P \) were introduced by Nica in [11, §6.2], where he showed that the spectrum of the diagonal subalgebra in the Toeplitz algebra is (homeomorphic to) the space of hereditary, directed, and nonempty subsets of \( P \). The homeomorphism of our spectrum \( \Omega_N \) to the space considered by Nica is obtained simply by sending an element \( \omega \) of \( \Omega_N \) to its intersection with \( P \).

Proposition 6.6. The canonical partial action \( \theta \) on \( \Omega_N \) is topologically free.

Proof. For each \( t \in P \) the set \( tP^{-1} = \{ x \in G : x \leq t \} \) is hereditary and directed; moreover, \( t \neq t' \) implies \( tP^{-1} \neq t'P^{-1} \). This gives a copy of \( P \) inside \( \Omega_N \) which is in fact dense [3, §6.2].

Suppose \( x \in G \); it is easy to see that the point \( tP^{-1} \) is in the domain of the partial homeomorphism \( \theta_x \) if and only if \( xt \in P \). In this case \( \theta_x(tP^{-1}) = (xt)P^{-1} \neq tP^{-1} \). Since no point in this dense subset is fixed by \( \theta_x \) for \( x \neq e \), the proof is finished. \( \square \)

As an application we obtain a characterization of faithful representations of the reduced crossed product which is slightly more general than [14, Theorem 3.7], in that it does away with the amenability hypothesis by focusing on the reduced crossed product. From this point of view, it becomes apparent that the faithfulness theorem for representations is really a theorem about reduced crossed products and that it is a manifestation of topological freeness.
Theorem 6.7. Suppose \((G, P)\) is a quasi-lattice ordered group. A representation of the reduced crossed product \(C(\Omega_N)\rtimes_{\alpha,r} G\) is faithful if and only if it is faithful on the diagonal \(C(\Omega_N)\).

Proof. Since \(\alpha\) is topologically free, the result follows from Theorem 2.4.

Of course we may use [14, Proposition 2.3(3)] to decide when the restriction to \(C(\Omega_N)\) of a representation \(\pi \times v\) of \(C(\Omega_N)\rtimes_{\alpha,r} G\) is faithful in terms of the generating partial isometries: the condition is that
\[
\pi(\prod_{i \in F} (1 - u_i u_i^*)) \neq 0
\]
for every finite subset \(F\) of \(P \setminus \{e\}\).

Since the diagonal algebra in Nica’s Wiener-Hopf C*-algebra \(T(G, P)\) is a faithful copy of \(C(\Omega_N)\) we can use the faithfulness theorem to express \(T(G, P)\) as the reduced crossed product by a partial action.

Corollary 6.8. If \((G, P)\) is a quasi-lattice ordered group, then
\[
C(\Omega_N)\rtimes_{\alpha,r} G \cong T(G, P).
\]

This isomorphism is essentially [20, Theorem 6.6]; although the partial action there is not given explicitly, it is not hard to see that it is the one above.

7. Cuntz-Krieger relations: the universal \(O_A\).

Let \(A = [a_{ij}]\) be a \(\{0, 1\}\)-valued \(n \times n\) matrix with no zero rows. A Cuntz-Krieger A-family is a collection of partial isometries \(\{s_i\}_{i=1}^n\) such that
\[
\sum_j s_j s_j^* = 1, \quad \text{and} \quad \sum_j a_{ij} s_j s_j^* = s_i^* s_i \quad \text{for} \quad i = 1, 2, \ldots, n.
\]

We define the algebra \(O_A\) to be the universal C*-algebra for Cuntz-Krieger A-families. That is, \(O_A\) is the C*-algebra generated by \(n\) partial isometries \(\{s_i\}_{i=1}^n\) satisfying the two conditions above, and such that if \(\{s_i'\}_{i=1}^n\) is any other collection satisfying the same conditions, the map \(s_i \mapsto s_i'\) extends to a C*-algebra homomorphism from \(C^*(\{s_i\}_{i=1}^n)\) onto \(C^*(\{s_i'\}_{i=1}^n)\).

This is not the original definition of \(O_A\), given in [3] only for \(A\) satisfying a certain condition (I) which implies the uniqueness of the C*-algebra \(C^*(\{s_i\})\) provided that \(s_i \neq 0\) for every \(i\). We have chosen to define \(O_A\) as a universal object, as in [14], because it allows us to treat more general matrices, and at the same time clarifies the presentation. With this definition, Cuntz and Krieger’s celebrated uniqueness result says that if \(A\) satisfies (I) then \(O_A\) is isomorphic to the C*-algebra generated by any \(A\)-family of nonzero partial isometries.

We will prove that \(O_A\) is a crossed product by a partial action of the free group \(\mathbb{F}_n\) on the space of infinite admissible paths, by showing first that it is the universal C*-algebra of partial representations of \(\mathbb{F}_n\) subject to certain relations, and then using Theorem 4.3 to compute the spectrum and the partial action. This will allow us to obtain Cuntz and Krieger’s uniqueness theorem from our Theorem 2.4. First we need to set some notation and recall some terminology.

Definition 7.1. Let \(|x|\) denote the length of a reduced word \(x \in \mathbb{F}_n\). A partial representation \(u\) of \(\mathbb{F}_n\) is semisaturated if it satisfies
\[
u_{tr} = u_t u_r \quad \text{whenever} \quad |tr| = |t| + |r|,
\]
and, similarly, if the partial action $\alpha$ of $\mathbb{F}_n$ satisfies
\[
\alpha_{tr} = \alpha_t \circ \alpha_r \quad \text{whenever} \quad |tr| = |t| + |r|,
\]
we say that it is a semisaturated partial action. The condition $|tr| = |t| + |r|$ means that there is no further reduction in the concatenation of the reduced words $t$ and $r$.

Unlike general partial representations, semisaturated ones are determined by their values on the generators $\{g_1, \ldots, g_n\}$ of the free group: if $t = g_i^{\pm 1} g_j^{\pm 1} \cdots g_k^{\pm 1}$ is a reduced word in $\mathbb{F}_n$ then $u_t = u_{g_i^{\pm 1}} u_{g_j^{\pm 1}} \cdots u_{g_k^{\pm 1}}$, and similarly for a semisaturated partial action. For this reason semisaturated partial actions are also called multiplicative in [24].

Semisaturated partial representations and partial actions can be characterized in terms of the range projections $e(t) = u_t u^*_t$, as in [1, Proposition 5.4] and [20, Lemma 5.2]: $u$ is semisaturated if and only if $e(tr)e(t) = e(tr)$ whenever $|tr| = |t| + |r|$, and similarly for partial actions.

Proposition 7.2. (cf. [1, Theorem 5.2]) Let $\{g_1, g_2, \ldots, g_n\}$ be the generators of $\mathbb{F}_n$. For every Cuntz-Krieger $A$-family $\{s_i\}_{i=1}^n$ there is a unique semisaturated partial representation $u$ of $\mathbb{F}_n$ such that $u_{g_i} = s_i$. The range projections $e(g) = u_g u^*_g$ satisfy the relations
\[
(\mathcal{CK}_{ss}) \quad e(tr)e(t) = e(tr) \quad \text{whenever} \quad |tr| = |t| + |r|,
\]
\[
(\mathcal{CK}_1) \quad \sum_{j=1}^n e(g_j) = 1, \quad \text{and}
\]
\[
(\mathcal{CK}_A) \quad \sum_{j=1}^n a_{ij} e(g_j) = e(g_i^{-1}) \quad \text{for} \ i = 1, \ldots, n,
\]
which we denote collectively by (\mathcal{CK}).

Conversely, if $u$ is a partial representation of $\mathbb{F}_n$ satisfying these relations then the partial isometries $s_i := u_{g_i}$ form a Cuntz-Krieger $A$-family.

Thus the Cuntz-Krieger algebra $\mathcal{O}_A$ (i.e., the universal $C^*$-algebra of Cuntz-Krieger $A$-families) is universal for partial representations of $\mathbb{F}_n$ subject to the relations (\mathcal{CK}).

From this, Theorem 4.4 implies that there is a partial action $\theta$ on the spectrum $\Omega_{\mathcal{CK}}$ such that $s_i \mapsto u_{g_i}$ extends to an isomorphism of $\mathcal{O}_A$ to the crossed product $C(\Omega_{\mathcal{CK}}) \rtimes \mathbb{F}_n$. Clearly this partial action is semisaturated because of (\mathcal{CK}_{ss}) and [20, Lemma 5.2].

Although a direct application of Proposition 4.1 naturally yields the spectrum $\Omega_{\mathcal{CK}}$ of the relations (\mathcal{CK}) as a subspace of $X_{\mathbb{F}_n}$, we will eventually identify this spectrum with the more familiar infinite path space, so we will state the result in terms of path space, which we define next.

Definition 7.3. An infinite (admissible) path is an infinite sequence $\mu = \mu_1\mu_2 \ldots$ of generators of $\mathbb{F}_n$ such that $a(\mu_j, \mu_{j+1}) = 1$ for every $j \in \mathbb{N}$. Infinite path space is the space $P^\infty_A$ of infinite admissible paths with the relative topology inherited as a closed and hence compact subspace of the infinite product space $\prod_{i=1}^\infty \{g_1, \ldots, g_n\}$.

Theorem 7.4. There is a unique semisaturated partial action $\theta$ of the free group $\mathbb{F}_n$ on infinite path space $P^\infty_A$ such that
\[
(7.1) \quad \theta_{g_i}(\mu) = g_i\mu \quad \text{for} \ \mu \in U_{g^{-1}_i} := \{\mu : a(g_i, \mu_1) = 1\} \subset P^\infty_A,
\]
where $g_{i\mu}$ means concatenation of $g_i$ at the beginning of $\mu$. The map $s_i \mapsto u_{g_i}$ extends to an isomorphism of $O_A$ to the crossed product $C(P_A^\infty) \rtimes g \mathbb{F}_n$.

The theorem will be proved in the following lemma and propositions by establishing a homeomorphism of $\Omega_{CK}$ to $P_A^\infty$, and then showing that the partial action carried over to $P_A^\infty$, which is necessarily semisaturated, satisfies (7.3).

**Definition 7.5.** A subset $\omega$ of $\mathbb{F}_n$ is connected if, when viewed as a subset of the Cayley graph of $\mathbb{F}_n$, it contains the shortest path between any two of its elements.

When $e \in \omega$ it is easy to see that $\omega$ is connected if and only if it contains the initial subwords of the reduced words in $\omega$. Next we show that the semisaturation relations single out the connected subsets in $X_{\mathbb{F}_n}$.

**Lemma 7.6.** The relations

$$e(t)e(tr) = e(tr)$$

for $t, r \in \mathbb{F}_n$ such that $|tr| = |t| + |r|$ are satisfied at the point $\omega \in X_{\mathbb{F}_n}$ if and only if $\omega$ is connected as a subset of $\mathbb{F}_n$.

**Proof.** Suppose $|tr| = |t| + |r|$. Then

$$(1_{tr}1_t)|_\omega = 1_{tr}|_\omega \iff (tr \in \omega \implies t \in \omega).$$

Since each $\omega \in X_{\mathbb{F}_n}$ contains $e$, it is closed under taking initial subwords if and only if it is connected. \qed

**Proposition 7.7.** A subset $\omega \subset \mathbb{F}_n$ is in the spectrum $\Omega_{CK}$ of the Cuntz-Krieger relations if and only if the following conditions hold

$(S_1)$ $e \in \omega$,
$(S_2)$ $\omega$ is connected,
$(S_3)$ for every $t \in \omega$ there is a unique generator $g_j = g_{j(\omega, t)}$ such that $tg_j \in \omega$, and
$(S_4)$ for every $t \in \omega$, we have that $tg_i^{-1} \in \omega$ if and only if $a_{i,j(\omega, t)} = 1$, with $j(\omega, t)$ given in $(S_3)$.

**Proof.** Let $Z$ be the set of $\omega$’s satisfying conditions $(S_1)$–$(S_4)$; we need to show $Z = \Omega_{CK}$. The first step is to show that $Z$ is $\theta$-invariant. To do this, suppose $\omega$ satisfies $(S_1)$–$(S_4)$, and let $x^{-1} \in \omega$. Then $\theta_x(\omega) = x\omega$ also satisfies $(S_1)$ because $x^{-1} \in \omega$; $(S_2)$ also holds for $x\omega$ because connected sets are translation-invariant. It is routine to check that $j(\omega, t)$ depends only on $t^{-1}\omega$, hence $j(x\omega, xt) = j(\omega, t)$, from which $(S_3)$ and $(S_4)$ with $x\omega$ in place of $\omega$ follow easily.

Assume now $\omega \in Z$. Condition $(S_2)$ implies that the semisaturation relation holds at $\omega$, from Lemma 7.6. From $(S_3)$ with $t = e$, there exists a unique $j(\omega, e)$ such that $g_{j(\omega, e)} \in \omega$, that is, such that $1_{g_{j(\omega, e)}}|_\omega = 1$, from which $(CK_1)$ holds at $\omega$. Setting $t = e$ in $(S_1)$, $g_i^{-1} \in \omega$ if and only if $a_{i,j(\omega, e)} = 1$, from which $(CK_A)$ holds at $\omega$. This implies that $Z \subset \Omega_{CK}$, because it is an invariant closed subset on which the relations are satisfied.

If $\omega \in \Omega_{CK}$ then $\sum_j 1_{g_j}(t^{-1}\omega) = 1$ for $t \in \omega$ by $(CK_1)$ and [4.1], so there is exactly one generator $g_j$ such that $1_{g_j}(t^{-1}\omega) = 1$, i.e., such that $tg_j \in \omega$, proving $(S_3)$. From $(CK_A)$ and [4.1],

$$\sum_{j=1}^n a_{ij}1_{g_j}(t^{-1}\omega) = 1_{g_i^{-1}(t^{-1}\omega)},$$

and since $1_{g_j}(t^{-1}\omega) \neq 0$ only for $j = j(\omega, t)$, $(S_4)$ follows. \qed
Proposition 7.8. Suppose \( y \in \mathbb{F}_n \). If the partial homeomorphism \( \theta_{y^{-1}} \) of \( \Omega_{CK} \) is nontrivial then \( y = rs^{-1} \) for two admissible words \( r, s \in \mathbb{F}_n^+ \) with the same final letter.

Proof. If the partial automorphism \( \theta_{y^{-1}} \) is nontrivial then \( y \in \omega \) for some \( \omega \in \Omega_{CK} \). Suppose somewhere in the reduced form of \( y \) there is an inverse generator followed by a generator so that \( y \) has an initial reduced subword of the form \( xg^{-1}g' \). By connectedness of \( \omega \) the subwords \( x \) and \( xg^{-1} \) are also in \( \omega \). But this violates condition \((S_3)\) at \( t = xg^{-1} \): the “forward continuations” \( x = (xg^{-1})g \) and \( x_1 = (xg^{-1})g' \) are different because \( g \neq g' \) and they are both in \( \omega \). Hence the reduced form of \( y \) is \( rs^{-1} \) with \( r \) and \( s \) admissible. By connectedness \( r \in \omega \), and by \((S_3)\) there is a unique generator \( g \) such that \( rg \in \omega \). Let \( s_t \) be the last letter of \( s \); again by connectedness, \( rs^{-1}_t \in \omega \), and it follows from \((S_4)\) that \( a(s_t, g) = 1 \). This makes \( sg \) an admissible word, and since \( y = (rg)(sg)^{-1} \) the proof is finished. \( \square \)

We aim to show that \( \Omega_{CK} \) is covariantly homeomorphic to infinite path space with the partial action given in (7.1). The appropriate homeomorphism is defined as follows.

Since every \( \omega \in \Omega_{CK} \) contains the identity element and satisfies \((S_3)\), it contains a unique generator \( g_1 \), and, again, a unique product \( g_1g_2 \), etc. By induction, for each \( \omega \in \Omega_{CK} \) there exists a unique infinite admissible path \( \omega^+ \) such that every finite initial segment of \( \omega^+ \), when viewed as an element of \( \mathbb{F}_n \), belongs to \( \omega \).

We may identify the infinite path \( \mu = \mu_1\mu_2\mu_3\cdots \) with the collection of its finite initial segments \( \{\mu_1, \mu_1\mu_2, \mu_1\mu_2\mu_3, \ldots\} \), and with this picture in mind the correspondence \( \omega \mapsto \omega^+ \) mentioned above comes simply from intersecting \( \omega \in \Omega_{CK} \) with \( \mathbb{F}_n^+ \), i.e., \( \omega^+ = \omega \cap \mathbb{F}_n^+ \).

Proposition 7.9. The map \( \omega \mapsto \omega \cap \mathbb{F}_n^+ \) is a homeomorphism of \( \Omega_{CK} \) onto \( P_\mathbb{A}_\infty \), the corresponding partial action \( \tilde{\theta}(\mu) = g_1 \) on the set \( U_{g^{-1}} := \{\mu : a(g, \mu_1) = 1\} \subset P_\mathbb{A}_\infty \).

Proof. We show first that the map \( \omega \mapsto \omega \cap \mathbb{F}_n^+ \) is injective. Assume that \( \omega \) and \( \omega' \) are in \( \Omega_{CK} \) and \( \omega \cap \mathbb{F}_n^+ = \omega' \cap \mathbb{F}_n^+ \). We will show that \( \omega \subset \omega' \) and hence, by symmetry, that they coincide. Let \( t \in \omega \). From Proposition 7.8 we know that \( t = \mu\nu^{-1} \) for admissible finite paths \( \mu, \nu \in \mathbb{F}_n^+ \). If \( |\nu| = 0 \), then \( t = \mu \in \mathbb{F}_n^+ \), so \( t \in \omega' \). If \( \nu \) is not the empty word, let \( \nu_\ell \) be its last letter. Since \( \omega \) is connected, \( \mu \) is in \( \omega \), and since \( \mu \) is positive, \( \mu \in \omega \cap \mathbb{F}_n^+ = \omega' \cap \mathbb{F}_n^+ \), so \( \mu \in \omega' \). It follows from \((S_3)\) that the next admissible generator after \( \mu \) is the same in both \( \omega \) and \( \omega' \), i.e., \( j(\mu, \omega) = j(\mu, \omega') \). Since \( \mu\nu_\ell^{-1} \) is in \( \omega \) by connectedness (because \( t = \mu\nu^{-1} \in \omega \)), we have \( a(\nu_\ell, j(\omega, \mu)) = 1 \), so condition \((S_4)\) puts \( \mu\nu_\ell^{-1} \) in \( \omega' \). Continuing the argument by induction gives that \( t = \mu\nu_\ell^{-1} \cdots \nu_1^{-1} \) is in \( \omega' \), as claimed.

In order to show that the map \( \omega \mapsto \omega \cap \mathbb{F}_n^+ \) is onto, suppose \( \mu \) is an infinite admissible path, and let

\[ \omega_\mu := \{t \in \mathbb{F}_n : t = (\mu_1\mu_2 \cdots \mu_k)(\nu)^{-1} \text{ with } k \geq 0 \text{ and } \nu\mu_{k+1} \text{ admissible} \}. \]

It is easy to show that \( \omega_\mu \) satisfies conditions \((S_1)-(S_4)\), so it is in \( \Omega_{CK} \), and clearly \( \omega_\mu \cap \mathbb{F}_n^+ = \mu \).

Let \( \mu \in P_\mathbb{A}_\infty \) and \( k \geq 1 \). The basic neighborhood

\[ V_{\mu, k} := \{\nu \in P_\mathbb{A}_\infty : \nu_i = \mu_i \text{ for } i \leq k\} \]

of \( \mu \) is the image of the set \( \{\omega \in \Omega_{CK} : \mu_1\mu_2 \cdots \mu_k \in \omega \} \), which is clearly open in \( \Omega_{CK} \). Hence the map \( \omega \mapsto \omega^+ \) is continuous, and since it is a bijection from a compact to a Hausdorff space, it is a homeomorphism.
The corresponding partial action \( \tilde{\theta} \) on \( P_A^\infty \) is semisaturated, and hence is characterized by its behaviour on generators. If \( g \) is a generator of \( \mathbb{F}_n \) then \( \tilde{\theta}_g(\mu) = \theta_g(\omega_\mu)^+ = (g\omega_\mu)^+ = g\mu \) for every \( \mu \) such that \( a(g, \mu_1) = 1 \).

**Proof.** (of Theorem [7.4]) By Proposition [7.2], \( \mathcal{O}_A \) is isomorphic to the crossed product \( C(\Omega_{CK}) \rtimes \mathbb{F}_n \), and by the preceding proposition we may replace \( \Omega_{CK} \) by \( P_A^\infty \) with the partial action defined in (7.1).

Next we discuss some basic properties of paths with an eye to characterizing the matrices for which the partial action is topologically free.

**Definition 7.10.** An infinite path \( \mu \in P_A^\infty \) is periodic if it is of the form \( \mu = x\gamma\gamma\gamma \cdots \) for \( x \) and \( \gamma \) finite admissible words. A path is aperiodic if it is not periodic.

Notice that the word \( \gamma \) above is an admissible circuit (this means \( \gamma \neq e \) and \( \gamma \gamma \) is admissible). The words \( x \) and \( \gamma \) in the definition of periodic paths are not unique, as evidenced by placing some parentheses: e.g., \( x\gamma\gamma\gamma \cdots = (x\gamma)\gamma^2\gamma^2 \cdots \). However, one may reduce a periodic path in a canonical way by requiring that \( \gamma \) be the shortest possible and that \( x \) contain no part of \( \gamma \) in the sense that the last letters of \( x \) and \( \gamma \) are different — if they are not then shorten \( x \) and shift back the origin of \( \gamma \). (The same effect is obtained by reducing the product \( x\gamma x^{-1} \).

**Definition 7.11.** An admissible circuit \( \gamma = \gamma_1\gamma_2 \cdots \gamma_k \) is terminal if the row corresponding to each \( \gamma_i \) in the matrix \( A \) has only one nonzero entry.

Note that, in the graph associated to \( A \), a terminal circuit is a circuit with no exit.

**Lemma 7.12.** The infinite admissible path \( \mu \) is an isolated point in \( P_A^\infty \) if and only if \( \mu = x\gamma\gamma\gamma \cdots \) for some terminal circuit \( \gamma \) and some admissible word \( x \).

**Proof.** If \( \mu = x\gamma\gamma\gamma \cdots \in P_A^\infty \) with \( \gamma \) an admissible terminal circuit then \( \mu \) is an isolated point in \( P_A^\infty \), because it is the only admissible path in the open set \( U := \{ \nu \in P_A^\infty : x\gamma \text{ is an initial segment of } \nu \} \).

Suppose \( \mu \in P_A^\infty \) is aperiodic. Since \( \mu \) is an infinite path, it will describe a circuit at least every \( n \) steps because there are only \( n \) generators. Because of this, the initial segments of \( \mu \) that can be continued by repeating a circuit are of unbounded length. Hence every neighborhood of \( \mu \) contains a periodic (admissible, infinite) path which is necessarily different from \( \mu \), which was assumed aperiodic. Therefore \( \mu \) is not isolated.

Periodic paths are also the only possible nontrivial fixed points of the partial action:

**Lemma 7.13.** The path \( \mu \in P_A^\infty \) is fixed by a nontrivial element \( t \in \mathbb{F}_n \) under the partial action \( \theta \) if and only if there exist admissible words \( x \) and \( \gamma \) such that \( t = x\gamma k x^{-1} \) with \( k = \pm 1 \) and \( \mu = x\gamma\gamma\gamma \cdots \).

**Proof.** Assume \( \mu \) is a periodic path in reduced form \( x\gamma\gamma\gamma \cdots \) and \( t = x\gamma k x^{-1} \) (we may suppose \( k = 1 \), otherwise change \( t \) to \( t^{-1} \)). Then \( \theta_{x^{-1}}(\mu) = \gamma\gamma\gamma \cdots \) and \( \theta_{x\gamma k}(\gamma\gamma\gamma \cdots) = x\gamma k\gamma\gamma\gamma \cdots = \mu \). Since \( \theta_{x\gamma k x^{-1}} \) extends \( \theta_{x\gamma x} \circ \theta_{x^{-1}} \) we have \( \theta_t(\mu) = \mu \).

To prove the converse, suppose \( \theta_t \) fixes the infinite path \( \mu \). By Proposition [7.3], \( t = rs^{-1} \) (in reduced form) for two admissible words \( r, s \). Since \( \mu \) is in the domain of \( \theta_t \), \( s \) must be an initial segment of \( \mu \), i.e., there exists \( \mu' \) such that \( \mu = s\mu' \) and hence \( rs^{-1}\mu = r\mu' \). Thus \( r\mu' = s\mu' \), so \( r \) and \( s \) have the same first letter, and second, etc., and one of the two must run out of letters before the other, for otherwise they would coincide. Say that \( r \) is longer, then
Cuntz and Krieger’s condition (I) is known to be equivalent to density of the aperiodic paths, to the absence of isolated points, and to the absence of terminal circuits for the matrix $A$. In the following proposition topological freeness of the partial action is added to the list.

**Proposition 7.14.** The following are equivalent:

1. The partial action $(C(P^\infty_A), \mathbb{F}_n, \theta)$ is topologically free.
2. The graph with incidence matrix $A$ has no terminal circuits.
3. There are no isolated points in $P^\infty_A$.
4. The aperiodic paths are dense in $P^\infty_A$.
5. The matrix $A$ satisfies Cuntz and Krieger’s condition (I).

**Proof.** By Lemma 7.13, a fixed point of the partial action is determined by the group element that fixes it. Specifically, the group element $t$ has a nonempty fixed point set if and only if $t = xγx^{-1}$ with $xγγ$ admissible. When this happens, the fixed point set for $t$ is just the singleton $\{xγγγ \cdots \} \subset P^\infty_A$. By Lemma 7.12 this singleton is open if and only if $γ$ is terminal, so (i) ⇐⇒ (ii) ⇐⇒ (iii).

The proof of (ii) ⇐⇒ (v) can be found in [13, Lemma 3.3] and (iv) ⇐⇒ (v) is from [5].

As the main result of this section we obtain the Cuntz-Krieger uniqueness theorem via an application of our characterization of faithful representations of crossed products of topologically free partial actions.

**Theorem 7.15.** ([5, Theorem 2.13]) Suppose $A$ has no terminal circuits. If $\{s_i\}_{i=1}^n$ and $\{s'_i\}_{i=1}^n$ are two Cuntz-Krieger $A$-families of nonzero partial isometries, then the map $s_i \mapsto s'_i$ gives an isomorphism of $C^*(\{s_i\}_{i=1}^n)$ to $C^*(\{s'_i\}_{i=1}^n)$.

**Proof.** The canonical partial action $θ$ on $P^\infty_A$ is topologically free by Proposition 7.14, and the reduced and full crossed products coincide by [1, Theorem 6.6].

It suffices to show that nonzero partial isometries give rise to faithful representations of $C(P^\infty_A)$, because then Theorem 2.6 implies that the representations of $C(P^\infty_A) \rtimes \mathbb{F}_n$ arising from $\{s_i\}$ and $\{s'_i\}$ are both faithful.

Everything hinges upon showing that if $(π, u)$ is a covariant representation in which $π$ is not faithful, then $u_g = 0$ for some generator $g$ of $\mathbb{F}_n$. Suppose $π$ is not faithful. Then there exists $f \in C(Ω\mathcal{C}_K)$ such that $f \neq 0$ and $π(f) = 0$. Without loss of generality we may assume $f$ to be positive. Let $μ ∈ P^\infty_A$ be a point with $f(μ) > ∥f∥/2$. Then there exists $k$ large enough such that $f > ∥f∥/2$ on the neighborhood

$$V_{μ,k} := \{ν ∈ P^\infty_A : ν_i = μ_i \text{ for } i ≤ k\}$$

of $μ$. Let $s = μ_1μ_2 \cdots μ_k$. Then $0 ≤ u_s u^*_s = π(1_s) ≤ (2/∥f∥)π(f) = 0$, so $u^*_s u_s = 0$. Since $u^*_s u_s = u^*_s u_s$ by [5, Lemma 2.1 (a)], we conclude that the partial isometry $uμ_k$ vanishes. □

**Remark 7.16.** It is also not hard to see that if $A$ is irreducible and not a permutation matrix, then the partial action on $P^\infty_A$ is minimal and topologically free, so the simplicity result for $O_A$ [5, Theorem 2.14] follows from our Corollary 2.9.
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