NUCLEARITY OF SEMIGROUP C*-ALGEBRAS AND THE CONNECTION TO AMENABILITY

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Abstract. We study C*-algebras associated with subsemigroups of groups. For a large class of such semigroups including positive cones in quasi-lattice ordered groups and left Ore semigroups, we describe the corresponding semigroup C*-algebras as C*-algebras of inverse semigroups, groupoid C*-algebras and full corners in associated group crossed products. These descriptions allow us to characterize nuclearity of semigroup C*-algebras in terms of faithfulness of left regular representations and amenability of group actions. Moreover, we also determine when boundary quotients of semigroup C*-algebras are UCT Kirchberg algebras. This leads to a unified approach to Cuntz algebras and ring C*-algebras.

1. Introduction

We continue the project started in [Li2] about C*-algebras associated with semigroups. The study of such semigroup C*-algebras goes back to L. Coburn ([Co1], [Co2]) and was continued in for example [Dou], [Mur1], [Mur2], [Mur3] and [Mur4]. While there is a canonical reduced version, namely the C*-algebra generated by the left regular representation of the (left cancellative) semigroup, G. Murphy showed in [Mur4] that the most obvious candidate for the full semigroup C*-algebra is intractable even for very simple (for instance abelian) semigroups. So one of the main difficulties was to find a good full version of semigroup C*-algebras, given by generators and relations, which could be viewed as the analogue of full group C*-algebras.

One big step forward was [Ni1]. A. Nica’s idea was to define full semigroup C*-algebras using not only the obvious relations but also additional ones reflecting the (right) ideal structure of the semigroup. This modification leads to interesting C*-algebras which can be analyzed and which exhibit good properties. However, A. Nica did not explicitly mention ideals of semigroups. Instead, he restricted his analysis to positive cones in quasi-lattice ordered groups which have a very simple ideal structure.

A. Nica’s ideas have been taken up by M. Laca in collaboration with I. Raeburn and J. Crisp ([La-Rae], [La1], [Cr-La1], [Cr-La2]). They studied the question when the left regular representation from the full to the reduced semigroup C*-algebra is faithful, and they described induced ideals of semigroup C*-algebras. However, the question when semigroup C*-algebras are nuclear was left untouched, and the

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connection between nuclearity and faithfulness of the left regular representation remained mysterious.

Recently, new examples of C*-algebras arising from number theory ([Cun], [Cu-Li1], [Li1], [Cu-Li2]) have motivated the author to generalize A. Nica’s work. For semigroups associated with number theoretic rings, the restriction to positive cones of quasi-lattice ordered groups corresponds to only considering principal ideal domains – a restriction which, especially for rings from algebraic number theory, would exclude all the interesting examples. Making explicit use of the ideal structure of semigroups, the author was able to extend A. Nica’s construction to arbitrary left cancellative semigroups in [Li2]. The same construction was introduced independently in [C-D-L] for particular examples of number theoretic interest. In general, it turns out that the full semigroup C*-algebras still have good properties. For instance, it is shown in [Li2] and also [Nor] that they are well-suited for studying amenability of semigroups. However, amenability is a strong assumption which interesting examples fail to have. One of the most striking examples is probably the \( n \)-fold free product \( \mathbb{N}^*_{0^n} \) of the natural numbers. This example is due to A. Nica, and he observed that it is closely related to the Cuntz algebra \( O_n \).

A closely related topic is the theory of semigroup crossed products (by endomorphisms). One of the most important ideas in the analysis of semigroup crossed products is the idea of dilation. It already goes back to J. Cuntz in his work on the Cuntz algebras. This dilation theory has then been fully developed, in the probably most general setting, by M. Laca in [La2]. He shows that one can use inductive limit procedures to dilate isometries to unitaries and endomorphisms to automorphisms so that in the end, semigroup crossed products can be embedded as full corners into group crossed products. This means that questions about semigroup crossed products translate into questions about group crossed products which have already been intensively studied. However, this dilation theory as described here only works for left Ore semigroups, and the question remains what to do for semigroups like the free product \( \mathbb{N}^*_{0^n} \).

Now, in the present paper, our main observation is that for semigroup C*-algebras in the sense of [Ni1] or [Li2], the left Ore condition is not essential for embedding semigroup C*-algebras as full corners into group crossed products.

More precisely, for a subsemigroup \( P \) of a group \( G \), we show that under two conditions, the full and reduced semigroup C*-algebras of \( P \) embed as full corners into full and reduced crossed products by \( G \). The underlying C*-dynamical system is in a canonical way built out of the inclusion \( P \subseteq G \) and a distinguished commutative subalgebra of the semigroup C*-algebra. The two conditions we have to impose are that the constructible right ideals of \( P \) are independent and that \( P \subseteq G \) satisfies the so-called Toeplitz condition. The first condition was introduced in [Li2] and guarantees that the canonical commutative subalgebras of the full and reduced semigroup C*-algebras coincide. This condition also plays a crucial role in [C-E-L]. The second condition is new. It basically says that compressing operators on \( \ell^2(G) \) to \( \ell^2(P) \) has good properties. We show that this condition is satisfied in typical examples. In particular, it holds for positive cones in quasi-lattice ordered groups and left Ore
semigroups. Our main point is that we do not need the left Ore condition, only the
two conditions described above. In order to embed full semigroup C*-algebras as full
corners into group crossed products, the idea is to write both semigroup C*-algebras
and the group crossed products into which we would like to embed as groupoid C*-
algebras. The underlying groupoids are equivalent more or less by construction, so
that we can use the observation by [M-R-W] that equivalence of groupoids give rise
to explicit imprimitivity bimodules of the corresponding groupoid C*-algebras. This
result allows us to show that certain universal norms coincide. We point out that
we work with the full version of semigroup C*-algebras introduced in § 3 in [Li2].

We then use this observation to give equivalent characterizations for nuclearity of
semigroup C*-algebras. For instance, we see that nuclearity can be expressed in
terms of amenable group actions. Moreover, nuclearity of semigroup C*-algebras
implies faithfulness of the corresponding left regular representations.

These two results on embeddability as full corners and nuclearity are our main re-
results. In addition, we extend existing results about induced ideals and boundary
actions from the quasi-lattice ordered case to our more general setting. This leads to
a unified approach to specific constructions like Cuntz algebras or ring C*-algebras,
and we obtain a general explanation why these examples are UCT Kirchberg al-
gebras.

The present paper is structured as follows:

In a first preliminary section, we describe the setting (§ 2.1) and analyze commuta-
tive C*-algebras generated by independent commuting projections (§ 2.2).

We then consider semigroup C*-algebras and the more general notion of semigroup
crossed products by automorphisms (semigroup C*-algebras are the crossed products
associated with the trivial action on the complex numbers). We first look at reduced
versions (§ 3). Whenever given a subsemigroup $P$ of a group $G$, there is a canonical
$G$-action on a certain C*-algebra associated with every semigroup action of $P$ by
automorphisms. We find conditions when the reduced semigroup crossed product
by automorphisms embeds as a full corner into the corresponding group crossed
product. This leads us to the Toeplitz condition mentioned above. It is introduced
and briefly discussed in § 4.

In § 5, we then describe reduced and full semigroup crossed products by automor-
phisms as crossed products by partial automorphisms of inverse semigroups and
groupoid crossed products. Here we need to assume that the constructible right
ideals of our semigroup are independent. The first main observation is that the
Toeplitz condition is precisely what we need to embed full semigroup crossed prod-
ucts by automorphisms as full corners into the corresponding full group crossed
products (see Theorem 5.20).

As a consequence of our first main result, we determine equivalent characterizations
of nuclearity for reduced and full semigroup C*-algebras in § 6.
In § 7, we study induced ideals of semigroup C*-algebras. We first extend our results on embeddability into full corners and nuclearity to the situation of ideals and quotients (see § 7.1). Induced ideals are obtained from invariant subsets of the spectrum of the canonical commutative subalgebra of the semigroup C*-algebra. Therefore, we explicitly describe this spectrum in § 7.2. Moreover, we extend the notion of the boundary from [La1] to our general setting. We analyze the boundary action in § 7.3 and find a criterion when the boundary quotient is a UCT Kirchberg algebra.

Finally, we turn to examples in § 8. For quasi-lattice ordered groups, we prove that the analysis from [La-Rae] may be extended to obtain the stronger property of nuclearity of the corresponding semigroup C*-algebras (see § 8.1). We also treat the case of the free product $\mathbb{N}_0^\infty$ in § 8.2. The boundary quotient in this case is the Cuntz algebra $\mathcal{O}_n$, and an application of our results yields a description of $\mathcal{O}_n$ – up to Morita equivalence – as a crossed product associated with the action of the free group $\mathbb{F}_n$ on the “positive part” of its Gromov boundary. Another class of examples is provided by left Ore semigroups (see § 8.3). It turns out that ring C*-algebras are the boundary quotients of the semigroup C*-algebras of the corresponding $ax + b$-semigroups. This explains why several aspects of the structure of ring C*-algebras are very similar to those of the Cuntz algebras.

In § 9, we discuss a few open questions which may be interesting for future research.

I would like to thank M. Laca for bringing [Cr-La1] and [Cr-La2] to my attention. I also thank J. Cuntz for pointing me towards [Kho-Ska1] and [Kho-Ska2]. Moreover, I thank R. Meyer who brought inverse semigroups to my mind.

2. Preliminaries

2.1. The setting. Throughout this paper, let $P$ be a subsemigroup of a group $G$. We assume that $P$ contains the unit element $e$ of $G$. All the semigroups in this paper will be unital, and all semigroup homomorphisms shall preserve the units. Moreover, we point out that we are only looking at discrete semigroups and discrete groups.

As explained in [Li2], the right ideal structure of $P$ plays an important role in the construction and analysis of the semigroup C*-algebras of $P$. By a right ideal of $P$, we mean a subset $X$ of $P$ which is closed under right multiplication, i.e. for all $x \in X$ and $p \in P$, the product $xp$ lies in $X$. Given a subset (for example a right ideal) $X$ of $P$ and a semigroup element $p$, we can form the left translate of $X$ by $p$, i.e. $pX := \{px : x \in X\}$, and also the pre-image of $X$ under left multiplication by $p$, i.e. $p^{-1}X := \{y \in P : py \in X\}$. We point out that $G$ also acts on itself by left translations, hence we can also translate a subset $X$ by a group element $g$. We denote the translation by $g \cdot X := \{gx : x \in X\}$. We have for $p$ in $P$ and $X \subseteq P$ that $pX = p \cdot X$, but $p^{-1}X \neq p^{-1} \cdot X$ in general. Instead, we have the relation $p^{-1}X = (p^{-1} \cdot X) \cap P$. 
The following family of right ideals was introduced in [Li2]; it plays a crucial role in this paper.

**Definition 2.1.** Let \( J \) be the smallest family of right ideals of \( P \) such that

- \( \emptyset, P \in J \);
- \( J \) is closed under left multiplication and taking pre-images under left multiplication (\( X \in J, p \in P \Rightarrow pX, p^{-1}X \in J \));
- \( J \) is closed under finite intersections (\( X_1, X_2 \in J \Rightarrow X_1 \cap X_2 \in J \)).

Elements in \( J \) are called constructible right ideals of \( P \).

As observed in § 3 in [Li2], it is not necessary to ask for the condition that \( J \) should be closed under finite intersections.

In our situation of a subsemigroup of a group, it is also important to consider the following

**Definition 2.2.** Let \( J^G_P \) be the smallest family of subsets of \( G \) which contains \( J \) and which is closed under left translations by group elements (\( Y \in J^G_P, g \in G \Rightarrow g \cdot Y \in J^G_P \) ) and finite intersections.

It is immediate from the definitions that \( J \) consists of \( \emptyset \) and all finite intersections of right ideals of the form \( q_1^{-1}p_1 \cdots q_n^{-1}p_nP \) (\( p_i, q_i \in P \)). Moreover, \( J^G_P \) is given by all finite intersections of subsets of the form \( g \cdot X \) (for \( g \in G \) and \( X \in J \)).

### 2.2. Families of subsets.

Let us now analyse a situation which will appear soon.

Let \( \mathfrak{P} \) be a discrete set and \( \mathcal{J} \) be a family of subsets of \( \mathfrak{P} \). We assume that \( \emptyset \in \mathcal{J} \) and that \( \mathcal{J} \) is closed under finite intersections.

**Definition 2.3.** \( \mathcal{J} \) is called independent if for all \( X, X_1, \ldots, X_n \) in \( \mathcal{J} \), we have that \( X_i \subseteq X \) for all \( 1 \leq i \leq n \) implies \( \bigcup_{i=1}^{n} X_i \subseteq X \).

In other words, \( \mathcal{J} \) is independent if whenever \( X = \bigcup_{i=1}^{n} X_i \) for \( X, X_1, \ldots, X_n \) in \( \mathcal{J} \), then there must be an index \( 1 \leq i \leq n \) such that \( X = X_i \).

This independence condition was introduced in [Li2].

For a subset \( X \) of \( \mathfrak{P} \), we write \( \mathbbm{1}_X \) for the characteristic function of \( X \) defined on \( \mathfrak{P} \). We view \( \mathbbm{1}_X \) as an element of \( \ell^\infty(\mathfrak{P}) \) and let \( \ell^\infty(\mathfrak{P}) \) act on \( \ell^2(\mathfrak{P}) \) by multiplication operators. Let \( E_X \) be the multiplication operator corresponding to \( \mathbbm{1}_X \).

**Definition 2.4.** We set \( D := C^*(\{ E_X : X \in \mathcal{J} \}) \subseteq \ell^\infty(\mathfrak{P}) \subseteq \mathcal{L}(\ell^2(\mathfrak{P})) \).

**Lemma 2.5.** If \( \mathcal{J} \) is independent, then the commutative \( C^* \)-algebra \( D \) satisfies the following universal property: Whenever \( T \) is a \( C^* \)-algebra and \( e_X, X \in \mathcal{J} \), are projections in \( T \) satisfying \( e_\emptyset = 0 \) and \( e_{X_1 \cap X_2} = e_{X_1} e_{X_2} \) for all \( X_1, X_2 \in \mathcal{J} \), then there exists a (unique) homomorphism \( D \to T \) given by \( E_X \mapsto e_X \) for all \( X \in \mathcal{J} \).
Proof. The idea is to write $D$ as an inductive limit of finite dimensional subalgebras. For a finite subset $F$ of $\mathcal{J}$ which is closed under intersections, set $D_F = C^\ast(\{E_X: X \in F\}) = \text{span}(\{E_X: X \in F\})$. As all the projections $E_X$ commute, we may orthogonalize them in $D_F$: For every $0 \neq X \in F$, form the projection $f(X \in F, D) := E_X - \bigvee_{X \supsetneq Y \in F} E_Y$ where $\bigvee E_Y$ is the smallest projection in $D$ which dominates all the $E_Y$. As $\mathcal{J}$ is independent, all these projections $f(X \in F, D)$ are non-zero (for $0 \neq X \in F$). Moreover, these projections are pairwise orthogonal, and they generate $D_F$. Thus we obtain $D_F = \bigoplus_{\emptyset \neq X \in F} \mathbb{C} \cdot f(X \in F, D)$. Similarly, form $f(X \in F, T) := e_X - \bigvee_{X \supsetneq Y \in F} e_Y$ in $T$. These projections $f(X \in F, T)$ are pairwise orthogonal by construction. Thus there exists by universal property of $\bigoplus_{\emptyset \neq X \in F} \mathbb{C} \cdot f(X \in F, D) \cong \mathbb{C}[\{\emptyset\}]$ a homomorphism $D_F \to T$ defined by $f(X \in F, D) \mapsto f(X \in F, T)$. By construction, $E_X = \bigoplus_{X \supsetneq Y \in F} f(Y \in F, D)$ is sent to $\bigoplus_{X \supsetneq Y \in F} f(Y \in F, T) = e_X$. Therefore, these homomorphisms $\{D_F \to T\}_F$ are compatible with the canonical inclusions $D_F \hookrightarrow D_F$ for $F \subseteq \tilde{F}$. Hence they define a homomorphism $D = \bigcup_D D_F \to T$. This homomorphism sends $E_X \in D$ to $e_X \in T$ for all $X \in \mathcal{J}$, as desired. \hfill $\square$

The next observation is essentially Proposition 2.24 in [Li2].

**Corollary 2.6.** If $\mathcal{J}$ is independent, then $\{E_X: \emptyset \neq X \in \mathcal{J}\}$ is linearly independent.

Proof. By Lemma 2.5, there exists a homomorphism $D \to D \otimes D, E_X \mapsto E_X \otimes E_X$. As $D$ is commutative, it does not matter which tensor product we choose. Restricting to $D^{\text{alg}} := \text{span}(\{E_X: X \in \mathcal{J}\})$, we obtain a homomorphism

$$D^{\text{alg}} \to D^{\text{alg}} \otimes D^{\text{alg}}, E_X \mapsto E_X \otimes E_X.$$  

As $D^{\text{alg}}$ is spanned by $\{E_X: X \in \mathcal{J}\}$, we can choose a subset $\mathcal{J}'$ of $\mathcal{J}$ such that $\{E_{X'}: X' \in \mathcal{J}'\}$ is a C-basis of $D^{\text{alg}}$. Now take $X \in \mathcal{J}$. We can write $E_X$ as a finite sum $E_X = \sum \lambda_i E_{X_i}'$, for some $X_i' \in \mathcal{J}'$. The homomorphism from (1) sends $E_X$ to $E_X \otimes E_X = \sum \lambda_i E_{X_i}' \otimes E_{X_i}'$ and $\sum \lambda_i E_{X_i}'$ to $\sum \lambda_i E_{X_i}' \otimes E_{X_i}'$. But $E_X$ and $\sum \lambda_i E_{X_i}'$ coincide, so they have to be sent to the same element. We conclude that

$$\sum \lambda_i E_{X_i}' \otimes E_{X_i}' = \sum \lambda_i E_{X_i}' \otimes E_{X_i}.$$  

As $\{E_{X'}: X' \in \mathcal{J}'\}$ is a C-basis for $D^{\text{alg}}$, $\{E_{X'} \otimes E_{X''}: X', X'' \in \mathcal{J}'\}$ is a C-basis for $D^{\text{alg}} \otimes D^{\text{alg}}$. Thus we can compare coefficients in (2) and deduce $\lambda_i \lambda_j = 0$ if $i \neq j$ and $\lambda_i^2 = \lambda_i$. It follows that there can at most be one non-zero coefficient $\lambda_i$ which must be 1. Thus either $E_X = 0 (\Leftrightarrow X = \emptyset)$ or $E_X = E_{X_i}'$ for some $X_i' \in \mathcal{J}'$. As $E_X = E_{X_i}'$ implies $X = X_i'$, we deduce that $\mathcal{J}' = \mathcal{J} \setminus \{\emptyset\}$. But this means that $\{E_X: \emptyset \neq X \in \mathcal{J}\}$ is a C-basis of $D^{\text{alg}}$, hence linearly independent. \hfill $\square$

**Remark 2.7.** The converse also holds, i.e. if $\{E_X: \emptyset \neq X \in \mathcal{J}\}$ is linearly independent, then $\mathcal{J}$ is independent. The reason is that an equation of the form $X = \bigcup_{i=1}^n X_i$ gives $E_X = \sum_{\emptyset \neq F \subseteq \{1, \ldots, n\}} (-1)^{|F| + 1} E_{\bigcap_{j \in F} X_j}$. 

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From now on, we always assume that $\mathcal{J}$ is independent. Let us describe the spectrum of $D$.

**Corollary 2.8.** For every function $\phi: \mathcal{J} \to \{0, 1\}$ such that $\phi(\emptyset) = 0$ and $\phi(X_1 \cap X_2) = \phi(X_1) \phi(X_2)$ for all $X_1, X_2 \in \mathcal{J}$, there exists a unique homomorphism $D \to \mathbb{C}$ determined by $E_X \mapsto \phi(X)$.

*Proof.* Just set $T = \mathbb{C}$ in Lemma 2.5. $\square$

Let us call a subset $F$ of $\mathcal{J}$ satisfying

- $X_1 \subseteq X_2 \in \mathcal{J}, X_1 \in F \Rightarrow X_2 \in F$,
- $X_1, X_2 \in F \Rightarrow X_1 \cap X_2 \in F$,
- $\emptyset \notin F$,

a $\mathcal{J}$-valued filter on $\mathcal{P}$.

**Corollary 2.9.** We can identify $\text{Spec} D$ with the set $\Sigma$ of all non-empty $\mathcal{J}$-valued filters on $\mathcal{P}$ via $\text{Spec} D \ni \chi \mapsto \{X \in \mathcal{J}: \chi(E_X) = 1\}$.

*Proof.* The inverse of this map is given by sending a non-empty $\mathcal{J}$-valued filter on $\mathcal{P}$ to the character $\chi$ of $D$ uniquely determined by $\chi(E_X) = 1$ if $X \in F$ and $\chi(E_X) = 0$ if $X \notin F$. Such a character exists by Corollary 2.8. $\square$

The topology of pointwise convergence on $\text{Spec} D$ induces a topology on $\Sigma$ such that the bijection

$$\text{Spec} D \ni \chi \mapsto \{X \in \mathcal{J}: \chi(E_X) = 1\} \in \Sigma$$

becomes a homeomorphism. To describe this topology, we set for $X, X'_1, \ldots, X'_n$ in $\mathcal{J}$:

$$U(X; X'_1, \ldots, X'_n) := \{F \in \Sigma: X \in F, X'_i \notin F \text{ for all } 1 \leq i \leq n\}$$

Then a basis for the topology on $\Sigma$ induced by the one on $\text{Spec} D$ is given by the open sets

$$\{U(X; X'_1, \ldots, X'_n): n \in \mathbb{Z}_{\geq 0}, X, X'_1, \ldots, X'_n \in \mathcal{J}\}.$$

Finally, we call a $\mathcal{J}$-valued filter on $\mathcal{P}$ which is maximal (in $\Sigma$) with respect to inclusion a $\mathcal{J}$-valued ultrafilter on $\mathcal{P}$.

**Definition 2.10.** We let $\Sigma_{\text{max}}$ be the set of all $\mathcal{J}$-valued ultrafilters on $\mathcal{P}$. The subset of $\text{Spec} D$ corresponding to $\Sigma_{\text{max}}$ under the identification (3) is denoted by $(\text{Spec} D)_{\text{max}}$. Moreover, we set $\partial \Sigma := \Sigma_{\text{max}} \subseteq \Sigma$ and denote the closed subset of $\text{Spec} D$ corresponding to $\partial \Sigma$ under the homeomorphism (3) by $\partial \text{Spec} D$.

Note that

$$\mathcal{F} \in \Sigma_{\text{max}} \iff \text{"for all } X \in \mathcal{J}, X \notin \mathcal{F} \text{ there is } X' \in \mathcal{F} : X \cap X' = \emptyset".$$
Let us first of all define reduced semigroup C*-algebras and reduced crossed products by automorphisms (see [Li2]). We start with reduced semigroup C*-algebras.

Recall that $P$ is a subsemigroup of a group $G$. Let $\{e_x: x \in P\}$ be the canonical orthonormal basis of $\ell^2(P)$. For every $p \in P$, the formula $V_p e_x = e_{px}$ extends to an isometry on $\ell^2(P)$. Now the reduced semigroup C*-algebra of $P$ is simply given as the sub-C*-algebra of $\mathcal{L}(\ell^2(P))$ generated by these isometries $\{V_p: p \in P\}$. We denote this concrete C*-algebra by $C_r^*(P)$, i.e. we set

**Definition 3.1.** $C_r^*(P) := C^*(\{V_p: p \in P\}) \subseteq \mathcal{L}(\ell^2(P))$.

As we have done in § 2.2, we denote by $E_X \in \mathcal{L}(\ell^2(P))$ the orthogonal projection onto $\ell^2(X) \leq \ell^2(P)$ for every subset $X$ of $P$. We then set

**Definition 3.2.** $D_r := C^*(\{E_X: X \in \mathcal{J}\})$.

As explained in [Li2], $D_r$ is a commutative sub-C*-algebra of $C_r^*(P)$.

Now we turn to crossed products. Let $A$ be a C*-algebra which we will always think of as a sub-C*-algebra of $\mathcal{L}(\mathcal{H})$ for some Hilbert space $\mathcal{H}$. Assume that we are given a $G$-action $\alpha$ on $A$. Define for every $a$ in $A$ the operator $a_{(\alpha,p)} \in \mathcal{L}(\mathcal{H} \otimes \ell^2(P))$ by setting $a_{(\alpha,p)}(\xi \otimes e_x) = (\alpha^{-1}_x(a) \otimes e_x) \xi$ for all $\xi \in \mathcal{H}$, $x \in P$.

**Definition 3.3.** The reduced automorphic crossed product of $A$ by $P$ is given by $A \rtimes_{\alpha, r}^a P := C^*(\{a_{(\alpha,p)}(I_{\mathcal{H}} \otimes V_p) : a \in A, p \in P\}) \subseteq \mathcal{L}(\mathcal{H} \otimes \ell^2(P))$ where $I_{\mathcal{H}}$ is the identity operator on $\mathcal{H}$.

Of course, we can canonically identify $C \rtimes_{\alpha, r}^a P$ with $C_r^*(P)$.

We now discuss the question whether $A \rtimes_{\alpha, r}^a P$ can be embedded as a full corner into an ordinary (reduced) group crossed product. Let $\lambda : G \rightarrow \mathcal{U}(\ell^2(G))$ be the left regular representation of $G$. The group $G$ acts on $\ell^\infty(G)$ by left translations. We call this action $\tau$, and we denote the action of $G$ on the multiplication operators on $\ell^2(G)$ corresponding to $\ell^\infty(G)$ by $\tau$ as well. It is clear that $\tau$ is spatially implemented by $\lambda$. As before, for a subset $Y$ of $G$, we let $E_Y \in \mathcal{L}(\ell^2(G))$ be the orthogonal projection onto $\ell^2(Y) \subseteq \ell^2(G)$. In particular, $E_P$ is the orthogonal projection onto $\ell^2(P) \subseteq \ell^2(G)$.

**Definition 3.4.** We let $D^G_\mathcal{J}$ be the smallest sub-C*-algebra of $\ell^\infty(G) \subseteq \mathcal{L}(\ell^2(G))$ which is $\tau$-invariant and contains $E_P$.

**Lemma 3.5.** $D^G_\mathcal{J} = \text{span}(\{E_Y: Y \in \mathcal{J}\})$.

Recall the definition of $\mathcal{J}^G_\mathcal{J}$ from § 2.1.

**Proof.** Every $Y$ in $\mathcal{J}^G_\mathcal{J}$ is of the form $\bigcap_{i=1}^n g_i \cdot X_i$ for $g_i \in G$, $X_i \in \mathcal{J}$. Thus $E_Y = \prod_{i=1}^n \tau_{g_i}(E_{X_i})$ lies in $D^G_\mathcal{J}$. This proves “$\subseteq$”. Conversely, the set $\{E_Y: Y \in \mathcal{J}^G_\mathcal{J}\}$ is
multiplicatively closed as \( \mathcal{F}_G^2 \) is closed under finite intersections. Moreover, this set is \( \tau \)-invariant and contains \( E_P \). Thus "\( \subseteq \)" holds as well.

As in the construction of reduced crossed products, we define for \( a \in A \) the operator \( a_{(a)} \in \mathcal{L}(\mathcal{H} \otimes \ell^2(G)) \) by \( a_{(a)}(\xi \otimes \varepsilon_x) = (\alpha_x^{-1}(a)\xi) \otimes \varepsilon_x \) for all \( \xi \) in \( \mathcal{H} \) and \( x \) in \( G \). The following is just Proposition 2.5.1 in [C-E-L] with general coefficients:

**Lemma 3.6.** The homomorphism \( A \otimes D_G^2 \to \mathcal{L}(\mathcal{H} \otimes \ell^2(G)) \) determined by \( a \otimes d \mapsto a_{(a)}(I_{\mathcal{H}} \otimes d) \) and the group homomorphism \( G \to \mathcal{U}(\mathcal{H} \otimes \ell^2(G)), g \mapsto I_{\mathcal{H}} \otimes \lambda_g \) define a covariant representation of \( (A \otimes D_G^2, G, \alpha \otimes \tau) \) on \( \mathcal{H} \otimes \ell^2(G) \). The corresponding representation of \( (A \otimes D_P^G, G_\tau \otimes \tau, r) G \) is faithful. It sends \( (a \otimes d)U_g \) to \( a_{(a)}(I_{\mathcal{H}} \otimes d)(I_{\mathcal{H}} \otimes \lambda_g) \).

Note that since \( D_P^G \) is commutative, it does not matter which tensor product \( A \otimes D_P^G \) we take.

**Proof.** An obvious computation shows that the maps described in the lemma define a covariant representation. Let us show that it gives rise to a faithful representation of the reduced crossed product.

By replacing \( \mathcal{H} \) by \( \mathcal{H} \otimes \ell^2(G) \) and \( a \in A \) by \( a_{(a)} \), we may without loss of generality assume that the \( G \)-action \( \alpha \) on \( A \) is spatially implemented. This means that there exists a group homomorphism \( G \to \mathcal{U}(\mathcal{H}), g \mapsto W_g \) such that \( \text{Ad}(W_g)(a) = \alpha_g(a) \). We realize the reduced crossed product \( (A \otimes D_P^G) \rtimes_{\alpha \otimes \tau, r} G \) as the sub-C*-algebra of \( \mathcal{L}(\mathcal{H} \otimes \ell^2(G) \otimes \ell^2(G)) \) generated by \( \{ (a \otimes d)_{\alpha \otimes \tau, r}(I_{\mathcal{H}} \otimes \lambda_g) : a \in A, d \in D_P^G, g \in G \} \) with \( (a \otimes d)_{\alpha \otimes \tau, r}(\xi \otimes \zeta \otimes \varepsilon_x) = (\alpha_x^{-1}(a)\xi) \otimes (\tau_x^{-1}(d)\zeta) \otimes \varepsilon_x \). Now define the unitary

\[
W : \mathcal{H} \otimes \ell^2(G) \otimes \ell^2(G) \to \mathcal{H} \otimes \ell^2(G) \otimes \ell^2(G), \xi \otimes \varepsilon_x \otimes \varepsilon_y \mapsto W_{x^{-1}} \xi \otimes \varepsilon_y \otimes \varepsilon_{x^{-1}}.
\]

A similar computation as in [C-E-L], Proposition 2.5.1 shows

\[
W((a \otimes d)_{\alpha \otimes \tau, r})W^* = (a_{(a)}(I_{\mathcal{H}} \otimes d))_{\ell^2(G)}, \text{ and } W(I_{\mathcal{H}} \otimes \lambda_g \otimes \lambda_g)W^* = (I_{\mathcal{H}} \otimes \lambda_g)_{\ell^2(G)}.
\]

Thus \( \text{Ad}(W) \) identifies \( (A \otimes D_P^G) \rtimes_{\alpha \otimes \tau, r} G \) with a sub-C*-algebra of \( \mathcal{L}(\mathcal{H} \otimes \ell^2(G)) \otimes I_{\ell^2(G)} \). Identifying \( \mathcal{L}(\mathcal{H} \otimes \ell^2(G)) \otimes I_{\ell^2(G)} \) with \( \mathcal{L}(\mathcal{H} \otimes \ell^2(G)) \) in the obvious way, we obtain the desired faithful representation.

**Definition 3.7.** Let \( A \rtimes_{\alpha, r} (P \subseteq G) \) be the image of \( (A \otimes D_P^G) \rtimes_{\alpha \otimes \tau, r} G \) under the representation from the last lemma. If \( A = \mathbb{C} \), then we set \( C^*_\tau(P \subseteq G) := \mathbb{C} \rtimes_{\tau, r} (P \subseteq G) \).

In the sequel, we denote for \( d \in D_P^G \) the canonical multiplier associated with \( d \) by \( 1 \otimes d \in M(A \otimes D_P^G) \subseteq M((A \otimes D_P^G) \rtimes_{\alpha \otimes \tau, r} G) \).

**Lemma 3.8.** \( 1 \otimes E_P \) yields the full corner \( (1 \otimes E_P)((A \otimes D_P^G) \rtimes_{\alpha \otimes \tau, r} G) \).

**Proof.** We have to show that \( \text{span}((A \otimes D_P^G) \rtimes_{\alpha \otimes \tau, r} G)(1 \otimes E_P)((A \otimes D_P^G) \rtimes_{\alpha \otimes \tau, r} G)) \) is dense in \( (A \otimes D_P^G) \rtimes_{\alpha \otimes \tau, r} G \).
For every $Y = \bigcap_{i=1}^{n} g_i : X_i \in \mathcal{J}^G_P$ ($g_i \in G$, $X_i \in \mathcal{J}$), $a \in A$ and $g \in G$, the operator $(a \otimes E_Y)U_g = (a \otimes E_Y)(\prod_{i=1}^{n} U_{g_i}(1 \otimes E_{X_i})U_{g_i}^*)U_g = (a \otimes E_Y)(\prod_{i=1}^{n} U_{g_i}(1 \otimes E_{X_i}))(1 \otimes E_P)U_{g_i}^*)U_g$ lies in $(A \otimes D^G_P) \rtimes_{\alpha \otimes \tau, r} G$ of $(A \otimes D^G_P) \rtimes_{\alpha \otimes \tau, r} G)$. Here $U_g$ are the canonical unitaries implementing the $G$-action.

In the sequel, we do not distinguish between $H \otimes \ell^2(P)$ and the subspace $(I_H \otimes E_P)(H \otimes \ell^2(G))$ of $H \otimes \ell^2(G)$. In this way, operators on $H \otimes \ell^2(P)$ act on $H \otimes \ell^2(G)$ (on the orthogonal complement of $(I_H \otimes E_P)(H \otimes \ell^2(G))$, they are simply 0). For instance, the operator $a_{(\alpha, p)}$ is the same as $(I_H \otimes E_P)_{a_{(\alpha)}}(I_H \otimes E_P)$ and $I_H \otimes V_p$ is nothing else but $(I_H \otimes E_P)((I_H \otimes \lambda_p)(I_H \otimes E_P))$ for all $p \in P$. As $A \rtimes_{\alpha, r} P$ is the $C^*$-algebra generated by $a_{(\alpha, p)}(I_H \otimes V_p)$ ($a \in A$, $p \in P$), we see that $A \rtimes_{\alpha, r} P$ is (or can be, in the way explained above, canonically identified with) a sub-$C^*$-algebra of the full corner $(I_H \otimes E_P)(A \rtimes_{\alpha, r} (P \subseteq G))(I_H \otimes E_P)$. We now address the question when these two $C^*$-algebras are actually the same.

**Lemma 3.9.** The following statements are equivalent:

(i) We have $A \rtimes_{\alpha, r} P = (I_H \otimes E_P)(A \rtimes_{\alpha, r} (P \subseteq G))(I_H \otimes E_P)$ for every $C^*$-dynamical system $(A, G, \alpha)$,

(ii) $C^*_\tau(P) = E_P C^*_\tau(P \subseteq G) E_P$,

(iii) for all $g \in G$, $E_P \lambda_g E_P$ lies in $C^*_\tau(P)$;

and either of these statements implies

(iv) $D_r \supseteq E_P D^G_P E_P$.

**Proof.** “(i) ⇒ (ii)” is trivial.

“(ii) ⇒ (iii)”: $E_P \lambda_g E_P = E_P E_P \lambda_g E_P \in E_P C^*_\tau(P \subseteq G) E_P = C^*_\tau(P)$.

“(iii) ⇒ (iv)”: By Lemma 3.5 and the definition of $\mathcal{J}^G_P$ from § 2.1, it suffices to prove that $E_P E_{g,X} E_P$ lies in $D_r$ for all $g \in G$ and $X \in \mathcal{J}$. First of all, $E_P E_{g,X} E_P = E_P \lambda_g E_X \lambda_g^* E_P = (E_P \lambda_g E_P) E_X (E_P \lambda_g E_P)$ lies in $C^*_\tau(P)$ by (iii). Moreover, $E_P E_{g,X} E_P$ is obviously contained in $\ell^\infty(P)$ viewed as multiplication operators on $\ell^2(P)$. Thus $E_P E_{g,X} E_P$ lies in $C^*_\tau(P) \cap \ell^\infty(P)$, and $C^*_\tau(P) \cap \ell^\infty(P) = D_r$ by Remark 3.12 in [Li2].

“(iii) & (iv) ⇒ (i)”: We have to show that for every $a \in A$, $Y \in \mathcal{J}^G_P$ and $g \in G$, $(I_H \otimes E_P)(a_{(\alpha)}(I_H \otimes E_Y)(I_H \otimes \lambda_g))(I_H \otimes E_P)$ lies in $A \rtimes_{\alpha, r} P$. We have

$$
(I_H \otimes E_P)(a_{(\alpha)}(I_H \otimes E_Y)(I_H \otimes \lambda_g))(I_H \otimes E_P)
= (I_H \otimes E_P)a_{(\alpha)}(I_H \otimes E_P)(I_H \otimes E_P E_Y \lambda_g E_P)
= a_{(\alpha, p)}(I_H \otimes (E_P E_Y E_P)(E_P \lambda_g E_P)).
$$

But $E_P E_Y E_P$ lies in $D_r$ by (iv) and $E_P \lambda_g E_P$ is in $C^*_\tau(P)$ by (iii). Since $a_{(\alpha, p)}(I_H \otimes C^*_\tau(P))$ lies in $A \rtimes_{\alpha, r} P$, we are done. □
Let us now summarize what we have obtained so far. Combining Lemmas 3.6, 3.8 and 3.9, we obtain

**Corollary 3.10.** If \( P \subseteq G \) satisfies one of the equivalent conditions (i), (ii) or (iii) from Lemma 3.9, then the homomorphism \( A \times_{\alpha,r} P \rightarrow (A \otimes D^G_p) \times_{\alpha \otimes \tau,r} G \) determined by \( a_{(\alpha,r)}((I_R \otimes V_p)) \mapsto (a \otimes E_P)(1 \otimes E_P)U_p(1 \otimes E_P) \) identifies \( A \times_{\alpha,r} P \) with the full corner \( (1 \otimes E_P)((A \otimes D^G_p) \times_{\alpha \otimes \tau,r} G)(1 \otimes E_P) \) of \( (A \otimes D^G_p) \times_{\alpha \otimes \tau,r} G \).

4. **The Toeplitz condition**

We now introduce a condition on the inclusion \( P \subseteq G \) which is (at least a priori) stronger than (iii) from Lemma 3.9.

**Definition 4.1.** We say that \( P \subseteq G \) satisfies the Toeplitz condition (or simply that \( P \subseteq G \) is Toeplitz) if for every \( g \in G \), there exist \( p_1, q_1, \ldots, p_n, q_n \) in \( P \) such that \( E_P \lambda g E_P = V_{p_1}^* V_{q_1} \cdots V_{p_n}^* V_{q_n} \).

This Toeplitz condition will play an important role in the next section, when we consider full versions. Moreover, we will see that in examples, the Toeplitz condition will naturally appear. In addition, it has the following consequences:

**Lemma 4.2.** If \( P \subseteq G \) is Toeplitz, then

(i) For all \( g \) in \( G \) and \( X \) in \( \mathcal{J} \), \( P \cap (g \cdot X) \) lies in \( \mathcal{J} \),

(ii) \( \mathcal{J}^G_P = \{ g \cdot X \colon g \in G, X \in \mathcal{J} \} \) (i.e. intersections are not needed).

If \( \mathcal{J} \) is independent and \( P \subseteq G \) is Toeplitz, then

(iii) \( \mathcal{J}^G_P \) is independent.

**Proof.** Given \( g \in G \), the Toeplitz condition says that there exist \( p_1, q_1, \ldots, p_n, q_n \) in \( P \) with \( E_P \lambda g E_P = V_{p_1}^* V_{q_1} \cdots V_{p_n}^* V_{q_n} \). Then \( E_P \cap (g \cdot X) = (E_P \lambda g E_P)E_X(E_P \lambda g E_P)^* = V_{p_1}^* V_{q_1} \cdots V_{p_n}^* V_{q_n} E_X V_{p_n}^* V_{q_n} \cdots V_{p_1}^* V_{q_1} = E_{[g_1, q_1, \ldots, q_n, X]} \). Thus we deduce \( P \cap (g \cdot X) = p_1^* q_1 \cdots p_n^* q_n X \in \mathcal{J} \). This proves (i). To prove (ii), we just have to show that the right hand side in (ii) is closed under finite intersections. Take \( g_1, g_2 \) in \( G \) and \( X_1, X_2 \) in \( \mathcal{J} \). Then \( (g_1 \cdot X_1) \cap (g_2 \cdot X_2) = g_1 \cdot (X_1 \cap ((g_1^{-1} g_2) \cdot X_2)) = g_1 \cdot (X_1 \cap P \cap (g_1^{-1} g_2) \cdot X_2) \) is of the desired form by (i).

Now let us prove (iii) assuming that \( \mathcal{J} \) is independent and \( P \subseteq G \) is Toeplitz. By (ii), it suffices to prove that given \( g, g_1, \ldots, g_n \) in \( G \) and \( X, X_1, \ldots, X_n \) in \( \mathcal{J} \) such that \( g \cdot X = \bigcup_{i=1}^n g_i \cdot X_i \), we must have \( g \cdot X = g_i \cdot X_i \) for some \( i \). Now \( g \cdot X = \bigcup_{i=1}^n g_i \cdot X_i \) implies \( X = \bigcup_{i=1}^n (g_i^{-1} g_i) \cdot X_i \). In particular, since \( X \subseteq P \), we must have \((g_i^{-1} g_i) \cdot X_i \subseteq P \) for all \( 1 \leq i \leq n \). Therefore \((g_i^{-1} g_i) \cdot X_i \subseteq P \cap ((g_i^{-1} g_i) \cdot X_i) \).
lies in $\mathcal{J}$ by (i). As $\mathcal{J}$ is independent, we must find $i$ such that $X = (g^{-1}g_i) \cdot X_i$. Thus $g \cdot X = g_i \cdot X_i$. 

\[ \square \]

5. Various descriptions of semigroup crossed products by automorphisms

5.1. The full versions. We now turn to full semigroup C*-algebras and full crossed products by automorphisms. We work with the version of full semigroup C*-algebras from [Li2], § 3. Recall that $P$ is a subsemigroup of the group $G$.

Definition 5.1. Let $C^*_s(P)$ be the universal C*-algebra generated by isometries \{\(v_p: p \in P\)\} and projections \{\(e_X: X \in \mathcal{J}\)\} satisfying the following relations:

\begin{enumerate}
    \item $v_pv_q = v_{pq}$ for all $p, q$ in $P$,
    \item $e_0 = 0$,
    \item whenever $p_1, q_1, \ldots, p_n, q_n \in P$ satisfy $p_1^{-1}q_1 \cdots p_n^{-1}q_n = e$ in $G$, then
      \[ v_{p_1}^*v_{q_1} \cdots v_{p_n}^*v_{q_n} = e_{[q_n^{-1}p_n^{-1}q_1^{-1}p_1]} . \]
\end{enumerate}

We set $D := C^*(\{e_X: X \in \mathcal{J}\}) \subseteq C^*_s(P)$.

These relations are satisfied in $C^*_s(P)$ by [Li2], Lemma 3.1. Therefore we obtain a homomorphism, the left regular representation, $\lambda: C^*_s(P) \to C^*_r(P)$ given by $v_p \mapsto V_p$ and $e_X \mapsto E_X$. As observed in [Li2], Lemma 3.3., the map $\mathcal{J} \ni X \mapsto e_X \in C^*_s(P)$ is a spectral measure, i.e. $e_P = 1$ and $e_{X_1 \cap X_2} = e_{X_1}e_{X_2}$.

We now define full crossed products by automorphisms. Let $A$ be a C*-algebra and $\alpha$ a $G$-action on $A$. In a certain sense, we now form a universal model of the reduced crossed product $A \rtimes_{\alpha,s}^\alpha P$.

Definition 5.2. The full crossed product of $(A, P, \alpha)$ is a C*-algebra $A \rtimes_{\alpha,s}^\alpha P$ which comes with two homomorphisms $\iota: A \to A \rtimes_{\alpha,s}^\alpha P$ and $(\overline{\cdot}): C^*_s(P) \to M(A \rtimes_{\alpha,s}^\alpha P)$, $x \mapsto \overline{x}$ with $\iota(\alpha_p(a))v_p = v_p\iota(a)$ for all $p \in P$, $a \in A$ such that the following universal property holds:

Whenever $T$ is a C*-algebra, $\iota': A \to T$ and $(\cdot)': C^*_s(P) \to M(T)$, $x \mapsto x'$ are homomorphisms satisfying

\begin{equation}
    \iota'(\alpha_p(a))v_p' = v_p' \iota'(a) \quad \text{for all } p \in P, \ a \in A,
\end{equation}

then there exists a unique homomorphism $\iota \times (\cdot)': A \rtimes_{\alpha,s}^\alpha P \to T$ sending $\iota(a)\overline{x}$ to $\iota'(a)x'$ for all $a \in A$ and $x \in C^*_s(P)$.

Existence of $(A \rtimes_{\alpha,s}^\alpha P, \iota, (\overline{\cdot}))$ follows from the existence of Murphy’s crossed product (see [Mur2], § 1) and the observation that our construction is – in a canonical way – a quotient of Murphy’s. Moreover, it is clear that $(A \rtimes_{\alpha,s}^\alpha P, \iota, (\overline{\cdot}))$ is unique up to canonical isomorphism.
The homomorphisms $A \to A \rtimes_{\alpha} P$, $a \mapsto a(\alpha_P)$ and $C^*_r(P) \to M(A \rtimes_{\alpha} P)$, $x \mapsto I_A \otimes (\lambda(x))$ satisfy the covariance relation (6). Thus, by universal property of $A \rtimes_{\alpha} P$, there exists a homomorphism $\lambda(A,P,\alpha) : A \rtimes_{\alpha} P \to A \rtimes_{\alpha} P$ sending $\iota(a)\pi$ to $a(\alpha_P)(I_A \otimes (\lambda(x)))$.

Of course, in case $A = \mathbb{C}$ we can canonically identify $\mathbb{C} \rtimes_{tr} P$ with $C^*_r(P)$ so that $\lambda(\mathbb{C},P,tr)$ becomes the left regular representation $\lambda$.

5.2. Inverse semigroups of partial isometries.

**Definition 5.3.** Let $S$ be the multiplicative subsemigroup of $C^*_r(P)$ generated by the isometries $v_q$ and their adjoints $v^*_p$, i.e.

$$S := \{v^*_p v_{q_1} \cdots v^*_p v_{q_n} : n \in \mathbb{Z}_{\geq 0}; p_i, q_i \in P\} \cup \{0\} \subseteq C^*_r(P).$$

Also, in the reduced case, let $S_r$ be the corresponding subsemigroup of $C^*_r(P)$, i.e.

$$S_r := \{V^*_p V_{q_1} \cdots V^*_p V_{q_n} : n \in \mathbb{Z}_{\geq 0}; p_i, q_i \in P\} \cup \{0\} = \lambda(S) \subseteq C^*_r(P).$$

It is clear that $S$ and $S_r$ are *-invariant semigroups of partial isometries, hence inverse semigroups.

**Lemma 5.4.** The map $g_r : S_r \setminus \{0\} \to G, V^*_p V_{q_1} \cdots V^*_p V_{q_n} \mapsto p_1^{-1} q_1 \cdots p_n^{-1} q_n$ is well-defined. For $0 \neq V \in S_r$, $g_r(V)$ is determined by the property that for every $x \in P$, $V_{\varepsilon_x} \neq 0 \Rightarrow V_{\varepsilon_x} = \varepsilon_{g_r(V)x}$. Moreover, we have $g_r(V^*) = (g_r(V))^{-1}$ for $0 \neq V \in S_r$ and $g_r(V_1 V_2) = g_r(V_1) g_r(V_2)$ for $V_1, V_2 \in S_r$ such that $V_1 V_2 \neq 0$.

**Proof.** For every $0 \neq V \in S_r$, we obviously have for every $x \in P$ that $V_{\varepsilon_x}$ is either 0 or of the form $\varepsilon_{p_1^{-1} q_1 \cdots p_n^{-1} q_n}$ if $V = V^*_p V_{q_1} \cdots V^*_p V_{q_n}$.

This lemma allows the following

**Definition 5.5.** We set $g := g_r \circ \lambda : S \to G, v^*_p v_{q_1} \cdots v^*_p v_{q_n} \mapsto p_1^{-1} q_1 \cdots p_n^{-1} q_n$.

**Lemma 5.6.** If $J$ is independent, then $\lambda : S \to C^*_r(P), s \mapsto \lambda(s)$ is injective, or in other words, $\lambda$ identifies $S$ with $S_r$.

**Proof.** Take two elements $s_1, s_2$ from $S$ with $s_1 \neq s_2$, and assume without loss of generality $s_1 \neq 0$, hence $s_1^* s_1 \neq 0$. As $g(s_1^* s_1) = e$, $s_1^* s_1$ lies in $D$ by relation III in Definition 5.1. As $J$ is independent, $\lambda$ is injective on $D$ by [Li2], Corollary 3.4. Thus $\lambda(s_1^* s_1) \neq 0$, hence also $\lambda(s_1) \neq 0$. So if $s_2 = 0$, we conclude that $\lambda(s_1) = \lambda(s_2)$.

We may now assume that $s_1 \neq 0$ and $s_2 \neq 0$. We start with the case $g(s_1) \neq g(s_2)$.

There exists $x \in P$ such that $\lambda(s_1)_{\varepsilon_x} = \varepsilon_{g(s_1)x}$. As $\lambda(s_2)_{\varepsilon_x}$ is either 0 or equal to $\varepsilon_{g(s_2)x} \neq \varepsilon_{g(s_1)x}$, we have $\lambda(s_1) \neq \lambda(s_2)$. If $g(s_1) = g(s_2)$, then $(s_1 - s_2)^*(s_1 - s_2)$ lies in $D$ by relation III in Definition 5.1. As $\lambda$ is injective on $D$ ($J$ is assumed to be independent) and $s_1 \neq s_2$ by assumption, we conclude that $\lambda((s_1 - s_2)^*(s_1 - s_2)) \neq 0$, hence $\lambda(s_1 - s_2) \neq 0$. □
5.3. Crossed products by partial automorphisms. Our goal is to describe $A \rtimes_{\alpha,s}^{a} P$ as a crossed product of $A \otimes D$ by $S$. The reader may consult [Sie] for the general construction of crossed products associated with partial actions of inverse semigroups.

First of all, it is easy to see that for every $s \in S$, we have an automorphism

$$\beta_s : A \otimes s^* Ds \to A \otimes sDs^*, \ a \otimes d \mapsto \alpha_{\beta(s)}(a) \otimes sds^*.$$  

Moreover, we have $s^*Ds = s^*ss^*Ds \subseteq s^*sD = s^*Ds^*s \subseteq s^*Ds$ so that $s^*Ds = s^*sD$ is an ideal of $D$. In this way, $S$ acts on $A \otimes D$ by partial automorphisms, i.e. we have a semigroup homomorphism $S \to \PAut (A \otimes D)$, $s \mapsto \beta_s$.

**Proposition 5.7.** We can identify $A \rtimes_{\alpha,s}^{a} P$ and $(A \otimes D) \rtimes_{\beta} S$ by mutually inverse homomorphisms

$$A \rtimes_{\alpha,s}^{a} P \to (A \otimes D) \rtimes_{\beta} S, \ i(a) \mapsto (a \otimes ss^*)\delta_s,$$
$$\ (A \otimes D) \rtimes_{\beta} S \to A \rtimes_{\alpha,s}^{a} P, \ (a \otimes ss^*)\delta_s \mapsto i(a)\pi.$$

**Proof.** We use the universal properties of these two crossed products to show existence of these homomorphisms. To construct the homomorphism $A \rtimes_{\alpha,s}^{a} P \to (A \otimes D) \rtimes_{\beta} S$, represent $(A \otimes D) \rtimes_{\beta} S$ faithfully and non-degenerately on a Hilbert space $H$. Proposition 4.7 in [Sie] yields representations of $A \otimes D$ and $S$ on $H$ such that (6) is satisfied. By universal property of $A \rtimes_{\alpha,s}^{a} P$, these representations give rise to the desired homomorphism $A \rtimes_{\alpha,s}^{a} P \to (A \otimes D) \rtimes_{\beta} S, \ i(a)\pi \mapsto (a \otimes ss^*)\delta_s$.

In the reverse direction, the homomorphisms $A \otimes D \to A \rtimes_{\alpha,s}^{a} P, \ a \otimes d \mapsto i(a)d$ and $S \to M(A \rtimes_{\alpha,s}^{a} P), \ s \mapsto \pi$ form a covariant representation of $(A \otimes D, S, \beta)$ in the sense of [Sie], Definition 3.4 (having represented $A \rtimes_{\alpha,s}^{a} P$ faithfully and non-degenerately on a Hilbert space). Then the universal property of $(A \otimes D) \rtimes_{\beta} S$ (see [Sie], Proposition 4.8) gives the desired homomorphism $(A \otimes D) \rtimes_{\beta} S \to A \rtimes_{\alpha,s}^{a} P$ sending $(a \otimes ss^*)\delta_s$ to $i(a)\pi$.

Finally, it is immediate that these homomorphisms are mutually inverses.  

5.4. Groupoids associated with inverse semigroups. To every inverse semigroup belongs a groupoid. The reader may consult [Pat], § 4.3 or [Kho-Ska1] for the general construction. Note that all the groupoids in this paper will be r-discrete (also called étale) and Hausdorff. We assume in the rest of this section (§ 5) that $\mathcal{J}$ is independent (see Definition 2.3) and that $P \subseteq G$ satisfies the Toeplitz condition (see Definition 4.1).

Let us now explain how to construct the groupoid for our specific inverse semigroup $S$. Set $E := \{s^*s : s \in S\}$, this is the set of idempotents of $S$. In our case, $E = \{e_X : X \in \mathcal{J}\}$. The unit space of the groupoid of $S$ is given by the semicharacters on $E$. This unit space can be canonically identified with Spec $D$. As $\mathcal{J}$ is independent, we can identify $D$ and $D_r$ using Corollary 3.4 from [Li2]. Thus $\lambda$ induces an identification of Spec $D$ with $\Omega := \Spec (D_r)$.
To form the groupoid of $S$, we take $\hat{S} := \{(s, \chi) \in S \times \Omega: \chi(\lambda(s^*s)) = 1\}$ equipped with the subspace topology of $S \times \Omega$. Here $\hat{S}$ is viewed as a discrete set, and $\Omega$ carries the usual topology of pointwise convergence. Next we define an equivalence relation $\sim$ on $\hat{S}$ by setting

$$(s_1, \chi_1) \sim (s_2, \chi_2) :\iff \chi_1 = \chi_2 \text{ and there is } e \in E \text{ with } \chi(\lambda(e)) = 1 \text{ and } s_1e = s_2e.$$  

Then the groupoid of $S$ is defined by $G(S) := \hat{S}/ \sim$ with the quotient topology induced from $\hat{S}$. We write $[s, \chi]$ for the equivalence class of $(s,\chi) \in \hat{S}$. The groupoid structure of $G(S)$ is given as follows: First, for $(s,\chi) \in \hat{S}$, let $s,\chi$ be the character $\chi(\lambda(s^*s)) = \chi \circ \Ad(\lambda(s)^*)$. Two elements $[s_1,\chi_1]$ and $[s_2,\chi_2]$ of $G(S)$ are composable if $s_2,\chi_2 = \chi_1$, and in that case, the product is given by $[s_1,\chi_1][s_2,\chi_2] = [s_1s_2,\chi_2]$. The inverse map is given by $[s,\chi]^{-1} = [s^*,s,\chi]$. Moreover, the range and source map are $r : G(S) \to \Omega, [s,\chi] \mapsto s,\chi$ and $d : G(S) \to \Omega, [s,\chi] \mapsto \chi$.

Let us now compare this groupoid with another one. Namely, we have a canonical transformation groupoid associated with the dynamical system $(D^G, G, \tau)$ since $D^G$ is commutative. Set $\Omega^G_p := \Spec(D^G_p)$. The group $G$ acts on $\Omega^G_p$ from the right by $\chi g = \chi \circ \tau_g$ (this is just the transpose of $\tau$). The corresponding transformation groupoid is denoted by $G := \Omega^G_p \times G$. As a topological space, $G$ is simply the product space $\Omega^G_p \times G$. Two elements $(\chi_1, g_1)$ and $(\chi_2, g_2)$ are composable if $\chi_1 g_1 = \chi_2$, and in this case we have $(\chi_1, g_1)(\chi_2, g_2) = (\chi_1, g_1g_2)$. The inverse map is given by $(\chi, g)^{-1} = (\chi g, g^{-1})$. Furthermore, the range and source maps are given by $r : G \to \Omega^G_p, (\chi, g) \mapsto \chi$ and $d : G \to \Omega^G_p, (\chi, g) \mapsto \chi g$.

We now would like to restrict $G$ to a subset of $\Omega^G_p$. By our assumption that $P \subseteq G$ is Toeplitz, we know that $D_r = E\!\!E_p D^G_p E\!\!E_p$ by Lemma 3.9. Therefore we can define a surjective homomorphism $c : D^G_p \to D_r, x \mapsto E\!\!E_p x E\!\!E_p$. This homomorphism induces an embedding $c^* : \Omega \to \Omega^G_p, \chi \mapsto \chi \circ c$. We set $N := c^*(\Omega)$.

**Lemma 5.8.** We have $N = \{\chi \in \Omega^G_p : \chi(E\!\!E_p) = 1\}$.

**Proof.** “$\subseteq$”: $(\chi \circ c)(E\!\!E_p) = \chi(E\!\!E_p) = 1$ for all $\chi \in \Omega$ as $E\!\!E_p$ is the unit of $D_r$.

“$\supseteq$”: If $\chi \in \Omega^G_p$ satisfies $\chi(E\!\!E_p) = 1$, then $\chi(x) = \chi(E\!\!E_p)\chi(x)\chi(E\!\!E_p) = (\chi \circ c)(x)$ for all $x \in D^G_p$. Thus $\chi = (\chi|_{D_r}) \circ c \in N$. 

**Corollary 5.9.** $N$ is clopen in $\Omega^G_p$ and $c^* : \Omega \to \Omega^G_p$ is open.

**Proof.** The first assertion is immediate from the previous lemma. To see our second claim, observe that $c^*:\Omega \to N$ is a homeomorphism, being a continuous bijection between compact Hausdorff spaces. Now given an open subset $U \subseteq \Omega$, $c^*(U)$ is open in $N$, hence also in $\Omega^G_p$ as $N$ is open.

We now form the groupoid

$$G^N_N := r^{-1}(N) \cap d^{-1}(N).$$
\(G_N^N\) inherits from \(G\) the structure of a topological groupoid by taking the subspace topology and restricting the product and the inverse map.

The next observation tells us that restricting to \(N\) does not lead so far away:

**Lemma 5.10.** \(N\) meets every orbit in \(G(0)\), i.e. for every \(\chi \in G(0) = \Omega_P^G\), there exists \(g \in G\) such that \(d(\chi, g)\) lies in \(N\). Moreover, the restricted range and source maps \(r|_{d^{-1}(N)} : d^{-1}(N) \to \Omega_P^G\) and \(d|_{d^{-1}(N)} : d^{-1}(N) \to N\) are open.

**Proof.** For every \(\chi \in \Omega_P^G\) there exists \(Y \in \mathcal{J}_P^G\) such that \(\chi(E_Y) = 1\). This subset \(Y\) of \(G\) must be of the form \(Y = \bigcap_{i=1}^n g_i \cdot X_i\) for some \(n \geq 1\), \(g_i \in G\) and \(X_i \in \mathcal{J}\). Thus \(\chi(E_Y) = 1\) implies \(\chi(E_{g_i \cdot X_i}) = 1\), hence \((\chi g_i)(E_{X_i}) = 1\). As \(E_{X_1} \leq E_P\), we conclude that \((\chi g_i)(E_P) = 1\), which means that \(d(\chi, g_i) = \chi g_i\) lies in \(N\) by Lemma 5.8.

To see that the restricted range and source maps are open, take an open subset \(U\) of \(G\). Then \(r(U \cap d^{-1}(N))\) is open as \(U\) and \(d^{-1}(N)\) are open (recall that \(N\) is open) and \(r\) is an open map from \(G\) to \(G(0)\). Also, \(d(U \cap d^{-1}(N)) = d(U) \cap N\) is open in \(N\) as \(U\) is open and \(d\) is an open map \(G \to G(0)\).

Setting \(G_N := d^{-1}(N)\), we have

**Corollary 5.11.** \(G_N\) together with the restricted range and source maps and the left \(G\)-action and the right \(G_N^N\)-action induced by the product in \(G\) is a \((G, G_N^N)\)-equivalence in the sense of [M-R-W].

**Proof.** This follows from the previous lemma using Example 2.7 in [M-R-W].

Now we return to the groupoid \(G(S)\) and compare it with \(G_N^N\).

**Proposition 5.12.** Under our standing assumptions that \(\mathcal{J}\) is independent and \(P \subseteq G\) is Toeplitz, we can identify \(G(S)\) with \(G_N^N\) as topological groupoids via

\[
\Phi : G(S) \to G_N^N, \ [s, \chi] \mapsto ((c^* \chi)g(s)^{-1}, g(s)).
\]

**Proof.** First of all, \(\Phi\) is well-defined: Namely, \((s_1, \chi) \sim (s_2, \chi)\) implies that there exists \(X \in \mathcal{J}\) such that \(\chi(E_X) = 1\) and \(s_1 e_X = s_2 e_X\). Thus \(\chi(\lambda(e_X s_1^* s_1 e_X)) = 1\), and we conclude that \(s_1 e_X = s_2 e_X\) is not zero. Using Lemma 5.4, we see that \(g(s_1) = g(s_1 e_X) = g(s_2 e_X) = g(s_2)\). Therefore, \(((c^* \chi)g(s)^{-1}, g(s))\) really only depends on the equivalence class of \((s, \chi) \in \hat{S}\).

To see that \(((c^* \chi)g(s)^{-1}, g(s))\) lies in \(G_N^N\), we have to check that the range and source of \(((c^* \chi)g(s)^{-1}, g(s))\) lie in \(N\). For the source this is obvious. To see that \(r((c^* \chi)g(s)^{-1}, g(s)) = (c^* \chi)g(s)^{-1}\) lies in \(N\), we show

\[
e^* (s, \chi) = (c^* \chi)g(s)^{-1}\text{ for all } (s, \chi) \in \hat{S}.
\]
Moreover, write $s = u_{p_1}^* v_{q_1} \cdots u_{p_n}^* v_{q_n}$. For $Y$ in $J_P^G$, we compute that $\lambda(s^*) E_P E_Y E_P \lambda(s) = E_{q_n^{-1} p_n \cdots q_1^{-1} p_1 (Y \cap P)} = E_{(g(s)^{-1} \tau(Y) \cap P) E_{q_n^{-1} p_n \cdots q_1^{-1} p_1 P}}$. Thus we deduce $c^*([s, \chi])(E_Y) = \chi(\lambda(s^*) E_P E_Y E_P \lambda(s)) = \chi(E_P \tau(g(s)^{-1}) (E_Y) E_P) \chi(\lambda(s^*) \lambda) = (\lambda(c^*) g(s)^{-1})(E_Y)$. This proves (8).

It is clear that (8) implies $(c^* \chi)(g(s)) \in N$. So far, we have shown that $\Phi$ is well-defined.

To show that $\Phi$ is injective, take $[s_1, \chi_1]$ and $[s_2, \chi_2]$ from $G(S)$. Assume that $\Phi([s_1, \chi_1]) = \Phi([s_2, \chi_2]) = (\chi, g)$. Then we must have $g(s_1) = g(s_2) = g$. Moreover, $c^* \chi_1$ and $c^* \chi_2$ must coincide with $\chi g$. The equality $c^* \chi_1 = c^* \chi_2$ implies $\chi_1 = \chi_2$ as $c^*$ is injective. Finally, to prove $[s_1, \chi_1] = [s_2, \chi_2]$, we observe that $(\chi g)(\lambda(s_1^* s_1)) = (\chi g)(\lambda(s_2^* s_2)) = 1$ implies $(\chi g)(\lambda(s_1^* s_1 s_2^* s_2)) = 1$. Now set $e := s_1^* s_1 s_2^* s_2$. This projection $e$ is of the form $e = e_X$ for some $X \in J$. We now claim that $\lambda(s_1 e) = \lambda(s_2 e)$. First of all, we have $\lambda(e) = E_X$. For $x \in X$, $\lambda(s_1 e) x = \varepsilon_{x_1}$ as $e$ is dominated by the support projection $s_1^* s_1$. Similarly, $\lambda(s_2 e) x = \varepsilon_{x_2}$ for all $x \in X$. Since we clearly have $\lambda(s_2 e) y = \lambda(s_1 e) y = 0$ for $y \notin X$, we have shown $\lambda(s_1 e) = \lambda(s_2 e)$. But $\lambda$ is injective on $S$ by Lemma 5.6, so that $s_1 e = s_2 e$. Hence by definition of the equivalence relation on $\tilde{S}$, we conclude that $[s_1, \chi_1] = [s_2, \chi_2]$.

To prove surjectivity of $\Phi$, take $(\chi, g) \in G^N$. $r(\chi, g) = \chi \in N$ and $d(\chi, g) = \chi g \in N$ imply that $\chi(E_{\tauP(g^{-1} P)}) = \chi(E_P)(\chi g)(E_P) = 1$. As $P \subseteq G$ is Toeplitz, there exists $s \in S$ such that $E_P \lambda g E_P = \lambda(s)$. Thus $(\chi g)(\lambda(s^* s)) = \chi(\tau g(E_P \lambda g^{-1} E_P \lambda g E_P)) = \chi(\tau g(\lambda(s^* s)) = \chi(E_{\tauP(g^{-1} P)}) = 1$. Thus $(s, (\chi g)|_D_{r})$ lies in $\tilde{S}$. Since $g(s) = g$, we obtain $\Phi([s, (\chi g)|_D_{r}]) = (c^* (\chi g)|_D_{r} g^{-1}, g) = (\chi, g)$.

Let us now prove that $\Phi$ is compatible with the groupoid structures. $[s_1, \chi_1]$ and $[s_2, \chi_2]$ are composable if and only if

$$s_2 \cdot \chi_2 = \chi_1$$
$$\leftrightarrow c^* \chi_1 = c^* [s_2 \cdot \chi_2] = \chi_2 \chi(g(s_2))^{-1} \quad (8)$$
$$\leftrightarrow (c^* \chi_1) g(s_1)^{-1} g(s_1) = (c^* \chi_2) g(s_2)^{-1}.$$

But this last equation is precisely the condition for compositibility of $\Phi[s_1, \chi_1] = ((c^* \chi_1) g(s_1)^{-1}, g(s_1))$ and $\Phi[s_2, \chi_2] = ((c^* \chi_2) g(s_2)^{-1}, g(s_2))$. If (9) is satisfied, then

$$\Phi([s_1, \chi_1][s_2, \chi_2]) = \Phi([s_1 s_2, \chi_2])$$
$$= (c^* \chi_2) g(s_1 s_2)^{-1}, g(s_1 s_2)) = (c^* \chi_2) g(s_2)^{-1} g(s_1)^{-1}, g(s_1) g(s_2))$$
$$= (c^* \chi_1) g(s_1)^{-1}, g(s_1) g(s_2)) = (c^* \chi_1) g(s_1)^{-1}, g(s_1)) (c^* \chi_2) g(s_2)^{-1}, g(s_2))$$
$$= \Phi([s_1, \chi_1]) \Phi([s_2, \chi_2]).$$

Moreover,

$$\Phi([s, \chi])^{-1} = \Phi([s^*, s \chi]) = (c^* (s, \chi) g(s)^{-1}, g(s^*))$$
$$= (c^* \chi)(g(s)^{-1} g(s), g(s)^{-1}) = (c^* \chi, g(s)^{-1})$$
$$= (c^* \chi)(g(s)^{-1}, g(s))^{-1} = (\Phi[s, \chi])^{-1}.$$
Finally, $\Phi$ is continuous by definition of the quotient topology as $\hat{S} \to \mathcal{G}^N$, $\Phi(s, \chi) \mapsto ((c^* \chi) g(s)^{-1}, g(s))$ is continuous. In addition, $\Phi$ is open as well. Namely, let $\pi : \hat{S} \to \mathcal{G}(S)$ be the canonical projection, and take an open subset $U$ of $\mathcal{G}(S)$. Then $\pi^{-1}(U)$ is open in $\hat{S}$. As $\hat{S} = \bigcup_{s \in S} \{s\} \times \Omega$, we must have that $\pi^{-1}(U) \cap (\{s\} \times \Omega)$ is open for every $s \in S$. In other words, for every $s$ in $S$ there exists an open subset $U_s$ of $\Omega$ such that $\pi^{-1}(U) = \bigcup_{s \in S} \{s\} \times U_s$. Hence $\Phi(U) = \bigcup_{s \in S} (c^* (U_s) g(s)^{-1}) \times \{g(s)\}$ is open in $\mathcal{G}$ as $c^*$ is open by Corollary 5.9.

5.5. Groupoid crossed products. We follow [Qui-Sie] and [Kho-Ska2] and describe $(A \otimes D) \rtimes_\beta S$ as a groupoid crossed product by $\mathcal{G}(S)$.

First of all, we think of $S$ as a subsemigroup of $\mathcal{G}(S)^{op}$, the inverse semigroup of open $\mathcal{G}(S)$-sets, via the embedding

$$S \to \mathcal{G}(S)^{op}, \ s \mapsto O_s := \pi(\{s\} \times \{\chi \in \Omega : \chi(\lambda(s^* s)) = 1\})$$

where $\pi$ is the canonical projection $\pi : \hat{S} \to \mathcal{G}(S)$. This embedding is explained in [Kho-Ska2], directly after Theorem 6.5.

Let us now define a groupoid dynamical system $(A \times \Omega, \mathcal{G}(S), \alpha(S))$ in the sense of [Muh-Wil], § 4.1. We let $A \times \Omega$ be the trivial C*-bundle over $\Omega$ with constant fibres $A$. Consider for every $[s, \chi] \in \mathcal{G}(S)$ the automorphism

$$\alpha(S)[s,\chi] : A \times \{\chi\} \to A \times \{s, \chi\}, \ (a, \chi) \mapsto (a g(s)(a), s, \chi).$$

It is straightforward to check that this family $(\alpha(S)[s,\chi])_{[s,\chi] \in \mathcal{G}(S)}$ gives rise to the desired groupoid dynamical system in the sense of [Muh-Wil], § 4.1. Moreover, it is also easy to see that the dynamical systems $(A \otimes D, S, \beta)$ and $(A \times \Omega, \mathcal{G}(S), \alpha(S))$ correspond to one another in the sense of [Qui-Sie], Theorem 5.3. In such a situation, we may apply Theorem 7.2 of [Qui-Sie] for full crossed products and Theorem 6.5 of [Kho-Ska2] in the reduced case and deduce

**Proposition 5.13.** The map $(a \otimes s ds^*)\delta_s \mapsto \begin{cases} [t, \psi] \mapsto \psi(\lambda(d)) a & \text{if } [t, \psi] \in O_s \\ 0 & \text{else} \end{cases}$ extends to isomorphisms $(A \otimes D) \rtimes_\beta S \cong (A \times 0) \rtimes_{\alpha(S)} \mathcal{G}(S)$ and $(A \otimes D) \rtimes_{\alpha, r} S \cong (A \times \Omega) \rtimes_{\alpha(S), r} \mathcal{G}(S)$.

To proceed, we describe the full and reduced crossed products of $(A \otimes D^G_P, G, \alpha \otimes \tau)$ as groupoid crossed products. We just have to follow Example 4.8 in [Muh-Wil] and § 6 of [Sims-Wil].

The action of the transformation groupoid $\mathcal{G} = \Omega^G_P \rtimes G$ on the trivial C*-bundle $A \times \Omega^G_P$ over $\Omega^G_P$ is given by the automorphisms $(\alpha \times \Omega^G_P)_{(x,g)} : A \times \{\chi g\} \to A \times \{\chi\}$, $(a, \chi g) \mapsto (a g(a), \chi)$. Identifying $A \otimes D^G_P$ with $C_0(\Omega^G_P, A)$ in the canonical way, we obtain from Example 4.8 in [Muh-Wil] and § 6 of [Sims-Wil]:

**Proposition 5.14.** The map $C_0(G, A \otimes D^G_P) \ni f \mapsto [(\chi, g) \mapsto f(g)(\chi)] \in (A \otimes \Omega^G_P) \rtimes_{\alpha \times \Omega^G_P} \mathcal{G}$ extends to an isomorphism $(A \otimes D^G_P) \rtimes_{\alpha \otimes \tau} G \cong (A \times \Omega^G_P) \rtimes_{\alpha \times \Omega^G_P} \mathcal{G}$. 
Similarly, the map \( C_c(G, A \otimes D^G_P) \ni f \mapsto [(\chi, g) \mapsto f(g)(\chi)] \in (A \times \Omega^G_P) \rtimes_{\alpha \times \Omega^G_P,r} G \) extends to an isomorphism \( (A \otimes D^G_P) \rtimes_{\alpha \otimes \Omega^G_P,G} G \cong (A \times \Omega^G_P) \rtimes_{\alpha \times \Omega^G_P,r} G \).

Let us now restrict the \( G \)-action \( \alpha \times \Omega^G_P \) to \( \mathcal{G}_N^N. \) We obtain an action \( \alpha \times N \) of \( \mathcal{G}_N^N \) on the sub-C*-bundle \( A \times N \) (i.e., just the trivial C*-bundle over \( N \) with constant fibres \( A \)). The following observation links the two groupoid dynamical systems we are considering:

**Lemma 5.15.** The groupoid dynamical system \((A \times \Omega^G_P, \mathcal{G}(S), \alpha(S))\) and \((A \times N, \mathcal{G}_N^N, \alpha \times N)\) are isomorphic. More precisely, the identifications \( \id \times c^*: A \times \Omega \cong A \times N \) and \( \Phi: \mathcal{G}(S) \to \mathcal{G}_N^N \), \( [s, \chi] \mapsto ((c^*\chi)g(s)^{-1}, g(s)) \) transport the action \( \alpha(S) \) to \( \alpha \times N \), in the sense that for every \( [s, \chi] \in \mathcal{G}(S) \) and \((a, \chi) \in A \times \Omega \), we have \((\alpha \times N)_{\Phi[s,\chi]}((\id \times c^*)(a, \chi)) = (\id \times c^*)(\alpha(S)[s,\chi](a, \chi))\).

**Proof.** We just have to compute that
\[
(\alpha \times N)_{\Phi[s,\chi]}((\id \times c^*)(a, \chi)) = (\alpha \times N)_{([c^*\chi]g(s)^{-1}, g(s))}(a, c^*\chi)
= (\alpha_{g(s)}(a), (c^*\chi)g(s)^{-1}) \overset{(8)}{=} (\alpha_{g(s)}(a), c^*(s, \chi))
= (\id \times c^*)(\alpha_{g(s)}(a), s, \chi) = (\id \times c^*)(\alpha(S)[s,\chi](a, \chi)).
\]
\[\square\]

**Corollary 5.16.** The map \( C_c(\mathcal{G}(S), A) \ni f \mapsto f \circ \Phi^{-1} \in C_c(\mathcal{G}_N^N, A) \) extends to isomorphisms
\[
(A \times \Omega) \rtimes_{\alpha(S)} \mathcal{G}(S) \xrightarrow{\cong} (A \times N) \rtimes_{\alpha \times N} \mathcal{G}_N^N,
(A \times \Omega) \rtimes_{\alpha(S),r} \mathcal{G}(S) \xrightarrow{\cong} (A \times N) \rtimes_{\alpha \times N,r} \mathcal{G}_N^N.
\]

We now want to see that the \((\mathcal{G}, \mathcal{G}^N_0)\)-equivalence \( \mathcal{G}_N \) of Corollary 5.11 gives rise to an equivalence between \((A \times \Omega^G_P, \mathcal{G}, \alpha \times \Omega^G_P)\) and \((A \times N, \mathcal{G}_N^N, \alpha \times N)\).

**Lemma 5.17.** Equip the trivial Banach-bundle \( A \times \mathcal{G}_N \) with the fibrewise imprimitivity bimodule structure given by the inner products
\[
\langle (a_1, \gamma), (a_2, \gamma) \rangle = (a_1a_2^*, r(\gamma)) \in A \times \Omega^G_P,
\langle (a_1, (\chi, g)), (a_2, (\chi, g)) \rangle_{A \times \{d(\gamma)\}} = (\alpha_{g^{-1}}(a_1a_2^*), \chi g) \in A \times N
\]
and the left and right actions
\[
(a_1, r(\gamma)) \cdot (a, \gamma) = (a_1a, \gamma) \text{ for } (a_1, r(\gamma)) \in A \times \Omega^G_P,
(a, (\chi, g)) \cdot (a_r, \chi g) = (aa_r(a_r), (\chi, g)) \text{ for } (a_r, \chi g) \in A \times N.
\]
Moreover, let \( \mathcal{G} \) act from the left on \( A \times \mathcal{G}_N \) by \((\chi_l, g_l) \cdot (a, \gamma) = (\alpha_{g_l}(a), (\chi_l, g_l)\gamma)\) and let \( \mathcal{G}_N^N \) act from the right on \( A \times \mathcal{G}_N \) by \((a, \gamma) \cdot \gamma_r = (a, \gamma \gamma_r)\).

Then in this way, \( A \times \mathcal{G}_N \) becomes an equivalence between \((A \times \Omega^G_P, \mathcal{G}, \alpha \times \Omega^G_P)\) and \((A \times N, \mathcal{G}_N^N, \alpha \times N)\) in the sense of Definition 5.1 in [Muh-Wil].
Proof. Just verify by straightforward computations that the axioms for an equivalence in Definition 5.1 from [Muh-Wil] are satisfied.

The reason why this is interesting for us is the following consequence of Theorem 5.5 in [Muh-Wil] and Corollary 19 from [Sims-Wil]:

**Lemma 5.18.** The canonical inclusion \( C_c(G_N^N, A) \hookrightarrow C_c(G, A) \) extends to (isometric!) embeddings

\[
(A \times N) \times_{\alpha \times N} G_N^N \hookrightarrow (A \times \Omega_P^C) \times_{\alpha \times \Omega^C G} G,
\]

\[
(A \times N) \times_{\alpha \times N, r} G_N^N \hookrightarrow (A \times \Omega_P^C) \times_{\alpha \times \Omega^C G} G.
\]

**Proof.** As \( N \) is clopen, \( G_N^N \) is a clopen subset of \( G \), so that we really have \( C_c(G_N^N, A) \subseteq C_c(G, A) \). As \( G_N \) is clopen as well, we actually have \( C_c(G_N^N, A) \subseteq C_c(G_N, A) \subseteq C_c(G, A) \).

Let us first treat the full crossed products. Take a function \( f \in C_c(G_N^N, A) \). All we have to show is that

\[
\|f\|_{(A \times N) \times_{\alpha \times N} G_N^N} = \|f\|_{(A \times \Omega_P^C) \times_{\alpha \times \Omega^C G} G}.
\]

We denote by \(*\) the convolution product in \((A \times \Omega_P^C) \times_{\alpha \times \Omega^C G} G\), and observe that its restriction to \( C_c(G_N^N, A) \) coincides with the convolution product coming from \((A \times N) \times_{\alpha \times N} G_N^N\). We certainly have

\[
\|f\|_{(A \times N) \times_{\alpha \times N} G_N^N} = \|f^* \|_{(A \times \Omega_P^C) \times_{\alpha \times \Omega^C G} G}.
\]

But now comes the crucial observation, namely that

\[
f_1^* \cdot f_2 = \langle \langle f_1, f_2 \rangle \rangle_{(A \times N) \times_{\alpha \times N} G_N^N},
\]

\[
f_1 \cdot f_2^* = (A \times \Omega_P^C) \times_{\alpha \times \Omega^C G} \langle \langle f_1, f_2 \rangle \rangle
\]

for all \( f_1, f_2 \in C_c(G_N, A) \). Here \( \langle \langle \cdot, \cdot \rangle \rangle \) are the inner products defined in Theorem 5.5 in [Muh-Wil]. The verification of (12) is a straightforward computation. In particular, we have for our function \( f \)

\[
f^* \cdot f = \langle \langle f, f \rangle \rangle_{(A \times N) \times_{\alpha \times N} G_N^N},
\]

\[
f \cdot f^* = (A \times \Omega_P^C) \times_{\alpha \times \Omega^C G} \langle \langle f, f \rangle \rangle.
\]

By Theorem 5.5 in [Muh-Wil], \( C_c(G_N, A) \) is a \((A \times \Omega_P^C) \times_{\alpha \times \Omega^C G} (A \times N) \times_{\alpha \times N} G_N^N\) pre-imprimitivity bimodule. Therefore, we conclude that

\[
\|\langle \langle f, f \rangle \rangle_{(A \times N) \times_{\alpha \times N} G_N^N}\| = \|\langle \langle f, f \rangle \rangle_{(A \times \Omega_P^C) \times_{\alpha \times \Omega^C G} G_N^N} \|,
\]

where we take the norm in \((A \times N) \times_{\alpha \times N} G_N^N\) on the left hand side and the norm in \((A \times \Omega_P^C) \times_{\alpha \times \Omega^C G} G\) on the right hand side. Inserting (13) and (11) into (14), we obtain (10), as desired.
To treat reduced crossed products, just use Theorem 14 or rather Corollary 19 of [Sims-Wil] instead of Theorem 5.5 in [Muh-Wil].

**Corollary 5.19.** The canonical inclusion \( C_c(G_N^N, A) \hookrightarrow C_c(G, A) \) extends to isomorphisms

\[
(A \times N) \rtimes_{\alpha \times N} G_N^N \cong 1_N \left( (A \times \Omega_P^G) \rtimes_{\alpha \times \Omega_P^G} G \right) 1_N,
\]

\[
(A \times N) \rtimes_{\alpha \times N, r} G_N^N \cong 1_N \left( (A \times \Omega_P^G) \rtimes_{\alpha \times \Omega_P^G, r} G \right) 1_N.
\]

Here \( 1_N \) is the characteristic function of the subset \( N \) of \( G \), and \( 1_N \) is viewed in a canonical way as a multiplier of \( (A \times \Omega_P^G) \rtimes_{\alpha \times \Omega_P^G} G \) and \( (A \times \Omega_P^G) \rtimes_{\alpha \times \Omega_P^G, r} G \), respectively.

Moreover, \( 1_N \left( (A \times \Omega_P^G) \rtimes_{\alpha \times \Omega_P^G} G \right) 1_N \) and \( 1_N \left( (A \times \Omega_P^G) \rtimes_{\alpha \times \Omega_P^G, r} G \right) 1_N \) are full corners in the corresponding full and reduced crossed products.

**Proof.** It is easy to see that \( C_c(G_N^N, A) = 1_N \ast C_c(G, A) \ast 1_N \). Thus the first part of the corollary follows from the previous lemma. Moreover, we also have \( C_c(G_N^N, A) = C_c(G, A) \ast 1_N \). Using this observation and also (12) from the proof of the previous lemma, the second part of our assertion follows from [Muh-Wil], Theorem 5.5 in the case of full crossed products and from [Sims-Wil], Corollary 19 in the reduced case.

Let us summarize what we have obtained so far.

**Theorem 5.20.** Let \( P \) be a subsemigroup of a group \( G \). Assume that \( J \) is independent (see Definition 2.3) and that \( P \subseteq G \) satisfies the Toeplitz condition from Definition 4.1. Then the following diagram commutes:

\[
\begin{align*}
A \rtimes_{\alpha, r} P & \xrightarrow{\lambda_{(A, P, \alpha)}} A \rtimes_{\alpha, r} P \\
1_N \left( (A \times \Omega_P^G) \rtimes_{\alpha \times \Omega_P^G} G \right) 1_N & \cong 1_N \left( (A \times \Omega_P^G) \rtimes_{\alpha \times \Omega_P^G, r} G \right) 1_N \\
(1 \otimes E_P) \left( (A \otimes D_P^G) \rtimes_{\alpha \otimes r} G \right) (1 \otimes E_P) & \cong (1 \otimes E_P) \left( (A \otimes D_P^G) \rtimes_{\alpha \otimes r} G \right) (1 \otimes E_P)
\end{align*}
\]
Moreover, $1\mathbb{N}$ and $1\otimes E_P$ give rise to full corners in the full and reduced crossed products associated with $(A \times \Omega^G_P, G, \alpha \times \Omega^G_P)$ and $(A \otimes D^G_P, G, \alpha \otimes \tau)$.

And finally, the square at the bottom of diagram (15) is obtained by restricting the commutative diagram

$$
\begin{array}{ccc}
(A \times \Omega^G_P) \rtimes_{\alpha \times \Omega^G_P} G & \rightarrow & (A \times \Omega^G_P) \rtimes_{\alpha \times \Omega^G_P} G \\
\downarrow \cong & & \downarrow \cong \\
(A \otimes D^G_P) \rtimes_{\alpha \otimes \tau} G & \rightarrow & (A \otimes D^G_P) \rtimes_{\alpha \otimes \tau} G 
\end{array}
$$

In all these diagrams, the horizontal arrows are given by the canonical projections (the regular representations), and the vertical maps are the isomorphisms we have explicitly constructed before.

**Proof.** We just have to collect what we have proven. The upper left isomorphism is given by Proposition 5.7. The second square from the top in (15) is given by Proposition 5.13. The same proposition also says that this square commutes. The third square and its commutativity is provided by Corollary 5.16. The fourth square and its commutativity is given by Corollary 5.19. And Proposition 5.14 gives the square at the bottom of (15) and that it is the restriction of the commutative diagram (16). Using Corollary 3.10, we can fill in the upper right vertical arrow as well so that also the first square commutes. That $1\mathbb{N}$ gives rise to full corners is shown in Corollary 5.19, and it corresponds to $1\otimes E_P$ under the isomorphism from Proposition 5.14. This completes the proof. □

6. Nuclearity

Using our results from the previous section, we obtain equivalent characterizations for nuclearity of semigroup C*-algebras.

**Theorem 6.1.** Let $P$ be a subsemigroup of a group $G$. Assume that $\mathcal{J}$ is independent (see Definition 2.3) and that $P \subseteq G$ satisfies the Toeplitz condition from Definition 4.1. Then the following are equivalent:

(i) $C^*_r(P)$ is nuclear.

(ii) $C^*_r(P)$ is nuclear.

(iii) Whenever given a $G$-action $\alpha$ on a C*-algebra $A$, the canonical homomorphism $\lambda_{(A,P,\alpha)} : A \rtimes^\alpha_{\alpha,s} P \rightarrow A \rtimes^\alpha_{\alpha,r} P$ is an isomorphism.

(iv) The groupoid $\mathcal{G}_N^G$ is amenable.

(v) The groupoid $\mathcal{G}$ is amenable.

Here $\mathcal{G}$ is the transformation groupoid $\Omega^G_P \rtimes G$ from § 5.4, and the groupoid $\mathcal{G}_N^G$ is the restriction of $\mathcal{G}$ also introduced in § 5.4.

Of course, amenability of $\mathcal{G}$ just means that $G$ acts amenably on $\Omega^G_P$. 
Proof. We prove “(ii) ⇔ (iv) ⇔ (v)” and “(iv) ⇒ (iii) ⇒ (i) ⇒ (ii)”.

To see “(ii) ⇔ (iv)”, plug in $A = \mathbb{C}$ in the diagram (15). Moreover, using that $(\mathbb{C} \times N) \rtimes_{\text{tr}} N, r G_N$ is canonically isomorphic to the reduced groupoid C*-algebra $C^*_r(G_N)$ by Example 10 in [Sims-Wil], we see that $C^*_r(P) \cong C^*_r(G_N)$. Since $G_N$ is an $r$-discrete (or étale) groupoid, it is known that $C^*_r(G_N)$ is nuclear if and only if $G_N$ is amenable (see for instance [Br-Oz], Chapter 5, Theorem 6.18).

For “(iv) ⇔ (v)”, recall that we have proven that $G$ is equivalent to $G_N$ in Corollary 5.11. As amenability is invariant under equivalences of groupoids by Theorem 2.2.17 in [An-Ren], we have proven “(iv) ⇔ (v)”.

To see “(iv) ⇒ (iii)”, note that amenability of $G_N$ implies that the fourth (counted from the top) horizontal map in diagram (15) is an isomorphism by [An-Ren], Proposition 6.1.10. By commutativity of (15), we deduce that $\lambda_{(A,P,\alpha)}$ must be an isomorphism.

For “(iii) ⇒ (i)”, first apply (iii) to $A = \mathbb{C}$ to deduce that $\lambda_{(A,P,\alpha)}$ is one by (iii). This means that $C^*_s(P)$ is nuclear.

Finally, to go from (i) to (ii), just observe that $C^*_s(P)$ is a quotient of $C^*_r(P)$ and apply [Bla], Corollary IV.3.1.13. \qed

Remark 6.2. In particular, we see that in the situation of Theorem 6.1, nuclearity of $C^*_r(P)$ (or $C^*_s(P)$) implies that the left regular representation $\lambda : C^*_r(P) \to C^*_l(P)$ is faithful.

Remark 6.3. It certainly suffices to consider unital $A$ in (iii) of Theorem 6.1.

For later purposes, we derive the following consequence:

Corollary 6.4. Let $P$ be a subsemigroup of a group $G$. Assume that $J$ is independent and that $P \subseteq G$ satisfies the Toeplitz condition. If $C^*_r(P)$ is nuclear, then there exists a net of completely positive contractions $\Theta_i : C^*_r(P) \to C^*_r(P)$ such that

1. $\lim_i \Theta_i(x) = x$ for all $x \in C^*_r(P)$,
2. for every $i$ there is a finitely supported function $d_i : G \to D_r$, $g \mapsto d_i(g)$ such that $\Theta_i(V) = d_i(g_r(V))V$ for all $0 \neq V \in S_r$.

($S_r$ and $g_r$ were introduced in § 5.2 and Lemma 5.4.)

**Proof.** As $C_r^*(P)$ is nuclear, $\mathcal{G} = \Omega^G_P \rtimes G$ is amenable by the previous theorem. Thus combining Theorem 6.18 and Proposition 6.16 from Chapter 5 in [Br-Oz], we obtain a net $h_i \in C_c(\mathcal{G})$ such that $h_i \to_i 1$ uniformly on compact subsets and $C_c(\mathcal{G}) \ni f \mapsto h_i \cdot f \in C_c(\mathcal{G})$ extends to a completely positive contraction on $C_r^*(\mathcal{G})$.

Under the canonical identification $D_P^G \rtimes_{\tau,r} G \cong C_r^*(\mathcal{G})$, we obtain a net of completely positive contractions $m_i$ such that $m_i(x) \to_i x$ for all $x \in D_P^G \rtimes_{\tau,r} G$ and for every $i$, there exists a finitely supported function $\tilde{h}_i : G \to D_P^G$ with $m_i(dU_g) = \tilde{h}_i(g)dU_g$ for all $d \in D_P^G$ and $g \in G$. To be precise, $\tilde{h}_i(g)$ is given by $\chi \mapsto h_i(\chi, g)$. Now, let $\Theta_i$ be the composition $C_r^*(\mathcal{G}) \cong E_P(D_P^G \rtimes_{\tau,r} G)E_P \subseteq D_P^G \rtimes_{\tau,r} G$ $m \mapsto D_P^G \rtimes_{\tau,r} G$. Here we have used Lemma 3.9. We have

$$
\Theta_i(V^*_i V_{p_1} \cdots V_{p_n} V_{q_m}) = m_i(E_{p_1}^{-1} \cdots p_n^{-1} q_{m} \cdot U_{p_1}^{-1} \cdots p_n^{-1} q_{m}) = (E_P \tilde{h}_i(p_1^{-1} q_{m} \cdots p_n^{-1} q_{m}) E_P) E_{p_1}^{-1} \cdots p_n^{-1} q_{m} \cdot U_{p_1}^{-1} \cdots p_n^{-1} q_{m}.
$$

Set $d_i(g) = E_P \tilde{h}_i(g)E_P$. Then $d_i$ lies in $D_r$ by the Toeplitz condition. Moreover, we see that $\Theta_i$ has image in $E_P(D_P^G \rtimes_{\tau,r} G)E_P$, so that identifying this corner back again with $C_r^*(\mathcal{G})$, we obtain the desired net of completely positive contractions. □

This observation will be used in the next section when we study induced ideals of semigroup C*-algebras. Now let us show that the existence of such completely positive contractions $\Theta_i$ on $C_r^*(\mathcal{G})$ implies nuclearity of $C_r^*(\mathcal{G})$. First, we set $D_g := \text{span}\{ s \in S : g(s) = g \} \subseteq C_r^*(\mathcal{G})$, and for a map $\Theta$ on $C_r^*(\mathcal{G})$, we let the $\text{d-supp}(\Theta)$ be $\text{d-supp}(\Theta) = \{ g \in G : \Theta|h\}_{D_g} \neq 0 \}$. By Theorem 6.1, we know that under the assumptions of Corollary 6.4, $\lambda : C_r^*(\mathcal{G}) \to C_r^*(\mathcal{G})$ is an isomorphism. Thus Corollary 6.4 gives us completely positive contractions $\Theta_i$ on $C_r^*(\mathcal{G})$ ($= C_r^*(\mathcal{G})$) such that $\lim_i \Theta_i(x) = x$ for all $x \in C_r^*(\mathcal{G})$ and $|\text{d-supp}(\Theta_i)| < \infty$ for all $i$. The following result shows that the existence of such $\Theta_i$ already implies nuclearity of $C_r^*(\mathcal{G})$:

**Proposition 6.5.** Let $P$ be a subsemigroup of a group $G$. Assume that $\mathcal{J}$ is independent. Moreover, assume that there exists a net of completely positive contractions $\Theta_i : C_r^*(\mathcal{G}) \to C_r^*(\mathcal{G})$ such that

\begin{align}
(17) \quad & \lim_i \Theta_i(x) = x \text{ for all } x \in C_r^*(\mathcal{G}), \\
(18) \quad & |\text{d-supp}(\Theta_i)| < \infty \text{ for all } i.
\end{align}

Then for every C*-algebra $A$, $\lambda : \lambda_{(\mathcal{J}, P, \mathcal{G})} : A \rtimes_{\tau,s} P \to A \rtimes_{\tau,r} P$ is an isomorphism.

In particular, $\lambda : C_r^*(\mathcal{G}) \to C_r^*(\mathcal{G})$ is an isomorphism and $C_r^*(\mathcal{G})$ is nuclear.

Note that we do not assume that $P \subseteq G$ is Toeplitz.
Proof. The proof is just the same as the one for “5) ⇒ 6)” in [Li2], § 4, but for arbitrary coefficients. For the sake of completeness, we write out the proof.

Let $E^A_s$ be the composite $A \times_{\text{tr},s}^a P \xrightarrow{\lambda(A,P,\text{tr})} A \times_{\text{tr},s}^a P \cong A \otimes_{\min} C_r^*(P) \xrightarrow{id\otimes\xi} A \otimes D_r \xrightarrow{\lambda|D} A \otimes D \to A \times_{\text{tr},s}^a P$. Here $E_r$ is the conditional expectation $C_r^*(P) \to D_r$ from [Li2], § 3.2. Moreover, we used that $\lambda|D : D \to D_r$ is an isomorphism as $J$ is independent. The last homomorphism is given by $A \otimes d \to \iota(a)\overline{d}$. Now set $D^A_g := \text{span}\{\iota(a)x : a \in A, x \in D_g\} \subseteq A \times_{\text{tr},s}^a P$. Obviously the algebraic sum $\sum_{g \in G} D^A_g$ is dense in $A \times_{\text{tr},s}^a P$. Moreover, we have by construction that $E^A_s|D^A_g = \text{id}_{D^A_g}$ and $E^A_s|D^A_g = 0$ if $g \neq e$.

Given a positive functional $\varphi$ on $A \times_{\text{tr},s}^a P$, set $d\text{-supp}(\varphi) = \{g \in G : \varphi|_{D^A_g} \neq 0\}$. If $|d\text{-supp}(\varphi)| < \infty$, then we have for all $x \in A \times_{\text{tr},s}^a P$:

\begin{equation}
|\varphi(x)|^2 \leq |d\text{-supp}(\varphi)| \|\varphi\| \|E^A_s(x^*x)|.
\end{equation}

To prove (19), let $d\text{-supp}(\varphi) = \{g_1, \ldots, g_n\}$. As $\sum_{g \in G} D^A_g$ is dense in $A \times_{\text{tr},s}^a P$, it suffices to prove (19) for $x \in \sum_{g \in G} D^A_g$. Take such an element $x$ and a finite subset $F \subseteq G$ such that $d\text{-supp}(\varphi) \subseteq F$ and $x = \sum_{g \in F} x_g$ with $x_g \in D^A_g$. Then the same computation as in the proof of Lemma 4.8 in [Li2] yields

\begin{align*}
|\varphi(x)|^2 &= |\sum_{i=1}^n \varphi(x_{g_i})|^2 \leq n \sum_{i=1}^n |\varphi(x_{g_i})|^2 \leq n \|\varphi\| \sum_{i=1}^n \varphi(x^*_g x_g) \\
&\leq n \|\varphi\| \varphi(\sum_{g \in F} x^*_g x_g) = n \|\varphi\| \varphi(E^A_s(\sum_{g,h \in F} x^*_g x_h)) \\
&= |d\text{-supp}(\varphi)| \|\varphi\| \varphi(E^A_s(x^*x)).
\end{align*}

This proves (19).

Now take $x \in \ker(\lambda(A,P,\text{tr}))$, $x \geq 0$, and a positive functional $\varphi$ on $A \times_{\text{tr},s}^a P$. Let $\varphi_i$ be the composition $A \times_{\text{tr},s}^a P \cong A \otimes_{\max} C_r^*(P) \xrightarrow{id\otimes\Theta_i} A \otimes_{\max} C_r^*(P) \cong A \times_{\text{tr},s}^a P \xrightarrow{\lambda} C$. These positive functionals $\varphi_i$ satisfy $\lim_i \varphi_i(x) = \varphi(x)$ and $|d\text{-supp}(\varphi_i)| < \infty$. As $\lambda(A,P,\text{tr})(x) = 0$, we must have $E^A_s(x^*x) = 0$ by construction of $E^A_s$. Thus by (19), we conclude that $\varphi_i(x) = 0$ for all $i$. Therefore $\varphi(x) = \lim_i \varphi_i(x) = 0$. As $\varphi$ was arbitrary, we conclude that $x = 0$. Hence $\lambda(A,P,\text{tr})$ is faithful, and we have proven the first part of our proposition. To see that $\lambda : C^*_r(P) \to C^*_r(P)$ is an isomorphism, just set $A = C$. And finally, to see that $C^*_r(P)$ is nuclear, just proceed as in the proof of Theorem 6.1, “(iii) ⇒ (i)”.

Under the (rather strong) assumption of left amenability, such $\Theta_i$ always exist:

**Lemma 6.6.** If $P$ is cancellative and left amenable, then there exists a net $\Theta_i$ as in Proposition 6.5 satisfying (17) and (18).
Proof. First of all, $P$ embeds into a group if it is cancellative and left amenable (see for instance [Li2], Corollary 4.5), so that we can form $C^*_s(P)$. As 5) in [Li2], § 4.1 holds if $P$ is left cancellative and left amenable, we can form the states $\varphi_i : C^*_s(P) \to \mathbb{C}$, $x \mapsto (\lambda(x)\xi_i, \xi_i)$ with the $\xi_i$ from 5) of § 4.1 in [Li2]. Let $\Theta_i$ be the composition $C^*_s(P) \xrightarrow{\Delta} C^*_s(P) \otimes_{\max} C^*_s(P) \xrightarrow{\varphi_i \otimes \text{id}} C^*_s(P)$, where $\Delta$ is given by (36) in [Li2]. By construction, we have $\Theta_i(s) = \varphi_i(s) s \rightarrow_i s$ for all $0 \neq s \in S$ by 5) in [Li2], § 4.1. Therefore the $\Theta_i$ satisfy (17). As the $\xi_i$ have finite support (see [Li2], § 4.1, 5)), it follows that $|\text{d-supp}(\Theta_i)| < \infty$ for all $i$ (compare also [Li2], § 4.2, “5) $\Rightarrow$ 6”). □

As a consequence, we obtain the following converse of Proposition 4.17 in [Li2]:

**Corollary 6.7.** If $P$ is cancellative, left amenable and if $\mathcal{J}$ is independent, then $C^*_s(P)$ is nuclear.

This result was also obtained independently in [Nor] using different methods.

### 7. Ideals induced from invariant spectral subsets

In this section, we always assume that $\mathcal{J}$ is independent and that $P \subseteq G$ satisfies the Toeplitz condition. In this situation, we have seen that the full and reduced semigroup C*-algebra of $P$ can be described up to Morita equivalence as full or reduced crossed products by $G$. So in principle, this reduces questions about the ideal structure of semigroup C*-algebras to corresponding questions about certain crossed products by $G$. However, in our concrete situation, there are certain induced ideals which play a distinguished role. We first of all show that nuclearity allows us to describe induced ideals in a satisfactory way. Moreover, building on our results from Section 5, we describe induced ideals (and their quotients) as crossed products by $G$. Using our observations from § 2.2, we describe it in terms of $\mathcal{J}$. Finally, we turn to the boundary of the spectrum and investigate the corresponding boundary action.

#### 7.1. Induced ideals

Let $I_r$ be an ideal of $D_r$, the diagonal sub-C*-algebra of $C^*_s(P)$. Restricting the canonical conditional expectation $\mathcal{L}(\ell^2(P)) \to \ell^\infty(P)$, we obtain a conditional expectation $\mathcal{E}_r : C^*_r(P) \to D_r$ (compare [Li2], § 3.2). Following [Ni1], we define the induced ideal

$$\text{Ind} I_r := \{ x \in C^*_r(P) : \text{Ad} (V) \mathcal{E}_r(x^* x) \in I_r \text{ for all } V \in S_r \}.$$

As A. Nica shows, the name “induced ideal” is justified because we could have obtained $\text{Ind} I_r$ by an induction process as described in [Ni1], § 6.1.

For the purpose of inducing ideals, it suffices to consider invariant ideals of $D_r$.

**Definition 7.1.** An ideal $I_r$ of $D_r$ is called invariant if $\text{Ad} (V)(I_r) \subseteq I_r$ for all $V \in S_r$.
The reason why we only need to consider invariant ideals is that given an ideal \( I_r \) of \( D_r \), we obtain the invariant ideal \( I_r^{(\text{inv})} := \{ d \in D_r : \text{Ad}(V)(d) \in I_r \text{ for all } V \in S_r \} \). And just as in [Ni1], we have \( \text{Ind} I_r = \text{Ind} I_r^{(\text{inv})} \).

We observe that the induction process is an injective map from the set of invariant ideals of \( D_r \) to the set of ideals of \( C^*_r(P) \).

**Lemma 7.2.** Every invariant ideal \( I_r \) of \( D_r \) satisfies \( (\text{Ind} I_r) \cap D_r = \mathcal{E}_r(\text{Ind} I_r) = I_r \).

**Proof.** \( (\text{Ind} I_r) \cap D_r \) is contained in \( \mathcal{E}_r(\text{Ind} I_r) \) as \( \mathcal{E}_r|_{D_r} = id_{D_r} \).

To see \( \mathcal{E}_r(\text{Ind} I_r) \subseteq I_r \), take \( x \in \text{Ind} I_r \). Then \( \mathcal{E}_r(x) \) lies in \( D_r \) and we have \( \mathcal{E}_r(x) \leq \mathcal{E}_r(x^*x) \in I_r \). Thus \( \mathcal{E}_r(x) \) lies in \( I_r \), and this implies \( x \in I_r \).

And finally, \( I_r \) is contained in \( \text{Ind} I_r \) (as \( \mathcal{E}_r|_{I_r} = id_{I_r} \)) and in \( D_r \) anyway. \( \square \)

Following ideas of [Ni1], we deduce the following consequence of nuclearity:

**Proposition 7.3.** If \( J \) is independent, if \( P \subseteq G \) is Toeplitz and if \( C^*_r(P) \) is nuclear, then \( \text{Ind} I_r \) coincides with the ideal \( \langle I_r \rangle \) of \( C^*_r(P) \) generated by \( I_r \).

**Proof.** It is clear that \( \text{Ind} I_r \supseteq \langle I_r \rangle \) as \( I_r \) is contained in \( \text{Ind} I_r \) by the previous lemma, and because \( \text{Ind} I_r \) is an ideal of \( C^*_r(P) \).

To prove that \( \text{Ind} I_r \subseteq \langle I_r \rangle \), first set, for \( g \in G \), \( (D_r)_g := \text{span}(\{ V \in S_r : g_r(V) = g \}) \). Moreover, let \( (\text{Ind} I_r)_c = \text{Ind} I_r \cap (\sum_{g \in G} (D_r)_g) = \left\{ x \in \sum_{g \in G} (D_r)_g : \mathcal{E}_r(x^*x) \in I_r \right\} \).

Here \( \sum_{g \in G} (D_r)_g \) means the algebraic sum (without taking the closure), i.e. the set of finite sums of the form \( \sum_{g \in G} x_g \) with \( x_g \in (D_r)_g \).

As a first step, let us prove \( (\text{Ind} I_r)_c \subseteq \langle I_r \rangle \): Take \( x = \sum_g x_g \in (\text{Ind} I_r)_c \). This means that \( \mathcal{E}_r(x^*x) = \sum_g x_g^*x_g \) lies in \( I_r \). Hence \( I_r \) is hereditary all the \( x_g^*x_g \) lie in \( I_r \). By polar decomposition (see [Bla], § II.3.2), we deduce that \( x_g \in \langle I_r \rangle \). Thus \( x \in \langle I_r \rangle \).

The second step is to prove \( \text{Ind} I_r \subseteq (\text{Ind} I_r)_c \). By Corollary 6.4, there exists a net \( \Theta_i \) of completely positive contractions \( C^*_r(P) \to \mathcal{C}_r^*(P) \) satisfying 1. and 2. from Corollary 6.4. From 2., we deduce that for all \( x \in C^*_r(P) \), we have \( \mathcal{E}_r(\Theta_i(x)) = \delta_i(e) \mathcal{E}_r(x) \) as this formula obviously holds for \( x = \sum_{g \in G} (D_r)_g \) because of 2. Now take \( x \in \text{Ind} I_r \). Then \( \Theta_i(x) \) lies in \( \text{Ind} I_r \) as well since \( \mathcal{E}_r(\Theta_i(x)^*\Theta_i(x)) \leq \mathcal{E}_r(\Theta_i(x^*x)) = d_i(e) \mathcal{E}_r(x^*x) \in I_r \). Moreover, as the \( d_i \) in Corollary 6.4 have finite support, we have \( \Theta_i(x) \in \sum_{g \in G} (D_r)_g \). Thus \( \Theta_i(x) \) is in \( (\text{Ind} I_r)_c \). And finally, by 1. in Corollary 6.4, \( x = \lim_i \Theta_i(x) \) lies in \( (\text{Ind} I_r)_c \). \( \square \)

Just as in [Ni1], we obtain the following characterization of induced ideals:
Corollary 7.4. If $\mathcal{J}$ is independent, if $P \subseteq G$ is Toeplitz and if $C_r^*(P)$ is nuclear, then

$$\{\text{Ind} \, I_r : I_r \triangleleft D_r \} = \{ J \triangleleft C_r^*(P) : \mathcal{E}_r(J) \subseteq J \}. $$

Proof. “$\subseteq$” holds by Lemma 7.2. To prove “$\supseteq$”, take an ideal $J$ of $C_r^*(P)$ such that $\mathcal{E}_r(J) \subseteq J$. As $J$ is an ideal of $C_r^*(P)$, $\mathcal{E}_r(J)$ is an invariant ideal of $D_r$. Moreover, $J$ is contained in $\text{Ind} \, \mathcal{E}_r(J)$ as for $x \in J$, $x^*x$ also lies in $J$, hence $\mathcal{E}_r(x^*x)$ lies in $\mathcal{E}_r(J)$. Thus by the last corollary, we have $\text{Ind} \, \mathcal{E}_r(J) = \{ \mathcal{E}_r(J) \} \subseteq J \subseteq \text{Ind} \, \mathcal{E}_r(J).$ □

At this point, we remark that associating $\langle I_r \rangle$ with an (invariant) ideal $I_r$ of $D_r$ is also a natural way of constructing ideals of $C_r^*(P)$ from those of $D_r$. Indeed, as we will see, this process is to a certain extent even more natural, at least for our purposes. But first, we observe that the assignment $I_r \rightarrow \langle I_r \rangle$ is also one-to-one (under the condition that $I_r$ is invariant):

Lemma 7.5. Given an invariant ideal $I_r$ of $D_r$, we have $\langle I_r \rangle \cap D_r = I_r$.

Proof. As we always have $\langle I_r \rangle \subseteq \text{Ind} \, I_r$, our claim follows from $I_r \subseteq \langle I_r \rangle \cap D_r \subseteq (\text{Ind} \, I_r) \cap D_r = I_r$. □

By our assumptions that $\mathcal{J}$ is independent and that $P \subseteq G$ is Toeplitz, we know that $C_r^*(P)$ is isomorphic to the full corner $E_P(D_P^G \rtimes_{\tau,r} G)E_P$ of the reduced crossed product $D_P^G \rtimes_{\tau,r} G$. Thus there is a one-to-one correspondence between ideals of $C_r^*(P)$ and $D_P^G \rtimes_{\tau,r} G$ given by $D_P^G \rtimes_{\tau,r} G \ni J \mapsto J|_P \triangleleft C_r^*(P)$. Here $J|_P$ is the ideal of $C_r^*(P)$ which corresponds to $E_P J E_P$ under the canonical identification $C_r^*(P) \cong E_P(D_P^G \rtimes_{\tau,r} G)E_P$ provided by Corollary 3.10. But even more, we also know that $J|_P$ is again isomorphic to a full corner of $J$, namely $E_P J E_P$.

Given an invariant ideal $I_r$ of $D_r$, our present goal is to find a $G$-invariant ideal $I_P^G$ of $D_P^G$ such that $(I_P^G \rtimes_{\tau,r} G)|_P = \langle I_r \rangle$. A natural candidate for $I_P^G$ would be the smallest $G$-invariant ideal of $D_P^G$ which contains $I_r$.

Definition 7.6. We set

$$I_P^G := \{ \tau_{g_1}(x_1) \cdots \tau_{g_n}(x_n) \cdot d : n \in \mathbb{Z}_{\geq 1}, g_i \in G, x_i \in I_r, d \in D_P^G \}. $$

We observe that it is an easy consequence of the construction of $I_P^G$ that in $\Omega_P^G$, we have $\text{Spec}(I_P^G) = (\text{Spec} I_r) \cdot G$. Here and in the sequel, we identify $\Omega$ with a subspace of $\Omega_P^G$ via the map $c^*$ from §5.4.

Lemma 7.7. If $P \subseteq G$ is Toeplitz, then the following hold:

(i) $(I_P^G \rtimes_{\tau,r} G)|_P = \langle I_r \rangle$,

(ii) $E_P I_P^G E_P = I_r$,

(iii) For all $g \in G$, $E_P \tau_g(I_r) E_P \subseteq I_r$.

(iv) $\text{Spec} I_r = \text{Spec} I_P^G \cap \Omega$. 
(v) \( \Omega_P^G \setminus \text{Spec } I_P^G = (\Omega \setminus \text{Spec } I_r) \cdot G \).

**Proof.** We first prove that these conditions are equivalent if \( P \subseteq G \) is Toeplitz, and then we show that the Toeplitz condition for \( P \subseteq G \) implies (iii).

To see “(i) \( \Rightarrow \) (ii)”, note that \( \langle I_r \rangle \cap D_r = I_r \) in \( C^*_r(P) \) implies that we have \( \langle I_r \rangle_{EP(D_E^G \rtimes_{\tau,r} G)EP} \cap D_r = I_r \) in \( EP(D_E^G \rtimes_{\tau,r} G)EP \). Thus if (i) holds, i.e. if \( EP(I_P^G \rtimes_{\tau,r} G)EP \cap D_r = I_r \).

“(ii) \( \Rightarrow \) (iii)” is clear as \( \tau_g(I_r) \subseteq I_P^G \).

To prove “(iii) \( \Rightarrow \) (i)”, we first observe that \( (I_P^G \rtimes_{\tau,r} G)|_P \supseteq \langle I_r \rangle \) always holds as \( I_P^G \supseteq I_r \). It remains to prove that (iii) implies the reverse inclusion. Upon identifying \( C^*_r(P) \) with \( EP(D_E^G \rtimes_{\tau,r} G)EP \), we have to prove, assuming (iii), that \( EP(I_P^G \rtimes_{\tau,r} G)EP \subseteq \langle I_r \rangle_{EP(D_E^G \rtimes_{\tau,r} G)EP} \). Take a generator of \( I_P^G \), say \( \tau_{g_1}(x_1) \cdots \tau_{g_n}(x_n) \cdot d \). Then for all \( g \in G \), \( EP\tau_{g_1}(x_1) \cdots \tau_{g_n}(x_n) \cdot d \cdot U_g EP = (EP\tau_{g_1}(x_1)EP) \cdot (EP\tau_{g_2}(x_2) \cdots \tau_{g_n}(x_n) \cdot d \cdot U_g EP) \), and since \( EP\tau_{g_1}(x_1)EP \) lies in \( I_r \) by (iii), we conclude \( EP\tau_{g_1}(x_1) \cdots \tau_{g_n}(x_n) \cdot d \cdot U_g EP \in \langle I_r \rangle_{EP(D_E^G \rtimes_{\tau,r} G)EP} \).

“(iii) \( \Rightarrow \) (iv)”: We always have \( \subseteq \). To prove “\( \supseteq \)”, take \( \chi \in \Omega \) such that \( \chi|_{I_P^G} \neq 0 \). Then we can find \( g \in G \) and \( x \in I_r \) with \( \chi(\tau_g(x)) \neq 0 \). Thus \( \chi(EP\tau_g(x)EP) \neq 0 \). As \( EP\tau_g(x)EP \) lies in \( I_r \) by (iii), we conclude \( \chi \in \text{Spec } I_r \).

“(iv) \( \Rightarrow \) (v)”: The inclusion “\( \subseteq \)” is easy to see. The other one (“\( \supseteq \)” follows from (iv) and G-invariance of \( \Omega_P^G \setminus \text{Spec } I_P^G \).

“(v) \( \Rightarrow \) (iii)”: We have to show that whenever \( \chi \in \Omega_P^G \) satisfies \( \chi|_{I_r} = 0 \), then for all \( g \in G \), \( \chi|_{EP\tau_g(I_r)EP} = 0 \) must hold as well. Take \( \chi \) such that \( \chi|_{I_r} = 0 \). If \( \chi(EP) = 0 \), there is nothing to show. Hence we may assume \( \chi(EP) = 1 \), i.e. \( \chi \in \Omega \). This means that \( \chi \in \Omega \setminus \text{Spec } I_r \). By (v), we conclude that \( \chi \notin \text{Spec } (I_P^G) \).

It remains to prove that the Toeplitz condition for \( P \subseteq G \) implies (iii). Given \( g \in G \), the Toeplitz condition yields \( p_1, q_1, \ldots, p_n, q_n \in P \) such that \( EP\lambda_g EP = V_{p_1}^{*} V_{q_1} \cdots V_{p_n}^{*} V_{q_n} \). Then, for every invariant ideal \( I_r \) of \( D_r \), we have
\[
EP\tau_g(I_r)EP = EP\lambda_g EP I_r EP\lambda_g EP = \text{Ad}(V_{p_1}^{*} V_{q_1} \cdots V_{p_n}^{*} V_{q_n})(I_r) \subseteq I_r
\]
as \( I_r \) is invariant. \( \square \)

**Remark 7.8.** In particular, if \( P \subseteq G \) is Toeplitz, then \( (\Omega \setminus \text{Spec } I_r) \cdot G \) is closed in \( \Omega_P^G \).

Now, the same arguments used in the proof of Theorem 5.20 and Theorem 6.1 give us the following

**Proposition 7.9.** Assume that \( F \) is independent and that \( P \subseteq G \) is Toeplitz. Let \( I_r \) be an invariant ideal of \( D_r \), and let \( I \) be the corresponding ideal of \( D \) such that
\[ \lambda(I) = I_r. \] Then the ideal \( \langle I_r \rangle \) of \( C^*_r(P) \) generated by \( I_r \) is isomorphic to the full corner of \( I^G_r \rtimes_{\tau,r} G \) determined by the characteristic function \( \mathbf{1}_{\text{Spec } I_r} \) of \( \text{Spec } I_r \subseteq \text{Spec } (I^G_r) \), and the ideal \( \langle I \rangle \) of \( C^*_s(P) \) generated by \( I \) is isomorphic to the full corner of \( I^G_s \rtimes_r G \) given by \( \mathbf{1}_{\text{Spec } I_r} \).

Moreover, the following are equivalent:

1. \( \langle I \rangle_{C^*_r(P)} \) is nuclear,
2. \( \langle I_r \rangle_{C^*_r(P)} \) is nuclear,
3. \( \tau \) the transformation groupoid \( \text{Spec } (I^G_r) \rtimes G = \langle (\text{Spec } I_r) \cdot G \rangle \rtimes G \) is amenable.

Either of these conditions implies that \( \lambda: \langle I \rangle_{C^*_r(P)} \to \langle I_r \rangle_{C^*_r(P)} \) is faithful.

For the corresponding quotients, we have that \( C^*_s(P)/\langle I \rangle \) is isomorphic to the full corner of \( (D^G_P/I^G_P) \rtimes_{\tau,r} G \cong C_0(\Omega^G_P \setminus \text{Spec } (I^G_P)) \rtimes_r G \) determined by the characteristic function \( \mathbf{1}_{\Omega \setminus \text{Spec } I_r} \). Moreover, if the sequence \( 0 \to C_0(\text{Spec } (I^G_P)) \rtimes_{\tau,r} G \to C_0(\Omega^G_P) \rtimes_{\tau,r} G \to C_0(\Omega^G_P \setminus \text{Spec } (I^G_P)) \rtimes_{\tau,r} G \to 0 \) is exact, then also \( C^*_s(P)/\langle I \rangle \) is isomorphic to the full corner of \( (D^G_P/I^G_P) \rtimes_{\tau,r} G \cong C_0(\Omega^G_P \setminus \text{Spec } (I^G_P)) \rtimes_{\tau,r} G \) associated with \( \mathbf{1}_{\Omega \setminus \text{Spec } I_r} \), and the following are equivalent:

1. \( \langle I \rangle_{C^*_s(P)} \) is nuclear,
2. \( \langle I_r \rangle_{C^*_s(P)} \) is nuclear,
3. \( \tau \) the transformation groupoid \( (\Omega^G_P \setminus \text{Spec } (I^G_P)) \rtimes G = \langle (\Omega \setminus (\text{Spec } I_r)) \cdot G \rangle \rtimes G \) is amenable;

and either of these conditions implies that \( \lambda: C^*_s(P)/\langle I \rangle \to C^*_s(P)/\langle I_r \rangle \) is faithful.

We also mention the following useful consequence:

**Lemma 7.10.** If \( P \subseteq G \) satisfies the Toeplitz condition, then the maps \( I_r \to I^G_r \) and \( E_P J E_P \to J \) are mutually inverse, inclusion-preserving bijections between the sets of invariant ideals of \( D_r \) and \( G \)-invariant ideals of \( D^G_r \).

**Proof.** By the Toeplitz condition, we have \( E_P I^G_r E_P = I_r \). To check \( (E_P J E_P)^G_r = J \), note that \( E_P(J \rtimes_{\tau,r} G)E_P = (E_P J E_P) \rtimes_{\tau,r} G \). As \( E_P \) is a full projection in \( D^G_P \rtimes_{\tau,r} G \), we conclude that \( J \rtimes_{\tau,r} G = (E_P J E_P)^G_r \), hence \( J = (E_P J E_P)^G_r \). \( \square \)

7.2. **Invariant spectral subsets.** As ideals of \( D_r \) correspond to subsets of \( \Omega = \text{Spec } D_r \), we now describe \( \Omega \) explicitly in terms of the family of constructible ideals \( J \), and we also describe the action of \( P \). This is just an application of our observations in § 2.2 because of our standing assumption that \( J \) is independent.

Let \( \Sigma \) be the set of non-empty \( J \)-valued filters on \( P \) as introduced before Corollary 2.9, equipped with the topology introduced after Corollary 2.9.
Lemma 7.11. We can identify $\Omega$ with $\Sigma$ via $\omega: \Omega \to \Sigma$, $\chi \mapsto \{X \in \mathcal{J} : \chi(E_X) = 1\}$.

For all $p \in P$, the map $\Sigma \to \Sigma$, $F \mapsto \{pX : X \in F\}$ gives rise to a homeomorphism $\Sigma \cong p\Sigma = \{F \in \Sigma : pP \subseteq F\}$. Let $p^{-1}: p\Sigma \to \Sigma, pF \mapsto F$ be its inverse. Define $\sigma_p: C(\Sigma) \to C(\Sigma), \sigma_p(d)(F) = d(p^{-1}F)$ if $F$ lies in $p\Sigma$ and $\sigma_p(d)(F) = 0$ if $F$ does not lie in $p\Sigma$ and $\sigma_p^*: C(\Sigma) \to C(\Sigma), \sigma_p(d)(F) = d(pF)$.

Then the homeomorphism $\omega: \Omega \to \Sigma$ induces an identification $\omega^*: C(\Sigma) \to D_r$ such that for every $p \in P$, the diagrams

\[
\begin{align*}
C(\Sigma) & \longrightarrow D_r \\
\sigma_p \downarrow & \quad \downarrow \text{Ad}(V_p) \\
C(\Sigma) & \longrightarrow D_r
\end{align*}
\]

and

\[
\begin{align*}
C(\Sigma) & \longrightarrow D_r \\
\sigma_p^* \downarrow & \quad \downarrow \text{Ad}(V_p^*) \\
C(\Sigma) & \longrightarrow D_r
\end{align*}
\]

commute.

Proof. This is straightforward to check. \qed

Corollary 7.12. An ideal $I_r$ of $D_r$ is invariant if and only if for all $p \in P$, we have $p\omega(\text{Spec } I_r) \subseteq \omega(\text{Spec } I_r)$ and $p^{-1}(\omega(\text{Spec } I_r) \cap p\Sigma) \subseteq \omega(\text{Spec } I_r)$.

Definition 7.13. A subset $C$ of $\Sigma$ is called invariant if for all $p \in P$, the conditions $pC \subseteq C$ and $p^{-1}(C \cap p\Sigma) \subseteq C$ are satisfied.

7.3. The boundary action. Finally, let us have a look at the boundary of $\Omega$. Recall the definition of the boundary $\partial \Omega$ from § 2.2.

Definition 7.14. Let $\Sigma_{\text{max}}$ be the set of all $\mathcal{J}$-valued ultrafilters on $P$, and let $\partial \Sigma$ be the closure $\Sigma_{\text{max}}$ of $\Sigma_{\text{max}}$ in $\Sigma$. We set $\Omega_{\text{max}} = \omega^{-1}(\Sigma_{\text{max}})$ and $\partial \Omega = \omega^{-1}(\partial \Sigma)$.

We note that this definition is essentially the one from [La1], extended from the case of quasi-lattice ordered groups to our situation.

Lemma 7.15. $\partial \Sigma$ is the minimal non-empty closed invariant subset of $\Sigma$.

Proof. Choose $F \in \Sigma_{\text{max}}$ and take $p \in P$.

We claim $pF \in \Sigma_{\text{max}}$. Assume that there exists $F' \in \Sigma$ such that $pF \subseteq F'$. Then $pP \subseteq F'$ so that $F' \in p\Sigma$. Thus $p^{-1}F'$ is an element of $\Sigma$ such that $F = p^{-1}pF \subseteq p^{-1}F'$. As $F$ is maximal, this implies $F = p^{-1}F'$. Hence $pF = pp^{-1}F' = F'$.

Next we claim that $p^{-1}F \in \Sigma_{\text{max}}$ if $F$ lies in $p\Sigma$. If $p^{-1}F \subseteq F'$ for some $F' \in \Sigma$, then $F = pp^{-1}F \subseteq pF'$ implies $F = pF'$ and thus $p^{-1}F = p^{-1}pF' = F'$. 


Thus we have seen that $\Sigma_{\text{max}}$ is invariant. As $\partial \Sigma$ is the closure of $\Sigma_{\text{max}}$, we conclude that $p(\partial \Sigma) \subseteq \partial \Sigma$ for all $p \in P$. As we know that $p\Sigma$ is clopen in $\Sigma$, we also deduce $p^{-1}(\partial \Sigma \cap p\Sigma) \subseteq \partial \Sigma$. Therefore $\partial \Sigma$ is invariant.

To prove minimality, let $\emptyset \neq C$ be a closed invariant subset of $\Sigma$. Take $F \subset C$ arbitrary, and choose some $F_{\text{max}} \in \Sigma_{\text{max}}$. For every $X \in F_{\text{max}}$, choose $x \in X$ ($X \neq \emptyset$). Then $xP \subset X$ implies that $X$ lies in $xF$ as $xP \subset X$ ($X$ is a right ideal). Set $F_X := xF$. Ordering elements in $F_{\text{max}}$ by inclusion (i.e. we set $X_1 \supseteq X_2$ if $X_1 \supseteq X_2$), we obtain a net $(F_X)_{X \in F_{\text{max}}}$ in $C$. As $\Sigma$ is compact ($\Omega$ is compact), we may assume, after passing to a convergent subnet if necessary, that $(F_X)_{X}$ converges to an element $F_m$ of $\Sigma$. As $C$ is closed, $F_m$ must lie in $C$. Moreover, for every $X \in F_{\text{max}}$, we have that $X' \supseteq X$ implies $X \in F_{X'}$. Thus $X$ lies in $F_m$. We conclude $F_{\text{max}} \subseteq F_m$, hence by maximality, $F_{\text{max}} = F_m$ lies in $C$. Thus $\partial \Sigma = \Sigma_{\text{max}}$ lies in $C$, and we are done.

As immediate consequences, we obtain

**Corollary 7.16.** $V(\partial \Omega) = \{d \in D_r: \chi(d) = 0 \text{ for all } \chi \in \partial \Omega\}$ is the maximal invariant proper ideal of $D_r$.

**Proof.** This is a direct consequence of minimality of $\partial \Omega$ and Corollary 7.12. □

**Corollary 7.17.** If $P \subseteq G$ satisfies the Toeplitz condition, then the $G$-action on $(\partial \Omega) \cdot G$ is minimal.

**Proof.** This is a direct consequence of the previous corollary and Lemma 7.10. □

Moreover, we deduce the analogue of [La1], Proposition 4.3:

**Corollary 7.18.** Given a proper ideal $J$ of $C^r_*(P)$ such that $E_r(J) \subseteq J$, we always have $J \subseteq \text{Ind} \, V(\partial \Omega)$.

**Proof.** As $J$ is a proper ideal of $C^r_*(P)$ and since $E_r(J) \subseteq J$, $E_r(J)$ is an invariant proper ideal of $D_r$. Thus $E_r(J) \subseteq V(\partial \Omega)$. Moreover, for every $x \in J$, we have $E_r(x^*x) \in E_r(J)$. Hence every element in $J$ lies in $\{x \in C^r_*(P): E_r(x^*x) \in V(\partial \Omega)\} = \text{Ind} \, V(\partial \Omega)$. □

Using similar ideas as in [La1], we now investigate when the action of $G$ on $(\partial \Omega) \cdot G \subseteq \Omega_\mathcal{F}$ is topologically free and a local boundary action (the first notion is introduced in [Ar-Sp], and the second one is introduced in [La-Sp]).

First of all, we set $G_0 := \{g \in G: (g \cdot P) \cap X \neq \emptyset \text{ and } (g^{-1} \cdot P) \cap X \neq \emptyset \text{ for all } \emptyset \neq X \in J\}$.

Clearly, $G_0 = \{g \in G: (g \cdot P) \neq \emptyset \text{ and } (g^{-1} \cdot P) \neq \emptyset \text{ for all } p \in P\}$.

Moreover, we have
Lemma 7.19. $G_0$ is a subgroup of $G$.

Proof. Take $g_1$, $g_2$ in $G_0$. Then for all $\emptyset \neq X \subset J$, we have
\[
((g_1g_2) \cdot P) \cap X = g_1 \cdot ((g_2 \cdot P) \cap (g_1^{-1} \cdot X)) \supseteq g_1 \cdot ((g_2 \cdot P) \cap (g_1^{-1} \cdot X)) \cap (g_1 \cdot P) = g_1 \cdot ((g_2 \cdot P) \cap (g_1^{-1} \cdot X) \cap P).
\]
Now $(g_1^{-1} \cdot X) \cap P = g_1^{-1} \cdot (X \cap (g_1 \cdot P)) \neq \emptyset$. Thus there exists $x \in P$ such that $x \in (g_1^{-1} \cdot X) \cap P$. Hence $xP \subseteq (g_1^{-1} \cdot X) \cap P$. Thus $\emptyset \neq (g_2 \cdot P) \cap (xP) \subseteq ((g_1g_2) \cdot P) \cap X$.

\begin{proof}[\textbf{Proposition 7.20}] $G$ acts topologically freely on $(\partial \Omega) \cdot G$ if and only if $G_0$ acts topologically freely on $(\partial \Omega) \cdot G$.
\end{proof}

Proof. \("\Rightarrow"\) is clear. For \("\Leftarrow"\), assume that for $\epsilon \neq g \in G$, we have that the fix point set of $(\partial \Omega) \cdot G$ under $g$ has non-empty interior, i.e. $\text{Fix}_g(\partial \Omega) \neq \emptyset$. Thus there exists an open subset $U$ of $(\partial \Omega) \cdot G$ such that $U \subseteq \text{Fix}_g(\partial \Omega)$. As $\partial \Omega = \overline{\Omega}_\text{max}$, we deduce $(\partial \Omega) \cdot G \subseteq \overline{\Omega}_\text{max} \cdot G$. Therefore there exists $\chi \in (\text{max} \cdot G) \cap U$. Choose $h \in G$ such that $\chi h$ lies in $\overline{\Omega}_\text{max}$.

Now assume that $G_0$ acts topologically freely on $(\partial \Omega) \cdot G$. Then for all $x \in G$, $x^{-1}gx$ cannot lie in $G_0$ as $\text{Fix}_g(\partial \Omega) \cdot (x^{-1}gx) = \text{Fix}_g(\partial \Omega) \cdot x^{-1}$. Now take any $X \subset J$ such that $(\chi h)(E_X) = 1$. Moreover, let $x \in X$. Then $x^{-1}h^{-1}ghx$ does not lie in $G_0$. Thus there exists $p \in P$ such that $((x^{-1}h^{-1}ghx) \cdot P) \cap (pP) = \emptyset$ or $((x^{-1}h^{-1}ghx) \cdot P) \cap (pP) = \emptyset$. In either case, we choose $\chi X \in \overline{\Omega}_\text{max}$ such that $\chi X(E_{xP}) = 1$. If $((x^{-1}h^{-1}ghx) \cdot P) \cap (pP) = \emptyset$, then $(xP) \cap ((h^{-1}ghx) \cdot P) = \emptyset$. This implies $\chi X(E_{(h^{-1}ghx) \cdot P}) = 0$. Thus $\chi X \cdot (h^{-1}gh) \neq \chi X$. Similarly, we obtain from $((x^{-1}h^{-1}ghx) \cdot P) \cap (pP) = \emptyset$ that $\chi X \cdot (h^{-1}gh) \neq \chi X$. In any case, we obtain $\chi X \cdot (h^{-1}gh) \neq \chi X h^{-1}$ does not lie in $\text{Fix}_{\chi X h^{-1}}(\partial \Omega \cdot G)$.

As against that, we have found for all $X \in \omega(\chi h)$ a character $\chi X$ such that $\chi X(E_X) = 1$. Thus ordering $X \in \omega(\chi h)$ by inclusion as in the proof of Lemma 7.15, we obtain a net $(\chi X)_X$ in $\overline{\Omega}_\text{max} \subseteq \Omega$. By passing over to a convergent subnet, we may assume that $\lim X \chi X = \chi \in \Omega$. Hence $\chi X(E_X) = 1$ for all $X \in \omega(\chi h)$. This implies $\omega(\chi h) \subseteq \omega(\chi)$, hence $\chi = \chi h$ as $\chi h$ lies in $\overline{\Omega}_\text{max}$. The conclusion is that $\lim X \chi X h^{-1} = \chi$. But we have seen $\chi X h^{-1} \notin \text{Fix}_{\chi X h^{-1}}(\partial \Omega \cdot G)$, and we also know $\chi \in [\text{Fix}_g(\partial \Omega) \cdot G(p)]^0$. This is a contradiction.

\begin{proof}[\textbf{Proposition 7.21}] If $P$ is not left reversible, then the $G$-action on $(\partial \Omega) \cdot G$ is a local boundary action in the sense of [La-Sp].
\end{proof}

Proof. We have to show that for every non-empty subset $U$ of $(\partial \Omega) \cdot G$, there exists an open subset $\Delta \subseteq U$ and an element $g \in G$ such that $\Delta g \subseteq \Delta$.

Let $U$ be as above. As $\overline{\Omega}_\text{max} = \partial \Omega$, we can find $\chi \in \Omega_\text{max}$ and $h \in G$ such that $\chi h \in U$, i.e. $\chi \in (Uh^{-1}) \cap \Omega$. As $\Omega$ is open in $\overline{\Omega}_\partial$, we can find $X$ in $J$ and $X_1$, ..., $X_n$ in $J$ such that $V = \{\psi \in (\partial \Omega) \cdot G: \psi(E_X) = 1, \psi(E_{X_i}) = 0 \text{ for all } 1 \leq i \leq n\}$ is contained in $Uh^{-1}$ and that $\chi \in V$ (see (4)). The latter condition means that $\chi(E_X) = 1$ and $\chi(E_{X_i}) = 0$ for all $1 \leq i \leq n$. As $\chi$ lies in $\Omega_\text{max}$, we conclude that for
all 1 \leq i \leq n$, there must be $X'_i$ in $J$ such that $\chi(E_{X'_i}) = 1$ and $X_i \cap X'_i = \emptyset$ (see (5)). Thus setting $\hat{X} = X \cap (\bigcap_{i=1}^n X'_i) \neq \emptyset$, we see that for any $\psi \in (\partial\Omega) \cdot G$, $\psi(E_X) = 1$ implies $\psi \in U^{-1}$. Choose $x \in \hat{X}$. As $P$ is not left reversible, we can find $p$ and $q$ in $P$ such that $(pP) \cap (qP) = \emptyset$. Now set $\Delta' = \{\psi \in (\partial\Omega) \cdot G \colon \psi(E_{xp}) = 1\}$. $\Delta'$ is clopen in $(\partial\Omega) \cdot G$. As $xp \subseteq \hat{X}$, we conclude that $\Delta' \subseteq U^{-1}$. Set $g' = xp^{-1}x^{-1} \in G$. Then $\psi' \in \Delta'g'$ implies that there exists $\psi \in (\partial\Omega) \cdot G$ such that $\psi(E_{xp}) = 1$ and $\psi = \psi'g'$. Thus $\psi \in (\partial\Omega) \cdot G$ and $\psi'(E_{xp}P) = \psi'(E_{g'\cdot(xP)}) = \psi(E_{xp}) = 1$. Thus $\psi'(E_{xp}P)$ is a local boundary action. As it is also topologically free, Theorem 9 from [La-Sp]

Remark 7.22. Proposition 7.21 clarifies the final remark in [La1], we have proven $\Delta' = \{\psi \in (\partial\Omega) \cdot G \colon \psi(E_{xp}) = 1\}$. $\Delta'$ is clopen in $(\partial\Omega) \cdot G$. As $xp \subseteq \hat{X}$, we conclude that $\Delta' \subseteq U^{-1}$. Set $g' = xp^{-1}x^{-1} \in G$. Then $\psi' \in \Delta'g'$ implies that there exists $\psi \in (\partial\Omega) \cdot G$ such that $\psi(E_{xp}) = 1$ and $\psi = \psi'g'$. Thus $\psi \in (\partial\Omega) \cdot G$ and $\psi'(E_{xp}P) = \psi'(E_{g'\cdot(xP)}) = \psi(E_{xp}) = 1$. Thus $\psi'(E_{xp}P)$ is a local boundary action. As it is also topologically free, Theorem 9 from [La-Sp]

Corollary 7.23. Assume that $G$ is countable, and that $P \subseteq G$ satisfies the Toeplitz condition. If $G$ acts amenably on $(\partial\Omega) \cdot G$, if $G_0$ acts topologically freely on $(\partial\Omega) \cdot G$ and if $C^*_\tau(P)$ does not have a non-zero character, then the boundary quotient $C^*_\tau(P)/\langle V(\partial\Omega) \rangle$ is a unital UCT Kirchberg algebra.

Proof. Since $G$ acts amenably on $(\partial\Omega) \cdot G$, we have $C_0((\partial\Omega) \cdot G) \rtimes_\tau G \cong C_0((\partial\Omega) \cdot G) \rtimes_{\tau, r} G$ by [Br-Oz], Chapter 5, Corollary 6.17. Moreover, as $G$ is countable, so is $P$. Thus $C_0((\partial\Omega) \cdot G) \rtimes_\tau G$ is separable. Since $G$ acts amenably on $(\partial\Omega) \cdot G$, $C_0((\partial\Omega) \cdot G) \rtimes_\tau G$ is nuclear by [Br-Oz], Chapter 5, Theorem 6.18. In addition, [Tu] implies that $C_0((\partial\Omega) \cdot G) \rtimes_\tau G$ satisfies the UCT. Moreover, as $P \subseteq G$ satisfies the Toeplitz condition, we obtain by Corollary 7.17 that the $G$-action on $(\partial\Omega) \cdot G$ is minimal. As $G_0$ acts topologically freely on $(\partial\Omega) \cdot G$, we know by Proposition 7.20 that $G$ acts topologically freely on $(\partial\Omega) \cdot G$. This shows that $C_0((\partial\Omega) \cdot G) \rtimes_\tau G$ is simple by [Ar-Sp]. Furthermore, it is shown in [Li2], Lemma 4.6 that $P$ is left reversible if and only if $C^*_\tau(P)$ has a non-zero character. Hence if $C^*_\tau(P)$ does not have a non-zero character, Proposition 7.21 implies that the $G$-action on $(\partial\Omega) \cdot G$ is a local boundary action. As it is also topologically free, Theorem 9 from [La-Sp] yields that $C_0((\partial\Omega) \cdot G) \rtimes_\tau G$ is purely infinite simple. So we have seen that under our assumptions, $C_0((\partial\Omega) \cdot G) \rtimes_\tau G$ is a purely infinite separable nuclear simple C*-algebra satisfying the UCT. Now apply Proposition 7.9, and we are done.

8. Examples

8.1. Quasi-lattice ordered groups. Recall from [Nil] that a pair $(G, P)$ consisting of a subsemigroup $P$ of a group $G$ is called quasi-lattice ordered if

\[(QL0) \quad P \cap P^{-1} = \{e\},\]

\[(QL1) \quad \text{for all } g \in G, \text{ the intersection } P \cap (g \cdot P) \text{ is either empty or of the form } pP \text{ for some } p \in P,\]
(QL2) for all \( p, q \) in \( P \), the intersection \( (pP) \cap (qP) \) is either empty or of the form \( rP \) for some \( r \in P \).

In the sequel, we will most of the time only use (QL1) and (QL2).

First of all, we observe that for every such \( P \subseteq G \) satisfying (QL2), we have \( J = \{ pP : p \in P \} \cup \{ \emptyset \} \). In this sense, the ideal structure (or rather the structure of the right constructible ideals) is very simple. It is immediate that \( J \) is independent. Moreover, \( P \subseteq G \) satisfies the Toeplitz condition (compare also [Ni1], § 2.4). Namely, take \( g \in G \). If \( E_P \lambda_g E_P \neq 0 \), then there exists \( p \in P \) such that \( P \cap (g \cdot P) = pP \) by (QL1). Thus there is \( q \in P \) with \( gq = p \), hence \( g = pq^{-1} \). It then follows that \( E_P \lambda_g E_P = E_{P \cap (g \cdot P)} \lambda_g \lambda^{-1} E_P = E_p \lambda_p \lambda_q^{-1} E_P = (E_P \lambda_p E_P) (E_P \lambda_q^{-1} E_P) = V_p V_q^* \).

Therefore, all our results apply.

As mentioned in the introduction, quasi-lattice ordered groups and their semigroup C*-algebras have been studied intensively, for instance in [Ni1], [Ni2], [La-Rae], [La1], [E-L-Q], [Cr-La1] and [Cr-La2]. The full semigroup C*-algebras have been described as semigroup crossed products by endomorphisms in [La-Rae]. Moreover, both full and reduced semigroup C*-algebras can be described as partial crossed products of the corresponding groups. This gives yet another description which is not discussed here, but which is certainly closely related to § 5. The induced ideals of reduced semigroup C*-algebras have been studied in [Ni1]. The \( \Theta_i \) we introduced in Corollary 6.4 can be viewed as a substitute for the positive definite functions \( \theta \) introduced in [Ni1], § 4.5. And the reader will see that for Proposition 7.3, we have essentially adapted A. Nica’s proof of the proposition in § 6.1 of [Ni1]. The boundary of the spectrum was introduced in [La1] and studied in [La1], [Cr-La2]. Our discussion of the boundary action in § 7.3 is modelled after [La1] and [Cr-La2].

Before we come to an explicit example, let us first show how the analysis in [La-Rae] can be extended. Namely, we obtain a strengthening of Proposition 6.6 in [La-Rae] with essentially the same proof as in [La-Rae]. We point out that the conclusion in this proposition should read “If \( G \) is amenable, then \( (G, P) \) is amenable” (compare also Remark 17 in [Cr-La1]). Let us start with the following

**Proposition 8.1** ([La-Rae], Lemma 4.1 for arbitrary coefficients). Let \( (G, P) \) and \( (H, Q) \) be quasi-lattice ordered. Assume that \( \varphi : G \to H \) is a group homomorphism such that \( \varphi(P) \subseteq Q \) and whenever \( x, y \) in \( P \) satisfy \( (xP) \cap (yP) \neq \emptyset \), then

\[
\varphi(x) = \varphi(y) \iff x = y, \tag{20}
\]

\[
\text{for } z \in P \text{ such that } (xP) \cap (yP) = zP, (\varphi(x)Q) \cap (\varphi(y)Q) = \varphi(z)Q. \tag{21}
\]

Moreover, let \( \alpha \) be a \( G \)-action on a C*-algebra \( A \).

Then \( B := \operatorname{span}\{ \iota(a)v_x v_y^* : a \in A; x, y \in P \text{ with } \varphi(x) = \varphi(y) \} \) is a sub-C*-algebra of \( A \rtimes_{\alpha, \varphi} P \) such that \( \lambda_{(A, P, \alpha)}|_B : B \to A \rtimes_{\alpha, \varphi} P \) is faithful.
Proof. Let $F \subseteq Q$ be a finite subset such that whenever $f_1$, $f_2$ in $F$ and $f_3$ in $Q$ satisfy $(f_1Q) \cap (f_2Q) = f_3Q$, then $f_3$ lies in $F$ as well. The set

$$\{ \iota(a)v_xv_y^* : a \in A; x, y \in P \text{ with } \varphi(x) = \varphi(y) \in F \}$$

is obviously $^*$-invariant. Moreover, given $\iota(a_1)v_{x_1}v_{y_1}^*$ and $\iota(a_2)v_{x_2}v_{y_2}^*$ from this set, let $(y_1P) \cap (x_2P) = zP$ with $z = y_1z_1 = y_2z_2$ for some $z_1, z_2$ in $P$. Then

$$\iota(a_1)v_{x_1}v_{y_1}^* \iota(a_2)v_{x_2}v_{y_2}^* = \iota(a_1\alpha_{x_1,y_1}^{-1}(a_2))v_{x_1}v_{y_1}^* v_{y_1}v_{y_1}^* v_{x_2}v_{x_2}^* v_{x_2}v_{y_2}^*$$

$$= \iota(a_1\alpha_{x_1,y_1}^{-1}(a_2))v_{x_1z_1}v_{y_2z_2}.$$  

Since $\varphi(x_1z_1) = \varphi(y_1z_1) = \varphi(z) = \varphi(x_2z_2) = \varphi(y_2z_2)$ lies in $F$ by (21), we have seen that (22) is multiplicatively closed. Hence

$$B_F := \text{span}\{ \iota(a)v_xv_y^* : a \in A; x, y \in P \text{ with } \varphi(x) = \varphi(y) \in F \}$$

is a sub-$C^*$-algebra of $A \rtimes_{\alpha,r}^a P$. As we can write $B = \bigcup_F B_F$, we see that $B$ is a sub-$C^*$-algebra of $A \rtimes_{\alpha,s}^a P$. Moreover, it suffices to prove faithfulness of $\lambda(A, \alpha, \rho)$ on $B_F$ for every $F$. Let us first take $F = \{ s \}$ and consider the representation $\lambda(A, \alpha, \rho)$ of $B_{\{ s \}}$ restricted to $\mathcal{H} \otimes \ell^2(P \cap \varphi^{-1}(\{ s \})) \subseteq \mathcal{H} \otimes \ell^2(P)$. Take $\iota(a)v_xv_y^* \in B_{\{ s \}}$. For $z \in \varphi^{-1}(\{ s \})$, either $z \notin yP$ which implies $a_{\alpha,\rho}(I_{\mathcal{H}} \otimes V_xV_y^*)(\xi \otimes \varepsilon_z) = 0$ for all $\xi \in \mathcal{H}$, or $z$ lies in $yP$. In the latter case, $(zP) \cap (yP) \neq \emptyset$ implies, since $\varphi(z) = \varphi(y) = s$ that $z = y$. Thus $a_{\alpha,\rho}(I_{\mathcal{H}} \otimes V_xV_y^*)(\xi \otimes \varepsilon_z) = \delta_{y,z}(\alpha_x^{-1}(a)\xi) \otimes \varepsilon_x$. This means that we have a commutative diagram

$$\begin{array}{ccc}
A \otimes_{\text{max}} K(\ell^2(P \cap \varphi^{-1}(\{ s \}))) & \longrightarrow & A \otimes_{\text{min}} K(\ell^2(P \cap \varphi^{-1}(\{ s \}))) \\
\downarrow & & \downarrow \subseteq \\
B_{\{ s \}} & \xrightarrow[\lambda(A, \alpha, \rho)]{\leftrightarrow} & \mathcal{L}(\mathcal{H} \otimes \ell^2(P \cap \varphi^{-1}(\{ s \})))
\end{array}$$

where the left vertical arrow sends $A \otimes_{\text{max}} K(\ell^2(P \cap \varphi^{-1}(\{ s \}))) \ni a \otimes e_{x,y}$ to $a_{\alpha,\rho}(v_xv_y^*) \in B_{\{ s \}}$. The upper horizontal arrow is the canonical homomorphism which is an isomorphism as the algebra of compact operators is nuclear. Thus $\lambda(A, \alpha, \rho)$ is faithful on $B_{\{ s \}}$.

To go from $B_{\{ s \}}$ to $B_F$, just proceed as in the proof of Lemma 4.1 in [La-Rae]. □

Corollary 8.2 (Proposition 6.6 of [La-Rae] revisited). Assume that under the hypothesis of the previous proposition, the group $H$ is amenable. Then for every $(A, G, \alpha)$ with $A$ unital, the canonical homomorphism $\lambda(A, \alpha, \rho) : A \rtimes_{\alpha,s}^a P \rightarrow A \rtimes_{\alpha,r}^a P$ is an isomorphism.

Proof. By [La-Rae], Proposition 6.1, we have a coaction $A \rtimes_{\alpha,s}^a P \rightarrow (A \rtimes_{\alpha,s}^a P) \otimes_{\text{max}} C^*(H)$ sending $\iota(a)v_x$ to $\iota(a)v_x \otimes u_{\varphi(x)}$. Here we used that $A \rtimes_{\alpha,s}^a P \cong A \rtimes_{\alpha,s}^a P$ (see [Li2], § 3.1) and the crossed product description of $A \rtimes_{\alpha,s}^a P$ from [Li2], Lemma 2.15. Thus, as explained in [La-Rae] after Definition 6.3, there exists a conditional expectation $\Psi_\delta : A \rtimes_{\alpha,s}^a P \rightarrow B$ sending $\iota(a)v_xv_y^*$ to $\delta_{\varphi(x),\varphi(y)}\iota(a)v_xv_y^*$. And by [La-Rae], Lemma 6.5, this conditional expectation $\Psi_\delta$ is faithful if $H$ is amenable. Now let $\varepsilon_{r}^{(A,\alpha,\rho)} : A \rtimes_{\alpha,r}^a P \rightarrow A \otimes D_r$ be the canonical faithful conditional expectation. Then
it is straightforward to see that \( \xi^r_{(A,P,\alpha)} \circ \lambda_{(A,P,\alpha)} = \xi^r_{(A,P,\alpha)} \circ (\lambda_{(A,P,\alpha)}(A)) \circ \Psi_\delta. \) As the right hand side is faithful by the previous proposition, \( \lambda_{(A,P,\alpha)} \) must be faithful. \( \square \)

Combining this with Theorem 6.1 (see also Remark 6.3), and using Proposition 19 of [Cr-La1], we obtain

**Corollary 8.3.** Let \((G,P)\) be a quasi-lattice ordered group which admits a map \( \varphi \) as in Proposition 8.1 such that \( H \) is amenable. Then \( C^*_\varphi(P) \) (\( \cong C^*_\varphi(P) \)) is nuclear.

In particular, if \((G,P)\) is the graph product of a family of quasi-lattice orders whose underlying groups are amenable, then \( C^*_\varphi(P) \) (\( \cong C^*_\varphi(P) \)) is nuclear.

### 8.2. Yet another description of Cuntz algebras

To give an explicit example, consider for \( n \geq 2 \) the semigroup \( \mathbb{N}_0^n \), the \( n \)-fold free product of the natural numbers. Let \( p_1, \ldots, p_n \) be the canonical generators of \( \mathbb{N}_0^n \). The semigroup \( \mathbb{N}_0^n \) sits inside the free group \( \mathbb{F}_n \) in a canonical way. This is an example of a quasi-lattice ordered group. It is due to [Ni1].

Let us now describe \( \Omega \) and \( \partial \Omega \). As \( \mathcal{F} = \{ p \mathbb{N}_0^n : p \in \mathbb{N}_0^n \} \cup \{ \emptyset \} \), \( \Omega \) can be identified with the set of all, finite or infinite, (reduced) words in the generators \( p_1, \ldots, p_n \).

Note that we do not allow inverses of the \( p_i \) in these words. The topology is the usual restricted product topology. Moreover, the boundary \( \partial \Omega \) is precisely the closed subset of all infinite words. \( \Omega \setminus (\partial \Omega) \) is then given by the open subset of all finite words. The semigroup \( \mathbb{N}_0^n \) acts by shifting from the left. The corresponding group action of \( \mathbb{F}_n \) is given as follows: \( \Omega \cdot \mathbb{F}_n \) is given by \( \mathbb{F}_n \cup (\partial \mathbb{F}_n) + \) where \( (\partial \mathbb{F}_n) + \) is the set of all infinite words which in reduced form only contain finitely many inverses of the generators \( p_1, \ldots, p_n \). The topology is obtained by restricting the canonical one from \( \mathbb{F}_n \cup (\partial \mathbb{F}_n) \). The free group \( \mathbb{F}_n \) acts by left translations. Moreover, the boundary \( (\partial \Omega) \cdot \mathbb{F}_n \) is given by \( (\partial \mathbb{F}_n) + \).

Let us now turn to the corresponding \( C^* \)-algebras. Since \( \mathbb{F}_n \) acts amenably on \( \Omega \cdot \mathbb{F}_n = \mathbb{F}_n \cup (\partial \mathbb{F}_n) + \) (this can be proven for instance as in [Br-Oz], Chapter 5, § 1), we do not have to distinguish between full and reduced versions. From the definition, it is clear that \( C^*(\mathbb{N}_0^n) \) is the universal \( C^* \)-algebra generated by \( n \) isometries \( v_1, \ldots, v_n \) whose range projections are orthogonal. Therefore \( C^*(\mathbb{N}_0^n) \) is nothing else but the canonical extension of the Cuntz algebra \( \mathcal{O}_n \). Moreover, it is not difficult to see that \( \text{Ind} \ V(\partial \Omega) = \langle V(\partial \Omega) \rangle \) is the ideal of \( C^*(\mathbb{N}_0^n) \) generated by the defect projection \( 1 - \sum_{i=1}^n v_i v_i^* \). Therefore the boundary quotient \( C^*(\mathbb{N}_0^n)/\langle V(\partial \Omega) \rangle \) is canonically isomorphic to \( \mathcal{O}_n \). Passing over to the group crossed products, we obtain

\[
C^*(\mathbb{N}_0^n) \sim_M C_0(\mathbb{F}_n \cup (\partial \mathbb{F}_n) +) \rtimes \mathbb{F}_n,
\]

\[
\langle V(\partial \Omega) \rangle \sim_M C_0(\mathbb{F}_n) \rtimes \mathbb{F}_n \cong \mathcal{K}(\ell^2(\mathbb{F}_n)),
\]

\[
C^*(\mathbb{N}_0^n)/\langle V(\partial \Omega) \rangle \sim_M C_0((\partial \mathbb{F}_n) +) \rtimes \mathbb{F}_n.
\]

The last line gives a description of \( \mathcal{O}_n \) as an ordinary group crossed product by \( \mathbb{F}_n \).

Moreover, the group \( G_0 \) from Proposition 7.20 is the trivial group in this particular case, and \( \mathbb{N}_0^n \) is not left reversible. Hence Corollary 7.23 says that \( C^*(\mathbb{N}_0^n)/\langle V(\partial \Omega) \rangle \)
is a (unital) UCT Kirchberg algebra. Of course, since we have already observed $C^*(\mathbb{N}_0^*)/\langle V(\partial \Omega) \rangle \cong \mathcal{O}_n$, this is not surprising. The point we would like to make is that we did not use anything we already knew about $\mathcal{O}_n$ to prove all this. So in a way, we have obtained an independent proof of the fact that $\mathcal{O}_n$ is a UCT Kirchberg algebra (though one has to admit that the proof of pure infiniteness in [La-Sp] is really just the original argument of J. Cuntz).

A similar analysis for the free product $\mathbb{N}_0^{*\infty}$ of countably infinitely many copies of the natural numbers yields that $C^*(\mathbb{N}_0^{*\infty}) \cong \mathcal{O}_{\infty}$ is a UCT Kirchberg algebra. In this case, the boundary is everything (i.e. $\Omega = \partial \Omega$) as observed in Remark 3.9 of [La1].

8.3. Left Ore semigroups. Another class of examples is given by left Ore semigroups. Recall that a semigroup $P$ is left Ore if and only if it can be embedded into a group $G$ such that $G = P^{-1}P$, $P \subseteq G$ always satisfies the Toeplitz condition. Namely, take $g \in G$ and write $g = p^{-1}q$ for $p, q \in P$. Then $E_P \lambda_q E_P = E_P \lambda_{p^{-1}} \lambda_q E_P = (E_P \lambda_{p^{-1}} E_P)(E_P \lambda_q E_P) = V^* p V q$. However, it is not clear whether $\mathcal{J}$ is always independent. So we have to assume this.

We remark that setting $\mathcal{J}' := \{ \cap_{i=1}^n p_i^1 P; n \in \mathbb{Z}_{\geq 1}, p_i \in P \} \cup \{ \emptyset \}$, we have $\mathcal{J} = \{ q^{-1} X; q \in P, X \in \mathcal{J}' \}$. Thus independence of $\mathcal{J}$ is equivalent to independence of $\mathcal{J}'$. Moreover, in the construction of full semigroup C*-algebras, it actually suffices to consider $\mathcal{J}'$ instead of $\mathcal{J}$. This is why in [Li1], only this smaller family $\mathcal{J}'$ of right ideals is considered.

Concrete examples of left Ore semigroups are for instance listed in [La2]. Let us briefly discuss the case of $ax + b$-semigroups. Given an integral domain $R$, we form the semidirect product $R \rtimes R^\times$, where $R^\times = R \setminus \{0\}$ acts on the additive group $(R, +)$ by left multiplication. This semigroup is left Ore and its enveloping group of left quotients is given by $Q(R) \rtimes Q(R)^\times$, where $Q(R)$ is the quotient field of $R$. In the case where $R$ is the ring of integers in a number field, the semigroup C*-algebra of $R \rtimes R^\times$ has been studied intensively in [C-D-L].

Let us now assume that $R \rtimes R^\times$ satisfies the condition that $\mathcal{J}$ is independent. We then observe that since $Q(R) \rtimes Q(R)^\times$ is solvable, the semigroup C*-algebra $C^*(R \rtimes R^\times)$ is nuclear, and full and reduced versions coincide. The boundary quotient of $C^*(R \rtimes R^\times)$ is canonically isomorphic to the ring C*-algebra $\mathfrak{R}[R]$ introduced in [Li1] (compare also [Sun1], [Sun2] for concrete examples). Moreover, in this case, the group $G_0$ from Proposition 7.20 is trivial and $R \rtimes R^\times$ is not left reversible if $R$ is not a field. Therefore, we can again apply Corollary 7.23 and deduce that the boundary quotient of $C^*(R \rtimes R^\times)$ is a UCT Kirchberg algebra. As this boundary quotient is nothing else but $\mathfrak{R}[R]$, we have reproven [Li1], Corollary 8 (for $\mathcal{F} = \emptyset$).
9. Open questions and future research

Of course, one obvious question is how restrictive our assumptions are. It would be interesting to see which semigroups have independent constructible right ideals, and when the Toeplitz condition is satisfied. Is there an intrinsic characterization in terms of the semigroup when a semigroup embeds into a group such that the Toeplitz condition holds? In this context, it would certainly be desirable to study more examples.

In this paper, we have only considered the case of subsemigroups of groups, and one might wonder what one can say about the general case of left cancellative semigroups. Recent work in [Nor] suggests that inverse semigroups might be useful.

Another question would be whether one could say more about dilation theory. Maybe the phenomenon that the left Ore condition is not really essential for embeddability as full corners into group crossed products occurs not only in our situation, but also in other ones. So it would be interesting to find out how general this phenomenon actually is.

One could also try to interpret our results in terms of geometric group theory: given a subsemigroup $P$ of a group $G$, what is the relationship between nuclearity of the semigroup $C^*$-algebra(s) of $P$ and exactness of $G$? Of course, it would be necessary to impose conditions on $P \subseteq G$. Otherwise, one could take the trivial subsemigroup, and the corresponding semigroup $C^*$-algebra is always nuclear. This just reflects the fact that every group acts amenably on itself. But if one asks for the condition that $P$ generates $G$, the problem of relating nuclearity of $C^*_r(P)$ and exactness of $G$ may become more interesting.

Our main result on nuclearity of semigroup $C^*$-algebras tells us that nuclearity implies faithfulness of the left regular representation. A natural question would be: What about the converse?

One could also study semigroup $C^*$-algebras and their ideals and quotients from the perspective of classification. An interesting question in this context would be which UCT Kirchberg algebras arise as the boundary quotients of semigroup $C^*$-algebras.

Finally, let us announce K-theoretic applications. Namely, J. Cuntz, S. Echterhoff and the author are planning to discuss in a forthcoming paper how the results of this present paper can be used to generalize the K-theoretic computations from [C-E-L] to a much larger class of semigroups.

References


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