

SEMICROSSED PRODUCTS OF THE DISK ALGEBRA

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ABSTRACT. If α is the endomorphism of the disk algebra, $A(\mathbb{D})$, induced by composition with a finite Blaschke product b , then the semicrossed product $A(\mathbb{D}) \times_{\alpha} \mathbb{Z}^+$ imbeds canonically, completely isometrically into $C(\mathbb{T}) \times_{\alpha} \mathbb{Z}^+$. Hence in the case of a non-constant Blaschke product b , the C^* -envelope has the form $C(\mathcal{S}_b) \times_s \mathbb{Z}$, where (\mathcal{S}_b, s) is the solenoid system for (\mathbb{T}, b) . In the case where b is a constant, the C^* -envelope of $A(\mathbb{D}) \times_{\alpha} \mathbb{Z}^+$ is strongly Morita equivalent to a crossed product of the form $C_0(\mathcal{S}_e) \times_s \mathbb{Z}$, where $e: \mathbb{T} \times \mathbb{N} \rightarrow \mathbb{T} \times \mathbb{N}$ is a suitable map and (\mathcal{S}_e, s) is the solenoid system for $(\mathbb{T} \times \mathbb{N}, e)$.

1. INTRODUCTION

If \mathcal{A} is a unital operator algebra and α is a completely contractive endomorphism, the semicrossed product is an operator algebra $\mathcal{A} \times_{\alpha} \mathbb{Z}_+$ which encodes the covariant representations of (\mathcal{A}, α) : namely completely contractive unital representations $\rho: \mathcal{A} \rightarrow \mathcal{B}(\mathcal{H})$ and contractions T satisfying

$$\rho(a)T = T\rho(\alpha(a)) \quad \text{for all } a \in \mathcal{A}.$$

Such algebras were defined by Peters [9] when \mathcal{A} is a C^* -algebra.

One can readily extend Peter's definition [9] of the semicrossed product of a C^* -algebra by a $*$ -endomorphism to unital operator algebras and unital completely contractive endomorphisms. One forms the *polynomial algebra* $\mathcal{P}(\mathcal{A}, \mathfrak{t})$ of formal polynomials of the form $p = \sum_{i=0}^n \mathfrak{t}^i a_i$, where $a_i \in \mathcal{A}$, with multiplication determined by the covariance relation $at = \mathfrak{t}\alpha(a)$ and the norm

$$\|p\| = \sup_{(\rho, T) \text{ covariant}} \left\| \sum_{i=0}^n T^i \rho(a_i) \right\|.$$

This supremum is clearly dominated by $\sum_{i=0}^n \|a_i\|$; so this norm is well defined. The completion is the semicrossed product $\mathcal{A} \times_{\alpha} \mathbb{Z}_+$. Since this is the supremum of operator algebra norms, it is also an operator algebra norm. By construction, for each covariant representation (ρ, T) , there is a unique completely contractive

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representation $\rho \times T$ of $\mathcal{A} \times_{\alpha} \mathbb{Z}_+$ into $\mathcal{B}(\mathcal{H})$ given by

$$\rho \times T(p) = \sum_{i=0}^n T^i \rho(a_i).$$

This is the defining property of the semicrossed product.

In this paper, we examine semicrossed products of the disk algebra by an endomorphism which extends to a $*$ -endomorphism of $C(\mathbb{T})$. In the case where the endomorphism is injective, these have the form $\alpha(f) = f \circ b$ where b is a non-constant Blaschke product. We show that every covariant representation of $(A(\mathbb{D}), \alpha)$ dilates to a covariant representation of $(C(\mathbb{T}), \alpha)$. This is readily dilated to a covariant representation (σ, V) , where σ is a $*$ -representation of $C(\mathbb{T})$ (so $\sigma(z)$ is unitary) and V is an isometry. To go further, we use the recent work of Kakariadis and Katsoulis [6] to show that $C(\mathbb{T}) \times_{\alpha} \mathbb{Z}^+$ imbeds completely isometrically into a C^* -crossed product $C(\mathcal{S}_b) \times_{\alpha} \mathbb{Z}$. In fact,

$$C_e^*(C(\mathbb{T}) \times_{\alpha} \mathbb{Z}^+) = C(\mathcal{S}_b) \times_{\alpha} \mathbb{Z},$$

and as a consequence, we obtain that (ρ, T) dilates to a covariant representation (τ, W) , where τ is a $*$ -representation of $C(\mathbb{T})$ (so $\sigma(z)$ is unitary) and W is a unitary.

In contrast, if α is induced by a constant Blaschke product, we can no longer identify $C_e^*(C(\mathbb{T}) \times_{\alpha} \mathbb{Z}^+)$ up to isomorphism. In that case, α is evaluation at a boundary point. Even though every covariant representation of $(A(\mathbb{D}), \alpha)$ dilates to a covariant representation of $(C(\mathbb{T}), \alpha)$, the theory of [6] is not directly applicable since α is not injective. Instead, we use the process of “adding tails to C^* -correspondences” [8], as modified in [3, 7], and we identify $C_e^*(C(\mathbb{T}) \times_{\alpha} \mathbb{Z}^+)$ up to strong Morita equivalence as a crossed product. In Theorem 2.6 we show that $C_e^*(C(\mathbb{T}) \times_{\alpha} \mathbb{Z}^+)$ is strongly Morita equivalent to a C^* -algebra of the form $C_0(\mathcal{S}_e) \times_s \mathbb{Z}$, where

$$e: \mathbb{T} \times \mathbb{N} \longrightarrow \mathbb{T} \times \mathbb{N}$$

is a suitable map and (\mathcal{S}_e, s) is the solenoid system for $(\mathbb{T} \times \mathbb{N}, e)$.

Semicrossed products of the the disc algebra were introduced and first studied by Buske and Peters in [1], following relevant work of Hoover, Peters and Wogen [5]. The algebras $A(\mathbb{D}) \times_{\alpha} \mathbb{Z}^+$, where α is an arbitrary endomorphism, were classified up to algebraic endomorphism in [2]. Results associated with their C^* -envelope can be found in [1, Proposition III.13] and [10, Theorem 2]. The results of the present paper subsume and extend these earlier results.

2. THE DISK ALGEBRA

The C^* -envelope of the disk algebra $A(\mathbb{D})$ is $C(\mathbb{T})$, the space of continuous functions on the unit circle. Suppose that α is an endomorphism of $C(\mathbb{T})$ which leaves $A(\mathbb{D})$ invariant. We refer to the restriction of α to $A(\mathbb{D})$ as α as well. Then $b = \alpha(z) \in A(\mathbb{D})$ and has spectrum

$$\sigma_{A(\mathbb{D})}(b) \subset \sigma_{A(\mathbb{D})}(z) = \overline{\mathbb{D}}$$

and

$$\sigma_{C(\mathbb{T})}(b) \subset \sigma_{C(\mathbb{T})}(z) = \mathbb{T}.$$

Thus $\|b\| = 1$ and $b(\mathbb{T}) \subset \mathbb{T}$. It follows that b is a finite Blaschke product. Therefore $\alpha(f) = f \circ b$ for all $f \in C(\mathbb{T})$. When b is not constant, α is completely isometric.

A (completely) contractive representation ρ of $A(\mathbb{D})$ is determined by $\rho(z) = A$, which must be a contraction. The converse follows from the matrix von Neumann

inequality and shows that $\rho(f) = f(A)$ is a complete contraction. A covariant representation of $(A(\mathbb{D}), \alpha)$ is thus determined by a pair of contractions (A, T) such that

$$AT = Tb(A).$$

The representation of $A(\mathbb{D}) \times_\alpha \mathbb{Z}^+$ is given by

$$\rho \times T \left(\sum_{i=0}^n t^i f_i \right) = \sum_{i=0}^n T^i f_i(A),$$

which extends to a completely contractive representation of the semicrossed product by the universal property.

A contractive representation σ of $C(\mathbb{T})$ is a $*$ -representation and is likewise determined by $U = \sigma(z)$, which must be unitary, and all unitary operators yield such a representation by the functional calculus. A covariant representation of $(C(\mathbb{T}), \alpha)$ is given by a pair (U, T) where U is unitary and T is a contraction satisfying $UT = Tb(U)$. To see this, multiply on the left by U^* and on the right by $b(U)^*$ to obtain the identity

$$U^*T = Tb(U)^* = T\bar{b}(U) = T\alpha(\bar{z})(U).$$

The set of functions $\{f \in C(\mathbb{T}) : f(U)T = T\alpha(f)(U)\}$ is easily seen to be a norm closed algebra. Since it contains z and \bar{z} , it is all of $C(\mathbb{T})$. So the covariance relation holds.

Theorem 2.1. *Let b be a finite Blaschke product, and let $\alpha(f) = f \circ b$. Then $A(\mathbb{D}) \times_\alpha \mathbb{Z}^+$ is (canonically completely isometrically isomorphic to) a subalgebra of $C(\mathbb{T}) \times_\alpha \mathbb{Z}^+$.*

Proof. To establish that $A(\mathbb{D}) \times_\alpha \mathbb{Z}^+$ is completely isometric to a subalgebra of $C(\mathbb{T}) \times_\alpha \mathbb{Z}^+$, it suffices to show that each (A, T) with $AT = Tb(A)$ has a dilation to a pair (U, S) with U unitary and S a contraction such that

$$US = Sb(U) \quad \text{and} \quad P_{\mathcal{H}}S^nU^m|_{\mathcal{H}} = T^nA^m \quad \text{for all } m, n \geq 0.$$

This latter condition is equivalent to \mathcal{H} being semi-invariant for the algebra generated by U and S .

The covariance relation can be restated as

$$\begin{bmatrix} A & 0 \\ 0 & b(A) \end{bmatrix} \begin{bmatrix} 0 & T \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & T \\ 0 & 0 \end{bmatrix} \begin{bmatrix} A & 0 \\ 0 & b(A) \end{bmatrix}.$$

Dilate A to a unitary U which leaves \mathcal{H} semi-invariant. Then $\begin{bmatrix} A & 0 \\ 0 & b(A) \end{bmatrix}$ dilates to $\begin{bmatrix} U & 0 \\ 0 & b(U) \end{bmatrix}$. By the Sz. Nagy-Foiaş Commutant Lifting Theorem, we may dilate $\begin{bmatrix} 0 & T \\ 0 & 0 \end{bmatrix}$ to a contraction of the form $\begin{bmatrix} * & S \\ * & * \end{bmatrix}$ which commutes with $\begin{bmatrix} U & 0 \\ 0 & \alpha(U) \end{bmatrix}$ and has $\mathcal{H} \oplus \mathcal{H}$ as a common semi-invariant subspace. Clearly, we may take the $*$ entries to all equal 0 without changing things. So (U, S) satisfies the same covariance relations $US = Sb(U)$. Therefore we have obtained a dilation to the covariance relations for $(C(\mathbb{T}), \alpha)$. □

Once we have a covariance relation for $(C(\mathbb{T}), \alpha)$, we can try to dilate further. Extending S to an isometry V follows a well-known path. Observe that

$$b(U)S^*S = S^*US = S^*Sb(U).$$

Thus $D = (I - S^*S)^{1/2}$ commutes with $b(U)$. Write $b^{(n)}$ for the composition of b with itself n times. Hence we can now use the standard Schaeffer dilation of S to an isometry V and simultaneously dilate U to U_1 as follows:

$$V = \begin{bmatrix} S & 0 & 0 & 0 & \dots \\ D & 0 & 0 & 0 & \dots \\ 0 & I & 0 & 0 & \dots \\ 0 & 0 & I & 0 & \dots \\ \vdots & \vdots & \vdots & \ddots & \ddots \end{bmatrix} \text{ and } U_1 = \begin{bmatrix} U & 0 & 0 & 0 & \dots \\ 0 & b(U_1) & 0 & 0 & \dots \\ 0 & 0 & b^{(2)}(U_1) & 0 & \dots \\ 0 & 0 & 0 & b^{(3)}(U_1) & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}.$$

A simple calculation shows that $U_1V = Vb(U_1)$. So as above, (U, V) satisfies the covariance relations for $(C(\mathbb{T}), \alpha)$.

We would like to make V a unitary as well. This is possible in the case where b is non-constant but the explicit construction is not obvious. Instead, we use the theory of C^* -envelopes and maximal dilations. First we need the following.

Lemma 2.2. *Let b be a finite Blaschke product, and let $\alpha(f) = f \circ b$. Then*

$$C_e^*(A(\mathbb{D}) \times_\alpha \mathbb{Z}^+) \simeq C_e^*(C(\mathbb{T}) \times_\alpha \mathbb{Z}^+).$$

Proof. The previous theorem identifies $A(\mathbb{D}) \times_\alpha \mathbb{Z}^+$ completely isometrically as a subalgebra of $C(\mathbb{T}) \times_\alpha \mathbb{Z}^+$. The C^* -envelope \mathcal{C} of $C(\mathbb{T}) \times_\alpha \mathbb{Z}^+$ is a Cuntz-Pimsner algebra containing a copy of $C(\mathbb{T})$ which is invariant under gauge actions. Now \mathcal{C} is a C^* -cover of $C(\mathbb{T}) \times_\alpha \mathbb{Z}^+$, so it is easy to see that it is also a C^* -cover of $A(\mathbb{D}) \times_\alpha \mathbb{Z}^+$. Since $A(\mathbb{D}) \times_\alpha \mathbb{Z}^+$ is invariant under the same gauge actions, its Shilov ideal $\mathcal{J} \subseteq \mathcal{C}$ will be invariant by these actions as well. If $\mathcal{J} \neq 0$, then by gauge invariance $\mathcal{J} \cap C(\mathbb{T}) \neq 0$. Since the quotient map

$$A(\mathbb{D}) \longrightarrow C(\mathbb{T})/(\mathcal{J} \cap C(\mathbb{T}))$$

is completely isometric, we obtain a contradiction. Hence $\mathcal{J} = 0$ and the conclusion follows. □

We now recall some of the theory of semicrossed products of C^* -algebras. When \mathfrak{A} is a C^* -algebra, the completely isometric endomorphisms are the faithful $*$ -endomorphisms. In this case, Peters shows [9, Prop. I.8] that there is a unique C^* -algebra \mathfrak{B} , a $*$ -automorphism β of \mathfrak{B} and an injection j of \mathfrak{A} into \mathfrak{B} so that $\beta \circ j = j\alpha$ and \mathfrak{B} is the closure of $\bigcup_{n \geq 0} \beta^{-n}(j(\mathfrak{A}))$. It follows [9, Prop. II.4] that $\mathfrak{A} \times_\alpha \mathbb{Z}_+$ is completely isometrically isomorphic to the subalgebra of the crossed product algebra $\mathfrak{B} \times_\beta \mathbb{Z}$ generated as a non-selfadjoint algebra by an isomorphic copy $j(\mathfrak{A})$ of \mathfrak{A} and the unitary u implementing β in the crossed product. Actually, Kakariadis and the second author [6, Thm. 2.5] show that $\mathfrak{B} \times_\beta \mathbb{Z}$ is the C^* -envelope of $\mathfrak{A} \times_\alpha \mathbb{Z}_+$. This last result is valid for semicrossed products of not necessarily unital C^* -algebras by (non-degenerate) injective $*$ -endomorphisms, and we will use it below in that form.

In the case where $\mathfrak{A} = C_0(X)$ is commutative and α is induced by an injective self-map of X , the pair (\mathfrak{B}, β) has an alternative description.

Definition 2.3. Let X be a topological space and ϕ a surjective self-map of X . We define the *solenoid system* of (X, ϕ) to be the pair (\mathcal{S}_ϕ, s) , where

$$\mathcal{S}_\phi = \{(x_n)_{n \geq 1} : x_n = \phi(x_{n+1}), x_n \in X, n \geq 1\}$$

equipped with the relative topology inherited from the product topology on $\prod_{i=1}^\infty X_i$, $X_i = X$, $i = 1, 2, \dots$, and s is the backward shift on \mathcal{S}_ϕ .

It is easy to see that if $\mathfrak{A} = C_0(X)$, with X a locally compact Hausdorff space, and α is induced by a surjective self-map ϕ of X , then the pair (\mathfrak{B}, β) for (\mathfrak{A}, α) described above is conjugate to the solenoid system (\mathcal{S}_ϕ, s) . Therefore, we obtain

Corollary 2.4. *Let b be a non-constant finite Blaschke product, and let $\alpha(f) = f \circ b$ on $C(\mathbb{T})$. Then*

$$C_e^*(A(\mathbb{D}) \times_\alpha \mathbb{Z}^+) = C(\mathcal{S}_b) \times_s \mathbb{Z},$$

where (\mathcal{S}_b, s) is the solenoid system of (\mathbb{T}, b) .

The above corollary leads to a dilation result, for which a direct proof is far from obvious.

Corollary 2.5. *Let α be an endomorphism of $A(\mathbb{D})$ induced by a non-constant finite Blaschke product and let $A, T \in \mathcal{B}(\mathcal{H})$ be contractions satisfying*

$$AT = T\alpha(A).$$

Then there exist unitary operators U and W on a Hilbert space $\mathcal{K} \supset \mathcal{H}$ which simultaneously dilate A and T , in the sense that

$$P_{\mathcal{H}}W^mU^n|_{\mathcal{H}} = T^mA^n \quad \text{for all } m, n \geq 0,$$

so that

$$UW = W\alpha(U).$$

Proof. Every covariant representation (A, T) of $(A(\mathbb{D}), \alpha)$ dilates to a covariant representation (U_1, V) of $(C(\mathbb{T}), \alpha)$. This in turn dilates to a maximal dilation τ of $C(\mathbb{T}) \times_\alpha \mathbb{Z}^+$, in the sense of Dritschel and McCullough [4]. The maximal dilations extend to $*$ -representations of the C^* -envelope. Then A dilated to $\tau(j(z)) = U$ is unitary and T dilates to the unitary W which implements the automorphism β on \mathfrak{B} and restricts to the action of α on $C(\mathbb{T})$. \square

The situation changes when we move to *non-injective* endomorphisms α of $A(\mathbb{D})$. Indeed, let $\lambda \in \mathbb{T}$ and consider the endomorphism α_λ of $A(\mathbb{D})$ induced by evaluation on λ , i.e.,

$$\alpha_\lambda(f)(z) = f(\lambda) \quad \text{for all } z \in \mathbb{D}.$$

(Thus α_λ is the endomorphism of $A(\mathbb{D})$ corresponding to a constant Blaschke product.) If two contractions A, T satisfy

$$AT = T\alpha_\lambda(A) = \lambda T,$$

then the existence of unitary operators U, W , dilating A and T respectively, implies that $A = \lambda I$. It is easy to construct a pair A, T satisfying $AT = \lambda T$ and yet $A \neq \lambda I$. This shows that the analogue Corollary 2.5 fails for $\alpha = \alpha_\lambda$ and therefore one does not expect $C_e^*(A(\mathbb{D}) \times_{\alpha_\lambda} \mathbb{Z}^+)$ to be isomorphic to the crossed product of a commutative C^* -algebra, at least under canonical identifications. However, as we have seen, a weakening of Corollary 2.5 is valid for $\alpha = \alpha_\lambda$ if one allows W to be an isometry instead of a unitary operator. In addition, we can identify $C_e^*(A(\mathbb{D}) \times_\alpha \mathbb{Z}^+)$ as being *strongly Morita equivalent* to a crossed product C^* -algebra. Indeed, if

$$e: \mathbb{T} \times \mathbb{N} \longrightarrow \mathbb{T} \times \mathbb{N}$$

is defined as

$$e(z, n) = \begin{cases} (1, 1) & \text{if } n = 1, \\ (z, n - 1) & \text{otherwise,} \end{cases}$$

then

Theorem 2.6. *Let $\alpha = \alpha_\lambda$ be an endomorphism of $A(\mathbb{D})$ induced by evaluation at a point $\lambda \in \mathbb{T}$. Then $C_e^*(A(\mathbb{D}) \times_\alpha \mathbb{Z}^+)$ is strongly Morita equivalent to $C_0(\mathcal{S}_e) \times_s \mathbb{Z}$, where $e: \mathbb{T} \times \mathbb{N} \rightarrow \mathbb{T} \times \mathbb{N}$ is defined above and (\mathcal{S}_e, s) is the solenoid system of $(\mathbb{T} \times \mathbb{N}, e)$.*

Proof. In light of Lemma 2.2, it suffices to identify the C^* -envelope of $C(\mathbb{T}) \times_\alpha \mathbb{Z}^+$. As α is no longer an injective endomorphism of $C(\mathbb{T})$, we invoke the process of adding tails to C^* -correspondences [8], as modified in [3, 7].

Indeed, [7, Example 4.3] implies that the C^* -envelope of the tensor algebra associated with the dynamical system $(C(\mathbb{T}), \alpha)$ is strongly Morita equivalent to the Cuntz-Pimsner algebra associated with the injective dynamical system $(\mathbb{T} \times \mathbb{N}, e)$ defined above. Therefore by invoking the solenoid system of $(\mathbb{T} \times \mathbb{N}, e)$, the conclusion follows from the discussion following Lemma 2.2. \square

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