GENERALISED MORPHISMS OF $k$-GRAPHS: $k$-MORPHS

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Abstract. In a number of recent papers, $(k+l)$-graphs have been constructed from $k$-graphs by inserting new edges in the last $l$ dimensions. These constructions have been motivated by $C^*$-algebraic considerations, so they have not been treated systematically at the level of higher-rank graphs themselves. Here we introduce $k$-morphs, which provide a systematic unifying framework for these various constructions. We think of $k$-morphs as the analogue, at the level of $k$-graphs, of $C^*$-correspondences between $C^*$-algebras. To make this analogy explicit, we introduce a category whose objects are $k$-graphs and whose morphisms are isomorphism classes of $k$-morphs. We show how to extend the assignment $\Lambda \mapsto C^*(\Lambda)$ to a functor from this category to the category whose objects are $C^*$-algebras and whose morphisms are isomorphism classes of $C^*$-correspondences.

1. Introduction

Over the last ten years, graph $C^*$-algebras and their analogues have been the subject of intense research interest (see for example [5, 7, 8, 13, 16, 20, 25, 38], or see [30] for a good overview). In particular, the higher-rank graphs and associated $C^*$-algebras introduced in [18] have recently been widely studied [10, 12, 19, 28]. Higher-rank graphs generalise directed graphs, so there are many points of similarity between the two theories, especially at the level of fundamental existence and uniqueness results. However, as both fields progress, the two sets of results are diverging more and more rapidly.

One reason for this is the relatively involved combinatorial structure of higher-rank graphs as opposed to “ordinary” one-dimensional graphs. It is fairly straightforward to modify an ordinary graph by simply adding vertices or edges because these are local operations. By contrast, adding vertices and edges to a higher-rank graph is quite complicated because the combinatorial peculiarities of higher-rank graphs mean that the addition of an edge at some vertex typically necessitates similar changes throughout a large portion of the higher-rank graph. A good illustration of this is the contrast between the straightforward process of “adding tails” to a directed graph [3] and the analogous but vastly more complicated “removing sources” construction for higher-rank graphs [11].

It has become clear recently, however, that if higher-rank graphs are not well-suited to constructions which involve localised modifications, they are amenable to a somewhat different style of construction which is not available in the one-dimensional setting and which is proving very profitable from a $C^*$-algebraic standpoint. Specifically, $k$-graphs lend themselves to constructions whereby one increases the rank of a graph or graphs by adding edges in new dimensions [15, 21, 27]. The resulting $(k+l)$-graph $C^*$-algebras have been analysed as direct limits [21, 27] and as crossed-products by group actions [15].

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So far these constructions of \((k + l)\)-graphs from \(k\)-graphs have been ad hoc: in each of [15, 21, 27], given a \(k\)-graph with natural symmetry or a pair of \(k\)-graphs with structural similarities, the authors have constructed a \((k+l)\)-graph with bare hands. In each case, the \((k + l)\)-graph contains copies of the original \(k\)-graph or \(-\)graphs in the first \(k\)-dimensions, and encodes the additional symmetry or structural similarities in the remaining \(l\) dimensions.

The purpose of this article is to replace these ad hoc methods with a unifying construction which is functorial with respect to the assignment of \(C^\ast\)-algebras to higher-rank graphs. More specifically, in Section 3 we axiomatise the data required to insert a set \(X\) of edges in a \((k + 1)\)st dimension by a copy of \(X\) so as to obtain a \((k + 1)\)-graph. We call a set \(X\) endowed with such data a \(\Lambda - \Gamma\) morph, or a \(k\)-morph from \(\Gamma\) to \(\Lambda\). Given a \(\Lambda_0 - \Lambda_1\) morph \(X_1\) and a \(\Lambda_1 - \Lambda_2\) morph \(X_2\), we define a fibred product \(X_1 \ast_{\Lambda_1} X_2\) which is a \(\Lambda_0 - \Lambda_2\) morph. We show in Theorem 3.10 that there is a category \(\mathcal{M}_k\) whose objects are \(k\)-graphs and whose morphisms are isomorphism classes of \(k\)-morphs.

In Sections 4 and 5 we discuss how \(k\)-morphs can be used as a model for constructions such as those of [15, 21, 27]. Given \(k\)-graphs \(\Lambda\) and \(\Gamma\), and a \(\Lambda - \Gamma\) morph \(X\), we define in Section 4 what we call a linking graph for \(X\). Roughly speaking, a linking graph for \(X\) is a \((k + 1)\)-graph \(\Sigma\) containing disjoint copies of \(\Lambda\) and \(\Gamma\) connected in the \((k + 1)\)st dimension by a copy of \(X\). We show in Proposition 4.5 that a linking graph always exists, is unique up to isomorphism, and is determined up to isomorphism by the isomorphism class of \(X\).

The constructions set out in [15, 21, 27] typically involve a system of linking graphs which are glued together in some systematic way. For example, we can think of the covering systems of [21] as a system, organised by an underlying Bratteli diagram, of linking graphs for \(k\)-morphs determined by \(k\)-graph coverings. To capture this idea, we introduce in Section 5 the notion of a \(\Gamma\)-system of \(k\)-morphs, and the notion of a \(\Gamma\)-bundle for a \(\Gamma\)-system. Given an \(l\)-graph \(\Gamma\), a \(\Gamma\) system consists of a collection \(\{\Lambda_v : v \in \Gamma^0\}\) of \(k\)-graphs connected by \(k\)-morphs \(\{X_\gamma : \gamma \in \Gamma\}\) so that composition in \(\Gamma\) corresponds in a consistent way to the fibred product operation on the associated \(k\)-morphs. A \(\Gamma\)-bundle for this system is then a \((k + l)\)-graph \(\Sigma\) together with a map \(f : \Sigma \to \Gamma\) such that \(f^{-1}(v) \cong \Lambda_v\) for each \(v \in \Gamma^0\) and such that \(f^{-1}(\{r(\gamma), s(\gamma)\})\) is a linking graph for \(X_\gamma\) for each \(\gamma \in \Gamma\). We call the map \(f\) the bundle map for the \(\Gamma\)-bundle \(\Sigma\). We show in Theorem 5.9 that every \(\Gamma\)-system admits a \(\Gamma\)-bundle, and that the \(\Gamma\)-bundle is unique up to isomorphism and depends only on the isomorphism class of the \(\Gamma\)-system. We indicate how to realise the \(k\)-graphs constructed in [15, 21, 27, 28] as \(\Gamma\)-bundles in a natural way.

A \(\Gamma\)-system \(X\) of \(k\)-morphs determines a functor from \(\Gamma\) into the category \(\mathcal{M}_k\) via the assignments \(v \mapsto \Lambda_v\) and \(\gamma \mapsto [X_\gamma]\) (where \([X_\gamma]\) is the isomorphism class of \(X_\gamma\)). One might initially hope that the isomorphism class of a \(\Gamma\)-bundle for the system would be determined by this functor, so that we could replace \(\Gamma\)-systems with functors. We show in Proposition 5.14 that when \(\Gamma\) is a 1-graph each \(\Gamma\)-system is indeed determined up to isomorphism by the functor \(\gamma \mapsto [X_\gamma]\). However this is the best we can hope for: Example 5.15(ii) shows that if \(\Gamma\) has rank 2 or more there may be non-isomorphic \(\Gamma\)-systems which determine the same functor from \(\Gamma\) to \(\mathcal{M}_k\); and an example of Spielberg’s, which we present as Example 5.15(iii), shows that there exists a 3-graph \(\Gamma\) and a functor \(\Gamma \to \mathcal{M}_0\) which is not the functor determined by any \(\Gamma\)-system of 0-graphs. In particular, \(\Gamma\)-systems cannot be replaced with functors.
An example of a $\Gamma$ system is the following. Let $X$ be a $\Lambda$-$\Lambda$ morph (we refer to these as $\Lambda$ endomorphs). Then $X$ gives rise to a $T_1$-system of $k$-morphs, where $T_1$ is the 1-graph with a single vertex and a single edge. We call the $T_1$-bundle for such a system the endomorph skew graph of $\Lambda$ by $X$, and denote it $\Lambda \times_X N$. When $X$ arises from an automorphism of $\Lambda$, we recover the crossed product graph of [15].

In Section 6 we discuss how our constructions behave at the level of $C^*$-algebras. The category $\mathcal{M}_k^\Lambda$ is reminiscent of the category (which we shall denote $\mathcal{C}$) of [9, 23, 37], whose objects are $C^*$-algebras and whose morphisms are isomorphism classes of $C^*$-correspondences (also known as Hilbert bimodules). To simplify arguments, we restrict our attention to a subcategory $\mathcal{M}^\Lambda_k$ of $\mathcal{M}_k$. We construct a $C^*$-correspondence $\mathcal{H}(X)$ for each $k$-morph $X$ in such a way that the isomorphism class of $\mathcal{H}(X)$ depends only on that of $X$. We show in Theorem 6.6 that the assignments $\Lambda \mapsto C^*(\Lambda)$ and $[X] \mapsto [\mathcal{H}(X)]$ determine a contravariant functor between $\mathcal{M}^\Lambda_k$ and $\mathcal{C}$. In the special case where $X$ is a $\Lambda$-endomorph, so that $[X] \in \text{End}_{\mathcal{M}^\Lambda_k}(\Lambda)$, Theorem 6.8 shows that the $C^*$-algebra of the endomorph skew graph is canonically isomorphic to the Cuntz-Pimsner algebra $\mathcal{O}_{\mathcal{H}(X)}$.

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2. Preliminaries

2.1. Higher-rank graphs. In this paper, unlike previous treatments of $k$-graphs [10, 12, 18, 31], we allow 0-graphs. To make sense of this, we take the convention that $\mathbb{N}^0$ is the trivial semigroup $\{0\}$. We will also insist that all $k$-graphs are nonempty.

Modulo the minor differences mentioned above, we will adopt the conventions of [18, 26] for $k$-graphs. Given a nonnegative integer $k$, a $k$-graph is a nonempty countable small category $\Lambda$ equipped with a functor $d : \Lambda \to \mathbb{N}^k$ satisfying the factorisation property: for all $\lambda \in \Lambda$ and $m, n \in \mathbb{N}^k$ such that $d(\lambda) = m + n$ there exist unique $\mu, \nu \in \Lambda$ such that $d(\mu) = m$, $d(\nu) = n$, and $\lambda = \mu \nu$. When $d(\lambda) = n$ we say $\lambda$ has degree $n$. By abuse of notation, we will use $d$ to denote the degree functor in every $k$-graph in this paper; the domain of $d$ is always clear from context.

For $k \geq 1$, the standard generators of $\mathbb{N}^k$ are denoted $e_1, \ldots, e_k$, and for $n \in \mathbb{N}^k$ and $1 \leq i \leq k$ we write $n_i$ for the $i$th coordinate of $n$.

For $n \in \mathbb{N}^k$, we write $\Lambda^n$ for $d^{-1}(n)$. In particular, $\Lambda^0$ is the vertex set. The vertices of $\Lambda$ are the elements of $\Lambda^0$. The factorisation property implies that $o : \Lambda \to \mathbb{N}^k$ is a bijection from the objects of $\Lambda$ to $\Lambda^0$. We will frequently use this bijection to silently identify $\text{Obj}(\Lambda)$ with $\Lambda^0$. The domain and codomain maps in the category $\Lambda$ therefore become maps $s, r : \Lambda \to \Lambda^0$. More precisely, for $\alpha \in \Lambda$, the source $s(\alpha)$ is the identity morphism associated with the object $\text{dom}(\alpha)$ and similarly, $r(\alpha) = \text{id}_{\text{cod}(\alpha)}$.

Note that a 0-graph is then a countable category whose only morphisms are the identity morphisms; we think of them as a collection of isolated vertices.

For $u, v \in \Lambda^0$ and $E \subseteq \Lambda$, we write $uE$ for $E \cap r^{-1}(u)$ and $Ev$ for $E \cap s^{-1}(v)$. For $n \in \mathbb{N}^k$, we denote by $\Lambda^{\leq n}$ the set

$$
\Lambda^{\leq n} = \{ \lambda \in \Lambda : d(\lambda) \leq n, s(\lambda)\Lambda^{e_i} = \emptyset \text{ whenever } d(\lambda) + e_i \leq n \}.
$$
We say that $\Lambda$ is row-finite if $v\Lambda^n$ is finite for all $v \in \Lambda^0$ and $n \in \mathbb{N}^k$. We say that $\Lambda$ is locally convex if whenever $1 \leq i < j \leq k$, $e \in \Lambda^{e_i}$, $f \in \Lambda^{e_j}$ and $r(e) = r(f)$, we can extend both $e$ and $f$ to paths $ee'$ and $ff'$ in $\Lambda^{e_i+e_j}$.

2.2. Maps between higher-rank graphs. A $k$-graph morphism is a degree-preserving functor. More generally, if $\omega : \mathbb{N}^k \rightarrow \mathbb{N}^l$ is a homomorphism, $\Lambda$ is a $k$-graph and $\Gamma$ is an $l$-graph, we say that a functor $f : \Lambda \rightarrow \Gamma$ is an $\omega$-quasimorphism if $d_\Gamma(f(\lambda)) = \omega(d(\lambda))$ for all $\lambda \in \Lambda$. A $k$-graph morphism is then an id$_k$-quasimorphism.

Let $\omega : \mathbb{N}^k \rightarrow \mathbb{N}^l$ be a homomorphism, and let $\Gamma$ be an $l$-graph. The pullback $\omega^*\Gamma$ is the $k$-graph $\omega^*\Gamma = \{(\gamma, n) \in \Gamma \times \mathbb{N}^k : \omega(n) = d(\gamma)\}$ with degree map $d_{\omega^*\Gamma}(\gamma, n) = n$ [18, Definition 1.9]. In the case where $\omega$ is injective, it will also sometimes be convenient to regard the subcategory $\Gamma^\omega := \bigcup_{n \in \mathbb{N}^k} \Gamma^\omega(n)$ of $\Gamma$ as a $k$-graph as follows. We define the degree functor $d_\omega$ on $\Gamma^\omega$ by $d_\omega(\gamma) = n$ when $\omega(n) = d(\gamma)$. Of course $\Gamma^\omega$ and $\omega^*\Gamma$ are isomorphic, but the former is a subset of $\Gamma$ whereas the latter is formally disjoint from $\Gamma$.

As in [26], a covering of a $k$-graph $\Lambda$ by a $k$-graph $\Gamma$ is a surjective $k$-graph morphism $p : \Gamma \rightarrow \Lambda$ such that for all $v \in \Gamma^0$, $p$ restricts to bijections between $v\Gamma$ and $v\Lambda$ and between $\Gamma v$ and $\Lambda p(v)$. The covering $p : \Gamma \rightarrow \Lambda$ is finite if $p^{-1}(v)$ is finite for all $v \in \Lambda^0$. Every covering $p : \Gamma \rightarrow \Lambda$ has the unique path lifting property: for every $\lambda \in \Lambda$ and $v \in \Gamma^0$ with $p(v) = s(\lambda)$ there is a unique $\gamma \in \Gamma$ such that $p(\gamma) = \lambda$ and $s(\gamma) = v$; and similarly at $r(\lambda)$.

2.3. $C^*$-algebras associated to higher-rank graphs. Given a row-finite, locally convex $k$-graph $(\Lambda, d)$, a Cuntz-Krieger $\Lambda$-family is a collection $\{t_\lambda : \lambda \in \Lambda\}$ of partial isometries satisfying the Cuntz-Krieger relations:

- $\{t_v : v \in \Lambda^0\}$ is a collection of mutually orthogonal projections;
- $t_\lambda t_\mu = t_{\lambda\mu}$ whenever $s(\lambda) = r(\mu)$;
- $t_\lambda^* t_{\lambda\mu} = t_{s(\lambda)}$ for all $\lambda \in \Lambda$; and
- $t_v = \sum_{\lambda \in v\Lambda \leq n} t_\lambda t_\lambda^*$ for all $v \in \Lambda^0$ and $n \in \mathbb{N}^k$.

The $k$-graph $C^*$-algebra $C^*(\Lambda)$ is the universal $C^*$-algebra generated by a Cuntz-Krieger $\Lambda$-family $\{s_\lambda : \lambda \in \Lambda\}$. That is, for every Cuntz-Krieger $\Lambda$-family $\{t_\lambda : \lambda \in \Lambda\}$ there is a homomorphism $\pi_t$ of $C^*(\Lambda)$ satisfying $\pi_t(s_\lambda) = t_\lambda$ for all $\lambda \in \Lambda$.

A $k$-graph with no sources is automatically locally convex with $\Lambda^{\leq n} = \Lambda^n$ for all $n \in \mathbb{N}^k$. Hence the definition of $C^*(\Lambda)$ above reduces in this case to [18, Definition 1.5].

By [31, Theorem 3.15], the generating partial isometries $\{s_\lambda : \lambda \in \Lambda\} \subset C^*(\Lambda)$ are all nonzero.

If $\Lambda$ is a 0-graph, then it trivially has no sources, and the last three Cuntz-Krieger relations follow from the first one. So $C^*(\Lambda)$ is the universal $C^*$-algebra generated by mutually orthogonal projections $\{s_v : v \in \Lambda^0\}$; that is, $C^*(\Lambda) \cong \alpha(\Lambda^0)$.

Let $\Lambda$ be a $k$-graph. There is a strongly continuous action $\gamma$ of $\mathbb{T}^k$ on $C^*(\Lambda)$, called the gauge-action, such that $\gamma_z(s_\lambda) = z^{d(\lambda)} s_\lambda$ for all $z \in \mathbb{T}^k$ and $\lambda \in \Lambda$.

2.4. $C^*$-correspondences. We define Hilbert modules following [22] and [4, §II.7]. Let $B$ be a $C^*$-algebra and let $\mathcal{H}$ be a right $B$-module. Then a $B$-valued inner product on $\mathcal{H}$ is a function $\langle \cdot, \cdot \rangle_B : \mathcal{H} \times \mathcal{H} \rightarrow B$ satisfying the following conditions for all $\xi, \eta, \zeta \in \mathcal{H}$, $b \in B$ and $\alpha, \beta \in \mathbb{C}$:

- $\langle \xi, \alpha \eta + \beta \zeta \rangle_B = \alpha \langle \xi, \eta \rangle_B + \beta \langle \xi, \zeta \rangle_B$,
- $\langle \xi, \eta \rangle_B = \langle \xi, \eta \rangle_B^b$, 

where $\langle \cdot, \cdot \rangle_B^b$ denotes the $B$-valued inner product on $\mathcal{H}^b$ associated to a $B$-valued inner product on $\mathcal{H}$.
\[\langle \xi, \eta \rangle_B = \langle \eta, \xi \rangle_B^\ast,\]
\[\langle \xi, \xi \rangle_B \geq 0 \text{ and } \langle \xi, \xi \rangle_B = 0 \text{ if and only if } \xi = 0.\]

If \(H\) is complete with respect to the norm given by \(\|\xi\|^2 = \langle \xi, \xi \rangle_B\) then \(H\) is said to be a (right-) Hilbert \(B\)-module. If the range of the inner product is not contained in any proper ideal in \(B\), \(H\) is said to be full. Note that \(B\) may be endowed with the structure of a full Hilbert \(B\)-module by taking \(\langle \xi, \eta \rangle_B = \xi^* \eta\) for all \(\xi, \eta \in B\). A map \(T : H \to H\) is an adjointable operator if there is a map \(T^* : H \to H\) such that \(\langle T\xi, \eta \rangle_B = \langle \xi, T^* \eta \rangle_B\) for all \(\xi, \eta \in H\). Such an operator is necessarily linear and bounded and the collection \(L(H)\) of all adjointable operators on \(H\) is a \(C^*\)-algebra. Each pair \(\xi, \eta \in H\) determines a rank-one operator \(\theta_{\xi, \eta}\) (with adjoint \(\theta_{\xi, \eta^*}\)) given by \(\theta_{\xi, \eta^*} = \xi (\eta, \cdot)\) for \(\xi \in H\). The \(C^*\)-subalgebra \(K(H)\) of \(L(H)\) generated by the \(\theta_{\xi, \eta}\) is called the algebra of compact operators on \(H\). Note that \(L(H)\) may be identified with the multiplier algebra of \(K(H)\).

Let \(A\) and \(B\) be \(C^*\)-algebras; then a \(C^*\)-correspondence from \(A\) to \(B\) or more briefly an \(A\)-\(B\) \(C^*\)-correspondence is a Hilbert \(B\)-module \(H\) together with a \(\ast\)-homomorphism \(\varphi : A \to L(H)\). Given a homomorphism \(\varphi : A \to B\), we may endow \(B\) with the structure of an \(A\)-\(B\) \(C^*\)-correspondence in a canonical way. So it is natural to think of an \(A\)-\(B\) \(C^*\)-correspondence as a generalised homomorphism from \(A\) to \(B\). A \(C^*\)-correspondence \(H\) is said to be nondegenerate if span \(\{\varphi(a) \xi : a \in A, \xi \in H\}\) is dense in \(H\) (some authors have also called such \(C^*\)-correspondences essential). We often suppress \(\varphi\) by writing \(a \cdot \xi\) for \(\varphi(a) \xi\).

As discussed in \([4, 9, 23, 37]\), there is a category \(\mathcal{C}\) with \(\text{Obj}(\mathcal{C})\) the class of \(C^*\)-algebras, and \(\text{Hom}_\mathcal{C}(A, B)\) the set of isomorphism classes of \(A\)-\(B\) \(C^*\)-correspondences with identity morphisms \([A]\). Composition

\[\text{Hom}_\mathcal{C}(B, C) \times \text{Hom}_\mathcal{C}(A, B) \to \text{Hom}_\mathcal{C}(A, C)\]

is defined by \(((H_1, H_2)) \mapsto [H_2 \otimes_B H_1]\) where \(H_2 \otimes_B H_1\) denotes the tensor product of \(C^*\)-correspondences. The \(C^*\)-correspondence \(H_1 \otimes H_2\) is called the internal tensor product of \(H_1\) and \(H_2\) by Blackadar and the interior tensor product by Lance (see \([1, II.7.4.1]\) and \([22\) Prop. 4.5] and the following discussion).

### 2.5. Representations of \(C^*\)-correspondences.

Let \(H\) be an \(A\)-\(A\) \(C^*\)-correspondence. Recall from \([29]\) that a representation of \(H\) in a \(C^*\)-algebra \(B\) is a pair \((t, \pi)\) where \(\pi : A \to B\) is a homomorphism, \(t : H \to B\) is linear, and such that for all \(a \in A\) and \(\xi, \eta \in H\), we have \(t(a \cdot \xi) = \pi(a) t(\xi), t(A \xi a) = t(\xi) \pi(a), \) and \(\pi((\xi, \eta)_A) = t(\xi^* t(\eta)).\)

Given a \(C^*\)-correspondence \(H\) over \(A\) and a representation \((t, \pi)\) of \(H\) on \(B\), there is a homomorphism \(t^{(1)} : K(H) \to B\) satisfying \(t^{(1)}(\theta_{\xi, \eta}) = t(\xi) t(\eta)^*\) for all \(\xi, \eta \in H\) (Pimsner denotes this homomorphism \(\pi^{(1)}\) in \([29]\)). In the cases of interest later in this paper, the left action of \(A\) on \(H\) is by elements of \(K(H)\) (that is \(\varphi : A \to L(H)\) in fact takes values in \(K(H)\)), so \(t^{(1)} \circ \varphi\) is a homomorphism from \(A\) to \(B\). In this case, the pair \((t, \pi)\) is said to be Cuntz-Pimsner covariant if \(t^{(1)} \circ \varphi = \pi\).

Given a \(C^*\)-correspondence \(H\) over \(A\), there is a representation \((j_H, j_A)\) in a \(C^*\)-algebra \(\mathcal{O}_H\) which is universal in the sense that given another representation \((t, \pi)\) of \(H\) in \(B\) there is a homomorphism \(t \times \pi : \mathcal{O}_H \to B\) satisfying \((t \times \pi) \circ j_H = t\) and \((t \times \pi) \circ j_A = \pi\).

### 3. \(k\)-morphs

In this section, we define \(k\)-morphs, provide some motivating examples, and show how isomorphism classes of \(k\)-morphs can be regarded as the morphisms of a category whose
objects are $k$-graphs. Conceptually, a $k$-morph may be thought of as a bridge between two $k$-graphs $\Lambda$ and $\Gamma$; it consists of a set $X$ and some structure maps which are precisely what is needed to build a $(k + 1)$-graph that contains disjoint copies of $\Lambda$ and $\Gamma$ and in which elements of $X$ become edges of degree $e_{k+1}$ from vertices in the copy of $\Gamma$ to vertices in the copy of $\Lambda$. We now give the formal definition.

**Definition 3.1.** Let $\Lambda$ and $\Gamma$ be $k$-graphs, let $X$ be a countable set, and fix functions $r : X \to \Lambda^0$ and $s : X \to \Gamma^0$. We will write $X \ast_{\Gamma^0} \Lambda$ for the fibre product $\{(x, \gamma) : x \in X, \gamma \in \Gamma, s(x) = r(\gamma)\}$. Likewise, we will write $\Lambda \ast_{\Lambda^0} X$ for the fibre product $\{(\lambda, x) : \lambda \in \Lambda, x \in X, s(\lambda) = r(x)\}$. Fix a bijection $\phi : X \ast_{\Gamma^0} \Lambda \to \Lambda \ast_{\Lambda^0} X$, and suppose that whenever $\phi(x_1, \gamma_1) = (\lambda_1, x_2)$, we have

1. $d(\gamma_1) = d(\lambda_1)$;
2. $s(\gamma_1) = s(x_2)$; and
3. $r(\lambda_1) = r(x_1)$.

Suppose further that whenever $\phi(x_1, \gamma_1) = (\lambda_1, x_2)$ and $\phi(x_2, \gamma_2) = (\lambda_2, x_3)$ we have

4. $\phi(x_1, \gamma_1 \gamma_2) = (\lambda_1 \lambda_2, x_3)$.

Then we call $X$ a $\Lambda$-$\Gamma$ morph, or simply a $k$-morph. If $\Lambda = \Gamma$, then we call $X$ a $\Lambda$ endomorph.

**Remark 3.2.** Technically a $\Lambda$-$\Gamma$ morph is a quadruple $(X, r, s, \phi)$, but by the usual abuse of notation, we will say “$X$ is a $\Lambda$-$\Gamma$ morph” without reference to the additional structure.

**Examples 3.3.** We now present a series of examples of $k$-morphs. In each case we shall describe the set $X$ and the structure maps; it is straightforward to check in each case that the resulting data define a $k$-morph.

1. Let $\Lambda$ and $\Gamma$ be $k$-graphs, and let $\alpha : \Gamma \to \Lambda$ be an isomorphism. Let $X(\alpha) = \Gamma^0$ and define structure maps $r_\alpha = \alpha$, $s_\alpha = \text{id}_{\Gamma^0}$ and $\phi(r(\gamma), \gamma) = (\alpha(\gamma), s(\gamma))$. Then $X(\alpha)$ is a $\Lambda$-$\Gamma$ morph. If $\Lambda = \Gamma$ so that $\alpha$ is an automorphism, then $X(\alpha)$ is a $\Lambda$ endomorph. In the special case where $\alpha$ is the identity isomorphism $\text{id}_\Lambda$, we refer to $X(\text{id}_\Lambda)$ as the identity endomorph on $\Lambda$. When it is useful to highlight its dependence on $\Lambda$ we will denote it as $I_\Lambda$.

2. Let $p : \Gamma \to \Lambda$ be a covering map. Let $p X = \Gamma^0$, and define structure maps by $r = p$, $s = \text{id}_{\Gamma^0}$ and $\phi(p(\gamma), s(\gamma)) = (p(\gamma), s(\gamma))$. Then $p X$ is a $\Lambda$-$\Gamma$ morph. Such a $k$-morph is called a covering $k$-morph. Note that if $p = \alpha$ is an isomorphism, then $p X$ is equal to the $k$-morph $X(\alpha)$ of the preceding example.

3. We may reverse the “direction” of the elements of $X$ in the preceding example to get a $\Gamma$-$\Lambda$ morph. Let $p : \Gamma \to \Lambda$ be a covering of $k$-graphs. Let $X_p := \Gamma^0$, and define structure maps by $r = p$, $s = p \circ \text{id}_{\Gamma^0}$, and $\phi(r(\gamma), p(\gamma)) = (\gamma, s(\gamma))$ (where we are using the unique path lifting property to recover $\gamma$ from $p(\gamma)$ and $r(\gamma)$). Then $X_p$ is a $\Gamma$-$\Lambda$ morph.

4. Let $\Lambda_1, \Lambda_2, \Gamma$ be $k$-graphs and $p : \Gamma \to \Lambda_1$, $q : \Gamma \to \Lambda_2$ be coverings. Let $p X_q = \Gamma^0$ and define structure maps by $r = p$, $s = q$, and $\phi(r(\gamma), q(\gamma)) = (p(\gamma), s(\gamma))$. Then $p X_q$ is a $\Lambda_1$-$\Lambda_2$ morph. This generalises the preceding two examples: if $\Lambda_2 = \Gamma$ and $q = \text{id}_\Gamma$, then $p X_{\text{id}_\Gamma} = p X$, and similarly if $\Lambda_1 = \Gamma$, then $\text{id}_\Lambda X_q = X_q$.

\footnote{Note that the conditions $\phi(x_1, \gamma_1) = (\lambda_1, x_2)$ and $\phi(x_2, \gamma_2) = (\lambda_2, x_3)$ together with (2) and (3) imply that $s(\gamma_1) = s(x_2) = r(\gamma_2)$ and $s(\lambda_1) = r(x_2) = r(\lambda_2)$; it then follows that $(\lambda_1 \lambda_2, x_3) \in \Lambda \ast_{\Lambda^0} X$ and $(x_1, \gamma_1 \gamma_2) \in X \ast_{\Gamma^0} \Lambda$.}
(v) Number (iv) (hence also numbers (iii) and (iii)) above can be enriched with multiple “edges” as in [21]. Let $p : \Gamma \to \Lambda_1$ and $q : \Gamma \to \Lambda_2$ be covering maps. Write $S_m$ for the group of permutations of $\{1,\ldots,m\}$; let $c$ be a cocycle from $\Gamma$ to $S_m$ (that is $c(\alpha)c(\beta) = c(\alpha\beta)$ whenever $\alpha$ and $\beta$ are composable in $\Gamma$). Set $\phi_\theta : \Gamma^0 \times \{1,\ldots,m\}$, and define structure maps by $r(v,i) = p(v)$, $s(v,i) = q(v)$ and $\phi((r(\gamma),i),q(\gamma)) = (p(\gamma),(s(\gamma),c(\gamma)^{-1}i))$. Then $\phi_\theta$ is a $\Lambda_1$–$\Lambda_2$ morph.

(vi) Let $(\Sigma, d)$ be a $(k+1)$-graph and $\iota : \mathbb{N}^k \to \mathbb{N}^{k+1}$ be the homomorphism $n \to (n,0)$. Recall from Section 2.2 that we can regard $\Sigma^\iota := \{\lambda \in \Sigma : d(\lambda) \in \iota(\mathbb{N}^k)\}$ as a $k$-graph. Let $X = \Sigma^\iota$, and define $r_X, s_X : X \to \Sigma^0$ to be the range and source maps $r, s$ inherited from $\Sigma$. The bijection $\phi$ is obtained from the factorisation property in $\Sigma$: $\phi(x,\lambda) = (x',\lambda')$ where $x' \in X$ and $\lambda' \in \Sigma^\iota$ are the unique elements satisfying $x\lambda = x'\lambda'$ in $\Sigma$. Then $X$ is a $\Sigma^\iota$ endomorph.

(vii) Let $\Lambda$ and $\Gamma$ be $k$-graphs, and let $X_1$ and $X_2$ be $\Lambda$–$\Gamma$ morphs. Then $X := X_1 \cup X_2$ is a $\Lambda$–$\Gamma$ morph with the inherited structure maps.

We next define a kind of fibred product of $k$-morphs. This fibred product, like tensor products, is not quite associative on $k$-morphs. However Proposition 3.6 and Lemma 3.8 show that it does determine an associative binary operation on isomorphism classes of $k$-morphs. Of course, we must first say exactly what we mean by an isomorphism of $k$-morphs.

**Definition 3.4.** Fix $k$-graphs $\Lambda$ and $\Gamma$. Let $X$ and $Y$ be $\Lambda$–$\Gamma$ morphs. We say that $X$ and $Y$ are isomorphic if there is a bijection $\theta : X \to Y$ which respects the structure maps, that is, $\theta$ intertwines the range and source maps and satisfies $$(\text{id}_\Lambda \times \theta) \circ \phi_X = \phi_Y \circ (\theta \times \text{id}_\Gamma).$$

We call such a bijection $\theta$ an isomorphism and write $X \cong Y$; we denote the isomorphism class of a $k$-morphism $X$ by $[X]$.

We now introduce the notation associated with fibred products of $k$-morphs, and then show in Proposition 3.6 that the resulting object is itself a $k$-morphism.

**Notation 3.5.** Let $\Lambda_0$, $\Lambda_1$ and $\Lambda_2$ be $k$-graphs, and let $X_i$ be a $\Lambda_{i-1}$–$\Lambda_i$ morph with structure maps $r_i, s_i$ and $\phi_i$ for $i = 1, 2$. Let

$$X_1 \ast_{\Lambda^0_1} X_2 = \{(x_1, x_2) \in X_1 \times X_2 : s(x_1) = r(x_2)\}.$$ 

Define $r : X_1 \ast_{\Lambda^0_1} X_2 \to \Lambda^0_0$ and $s : X_1 \ast_{\Lambda^0_1} X_2 \to \Lambda^0_2$ by

$$r(x_1, x_2) = r_1(x_1) \quad \text{and} \quad s(x_1, x_2) = s_2(x_2).$$

To define $\phi : X_1 \ast_{\Lambda^0_1} X_2 \ast_{\Lambda^0_2} \Lambda_2 \to \Lambda_0 \ast_{\Lambda^0_0} X_1 \ast_{\Lambda^0_1} X_2$, fix $((x_1, x_2), (\lambda_2)) \in X_1 \ast_{\Lambda^0_1} X_2 \ast_{\Lambda^0_2} \Lambda_2$. Then $s_2(x_2) = r(\lambda_2)$, so $\phi_2(x_2, \lambda_2) = (\lambda_1, x'_2)$ for some $\lambda_1 \in \Lambda_1$ and $x'_2 \in X_2$. Moreover, $r(\lambda_1) = r_2(x_2) = s_1(x_1)$, so $\phi_1(x_1, \lambda_1) = (\lambda_0, x'_1)$ for some $\lambda_0 \in \Lambda_0$ and $x'_1 \in X_1$ with $s_1(x'_1) = r_2(x'_2)$. We define

$$\phi((x_1, x_2), \lambda_2) = (\lambda_0, (x'_1, x'_2)).$$

**Proposition 3.6.** With the notation above, $X_1 \ast_{\Lambda^0_1} X_2$ is a $\Lambda_0$–$\Lambda_2$ morph. Moreover, the isomorphism class $[X_1 \ast_{\Lambda^0_1} X_2]$ depends only on the isomorphism classes $[X_1]$ and $[X_2]$. 
Proof. Conditions (1)–(3) of Definition 3.1 are easily checked using (3.1) and that $X_1$ and $X_2$ are $k$-morphs, so we need only check (4).

Fix a composable pair $\mu_2, \nu_2 \in \Lambda_2$ and $(x_1, x_2) \in X_1 *_{\Lambda_0} X_2$ such that $s(x_1, x_2) = r(\mu_2)$. Let $x_i', x_i'' \in X_i$ for $i = 1, 2$ and $\mu_i, \nu_i \in \Lambda_i$ for $i = 0, 1$ be the unique elements such that

\begin{align}
(3.2) & \quad \phi_i(x_i, \mu_i) = (\mu_{i-1}, x_i') \\
(3.3) & \quad \phi_i(x_i', \nu_i) = (\nu_{i-1}, x_i'').
\end{align}

so that by (3.1),

\begin{align}
(3.4) & \quad \phi((x_1, x_2), \mu_2) = (\mu_0, (x_1', x_2')) \\
(3.5) & \quad \phi((x_1', x_2'), \nu_2) = (\nu_0, (x_1'', x_2'')).
\end{align}

By definition, $\phi((x_1, x_2), \mu_2 \nu_2)$ is calculated as follows: we write $\phi_2(x_2, \mu_2 \nu_2) = (\lambda, y)$ and then write $\phi_1(x_1, \lambda) = (\lambda', y')$; we then have $\phi((x_1, x_2), \mu_2 \nu_2) = (\lambda', y')$. By Definition 3.1(4) for the $k$-morph $X_2$, and equations (3.2) and (3.3), we have $\lambda = \mu_0 \nu_1$ and $y = x_2$. Now Definition 3.1(4) for the $k$-morph $X_1$, and equations (3.2) and (3.3) force $\lambda' = \mu_0 \nu_0$ and $y' = x_2''$. That is, $\phi((x_1, x_2), \mu_2 \nu_2) = (\mu_0 \nu_0, (x_1'', x_2''))$. Combining this with equations (3.4) and (3.5) shows that $X_1 *_{\Lambda_0} X_2$ satisfies Definition 3.1(4), and therefore is a $k$-morph.

For the last statement, one checks that if $\theta_1 : X_1 \to X_1'$ and $\theta_2 : X_2 \to X_2'$ are isomorphisms, then $\theta_1 \times \theta_2$ is an isomorphism of $X_1 *_{\Lambda_0} X_2$ onto $X_1' *_{\Lambda_0} X_2'$. □

Remarks 3.7.

(i) Let $\Lambda_0, \Lambda_1$ and $\Lambda_2$ be $k$-graphs, and let $q : \Lambda_2 \to \Lambda_1$ and $p : \Lambda_1 \to \Lambda_0$ be coverings. Then $p q$ is a covering of $\Lambda_0$ by $\Lambda_2$. Furthermore, $p X *_{\Lambda_0} q X = \{(q(v), v) : v \in \Lambda_0^q\}$. One can easily check that $\theta : v \mapsto (q(v), v)$ determines an isomorphism of $k$-morphs $p q X \cong p X *_{\Lambda_0} q X$.

(ii) Fix coverings $p : \Gamma \to \Lambda_1$ and $q : \Lambda_1 \to \Lambda_2$. Let $p X, q X$ and $p X q$ be as in parts (ii), (iii) and (iv) respectively of Examples 3.3. Then we have $p X q \cong p X *_{\Gamma_0} X q$. The isomorphism $\theta$ is defined by $\theta(x) = (x, x)$. To state the next lemma, we describe the fibred product of $n$ $k$-morphs. Let $\Lambda_0, \Lambda_1, \ldots, \Lambda_n$ be $k$-graphs, and let $X_i$ be a $\Lambda_{i-1} - \Lambda_i$ morph for $i = 1, \ldots, n$. Let

$$X_1 *_{\Lambda_0} \cdots *_{\Lambda_{n-1}} X_n = \{(x_1, \ldots, x_n) \in X_1 \times \cdots \times X_n : s(x_i) = r(x_{i+1}) \text{ for } 1 \leq i \leq n\}.$$  

Define structure maps $r, s, \phi$ associated to $X = X_1 *_{\Lambda_0} \cdots *_{\Lambda_{n-1}} X_n$ as follows. We set $r(x_1, \ldots, x_n) = r(x_1)$ and $s(x_1, \ldots, x_n) = s(x_n)$. Given $((x_1, \ldots, x_n), \lambda_n) \in X *_{\Lambda_n} X_n$, let $\lambda_i \in \Lambda_i$ and $x_i' \in X_i$ be the unique elements such that

$$\phi_i(x_i, \lambda_i) = (\lambda_{i-1}, x_i') \text{ for } 1 \leq i \leq n.$$  

Since each $X_i$ is a $k$-morph, we have $s(x_i') = s(\lambda_i) = r(x_{i+1}')$ for $1 \leq i \leq n - 1$. So we define $\phi$ by $\phi((x_1, \ldots, x_n), \lambda_n) = (\lambda_0, (x_1', \ldots, x_n'))$. 

\[ \Box \]
**Theorem 3.10.** There is a category $\Lambda$ associated to $\text{Hom}_{\mathcal{B}}$ not similar to that of Proposition 3.6. from the definition of $\phi$, implemented by $\theta$ 1

**Proof.** We first show that $X$ is a $k$-morphism: properties (1)–(3) of Definition 3.1 are clear from the definition of $\phi_X$, and Definition 3.1(4) is established by iterating an argument similar to that of Proposition 3.6.

It is easy to see that the bijection $\theta_{m,n-m}$ determines an isomorphism. □

**Notation 3.9.** Let $X$ be a $\Lambda$ endomorph. For $n \geq 2$, we write $X^n$ for the $k$-morphism

$$X^n := X *_{\Lambda^0} X *_{\Lambda^0} \cdots *_{\Lambda^0} X.$$ 

By $X^1$, we mean $X$, and by $X^0$, we mean $I_{\Lambda}$.

**Theorem 3.10.** There is a category $\mathcal{M}_k$ such that: $\text{Obj}(\mathcal{M}_k)$ is the class of $k$-graphs; $\text{Hom}_{\mathcal{M}_k}(\Gamma, \Lambda)$ is the set of isomorphism classes of $\Lambda - \Gamma$ morphs; the identity morphism associated to $\Lambda \in \text{Obj}(\mathcal{M}_k)$ is $[I_{\Lambda}]$; and the composition map

$$\text{Hom}_{\mathcal{M}_k}(\Lambda_1, \Lambda_0) \times \text{Hom}_{\mathcal{M}_k}(\Lambda_2, \Lambda_1) \to \text{Hom}_{\mathcal{M}_k}(\Lambda_2, \Lambda_0)$$

is defined by $([X_1], [X_2]) \mapsto [X_1 *_{\Lambda^0} X_2]$.

**Proof.** Remark 3.7(iii), shows that the $[I_{\Lambda}]$ act as identity morphisms. Proposition 3.6 shows that the composition map is well-defined. Since Lemma 3.8 gives

$$(X_1 *_{\Lambda^0} X_2) *_{\Lambda^0} X_3 \cong X \cong X_1 *_{\Lambda^0} (X_2 *_{\Lambda^0} X_3)$$

whenever the expressions make sense, the composition map is also associative. □

**Remark 3.11.** In light of the preceding theorem, it is natural to ask when the isomorphism class of a $k$-morphism is an invertible morph of $\mathcal{M}_k$.

By an abuse of terminology, we will say that a $\Lambda - \Gamma$ morph $X$ is **invertible** if $[X]$ is invertible in $\mathcal{M}_k$; that is, if there is a $\Gamma - \Lambda$ morph $Y$ such that $X *_{\Gamma^0} Y \cong I_{\Lambda}$ and $Y *_{\Lambda^0} X \cong I_{\Gamma}$. We claim that $X$ is invertible if and only if $X$ is isomorphic to $X(\alpha)$ for some isomorphism $\alpha : \Gamma \to \Lambda$.

To see this, we first show that the range and source maps on $X$ are bijections. Certainly the range and source maps on $X$ and $Y$ are surjective. In particular, $s : X \to \Gamma^0$ and $r : Y \to \Gamma^0$ are surjective, and hence the projections from $X *_{\Gamma^0} Y$ to $X$ and $Y$ are surjective. As $X *_{\Gamma^0} Y$ is isomorphic to $I_{\Lambda}$, the range and source maps on $X *_{\Gamma^0} Y$ are bijections. Since the range map on $X *_{\Gamma^0} Y$ is defined by first projecting onto the first coordinate in $X *_{\Gamma^0} Y$ and then applying the range map on $X$, it follows that the range map on $X$ is bijective. A similar argument shows that the source map on $Y$ is bijective. Applying the same argument to $Y *_{\Lambda^0} X \cong I_{\Lambda}$ shows that the range map on $Y$ and the source map on $X$ are both bijective.

We may now define $\alpha : \Gamma \to \Lambda$ as follows. Given $\gamma \in \Gamma$, there is a unique $x \in X$ with $s(x) = r(\gamma)$. We then have $\phi(x, \gamma) = (\lambda, x')$ for some $\lambda \in \Lambda$ and $x' \in X$, and we define $\alpha(\gamma) = \lambda$. The properties of $\phi$ can be used to show that $\alpha$ is an isomorphism of $k$-graphs, and it is straightforward to check that $X \cong X(\alpha)$.
4. Linking graphs

In this section, we define the notion of a linking graph $\Sigma$ for a $\Lambda \hookrightarrow \Gamma$ morph $X$. Linking graphs generalise the $(k + 1)$-graphs $\Lambda \xleftarrow{k} \Gamma$ built from covering maps $p$ in [21].

We begin by showing how appropriate inclusions of $k$-graphs $\Lambda$ and $\Gamma$ in a $(k + 1)$-graph $\Sigma$ can be used to manufacture a $\Lambda \hookrightarrow \Gamma$ morph $X$. This will provide a template for linking graphs (see Definition 4.3).

**Notation 4.1.** Let $\Sigma$ be a $(k + 1)$-graph, and let $\Lambda$ and $\Gamma$ be $k$-graphs. Let $i : \mathbb{N}_k \to \mathbb{N}_{k+1}$ be the inclusion $i(n) = (n, 0)$. Suppose that $i : \Lambda \sqcup \Gamma \to \Sigma$ is an $i$-quasimorphism (where $\sqcup$ denotes a disjoint union) such that $i$ induces a $k$-graph isomorphism $\Lambda \sqcup \Gamma \cong \Sigma^i$. Suppose further that for all $\alpha \in \Sigma^{k+1}$, $s(\alpha) \in i(\Gamma^0)$ and $r(\alpha) \in i(\Lambda^0)$.

Let $X(\Lambda, \Gamma, \Sigma, i) = \Sigma^{k+1}$. Define structure maps on $X = X(\Lambda, \Gamma, \Sigma, i)$ as follows. For $\alpha \in X$, $r_X(\alpha)$ is the unique vertex $v \in \Lambda^0$ such that $i(v) = r(\alpha)$, and similarly for $s_X(\alpha)$.

**Lemma 4.2.** With the notation just established, $X(\Lambda, \Gamma, \Sigma, i)$ is a $\Lambda \hookrightarrow \Gamma$ morph.

**Proof.** Properties 1-3 of Definition 3.1 are clear because $\Sigma$ is a $(k + 1)$-graph and $i$ is a quasimorphism. Property 4 follows from the associativity of composition in $\Sigma$. □

**Definition 4.3.** Let $\Lambda, \Gamma$ be $k$-graphs and let $X$ be a $\Lambda \hookrightarrow \Gamma$ morph. Suppose that $\Sigma, i$ and $\sigma$ are as in Notation 4.1. We say that the pair $(\Sigma, i)$ is a linking graph for $X$ if the $\Lambda \hookrightarrow \Gamma$ morph $X(\Lambda, \Gamma, \Sigma, i)$ is isomorphic to $X$.

In practice, we will just say that $\Sigma$ is a linking graph for $X$, leaving $i$ implicit.

**Example 4.4.** Let $p : \Gamma \to \Lambda$ be a covering of $k$-graphs, and let $p_X$ the $k$-morphism described in Examples 3.3. Then the $(k + 1)$-graph $\Lambda \xleftarrow{k+1} \Gamma$ of [21, Proposition 2.6] is a linking graph for $p_X$.

Note that if $\Sigma$ is a linking graph for a $k$-morphism, then necessarily $d_\Sigma(\Sigma) \subset \mathbb{N}_k \times \{0, 1\}$.

**Proposition 4.5.** Let $\Lambda, \Gamma$ be $k$-graphs and let $X$ be a $\Lambda \hookrightarrow \Gamma$ morph. Then there exists a linking graph for $X$, and this linking graph is unique up to isomorphism.

**Proof.** As a set, we define $\Sigma = \Lambda \sqcup \Gamma \sqcup (\Lambda \star_{\Lambda^0} X)$. We endow $\Sigma$ with the structure of a $(k + 1)$-graph as follows. First set $\Sigma^0 = \Lambda^0 \sqcup \Gamma^0$. The restrictions of $r_\Sigma$ and $s_\Sigma$ to $\Lambda \sqcup \Gamma$ are inherited from the range and source maps on $\Lambda$ and $\Gamma$. For $\sigma \in \Lambda \sqcup \Gamma$, set $d_\Sigma(\sigma) = (d(\sigma), 0)$. For $\lambda, x \in \Lambda \star_{\Lambda^0} X$, let $r_\Sigma(\lambda, x) = r(\lambda)$, $s_\Sigma(\lambda, x) = s_X(x)$ and $d_\Sigma(\lambda, x) = (d(\lambda), 1)$. Now fix $\sigma_1, \sigma_2 \in \Sigma$ such that $s_\Sigma(\sigma_1) = r_\Sigma(\sigma_2)$. We must define the composition $\sigma_1 \sigma_2$. There are three cases to consider.

1. If $\sigma_1, \sigma_2 \in \Gamma \sqcup \Lambda$, their composition as elements of $\Sigma$ is computed in $\Lambda \sqcup \Gamma$.
2. If $\sigma_1 = \mu \in \Lambda$, and $\sigma_2 = (\nu, x) \in \Lambda \star_{\Lambda^0} X$, we define $\sigma_1 \sigma_2 = (\mu \nu, x) \in \Lambda \star_{\Lambda^0} X$.
3. If $\sigma_1 = (\mu, x) \in \Lambda \star_{\Lambda^0} X$ and $\sigma_2 = \nu \in \Gamma$, we write $\phi(\mu, x) = (\mu', x')$, and define $\sigma_1 \sigma_2 = (\mu', x') \in \Lambda \star_{\Lambda^0} X$.

Associativity follows from Definition 3.3.1.

It is straightforward to check that $d_\Sigma : \Sigma \to \mathbb{N}_k \times \{0, 1\}$ is a functor. To show that $\Sigma$ has the factorisation property, fix $\sigma \in \Sigma$, and suppose $d_\Sigma(\sigma) = m + n$; we must show that
there exist unique paths \( \tau \in \Sigma^m \) and \( \rho \in \Sigma^n \) with \( \sigma = \tau \rho \). By definition of \( d_\Sigma \), we have \( d_\Sigma(\sigma)_{k+1} \leq 1 \). If \( m_{k+1} = n_{k+1} = 0 \), then \( \sigma \in \Lambda \sqcup \Gamma \), and the factorisation property in \( \Lambda \sqcup \Gamma \) produces the desired paths \( \tau \) and \( \rho \). If \( m_{k+1} = 0 \) and \( n_{k+1} = 1 \), then \( \sigma \in \Lambda \ast_\Lambda^0 X \), say \( \sigma = (\lambda, x) \). By the factorisation property in \( \Lambda \), there is a unique factorisation \( \lambda = \mu \nu \) where \( d(\mu) = (m_1, \ldots, m_k) \), and then \( \tau = \mu \) and \( \rho = (\nu, x) \) are the desired paths. Finally, suppose that \( m_{k+1} = 1 \) and \( n_{k+1} = 0 \), and let \( p \in \mathbb{N}^k \) be the element such that \( m = (p, 1) \).

Again, write \( \sigma = (\lambda, x) \in \Lambda \ast_\Lambda^0 X \). Use the factorisation property in \( \Lambda \) to write \( \lambda = \mu \nu \) where \( d(\mu) = p \). We have \((\nu, x) \in \Lambda \ast_\Lambda^0 X\), so \( \phi(\nu, x) = (x', \nu') \) for some \( x' \in X \) and \( \nu' \in \Gamma \). One checks that \( \tau = (\mu, x') \) and \( \rho = \nu' \) are the desired paths.

For uniqueness, let \( \Sigma' \) be a linking graph for \( X \). Then there are a quasi-morphism \( i' : \Lambda \sqcup \Gamma \to \Sigma' \) satisfying the conditions set forth in Notation 4.1 and an isomorphism \( \psi : \Sigma \to \Sigma' \) as follows. For \( \sigma \in \Lambda \sqcup \Gamma \subset \Sigma \), we set \( \tilde{\psi}(\sigma) = i'(\sigma) \); and for \( \sigma = (\lambda, x) \in \Lambda \ast_\Lambda^0 X \), we set \( \tilde{\psi}(\lambda, x) = i'(\lambda)\psi(x) \). One then checks that \( \tilde{\psi} \) is an isomorphism.

\[ \text{Remark 4.6. If } X \text{ and } X' \text{ are isomorphic } k\text{-morphs, then any linking graph for } X \text{ is by definition also a linking graph for } X'. \text{ Hence Proposition 4.5 implies that, up to isomorphism, there is a unique linking graph for each isomorphism class of } k\text{-morphs.} \]

5. \( \Gamma \)-systems and \( \Gamma \)-bundles

In this section, we describe a generalisation, based on \( k\)-morphs and linking graphs, of the \((k+1)\)-graphs \( \lim(\Lambda_n; p_n) \) constructed in [21] from a sequence of coverings \( p_n : \Lambda_{n+1} \to \Lambda_n \) of \( k\)-graphs. The idea is that the sequence \( (p_n)_{n=0}^\infty \) of coverings determines a consistent collection of \( k\)-morphs

\[ X_{(m,n)} = p_mX \ast_{\Lambda_{m+1}^0} \cdots \ast_{\Lambda_{n-1}^0} p_{n-1}X \]

indexed by pairs \( (m, n) \in \mathbb{N} \times \mathbb{N} \) such that \( m \leq n \). Recall from [18] that such pairs are morphisms in the \( 1\)-graph \( \Omega_1 \) whose vertices are identified with \( \mathbb{N} \). That is, a sequence of coverings as in [21] gives rise to a consistent collection of \( k\)-morphs indexed by a 1-graph.

We generalise this situation by replacing \( \Omega_1 \) with an \( l\)-graph \( \Gamma \). Given a consistent collection (which we call a \( \Gamma \)-system) of \( k\)-morphs indexed by paths in \( \Gamma \), we construct a \((k+l)\)-graph \( \Sigma \) which we call a \( \Gamma \)-bundle. As we shall see, each \( \Gamma \)-system \( X \) determines a functor \( F_X \) from \( \Gamma \) to \( \mathcal{M}_k \). Na"ively, one might expect to be able to recover \( \Sigma \) from \( F_X \), thus obviating the need to discuss \( \Gamma \)-systems at all. It turns out, however, that this is not the case: not only do there exist functors from which we may build two non-isomorphic \((k+l)\)-graphs, but there also exist functors from which no \((k+l)\)-graph may be built (see Examples 5.15).

\[ \text{Definition 5.1. Let } \Gamma \text{ be an } l\text{-graph, and let } k \geq 0. \text{ Fix} \]

- for each vertex \( v \in \Gamma^0 \) a \( k\)-graph \( \Lambda_v \);
- for each \( \gamma \in \Gamma \) a \( \Lambda_{r(\gamma)} \ast_{\Lambda_{s(\gamma)}} X_{\gamma} \); and
- for each composable pair \( \alpha, \beta \in \Gamma \) an isomorphism \( \theta_{\alpha,\beta} : X_\alpha \ast_{\Lambda_{s(\alpha)}} X_\beta \to X_{\alpha\beta} \).

Suppose that \( \Lambda, X \) and \( \theta \) have the following properties:

1. \( \text{(1) for each } v \in \Gamma^0, \text{ } X_v = I_{\Lambda_v}, \)
2. \( \text{(2) for each } \gamma \in \Gamma, \text{ the isomorphisms } \theta_{r(\gamma),\gamma} \text{ and } \theta_{\gamma,s(\gamma)} \text{ are those of Remark 3.7[31],} \)

and
(3) for each composable triple $\alpha, \beta, \gamma \in \Gamma$, the following diagram commutes.

\[
\begin{array}{ccc}
X_\alpha \ast_{\Lambda^0_{s(\alpha)}} X_\beta \ast_{\Lambda^0_{s(\beta)}} X_\gamma & \xrightarrow{\theta_{\alpha,\beta} \times \text{id}_{X_\gamma}} & X_{\alpha \beta} \ast_{\Lambda^0_{s(\alpha)}} X_\gamma \\
\text{id}_{X_\alpha} \times \theta_{\beta,\gamma} & \downarrow & \downarrow \theta_{\alpha,\beta,\gamma} \\
X_\alpha \ast_{\Lambda^0_{s(\alpha)}} X_\beta & \xrightarrow{\theta_{\alpha,\beta,\gamma}} & X_{\alpha \beta \gamma}
\end{array}
\]

Then we say that $X$ is a $\Gamma$-system of $k$-morphs with data $\Lambda, \theta$ or just that $X$ is a $\Gamma$-system, in which case $\Lambda$ and $\theta$ are implicit.

Remark 5.2. Given a $\Gamma$-system $X$ of $k$-morphs, there is a functor $F_X$ from $\Gamma$ to $\mathcal{M}_k$ determined by $F_X(\gamma) = [X_\gamma]$; in particular, the object map satisfies $F_X^N(v) = \Lambda_v$. However, the $\Gamma$-system $X$ contains more information than the functor $F_X$: the $\Gamma$-system picks out a concrete representative $X_\gamma$ of each isomorphism class $F_X(\gamma)$ and a compatible system of concrete isomorphisms $X_\alpha \ast_{\Lambda^0_{s(\alpha)}} X_\beta \cong X_{\alpha \beta}$ implementing the compositions $F_X(\alpha)F_X(\beta) = F_X(\alpha \beta)$. We show that this distinction is important in Examples 5.15.

Examples 5.3.

(i) Fix $k$-graphs $\Lambda$ and $\Gamma$ and a $\Lambda$-graph $X$. Let $E$ be the unique 1-graph with a single edge $e$ and two vertices $r(e)$ and $s(e)$. Setting $\Lambda_{r(e)} = \Lambda$, $\Lambda_{s(e)} = \Gamma$, $X_{r(e)} = I_\Lambda$, $X_{s(e)} = I_\Gamma$, and $X_e = X$, we obtain an $E$-system of $k$-morphs.

(ii) Fix a $k$-graph $\Lambda$ and a $\Lambda$ endomorph $X$. Recall from [18, Examples 1.7(iii)] that $T_1$ denotes the unique 1-graph with a single edge $e$ and a single vertex $v = r(e) = s(e)$. The degree functor is an isomorphism of $T_1$ onto $\mathbb{N}$, and we use it to identify the two. Let $\Lambda_0 = \Lambda$, and for $n \geq 0$ let $X_n = X^*n$ as in Notation 3.9. Then the isomorphisms $\theta_{m,n} : X_m \ast_{\Lambda^0} X_n \rightarrow X_{m+n}$ of Lemma 3.8 give this collection of $k$-morphs the structure of a $T_1$-system.

(iii) Fix an $L$-graph $\Gamma$, a countable discrete group $G$, and a functor $c : \Gamma \rightarrow G$. For each $v \in \Gamma^0$, let $\Lambda_v$ be the 0-graph such that $\Lambda_v^0 = G$. For $\gamma \in \Gamma$, there is an automorphism $\alpha_{c(\gamma)} : \Lambda_{s(\gamma)} \rightarrow \Lambda_{r(\gamma)}$ determined by $\alpha_{c(\gamma)}(g) = c(\gamma)g$ for $g \in \Lambda_{s(\gamma)}^0$. For each $\gamma \in \Gamma$, let $X_\gamma$ be the 0-morph $X(\alpha_{c(\gamma)})$ arising from $\alpha_{c(\gamma)}$ as in Example 3.3(iii). The isomorphisms $X(\alpha_{c(\gamma)}) \cong X(\alpha_{c(\gamma)}) \ast_G X(\alpha_{c(\gamma)})$ described in Remark 3.7(ii), give this collection of 0-morphs the structure of a $\Gamma$-system, denoted $X(\gamma)$, of 0-morphs.

(iv) Let $\text{Cov}_k$ denote the category whose objects are $k$-graphs and whose morphisms are $k$-graph coverings, and let $\Gamma$ be an $L$-graph. Let $F$ be a functor from $\Gamma$ to $\text{Cov}_k$. For each $v \in \Gamma^0$, let $\Lambda_v$ be the $k$-graph $F^0(v)$ and for each $\gamma \in \Gamma$, let $X_\gamma = F(\gamma)X$. Then the isomorphisms $\theta_{\gamma,\gamma'} : X_\gamma \ast_{\Lambda^0_{s(\gamma)}} X_{\gamma'} \rightarrow X_{\gamma \gamma'}$ of Remark 3.7(ii) give this collection of $k$-morphs the structure of a $\Gamma$-system. For instance, the covering systems of [21] give rise to $\Omega_1$-systems.

(v) Let $\Sigma$ be a 2-graph satisfying the hypotheses of [28, Theorem 3.1]. That is, each vertex lies on a unique simple cycle in the graph whose edges are $\Sigma^{e2}$, and the graph with edge-set $\Sigma^e$ contains no cycles. The simple cycles in edges in $\Sigma^{e2}$ determine an equivalence relation on vertices in $\Sigma$ by $v \sim w$ if and only if $v\Sigma^{ne2}w \neq \emptyset$ for some $n \in \mathbb{N}$. We write $[v]$ for the equivalence class of $v \in \Sigma^0$ under this relation. There is a 1-graph $\Gamma$ with

\[\Gamma^0 = \{[v] : v \in \Sigma^0\} \quad \text{and} \quad \Gamma^1 = \{(\{v\}, [w]) : [v], [w] \in \Sigma^0/\sim, [v]\Sigma^e[w] \neq \emptyset\}\]
where \( r([v],[w]) = [v] \) and \( s([v],[w]) = [w] \). For \( [v] \in \Gamma^0 \), we denote by \( \Lambda_{[v]} \) the sub-1-graph of \( \Sigma \) such that \( \Lambda_{[v]} = [v] \Sigma^2 \); so each \( \Lambda_{[v]} \) is the path-category of a simple cycle. For each path \( \gamma \in \Gamma \), we define \( X_\gamma = r(\gamma) \Sigma^{d(\gamma)} s(\gamma) \), and we endow it with the range and source maps \( r : X_\gamma \to \Lambda_{r(\gamma)}^0 \) and \( s : X_\gamma \to \Lambda_{s(\gamma)}^0 \) inherited from \( \Sigma \), and with the map \( \phi : X_\gamma \star_{s(\gamma)} X_\gamma \to \Lambda_{r(\gamma)} \star_{r(\gamma)} X_\gamma \) determined by the factorisation property in \( \Sigma \). Then each \( X_\gamma \) is a \( \Lambda_{r(\gamma)} \star_{r(\gamma)} \Lambda_{s(\gamma)} \) morph, composition in \( \Sigma \) defines isomorphisms \( \theta_{\alpha,\beta} : X_\alpha \star_{s(\alpha)} X_\beta \to X_{\alpha\beta} \) and from this structure we obtain a \( \Gamma \)-system of 1-morphisms which we denote by \( X(\Sigma) \). If \( \Sigma \) is a rank-2 Bratteli diagram as in [28, Section 4], then \( \Gamma \) is the path-category of a Bratteli diagram.

The next step is to show how to assemble a \((k+l)\)-graph from the data contained in a \( \Gamma \)-system of \( k \)-graphs. This construction should simultaneously generalise the linking graphs of the previous section, and the construction of the skew-product of a \( k \)-graph by a group.

The model for this construction is the following prototypical \( \Gamma \)-system which generalises the construction of Example 5.3(v).

**Notation 5.4.** Let \( \Sigma \) be a \((k+l)\)-graph, and let \( \Gamma \) be an \( l \)-graph. Let \( \pi : \mathbb{N}^{k+l} \to \mathbb{N}^l \) denote the projection onto the last \( l \) coordinates; that is \( \pi(m,n) = n \). Suppose \( f : \Sigma \to \Gamma \) is a \( \pi \)-quasimorphism which restricts to a surjection of \( \Sigma^0 \) onto \( \Gamma^0 \). Let \( \iota : \mathbb{N}^k \to \mathbb{N}^{(k+l)} \) be the inclusion \( \iota(m) = (m,0) \) and let \( j : \mathbb{N}^l \to \mathbb{N}^{k+l} \) be the inclusion \( j(n) = (0,n) \). For each \( v \in \Gamma^0 \), we define \( \Lambda_v = f^{-1}(v) \) which is a sub-\( k \)-graph of \( \Sigma^i \). For \( \gamma \in \Gamma \), we define \( X(f)_\gamma = f^{-1}(\gamma) \cap \Sigma^i \) (note that for each \( x \in X(f)_\gamma \), \( d_\Sigma(x) = (0,d(\gamma)) \)). Each \( X(f)_\gamma \) becomes a \( \Lambda_{r(\gamma)} \star_{r(\gamma)} \Lambda_{s(\gamma)} \) morph under the range, source and factorisation maps inherited from \( \Sigma \). Composition in \( \Sigma \) defines maps

\[ \theta_{\gamma_1,\gamma_2} : X(f)_{\gamma_1} \star_{\Lambda_{s(\gamma_1)}} X(f)_{\gamma_2} \to X(f)_{\gamma_1 \gamma_2} \]

for each composable pair \( (\gamma_1, \gamma_2) \) in \( \Gamma \). Moreover, under these structure maps, \( X(f) \) becomes a \( \Gamma \)-system of \( k \)-graphs: conditions (1) and (2) of Definition 5.1 are satisfied by definition, and condition (3) follows from associativity of composition in \( \Sigma \).

We will show that every \( \Gamma \)-system is isomorphic to one of the form \( X(f) \) for some \( \pi \)-quasimorphism \( f : \Sigma \to \Gamma \). We must first make clear what we mean by an isomorphism of \( \Gamma \)-systems.

**Definition 5.5.** Let \( \Gamma \) be a \( l \)-graph. Suppose that \((\Lambda, X, \theta)\) and \((\Xi, \mathcal{Y}, \psi)\) are \( \Gamma \)-systems of \( k \)-graphs. An isomorphism from \( X \) to \( Y \) consists of \( k \)-graph isomorphisms \( h^0_v : \Lambda_v \to \Xi_v \) and bijections \( h_\gamma : X_\gamma \to Y_\gamma \) which intertwine all the structure maps. That is:

1. For each \( \gamma \in \Gamma \), \( s \circ h_\gamma = h^0_{s(\gamma)} \circ s \) and \( r \circ h_\gamma = h^0_{r(\gamma)} \circ r \). For each \( \gamma \in \Gamma \),

\[ (h^0_{r(\gamma)} \times h_\gamma) \circ \phi_{X_\gamma} = (h_\gamma \circ h^0_{s(\gamma)}) \circ \phi_{Y_\gamma} \]

2. For every composable pair \( \alpha, \beta \in \Gamma \),

\[ h_{\alpha \beta} \circ \theta_{\alpha,\beta} = \psi_{\alpha,\beta} \circ (h_{\alpha} \times h_{\beta}) \]

We can now say what we mean by a \( \Gamma \)-bundle for a \( \Gamma \)-system.

**Definition 5.6.** Let \( \Gamma \) be an \( l \)-graph, and let \( X \) be a \( \Gamma \)-system of \( k \)-graphs. Let \( \pi : \mathbb{N}^{k+l} \to \mathbb{N}^l \) be the projection onto the last \( l \) coordinates. A \( \Gamma \)-bundle for \( X \) is a \((k+l)\)-graph \( \Sigma \) endowed with a \( \pi \)-quasimorphism \( f : \Sigma \to \Gamma \) which restricts to a surjection of
\[\Sigma^0\] onto \(\Gamma^0\) such that the \(\Gamma\)-system \(X(f)\) of Notation 5.4 is isomorphic to \(X\). We call the \(\pi\)-quasimorphism \(f\) the bundle map for the \(\Gamma\)-system.

**Remark 5.7.** Our formulation of \(\Gamma\)-bundles emphasises that the construction of Notation 5.4 is prototypical: given a \(\pi\)-quasimorphism \(\phi : \Sigma \to \Gamma\), the \((k + l)\)-graph \(\Sigma\) is automatically a \(\Gamma\)-bundle (with bundle map \(f\)) for the resulting \(\Gamma\)-system \(X(f)\).

**Remark 5.8.** Let \(X\) be a \(\Gamma\)-system of \(k\)-graphs, and suppose that \(\Sigma\) is a \(\Gamma\)-bundle for \(X\). The maps \(h_v^0\) and \(h_\gamma\) of Definition 5.5 determine injective quasimorphisms \(h_v^0 : \Lambda_v \to \Sigma\) for each \(v \in \Gamma^0\), and inclusions \(h_\gamma : \mathcal{X}_\gamma \to \Sigma^{d(\gamma)}\). Moreover, the factorisation property implies that every element of \(\sigma \in \Sigma\) can be expressed as \(\sigma = h_{f(\sigma)}(x)h_{s(f(\sigma))}^0(\lambda)\) for unique elements, \(x \in \mathcal{X}_{f(\sigma)}\) and \(\lambda \in \Lambda_{s(f(\sigma))}\).

We now show that every \(\Gamma\)-system admits a \(\Gamma\)-bundle.

**Theorem 5.9.** Let \(\Gamma\) be an \(l\)-graph and let \(X\) be a \(\Gamma\)-system of \(k\)-morphs. Then there exists a \(\Gamma\)-bundle \(\Sigma\) for \(X\). Moreover, \(\Sigma\) is unique up to isomorphism: that is, if \(\Psi\) is another \(\Gamma\)-bundle for \(X\), then there is an isomorphism \(\Sigma \cong \Psi\) of \((k + l)\)-graphs which intertwines the bundle maps on \(\Sigma\) and \(\Psi\).

**Proof.** Throughout this proof, for \(\gamma \in \Gamma\), we will write \(\phi_\gamma\) for the isomorphism \(\phi_{X_\gamma} : X_\gamma \ast_{\Lambda_{s(\gamma)}} \Lambda_{s(\gamma)} \to X_\gamma \ast_{\Lambda_{r(\gamma)}} \Lambda_{r(\gamma)} \ast_{\Lambda_0} \mathcal{X}_\gamma\) associated with the \(k\)-morph \(X_\gamma\).

We must first construct a \(\Gamma\)-bundle for \(X\), and then show that it is unique. We begin by constructing the \((k + l)\)-graph \(\Sigma\). Define a set \(\Sigma\) by

\[\Sigma = \{(\lambda, \gamma, x) : \gamma \in \Gamma, \lambda \in \Lambda_{r(\gamma)}, x \in \mathcal{X}_\gamma\}.\]

Define \(d : \Sigma \to \mathbb{N}^{k+l}\) by \(d(\lambda, \gamma, x) = (d(\lambda), d(\gamma))\). We write \(\Sigma^p\) for the set \(d^{-1}(p) \subset \Sigma\) for each \(p \in \mathbb{N}^{k+l}\). By condition 1 of Definition 5.1, for \(v \in \Gamma^0\), \(X_v = I(\Lambda_v)\) is equal as a set to \(\Lambda_v^0\). Hence \(\Sigma^0 = \{(u, v, u) : v \in \Gamma^0, u \in \Lambda_v^0\}\). To simplify notation and to help distinguish vertices from arbitrary paths, we will discard the redundant \(u\), and write \((u, v, u)\) for the element \((u, v, u)\) of \(\Sigma^0\).

Define \(r, s : \Sigma \to \Sigma^0\) by

\[r(\lambda, \gamma, x) = (r(\lambda), r(\gamma)) \quad \text{and} \quad s(\lambda, \gamma, x) = (s(\lambda), s(\gamma)).\]

Suppose that \(s(\lambda_0, \gamma_0, x_0) = r(\lambda_1, \gamma_1, x_1)\), and define \(\lambda'_1\) and \(x'_1\) by \(\phi_{\gamma_0}(x_0, \lambda_1) = (\lambda'_1, x'_0)\). We define

\[(\lambda_0, \gamma_0, x_0)(\lambda_1, \gamma_1, x_1) = (\lambda_0 \lambda'_1, \gamma_0 \gamma_1, \theta_{\gamma_0, \gamma_1}(x'_0, x_1)).\]

It is easy to check that the triple on the right lies in \(\Sigma\) and that

\[d(\lambda_0 \lambda'_1, \gamma_0 \gamma_1, \theta_{\gamma_0, \gamma_1}(x'_0, x_1)) = d(\lambda_0, \gamma_0, x_0) + d(\lambda_1, \gamma_1, x_1).\]

We aim to show that \(\Sigma\) is a \((k + l)\)-graph when endowed with these structure maps. We must check that the composition we have defined is associative, and that under this composition, \((\Sigma, d)\) satisfies the factorisation property. To see that the composition is associative, we fix a composable triple \((\lambda_0, \gamma_0, x_0), (\lambda_1, \gamma_1, x_1), (\lambda_2, \gamma_2, x_2)\) of elements of \(\Sigma\). Let \(v_i = r(\gamma_i)\) and \(v_{i+1} = s(\gamma_i)\) for \(i = 0, 1, 2\). Define \(x'_0, x'_1, x'_2, \lambda'_1, \lambda'_2\) and \(\lambda''_2\) by

\[\phi_{\gamma_0}(x_0, \lambda_1) = (\lambda'_1, x'_0),\]

\[\phi_{\gamma_1}(x_1, \lambda_2) = (\lambda'_2, x'_1),\]

and

\[\phi_{\gamma_0}(x'_0, \lambda'_2) = (\lambda''_2, x'_0).\]
We may visualise the situation as follows:

To prove associativity, we must show that the products

\[(\lambda_0, \gamma_0, x_0) (\lambda_1, \gamma_1, x_1) (\lambda_2, \gamma_2, x_2)\]

and

\[(\lambda_0, \gamma_0, x_0) (\lambda_1, \gamma_1, x_1) (\lambda_2, \gamma_2, x_2)\]

coincide. We begin by calculating the first of these. First, notice that the pair \((x_0', x_1)\), \((\lambda_2)\) belongs to \((X_{\gamma_0} * \Lambda_{\alpha_{\gamma_1}} X_{\gamma_1}) * \Lambda_{\alpha_{\gamma_2}} \Lambda_{\gamma_2}\). We have

\[(5.1) \quad \phi_{X_{\gamma_0} * \Lambda_{\alpha_{\gamma_1}} X_{\gamma_1}} ((x_0', x_1), \lambda_2) = (\lambda_2', (x_0', x_1'))\]

by definition of \(\phi_{X_{\gamma_0} * \Lambda_{\alpha_{\gamma_1}} X_{\gamma_1}}\) and of the elements \(\lambda_2', x_0''\) and \(x_1'\) given above. Since \(\theta_{\gamma_0, \gamma_1} : X_{\gamma_0} * \Lambda_{\alpha_{\gamma_1}} X_{\gamma_1} \to X_{\gamma_0, \gamma_1}\) is an isomorphism of \(k\)-morphs,

\[(5.2) \quad \phi_{\lambda_0, \gamma_0, \gamma_1} (\theta_{\gamma_0, \gamma_1} (x_0', x_1), \lambda_2) = (\lambda_2' \theta_{\gamma_0, \gamma_1} (x_0'', x_1'))\]

determined by \(5.1\). Therefore,

\[
(\lambda_0, \gamma_0, x_0) (\lambda_1, \gamma_1, x_1) (\lambda_2, \gamma_2, x_2) = (\lambda_0 \lambda_1, \gamma_0 \gamma_1, \theta_{\gamma_0, \gamma_1} (x_0', x_1)) (\lambda_2, \gamma_2, x_2) = ((\lambda_0 \lambda_1) \lambda_2', \gamma_0 \gamma_1, \gamma_2, \theta_{\gamma_0, \gamma_1} (x_0'' \theta_{\gamma_0, \gamma_1} (x_0', x_1'), x_2)),
\]

where the second step uses \(5.2\). Similar calculations show that

\[(\lambda_0, \lambda_1, \gamma_1, \gamma_2, x_0, x_1, x_2) = (\lambda_0, \lambda_0 \lambda_1, \gamma_0 \gamma_1, \gamma_2, \theta_{\gamma_0, \gamma_1} (x_0'', \theta_{\gamma_0, \gamma_1} (x_0', x_1'), x_2)).\]

Associativity in \(\Sigma\) now follows from associativity in \(\Lambda_{\alpha_{\gamma_0}}\) and \(\Gamma\), and property (3) of Definition 5.1.

To establish the factorisation property in \(\Sigma\), fix \(m, p \in \mathbb{N}^k\) and \(n, q \in \mathbb{N}^l\) and an element \((\lambda, \gamma, x) \in \Sigma^{(m+p, n+q)}\). By the factorisation properties in \(\Lambda_{\chi_{(\gamma)}}\) and in \(\Gamma\), there are unique factorisations \(\lambda = \lambda_0 \lambda_1\) and \(\gamma = \gamma_0 \gamma_1\) where \(d(\lambda_0) = m, d(\lambda_1) = p, d(\gamma_0) = n\) and \(d(\gamma_1) = q\). Since \(\theta_{\gamma_0, \gamma_1}\) is an isomorphism, there are unique elements \(x_0 \in X_{\gamma_0}\) and \(x_1 \in X_{\gamma_1}\) such that \(x = \theta_{\gamma_0, \gamma_1} (x_0, x_1)\). As \(\phi_{\gamma_0}\) is also a bijection, there are unique elements \(\lambda_1' \in \Lambda_{\chi_{(\gamma_0)}}\)
and \( x'_0 \in X_m \) such that \( \phi_{\gamma_0}(x'_0, X'_\gamma) = (\lambda_1, x_0) \). We then have \( d(\lambda_0, \gamma_0, x'_0) = (m, p) \) and \( d(\lambda_1, \gamma_1, x_1) = (n, q) \), and

\[
(\lambda, \gamma, x) = (\lambda_0, \gamma_0, x'_0)(\lambda'_1, \gamma_1, x_1)
\]

by definition. Uniqueness is clear. We have now established that \( \Sigma \) is a \((k + l)\)-graph.

The formula \( f(\lambda, \gamma, x) = \gamma \) defines a \( \pi \)-quasimorphism from \( \Sigma \) onto \( \Gamma \). Let \( \iota : \mathbb{N}^k \to \mathbb{N}^{k+l} \) and \( j : \mathbb{N}^l \to \mathbb{N}^{k+l} \) be as in Notation 5.4. For each \( v \in \Gamma^0 \), \( f^{-1}(v) = \{ (\lambda, v, s(\lambda)) : \lambda \in \Lambda_v \} \), and \( h^0_v : f^{-1}(v) \to \Lambda_v \) defined by \( h^0_v(\lambda, v, s(\lambda)) = \lambda \) is an isomorphism of \( k \)-graphs. For each \( \gamma \in \Gamma \), \( f^{-1}(\gamma) \cap \Sigma^j = \{ (r(x), \gamma, x) : x \in X_j \} \), and \( h_\gamma : f^{-1}(\gamma) \cap \Sigma^j \to X_\gamma \) defined by \( (r(x), \gamma, x) = x \) is a bijection. Routine calculations show that these maps satisfy conditions (1) and (2) of Definition 5.5. Hence \( \Sigma \) is a \( \Gamma \)-bundle for \( X \) as claimed when equipped with the bundle map \( f : \Sigma \to \Gamma \).

It remains to establish the uniqueness of the \( \Gamma \)-bundle. Suppose that \( \Psi \) is another \( \Gamma \)-bundle for \( X \) with bundle map \( g \). So we have isomorphisms \( h^0_v : \Lambda_v \to g^{-1}(v) \) for each \( v \in \Gamma^0 \) and bijections \( h_\gamma : X_\gamma \to g^{-1}(\gamma) \cap \Psi^j \) determining an isomorphism of \( \Gamma \)-systems. Define \( H : \Sigma \to \Psi \) by

\[
H(\lambda, \gamma, x) = h^0_v(\gamma)h_\gamma(x) \quad \text{for all} \ (\lambda, x, \gamma) \in \Sigma.
\]

The factorisation property in \( \Psi \) ensures that each \( \psi \in \Psi \) with \( d(\psi) = (m, n) \) can be written uniquely as \( \psi = \psi_m\psi_n \) where \( d(\psi_m) = (m, 0) \) and \( d(\psi_n) = (0, n) \). We then have \( \psi_m \in g^{-1}(g(r(\psi))) \), and \( \psi_n \in g^{-1}(g(\psi)) \cap \Psi^j \). Bijectivity of \( H \) follows from this. It is clear that \( H \) respects the degree map, and intertwines the range and source maps.

A straightforward calculation shows that it also respects composition, and hence is an isomorphism of \((k + l)\)-graphs.

\[\Box\]

Remark 5.10. Theorem 5.9 implies that it makes sense to talk about the \( \Gamma \)-bundle for a \( \Gamma \)-system \( X \), and we shall frequently do so. Unless specified otherwise, the bundle is denoted \( \Sigma \) and the bundle map is denoted \( f \).

**Examples 5.11.**

(i) Let \( \Lambda \) and \( \Gamma \) be \( k \)-graphs, and let \( X \) be a \( \Lambda - \Gamma \) morph. As noted in Example 3.3(i), this corresponds to an \( E \)-system of \( k \)-graphs where \( E \) is the 1-graph with a single edge \( e \) and two vertices \( r(e) \) and \( s(e) \). An \( E \)-bundle for this \( E \)-system amounts to a linking graph for \( X \).

(ii) Let \( \Lambda \) be a \( k \)-graph, and \( X \) a \( \Lambda \) endomorph. As noted in Example 3.3(ii), this corresponds to a \( T_1 \)-system of \( k \)-graphs. We shall denote the \( T_1 \)-bundle for this system by \( \Lambda \times_X \mathbb{N} \). We call \( \Lambda \times_X \mathbb{N} \) the endomorph skew-graph for \( X \). Every \((k+1)\)-graph arises this way: given a \((k+1)\)-graph \( \Sigma \), with \( \Lambda = \Sigma^k \) and \( X = \Sigma^{k+1} \) as in Example 3.3(vi), \( \Sigma \) is isomorphic to \( \Lambda \times_X \mathbb{N} \).

(iii) Let \( \Lambda \) be a \( k \)-graph, and let \( \alpha \) be an automorphism of \( \Lambda \). Let \( X = X(\alpha) \) be the associated \( \Lambda \) endomorph. In this case, the endomorph skew-graph \( \Lambda \times_X \mathbb{N} \) discussed in the preceding example is the same as the crossed-product \((k+1)\)-graph \( \Lambda \times_\alpha \mathbb{Z} \) of [15]. More generally, let \( T_l \) denote the \( l \)-graph isomorphic to \( \mathbb{N}^l \), and suppose that \( \alpha \) is an action of \( \mathbb{Z}^l \) by automorphisms of \( \Lambda \). Let \( X_n = X(\alpha^n) \) for each \( n \in T_l \), and let \( \theta_{n,m} : X_m \rtimes_\alpha X_n \to X_{m+n} \) be the isomorphism of Remark 3.7(i). Then the \( X_n \) form a \( T_l \)-system \( X(\alpha) \), and the crossed product \((k+l)\)-graph \( \Lambda \times_\alpha \mathbb{Z}^l \) described in [15] is a \( T_l \)-bundle for \( X(\alpha) \).
(iv) Fix a functor $c$ from an $l$-graph $\Gamma$ to a group $G$, and construct from this a $\Gamma$-system $X(c)$ of 0-morphs as in Example 5.3(iii). Then the skew-product $k$-graph $G \times_c \Gamma$ of [18] is a $\Gamma$-bundle for the $\Gamma$-system $X(c)$; the bundle map is the functor $f(g, \gamma) := \gamma$.

(v) Let $\Sigma$ be a 2-graph satisfying the hypotheses of [28] Theorem 3.1, and let $\Gamma$ and $X$ be as in Example 5.3(iii). Then $\Sigma$ is a $\Gamma$-bundle for $X$ and the bundle map is the natural quotient map $\Lambda \rightarrow \Sigma$. In particular, we may regard a rank-2 Bratteli diagram $\Sigma$ as a bundle of cycle-graphs over the path-category of a conventional Bratteli diagram.

Our $\Gamma$-bundle construction is quite general: the next proposition shows that every $k$-graph $\Lambda$ is a $T_k$-bundle for some $T_k$-system. It is a strong point of our formulation of $\Gamma$-bundles that the proof of this result is almost trivial (see Remark 5.7).

**Proposition 5.12.** Let $\Lambda$ be a $k$-graph. Let $T_k$ denote the $k$-graph isomorphic to $\N^k$. Then the degree map on $\Lambda$ determines an id$_\Lambda$-quasimorphism (also denoted $d$) from $\Lambda$ onto $T_k$. In particular $\Lambda$ is a $T_k$-bundle (with bundle map $d$) for the $T_k$-system $X(d)$ of 0-morphs described in Notation 5.4.

**Remark 5.13.** If $p : \Gamma \rightarrow \Lambda$ is a covering of $k$-graphs then $p$ is an id$_\Lambda$-quasimorphism. Hence $p$ induces a $\Lambda$-system of 0-morphs as in Notation 5.4. Moreover, these 0-morphs are all invertible (see Remark 3.11).

Conversely, given a $k$-graph $\Lambda$, and a $\Lambda$-system of invertible 0-morphs, the bundle map associated to a $\Lambda$-bundle for the system is a covering map.

We conclude the section by investigating the relationship between $\Gamma$-systems and functors from $\Gamma$ into $\mathcal{M}_k$. If $\Gamma$ is a 1-graph, the two are essentially the same thing.

**Proposition 5.14.** Let $\Gamma$ be a 1-graph, and let $F : \Gamma \rightarrow \mathcal{M}_k$ be a functor. Then there is, up to isomorphism, exactly one $\Gamma$-system $X$ of $k$-graphs such that $F(\gamma) = [X_\gamma]$ for all $\gamma \in \Gamma$.

**Proof.** For each $v \in \Gamma^0$, set $\Lambda_v = F^0(v)$, and $X_v = I(\Lambda_v)$. For each edge $e \in \Gamma^1$, fix a $k$-morphism $X_e$ such that $[X_e] = F(e)$. For $n \geq 2$ and a path $\alpha = e_1 \cdots e_n \in \Gamma^n$, let $X_\alpha = X_{e_1} *^{\Lambda_{\epsilon(e_1)}} X_{e_2} *^{\Lambda_{\epsilon(e_2)}} \cdots *^{\Lambda_{\epsilon(e_{n-1})}} X_{e_n}$ as in Lemma 3.8, and for composable $\alpha, \beta$, let $\theta_{\alpha, \beta}$ be the isomorphism described in the same lemma. It is easy to verify that this data determines a $\Gamma$-system of $k$-morphs which induces the functor $F$.

Now suppose that $Y$ is another $\Gamma$ system of $k$-morphs (with data $\Lambda, \psi$) which induces $F$. Let $\psi_{\alpha, \beta} : Y_{\alpha} *^{\Lambda_{\psi(\alpha)}} Y_{\beta} \rightarrow Y_{\alpha \beta}$ denote the isomorphisms in the $\Gamma$-system $Y$. In particular, each $Y_\alpha$ is a $\Lambda_{r(\alpha)} - \Lambda_{s(\alpha)}$ morph which is isomorphic to $X_\alpha$. For $v \in \Gamma^0$, let $h_v^0$ denote the identity map on $\Lambda_v$. For each $e \in \Gamma^1$, we may fix an isomorphism $h_e : X_e \rightarrow Y_e$. By induction on $n$, for $\alpha \in \Gamma^n$ and $f \in \Gamma^1$ with $s(\alpha) = r(f)$, we may define an isomorphism $h_{\alpha f}$ from $X_{\alpha f}$ to $Y_{\alpha f}$ by

$$X_{\alpha f} \cong X_{\alpha} *^{\Lambda_{\psi(\alpha)}} X_f \xrightarrow{h_{\alpha \times hf}} Y_{\alpha} *^{\Lambda_{\psi(\alpha)}} Y_f \xrightarrow{\psi_{\alpha, hf}} Y_{\alpha f}.$$

As the isomorphisms $h_\alpha$ are defined using the structure maps in $X$ and $Y$, it is easy to check that they determine an isomorphism of $\Gamma$-systems. \[\Box\]

**Examples 5.15.** We cannot expect an analogue of Proposition 5.14 to hold if $\Gamma$ is an $l$-graph with $l > 1$, as the following two examples show.
(i) Let $\Gamma = T_2$ (the 2-graph isomorphic to $\mathbb{N}^2$), and let $\Lambda$ be the 0-graph consisting of a single vertex $v$. Each finite set is a $\Lambda$ endomorph when endowed with the only possible structure maps. In particular, each multiplicative map $x : \mathbb{N}^2 \to \mathbb{N}$ determines a functor from $T_2$ to $M_0$: the image of $n \in \mathbb{N}^2$ is (the isomorphism class of) the $\Lambda$ endomorph $X_n$ with $x(n)$ elements.

Example 6.1 of [18] describes two non-isomorphic 2-graphs $\Lambda$ and $\Lambda'$ each with a single vertex, two edges of degree $e_1$ and two edges of degree $e_2$. As in Notation 5.4, $\Lambda$ and $\Lambda'$ determine $T_2$-systems $X$ and $X'$ such that $\Lambda$ is a $T_2$-bundle for $X$ and $\Lambda'$ is a $T_2$-bundle for $X'$. By Theorem 5.9, $X$ and $X'$ are non-isomorphic. However, $X$ and $X'$ determine the same functor $F : T_2 \to M_0$ with $F^0(0) = \Lambda$, namely the one corresponding to the multiplicative map $x : \mathbb{N}^2 \to \mathbb{N}$ given by $x(n) = 2^{n_1 + n_2}$.

(ii) The following example is due to Jack Spielberg [39]. We thank Jack for allowing us to reproduce it here. The following diagram represents a 3-coloured graph where the edges have colours $c_1$, $c_2$ and $c_3$; we draw $c_1$-coloured edges as solid lines, $c_2$-coloured edges as dashed lines, and $c_3$-coloured edges as dotted lines.

For distinct $1 \leq i, j \leq 3$, there is a unique range- and source-preserving bijection $\theta_{i,j}$ between $c_ic_j$-coloured paths and $c_jc_i$-coloured paths. For example, the only $c_2c_1$-coloured path with the same range and source as the $c_1c_2$-coloured path $f_5g_1$ is $g_6f_2$, so $\theta_{1,2}(f_5g_1) = g_6f_2$. Thus, the factorisation rules in any 3-graph with the skeleton pictured above must be implemented by the $\theta_{i,j}$. To see that no such 3-graph exists, we consider the two possible ways of reversing the colouring of the path $h_8g_6f_2$ using the $\theta_{i,j}$:

$$h_8g_6f_2 \to h_8f_5g_1 \to f_7h_3g_1 \to f_7g_3h_1 \quad \text{and} \quad h_8g_6f_2 \to g_6h_6f_2 \to g_8f_4h_2 \to f_8g_4h_2.$$ 

Since $f_8 \neq f_7$, $g_3 \neq g_4$ and $h_1 \neq h_2$, the $\theta_{i,j}$ do not specify a valid collection of factorisation rules (see [31, Section 2]).

Let $\Gamma = T_3$ (the 3-graph isomorphic to $\mathbb{N}^3$), and let $\Lambda$ be the 0-graph whose vertices are those in the diagram above. The sets $X_1 := \{f_1, \ldots, f_8\}$, $X_2 := \{g_1, \ldots, g_8\}$, $X_3 := \{h_1, \ldots, h_8\}$.
Lemma 6.2. \{g_1, \ldots, g_8\} and \(X_3 = \{h_1, \ldots, h_8\}\) are \(\Lambda\)-endomorphs when endowed with the obvious structure maps. For \(i \neq j\), \(\theta_{i,j}\) determines an isomorphism \(X_i \ast_{\Lambda^0} X_j \cong X_j \ast_{\Lambda^0} X_i\), so there is a unique functor \(F : \Gamma \cong \mathbb{N}^3 \to \mathcal{M}_0\) such that \(F^*(v) = \Lambda\) and \(F(e_i) = [X_i]\) for \(i = 1, 2, 3\). However, this functor is not determined by any \(T_3\)-system of 0-morphs: the \(T_3\)-bundle for such a system would be a 3-graph whose skeleton was the 3-coloured graph we started with.

6. \textit{C\(^*\)-Correspondences and Functoriality}

In this section we consider how the constructions of the preceding sections behave with respect to higher-rank graph \(C\(^*\)-algebras. To keep the length of the paper down, we restrict attention to \(\Lambda-\Gamma\) morphs such that

\[(\star) \quad \Lambda \text{ and } \Gamma \text{ are row-finite } k\text{-graphs with no sources, } s : X \to \Gamma^0 \text{ is surjective, and } r : X \to \Lambda^0 \text{ is surjective and finite-to-one.}\]

This simplifying assumption ensures that the \(\Gamma\)-bundles we construct are covered by the results of [31].

To each \(k\)-morph \(X\) satisfying \((\star)\), we associate a \(C\(^*\)-correspondence \(\mathcal{H}(X)\). The germ of this construction, at least for \(k\)-morphs arising from covering maps, is present in the proof of [21] Proposition 3.2. However, here we make it explicit and extend it to arbitrary \(k\)-morphs.

In Theorem 6.6 we show that the assignment \([X] \mapsto [\mathcal{H}(X)]\) determines a contravariant functor to the category \(C\(^*\)-algebras and whose morphisms are isomorphism classes of \(C\(^*\)-correspondences. Theorem 6.8 shows that when \(X\) is a \(\Lambda\) endomorph satisfying \((\star)\), the Cuntz-Pimsner algebra of \(\mathcal{H}(X)\) is isomorphic to the \((k+1)\)-graph \(C\(^*\)-algebra \(C\(^*\)(\(\Lambda \times_X \mathbb{N}\)).

Proposition 6.1. There is a subcategory \(\mathcal{M}_k^\Lambda\) of \(\mathcal{M}_k\) whose objects are row-finite \(k\)-graphs with no sources, and whose morphisms are isomorphism classes of \(k\)-morphs \(X\) satisfying \((\star)\).

Proof. This follows from the observation that if \(k\)-morphs \(X_1\) and \(X_2\) satisfy \((\star)\), then so does their product. \(\square\)

Lemma 6.2. Let \(\Lambda\) and \(\Gamma\) be \(k\)-graphs and let \(X\) be a \(\Lambda-\Gamma\) morph satisfying \((\star)\). Let \((\Sigma, i)\) be a linking graph for \(X\). Then \(\Sigma\) is row-finite and locally convex, and there are injective homomorphisms

\[i_\Lambda^* : C^*(\Lambda) \to C^*(\Sigma) \text{ such that } i_\Lambda^*(s_\lambda) = s_{i(\lambda)}, \text{ and} \]

\[i_\Gamma^* : C^*(\Gamma) \to C^*(\Sigma) \text{ such that } i_\Gamma^*(s_\gamma) = s_{i(\gamma)}.\]

The series \(\sum_{v \in \Lambda^0} s_{i(v)}\) and \(\sum_{w \in \Gamma^0} s_{i(w)}\) converge strictly to complementary full projections \(P_\Lambda\) and \(P_\Gamma\) in \(MC^*(\Sigma)\). The homomorphism \(i_\Lambda^*\) induces an isomorphism \(C^*(\Gamma) \cong P_\Gamma C^*(\Sigma) P_\Gamma\). The homomorphism \(i_\Lambda^*\) induces an embedding \(C^*(\Lambda) \hookrightarrow P_\Lambda C^*(\Sigma) P_\Lambda\) which takes an approximate identity for \(C^*(\Lambda)\) to an approximate identity for \(P_\Lambda C^*(\Sigma) P_\Lambda\).

Proof. The linking graph \(\Sigma\) is row-finite because \((\star)\) ensures that \(\Lambda\) and \(\Gamma\) are both row-finite and the range map on \(X\) is finite-to-one. To see that \(\Sigma\) is locally convex, suppose that \(e, f \in \Sigma\) satisfy \(r(e) = r(f), d(e) = e_i\) and \(d(f) = e_j\) where \(1 \leq i < j \leq k + 1\). If \(j \leq k\), then \(s(e)\Sigma^{e_i}\) and \(s(f)\Sigma^{e_i}\) are nonempty because \(\Lambda\) and \(\Gamma\) have no sources. If
\[ d(f) = e_{k+1}, \text{ then } s(e)\Sigma^{k+1} \text{ is nonempty because } r : X \to \Lambda^0 \text{ is surjective by } \Box, \text{ and } s(f)\Sigma^k \text{ is nonempty because } \Gamma \text{ has no sources.} \]

The existence of homomorphisms \( i^*_\Lambda \) and \( i^*_\Gamma \) satisfying the required formulæ follows from the universal properties of \( C^*(\Lambda) \) and \( C^*(\Gamma) \), and their injectivity follows from the gauge-invariant uniqueness theorem \[ \text{Theorem 3.4.} \]

A standard argument (see for example \[ \text{Proposition 3.2.} \]) shows that \( P_\Lambda \) and \( P_\Gamma \) make sense and are complementary projections. To see that \( C \) isomorphism class of \( \Lambda \) and \( \Gamma \) are full, we fix a generator \( s_\sigma \) of \( C^*(\Sigma) \) and show that \( s_\sigma \in C^*(\Sigma)P_\Lambda C^*(\Sigma) \). If \( r(\sigma) \in i_\Lambda(\Lambda^0) \), then \( s_\sigma = P_\Lambda s_\sigma \); and if \( r(\sigma) \in i_\Gamma(\Gamma^0) \), then since the source map on \( X \) is surjective by \( \Box \), we have \( s_\sigma = s_\sigma^* P_\Lambda s_\sigma \) for some \( \alpha \in \Sigma^{k+1} \). To see that \( P_\Gamma \) is full, we fix a generator \( s_\sigma \) of \( C^*(\Sigma) \) and show that \( s_\sigma \in C^*(\Sigma)P_\Gamma C^*(\Sigma) \). If \( s(\sigma) \in i_\Gamma(\Gamma^0) \), then \( s_\sigma = s_\sigma P_\Gamma \); and if \( s(\sigma) \in i_\Lambda(\Lambda^0) \), then since the range map on \( X \) is surjective and finite-to-one by \( \Box \), we have

\[
\sum_{\alpha \in \alpha(\sigma)\Sigma^{k+1}} \alpha s_\alpha P_\Gamma s_\alpha^*. 
\]

We have \( P_\Gamma C^*(\Sigma)P_\Gamma = \text{span}\{s_\alpha s_\beta^* : \alpha, \beta \in \Sigma, r(\alpha), r(\beta) \in i(\Gamma^0)\} = \text{span}\{i^*_\Gamma(s_\gamma s_\gamma^*) : \gamma_1, \gamma_2 \in \Gamma, \gamma_1 = \gamma_2\} \), and it follows from an application of the gauge-invariant uniqueness theorem \[ \text{Theorem 4.1.} \] that \( i^*_\Gamma \) implements the desired isomorphism \( C^*(\Gamma) \cong P_\Gamma C^*(\Sigma)P_\Gamma \). Since \( \Sigma \) is row-finite and locally convex, the Cuntz-Krieger relations in \( C^*(\Sigma) \) ensure that the partial isometrics \( \{s_\lambda(\lambda) : \lambda \in \Lambda\} \) form a Cuntz-Krieger \( \Lambda \)-family. Another application of \[ \text{Theorem 4.1.} \] then shows that \( i^*_\Lambda : C^*(\Lambda) \to P_\Lambda C^*(\Sigma)P_\Lambda \) is injective. For each finite subset \( F \subset \Lambda^0 \), let \( p_F \) denote the projection \( \sum_{v \in F} v \). Then the net \( (p_F)_{F \subset \Lambda^0 \text{ finite}} \) is an approximate identity for \( C^*(\Lambda) \), and \( (i^*_\Lambda(p_F))_{F \subset \Lambda^0 \text{ finite}} \) converges strictly to \( P_\Lambda \) by definition of \( P_\Lambda \).

**Definition 6.3.** Resume the hypotheses of Lemma \[ \text{Lemma 6.2.} \] Let \( \mathcal{H}(X) \) denote the vector space \( P_\Lambda C^*(\Sigma)P_\Gamma \). Define a left action of \( C^*(\Lambda) \) and a right action of \( C^*(\Gamma) \) on \( \mathcal{H}(X) \) by

\[
a \cdot \xi \cdot b = i^*_\Lambda(a) \xi i^*_\Gamma(b) \quad \text{for } a \in C^*(\Lambda), b \in C^*(\Gamma) \text{ and } \xi \in \mathcal{H}(X) \]

where the product is taken in \( C^*(\Sigma) \). Define \( \langle \cdot, \cdot \rangle_{C^*(\Gamma)} : \mathcal{H}(X) \times \mathcal{H}(X) \to C^*(\Gamma) \) as follows: \( \langle \xi, \eta \rangle_{C^*(\Gamma)} \) is the unique element of \( C^*(\Gamma) \) such that

\[
\xi^* \eta = i^*_\Gamma(\langle \xi, \eta \rangle_{C^*(\Gamma)})
\]

where \( \xi^* \eta \) is calculated in \( C^*(\Sigma) \).

**Proposition 6.4.** Let \( \Lambda \) and \( \Gamma \) be \( k \)-graphs and let \( X \) be a \( \Lambda-\Gamma \) morph satisfying \( \Box \). The space \( \mathcal{H}(X) \) defined above satisfies

\[
\mathcal{H}(X) = \text{span}\{s_{r(\alpha)} s_{r(\beta)}^* : x \in X, \alpha, \beta \in \Gamma, s(x) = r(\alpha), s(\alpha) = s(\beta)\}.
\]

Under the operations defined above, \( \mathcal{H}(X) \) is a full nondegenerate \( C^*(\Lambda)-C^*(\Gamma) \) \( C^* \)-correspondence, and the left-action is implemented by an injective homomorphism of \( C^*(\Lambda) \) into \( K(\mathcal{H}(X)) \). Moreover, the isomorphism class of \( \mathcal{H}(X) \) depends only on the isomorphism class of \( X \).

**Remark 6.5.** If we do not insist on \( \Box \), but assume only that \( \Sigma \) is finitely aligned (so that \( C^*(\Sigma) \) makes sense), then Definition \[ \text{6.3.} \] still specifies a \( C^*(\Lambda)-C^*(\Gamma) \) correspondence \( \mathcal{H}(X) \) satisfying \[ \text{6.1.} \] However our proofs of the remaining assertions of Proposition \[ \text{6.4.} \] and of Theorems \[ \text{6.6 and 6.8.} \] all rely on \( \Box \) via their dependence on Lemma \[ \text{6.2.} \]
Proof of Proposition 6.4. Fix a nonzero spanning element $s_\mu s_\nu^*$ of $C^*(\Sigma)$. Then $s_\mu s_\nu^* \in P_\Lambda C^*(\Sigma)P_\Gamma$ only if $r(\mu) \in i(\Lambda^0)$, $r(\nu) \in i(\Gamma^0)$, and $s(\mu) = s(\nu)$. Since $r(\nu) \in i(\Gamma^0)$ implies $s(\nu) \in \Gamma^0$, we have $\nu \in i(\Gamma)$. Since $s(\mu) = s(\nu)$, we also have $\mu \in i(\Lambda^0)\Sigma i(\Gamma^0)$, and the factorisation property in $\Sigma$ forces $\mu = xi(\alpha)$ for some $x \in X$ and $\alpha \in \Gamma$ with $s(x) = r(\alpha)$. This establishes (6.1).

Since $P_\Lambda$ and $P_\Gamma$ are complementary full projections in $MC^*(\Sigma)$, Theorem 3.19 of [33] implies that $\mathcal{H}(X)$ is an imprimitivity bimodule for the two corners $P_\Lambda C^*(\Sigma)P_\Lambda \cong K(\mathcal{H}(X))$ and $P_\Gamma C^*(\Sigma)P_\Gamma \cong C^*(\Gamma)$. That $\mathcal{H}(X)$ is full follows from the definition of an imprimitivity bimodule (see [33] Definition 3.1]). The injective homomorphism $C^*(\Lambda) \rightarrow K(\mathcal{H}(X))$ comes from the embedding $C^*(\Lambda) \rightarrow P_\Lambda C^*(\Sigma)P_\Lambda$ induced by $i_\Lambda^*$ and the identification $P_\Lambda C^*(\Sigma)P_\Lambda \cong K(\mathcal{H}(X))$. Since $i_\Lambda^*$ maps an approximate identity for $C^*(\Lambda)$ to an approximate identity for $P_\Lambda C^*(\Sigma)P_\Lambda$, $\mathcal{H}(X)$ is nondegenerate.

The final statement follows from Remark 4.6.

For the following, recall from Section 2.4 that $C$ denotes the category whose objects are $C^*$-algebras and whose morphisms are isomorphism classes of $C^*$-correspondences.

Theorem 6.6. For each $k \geq 0$, the assignments $\Lambda \mapsto C^*(\Lambda)$ and $[X] \mapsto [\mathcal{H}(X)]$ determine a contravariant functor $\mathcal{H}_k$ from $\mathcal{M}_k^\Sigma$ to $C$.

Proof. We need only show that for $\Lambda_0, \Lambda_1, \Lambda_2 \in \text{Obj}(\mathcal{M}_k^\Sigma)$ and $[X_i] \in \text{Hom}_{\mathcal{M}_k^\Sigma}(\Lambda_i, \Lambda_{i-1})$, there is an isomorphism of $C^*$-correspondences

$$\mathcal{H}(X_1) \otimes_{C^*(\Lambda_1)} \mathcal{H}(X_2) \cong \mathcal{H}(X_1 \ast_{\Lambda_1^0} X_2).$$

For $i = 1, 2$, let $\Sigma_i$ be a linking graph for $X_i$, and let $\Sigma_{12}$ be a linking graph for $X_1 \ast_{\Lambda_1^0} X_2$. Let $\Gamma$ be the 1-graph with two edges $a_1, a_2$ and three distinct vertices $v_0 = r(a_1), v_1 = s(a_1) = r(a_2)$ and $v_2 = s(a_2)$. Then $\Lambda_{v_i} := \Lambda_i$, $X_{a_i} := X_i$ and $X_{a_1 a_2} := X_1 \ast_{\Lambda_1^0} X_2$ defines a $\Gamma$-system of $k$-morphs ($\theta_{X_1,X_2}$ is the identity on $X_1 \ast_{\Lambda_1^0} X_2$). Let $\Sigma$ be a $\Gamma$-bundle for this system, and let $f : \Sigma \rightarrow \Gamma$ be the bundle map. For $i = 0, 1, 2$, let $P_i = \sum_{w \in f^{-1}(v_i)} s_w \in MC^*(\Sigma)$.

By applications of the gauge-invariant uniqueness theorem [31] Theorem 4.1], there are canonical isomorphisms

$$C^*(\Sigma_1) \cong (P_0 + P_1)C^*(\Sigma)(P_0 + P_1)$$
$$C^*(\Sigma_2) \cong (P_1 + P_2)C^*(\Sigma)(P_1 + P_2),$$
$$C^*(\Sigma_{12}) \cong (P_0 + P_2)C^*(\Sigma)(P_0 + P_2)$$
(to establish the third of these isomorphisms, we must slightly modify the gauge action on $(P_0 + P_2)C^*(\Sigma)(P_0 + P_2)$). In particular, it follows that

$$\mathcal{H}(X_1) \cong P_0 C^*(\Sigma)P_1$$
$$\mathcal{H}(X_2) \cong P_1 C^*(\Sigma)P_2,$$
$$\mathcal{H}(X_1 \ast_{\Lambda_1^0} X_2) \cong P_0 C^*(\Sigma)P_2.$$

As in Lemma 6.2 the $P_i$ are all full projections in $MC^*(\Sigma)$, so

$$\mathcal{H}(X_1 \ast_{\Lambda_1^0} X_2) \cong P_0 C^*(\Sigma)P_2 = (P_0 C^*(\Sigma)P_1)(P_1 C^*(\Sigma)P_2),$$

and hence, if we identify $\mathcal{H}(X_1) \otimes_{C^*(\Lambda_1)} \mathcal{H}(X_2)$ with $(P_0 C^*(\Sigma)P_1) \otimes_{P_1 C^*(\Sigma)} P_1 C^*(\Sigma)P_2$, multiplication in $C^*(\Sigma)$ induces an isomorphism

$$\mathcal{H}(X_1) \otimes_{C^*(\Lambda_1)} \mathcal{H}(X_2) \cong (P_0 C^*(\Sigma)P_1)(P_1 C^*(\Sigma)P_2).$$
This completes the proof.

We now present an alternative construction of the $C^*$-correspondence $\mathcal{H}(X)$ (see [6] for a similar construction). In the following, given a $k$-morph $X$, we denote the point-mass function at $x \in X$ by $\delta_x \in C_c(X)$. We regard $C_c(X)$ as a right pre-Hilbert $C_0(\Gamma^0)$ module with pointwise operations.

**Proposition 6.7.** Let $\Lambda$ and $\Gamma$ be $k$-graphs, and $X$ a $\Lambda$–$\Gamma$ morph satisfying (6). Let $(\Sigma, i)$ be a linking graph for $X$, and identify $X$ with $\Sigma^{\ast k+1}$. Let $\mathcal{H}(X)$ be the $C^*$-correspondence obtained from Proposition 6.4. Then there is an isomorphism of right-Hilbert $C^*(\Gamma)$-modules

$$\mathcal{H}(X) \cong C_c(X) \otimes_{C_0(\Gamma^0)} C^*(\Gamma)$$

determined by

$$s_{x_i(a)} s_{i(i)}^* \mapsto \delta_x \otimes s_\alpha s_\beta^* \quad \text{for } x \in \Sigma^{\ast k+1}, \; \alpha, \beta \in \Gamma.$$

This isomorphism carries the left action of $s_\lambda \in C^*(\Lambda)$ on $\mathcal{H}(X)$ to

$$s_\lambda \cdot (\delta_x \otimes s_\alpha s_\beta^*) = \delta_x \otimes s_\gamma s_\alpha s_\beta^* \quad \text{for } x \in \Sigma^{\ast k+1} \text{ and } \alpha, \beta \in \Gamma$$

where $\phi_x(x', \gamma) = (\lambda, x)$.

**Proof.** For the first statement, we just need to check that the formula (6.2) extends to an inner-product preserving map. For all $x, x' \in \Sigma^{\ast k+1}, \; \alpha \in s(x)\Gamma, \; \alpha' \in s(x')\Gamma, \; \beta \in \Gamma s(\alpha)$ and $\beta' \in \Gamma s(\alpha')$, we have

$$(\delta_x \otimes s_\alpha s_\beta^*, \delta_{x'} \otimes s_{\alpha'} s_{\beta'}^*) = \langle s_\alpha s_\beta^*, (\delta_x, \delta_{x'}) \cdot s_{\alpha'} s_{\beta'}^* \rangle = \begin{cases} s_\beta s_\alpha s_{\alpha'} s_{\beta'}^* & \text{if } x = x' \\ 0 & \text{otherwise.} \end{cases}$$

Since $s_{x_i(a)}^* s_{i(i)}^* = s_{i(a)}^* (s_x s_{x'} s_{i(a')}) s_{i(a')}$, the third Cuntz-Krieger relation in $C^*(\Sigma)$ forces

$$s_{x_i(a)}^* s_{x'i(i)} = \begin{cases} s_{i(a)}^* s_{i(a')} & \text{if } x = x' \\ 0 & \text{otherwise;} \end{cases}$$

then equations (6.3) and (6.2) and the definition of the inner product on $\mathcal{H}(X)$ imply that

$$\langle \delta_x \otimes s_\alpha s_\beta^*, \delta_{x'} \otimes s_{\alpha'} s_{\beta'}^* \rangle = \langle s_{x_i(a)} s_{i(a')} s_{i(a')}^* \rangle.$$
to \( X \) regarded as a \( \Lambda \) endomorph. There are a homomorphism \( \pi : C^*(\Lambda) \to C^*(\Lambda \times X \mathbb{N}) \) and a linear map \( t : \mathcal{H}(X) \to C^*(\Lambda \times X \mathbb{N}) \) determined by

\[
\pi(s_\lambda) = s_{h_\lambda(\lambda)} \quad \text{and} \quad t(s_{x_{(\alpha)}}, s_{i_{(\beta)}}') = s_{h_1(x)} s_{h_\lambda(\alpha)} s_{h_\lambda(\beta)}'.
\]

The pair \((t, \pi)\) is a Cuntz-Pimsner covariant representation of \( \mathcal{H}(X) \), and the induced \( C^*\)-homomorphism \( t \times \pi : \mathcal{O}_{\mathcal{H}(X)} \to C^*(\Lambda \times X \mathbb{N}) \) is an isomorphism.

**Proof.** The universal property of \( C^*(\Lambda) \) shows that there is a homomorphism \( \pi : C^*(\Lambda) \to C^*(\Lambda \times X \mathbb{N}) \) satisfying \( \pi(s_\lambda) = s_{h_\lambda(\lambda)} \) for all \( \lambda \in \Lambda \). This homomorphism \( \pi \) is equivariant for the gauge action on \( C^*(\Lambda) \) and the restriction of the gauge action on \( C^*(\Lambda \times X \mathbb{N}) \) to the first \( k \) coordinates of \( \mathbb{T}^{k+1} \). Hence an application of the gauge-invariant uniqueness theorem for \( C^*(\Lambda) \) [18 Theorem 3.4] shows that \( \pi \) is injective.

To see that the formula given for \( t \) determines a well-defined linear map, we will show that for any finite linear combination of the form \( \sum_{j=1}^n a_j s_{x_j_{(\alpha)}} s_{i_{(\beta)}}' \) in \( \mathcal{H}(X) \), we have

\[
\left\| \sum_{j=1}^n a_j s_{x_j_{(\alpha)}} s_{i_{(\beta)}}' \right\|_{\mathcal{H}(X)} = \left\| \sum_{j=1}^n a_j s_{h_1(x_j)} s_{h_\lambda(\alpha)} s_{h_\lambda(\beta)}' \right\|_{C^*(\Lambda \times X \mathbb{N})}.
\]

We have already shown that \( \pi \) is injective, so by the \( C^*\)-identity for \( C^*(\Lambda \times X \mathbb{N}) \) and the definition of the norm on \( \mathcal{H}(X) \) it suffices to show that for spanning elements \( s_{x_{(\alpha)}}, s_{i_{(\beta)}}' \) and \( s_{x'_{(\alpha')}, s_{i'_{(\beta')}}} \) of \( \mathcal{H}(X) \), we have

\[
\pi((s_{x_{(\alpha)}}, s_{i_{(\beta)}}'), (s_{x'_{(\alpha')}, s_{i'_{(\beta')}}})) = t(s_{x_{(\alpha)}}, s_{i_{(\beta)}}') t(s_{x'_{(\alpha')}, s_{i'_{(\beta')}}}).
\]

This follows from a routine calculation like (6.3) above.

It follows by linearity from the preceding paragraph that \( \pi((\xi, \eta))_{C^*(\Lambda)}(\lambda) = \pi(\xi) t(\eta) \) for all \( \xi, \eta \in \mathcal{H}(X) \). To see that \((t, \pi)\) is a representation, it therefore suffices to show that for a generator \( s_\lambda \) of \( C^*(\Lambda) \) and spanning elements \( s_{x_{(\alpha)}}, s_{i_{(\beta)}}' \) and \( s_{x'_{(\alpha')}, s_{i'_{(\beta')}}} \) of \( \mathcal{H}(X) \),

\[
\pi(s_\lambda) t(s_{x_{(\alpha)}}, s_{i_{(\beta)}}') = t(s_\lambda, (s_{x_{(\alpha)}}, s_{i_{(\beta)}}')), \quad \text{and} \quad t(s_{x_{(\alpha)}}, s_{i_{(\beta)}}') \pi(s_\lambda) = t((s_{x_{(\alpha)}}, s_{i_{(\beta)}}'), s_\lambda).
\]

One verifies these identities with short calculations using the definitions of \( t \) and \( \pi \) and the structure of \( \mathcal{H}(X) \). We give the first of these calculations as it is the least elementary. Fix \( s_\lambda \) and \( s_{x_{(\alpha)}}, s_{i_{(\beta)}}' \) as above, and let \( x' \) and \( \lambda' \) be the elements such that \( \phi_X(x', \lambda') = (\lambda, x) \). Then \( s_\lambda = s_{x_{(\alpha)}}, s_{i_{(\beta)}}' \) and we have

\[
\pi(s_\lambda) t(s_{x_{(\alpha)}}, s_{i_{(\beta)}}') = s_{h_\lambda(\lambda)} s_{h_1(x)} s_{h_\lambda(\alpha)} s_{h_\lambda(\beta)}' = s_{h_1(x)} s_{h_\lambda(\alpha)} s_{h_\lambda(\beta)}' = t(s_\lambda, (s_{x_{(\alpha)}}, s_{i_{(\beta)}}')).
\]

To check that \((t, \pi)\) is Cuntz-Pimsner covariant, fix \( \lambda \in \Lambda \), and note that the left action of \( s_\lambda \) on \( \mathcal{H}(X) \) is implemented by

\[
\sum_{r(x) = s_\lambda(\lambda)} s_{x'_{(\lambda')}}, s_x \in \mathcal{K}(\mathcal{H}(X)).
\]

Hence if \( \varphi \) denotes the homomorphism which implements the left action, we have

\[
t^{(1)}(\varphi(s_\lambda)) = \sum_{r(x) = s_\lambda(\lambda)} t(s_{x'_{(\lambda')}}, t(s_x)^* = \sum_{r(x) = s_\lambda(\lambda)} \pi(s_\lambda) t(s_x) t(s_x)^*,
\]

and this is equal to \( \pi(s_\lambda) \) by the fourth Cuntz-Krieger relation in \( C^*(\Lambda \times X \mathbb{N}) \).

The restriction of the gauge-action on \( C^*(\Lambda \times X \mathbb{N}) \) to the last coordinate in \( \mathbb{T}^{k+1} \) is compatible with the gauge action on \( \mathcal{O}_{\mathcal{H}(X)} \). The gauge-invariant uniqueness theorem [14]
Theorem 4.1] for \(\mathcal{O}_{H(X)}\) (see also [17] Theorem 6.4]) now implies that \(t \times \pi\) is injective. It remains only to observe that for \(h_n(x)h_\Lambda(\lambda) \in \Lambda \times X \mathbb{N}\), we can write \(x = (x_1, \ldots, x_n)\) where each \(x_i \in X\), and \(r(x_{i+1}) = s(x_i)\), and then

\[
s_{h_n(x)}h_\Lambda(\lambda) = t(s_{x_1}) \cdots t(s_{x_n})\pi(s_\lambda)
\]

(if \(n = 0\), then \(x = r(\lambda) \in I(\Lambda)\), so \(s_{h_n(x)}h_\Lambda(\lambda) = \pi(s_\lambda)\)). Hence \(t \times \pi\) is surjective. \(\square\)

Remark 6.9. Let \(\Sigma\) be a row-finite \((k + 1)\)-graph with no sources such that \(\Sigma^{n}v \neq \emptyset\) for all \(n \in \mathbb{N}^{k+1}\) and \(v \in \Sigma^0\). Let \(\Sigma'\) and \(X\) be the \(k\)-graph and \(\Sigma'\) endomorph discussed in Example 3.3[6]. Then \(X\) satisfies \(\mathcal{X}\). As in Example 5.11[1], we have that \(\Sigma\) is isomorphic to the endomorph skew graph \(\Sigma' \times_X \mathbb{N}\). Hence Theorem 6.8 implies that \(C^*(\Sigma) \cong \mathcal{O}_{H(X)}\); that is the \(C^*\)-algebra of \(\Sigma\) can be realised as the Cuntz-Pimsner algebra of a \(C^*\)-correspondence over \(C^*(\Sigma')\).

Remark 6.10. Let \(\Lambda \in \text{Obj}(\mathcal{M}^\mathbb{Z}_k\), let \(\alpha\) be an automorphism of \(\Lambda\), and let \(X = X(\alpha)\) be the associated endomorph; clearly \(X\) satisfies \(\mathcal{X}\). Let \(\tilde{\alpha}\) denote the induced automorphism of \(C^*(\Lambda)\). As in Example 5.11[1], the endomorph skew graph \(\Lambda \times_X \mathbb{N}\) is isomorphic to the crossed product \((k + 1)\)-graph \(\Lambda \times_\alpha \mathbb{Z}\) constructed in [15].

In this situation, the bimodule \(\mathcal{H}(X)\) constructed above is isomorphic to the bimodule constructed by Pimsner in [29, Example 3, p.193] with \(A = C^*(\Lambda)\) and \(\pi = \tilde{\alpha}\). We therefore recover the isomorphism \(C^*(\Lambda \times_\alpha \mathbb{Z}) \cong C^*(\Lambda) \times_\tilde{\alpha} \mathbb{Z}\) of [15, Theorem 3.5] from Theorem 6.8 and Pimsner’s result.

Corollary 6.11. Let \(\Lambda, \Gamma\) be \(k\)-graphs, let \(R\) be a \(\Lambda-\Gamma\) morph and \(S\) a \(\Gamma-\Lambda\) morph. Suppose \(R\) and \(S\) satisfy \(\mathcal{Z}\). Let \(X\) be the \(\Lambda\) endomorph \(S \ast_\Lambda R\), and let \(Y\) be the \(\Gamma\)-endomorph \(R \ast_\Gamma S\). Then the \((k + 1)\)-graph algebras \(C^*(\Lambda \times_X \mathbb{N})\) and \(C^*(\Gamma \times_Y \mathbb{N})\) are Morita equivalent.

In particular the above Morita equivalence holds if \(X = pH_q\) and \(Y = X_q \ast_\Lambda^q \ast_\Lambda^p X\) where \(p, q: \Gamma \to \Lambda\) are finite coverings of row-finite \(k\)-graphs.

Proof. Theorem 6.6 implies that \(\mathcal{H}(X) \cong \mathcal{H}(S) \otimes_{C^*(\Gamma)} \mathcal{H}(R)\), and \(\mathcal{H}(Y) \cong \mathcal{H}(R) \otimes_{C^*(\Lambda)} \mathcal{H}(S)\). By Theorem 6.7, \(E := \mathcal{H}(X)\), and \(F := \mathcal{H}(Y)\) satisfy the hypotheses of [24, Theorem 3.14] (the \(C^*\)-correspondences \(\mathcal{H}(R)\) and \(\mathcal{H}(S)\) implement the elementary strong shift equivalence). Hence \(\mathcal{O}_{\mathcal{H}(X)}\) and \(\mathcal{O}_{\mathcal{H}(Y)}\) are Morita equivalent, and our result follows from Theorem 6.8. \(\square\)

Remark 6.12. When \(k = 0\), the first statement of the above Corollary reduces to Bates’ results on shift-equivalence for 1-graphs [2].

Example 6.13. For \(n \in \mathbb{N}\setminus \{0\}\), let \(D_n\) be the directed graph with \(n\) vertices \(\{v_0, \ldots, v_{n-1}\}\) and edges \(\{x_i, y_i: 0 \leq i \leq n - 1\}\) where \(r(x_i) = v_i = s(y_i)\) and \(s(x_i) = v_{i+1} = r(y_i)\) (see [21, Section 6.2]). In particular, \(D_1\) is equal to the bouquet of two loops whose \(C^*\)-algebra is canonically isomorphic to \(\mathcal{O}_2\). We will consider a \(D_1\) endomorph \(pX_q\) constructed from coverings \(p, q: D_2 \to D_1\). To reduce confusion, we will denote \(x_0, y_0 \in D_1\) by \(x\) and \(y\).

The covering maps \(p, q: D_2 \to D_1\) are defined as follows

\[
\begin{align*}
p(x_0) &= x, & p(y_0) &= y, \\
p(x_1) &= x, & p(y_1) &= y, \\
q(x_0) &= x, & q(y_0) &= y, \\
q(x_1) &= y, & q(y_1) &= x.
\end{align*}
\]
Construct $X = pX_q$ as in Example 3.3[iv] (so, as a set, $X = D^0_2$). The endomorph skew-graph $\Lambda = D_1 \times X \mathbb{N}$ is a 2-graph whose skeleton and factorisation rules can be described as follows: $\Lambda^0 = \nu, \Lambda^{a1} = \{x, y\}, \Lambda^{a2} = X = \{v_0, v_1\}$, and

\[
v_0x = yv_1, \quad v_0y = xv_1, \quad v_1x = xv_0, \quad \text{and} \quad v_1y = yv_0.
\]

Results of [11, 35, 36] can be used to see that $C^*(\Lambda)$ is a Kirchberg algebra (the details appear in an unpublished manuscript of D. Robertson [34]) and has trivial $K$-theory. Hence $C^*(\Lambda)$ is isomorphic $O_2$ by the Kirchberg-Phillips theorem.

Using Proposition 6.7 we see that $H(X) \cong C^2 \otimes_C O_2$ as a right-Hilbert $O_2$-module (where $C^2$ is the two-dimensional Hilbert space with orthonormal basis $\{\delta_0, \delta_1\}$). The left action of $O_2 = C^*(\{S_0, S_1\})$ is determined by

\[
S_0 \cdot (\delta_0 \otimes_C 1_{O_2}) = \delta_1 \otimes_C S_0, \quad S_0 \cdot (\delta_1 \otimes_C 1_{O_2}) = \delta_0 \otimes_C S_1,
\]

\[
S_1 \cdot (\delta_0 \otimes_C 1_{O_2}) = \delta_1 \otimes_C S_1, \quad S_1 \cdot (\delta_1 \otimes_C 1_{O_2}) = \delta_0 \otimes_C S_0.
\]

By Theorem 6.8 the Cuntz-Pimsner algebra $O_{H(X)}$ of this $C^*$-correspondence is isomorphic to $C^*(\Lambda)$ which, as we saw above, is isomorphic to $O_2$.

Let $Y = X_q \ast_{A_0} pX$. Note that $Y$ satisfies (5). The endomorph skew-graph $D_2 \times_Y \mathbb{N}$ has skeleton

![Diagram](image)

with factorisation rules

\[
ap_{00}b_0 = y_0a_{11} \quad a_{00}x_1 = x_1a_{11} \quad a_{10}y_0 = x_0a_{01} \quad a_{10}x_1 = y_1a_{01}
\]

\[
ap_{11}x_0 = y_1a_{01} \quad a_{11}y_1 = x_0a_{01} \quad a_{01}x_0 = x_0a_{10} \quad a_{01}y_1 = y_1a_{10}
\]

Corollary 6.11 shows that $C^*(D_2 \times_Y \mathbb{N})$ is Morita equivalent to $C^*(\Lambda) \cong O_2$, and as it is also unital, it is in fact isomorphic to $O_2$.

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