ON WHEN A GRADED RING IS GRADED EQUIVALENT TO A CROSSED PRODUCT

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Abstract. Let \( R \) be a ring graded by a group \( G \). We are concerned with describing those \( G \)-graded rings that are graded equivalent to \( G \)-crossed products. We give necessary and sufficient conditions for when a strongly graded ring is graded equivalent to a crossed product, provided that the 1-component is either Azumaya or semiperfect. Our result uses the torsion product theorem of Bass and Guralnick. We also construct various examples of such rings.

1. Introduction

In this paper, all rings have an identity element. Let \( R \) and \( S \) be rings graded by a group \( G \). Following [12], [16], [13], and [14], we say that \( R \) and \( S \) are graded equivalent provided there is a graded \( R \)-module \( P \) such that \( P \) is an \( R \)-progenerator and \( \text{End}_R(P) \cong S \) as graded rings. This paper considers the following problem:

Describe those \( G \)-graded rings that are graded equivalent to \( G \)-crossed products.

The significance of working with a \( G \)-graded ring that is graded equivalent to a \( G \)-crossed product is that graded equivalence, in a certain sense, “preserves” the categorical structure of the crossed product. For example, if \( R \) is strongly \( G \)-graded and graded equivalent to a \( G \)-crossed product \( S \), then not only are the categories \( R\text{-mod} \) and \( S\text{-mod} \) equivalent, but so are the categories \( R_H\text{-mod} \) and \( S_H\text{-mod} \) for each subgroup \( H \) of \( G \). \( \text{End}_R(P) \) denotes the truncation of \( R \) at the subgroup \( H \). See [14].

The Cohen-Montgomery duality theory is an important application of how problems about graded rings can be reduced to problems about crossed products via graded equivalence. Briefly, if \( R \) is a ring graded by a finite group \( G \), Cohen and Montgomery construct a ring \( R \# G \) (the smash product of \( R \) by \( G \)) in such a way that \( G \) acts as automorphisms on \( R \# G \). If \( P = \coprod_{g \in G} R(g) \), where \( R(g) = R \) as \( R \)-modules but is graded via \( R(g)_{h} = R_{gh} \), then \( P \) is a graded \( R \)-module and an \( R \)-progenerator such that \( \text{End}_R(P) \) and the skew group ring \( (R \# G) \ast G \) are isomorphic as graded rings ([18]). Consequently, if \( G \) is finite, a \( G \)-graded ring \( R \) is always graded equivalent to the skew group ring \( (R \# G) \ast G \). On the other hand, if \( G \) is infinite, then \( R \) may not be graded equivalent to a crossed product ([15]). In light of this, the problem posed above may be rephrased as describing those
G-graded rings that are graded equivalent to G-crossed products, when the group

Since Menini and Năstăsescu have determined when a G-graded ring is graded
equivalent to a G-strongly graded ring ([16, Theorem 2.2]), and since any crossed
product is strongly graded, we assume, for the remainder of this paper, that R
is strongly graded. We show, in Theorem 3, that any G-strongly graded ring R
such that the 1-component is semiperfect is graded equivalent to a crossed product.
Our main result, however, is Theorem 10, which provides necessary and sufficient
conditions for when a strongly graded ring is graded equivalent to a crossed product,
whenever the 1-component is commutative, Noetherian with Krull dimension d. We
extend this result, in Corollary 14, by requiring only that the 1-component be an
Azumaya algebra. To illustrate these theorems, we provide various examples in §5.

As a last introductory remark, if we were to consider rings without identity
elements and appropriately alter the definition of graded equivalence, then every
G-graded ring R is graded equivalent to a skew group ring $T \ast G$, where T need not
have an identity element. See [6], [18], [13], and [14]. In contrast, our requirement
for this paper is to work only with rings with identity.

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2. Definitions and preliminaries

Throughout this paper, all 1-sided modules are left modules and we write mod-
ule homomorphisms on the right. Ring and group homomorphisms, however, are
written on the left.

**Definition 1.** If T is any ring, let $T^\bullet$ denote the units of T, Pic($T$) denote the
set of isomorphism classes of invertible T-bimodules and Picent($T$) denote the set
of isomorphism classes of invertible bimodules that are centralized by the center
of T. Following [11], let Pic$_n$(T) denote the isomorphism classes of invertible T-
bimodules $P$ for which there is a left isomorphism $P^{(n)} \cong T^{(n)}$. (In this paper, the
notation $X^{(n)}$ refers to the direct sum of n copies of X.) Analogously, we define
Picent$_n$(T).

For any T-bimodule X and for any $\sigma \in \text{Aut}(T)$, we define a new bimodule $1(X)_\sigma$.
As a left module, $1(X)_\sigma = X$, while the right T-action is given by $x \cdot t = x\sigma(t)$.
In particular, this definition induces a group homomorphism $\omega : \text{Aut}(T) \to \text{Pic}(T)$
which is defined via $\omega : \sigma \mapsto 1(T)_\sigma$. See [8, Theorem 55.11] for further details.

Finally, R denotes a strongly G-graded ring, which we write as $R = \bigoplus_{g \in G} R_g$.
Recall that a crossed product is a G-graded ring R such that each component $R_g$
contains a unit $u_g$ of the ring R ([17, Example 2, p. 18]), a skew group ring is a
G-crossed product such that the set of units $\{u_g | g \in G\}$ forms a group and is
isomorphic to G, and a twisted group ring R is a crossed product ring such that
each component contains a unit of R that commutes with $R_1$. Since R is strongly
graded, we define the component group of R, Comp(R), to be the subgroup of
Pic($R_1$) consisting of the bimodule isomorphism classes of the components $R_g$ of
R.

**Lemma 2.** Let R be G-strongly graded.

1. $R_g \cong R_1$ as left modules $\iff$ $R_g$ contains a unit of R $\iff$ $1(R_1)_\theta$ (as
$R_1$-bimodules) for some $\theta \in \text{Aut}(R_1)$ $\iff$ $R_g \in \text{im} \omega$. 

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(2) $R$ is a crossed product $\iff$ $\text{Comp}(R) \subset \text{im} \omega \iff$ there exists a map $\Theta : G \to R^*$ such that $R_g = R_1 \cdot \Theta(g) = \Theta(g) \cdot R_1 \iff$ there exists a map $\Delta : G \to \text{Aut}(R_1)$ such that $R_g \cong \text{im}(R_1)_{\Delta(g)}$ as bimodules.

(3) $R$ is a twisted group ring $\iff$ $\text{Comp}(R) = 1$ (as a subgroup of $\text{Pic}(R_1)$) $\iff$ there exists a map $\Theta : G \to R^*$ such that $R_g = R_1 \cdot \Theta(g)$ and $\Theta(g)$ commutes with the elements of $R_1$.

(4) $R$ is a skew group ring $\iff$ there exists a group homomorphism $\Theta : G \to R^*$ such that $R_g = R_1 \cdot \Theta(g) = \Theta(g) \cdot R_1 \iff$ there exists a group homomorphism $\Delta : G \to \text{Aut}(R_1)$ such that $R_g \cong \text{im}(R_1)_{\Delta(g)}$ as bimodules.

(5) (Dade) $R$ is graded equivalent to a crossed product $\iff$ there is a progenerator $P$ of $\text{mod}(R_1)$ such that $P$ is ‘fixed’ under the tensor action of $\text{Comp}(R)$ (i.e., $R_g \otimes P \cong P$ for every $g \in G$).

Proof. (1) This is a special case of [8, Theorem 55.12].

(2) $R$ is a crossed product if and only if each component $R_g$ contains a unit $u_g$ of $R$. Now apply (1).

(3) $R$ is a twisted group ring if and only if each component $R_g$ contains a unit $u_g$ of $R$ and $u_g$ commutes with the elements of $R_1$. Thus, $R$ is a twisted group ring $\iff$ each $R_g \cong R_1$ as bimodules $\iff$ $\text{Comp}(R) = 1$.

(4) $R$ is a skew group ring if and only if each component $R_g$ contains a unit $u_g$ of $R$ and the set of these units $\{u_g|g \in G\}$ forms a group isomorphic to $G$.

(5) This is [9, Corollary 5.14].

The above lemma affords us an opportunity to solve the problem posed in the Introduction when $R_1$ is semiperfect.

**Theorem 3** (The semiperfect case). If $R$ is a $G$-strongly graded ring such that $R_1$ is semiperfect, then $R$ is graded equivalent to a $G$-crossed product $S$. Moreover, $S_1$ is the basic ring of $R_1$.

Proof. Set $T = R_1$. Using [2, Proposition 27.10], there exists a set $\{e_1, \ldots, e_m\}$ of pairwise orthogonal idempotents such that $Te_1, \ldots, Te_m$ is a complete irredundant set of representatives of the primitive left $T$-modules. In particular, if $X$ is a projective, indecomposable, left $T$-module, then $X \cong Te_i$ for some $i$. Set $Q = \bigoplus_{i=1}^m Te_i$. Then $Q$ is a left $T$-progenerator. If $P \in \text{Pic}(T)$, then $P \otimes Te_i$ is a projective indecomposable since $P^{-1} \otimes (P \otimes Te_i) \cong Te_i$. Moreover, $P \otimes Te_i \cong P \otimes Te_j \iff i = j$. Consequently, $P \otimes Q \cong \bigoplus_{i=1}^m (P \otimes Te_i) \cong \bigoplus_{i=1}^m Te_i = Q$. In particular, $R_g \otimes Q \cong Q$ for every $g \in G$. Thus, by Lemma 2(5), $R$ is graded equivalent to a crossed product $S = \text{End}_R(R \otimes Q)$ where $S_1 = \text{End}_T(Q)$. It follows that $S_g \cong \text{Hom}_T(Q, R_g \otimes Q)$. 

3. **Matrix rings**

We begin this section with an important but easy example of graded equivalence.

**Example 4** ($R$ and $M_n(R)$ are graded equivalent). Let $R$ be any $G$-graded ring. For any positive integer $n$, $M_n(R)$ is also $G$-graded with the grading defined by $M_n(R)_{ij} = M_n(R_{ij})$. If $P$ is the free $R$-module of rank $n$ with the induced grading, it follows that $P$ is a graded, $R$-progenerator such that $\text{End}_R(P) \cong M_n(R)$. Thus, $R$ and $M_n(R)$ are $G$-graded equivalent.
Using the above example and Lemma 2, we can now prove the following key proposition that characterizes when a strongly graded ring $R$ is graded equivalent to a crossed product of the form $M_n(R)$.

**Theorem 5.** The following statements are equivalent:

1. There is a positive integer $n$ such that $R$ is graded equivalent to a crossed product of the form $M_n(R)$, which is graded via $M_n(R)_g = M_n(R_g)$.
2. $\text{Comp}(R) \subset \text{Pic}_n(R_1)$ for some positive integer $n$.
3. There exists a positive integer $n$ such that, for each $g \in G$, there exists an isomorphism $\mu_g : R_1^{(n)} \to R_g^{(n)}$ as left modules.
4. There exist a positive integer $n$ and a function $\Theta : G \to (M_n(R))^\bullet$ such that $M_n(R_g) = M_n(R_1) \cdot \Theta(g) = \Theta(g) \cdot M_n(R_1)$.
5. There exist a positive integer $n$ and a function $\Delta : G \to \text{Aut}(M_n(R_1))$ such that $M_n(R_g) \cong (M_n(R_1))_{\Delta(g)}$ as bimodules.

Proof. First observe that statements (1), (4), and (5) are equivalent by Lemma 2 and Example 4. Statements (2) and (3) are equivalent by Definition 1. It suffices to show that (2) and (4) are equivalent.

$(2) \Rightarrow (4)$ Since $\text{Comp}(R) \subset \text{Pic}_n(R_1)$, there is, for each $g \in G$, a left module isomorphism $\Theta(g) : R_1^{(n)} \to R_g^{(n)}$. If we identify $\text{Hom}_{R_1}(R_1, R_g)$ with $R_g$, we may identify $\Theta(g)$ as an element of $M_n(R_g)$. We have that $M_n(R_1) \cdot \Theta(g) \subset M_n(R_g)$ and $M_n(R_g) \cdot \Theta(g)^{-1} \subset M_n(R_1)$, which yields $M_n(R_1) \cdot \Theta(g) = M_n(R_g)$. Thus, (4) holds by Lemma 2.

$(4) \Rightarrow (2)$ Since $M_n(R_g) = M_n(R_1) \Theta(g)$, $M_n(R_g) \subset \text{Pic}_n(M_n(R_1))$ by Lemma 2. But, by [10, Lemma 3.1], $\text{Pic}_1(M_n(R_1)) \cong \text{Pic}_n(R_1)$ via the mapping $M_n(X) \mapsto X$. It follows that $R_g \in \text{Pic}_n(R_1)$ and so $\text{Comp}(R) \subset \text{Pic}_n(R_1)$.

The set of units $\{\Theta(g) | g \in G\}$ in $M_n(R)$ that appear in the proof of Theorem 5 need not be a group under multiplication; this precisely is the obstruction preventing $M_n(R)$ from being a skew group ring.

**Theorem 6.** The following statements are equivalent:

1. There is a positive integer $n$ such that $R$ is graded equivalent to a skew group ring $M_n(R)$ with grading $M_n(R) = \bigoplus_{g \in G} M_n(R_g)$.
2. $\text{Comp}(R) \subset \text{Pic}_n(R_1)$ for some positive integer $n$ and the map $\Theta : G \to M_n(R)$ is a group homomorphism.
3. $\text{Comp}(R) \subset \text{Pic}_n(R_1)$ for some positive integer $n$ and the map $\Delta : G \to \text{Aut}(M_n(R_1))$ (from Theorem 5) is a group homomorphism.

Proof. We first observe that (2) and (3) are equivalent by Lemma 2.

$(2) \Rightarrow (1)$ Since $\text{Comp}(R) \subset \text{Pic}_n(R_1)$ for some positive integer $n$, $R$ is graded equivalent to a crossed product ring of the form $M_n(R)$ by Theorem 5. Moreover, there is a map $\Theta : G \to M_n(R)^\bullet$ such that $M_n(R_g) = M_n(R_1) \cdot \Theta(g)$. If $\Theta$ is a group homomorphism, then it follows that the 2-cocycle $\tau : G \times G \to M_n(R_1)^\bullet$ that defines the crossed product structure of $M_n(R)$ is trivial and so $M_n(R)$ is a skew group ring. See [17, p. 3].

$(1) \Rightarrow (2)$ If $R$ is graded equivalent to a skew group ring of the form $M_n(R)$, then, by Theorem 5, $\text{Comp}(R) \subset \text{Pic}_n(R)$. Since $M_n(R)$ is a skew group ring with grading given by $M_n(R_g) = M_n(R_g)$, it follows that the 2-cocycle $\tau : G \times G \to M_n(R_1)^\bullet$ is trivial and so $\Theta(g) \cdot \Theta(h) = \Theta(gh)$ for each $g, h \in G$. Consequently, the map $\Theta$ is a group homomorphism. \qed
In contrast to the result above, a strongly graded ring $R$ is graded equivalent to a twisted group ring of the form $M_n(R)$ with grading defined by $M_n(R)_g = M_n(R_g)$ if and only if $R$ itself is a twisted group ring.

**Theorem 7.** The following statements are equivalent:

1. There is a positive integer $n$ such that $R$ is graded equivalent to a twisted group ring $M_n(R)$, with grading defined by $M_n(R)_g = M_n(R_g)$.
2. $R$ is a twisted group ring.
3. For every positive integer $n$, $M_n(R)$ is a twisted group ring with grading defined by $M_n(R)_g = M_n(R_g)$.

**Proof.** It is clear that (2) implies (1) and it is not difficult to see that (2) is equivalent to (3). Thus, it suffices to prove (1) implies (2).

If $M_n(R)$ is a twisted group ring, then, by Lemma 2, each $M_n(R_g) \cong M_n(R_1)$ as $M_n(R_1)$-bimodules. Thus, for each $g \in G$, there is a linear isomorphism $f_g : M_n(R_1) \to M_n(R_g)$ that commutes with all matrices from $M_n(R_1)$. Using the idempotent matrix $E$ which has 1 in the $(1, 1)$-entry and zeros elsewhere, it follows that $f_g$ induces a $R_1$-bimodule isomorphism between $R_1$ and $R_g$. Since this holds for each $g \in G$, we see that each $R_g \cong R_1$ as $T$-bimodules. Consequently, $R$ is a twisted group ring by Lemma 2.

Finally, combining Theorems 6 and 7, we get the following corollary:

**Corollary 8.** $R$ is graded equivalent to a group ring of the form $M_n(R)$ with grading defined by $M_n(R)_g = M_n(R_g)$ if and only if $R$ is a twisted group ring and the map $\Phi : G \to M_n(R)^*$ from Theorem 5 is a group homomorphism.

4. **The commutative and the locally free cases**

Let $G$ be a group, let $T$ be a commutative, Noetherian ring of Krull dimension $d$, and let $R$ denote a ring strongly graded by $G$, whose 1-component is $T$ (i.e., $T = R_1$).

**Remark 9.** (1) There is a split exact sequence

\[ 1 \to \text{Picent}(T) \to \text{Pic}(T) \xrightarrow{\Phi} \text{Aut}(T) \to 1 \]

where $\Phi$ is given by $M \mapsto \Phi_M$ and $\Phi_M$ is an automorphism of $T$ defined by the relation $tm = m\Phi_M(t)$ for all $m \in M$ and $t \in T$. The back map is $\omega : \text{Aut}(T) \to \text{Pic}(T)$, defined in Definition 1. Thus, $\text{Pic}(T)$ is the semi-direct product of $\text{Picent}(T)$ and $\text{Aut}(T)$ ([8, Theorem 55.13]). In particular, for each $P \in \text{Pic}(T)$, there is a unique element $\Phi_P \in \text{Aut}(T)$ and a unique element $Q(P) \in \text{Picent}(T)$ such that $P = 1(Q)_{\Phi_P}$. It is easy to see that $Q(P) = 1(P)_{\Phi_P}$. See [8, §55] for more details.

Let $Q : \text{Pic}(T) \to \text{Picent}(T)$ denote the projection of $\text{Pic}(T)$ into $\text{Picent}(T)$; i.e., $Q(P) = 1(P)_{\Phi_P}$. Note that $Q$ need not be a group homomorphism.

(2) Let $\text{Compcent}(R)$ denote the subgroup generated by the image of $\text{Comp}(R)$ inside $\text{Picent}(T)$ under the projection map $Q : \text{Pic}(T) \to \text{Picent}(T)$. Observe that since $\text{Compcent}(R)$ is contained in the abelian group $\text{Picent}(T)$, $\text{Compcent}(R)$ has a finite torsion exponent if and only if the set $Q(\text{Comp}(R))$ has a finite torsion exponent.

The crux of the proof of the following theorem is a result of Bass and Guralnick, which connects the multiplicative structure of $\text{Pic}(R_1)$ with the additive structure.
of $K_0(R_1)$ ([4] and [5]). The work of Bass and Guralnick, in turn, heavily depends on some nontrivial $K$-theoretical results of Bass. In particular, Bass proves in [3, Corollary 4.5, p. 476] that if $T$ is a commutative, Noetherian ring of Krull dimension $d$ and $P$ is a faithful, finitely generated, projective $T$-module such that $l$ is the least common multiple of its local ranks, then there is a (finitely generated) projective $T$-module $Q$ such that $P \otimes Q \cong T^{l+1}$. For example, if $P \in \text{Pic}(T)$, then $l = 1$ and $Q$ is simply the multiplicative inverse of $P$ in $\text{Pic}(T)$.

**Theorem 10.** The following statements are equivalent:

1. The ring $R$ is graded equivalent to a crossed product.
2. The group $\text{Compcent}(R)$ has a torsion exponent.
3. $\text{Comp}(R) \subset \text{Pic}_n(T)$ for some integer $n$.
4. There is a positive integer $n$ such that $\text{M}_R(R)$ is a crossed product with grading defined by $\text{M}_R(R)_g = \text{M}_R(R_g)$ and $R$ and $\text{M}_R(R)$ are graded equivalent.

**Proof.** First observe that statements (3) and (4) are equivalent by Theorem 5. Clearly, (4) $\Rightarrow$ (1) and so it suffices to show (1) $\Rightarrow$ (2) $\Rightarrow$ (3).

(1) $\Rightarrow$ (2) Since $R$ is strongly graded, we know, by Lemma 2 (statement (5)), that there is a left progenitor $P_l$ for $\text{mod}(T)$ such that $R_g \otimes_T P_l \cong P_l$ for all $g \in G$. Let $l$ denote the least common multiple of the local ranks of $P_l$ and set $n = d^{l+1}$, where $d$ is the Krull dimension of $T$. By [3, Corollary 4.5, p. 476] and the fact that $P_l$ is faithful, there is a projective $T$-module $S'$ such that $P_1 \otimes S' \cong T^{(n)}$.

Fix $g \in G$. Since $T \otimes P_l \cong R_g \otimes P_l$, it follows that $T \otimes P_l \otimes S' \cong R_g \otimes P_l \otimes S'$ and so $T^{(n)} \cong R_g^{(n)}$, as left modules. Since $Q(R_g) = 1(R_g)_{R_g^{-1}}$, we see that, as left modules, $Q(R_g)$ and $R_g$ are isomorphic. Consequently, $T^{(n)} \cong Q(R_g)^{(n)}$, as left modules. Taking $n$th exterior products, we see that $\bigotimes^n Q(R_g) \cong R$ and so $n$ is a torsion exponent for $\text{Compcent}(R)$.

(2) $\Rightarrow$ (3) Assume that $\text{Compcent}(R)$ has torsion exponent $e$ and set $n = e^{d+1}$. Fix $g \in G$ and set $I = Q(R_g)$. By [5, Theorem 1], there exists a commutative extension ring $S$ of $T$ such that $I \otimes_T S \cong S$ (as $S$-modules) and $S$ is $T$-projective of rank $e$. By [3, Corollary 4.5, p. 476], there exists a projective $T$-module $Q$ such that $S \otimes_T Q \cong T^{(n)}$. Thus,

$$T^{(n)} \cong S \otimes_T Q \cong (I \otimes_T S) \otimes_T Q \cong I \otimes_T (S \otimes_T Q) \cong I \otimes_T T^{(n)} \cong I^{(n)}.$$ 

However, $R_g \cong Q(R_g)$ as left modules (as we have seen above) and so we have $R_g^{(n)} \cong T^{(n)}$. Thus, $\text{Comp}(R) \subset \text{Pic}_n(T)$.

**Corollary 11.** If $R_1$ belongs to the center of $R$, then $\text{Comp}(R)$ is graded equivalent to a crossed product if and only if $\text{Comp}(R)$ has a torsion exponent.
We turn our attention to a noncommutative version of Theorem 10. We shall require that there is a bijection between \( \text{Comp}(R) \) and a subgroup of \( \text{Picent}(\text{center of the 1-component}) \).

**Definition 12.** Let \( R_1 \) be an arbitrary ring, let \( C \) denote the center of \( R_1 \) and assume \( C \) is Noetherian of Krull dimension \( d \). Following [11], if \( \text{Div}(R_1) \) denotes the category of isomorphism classes of bimodule direct summands of some number of copies of \( R_1 \), then there is a categorical bijection between \( \text{Div}(R_1) \) and the category \( \text{Proj}(C) \) of finitely generated projective \( C \)-modules. Let \( F : \text{Div}(R_1) \to \text{Proj}(C) \) denote this bijection. Set \( \text{DPic}(R_1) = \text{Div}(R_1) \cap \text{Pic}(R_1) \), which is a subset of \( \text{Picent}(R_1) \) (since the elements of \( \text{Div}(R_1) \) are centralized by the center of \( R_1 \)). By the above correspondence, there is a categorical bijection \( F : \text{DPic}(R_1) \to \text{Picent}(C) \), \( F \) preserves direct summands and tensor products (see [11, p. 927]), and \( F(R_1) = C \).

**Theorem 13.** If each \( R_g \in \text{DPic}(R_1) \), then the ring \( R \) is graded equivalent to a crossed product if and only if \( \text{Comp}(R) \) has a torsion exponent.

**Proof.** Since each \( R_g \in \text{DPic}(R_1) \), it follows that \( \text{Comp}(R) \subset \text{Picent}(R_1) \) and \( \text{Comp}(R) = \text{Compcent}(R) \). Suppose \( R \) is graded equivalent to a crossed product. As before, there exists a progenerator \( P_1 \) for \( R_1 \) such that \( R_g \otimes_{R_1} P_1 \cong P_1 \) for all \( g \in G \). Applying the categorical bijection \( F \) mentioned in Definition 12, we see that \( F(R_g) \subset C \) for all \( g \in G \). Now by the proof of Theorem 10, there is a finite torsion exponent for the set \( \{F(R_g) | g \in G\} \) and hence, \( \text{Comp}(R) \) also has a finite exponent.

Conversely, if \( \text{Comp}(R) \) has a finite torsion exponent, then so does \( F(\text{Comp}(R)) \). Invoking the proof of Theorem 10, there exists an integer \( n \) such that \( F(R_g) \otimes C^n \cong C^n \) for all \( g \in G \). Since \( F(R_1) = C \), it follows that \( R^n_1 \) is a progenerator for \( R_1 \) such that \( R_g \otimes R^n_1 \cong R^n_1 \) for all \( g \in G \). Hence, \( R \) is graded equivalent to a crossed product by Lemma 2.

**Corollary 14.** Let \( R \) be a ring strongly graded by \( G \) such that \( R_1 \) is an Azumaya algebra of degree \( n \) with center \( C \). Assume each \( R_g \) is centralized by the center of \( R \). Then \( R \) is graded equivalent to a crossed product if and only if \( \text{Comp}(R) \) has a torsion exponent.

**Proof.** By hypothesis, \( \text{Comp}(R) \subset \text{Picent}(R_1) \). By [10, Proposition 4.1], \( \text{DPic}(R_1) = \text{Picent}(R_1) \). Now apply Theorem 13.

### 5. Examples

We construct various examples of graded rings where the group \( \text{Comp}(R) \) is prescribed. We first show that any group \( G \) can appear as \( \text{Comp}(R) \) for some skew group ring \( R \). We thank M. Beattie for her help on this example.

**Example 15.** Let \( G \) be any group and let \( S = k[X_g | g \in G] \) be a polynomial ring over a field \( k \) in commuting indeterminants indexed by \( G \). Note that \( G \cong \{ \phi_g : X_h \mapsto X_{gh} | g \in G \} \subset \text{Aut}(S) \). Define \( R = S \ast G \), the skew group ring. Since \( R_g = S \ast \phi_g \), we see that \( R_g \cong \langle 1 \rangle_{\phi_g} \) as bimodules. But \( \langle 1 \rangle_{\phi_g} \cong \langle 1 \rangle_{\phi_h} \iff g = h \), and so, \( G \cong \text{Comp}(R) \).

The preceding example implies, of course, that any abelian group can be realized as the component group of a strongly graded ring. However, D. F. Anderson [1] has
a nice construction technique for integral domains that are graded by commutative, torsionless, cancellative monoids. Once we put Anderson’s result in our perspective, we shall see that not only can we construct a commutative, strongly $G$-graded ring $R$ with a prescribed $\text{Comp}(R)$ group, but we can partially prescribe $\text{Pic}(R_1)$ and $\text{Pic}(R)$ as well.

**Proposition 16** (cf. [1, Theorem, p. 249]). Let $R$ be a strongly $G$-graded, commutative ring. If $\theta : \text{Picent}(R_1) \rightarrow \text{Picent}(R)$ is defined via $I \rightarrow IR$, then $\text{Comp}(R) = \ker(\theta)$.

**Proof.** (\(\subset\)) If $[R_g] \in \text{Comp}(R)$, then

$$R_g \cdot R = R_g \left( \bigoplus_{x \in G} R_s \right) = \bigoplus_{x \in G} R_{gs} = R$$

and so $[R_g] \in \ker(\theta)$.

(\(\supset\)) Let $[I] \in \ker(\theta)$ so that $IR \cong R$, as bimodules. Since $IR$ is a nonzero, homogeneous, principal ideal, there exists $z \in R_g$ for some $g \in G$ such that $IR = zR$. Since we may assume that $I \subset R_1$, we see that $IR = \bigoplus_{x \in G} IR_s = zR = \bigoplus_{x \in G} zR_s$ and so $I = zR_{g^{-1}}$. Consequently, $[I] = [R_{g^{-1}}]$ as an element in $\text{Comp}(R)$. \(\square\)

**Corollary 17** (cf. [1, Example, p. 251]). Given a short exact sequence of abelian groups $1 \rightarrow A \rightarrow B \rightarrow C \rightarrow 1$, there exists a strongly graded, commutative ring $R$ such that $\text{Comp}(R) \cong A$, $\text{Pic}(R_1) \cong B$, and $\text{Pic}(R) \cong C$.

**Proof.** By [1, Example, p. 251], there exists a strongly graded commutative ring $R$ such that $\text{Pic} R_1 \cong B$, $\text{Pic} R \cong C$, and $\ker \theta \cong A$. Now apply Proposition 16. \(\square\)

We close with a final example of a noncommutative strongly graded ring $R$ that is graded equivalent to a crossed product, but has the property that $\text{Comp}(R) \not\subseteq \text{Pic}_n(R_1)$ and $\text{Comp}(R)$ is torsionfree. Moreover, $R_1$ is Azumaya. Yet $R$ is graded equivalent to a crossed product by Theorem 3. This serves to show that Theorem 10 cannot be extended to arbitrary rings without modification. We thank L. Levy for his help on this example.

**Example 18.** Let $k$ be any field and let $K = k[x_i | i \in \mathbb{Z}]$, the rational function field with countably many indeterminants. Define $\sigma \in \text{Aut}(K)$ via the rule $X_i \mapsto X_{i+1}$ and extend linearly. It follows that $\langle \sigma \rangle$ is an infinite cyclic subgroup of $\text{Aut}(K)$; let $G = \langle \sigma \rangle$.

Set $T$ to be the following ring and $X$ to be the following $T$-bimodule, both contained in $M_3(K)$:

$$T = \begin{pmatrix} K & K & 0 \\ K & K & 0 \\ 0 & 0 & K \end{pmatrix}, \quad X = \begin{pmatrix} 0 & 0 & K \\ 0 & 0 & K \\ K & K & 0 \end{pmatrix}.$$  

Note that $X \otimes X \cong X : X = T$ and so $X \in \text{Pic}(T)$. Finally, $T$ is a semiperfect, Azumaya algebra.

Set $R$ to be a $\mathbb{Z}$-graded ring defined via $R = \bigoplus_{n \in \mathbb{Z}} R_n$ where $R_n = X^n \cdot \sigma^n$. The $T$-bimodule $R_n$ inherits the left $T$-multiplication from the left $T$-action on $X$, and the right $T$-action is skewed by $\sigma^n : x \cdot t = x(\sigma^n(t))$. Notice that $\bigotimes R_m \cong R_m \not\cong T$ and so $\text{Comp}(R)$ is torsionfree. Further, since $X^{(n)} \not\cong T^{(n)}$ for any positive integer $n$, $\text{Comp}(R) \not\subseteq \text{Pic}_n(R)$. Nonetheless, since $T$ is semiperfect, $R$ is graded equivalent...
to a crossed product $S$ by Theorem 3. In fact, we see that $S_1$ is the matrix ring

$$S_1 = \begin{pmatrix} K & 0 \\ 0 & K \end{pmatrix}$$

so that $S = \bigoplus S_n$ where

$$S_n = S_1 \cdot \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}^n \cdot x^n.$$  

References
2. F. Anderson and K. Fuller, Rings and categories of modules, Springer-Verlag, New York, 1974. MR 54:5281
15. , A strongly graded ring that is not graded equivalent to a skew group ring, Comm. Algebra 22 (1994), 4795–4799. MR 95c:16055

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