A simple $C^*$-algebra with a finite and an infinite projection

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Dedicated to Richard V. Kadison on the occasion of his 75th birthday

Abstract
An example is given of a simple, unital $C^*$-algebra which contains an infinite and a non-zero finite projection. This $C^*$-algebra is also an example of an infinite simple $C^*$-algebra which is not purely infinite. A corner of this $C^*$-algebra is a finite, simple, unital $C^*$-algebra which is not stably finite.

Our example shows that the type decomposition for von Neumann factors does not carry over to simple $C^*$-algebras.

We also give an example of a simple, separable, nuclear, $C^*$-algebra in the UCT class which contains an infinite and a non-zero finite projection. This nuclear $C^*$-algebra arises as a crossed product $D \rtimes \alpha \mathbb{Z}$, where $D$ is an inductive limit of type I $C^*$-algebras.

1 Introduction

The first interesting class of simple $C^*$-algebras (not counting the simple von Neumann algebras) were the UHF-algebras, also called Glimm algebras, constructed by Glimm in 1959 ([2]). Several other classes of simple $C^*$-algebras were found over the following 25 years including the (simple) AF-algebras, the irrational rotation $C^*$-algebras, the free group $C^*$-algebras $C^*_\text{red}(\mathbb{F}_n)$ (and other reduced group $C^*$-algebras), the Cuntz algebras $\mathcal{O}_n$ and the Cuntz–Krieger algebras $\mathcal{O}_A$, $C^*$-algebras arising from minimal dynamical systems and from foliations, and certain inductive limit $C^*$-algebras, among many other examples. Parallel with the appearance of these examples of simple $C^*$-algebras it was asked if there is a classification for simple $C^*$-algebras similar to the classification of von Neumann factors into types. Inspired by work of Dixmier in the 1960’s, Cuntz studied this and related questions about the structure of simple $C^*$-algebras in his papers [14], [17], and [15].
A von Neumann algebra is simple precisely when it is either a factor of type I
\( n < \infty \) (in which case it is isomorphic to \( M_n(\mathbb{C}) \)), a factor of type II\(_1\), or a separable factor of type III. This leads to the question if (non type I) simple \( C^*\)-algebras can be divided into two subclasses, one that resembles type II\(_1\) factors and another that resembles type III factors. A II\(_1\) factor is an infinite dimensional factor in which all projections are finite (in the sense of Murray–von Neumann’s comparison theory for projections), and II\(_1\) factors have a unique trace. A factor is of type III if all its non-zero projections are infinite, and type III factors admit no traces. Cuntz asked in [17] if each simple \( C^*\)-algebra similarly must have the property that its (non-zero) projections either all are finite or all are infinite. Or can a simple \( C^*\)-algebra contain both a (non-zero) finite and an infinite projection? We answer the latter question in the affirmative. In other words, we exhibit a simple (non type I) \( C^*\)-algebras that neither corresponds to a type II\(_1\) or to a type III factor.

It was shown in the early 1980’s that simple \( C^*\)-algebras, in contrast to von Neumann factors, can fail to have non-trivial projections. Blackadar ([3]) and Connes ([12]) found examples of unital, simple \( C^*\)-algebras with no projections other than 0 and 1—before it was shown that \( C^*_{\text{red}}(\mathbb{F}_2) \) is a simple unital \( C^*\)-algebra with no non-trivial projections. Simple \( C^*\)-algebras can fail to have projections in a more severe way: Blackadar found in [1] an example of a stably projectionless simple \( C^*\)-algebras. (A \( C^*\)-algebra \( A \) is stably projectionless if 0 is the only projection in \( A \otimes \mathcal{K} \).) Blackadar and Cuntz proved in [8] that every stably projectionless simple \( C^*\)-algebra is finite in the sense of admitting a (densely defined) quasitrace. (Every quasitrace on an exact \( C^*\)-algebra extends to a trace as shown by Haagerup [23] (and Kirchberg [27]).) These results lead to the dichotomy for a simple \( C^*\)-algebra \( A \): Either \( A \) admits a (densely defined) quasitrace (in which case \( A \) is stably finite), or \( A \) is stably infinite, i.e., \( A \otimes \mathcal{K} \) contains an infinite projection.

Cuntz defined in [16] a simple \( C^*\)-algebra to be purely infinite if all its non-zero hereditary sub-\( C^*\)-algebras contain an infinite projection. Cuntz showed in [13] that his algebras \( \mathcal{O}_n, 2 \leq n \leq \infty \), are simple and purely infinite. The separable, nuclear, simple, purely infinite \( C^*\)-algebras are classified up to isomorphism by \( K\) or \( KK\)-theory by the spectacular theorem of Kirchberg ([28] and [26]) and Phillips ([33]). This result has made it an important question to decide which simple \( C^*\)-algebras are purely infinite. We show here that not all stably infinite simple \( C^*\)-algebras \( A \) are purely infinite.

Villadsen ([41]) was the first to show that the \( K_0\)-group of a simple \( C^*\)-algebra need not be weakly unperforated; Villadsen ([42]) also showed that a unital, finite, simple \( C^*\)-algebra can have stable rank different from one—thus answering in the negative two longstanding open questions for simple \( C^*\)-algebras.

If \( B \) is a unital, simple \( C^*\)-algebra with an infinite and a non-zero finite projection,
then its semigroup of Murray–von Neumann equivalence classes of projections must fail to be weakly unperforated (see Remark 7.8). It is therefore no surprise that Villadsen’s ideas play a crucial role in this article. Our article is also a continuation of the work by the author in [37] and [38] where it is shown that one can find a $C^*$-algebra $A$ such that $M_2(A)$ is stable but $A$ is not stable; and, related to this, one can find a (non-simple) unital $C^*$-algebra $B$, such that $B$ is finite and $M_2(B)$ is properly infinite. We show here (Theorem 5.6) that one can make this example simple by passing to a suitable inductive limit.

In Section 6 (added March 2002) an example is given of a crossed product $C^*$-algebra $D \rtimes \alpha \mathbb{Z}$, where $D$ is an inductive limit of type I $C^*$-algebras, such that $D \rtimes \alpha \mathbb{Z}$ is simple and contains an infinite and a non-zero finite projection. This new example is nuclear and separable. It shows that simple $C^*$-algebras with this rather pathological behavior can arise from a quite natural setting. It shows that Elliott’s classification conjecture (in its present formulation) does not hold (cf. Corollary 7.9); and it also serves as an example of a separable nuclear simple $C^*$-algebra that is tensorially prime (cf. Corollary 7.5).

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The present revised version (with the nuclear example in Section 6 and where the construction in Section 5 is simplified) was completed in March 2002. A part of the work leading to this construction was obtained during a visit in January 2002 to the University of Münster. I thank Joachim Cuntz and Eberhard Kirchberg for their hospitality, and I am indebted to Eberhard Kirchberg for several conversations during the visit that led me to this construction.

2 Finite, infinite, and properly infinite projections

A projection $p$ in a $C^*$-algebra $A$ is called *infinite* if it is equivalent (in the sense of Murray and von Neumann) to a proper subprojection of itself; and $p$ is said to be *finite* otherwise. If $p$ is non-zero and if there are mutually orthogonal subprojections $p_1$ and $p_2$ of $p$ such
that $p \sim p_1 \sim p_2$, then $p$ is properly infinite. A unital $C^*$-algebra is said to be properly infinite if its unit is a properly infinite projection.

If $p$ and $q$ are projections in $A$, then let $p \oplus q$ denote the projection $\text{diag}(p,q)$ in $M_2(A)$. Two projections $p \in M_n(A)$ and $q \in M_m(A)$ can be compared as follows: Write $p \sim q$ if there exists $v$ in $M_{m,n}(A)$ such that $v^*v = p$ and $vv^* = q$, and write $p \precsim q$ if $p$ is equivalent (in this sense) to a subprojection of $q$.

In the proposition below, where some well-known properties of properly infinite projections are recorded, $\mathcal{O}_\infty$ denotes the Cuntz algebra generated by infinitely many isometries with pairwise orthogonal range projections, and $\mathcal{E}_2$ is the Cuntz--Toeplitz algebra generated by two isometries with orthogonal range projections (13).

Proposition 2.1 The following five conditions are equivalent for every non-zero projection $p$ in a $C^*$-algebra $A$:

(i) $p$ is properly infinite;

(ii) $p \oplus p \precsim p$;

(iii) there is a unital $^*$-homomorphism $\mathcal{E}_2 \to pAp$;

(iv) there is a unital $^*$-homomorphism $\mathcal{O}_\infty \to pAp$;

(v) for every closed two-sided ideal $I$ in $A$, either $p \in I$ or $p + I$ is infinite in $A/I$.

The equivalences between (i), (ii), and (iii) are trivial. The equivalence between (iii) and (iv) follows from the fact that there are unital embeddings $\mathcal{E}_2 \to \mathcal{O}_\infty$ and $\mathcal{O}_\infty \to \mathcal{E}_2$. The equivalence between (i) and (v) is proved in [29, Corollary 3.15]; a result that extends Cuntz’ important observation from [14] that every infinite projection in a simple $C^*$-algebra is properly infinite.

We shall use the following two well-known results about properly infinite projections.

Lemma 2.2 Let $p$ and $q$ be projections in a $C^*$-algebra $A$. Suppose that $p$ is properly infinite. Then $q \precsim p$ if and only if $q$ belongs to the closed two-sided ideal in $A$ generated by $p$.

Proof: If $q \precsim p$, then, by definition, $q \sim q_0 \leq p$ for some projection $q_0$ in $A$. This entails that $q$ belongs to the ideal generated by $p$. Conversely, if $q$ belongs to the ideal generated by $p$, then $q \precsim \bigoplus_{j=1}^n p$ for some $n$ (cf. [10, Exercise 4.8]), and $\bigoplus_{j=1}^n p \precsim p$ if $p$ is properly infinite by iterated applications of Proposition 2.1 (ii).
Proposition 2.3 Let \( B \) be the inductive limit of a sequence \( B_1 \to B_2 \to B_3 \to \cdots \) of unital \( C^* \)-algebras with unital connecting maps. Then \( B \) is properly infinite if and only if \( B_n \) is properly infinite for all \( n \) larger than some \( n_0 \).

Proof: If \( B_n \) is properly infinite for some \( n \), then there are unital \(*\)-homomorphisms \( \mathcal{E}_2 \to B_n \to B \), and hence \( B \) is properly infinite. Conversely, if \( B \) is properly infinite, then there is a unital \(*\)-homomorphism \( \mathcal{E}_2 \to B \). The \( C^* \)-algebra \( \mathcal{E}_2 \) is semiprojective, as shown by Blackadar in [4]. By semiprojectivity (see again [4]), the unital \(*\)-homomorphism \( \mathcal{E}_2 \to B \) lifts to a unital \(*\)-homomorphism \( \mathcal{E}_2 \to \prod_{n=n_0}^\infty B_n \) for some \( n_0 \). This shows that \( B_n \) is properly infinite for all \( n \geq n_0 \). \(\square\)

3 Vector bundles over products of spheres

We consider here complex vector bundles over the sphere \( S^2 \) and over finite products of spheres, \((S^2)^n\).

For each \( k \leq n \), let \( \pi_k: (S^2)^n \to S^2 \) denote the \( k \)th coordinate mapping, and let \( \rho_{m,n}: (S^2)^m \to (S^2)^n \) be given by

\[
\rho_{m,n}(x_1, x_2, \ldots, x_m) = (x_1, x_2, \ldots, x_n), \quad (x_1, x_2, \ldots, x_m) \in (S^2)^m.
\] (3.1)

when \( m \geq n \).

Whenever \( f: X \to Y \) is a continuous map and \( \xi \) is a \( k \)-dimensional complex vector bundle over \( Y \), let \( f^*(\xi) \) denote the vector bundle over \( X \) induced by \( f \). Let \( e(\xi) \in H^{2k}(Y, \mathbb{Z}) \) denote the Euler class of \( \xi \). Denote also by \( f^* \) the induced map \( H^*(Y, \mathbb{Z}) \to H^*(X, \mathbb{Z}) \). By functoriality of the Euler class we have \( f^*(e(\xi)) = e(f^*\xi) \).

For any vector bundle \( \xi \) over \((S^2)^n\) and for every \( m \geq n \) we have a vector bundle \( \xi' = \rho_{m,n}^*(\xi) \) over \((S^2)^m\). It follows from the K"unneth Theorem (see [33, Theorem A6]), that the map

\[
\rho_{m,n}^*: H^*((S^2)^n, \mathbb{Z}) \to H^*((S^2)^m, \mathbb{Z})
\]

is injective; so if \( e(\xi) \) is non-zero, then so is \( e(\xi') \). Our main concern with vector bundles will be whether or not they have non-zero Euler class, and from that point of view it does not matter if we replace the base space \((S^2)^n\) with \((S^2)^m\) for some \( m \geq n \).

We remind the reader of some properties of the Euler class for complex vector bundles \( \xi_1, \xi_2, \ldots, \xi_n \) over a base space \( X \). First of all we have the product formula (see [33, Property
$e(\xi_1 \oplus \xi_2 \oplus \cdots \oplus \xi_n) = e(\xi_1) \cdot e(\xi_2) \cdots e(\xi_n). \quad (3.2)$

Let $\theta$ denote the trivial complex line bundle over $X$. The Euler class of $\theta$ is zero; and so it follows from the product formula that $e(\xi) = 0$ whenever $\xi$ is a complex vector bundle that dominates $\theta$ in the sense that $\xi \cong \theta \oplus \eta$ for some complex vector bundle $\eta$.

Combining the formula

\[
\text{ch}(\xi) = 1 + e(\xi) + \frac{1}{2}e(\xi)^2 + \frac{1}{6}e(\xi)^3 + \cdots,
\]

that relates the Chern character and the Euler class of a complex line bundle $\xi$ (see [33, Problem 16-B]), with the fact that the Chern character is multiplicative, yields the formula

\[
e(\xi_1 \otimes \xi_2 \otimes \cdots \otimes \xi_n) = e(\xi_1) + e(\xi_2) + \cdots + e(\xi_n), \quad (3.3)
\]

that holds for all complex line bundles $\xi_1, \ldots, \xi_n$ over $X$.

Let $\zeta$ be a complex line bundle over $S^2$ such that its Euler class $e(\zeta)$, which is an element in $H^2(S^2, \mathbb{Z})$, is non-zero. (Any such line bundle will do, but the reader may take $\zeta$ to be the Hopf bundle over $S^2$.) For each natural number $n$ and for each non-empty, finite subset $I = \{n_1, n_2, \ldots, n_k\}$ of $N$ define complex line bundles $\zeta_n$ and $\zeta_I$ over $(S^2)^m$ (for all $m \geq n$, respectively, $m \geq \max\{n_1, \ldots, n_k\}$) by

\[
\zeta_n = \pi_n^*(\zeta), \quad \zeta_I = \zeta_{n_1} \otimes \zeta_{n_2} \otimes \cdots \otimes \zeta_{n_k}, \quad (3.4)
\]

where, as above, $\pi_n: (S^2)^m \to S^2$ is the $n$th coordinate map. The Euler classes (in $H^2((S^2)^m, \mathbb{Z})$) of these line bundles are by functoriality and equation (3.3) given by

\[
e(\zeta_n) = \pi_n^*(e(\zeta)), \quad (3.5)
\]
\[
e(\zeta_I) = \pi_{n_1}^*(e(\zeta)) + \pi_{n_2}^*(e(\zeta)) + \cdots + \pi_{n_k}^*(e(\zeta)). \quad (3.6)
\]

**Lemma 3.1** For each $n$ and for each $m \geq n$ there is a complex line bundle $\eta_n$ over $(S^2)^m$ such that $\zeta_n \oplus \zeta_n \cong \theta \oplus \eta_n$.

**Proof:** Since

\[
\dim(\zeta \oplus \zeta) = 2 \geq 1 \geq \frac{1}{2}(\dim(S^2) - 1),
\]
it follows from [23, 9.1.2] that there is a complex vector bundle \( \eta \) over \( S^2 \) of dimension \( \dim(\eta) = 2 - 1 = 1 \) such that \( \zeta \oplus \zeta \cong \theta \oplus \eta \). We conclude that

\[
\zeta_n \oplus \zeta_n = \pi_n^*(\zeta \oplus \zeta) \cong \pi_n^*(\theta \oplus \eta) = \theta \oplus \pi_n^*(\eta).
\]

\[\square\]

**Proposition 3.2** Let \( I_1, I_2, \ldots, I_m \) be non-empty, finite subsets of \( \mathbb{N} \). The following three conditions are equivalent:

(i) \( e(\zeta_{I_1} \oplus \zeta_{I_2} \oplus \cdots \oplus \zeta_{I_m}) \neq 0 \).

(ii) For all subsets \( F \) of \( \{1, 2, \ldots, m\} \) we have \( |\bigcup_{j \in F} I_j| \geq |F| \).

(iii) There exists a matching \( t_1 \in I_1, t_2 \in I_2, \ldots, t_m \in I_m \) (i.e., the elements \( t_1, \ldots, t_m \) are pairwise distinct).

**Proof:** Choose \( N \) large enough so that each \( \zeta_{I_j} \) is a vector bundle over \((S^2)^N\).

(ii) \(\Leftrightarrow\) (iii) is the Marriage Theorem (see any textbook on combinatorics).

(i) \(\Rightarrow\) (ii). Assume that \( |\bigcup_{j \in F} I_j| < |F| \) for some (necessarily non-empty) subset \( F = \{j_1, j_2, \ldots, j_k\} \) of \( \{1, 2, \ldots, m\} \), and write

\[
J \overset{\text{def}}{=} \bigcup_{j \in F} I_j = \{n_1, n_2, \ldots, n_l\}.
\]

Let \( \rho: (S^2)^N \to (S^2)^l \) be given by \( \rho(x) = (\pi_{n_1}(x), \pi_{n_2}(x), \ldots, \pi_{n_l}(x)) \). Then

\[
\xi = \zeta_{I_{j_1}} \oplus \zeta_{I_{j_2}} \oplus \cdots \oplus \zeta_{I_{j_k}} = \rho^*(\eta)
\]

for some \( k \)-dimensional vector bundle \( \eta \) over \((S^2)^l\). Now, \( e(\eta) \) belongs to \( H^{2k}((S^2)^l, \mathbb{Z}) \), and \( H^{2k}((S^2)^l, \mathbb{Z}) = 0 \) because \( 2k > 2l \). Hence \( e(\xi) = \rho^*(e(\eta)) = 0 \), so by the product formula \((3.2)\) we get

\[
e(\zeta_{I_1} \oplus \zeta_{I_2} \oplus \cdots \oplus \zeta_{I_m}) = e(\xi) \cdot \prod_{j \in F} e(\zeta_{I_j}) = 0.
\]

(iii) \(\Rightarrow\) (i). Put

\[
x_j = \pi_j^*(e(\zeta)) \in H^2((S^2)^N, \mathbb{Z}), \quad j = 1, 2, \ldots, N.
\]
The element
\[ z = x_1 \cdot x_2 \cdots x_N \in H^{2N}(S^2)^N, \mathbb{Z} \]
is non-zero by the Künneth Theorem ([33, Theorem A6]). Using that \( x_i^2 = 0 \) and that \( x_i x_j = x_j x_i \) for all \( i, j \) it follows that if \( i_1, i_2, \ldots, i_N \) belong to \( \{1, 2, \ldots, N\} \), then
\[ x_{i_1} \cdot x_{i_2} \cdots x_{i_N} = \begin{cases} 
  z, & \text{if } i_1, \ldots, i_N \text{ are distinct,} \\
  0, & \text{otherwise.}
\end{cases} \tag{3.7} \]

Now, by (3.2) and (3.6),
\[
e(\zeta_{I_1} \oplus \zeta_{I_2} \oplus \cdots \oplus \zeta_{I_m}) = e(\zeta_{I_1}) \cdot e(\zeta_{I_2}) \cdots e(\zeta_{I_m})
\]
\[
= (\sum_{i \in I_1} \pi_i^*(e(\zeta))) \cdot (\sum_{i \in I_2} \pi_i^*(e(\zeta))) \cdots (\sum_{i \in I_m} \pi_i^*(e(\zeta)))
\]
\[
= (\sum_{i \in I_1} x_i) \cdot (\sum_{i \in I_2} x_i) \cdots (\sum_{i \in I_m} x_i)
\]
\[
= \sum_{(i_1, \ldots, i_m) \in I_1 \times \cdots \times I_m} x_{i_1} \cdot x_{i_2} \cdots x_{i_m}.
\]

Assume that (iii) holds, and write
\[
\{1, 2, \ldots, N\} \setminus \{t_1, t_2, \ldots, t_m\} = \{s_1, s_2, \ldots, s_{N-m}\}.
\]

Let \( k \) denote the number of permutations \( \sigma \) on \( \{1, 2, \ldots, m\} \) such that \( t_{\sigma(j)} \in I_j \) for \( j = 1, 2, \ldots, m \). The identity permutation has this property, so \( k \geq 1 \). The formula for \( e(\zeta_{I_1} \oplus \cdots \oplus \zeta_{I_m}) \) above and equation (3.7) yield
\[
e(\zeta_{I_1} \oplus \zeta_{I_2} \oplus \cdots \oplus \zeta_{I_m}) \cdot x_{s_1} \cdot x_{s_2} \cdots x_{s_{N-m}} = k z \neq 0.
\]

It follows that \( e(\zeta_{I_1} \oplus \cdots \oplus \zeta_{I_m}) \neq 0 \) as desired. \( \square \)

4 Projections in a certain multiplier algebra

There is a well-known one-to-one correspondence between isomorphism classes of complex vector bundles over a compact Hausdorff space \( X \) and Murray–von Neumann equivalence classes of projections in matrix algebras over \( C(X) \) (and in \( C(X) \otimes K \)). The vector bundle
corresponding to a projection \( p \) in \( M_n(C(X)) = C(X, M_n) \) is

\[
\xi_p = \{(x, v) : x \in X, \ v \in p(x)(\mathbb{C}^n)\},
\]

(equipped with the topology given from the natural inclusion \( \xi_p \subseteq X \times \mathbb{C}^n \)), so that the fibre \( (\xi_p)_x \) over \( x \in X \) is the range of the projection \( p(x) \). If \( p \) and \( q \) are two projections in \( C(X) \otimes \mathcal{K} \), then \( \xi_p \cong \xi_q \) if and only if \( p \sim q \). It follows from Swan’s theorem, which to each complex vector bundle \( \xi \) gives a complex vector bundle \( \eta \) such that \( \xi \oplus \eta \) is isomorphic to the trivial \( n \)-dimensional complex vector bundle over \( X \) for some \( n \), that every complex vector bundle is isomorphic to \( \xi_p \) for some projection \( p \) in \( M_n(C(X)) \) for some \( n \).

View each matrix algebra \( M_n(\mathbb{C}) \) as a sub-\( C^* \)-algebra of \( \mathcal{K} \) via the embeddings

\[
\mathbb{C} \leftarrow M_2(\mathbb{C}) \leftarrow M_3(\mathbb{C}) \leftarrow \cdots \leftarrow \mathcal{K},
\]

where \( M_n(\mathbb{C}) \) is mapped into the upper left corner of \( M_{n+1}(\mathbb{C}) \). Identify \( C(X, \mathcal{K}) \) with \( C(X) \otimes \mathcal{K} \) and identify \( C(X, M_n) \) with \( C(X) \otimes M_n(\mathbb{C}) \).

In Section \[3\] we picked a non-trivial complex line bundle \( \zeta \) over \( S^2 \) (eg., the Hopf bundle). This line bundle \( \zeta \) corresponds to a projection \( p \) in some matrix algebra over \( C(S^2) \), and, as is well known, such a projection \( p \) can be found in \( M_2(C(S^2)) = C(S^2, M_2) \). (The projection \( p \in M_2(S^2, M_2) \) corresponding to the Hopf bundle is in operator algebra texts often referred to as the Bott projection.) Put

\[
Z = \prod_{n=1}^{\infty} S^2.
\]

Let \( \pi_n : Z \to S^2 \) be the \( n \)th coordinate map, and let \( \rho_{\infty, n} : Z \to (S^2)^n \) be given by

\[
\rho_{\infty, n}(x_1, x_2, x_3, \ldots) = (x_1, x_2, \ldots, x_n), \quad (x_1, x_2, x_3, \ldots) \in Z.
\]

With \( \tilde{\rho}_n : C((S^2)^n) \to C((S^2)^{n+1}) \) being the \( * \)-homomorphism induced by the map \( \rho_n = \rho_{n+1, n} \) defined in \([3, 4]\) we obtain that \( C(Z) \) is the inductive limit

\[
C(S^2) \xrightarrow{\tilde{\rho}_1} C((S^2)^2) \xrightarrow{\tilde{\rho}_2} C((S^2)^3) \xrightarrow{\tilde{\rho}_3} \cdots \xrightarrow{\tilde{\rho}_n} C(Z)
\]

with inductive limit maps \( \tilde{\rho}_{\infty, n} : C((S^2)^n) \to C(Z) \).

For \( n \in \mathbb{N} \) and for each non-empty finite subset \( I = \{n_1, n_2, \ldots, n_k\} \) of \( \mathbb{N} \), let \( p_n \) and
$p_I$ be the projections in $C(Z) \otimes K = C(Z, K)$ given by

\begin{align*}
p_n(x) &= p(x_n), \quad (4.1) \\
p_I(x) &= p(x_{n_1}) \otimes p(x_{n_2}) \otimes \cdots \otimes p(x_{n_k}) \\
&= p_{n_1}(x) \otimes p_{n_2}(x) \otimes \cdots \otimes p_{n_k}(x), \quad (4.2)
\end{align*}
for all $x = (x_1, x_2, \ldots) \in Z$ (identifying $M_2$, respectively, $M_2 \otimes M_2 \otimes \cdots \otimes M_2$ with sub-$C^*$-algebras of $K$).

We shall now make use of the multiplier algebra, $\mathcal{M}(C(Z) \otimes K)$, of $C(Z) \otimes K = C(Z, K)$. We can identify this multiplier algebra with the set of all bounded functions $f: Z \to B(H)$ for which $f$ and $f^*$ are continuous, when $B(H)$, the bounded operators on the Hilbert space $H$ on which $K$ acts, is given the strong operator topology.

It is convenient to have a convention for adding finitely or infinitely many projections in $\mathcal{M}(C(Z) \otimes K)$, or more generally in $\mathcal{M}(A)$, where $A$ is any stable $C^*$-algebra—a convention that extends the notion of forming direct sums of projections discussed in Section 2.

Assuming that $A$ is a stable $C^*$-algebra, so that $A = A_0 \otimes K$ for some $C^*$-algebra $A_0$, then we can take a sequence $\{T_j\}_{j=1}^\infty$ of isometries in $C \otimes B(H) \subseteq \mathcal{M}(A_0 \otimes K) = \mathcal{M}(A)$ such that $1 = \sum_{j=1}^\infty T_j T_j^*$ in the strict topology. (Notice that 1 is a properly infinite projection in $\mathcal{M}(A).$) For any sequence $q_1, q_2, \ldots$ of projections in $A$ and for any sequence $Q_1, Q_2, \ldots$ of projections in $\mathcal{M}(A)$, define

\begin{align*}
q_1 \oplus q_2 \oplus \cdots \oplus q_n &= \sum_{j=1}^n T_j q_j T_j^* \in A, \quad (4.3) \\
\bigoplus_{j=1}^\infty q_j &= \sum_{j=1}^\infty T_j q_j T_j^* \in \mathcal{M}(A), \quad (4.4) \\
Q_1 \oplus Q_2 \oplus \cdots \oplus Q_n &= \sum_{j=1}^n T_j Q_j T_j^* \in \mathcal{M}(A), \quad (4.5) \\
\bigoplus_{j=1}^\infty Q_j &= \sum_{j=1}^\infty T_j Q_j T_j^* \in \mathcal{M}(A), \quad (4.6)
\end{align*}

Observe that $q'_j = T_j q_j T_j^* \sim q_j$, that the projections $q'_1, q'_2, \ldots$ are mutually orthogonal, and that the sum $\sum_{j=1}^\infty q'_j$ is strictly convergent. The projections in (4.3)–(4.6) are, up to unitary equivalence in $\mathcal{M}(A)$, independent of the choice of isometries $\{T_j\}_{j=1}^\infty$. Indeed, if $\{R_j\}_{j=1}^\infty$ is another sequence of isometries in $\mathcal{M}(A)$ with $1 = \sum_{j=1}^\infty R_j R_j^*$, then $U = \sum_{j=1}^\infty R_j T_j^*$ is
a unitary element in $\mathcal{M}(A)$ and

$$
\sum_{j=1}^{\infty} R_j X_j R_j^* = U \left( \sum_{j=1}^{\infty} T_j X_j T_j^* \right) U^*
$$

for any bounded sequence $\{X_j\}_{j=1}^{\infty}$ in $\mathcal{M}(A)$. It follows in particular that

$$
\bigoplus_{j=1}^{\infty} q_j \sim \bigoplus_{j=1}^{\infty} q_{\sigma(j)}
$$

for every permutation $\sigma$ on $\mathbb{N}$.

In the lemma below the correspondence between projections and vector bundles is the mapping $p \mapsto \xi_p$ defined at the beginning of this section. By identifying the projections $p_0, p_1, p_{I_1}, \ldots, p_{I_k}$ with projections in $C((S^2)^N) \otimes \mathcal{K}$, where $N$ is any integer large enough to ensure that these projections belong to the image of

$$
\hat{\rho}_{\infty,N} \otimes \text{id}_\mathcal{K} : C((S^2)^N) \otimes \mathcal{K} \to C(Z) \otimes \mathcal{K},
$$

we can take the base space to be $(S^2)^N$.

**Lemma 4.1** Let $\zeta_n$ and $\zeta_I$ be the complex line bundles defined in (3.4).

(i) The vector bundle $\zeta_n$ corresponds to $p_n$ for each $n$ in $\mathbb{N}$.

(ii) The vector bundle $\zeta_I$ corresponds to $p_I$ for each non-empty finite subset $I$ of $\mathbb{N}$.

(iii) The vector bundle $\zeta_{I_1} \oplus \zeta_{I_2} \oplus \cdots \oplus \zeta_{I_k}$ corresponds to $p_{I_1} \oplus p_{I_2} \oplus \cdots \oplus p_{I_k}$ whenever $I_1, \ldots, I_k$ are non-empty finite subsets of $\mathbb{N}$.

**Proof:** (i). Since $p$ corresponds to $\zeta$, $p_n = p \circ \pi_n$ corresponds to $\zeta_n = \pi_n^*(\zeta)$, where $\pi_n : (S^2)^N \to S^2$ is the $n$th coordinate map.

(ii). Write $I = \{n_1, n_2, \ldots, n_k\}$. We shall here view $p_n$ as a projection in $C((S^2)^N, M_2)$ and $p_I$ as a projection in $C((S^2)^N, M_2 \otimes \cdots \otimes M_2)$. By (i), $\zeta_n$ is the complex line bundle over $(S^2)^N$ whose fibre over $x \in (S^2)^N$ is equal to $p_n(x)(\mathbb{C}^2)$. The fibre of the complex line bundle $\zeta_I = \zeta_{n_1} \otimes \zeta_{n_2} \otimes \cdots \otimes \zeta_{n_k}$ over $x \in (S^2)^N$ is by definition

$$
(\zeta_I)_x = (\zeta_{n_1})_x \otimes (\zeta_{n_2})_x \otimes \cdots \otimes (\zeta_{n_k})_x
= p_{n_1}(x)(\mathbb{C}^2) \otimes p_{n_2}(x)(\mathbb{C}^2) \otimes \cdots \otimes p_{n_k}(x)(\mathbb{C}^2)
= p_I(x)(\mathbb{C}^2 \otimes \mathbb{C}^2 \otimes \cdots \otimes \mathbb{C}^2).
$$
This shows that $\zeta_I$ corresponds to $p_I$.

(iii). This follows from (ii) and additivity of the map $p \mapsto \xi_p$. \hfill \qed

The two next results are formulated for an arbitrary stable $C^\ast$-algebra $A$ and its multiplier algebra $\mathcal{M}(A)$, but it shall primarily be used in the case where $A = C(Z) \otimes \mathcal{K}$.

The lemma below is a trivial, but much used, generalization of \eqref{4.7}:

**Lemma 4.2** Let $A$ be a stable $C^\ast$-algebra, and let $q_1, q_2, \ldots$ and $r_1, r_2, \ldots$ be two sequences of projections in $A$. Assume that there is a permutation $\sigma$ on $\mathbb{N}$ such that $q_j \preceq r_{\sigma(j)}$, respectively $q_j \sim r_{\sigma(j)}$, in $A$ for all $j$ in $\mathbb{N}$. Then $\bigoplus_{j=1}^\infty q_j \preceq \bigoplus_{j=1}^\infty r_j$, respectively $\bigoplus_{j=1}^\infty q_j \sim \bigoplus_{j=1}^\infty r_j$, in $\mathcal{M}(A)$.

We shall also use the following two well-known facts about projections in multiplier algebras. An element in a $C^\ast$-algebra $A$ is said to be full in $A$ if it is not contained in any proper closed two-sided ideal of $A$.

**Lemma 4.3** Let $A$ be a stable $C^\ast$-algebra. The following three conditions are equivalent for all projections $Q$ in $\mathcal{M}(A)$:

(i) $Q \sim 1$,  (ii) $Q$ is properly infinite and full in $\mathcal{M}(A)$,  (iii) $1 \preceq Q$.

**Proof:** (i) $\Rightarrow$ (iii) is trivial. Assume that $1 \preceq Q$. Then $Q$ is full in $\mathcal{M}(A)$ (the closed two-sided ideal in $\mathcal{M}(A)$ generated by $Q$ contains 1 and hence all of $\mathcal{M}(A)$). It was noted above (4.3) that 1 is properly infinite in $\mathcal{M}(A)$, and so $Q \oplus Q \preceq 1 \oplus 1 \preceq 1 \preceq Q$, whence $Q$ is properly infinite; cf. Proposition 2.1. This proves (iii) $\Rightarrow$ (ii). Assume finally that $Q$ is properly infinite and full in $\mathcal{M}(A)$. Since $K_0(\mathcal{M}(A)) = 0$ (see \cite[Proposition 12.2.1]{7}) the two projections $Q$ and 1 represent the same element in $K_0(\mathcal{M}(A))$; and since these two projections both are properly infinite and full they must be Murray–von Neumann equivalent (see \cite[Section 1]{16} or \cite[Exercise 4.9 (iii)]{11}), i.e., $Q \sim 1$. \hfill \qed

**Lemma 4.4** Let $A$ be a stable $C^\ast$-algebra and let $q, q_1, q_2, \ldots$ be projections in $A$. If $q \preceq \bigoplus_{j=1}^\infty q_j$ in $\mathcal{M}(A)$, then $q \preceq q_1 \oplus q_2 \oplus \cdots \oplus q_k$ in $A$ for some $k$.

**Proof:** We have $\bigoplus_{j=1}^\infty q_j = \sum_{j=1}^\infty q_j' \ (= Q)$ for some strictly summable sequence of mutually orthogonal projections $q_1', q_2', \ldots$ in $A$ with $q_j' \sim q_j$. By the assumption that $q \preceq Q$ there is a partial isometry $v$ in $\mathcal{M}(A)$ such that $vv^* = q$ and $v^*v \leq Q$. As $v = qv$, $v$ belongs to $A$, and by the strict convergence of the sum $Q = \sum_{j=1}^\infty q_j'$ there is $k$ such that

$$\|v - v \sum_{j=1}^k q_j'\| < 1/2.$$
Put \( x = v \sum_{j=1}^k q'_j \). Then \( xx^* \leq q, x^*x \leq q'_1 + \cdots + q'_k \), and \( \|xx^* - q\| < 1 \). This shows that \( xx^* \) is invertible in \( qAq \) with inverse \( (xx^*)^{-1} \). Put \( u = (xx^*)^{-1/2}x \). Then \( uu^* = q \) and \( u^*u \leq q'_1 + \cdots + q'_k \), whence \( q \precsim q_1 \oplus \cdots \oplus q_k \). □

Let \( g \) be a constant one-dimensional projection in \( C(Z, \mathcal{K}) = C(Z) \otimes \mathcal{K} \) (that corresponds to the trivial complex line bundle \( \theta \) over \( X \)). The (easy-to-prove) statement in part (iii) of the proposition below is not used in this paper, but it may have some independent interest.

**Proposition 4.5** Let \( I_1, I_2, \ldots \) be a sequence of non-empty, finite subsets of \( \mathbb{N} \). Put

\[
Q = \bigoplus_{j=1}^\infty p_{I_j} \in \mathcal{M}(C(Z) \otimes \mathcal{K}).
\]

(i) If \( \big| \bigcup_{j \in F} I_j \big| \geq |F| \) for all finite subsets \( F \) of \( \mathbb{N} \), then \( g \nless Q \) and \( Q \) is not properly infinite.

(ii) \( g \nless p_n \oplus p_n \) for every natural number \( n \).

(iii) If infinitely many of the sets \( I_1, I_2, \ldots \) are singletons, then \( Q \oplus Q \) is properly infinite and \( Q \oplus Q \sim 1 \) in \( \mathcal{M}(C(Z) \otimes \mathcal{K}) \).

**Proof:** (i). We show first that \( g \nless Q \) in \( \mathcal{M}(C(Z) \otimes \mathcal{K}) \). Indeed, assume to the contrary that \( g \nless Q \). Then

\[
g \nless p_{I_1} \oplus p_{I_2} \oplus \cdots \oplus p_{I_k} \tag{4.8}
\]

in \( C(Z) \otimes \mathcal{K} \) for some \( k \) by Lemma 4.4. As noted earlier, \( C(Z) \otimes \mathcal{K} \) is an inductive limit

\[
C(S^2) \otimes \mathcal{K} \xrightarrow{\hat{\rho}_1 \otimes \text{id}_K} C((S^2)^2) \otimes \mathcal{K} \xrightarrow{\hat{\rho}_2 \otimes \text{id}_K} C((S^2)^3) \otimes \mathcal{K} \xrightarrow{\cdots} C(Z) \otimes \mathcal{K}.
\]

Take \( N \) such that all projections appearing in (4.8) belong to the image of \( \hat{\rho}_{\infty,n} \otimes \text{id}_K : C((S^2)^n) \otimes \mathcal{K} \to C(Z) \otimes \mathcal{K} \)

whenever \( n \geq N \). Use a standard inductive limit argument to see that (4.8) holds relatively to \( C((S^2)^n) \otimes \mathcal{K} \) for some large enough \( n \geq N \). In the language of vector bundles over \( (S^2)^n \), (4.8) and Lemma 4.1 imply that

\[
\theta \oplus \eta \cong \zeta_{I_1} \oplus \zeta_{I_2} \oplus \cdots \oplus \zeta_{I_k} \tag{4.9}
\]
for some vector bundle \( \eta \) over \((S^2)^n\). Now, (4.9) and (1.2) imply that \( e(\zeta_1 \oplus \cdots \oplus \zeta_k) = 0 \), in contradiction with Proposition 3.2 and the assumption on the sets \( I_j \).

The projection \( p_I \) is a full element in \( C(Z) \otimes K \) and \( p_I \leq Q \). Hence \( g \) belongs to the ideal generated by \( Q \). It now follows from Lemma 2.2 and from the fact that \( g \not\subseteq Q \) that \( Q \) cannot be properly infinite.

(ii) follows from Lemma 3.1 and Lemma 4.1.

(iii). The unit 1 of \( M(A) \) denotes the multiplier algebra of \( A \) and that it can be identified with the set of bounded *-strongly continuous functions \( f: Z \to B(H) \).

Choose an injective function \( \nu: \mathbb{Z} \times \mathbb{N} \to \mathbb{N} \). Choose points \( c_{j,i} \in S^2 \) for all \( j, i \in \mathbb{N} \) with \( j \geq i \) such that

\[
\{(c_{j,1}, c_{j,2}, \ldots, c_{j,n}) \mid j \geq n\} = S^2 \times S^2 \times \cdots \times S^2
\]

for every natural number \( n \). Set

\[
I_j = \{\nu(j,1), \nu(j,2), \ldots, \nu(j,j)\},
\]

for \( j \in \mathbb{N} \).

Define *-homomorphisms \( \varphi_j: A \to A \) for all integers \( j \) as follows. For \( j \leq 0 \), set

\[
\varphi_j(f)(x) = f(x_{\nu(j,1)}, x_{\nu(j,2)}, x_{\nu(j,3)}, \ldots), \quad f \in A, \ x = (x_1, x_2, \ldots) \in Z.
\]

Let \( p_n \) and \( p_I \) be the projections in \( A = C(Z, K) \) defined in (4.1) and (4.2). Choose an

5 A non-exact example

We construct here a simple, unital \( C^* \)-algebra that contains a finite and an infinite projection; thus proving one of our main results: Theorem 5.6 below.

Let again \( Z \) denote the infinite product space \( \prod_{j=1}^\infty S^2 \). Set \( A = C(Z) \otimes K = C(Z, K) \); recall from Section 4 that \( M(A) \) denotes the multiplier algebra of \( A \) and that it can be identified with the set of bounded *-strongly continuous functions \( f: Z \to B(H) \).

Choose an injective function \( \nu: \mathbb{Z} \times \mathbb{N} \to \mathbb{N} \). Choose points \( c_{j,i} \in S^2 \) for all \( j, i \in \mathbb{N} \) with \( j \geq i \) such that

\[
\{(c_{j,1}, c_{j,2}, \ldots, c_{j,n}) \mid j \geq n\} = S^2 \times S^2 \times \cdots \times S^2
\]

for every natural number \( n \). Set

\[
I_j = \{\nu(j,1), \nu(j,2), \ldots, \nu(j,j)\},
\]

for \( j \in \mathbb{N} \).

Define *-homomorphisms \( \varphi_j: A \to A \) for all integers \( j \) as follows. For \( j \leq 0 \), set

\[
\varphi_j(f)(x) = f(x_{\nu(j,1)}, x_{\nu(j,2)}, x_{\nu(j,3)}, \ldots), \quad f \in A, \ x = (x_1, x_2, \ldots) \in Z.
\]
isomorphism $\tau: \mathcal{K} \otimes \mathcal{K} \to \mathcal{K}$. For $f$ in $A$, $x = (x_1, x_2, \ldots)$ in $Z$, and $j \geq 1$ define

$$\varphi_j(f)(x) = \tau(f(c_{j,1}, \ldots, c_{j,j}, x_{\nu(j,j+1)}, x_{\nu(j,j+2)}, \ldots) \otimes p_{I_j}(x)). \quad (5.4)$$

Choose a sequence $\{S_j\}_{j=\infty}^{\infty}$ of isometries in $\mathcal{M}(A)$ such that $\sum_{j=\infty}^{\infty} S_j S_j^* = 1$ with the sum being strictly convergent. Define a $^*$-homomorphism $\psi: A \to \mathcal{M}(A)$ by

$$\psi(f) = \sum_{j=\infty}^{\infty} S_j \varphi_j(f) S_j^*, \quad f \in A. \quad (5.5)$$

**Lemma 5.1** Let $\{e_n\}_{n=1}^{\infty}$ be an increasing approximate unit for $A$. Then $\{\psi(e_n)\}_{n=1}^{\infty}$ converges strictly to a projection $F \in \mathcal{M}(A)$, and $F$ is equivalent to the identity 1 in $\mathcal{M}(A)$.

**Proof:** If $\psi(e_n)$ converges strictly to $F \in \mathcal{M}(A)$ for some approximate unit $\{e_n\}$ for $A$, then this conclusion will hold for all approximate units for $A$. We can therefore take $\{e_n\}_{n=1}^{\infty}$ to be the approximate unit given by $e_n(x) = \widehat{e}_n$, where $\{\widehat{e}_n\}_{n=1}^{\infty}$ is an increasing approximate unit for $\mathcal{K}$.

We show first that $\{\varphi_j(e_n)\}_{n=1}^{\infty}$ converges strictly to a projection $F_j$ in $\mathcal{M}(A)$ for each $j \in \mathbb{Z}$. Indeed, since $\varphi_j(e_n) = e_n$ when $j \leq 0$ it follows that $\varphi_j(e_n) \to 1$ strictly; and so $F_j = 1$ when $j \leq 0$. Consider next the case $j \geq 1$. Here we have $\varphi_j(e_n)(x) = \tau(\widehat{e}_n \otimes p_{I_j}(x))$. Extend $\tau: \mathcal{K} \otimes \mathcal{K} \to \mathcal{K}$ to a strongly continuous unital $^*$-homomorphism $\overline{\tau}: B(H \otimes H) \to B(H)$ and define $F_j$ in $\mathcal{M}(A)$ by $F_j(x) = \overline{\tau}(1 \otimes p_{I_j}(x))$ for $x \in Z$. Then $F_j$ is a projection and $\{\varphi_j(e_n)\}_{n=1}^{\infty}$ converges strictly to $F_j$.

Now,

$$\psi(e_n) = \sum_{j=\infty}^{\infty} S_j \varphi_j(e_n) S_j^* \xrightarrow{n \to \infty} \sum_{j=\infty}^{\infty} S_j F_j S_j^* \overset{\text{def}}{=} F \in \mathcal{M}(A),$$

As $1 = F_0 \sim S_0 F_0 S_0^* \leq F$ it follows from Lemma 1.3 that $F \sim 1$ in $\mathcal{M}(A)$.

Take an isometry $T$ in $\mathcal{M}(A)$ with $TT^* = F$ (where $F$ is an in Lemma 5.1). Define

$$\varphi(f) = T^* \psi(f) T = \sum_{j=\infty}^{\infty} T^* S_j \varphi_j(f) S_j^* T, \quad f \in A. \quad (5.6)$$

Then $\varphi: A \to \mathcal{M}(A)$ is a $^*$-homomorphism that maps an approximate unit for $A$ into a sequence in $\mathcal{M}(A)$ that converges strictly to the identity in $\mathcal{M}(A)$ (by Lemma 5.1 and the choice of $T$). It follows from [32, Proposition 2.5] that $\varphi$ extends to a unital $^*$-homomorphism $\overline{\varphi}: \mathcal{M}(A) \to \mathcal{M}(A)$. 

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We collect below some properties of the $\ast$-homomorphisms $\varphi$ and $\overline{\varphi}$. A subset of a $C^*$-algebra $A$ is called full in $A$ if it is not contained in any proper closed two-sided ideal in $A$.

**Proposition 5.2** Let $p_1$ be the projection in $A$ defined in (4.1) and let $g$ be a constant 1-dimensional projection in $A = C(Z, K)$.

(i) $\varphi(g) \sim 1$ in $M(A)$, and so $\varphi(f)$ is full in $M(A)$ for every full element $f$ in $A$.

(ii) If $f$ is a non-zero element in $M(A)$, then $\overline{\varphi}(f)$ does not belong to $A$, and $A\overline{\varphi}(f)$ is full in $A$.

(iii) If $f$ is a non-zero element in $M(A)$, then $A\overline{\varphi}^k(f)$ is full in $A$ for every $k \in \mathbb{N}$.

(iv) None of the projections $\overline{\varphi}^k(p_1)$, $k \in \mathbb{N}$, are properly infinite in $M(A)$.

It follows immediately from (ii) that $\overline{\varphi}$ and $\varphi$ are injective, and that $\overline{\varphi}(M(A)) \cap A = \{0\}$ and $\varphi(A) \cap A = \{0\}$.

The proof of Proposition 5.2 is divided into a few lemmas, the first of which (included for emphasis) is standard and follows from the fact that any closed two-sided ideal in $C(Z, K)$ is equal to $C_0(U, K)$ for some open subset $U$ of $Z$.

**Lemma 5.3** Let $f$ be an element in $A = C(Z, K)$. Then $f$ is full in $A$ if and only if $f(x) \neq 0$ for all $x \in Z$.

**Proof of Proposition 5.2 (i):** Observe first that $\varphi_j(g) = g$ for every $j \leq 0$. Accordingly,

$$1 \sim \bigoplus_{j=-\infty}^{0} g \sim \sum_{j=-\infty}^{0} T^* S_j \varphi_j(g) S_j^* T \leq \varphi(g) \text{ in } M(A).$$

This and Lemma 4.3 imply that $\varphi(g) \sim 1$ and that $g$ is full in $M(A)$. If $f$ is any full element in $A$, then the closed two-sided ideal generated by $\varphi(f)$ contains $\varphi(g)$ and therefore all of $M(A)$. This proves the second claim in (i).

**Proof of Proposition 5.2 (ii):** Take a non-zero element $f$ in $M(A)$. There is an element $a$ in $A$ such that $af \neq 0$. The two claims in (ii) will clearly follow if we can show that $\overline{\varphi}(af) \notin A$ and that $A\overline{\varphi}(af)$ is full in $A$, and we can therefore, upon replacing $f$ by $af$, assume that $f$ is a non-zero element in $A = C(Z, K)$. 

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There are $\delta > 0$, $r \in \mathbb{N}$, and non-empty open subsets $U_1, \ldots, U_r$ of $S^2$ such that

$$x \in U_1 \times U_2 \times \cdots \times U_r \times S^2 \times S^2 \times \cdots \implies \|f(x)\| \geq \delta. \quad (5.7)$$

Use (5.1) to find an infinite set $\Lambda$ of integers $j \geq r$ such that

$$(c_{j,1}, c_{j,2}, \ldots, c_{j,r}) \in U_1 \times U_2 \times \cdots \times U_r \quad \text{for all } j \in \Lambda. \quad (5.8)$$

It follows from Lemma 5.3, (5.4), (5.7), and (5.8) that $\|\varphi_j(f)\| \geq \delta$ and $\varphi_j(f)$ is full in $A$ for every $j$ in the infinite set $\Lambda$. This entails that $\varphi(f) = \sum_{j=-\infty}^{\infty} T^* S_j \varphi_j(f) S^*_j T$ does not belong to $A$. (A strictly convergent sum $\sum_{j=-\infty}^{\infty} a_j$ of pairwise orthogonal elements from $A$ belongs to $A$ if and only if $\lim_{j \to \pm \infty} \|a_j\| = 0$.) The closed two-sided ideal in $A$ generated by $A \varphi(f)$ contains the full element $\varphi_j(f) = S^*_j T \varphi(f) T^* S_j$ and therefore all of $A$ (for each—and hence at least one—$j$ in $\Lambda$). \hfill \Box

**Proof of Proposition 5.2 (iii):** This follows from injectivity of $\varphi$ and Proposition 5.2 (ii). \hfill \Box

We proceed to prove Proposition 5.2 (iv).

**Lemma 5.4** Let $J$ be a finite subset of $\mathbb{N}$ and let $j$ be an integer. Then $\varphi_j(p_J) \sim p_{\alpha_j(J)}$, where

$$\alpha_j(J) = \begin{cases} \nu(j, J), & j \leq 0 \\ \nu(j, J \setminus \{1, 2, \ldots, j\}) \cup I_j, & j \geq 1. \end{cases} \quad (5.9)$$

We have in particular that $\nu(j, J) \subseteq \alpha_j(J)$ for all finite subsets $J$ of $\mathbb{N}$ and for all $j \in \mathbb{Z}$.

**Proof:** Write $J = \{t_1, t_2, \ldots, t_k\}$, where $t_1 < t_2 < \cdots < t_k$. We consider first the case where $j \leq 0$. Then

$$\varphi_j(p_J)(x) = p_J(x_{\nu(j,1)}, x_{\nu(j,2)}, x_{\nu(j,3)}, \ldots) = p(x_{\nu(j,t_1)}) \otimes p(x_{\nu(j,t_2)}) \otimes \cdots \otimes p(x_{\nu(j,t_k)}) = p_{\nu(j,t_1)}(x) \otimes p_{\nu(j,t_2)}(x) \otimes \cdots \otimes p_{\nu(j,t_k)}(x) = p_{\nu(j,J)}(x),$$

as desired.

Suppose next that $j \geq 1$. Let $m$ be such that $t_{m-1} \leq j < t_m$ (with the convention
\[ t_0 = 0 \]. Put

\[
q(x) = p_J(c_{j,1}, \ldots, c_{j,j}, x_{\nu(j,j+1)}, x_{\nu(j,j+2)}, \ldots)
\]

\[
= p(c_{j,t_1}) \otimes \cdots \otimes p(c_{j,t_{m-1}}) \otimes p(x_{\nu(j,t_m)}) \otimes \cdots \otimes p(x_{\nu(j,t_k)})
\]

\[
= p(c_{j,t_1}) \otimes \cdots \otimes p(c_{j,t_{m-1}}) \otimes p(\nu(j,t_m)(x)) \otimes \cdots \otimes p(\nu(j,t_k)(x))
\]

\[
= p(c_{j,t_1}) \otimes \cdots \otimes p(c_{j,t_{m-1}}) \otimes p(\nu(j,J) \setminus \{1,2,\ldots,k\})(x).
\]

Thus \( q \sim p_{\nu(j,J) \setminus \{1,2,\ldots,k\}} \). Now, \( \varphi_j(p_J)(x) = \tau(q(x) \otimes p_I(x)) \). Hence \( \varphi_j(p_J) \) is equivalent to the projection defined by

\[
x \mapsto \tau(p_{\nu(j,J) \setminus \{1,2,\ldots,k\}}(x) \otimes p_I(x)),
\]

and this projection is equivalent to \( p_{\nu(j,J) \setminus \{1,2,\ldots,k\}} \cup I_j \).

The last claim follows from the definition of the sets \( I_j \) in (5.2).

\[ \square \]

**Lemma 5.5** Let \( J_1, J_2, \ldots \) be finite subsets of \( \mathbb{N} \). Put \( Q = \bigoplus_{i=1}^{\infty} p_{J_i} \in M(A) \). Then

\[
\varphi(Q) \sim \bigoplus_{i=1}^{\infty} \bigoplus_{j=-\infty}^{\infty} p_{\alpha_j(J_i)}.
\]

Moreover, if \( |J_i| \geq |F| \) for all finite subsets \( F \) of \( \mathbb{N} \), then \( |\bigcup_{(j,i) \in G} \alpha_j(J_i)| \geq |G| \) for all finite subsets \( G \) of \( \mathbb{Z} \times \mathbb{N} \).

**Proof:** By (4.4), \( Q = \sum_{i=1}^{\infty} T_i p_{J_i} T_i^* \); and because \( \varphi \) is strictly continuous we get

\[
\varphi(Q) = \sum_{i=1}^{\infty} \varphi(T_i) \varphi(p_{J_i}) \varphi(T_i)^* \sim \bigoplus_{i=1}^{\infty} \varphi(p_{J_i}) \sim \bigoplus_{i=1}^{\infty} \bigoplus_{j=-\infty}^{\infty} \varphi_j(p_{J_i}) \sim \bigoplus_{i=1}^{\infty} \bigoplus_{j=-\infty}^{\infty} p_{\alpha_j(J_i)},
\]

where the first equivalence is proved below (4.3)–(4.4), and the last equivalence follows from Lemma 5.4.

By the Marriage Theorem we can find natural numbers \( t_i \in J_i \) such that \( \{t_i\}_{i \in \mathbb{N}} \) are mutually distinct. Set \( s_{j,i} = \nu(j, t_i) \). Then \( s_{j,i} \) belongs to \( \alpha_j(J_i) \) by Lemma 5.4, and \( \{s_{j,i}\}_{(j,i) \in \mathbb{Z} \times \mathbb{N}} \) are mutually distinct because \( \nu \) is injective and the \( t_i \)'s are mutually distinct. This proves the second claim of the lemma.

**Proof of Proposition 5.2 (iv):** Put \( Q_0 = p_1 \) and put \( Q_n = \varphi^n(Q_0) \). We must show that none of the projections \( Q_n, n \geq 0 \), are properly infinite. It is clear that \( Q_0 \) is finite, and hence not properly infinite.
Use Lemmas 5.4 and 5.5 to see that

\[ Q_1 = \sum_{j=\infty}^{\infty} T^* S_j \varphi_j(p_1) S_j^* T \sim \bigoplus_{j=\infty}^{\infty} \varphi_j(p_1) \sim \bigoplus_{j=\infty}^{0} p_{\nu(j,1)} \oplus \bigoplus_{j=1}^{\infty} p_{t_j} = \bigoplus_{j=-\infty}^{\infty} p_{J_j}, \]

where \( J_j = \{ \nu(j,1) \} \) for \( j \leq 0 \) and \( J_j = I_j \) for \( j \geq 1 \). It is easily seen that the sequence of sets \( \{ J_j \}_{j=-\infty}^{\infty} \) satisfies the condition \( |\bigcup_{j \in F} J_j| \geq |F| \) for all finite subsets \( F \) of \( \mathbb{Z} \). Hence \( Q_1 \) is not properly infinite by Proposition 4.5 (i).

The claim that \( Q_n \) is not properly infinite for all \( n \) follows by induction using Lemma 5.5 and Proposition 4.5 (i). \( \square \)

**Theorem 5.6** Consider the inductive limit \( B \) of the sequence:

\[
\mathcal{M}(C(Z) \otimes K) \xrightarrow{\varphi} \mathcal{M}(C(Z) \otimes K) \xrightarrow{\varphi} \mathcal{M}(C(Z) \otimes K) \xrightarrow{\varphi} \cdots \longrightarrow B.
\]

Then \( B \) has the following properties:

(i) \( B \) is unital and simple.

(ii) The unit of \( B \) is infinite.

(iii) \( B \) contains a non-zero finite projection.

(iv) \( K_0(B) = 0 \) and \( K_1(B) = 0 \).

**Proof:** (i). \( B \) is unital being the inductive limit of a sequence of unital \( C^* \)-algebras with unital connecting maps.

Write again \( A \) for \( C(Z) \otimes K \), and let \( \varphi_{\infty,n} : \mathcal{M}(A) \to B \) be the inductive limit map from the \( n \)th copy of \( \mathcal{M}(A) \) into \( B \). Let \( L \) be a non-zero closed two-sided ideal in \( B \), and set

\[ L_n = \varphi_{\infty,n}^{-1}(L) \triangleleft \mathcal{M}(A). \]

Then \( L_n \) is non-zero for some \( n \). Since \( A \) is an essential ideal in \( \mathcal{M}(A) \), also \( A \cap L_n \) is non-zero.

Take a non-zero element \( e \) in \( A \cap L_n \). Then \( \varphi(e) \) belongs to \( L_{n+1} \), hence \( A \varphi(e) \subseteq L_{n+1} \), and so it follows from Proposition 5.2 (ii) that \( A \subseteq L_{n+1} \). Take now a full element \( f \) in \( A \subseteq L_{n+1} \). Then \( \varphi(f) \) belongs to \( L_{n+2} \). It follows from Proposition 5.2 (i) that \( \varphi(f) \) is full in \( \mathcal{M}(A) \) and therefore \( L_{n+2} = \mathcal{M}(A) \). Hence \( L = B \), and this shows that \( B \) is simple.

(ii). This is clear because the unit of \( \mathcal{M}(A) \) is infinite.
(iii). As in the proof of Proposition 5.2 (iv), set \( Q_0 = p_1 \) and \( Q_n = \varphi^n(Q_0) \) for \( n \geq 1 \). Put \( Q = \varphi_{\infty,0}(Q_0) \in B \). It is shown in Proposition 5.2 (ii) that \( \varphi \) is injective, which implies that \( \varphi_{\infty,0} \) is injective, and hence \( Q \) is non-zero. We show next that \( Q \) is finite.

Assume that \( Q \) were infinite. Then \( Q \) is properly infinite by Cuntz’ result (see Proposition 2.1) because \( B \) is simple. Applying Proposition 2.3 to the sequence

\[
Q_0 M(A)Q_0 \xrightarrow{\lambda_0} Q_1 M(A)Q_1 \xrightarrow{\lambda_1} Q_2 M(A)Q_2 \rightarrow \cdots \rightarrow QBQ,
\]

with the unital connecting maps \( \lambda_j = \varphi_{|Q_j M(A)Q_j} \), we obtain that \( Q_n \) is properly infinite for all sufficiently large \( n \). But this contradicts Proposition 5.2 (iv).

(iv). This follows from the fact that the multiplier algebra of a stable \( C^* \)-algebra has trivial \( K \)-theory (see [7, Proposition 12.2.1]).

It follows Proposition 5.2 (ii) and Proposition 5.2 (i) that the finite projection \( Q \) in \( B \) (found in part (iii) above) satisfies

\[
Q \oplus Q \sim \varphi_{\infty,0}(Q_0 \oplus Q_0) = \varphi_{\infty,0}(p_1 \oplus p_1) \simeq \varphi_{\infty,0}(g) = \varphi_{\infty,1}(\varphi(g)) \sim 1,
\]

whence \( Q \oplus Q \sim 1 \) by Lemma 4.3. In other words, the corner \( C^* \)-algebra \( QBQ \) is unital, finite, and simple, and \( M_2(QBQ) \cong B \) is infinite.

The \( C^* \)-algebra \( B \) from Theorem 5.6 is not separable and not exact. To see the latter, note that \( B(H) \), the bounded operators on a separable, infinite dimensional Hilbert space \( H \), can be embedded into \( M(A) = M(C(Z) \otimes K) \) and hence into \( B \). As \( B(H) \) is non-exact (see Wasserman [43, 2.5.4]) it follows from Kirchberg’s result that exactness passes to sub-\( C^* \)-algebras (see [43, 2.5.2]) that \( B \) is non-exact. We use the lemma below from [3] to construct a non-exact separable example.

**Lemma 5.7 (Blackadar)** Let \( B \) be a simple \( C^* \)-algebra and let \( X \) be a countable subset of \( B \). It follows that \( B \) has a separable, simple sub-\( C^* \)-algebra \( B_0 \) that contains \( X \).

**Corollary 5.8** There exists a unital, separable, non-exact, simple \( C^* \)-algebra \( B_0 \) such that \( B_0 \) contains an infinite and a non-zero finite projection.

**Proof:** Let \( B \) be as in Theorem 5.6. Let \( s \) be a non-unitary isometry in \( B \) and let \( q \) be a non-zero finite projection in \( B \). The universal \( C^* \)-algebra, \( C^*(\mathbb{F}_2) \), generated by two unitaries is separable and non-exact (see Wassermann [43, Corollary 3.7]). It admits an
embedding into $M(C(Z) \otimes K)$ and hence into $B$. Let $u, v \in B$ be the images of the two (canonical) unitary generators in $C^*(\mathbb{F}_2)$. Use Lemma 5.7 to find a separable, simple, and unital $C^*$-algebra $B_0$ that contains $\{u, v, s, q\}$.

Then $B_0$ is infinite because it contains the non-unitary isometry $s$; and it contains the finite projection $q$. Finally, $B_0$ is non-exact because it contains the non-exact sub-$C^*$-algebra $C^*(u, v) \cong C^*(\mathbb{F}_2)$. 

\[\square\]

6 A nuclear example

We show here that an elaboration of the construction in Section 5 yields a nuclear and separable example of a simple $C^*$-algebra with a finite and an infinite projection.

The construction requires that we make a specific choice for the injective map $\nu: \mathbb{Z} \times \mathbb{N} \to \mathbb{N}$ from Section 5.

Let $\{\Lambda_r\}_{r=0}^\infty$ be a partition of the set $\mathbb{N}$ such that $\Lambda_0 = \{1\}$ and such that $\Lambda_r$ is infinite for each $r \geq 1$. For each $r \geq 1$ choose an injective map $\gamma_r: \mathbb{Z} \times \Lambda_{r-1} \to \Lambda_r$ and define $\nu: \mathbb{Z} \times \mathbb{N} \to \mathbb{N}$ by:

$$\nu(j, t) = \gamma_r(j, t), \quad r \in \mathbb{N}, \ t \in \Lambda_{r-1}, \ j \in \mathbb{Z}. \quad (6.1)$$

Observe that

$$t \in \Lambda_r \iff \nu(j, t) \in \Lambda_{r+1}, \quad j \in \mathbb{Z}. \quad (6.2)$$

To see that $\nu$ is injective assume that $\nu(j, t) = \nu(i, s)$. Then $\nu(j, t) = \nu(i, s) \in \Lambda_r$ for some $r \geq 1$. Therefore both $s$ and $t$ belong to $\Lambda_{r-1}$. Now, $\gamma_r(j, t) = \nu(j, t) = \nu(i, s) = \gamma_r(i, s)$, which entails that $(j, t) = (i, s)$ by injectivity of $\gamma_r$.

Let $\alpha_j$ be as defined in Lemma 5.4 (wrt. the new choice of $\nu$). Let $\Gamma_0 \subseteq P(\mathbb{N})$ be the family containing the one set $\{1\}$, and set

$$\Gamma_{n+1} = \{\alpha_j(I) \mid I \in \Gamma_n, \ j \in \mathbb{Z}\} \subseteq P(\mathbb{N}),$$

for $n \geq 0$. Set $\Gamma = \bigcup_{n=0}^\infty \Gamma_n$. Observe that each $I \in \Gamma$ is a finite subset of $\mathbb{N}$.

Put $Q_0 = p_1 \in A$ (cf. (4.1)) and put $Q_n = \mathfrak{F}^n(Q_0) \in \mathcal{M}(A)$ (where $\mathfrak{F}$ is the endomorphism on $\mathcal{M}(A)$ defined in Section 5 above Proposition 5.2). It then follows by induction
from Lemma 5.5 that
\[ Q_n \sim \bigoplus_{I \in \Gamma} p_I, \quad n \geq 0, \quad (6.3) \]

when \( p_I \in A \) is as defined in (6.2).

**Lemma 6.1** There is an injective function \( t: \Gamma \to \mathbb{N} \) such that \( t(I) \in I \) for all \( I \in \Gamma \). It follows in particular that
\[ | \bigcup_{I \in F} I | \geq |F| \]
for all finite subsets \( F \) of \( \Gamma \).

**Proof:** Define \( t \) recursively on each \( \Gamma_n \) as follows. For \( n = 0 \) we set \( t(\{1\}) = 1 \). Assume that \( t \) has been defined on \( \Gamma_{n-1} \) for some \( n \geq 1 \). Then define \( t \) on \( \Gamma_n \) by
\[ t(\alpha_j(I)) = \nu(j, t(I)) \]
for \( I \in \Gamma_{n-1} \) and \( j \in \mathbb{Z} \). It follows from Lemma 5.4 that \( t(I) \in I \) for all \( I \in \Gamma \).

It therefore follows by induction that \( t(I) \in I \) for all \( I \in \Gamma \).

We show next that \( t(I) \in \Lambda_n \) if \( I \in \Gamma_n \). This is clear for \( n = 0 \). Let \( n \geq 1 \) and let \( I \in \Gamma_n \) be given. Then \( I = \alpha_j(I') \) for some \( I' \in \Gamma_{n-1} \) and some \( j \in \mathbb{Z} \). It follows that \( t(I) = t(\alpha_j(I')) = \nu(j, t(I')) \). Hence \( t(I) \in \Lambda_n \) if \( t(I') \in \Lambda_{n-1} \), cf. (6.2). Now the claim follows by induction on \( n \).

We proceed to show that \( t \) is injective. If \( I, J \in \Gamma \) are such that \( t(I) = t(J) \), then \( t(I) = t(J) \in \Lambda_n \) for some \( n \), whence \( I, J \) both belong to \( \Gamma_n \). It therefore suffices to show that \( t|_{\Gamma_n} \) is injective for each \( n \). We prove this by induction on \( n \). It is trivial that \( t|_{\Gamma_0} \) is injective. Assume that \( t|_{\Gamma_{n-1}} \) is injective for some \( n \geq 1 \). Let \( I, J \in \Gamma_n \) be such that \( t(I) = t(J) \). Then \( I = \alpha_i(I') \) and \( J = \alpha_j(J') \) for some \( i, j \in \mathbb{Z} \) and some \( I', J' \in \Gamma_{n-1} \), and
\[ \nu(i, t(I')) = t(\alpha_i(I')) = t(I) = t(J) = t(\alpha_j(J')) = \nu(j, t(J')). \]

Since \( \nu \) is injective we deduce that \( i = j \) and \( t(I') = t(J') \). By injectivity of \( t|_{\Gamma_{n-1}} \) we obtain \( I' = J' \), and this proves that \( I = J \). It has now been shown that \( t|_{\Gamma_n} \) is injective, and the induction step is complete. \( \square \)

Let \( g \in A = C(Z, K) \) be a constant 1-dimensional projection, and let \( Q_n \) be as defined above (6.3).
Lemma 6.2  For each natural number $m$ we have

$$g \preceq Q_0 \oplus Q_1 \oplus \cdots \oplus Q_m \quad \text{in } \mathcal{M}(A).$$

Proof: From (6.3) (and Lemma 4.2) we deduce that

$$Q_0 \oplus Q_1 \oplus \cdots \oplus Q_n \sim \bigoplus_{I \in \Gamma_0 \cup \cdots \cup \Gamma_n} p_I.$$ 

The claim of the lemma now follows from Proposition 4.5 (i) together with Lemma 6.1. $\square$

As in Theorem 5.6 consider the inductive limit

$$\mathcal{M}(A) \xrightarrow{\varphi} \mathcal{M}(A) \xrightarrow{\varphi} \mathcal{M}(A) \xrightarrow{\varphi} \cdots \xrightarrow{\varphi} B,$$  \hspace{1cm} (6.4)

where $A = C(Z) \otimes K$. Let $\mu_{\infty,n} : \mathcal{M}(A) \to B$ be the inductive limit map (from the $n$th copy of $\mathcal{M}(A)$) for $n \geq 0$. The endomorphism $\varphi$ on $\mathcal{M}(A)$ extends to an automorphism $\alpha$ on $B$ that satisfies $\alpha(\mu_{\infty,n}(x)) = \mu_{\infty,n}(\varphi(x))$ for $x \in \mathcal{M}(A)$ and all $n \in \mathbb{N}$. (The inverse of $\alpha$ is on the dense subset $\bigcup_{n=0}^{\infty} \mu_{\infty,n}(\mathcal{M}(A))$ of $B$ given by $\alpha^{-1}(\mu_{\infty,n}(x)) = \mu_{\infty,n+1}(x)$.)

Put $A_0 = \mu_{\infty,0}(A) \subseteq B$, put $A_n = \alpha^n(A_0) \subseteq B$ for all $n \in \mathbb{Z}$, and put

$$D_n = C^*(A_{-n}, A_{-n+1}, \ldots, A_0, \ldots A_{n-1}, A_n), \quad D = \bigcup_{n=1}^{\infty} D_n.$$  \hspace{1cm} (6.5)

It is shown in Lemma 6.6 below that each $D_n$ is a type I $C^*$-algebra, and so the $C^*$-algebra $D$ is an inductive limit of type I algebras. In particular, $D$ is nuclear and belongs to the UCT class $\mathcal{N}$. Moreover, $D$ is $\alpha$-invariant (by construction). Observe that $A_{m-n} = \mu_{\infty,n}(\varphi^m(A))$ for all non-negative integers $m$ and $n$.

Put $Q = \mu_{\infty,0}(p_1) (= \mu_{\infty,n}(Q_n))$ in $D \subseteq B$, and, as above, let $g \in A = C(Z,K)$ be a constant 1-dimensional projection.

Lemma 6.3  The following two relations hold in $D$ and in $B$:

(i) $\mu_{\infty,0}(g) \preceq Q \oplus Q$.

(ii) $\mu_{\infty,0}(g) \preceq \bigoplus_{j=-N}^{N} \alpha^j(Q)$ for all natural numbers $N$.

Proof: (i) follows immediately from Proposition 4.5 (ii).
(ii). Assume, to reach a contradiction, that \( \mu_{\infty,0}(g) \preceq \sum_{j=-N}^N \alpha^j(Q) \) in \( B \) (or in \( D \)) for some \( N \in \mathbb{N} \). For \( j \geq -N \) we have

\[
\alpha^j(Q) = \alpha^j(\mu_{\infty,0}(Q_0)) = \alpha^j(\mu_{\infty,N}(\varphi^N(Q_0))) = \mu_{\infty,N}(\varphi^{N+j}(Q_0)).
\]

The relation \( \mu_{\infty,0}(g) \preceq \sum_{j=-N}^N \alpha^j(Q) \) can therefore be rewritten as

\[
\mu_{\infty,N}(\varphi^N(g)) \preceq \bigoplus_{j=0}^{2N} \mu_{\infty,N}(\varphi^j(Q_0)) \quad \text{in } B.
\]

By a standard property of inductive limits this entails that

\[
\mu_{M,N}(\varphi^N(g)) \preceq \bigoplus_{j=0}^{2N} \mu_{M,N}(\varphi^j(Q_0)) \quad \text{in } \mathcal{M}(A),
\]

for some \( M \geq N \), or, equivalently,

\[
\varphi^M(g) \preceq \bigoplus_{j=0}^{2N} \varphi^{j+M-N}(Q_0) = \bigoplus_{j=M-N}^{N+M} \varphi^j(Q_0) = \bigoplus_{j=M-N}^{N+M} Q_j \preceq \bigoplus_{j=0}^{N+M} Q_j \quad \text{in } \mathcal{M}(A).
\]

Use now that \( g \preceq \varphi^M(g) \) (which holds because \( \varphi_j(g) = g \) for \( j \leq 0 \), cf. (5.3)) to conclude that \( g \preceq \bigoplus_{j=0}^{N+M} Q_j \) in \( \mathcal{M}(A) \), in contradiction with Lemma 6.2. \( \square \)

Let \( C \) be an arbitrary unital \( C^* \)-algebra and let \( \gamma \) be an automorphism on \( C \).

Let \( K \) denote the compact operators on \( \ell^2(\mathbb{Z}) \) and let \( \{ e_{i,j} \}_{i,j \in \mathbb{Z}} \) be a set of matrix units for \( K \). Define a unital injective \( * \)-homomorphism \( \psi: C \to \mathcal{M}(C \otimes K) \) and a unitary \( U \in \mathcal{M}(C \otimes K) \) by

\[
\psi(c) = \sum_{n \in \mathbb{Z}} \gamma^n(c) \otimes e_{n,n}, \quad U = \sum_{n \in \mathbb{Z}} 1 \otimes e_{n,n+1}, \quad c \in C,
\]

(the sums converge strictly in \( \mathcal{M}(C \otimes K) \)). It is easily seen that

\[
U \psi(c) U^* = \psi(\gamma(c)), \quad c \in C,
\]

so that \( \psi \) extends to a representation \( \tilde{\psi}: C \rtimes_{\gamma} \mathbb{Z} \to \mathcal{M}(C \otimes K) \). The following standard argument shows that the representation \( \tilde{\psi} \) is faithful.

Put \( V_t = \sum_{n \in \mathbb{Z}} 1 \otimes t^{-n} e_{n,n} \in \mathcal{M}(C \otimes K) \) for \( t \in \mathbb{T} \), and check that \( V_t \) is a unitary element that satisfies \( V_t \psi(c)V_t^* = \psi(c) \) and \( V_t U V_t^* = tU \) for all \( t \in \mathbb{T} \). Let \( E: C \rtimes_{\gamma} \mathbb{Z} \to \mathcal{M}(C \otimes K) \).
$C$ be the canonical faithful conditional expectation, and define $F: \text{Im}(\tilde{\psi}) \to \text{Im}(\tilde{\psi})$ by $F(x) = \int_T V_t x V_t^* \, dt$. Then $F(\tilde{\psi}(x)) = \psi(E(x))$ for all $x \in C \rtimes_\gamma \mathbb{Z}$. Now, if $\tilde{\psi}(x) = 0$ for some positive element $x$ in $C \rtimes_\gamma \mathbb{Z}$, then $\psi(E(x)) = F(\tilde{\psi}(x)) = 0$, whence $E(x) = 0$ (by injectivity of $\psi$), and $x = 0$ (because $E$ is faithful).

**Lemma 6.4** Let $C$ be a unital $C^*$-algebra and let $\gamma$ be an automorphism on $C$. Suppose that $p, q$ are projections in $C$ such that

(i) $p \precsim \bigoplus_{j=1}^m q$ in $C$ for some natural number $m$, and

(ii) $p \precsim \bigoplus_{j=-N}^N \gamma^j(q)$ for all natural numbers $N$.

Then $q$ is not properly infinite in $C \rtimes_\gamma \mathbb{Z}$.

**Proof:** It suffices to show that $\psi(q)$ is not properly infinite in $\mathcal{M}(C \otimes \mathcal{K})$. Assume, to reach a contradiction, that $\psi(q)$ is properly infinite in $\mathcal{M}(C \otimes \mathcal{K})$. Then $\bigoplus_{j=1}^m \psi(q) \precsim \psi(q)$ by Proposition 2.1. As $q \otimes e_{0,0} \leq \psi(q)$ we can use (i) to obtain

$$p \otimes e_{0,0} \precsim \bigoplus_{j=1}^m q \otimes e_{0,0} \leq \bigoplus_{j=1}^m \psi(q) \precsim \psi(q) = \sum_{j=-\infty}^{\infty} \gamma^j(q) \otimes e_{j,j}$$

in $\mathcal{M}(C \otimes \mathcal{K})$. By Lemma 4.4 this entails that

$$p \otimes e_{0,0} \precsim \sum_{j=-N}^{N} \gamma^j(q) \otimes e_{j,j} \text{ in } C \otimes \mathcal{K},$$

for some $N \in \mathbb{N}$, or, equivalently, that $p \precsim \bigoplus_{j=-N}^{N} \gamma^j(q)$ in $C$, in contradiction with assumption (ii).

Returning now to our specific $C^*$-algebra $B$ from (6.4), Lemmas 6.3 and 6.4 imply that:

**Lemma 6.5** The projection $Q = \mu_{\infty,0}(p_1)$ is not properly infinite in $B \rtimes_\alpha \mathbb{Z}$.

**Lemma 6.6** The $C^*$-algebra $D_n = C^*(A_{-n}, A_{-n+1}, \ldots, A_0, \ldots, A_n)$ is of type I for each $n \in \mathbb{N}$.

**Proof:** Note first that

$$A_n A_m \subseteq A_{\min\{n,m\}}, \quad n, m \in \mathbb{Z}. \quad (6.6)$$
Indeed, we can assume without loss of generality that \( n \leq m \), and then deduce

\[
A_n A_m = \alpha^n(\mu_{\infty,0}(A\varphi^{m-n}(A))) \subseteq \alpha^n(\mu_{\infty,0}(A)) = A_n.
\]

Since \( A \cap \varphi^{m-n}(A) = \{0\} \) when \( n < m \), cf. Proposition 5.2 (ii), it follows also that

\[
A_n \cap A_m = \{0\}, \quad n \neq m. \tag{6.7}
\]

Use (6.8) to see that the \( \mathcal{C}^* \)-algebra \( D_{m,n} \) generated by \( A_m, A_{m+1}, \ldots, A_n \), for \( m \leq n \), is equal to

\[
D_{m,n} = A_m + A_{m+1} + \cdots + A_{n-1} + A_n. \tag{6.8}
\]

(To see that the right-hand side of (6.8) is norm closed, use successively the fact that if \( E \) is a \( \mathcal{C}^* \)-algebra, \( I \) is a closed two-sided ideal in \( E \), and \( F \) is a sub-\( \mathcal{C}^* \)-algebra of \( E \), then \( I + F \) is a sub-\( \mathcal{C}^* \)-algebra of \( E \).) It follows from (6.6), (6.7), and (6.8) that we have a decomposition series

\[
0 \vartriangleleft A_{-n} \vartriangleleft D_{-n,-n+1} \vartriangleleft D_{-n,-n+2} \vartriangleleft \cdots \vartriangleleft D_{-n,n-1} \vartriangleleft D_{-n,n} = D_n
\]

for \( D_n \) and that each successive quotient is isomorphic to \( A = \mathcal{C}(\mathbb{Z}) \otimes \mathbb{K} \). This proves that \( D_n \) is a type I \( \mathcal{C}^* \)-algebra. \( \square \)

**Lemma 6.7** The crossed product \( \mathcal{C}^* \)-algebra \( D \rtimes_\alpha \mathbb{Z} \) contains an infinite projection and a non-zero projection which is not properly infinite. The \( \mathcal{C}^* \)-algebra \( D \) has no non-trivial \( \alpha^n \)-invariant closed two-sided ideal for any non-zero integer \( n \).

**Proof:** The projection \( Q = \mu_{\infty,0}(p_1) \) belongs to \( A_0 = \mu_{\infty,0}(A) \subseteq D \), and it is non-zero because \( \mu_{\infty,0} \) is injective (which again is because \( \varphi \) is injective). We have \( D \subseteq B \) and hence

\[
Q \in D \rtimes_\alpha \mathbb{Z} \subseteq B \rtimes_\alpha \mathbb{Z}.
\]

Since \( Q \) is not properly infinite in \( B \rtimes_\alpha \mathbb{Z} \) (by Lemma 5.3) it follows that \( Q \) is not properly infinite in \( D \rtimes_\alpha \mathbb{Z} \).

Put \( P = \mu_{\infty,0}(g) \in A_0 \subseteq D \), where \( g \) is a constant 1-dimensional projection in \( A = \mathcal{C}(\mathbb{Z}) \otimes \mathbb{K} \).
\( C(Z, \mathcal{K}) \). We have

\[
g = \phi_0(g) \sim S_0\phi_0(g)S_0^* < \sum_{j=-\infty}^{\infty} S_j\phi_j(g)S_j^* = \overline{\phi}(g),
\]

cf. \((5.3)\). Hence \( P = \mu_{\infty,0}(g) \) is equivalent to a proper subprojection of \( \mu_{\infty,0}(\overline{\phi}(g)) \). As \( \mu_{\infty,0}(\overline{\phi}(g)) = \alpha(\mu_{\infty,0}(g)) \sim P \) in \( D \times_\alpha \mathbb{Z} \) we conclude that \( P \) is an infinite projection in \( D \times_\alpha \mathbb{Z} \).

Suppose that \( n \) is a non-zero integer (that we can take to be positive) and that \( I \) is a non-zero closed two-sided \( \alpha_n \)-invariant ideal in \( D \). Then \( I \cap D_{kn} \) is non-zero for some natural number \( k \), cf. \((5.3)\). As \( I \) is \( \alpha_n \)-invariant, \( I \cap \alpha_{kn}(D_{kn}) \) is non-zero, and

\[
\alpha_{kn}(D_{kn}) = C^*(A_0, A_1, \ldots, A_{2kn}) = \mu_{\infty,0}(C^*(A, \overline{\phi}(A), \ldots, \overline{\phi}(2kn)(A))).
\]

Because \( A_0 = \mu_{\infty,0}(A) \) is an essential ideal in \( \alpha_{kn}(D_{kn}) \) it follows that \( I \cap A_0 \) is non-zero. Take a non-zero element \( f \) in \( I \cap A_0 \), and write \( f = \mu_{\infty,0}(f_0) \) for some non-zero element \( f_0 \) in \( A \). Use Proposition \((5.2)\) \((iii)\) to conclude that

\[
A_{-m}f = \mu_{\infty,0}(A_{\overline{\phi}_m}(f_0))
\]

is full in \( \mu_{\infty,0}(A) = A_{-m} \), and hence that \( A_{-m} \subseteq I \), for every natural number \( m \). Since \( I \) is \( \alpha_n \)-invariant, \( A_{-m+rn} = \alpha^n(A_{-m}) \subseteq I \) for all \( m \in \mathbb{N} \) and all \( r \in \mathbb{Z} \). This shows that \( A_m \subseteq I \) for all \( m \), which finally entails that \( I = D \). \( \square \)

We remind the reader of the notion of properly outer automorphism introduced by Elliott in \([19]\):

**Definition 6.8** An automorphism \( \gamma \) on a \( C^* \)-algebra \( E \) is called properly outer if for every non-zero \( \gamma \)-invariant closed two-sided ideal \( I \) of \( E \) and for every unitary \( u \) in \( \mathcal{M}(I) \) one has \( \| \gamma|_I - \text{Ad} u \| = 2 \) (the norm is the operator norm).

Olesen and Pedersen list in \([34, \text{Theorem 6.6}]\) eleven conditions on an automorphism \( \gamma \) that all are equivalent to \( \gamma \) being properly outer. We shall use the following sufficient (but not necessary) condition for being properly outer: If \( E \) has no non-trivial \( \gamma \)-invariant ideals and if \( \gamma(p) \sim p \) for some projection \( p \) in \( E \), then \( \gamma \) is properly outer. To see this, note first that \( p \sim upu^* = (\text{Ad} u)(p) \) for every unitary \( u \) in \( \mathcal{M}(E) \) (the equivalence holds relatively to \( E \)). We therefore have \( \gamma(p) \sim (\text{Ad} u)(p), \) whence \( \| \gamma(p) - (\text{Ad} u)(p) \| = 1. \) This shows that \( \| \gamma - \text{Ad} u \| \geq 1 \) for all unitaries \( u \) in \( \mathcal{M}(E) \), whence \( \gamma \) is properly outer (by \((ii) \Leftrightarrow \)...
(iii) of [34, Theorem 6.6]).

One can argue along another line by taking an approximate unit \( \{ e_\lambda \} \) for \( E \), such that \( e_\lambda \geq p \) for all \( \lambda \), and set \( x_\lambda = 2p - e_\lambda \). Then \( x_\lambda \) is a contraction in \( E \) for all \( \lambda \), and one can check that \( \lim_{\lambda \to \infty} \| \gamma(x_\lambda) - (\text{Ad } u)(x_\lambda) \| = 2 \), thus showing directly that \( \| \gamma - \text{Ad } u \| = 2 \) for all unitaries \( u \) in \( \mathcal{M}(E) \) whenever \( \gamma(p) \sim p \) for some projection \( p \) in \( E \).

More generally, \( \gamma \) is properly outer if for each non-zero \( \gamma \)-invariant ideal \( I \) of \( E \) there is a projection \( p \) in \( I \) such that \( \gamma(p) \sim p \).

**Lemma 6.9** The automorphism \( \alpha^n \) on \( D \) is properly outer for every non-zero integer \( n \).

**Proof:** We know from Lemma 6.7 that \( D \) has no \( \alpha^n \)-invariant ideals (when \( n \neq 0 \)), so the lemma will follow from the claim (verified below) that \( \alpha^n(Q) \sim Q \) for all \( n \neq 0 \) (where \( Q \) is as in Lemma 6.3).

Assume, to reach a contradiction, that \( \alpha^n(Q) \sim Q \) for some non-zero integer \( n \) (that we can take to be positive). Then, by Lemma 6.3 (i), \( \mu_{\infty,0}(g) \precsim Q \oplus Q \sim Q \oplus \alpha^n(Q) \precsim \bigoplus_{j=0}^n \alpha^j(Q) \) in \( D \), in contradiction with Lemma 6.3 (ii). \( \square \)

We now have all ingredients to prove our main result:

**Theorem 6.10** There is a separable \( C^* \)-algebra \( D \) and an automorphism \( \alpha \) on \( D \) such that:

(i) \( D \) is an inductive limit of type I \( C^* \)-algebras.

(ii) \( D \rtimes_{\alpha} \mathbb{Z} \) is simple and contains an infinite and a non-zero finite projection.

(iii) \( D \rtimes_{\alpha} \mathbb{Z} \) is nuclear and belongs to the UCT class \( \mathcal{N} \).

**Proof:** Let \( D \) be the \( C^* \)-algebra and let \( \alpha \) the automorphism on \( D \) defined in (and above) (6.5). Since \( D \) is the union of an increasing sequence of sub-\( C^* \)-algebras \( D_n \) (cf. (6.5)) and each \( D_n \) is of type I (by Lemma 6.6), we conclude that \( D \) is an inductive limit of type I \( C^* \)-algebras, and hence that the crossed product \( D \rtimes_{\alpha} \mathbb{Z} \) is nuclear, separable, and belongs to the UCT class \( \mathcal{N} \).

Since \( D \) has no non-trivial \( \alpha \)-invariant ideals (by Lemma 6.7) and \( \alpha^n \) is properly outer for all \( n \neq 0 \) (by Lemma 6.9), it follows from Olesen and Pedersen, [34, Theorem 7.2], (a result that extends results from Elliott, [19], and Kishimoto, [31]) that \( D \rtimes_{\alpha} \mathbb{Z} \) is simple. By simplicity of \( D \rtimes_{\alpha} \mathbb{Z} \), the (non-zero) projection \( Q \), which in Lemma 6.7 is proved to be not properly infinite, must be finite in \( D \rtimes_{\alpha} \mathbb{Z} \), cf. Proposition 2.1. The existence of an infinite projection in \( D \rtimes_{\alpha} \mathbb{Z} \) follows from Lemma 6.7, and this completes the proof. \( \square \)
7 Applications of the main results

We begin by listing some corollaries to Theorems 5.6 and 6.10.

**Corollary 7.1** There is a nuclear, unital, separable, infinite, simple $C^*$-algebra $A$ in the UCT class $\mathcal{N}$ such that $A$ is not purely infinite.

**Proof:** Take the $C^*$-algebra $D \rtimes_\alpha \mathbb{Z}$ from Theorem 6.10, and take a properly infinite projection $p$ and a non-zero finite projection $q$ in that $C^*$-algebra. Then $q \sim q_0 \leq p$ for some projection $q_0$ in $D \rtimes_\alpha \mathbb{Z}$ by Lemma 2.2. Hence $A = p(D \rtimes_\alpha \mathbb{Z})p$ is infinite; and $A$ is not purely infinite because it contains the non-zero finite projection $q_0$. \hfill \Box

**Corollary 7.2** There is a nuclear, unital, separable, finite, simple $C^*$-algebra $A$ that is not stably finite, and hence does not admit a tracial state (nor a non-zero quasitrace).

**Proof:** Take the $C^*$-algebra $E = D \rtimes_\alpha \mathbb{Z}$ from Theorem 6.10 and a non-zero finite projection $q$ in $E$. Put $A = qEq$. Then $A$ is finite, simple, and unital. Since $A \otimes \mathcal{K} \cong E \otimes \mathcal{K}$ we conclude that $A \otimes \mathcal{K}$ (and hence $M_n(A)$ for some large enough $n$) contains an infinite projection, so $A$ is not stably finite.

Every simple, infinite $C^*$-algebra is properly infinite, so $M_n(A)$ is properly infinite. No properly infinite $C^*$-algebra can admit a non-zero trace (or a quasitrace), so $M_n(A)$, and hence $A$, do not admit a tracial state (nor a non-zero quasitrace). \hfill \Box

A $C^*$-algebra $A$ is said to have the **cancellation property** if the implication

\[ p \oplus r \sim q \oplus r \implies p \sim q \]  

(7.1)

holds for all projections $p, q, r$ in $A \otimes \mathcal{K}$. It is known that all $C^*$-algebras of stable rank one have the cancellation property and that no infinite $C^*$-algebra has the cancellation property. There is no example of a stably finite, simple $C^*$-algebra which is known not to have the cancellation property (but Villadsen’s $C^*$-algebras from [12] are candidates).

A $C^*$-algebra $A$ is said to have the **weak cancellation property** if (7.1) holds for those projections $p, q, r$ in $A \otimes \mathcal{K}$ where $p$ and $q$ generate the same ideal of $A$.

**Corollary 7.3** There is a nuclear, unital, separable, simple $C^*$-algebra $A$ that does not have the weak cancellation property.
Proof: Take $A$ as in Corollary 7.1, and take a non-zero finite projection $q$ in $A$. Since $A$ is properly infinite, we can find isometries $s_1, s_2$ in $A$ with orthogonal range projections; cf. Proposition 2.1. Put $p = s_1qs_1^* + (1 - s_1s_1^*)$. Then $p$ is infinite because $s_2s_2^* \leq p$, and so $p \sim q$ (because $q$ is finite). On the other hand, $q$ and $p$ generate the same ideal of $A$—namely $A$ itself—and

$$p \oplus 1 = (s_1qs_1^* + (1 - s_1s_1^*)) \oplus 1 \sim s_1qs_1^* \oplus (1 - s_1s_1^*) \oplus s_1s_1^* \sim q \oplus 1.$$

□

It was shown in [30, Theorem 9.1] that the following implications hold for any separable $C^*$-algebra $A$ and for any free filter $\omega$ on $\mathbb{N}$:

\[
A \text{ is purely infinite } \implies A \text{ is weakly purely infinite } \iff A_\omega \text{ is traceless } \implies A \text{ is traceless },
\]

and the first three properties are equivalent for all simple $C^*$-algebras $A$. (A $C^*$-algebra is here said to be traceless if no algebraic ideal in $A$ admits a non-zero quasitrace. See [30] for the definition of being weakly purely infinite.) It was not known in [30] if the reverse of the third implication holds (for simple or for non-simple $C^*$-algebras), but we can now answer this in the negative:

**Corollary 7.4** Let $\omega$ be any free filter on $\mathbb{N}$. There is a nuclear, unital, separable, simple $C^*$-algebra $A$ which is traceless, but where $\ell^\infty(A)$ and $A_\omega$ admit non-zero quasitraces defined on some (possibly non-dense) algebraic ideal.

**Proof:** Take $A$ as in Corollary 7.2. Then $A$ is algebraically simple and $A$ admits no (everywhere defined) non-zero quasitrace. Hence $A$ is traceless in the sense of [30]. Because $A$ is simple and not purely infinite, $A_\omega$ cannot be traceless. Since $A_\omega$ is a quotient of $\ell^\infty(A)$, the latter $C^*$-algebra cannot be traceless either. □

Kirchberg has shown in [26] (see also [39, Theorem 4.1.10]) that every exact simple $C^*$-algebra which is tensorially non-prime (i.e., is isomorphic to a tensor product $D_1 \otimes D_2$, where $D_1$ and $D_2$ both are simple non-type I $C^*$-algebras) is either stably finite or purely infinite. Liming Ge has proved in [21] that the $\text{II}_1$-factor $\mathcal{L}(\mathbb{F}_2)$ is (tensorially) prime (in the von Neumann algebra sense), and it follows easily from this result that the $C^*$-algebra
$C_{\text{red}}(\mathbb{F}_2)$ is tensorially prime. We can now exhibit a simple, nuclear $C^*$-algebra that is tensorially prime:

**Corollary 7.5** The $C^*$-algebra $D \rtimes_{\alpha} \mathbb{Z}$ from Theorem 6.10 is simple, separable, nuclear, and tensorially prime, and so is $p(D \rtimes_{\alpha} \mathbb{Z})$ for every non-zero projection $p$ in $D \rtimes_{\alpha} \mathbb{Z}$.

**Proof:** The $C^*$-algebra $D \rtimes_{\alpha} \mathbb{Z}$ is simple, separable, nuclear; cf. Theorem 6.10. It is not stably finite because it contains an infinite projection, and it is not purely infinite because it contains a non-zero finite projection. The (unital) $C^*$-algebra $p(D \rtimes_{\alpha} \mathbb{Z})$ is stably isomorphic to $D \rtimes_{\alpha} \mathbb{Z}$ and is hence also simple, separable, nuclear, and neither stably finite nor purely infinite. It therefore follows from Kirchberg’s theorem (quoted above) that these $C^*$-algebras must be tensorially prime. □

Villadsen’s $C^*$-algebras from [41] and [42] are, besides being simple and nuclear, probably also tensorially prime (although to the knowledge of the author this has not yet been proven). Jiang and Su have in [25] found a non-type I, unital, simple $C^*$-algebra $Z$ for which $A \cong A \otimes Z$ is known to hold for a large class of well-behaved simple $C^*$-algebras $A$, such as for example the irrational rotation $C^*$-algebras and more generally all $C^*$-algebras that are covered by a classification theorem (cf. [20] or [39]). Such $C^*$-algebras $A$ are therefore not tensorially prime.

The real rank of the $C^*$-algebras found in Theorems 6.6 and 6.10 have not been determined, but we guess that they have real rank $\geq 1$. That leaves open the following question:

**Question 7.6** Does there exist a (separable) unital, simple $C^*$-algebra $A$ such that $A$ contains an infinite and a non-zero finite projection, and such that:

(i) $A$ is of real rank zero?

(ii) $A$ is both nuclear and of real rank zero?

It appears to be difficult (if not impossible) to construct simple $C^*$-algebras of real rank zero that exhibit bad comparison properties; cf. Remark 7.8 below.

George Elliott suggested the following:

**Question 7.7** Does there exist a (separable), (nuclear), unital, simple $C^*$-algebra $A$ such that all non-zero projections in $A$ are infinite but $A$ is not purely infinite?
If Question 7.7 has affirmative answer, and \( A \) is a unital, simple \( C^* \)-algebra whose non-zero projections are infinite and \( A \) is not purely infinite, then the real rank of \( A \) cannot be zero. Indeed, a simple \( C^* \)-algebra is purely infinite if and only if it has real rank zero and all its non-zero projections are infinite.

**Remark 7.8 (Comparison and dimension ranges)** Suppose that \( A \) is a unital, simple, infinite \( C^* \)-algebra with a non-zero finite projection \( e \). By simplicity of \( A \) there is a natural number \( k \) such that \( 1 \not\leq e \oplus e \oplus \cdots \oplus e \) (with \( k \) copies of \( e \)). Let \( s_1, s_2, \ldots \) be a sequence of isometries in \( A \) with orthogonal range projections; cf. Proposition 2.1. Letting \([p]\) denote the Murray–von Neumann equivalence class of the projection \( p \), we have

\[
n[1] = [s_1s_1^* + s_2s_2^* + \cdots + s_ns_n^*] \leq [1] \leq k[e]
\]

for every natural number \( n \). But \([1] \not\leq [e] \) because \( e \) is finite and 1 is infinite.

This shows that if \( A \) is a simple \( C^* \)-algebra with a finite and an infinite projection, then the semigroup \( D(A) \) of Murray–von Neumann equivalence classes of projections in \( A \otimes K \) is not weakly unperforated.

(An ordered abelian semigroup \((S, +, \leq)\) is said to be *weakly unperforated* if

\[
\forall g, h \in S \forall n \in \mathbb{N} : ng < nh \implies g \leq h.
\]

The order structure on \( D(A) \) is the algebraic order given by \( g \leq h \) if and only if \( h = g + f \) for some \( f \) in \( D(A) \).)

Villadsen showed in [11] that \( K_0(A) \), and also the semigroup \( D(A) \), of a *simple, stably finite* \( C^* \)-algebra \( A \) can fail to be weakly unperforated. The present article is a natural continuation of Villadsen’s work to the stably infinite case.

Let \((S, +)\) be an abelian semigroup with a zero-element 0. An element \( g \in S \) is called *infinite* if \( g + x = g \) for some non-zero \( x \in S \), and \( g \) is called *finite* otherwise. The sets of finite, respectively, infinite elements in \( S \) are denoted by \( S_{\text{fin}} \) and \( S_{\text{inf}} \). One has \( S = S_{\text{fin}} \uplus S_{\text{inf}} \) and \( S + S_{\text{inf}} \subseteq S_{\text{inf}} \), but the sum of two finite elements can be infinite.

It is standard and easy to see that the finite and infinite elements in the semigroup \( D(A) \) are given by

\[
D_{\text{fin}}(A) = \{[f] : f \text{ is a finite projection in } A\},
\]

\[
D_{\text{inf}}(A) = \{[f] : f \text{ is an infinite projection in } A\}.
\]

If \( A \) is a simple \( C^* \)-algebra that contains an infinite projection, then the Grothendieck
map $\gamma : \mathcal{D}(A) \to K_0(A)$ restricts to an isomorphism $\mathcal{D}_{\text{inf}}(A) \to K_0(A)$ as shown by Cuntz in [16, Section 1]. We can therefore identify $\mathcal{D}_{\text{inf}}(A)$ with $K_0(A)$, in which case we can write

$$\mathcal{D}(A) = \mathcal{D}_{\text{fin}}(A) \amalg K_0(A).$$

Note that $[0]$ belongs to $\mathcal{D}_{\text{fin}}(A)$, and that $\mathcal{D}_{\text{fin}}(A) = \{[0]\}$ if and only if all non-zero projections in $A \otimes K$ are infinite. One can therefore detect the existence of non-zero finite elements in $A \otimes K$ from the semigroup $\mathcal{D}(A)$; and $K_0(A)$ contains all information about $\mathcal{D}(A)$ if and only if all non-zero projections in $A \otimes K$ are infinite.

In general, when $A$ is simple and contains both infinite and non-zero finite projections, then $\mathcal{D}_{\text{fin}}(A)$ can be very complicated and large. One can show that $\mathcal{D}_{\text{fin}}(B)$ is uncountable, when $B$ is as in Theorem 5.6. We have no description of $\mathcal{D}(A)$, when $A = D \rtimes_\alpha \mathbb{Z}$ from Theorem 6.10.

We remark finally, that if $A$ is simple and if $g$ is a non-zero element in $\mathcal{D}_{\text{fin}}(A)$, then $ng \in \mathcal{D}_{\text{inf}}(A)$ for some $n \in \mathbb{N}$. In other words, $\mathcal{D}_{\text{inf}}(A)$ eventually absorbs all non-zero elements in $\mathcal{D}(A)$.

The example found in Theorem 6.10 provides a counterexample to Elliott’s classification conjecture (see for example [20]) as it is formulated (by the author) in [39, Section 2.2]. The conjecture asserts that

$$(K_0(A), K_0(A)^+, [1_A]_0, K_1(A), T(A), r_A : T(A) \to S(K_0(A))) \quad (7.2)$$

is a complete invariant for unital, separable, nuclear, simple $C^*$-algebras. If $A$ is stably infinite (i.e., if $A \otimes K$ contains an infinite projection), then $K_0(A)^+ = K_0(A)$ and $T(A) = \emptyset$. The Elliott invariant for unital, simple, stably infinite $C^*$-algebras therefore degenerates to the triple $(K_0(A), [1_A]_0, K_1(A))$. We say that $(K_0(A), [1_A]_0, K_1(A)) \cong (G_0, g_0, G_1)$ if there are group isomorphisms $\alpha_0 : K_0(A) \to G_0$ and $\alpha_1 : K_1(A) \to G_1$ such that $\alpha_0([1_A]_0) = g_0$.

**Corollary 7.9** There are two non-isomorphic nuclear, unital, separable, simple, stably infinite $C^*$-algebras $A$ and $B$ (both in the UCT class $\mathcal{N}$) such that

$$(K_0(A), [1_A]_0, K_1(A)) \cong (K_0(B), [1_B]_0, K_1(B)).$$

**Proof:** Take the $C^*$-algebra $A$ from Corollary 7.1. It follows from [36, Theorem 3.6] that there is a nuclear, unital, separable, simple, purely infinite $C^*$-algebra $B$ in the UCT class $\mathcal{N}$ such that

$$(K_0(A), [1_A]_0, K_1(A)) \cong (K_0(B), [1_B]_0, K_1(B)).$$
Since $B$ is purely infinite and $A$ is not purely infinite, we have $A \not\cong B$. □

One can amend the Elliott invariant by replacing the triple $(K_0(A), K_0(A)^+, [1_A]_0)$ (for a unital $C^*$-algebra $A$) with the pair $(\mathcal{D}(A), [1_A])$, cf. Remark 7.8 above, where $\mathcal{D}(A)$ carries the structure of a semigroup. In the unital, stably infinite case, the amended invariant will then become $(\mathcal{D}(A), [1_A], K_1(A))$. (Since $K_0(A)$ is the Grothendieck group of $\mathcal{D}(A)$, and $K_0(A)^+$, respectively, $[1_A]_0$, are the images of $\mathcal{D}(A)$, respectively, $[1_A]$, under the Grothendieck map $\gamma: \mathcal{D}(A) \to K_0(A)$, one can recover $(K_0(A), K_0(A)^+, [1_A]_0)$ from $(\mathcal{D}(A), [1_A])$.

The invariant $(\mathcal{D}(A), [1_A])$ can detect if $A$ has a non-zero finite projection, cf. Remark 7.8 and the triples $(\mathcal{D}(A), [1_A], K_1(A))$ and $(\mathcal{D}(B), [1_B], K_1(B))$ are therefore non-isomorphic, when $A$ and $B$ are as in Corollary 7.9. We have no example to show that $(\mathcal{D}(A), [1_A], K_1(A))$ is not a complete invariant for nuclear, unital, simple, separable, stably infinite $C^*$-algebras. On the other hand, there is no evidence to suggest that $(\mathcal{D}(A), [1_A], K_1(A))$ indeed is a complete invariant for this class of $C^*$-algebras.

The Elliott conjecture can also be amended by restricting the class of $C^*$-algebras that are to be classified. One possibility is to consider only those unital, separable, nuclear, simple $C^*$-algebras $A$ for which $A \cong A \otimes \mathcal{Z}$ where $\mathcal{Z}$ is the Jiang–Su algebra (see the comment below Corollary 7.3). It seems plausible that the Elliott invariant (7.2) actually is a complete invariant for this class of $C^*$-algebras; and one could hope that the condition $A \cong A \otimes \mathcal{Z}$ has an alternative intrinsic equivalent formulation, for example in terms of the existence of sufficiently many central sequences.

**Remark 7.10 (A non-simple example)** Examples of non-simple unital $C^*$-algebras $A$, such that $A$ is finite and $M_2(A)$ is infinite, have been known for a long time. Such examples were independently discovered by Clarke in [9] and by Blackadar (see Blackadar [7, Exercise 6.10.1]): One such example is obtained by taking a unital extension

$$
0 \longrightarrow \mathcal{K} \longrightarrow A \longrightarrow C(S^3) \longrightarrow 0
$$

with non-zero index map $\delta: K_1(C(S^3)) \to K_0(\mathcal{K})$. Then $A$ is finite and $M_2(A)$ is infinite.

The proof uses that any isometry or co-isometry $s$ in $A$ (or in a matrix algebra over $A$) is mapped to a unitary element $u$ in (a matrix algebra over) $C(S^3)$; and every unitary $u$ in $M_n(C(S^3))$ lifts to an isometry or a co-isometry $s$ in $M_n(A)$. Moreover, the isometry or co-isometry $s$ is non-unitary if and only if the unitary element $u$ has non-zero index. The unitary group of $C(S^3)$ is connected, so all unitaries here have zero index. Hence $A$ contains no non-unitary isometry, so $A$ is finite. By construction of the extension, the
generator of $K_1(C(S^3))$, which is a unitary element in $M_2(C(S^3))$, has non-zero index, and so it lifts to a non-unitary isometry or co-isometry in $M_2(A)$, whence $M_2(A)$ is infinite.

The $C^*$-algebra $M_2(A)$ is not properly infinite since the quotient, $M_2(A)/M_2(K) \cong M_2(C(S^3))$, is finite.

An example of a unital, finite, (non-simple) $C^*$-algebra $A$ such that $M_2(A)$ is properly infinite was found in [38].

**Remark 7.11 (Inductive limits)** Suppose that

\[ B_1 \longrightarrow B_2 \longrightarrow B_3 \longrightarrow \cdots \longrightarrow B \]

is an inductive limit with unital connecting maps, and that $B$ is a simple $C^*$-algebra such that $B$ is finite and $M_2(B)$ is infinite. Then $M_2(B)$ is properly infinite, and it follows from Proposition 2.3 that $B_n$ is finite and $M_2(B_n)$ is properly infinite for all sufficiently large $n$. It is therefore not possible to construct an example of a simple $C^*$-algebra, which is finite, but not stably finite, by taking an inductive limit of $C^*$-algebras arising as in the example described in Remark 7.10.

**Remark 7.12 (Free products)** Let $B$ be a simple, unital $C^*$-algebra such that $B$ is finite and $M_2(B)$ is infinite. Then we have unital $\ast$-homomorphisms

\[ \varphi_1 : M_2(\mathbb{C}) \to M_2(B), \quad \varphi_2 : O_\infty \to M_2(B), \]

such that $\varphi_1(e)$ is a finite projection in $M_2(B)$ whenever $e$ is a one-dimensional projection in $M_2(\mathbb{C})$.

The existence of $B$ (already obtained in the non-simple case in [38]) shows that the image of $e$ in the universal unital free product $C^*$-algebra $M_2(\mathbb{C}) \ast O_\infty$ is not properly infinite.

It is tempting to turn this around and seek a simple $C^*$-algebra $A$ with a finite and an infinite projection by defining $A$ to be a suitable free product of $M_2(\mathbb{C})$ and $O_\infty$. However, the universal unital free product $M_2(\mathbb{C}) \ast O_\infty$ is not simple. The reduced free product $C^*$-algebra

\[ (A, \rho) = (M_2(\mathbb{C}), \rho_1) \ast (O_\infty, \rho_2), \]

with respect to faithful states $\rho_1$ and $\rho_2$, is simple (at least for many choices of the states $\rho_1$ and $\rho_2$, see for example [4]) and properly infinite, but no non-zero projection $e$ in $M_2(\mathbb{C})$ is finite in $A$. The Cuntz algebra $O_\infty$ contains a sequence of non-zero mutually orthogonal
projections, and it therefore contains a projection $f$ with $\rho_2(f) < \rho_1(e)$. Now, $e$ and $f$ are free with respect to the state $\rho$ and $\rho(f) < \rho(e)$. This implies that $f \preceq e$ (see [1]), and therefore $e$ must be infinite.

It is shown in [18] that reduced free product $C^*$-algebras often have weakly unperforated $K_0$-groups, which is another reason why this class of $C^*$-algebras is unlikely to provide an example of a simple $C^*$-algebra with finite and infinite projections; cf. Remark 7.8.

We conclude this article by remarking that ring theorists for a long time have known about finite simple rings that are not stably finite:

**Remark 7.13 (An example from ring theory)** A unital ring $R$ is called **weakly finite** if $xy = 1$ implies $yx = 1$ for all $x, y$ in $R$, and $R$ is called **weakly $n$-finite** if $M_n(R)$ is weakly finite. (A finite ring is a ring with finitely many elements!) A (unital) non-weakly finite simple ring $R$ is properly infinite in the sense that there are idempotents $e, f$ in $R$ such that $1 \sim e \sim f$ and $ef = fe = 0$. (Equivalence of idempotents is given by $e \sim f$ if and only if $e = xy$ and $f = yx$ for some $x, y$ in $R$.)

An example of a unital, simple ring which is weakly finite but not weakly 2-finite was constructed by P. M. Cohn as follows:

Take natural numbers $2 \leq m < n$ and consider the universal ring $V_{m,n}$ generated by $2mn$ elements $\{x_{ij}\}$ and $\{y_{ji}\}$, $i = 1, \ldots, m$ and $j = 1, \ldots, n$, satisfying the relations $XY = I_m$ and $YX = I_n$, where $X = (x_{ij}) \in M_{m,n}(R)$, $Y = (y_{ij}) \in M_{n,m}(R)$, and $I_m$ and $I_n$ are the units of the matrix rings $M_m(R)$ and $M_n(R)$. The rings $M_m(V_{m,n})$ and $M_n(V_{m,n})$ are isomorphic and $M_n(V_{m,n})$ is not weakly finite. Therefore $M_m(V_{m,n})$ is not weakly finite. In other words, $V_{m,n}$ is not weakly $m$-finite.

It is shown by Cohn in [11, Theorem 2.11.1] (see also the remarks at the end of Section 2.11 of that book) that $V_{m,n}$ is a so-called $(m - 1)$-fir, and hence a 1-fir; and a ring is a 1-fir if and only if it is an integral domain (i.e., if it has no non-zero zero-divisors). Cohn proved in [10] that every integral domain embeds into a simple integral domain. In particular, $V_{m,n}$ is a subring of a simple integral domain $R_{m,n}$ whenever $2 \leq m < n$. Now, $R_{m,n}$ is weakly finite (an integral domain has no idempotents other than 0 and 1 and must hence be weakly finite), and $R_{m,n}$ is not weakly $m$-finite (because it contains $V_{m,n}$).

This example cannot in any obvious way be carried over to $C^*$-algebras, first of all because no $C^*$-algebra other than $\mathbb{C}$ is an integral domain.

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