

**ACTION OPERADS, FREE ALGEBRAS ON INVERTIBLE  
OBJECTS, AND THE CLASSIFICATION OF 3-GROUPS**

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## 1. OPERADS AND THEIR ALGEBRAS

## 1.1. Operads.

**Definition 1.1.** Operads  $O$ **Definition 1.2.** Action operads  $G$ **Example 1.3.** The symmetric operad  $S$ **Example 1.4.** The braid operad  $B$ **Definition 1.5.**  $G$ -operads

## 1.2. Operad algebras.

**Definition 1.6.** Operad algebras**Definition 1.7.**  $G$ -operad algebras

## 1.3. EG-algebras.

**Definition 1.8.** The  $G$ -operad  $EG$ **Definition 1.9.** The monad  $EG$ **Definition 1.10.** EG-algebras**Proposition 1.11.**  *$G$ -operad algebras are monoidal categories with permutation-like structure***Corollary 1.12.** *Braided monoidal categories are  $G$ -operad algebras***Definition 1.13.** A strict monoidal category  $X$  is said to be *spacial* if, for any object  $x \in \text{Ob}(X)$  and any endomorphism of the unit object  $f : I \rightarrow I$ ,

$$f \otimes \text{id}_x = \text{id}_x \otimes f$$

The motivation for the name ‘spacial’ comes from the context of string diagrams [4]. In a string diagram, the act of tensoring two strings together is represented by placing those strings side by side. Since the defining feature of the unit object is that tensoring it with other objects should have no effect, the unit object is therefore represented diagrammatically by the absence of a string. An endomorphism of the unit thus appears as an entity with no input or output strings, detached from the rest of the diagram. In a real-world version of these diagrams, made out of physical strings arranged in real space, we could use this detachedness to grab these endomorphisms and slide them over or under any strings we please, without affecting anything else in the diagram. This ability is embodied algebraically by the equation above, and hence categories which obey it are called ‘spacial’.

**Lemma 1.14.** *All EG-algebras are spacial.*

*Proof.* Let  $X$  be an EG-algebra, and fix  $x \in \text{Ob}(X)$  and  $f : I \rightarrow I$ . From the surjectivity of  $\pi : G(2) \rightarrow S_2$  we know that the set  $\pi^{-1}((12))$  is non-empty, and from the rules for composition of action morphisms we see that for any such  $g \in \pi^{-1}((12))$ ,

$$\begin{aligned} \alpha(g; \text{id}_x, \text{id}_I) \circ \alpha(e_2; \text{id}_x, f) &= \alpha(g; \text{id}_x, f) \\ &= \alpha(e_2; f, \text{id}_x) \circ \alpha(g; \text{id}_x, \text{id}_I) \end{aligned}$$

Thus in order to obtain the result we’re after, it will suffice to find a particular  $g \in \pi^{-1}((12))$  for which

$$\alpha(g; \text{id}_x, \text{id}_I) = \text{id}_x$$

However, since

$$\begin{aligned}\alpha(g; \text{id}_x, \text{id}_I) &= \alpha(g; \text{id}_x, \alpha(e_0; -)) \\ &= \alpha(\mu(g; e_1, e_0); \text{id}_x)\end{aligned}$$

all we really need is to find a  $g \in \pi^{-1}((12))$  for which

$$\mu(g; e_1, e_0) = e_1$$

To this end, choose an arbitrary element  $h \in \pi^{-1}((12))$ . This  $h$  probably won't obey the above equation, but we can use it to construct a new element  $g$  which does. Specifically, define

$$k := \mu(h; e_1, e_0)$$

and then consider

$$g := h \cdot \mu(e_2; k^{-1}, e_1)$$

To see that this is the correct choice of  $g$ , first note that we must have  $\pi(k) = e_1$ , since this is the only element of  $S_1$ . Following from that, we have

$$\begin{aligned}\pi(\mu(e_2; k^{-1}, e_1)) &= \mu(\pi(e_2); \pi(k^{-1}), \pi(e_1)) \\ &= \mu(e_2; e_1, e_1) \\ &= e_2\end{aligned}$$

and hence

$$\begin{aligned}\pi(g) &= \pi(h \cdot \mu(e_2; k^{-1}, e_1)) \\ &= \pi(h) \cdot \pi(\mu(e_2; k^{-1}, e_1)) \\ &= (12) \cdot e_2 \\ &= (12).\end{aligned}$$

So  $g$  is indeed in  $\pi^{-1}((12))$ , and furthermore

$$\begin{aligned}\mu(g; e_1, e_0) &= \mu(h \cdot \mu(e_2; k^{-1}, e_1); e_1, e_0) \\ &= \mu(h; e_1, e_0) \cdot \mu(\mu(e_2; k^{-1}, e_1); e_1, e_0) \\ &= \mu(h; e_1, e_0) \cdot \mu(e_2; \mu(k^{-1}; e_1), \mu(e_1; e_0)) \\ &= \mu(h; e_1, e_0) \cdot \mu(e_2; k^{-1}, e_0) \\ &= k \cdot k^{-1} \\ &= e_1\end{aligned}$$

Therefore,  $h \cdot \mu(e_2; k^{-1}, e_1)$  is exactly the  $g$  we were looking for, and so working backwards through the proof we obtain the required result:

$$\begin{aligned}\mu(g; e_1, e_0) &= e_1 \\ \implies \alpha(g; \text{id}_x, \text{id}_I) &= \text{id}_x\end{aligned}$$

$$\begin{aligned}\alpha(g; \text{id}_x, \text{id}_I) \circ \alpha(e_2; \text{id}_x, f) &= \alpha(e_2; f, \text{id}_x) \circ \alpha(g; \text{id}_x, \text{id}_I) \\ \implies \alpha(e_2; \text{id}_x, f) &= \alpha(e_2; f, \text{id}_I)\end{aligned}$$

□

**1.4. The free EG-algebra on  $n$  objects.** Our goal for the next few chapters will be to understand the free braided monoidal category on a finite number of invertible objects. Thus, now that we have a firm grasp on action operads and their algebras, we should begin to think about the simpler free constructions they can form. We will use this extensively when calculating the invertible case later on.

In the paper [5], Gurski establishes how to construct free  $G$ -operad algebras through the use of the monad  $EG$ . What follows in this section is a quick summary

of the results which will be useful for our purposes. For a more detailed treatment please refer to [5].

**Proposition 1.15.** *There exists a free EG-algebra on  $n$  objects. That is, there is an EG-algebra  $Y$  such that for any other EG-algebra  $X$ , we have an isomorphism of categories*

$$\mathbf{EGAlg}_S(Y, X) \cong X^n$$

*Proof.* There is an obvious forgetful 2-functor  $U : \mathbf{EGAlg}_S \rightarrow \mathbf{Cat}$  sending EG-algebras to their underlying categories.  $U$  has a left adjoint, which we call the free 2-functor  $F : \mathbf{Cat} \rightarrow \mathbf{EGAlg}_S$  adjoint to it. It follows immediately that

$$\begin{aligned} U(X)^n &= \mathbf{Cat}(\{z_1, \dots, z_n\}, U(X)) \\ &\cong \mathbf{EGAlg}_S(F(\{z_1, \dots, z_n\}), X) \end{aligned}$$

where  $\{z_1, \dots, z_n\}$  is any set with  $n$  distinct elements. Since  $X$  and  $U(X)$  are obviously isomorphic as categories, this shows that  $F(\{z_1, \dots, z_n\})$  is the free algebra on  $n$  objects as required.  $\square$

**Definition 1.16.** Let  $\{z_1, \dots, z_n\}$  be an  $n$ -object set, which we will also consider as a discrete category. Then we will denote by  $\mathbb{G}_n$  the EG-algebra whose underlying category is  $\mathbf{EG}(\{z_1, \dots, z_n\})$  and whose action

$$\alpha : \mathbf{EG}(\mathbf{EG}(\{z_1, \dots, z_n\})) \rightarrow \mathbf{EG}(\{z_1, \dots, z_n\})$$

is the appropriate component of the multiplication natural transformation  $\mu : \mathbf{EG} \circ \mathbf{EG} \rightarrow \mathbf{EG}$  of the 2-monad  $\mathbf{EG}$ .

**Theorem 1.17.**  $\mathbb{G}_n$  is the free EG-algebra on  $n$  objects. That is,

$$F(\{z_1, \dots, z_n\}) = \mathbb{G}_n$$

*Proof.*  $\square$

Definition 1.16 is a fairly opaque definition, so we'll spend a little time unpacking it. Recall from Definition 1.9 that  $\mathbf{EG}(\{z_1, \dots, z_n\})$  is the coequalizer of the maps

$$\coprod_{m \geq 0} \mathbf{EG}(m) \times G(m) \times \{z_1, \dots, z_n\}^m \rightrightarrows \coprod_{m \geq 0} \mathbf{EG}(m) \times \{z_1, \dots, z_n\}^m$$

that comes from the action of  $G(m)$  on  $\mathbf{EG}(m)$  by multiplication on the right,

$$\begin{aligned} \mathbf{EG}(m) \times G(m) &\rightarrow \mathbf{EG}(m) \\ (g, h) &\mapsto gh \\ (! : g \rightarrow g', \text{id}_h) &\mapsto ! : gh \rightarrow g'h \end{aligned}$$

and the action of  $G(m)$  on  $\{z_1, \dots, z_n\}^m$  by permutation,

$$\begin{aligned} G(m) \times \{z_1, \dots, z_n\}^m &\rightarrow \{z_1, \dots, z_n\}^m \\ (h; x_1, \dots, x_m) &\mapsto (x_{\pi(h^{-1})(1)}, \dots, x_{\pi(h^{-1})(m)}) \\ (\text{id}_h; \text{id}_{(x_1, \dots, x_m)}) &\mapsto \text{id}_{(x_{\pi(h^{-1})(1)}, \dots, x_{\pi(h^{-1})(m)})} \end{aligned}$$

First, objects in this algebra are equivalence classes of tuples  $(g; x_1, \dots, x_m)$ , for  $g \in G(m)$  and  $x_i \in \{z_1, \dots, z_n\}$ , under the relation

$$(gh; x_1, \dots, x_m) \sim (g; x_{\pi(h)^{-1}(1)}, \dots, x_{\pi(h)^{-1}(m)})$$

Notice that using this relation we can rewrite any object uniquely in the form  $[e; x_1, \dots, x_m]$  for some  $m \in \mathbb{N}$  and  $x_i \in \{z_1, \dots, z_n\}$ . This means that each equivalence class is just the tensor product  $x_1 \otimes \dots \otimes x_m$  in the underlying monoidal

category of  $\mathbb{G}_n$ , for some unique sequence of generators. That is, we can view the objects of  $\mathbb{G}_n$  as elements of the monoid freely generated by each of the  $z_i$ , or in other words:

**Lemma 1.18.**  *$\text{Ob}(\mathbb{G}_n)$  is the free monoid on  $n$  generators,  $\mathbb{N}^{*n}$ , the free product of  $n$  copies of  $\mathbb{N}$ .*

Similarly, the morphisms of  $\mathbb{G}_n$  are the maps

$$(!; \text{id}_{x_1}, \dots, \text{id}_{x_m}) : (g; x_1, \dots, x_m) \rightarrow (g'; x_1, \dots, x_m)$$

with  $g, g' \in G(m)$  and  $x_i \in \{z_1, \dots, z_n\}$ . Using the relation  $\sim$  on objects we can rewrite each of these morphisms in the form

$$[h; \text{id}_{y_1}, \dots, \text{id}_{y_m}] : y_1 \otimes \dots \otimes y_m \rightarrow y_{\pi(h^{-1})(1)} \otimes \dots \otimes y_{\pi(h^{-1})(m)}$$

where

$$h = g'g^{-1}, \quad y_i = x_{\pi(g^{-1})(i)}$$

The EG-action of  $\mathbb{G}_n$  is permutation and tensor product, and the action on morphisms is given by

$$\alpha(g; [h_1; \text{id}_{x_1}, \dots, \text{id}_{x_{m_1}}], \dots, [h_k; \text{id}_{x_1}, \dots, \text{id}_{x_{m_k}}]) = [\mu(g; h_1, \dots, h_k); \text{id}_{x_1}, \dots, \text{id}_{x_{m_k}}]$$

Notice that using tensor product notation the object  $[e; x]$  is simply  $x$ , and so  $[e; \text{id}_x] = \text{id}_{[e; x]}$  should be written as  $\text{id}_x$ . Hence by the above  $[g; \text{id}_{x_1}, \dots, \text{id}_{x_m}]$  is really just  $\alpha(g; \text{id}_{x_1}, \dots, \text{id}_{x_m})$ , and so we have the following:

**Lemma 1.19.** *Each morphism of  $\mathbb{G}_n$  can be expressed uniquely as an action morphism  $\alpha(g; \text{id}_{x_1}, \dots, \text{id}_{x_m})$ , for some  $g, g' \in G(m)$  and  $x_i \in \{z_1, \dots, z_n\}$ .*

From this, we can also determine  $\mathbb{G}_n$ 's connected components.

**Proposition 1.20.** *The connected components of  $\mathbb{G}_n$  are  $\mathbb{N}^n$ , with the assignment  $[\ ] : \mathbb{N}^{*n} \rightarrow \mathbb{N}^n$  of objects to their component being the quotient map of abelianisation.*

*Proof.* By Lemma 1.19, all morphisms in  $\mathbb{G}_n$  can be written uniquely as  $\alpha(g; \text{id}_{x_1}, \dots, \text{id}_{x_m})$ , for some  $g \in G(m)$  and  $x_i \in \{z_1, \dots, z_n\}$ , the set of generators of  $\mathbb{N}^{*n}$ . Since maps of this form have source  $x_1 \otimes \dots \otimes x_m$  and target  $x_{\pi(g^{-1})(1)} \otimes \dots \otimes x_{\pi(g^{-1})(m)}$ , we see that there can only exist a morphism between two objects if they can be expanded as tensor products which are permutations of one another. Moreover, for any two objects where this is true — say source  $x_1 \otimes \dots \otimes x_m$  and target  $x_{\sigma^{-1}(1)} \otimes \dots \otimes x_{\sigma^{-1}(m)}$  — we can always find a map  $\alpha(g; \text{id}_{x_1}, \dots, \text{id}_{x_m})$  between them, because  $\pi : G(m) \rightarrow S_m$  is surjective and so there must exist at least one  $g$  with  $\pi(g) = \sigma$ . Thus two objects of  $\mathbb{G}_n$  share a connected component if and only if they are tensor products that differ by a permutation, and therefore the canonical map  $[\ ] : \text{Ob}(\mathbb{G}_n) \rightarrow \pi_0(\mathbb{G}_n)$  sending each object to its connected component is just the map which forgets about these permutations, making the free product on  $\mathbb{N}^{*n}$  commutative. That is,  $[\ ]$  is the quotient map for the abelianisation  $\text{ab} : \mathbb{N}^{*n} \rightarrow (\mathbb{N}^{*n})^{\text{ab}}$ , and so  $\pi_0(\mathbb{G}_n) = \mathbb{N}^n$ .  $\square$

## 2. FREE INVERTIBLE ALGEBRAS AS INITIAL OBJECTS

**2.1. The free algebra on  $n$  invertible objects.** We saw in Proposition 1.15 that the existence of a free EG-algebra on  $n$  objects can be proven by taking the left adjoint of a 2-functor which forgets about the algebra structure. Now we want to extend this idea into the realm of algebras on invertible objects. For the

analogous approach, we will need to find a new 2-functor that lets us forget about non-invertible objects, and then hopefully we can find its left adjoint too, and use it to freely add inverses to  $\mathbb{G}_n$ . First though, we need to make this concept of ‘forgetting non-invertible objects’ a little more precise.

**Definition 2.1.** Given an EG-algebra  $X$ , we denote by  $X_{\text{inv}}$  the sub-EG-algebra containing all invertible objects in  $X$  and the isomorphisms between them.

Note that this is indeed a well-defined EG-algebra. If  $x_1, \dots, x_m$  are invertible objects with inverses  $x_1^*, \dots, x_m^*$ , then  $\alpha(g; x_1, \dots, x_m)$  is an invertible object with inverse  $\alpha(g; x_m^*, \dots, x_1^*)$ , since

$$\begin{aligned} & \alpha(g; x_1, \dots, x_m) \otimes \alpha(g; x_m^*, \dots, x_1^*) \\ &= (x_{\pi(g)^{-1}(1)} \otimes \dots \otimes x_{\pi(g)^{-1}(m)}) \otimes (x_{\pi(g)^{-1}(m)}^* \otimes \dots \otimes x_{\pi(g)^{-1}(1)}^*) \\ &= I \\ & \alpha(g; x_m^*, \dots, x_1^*) \otimes \alpha(g; x_1, \dots, x_m) \\ &= (x_{\pi(g)^{-1}(m)}^* \otimes \dots \otimes x_{\pi(g)^{-1}(1)}^*) \otimes (x_{\pi(g)^{-1}(1)} \otimes \dots \otimes x_{\pi(g)^{-1}(m)}) \\ &= I \end{aligned}$$

Likewise, if  $f_1, \dots, f_m$  are isomorphisms from invertible objects  $x_1, \dots, x_m$  to invertible objects  $y_1, \dots, y_m$ , then  $\alpha(g; f_1, \dots, f_m)$  is a map from the invertible object  $\alpha(g; x_1, \dots, x_m)$  to the invertible object  $\alpha(g; y_1, \dots, y_m)$ , and it has an inverse  $\alpha(g^{-1}; f_{\pi(g)(1)}^{-1}, \dots, f_{\pi(g)(m)}^{-1})$ , since

$$\begin{aligned} & \alpha(g^{-1}; f_{\pi(g)(1)}^{-1}, \dots, f_{\pi(g)(m)}^{-1}) \circ \alpha(g; f_1, \dots, f_m) \\ &= \alpha(g^{-1}g; f_1^{-1}f_1, \dots, f_m^{-1}f_m) \\ &= \text{id}_{x_1 \otimes \dots \otimes x_m} \\ & \alpha(g; f_1, \dots, f_m) \circ \alpha(g^{-1}; f_{\pi(g)(1)}^{-1}, \dots, f_{\pi(g)(m)}^{-1}) \\ &= \alpha(gg^{-1}; f_{\pi(g)(1)}f_{\pi(g)(1)}^{-1}, \dots, f_{\pi(g)(m)}f_{\pi(g)(m)}^{-1}) \\ &= \text{id}_{y_{\pi(g)(1)} \otimes \dots \otimes y_{\pi(g)(m)}} \end{aligned}$$

Clearly then,  $X_{\text{inv}}$  is the correct algebra for our new forgetful 2-functor to send  $X$  to. Knowing this, we can construct the rest of the functor fairly easily.

**Proposition 2.2.** *The assignment  $X \mapsto X_{\text{inv}}$  can be extended to a 2-functor  $(-)_{\text{inv}} : \text{EGAlg}_S \rightarrow \text{EGAlg}_S$ .*

*Proof.* Let  $F : X \rightarrow Y$  be a (strict) map of EG-algebras. If  $x$  is an invertible object in  $X$  with inverse  $x^*$ , then  $F(x)$  is an invertible object in  $Y$  with inverse  $F(x^*)$ , by

$$F(x) \otimes F(x^*) = F(x \otimes x^*) = F(I) = I$$

$$F(x^*) \otimes F(x) = F(x^* \otimes x) = F(I) = I$$

Since  $F$  sends invertible objects to invertible objects, it will also send isomorphisms of invertible objects to isomorphisms of invertible objects. In other words, the map  $F : X \rightarrow Y$  can be restricted to a map  $F_{\text{inv}} : X_{\text{inv}} \rightarrow Y_{\text{inv}}$ . Moreover, we have that

$$(F \circ G)_{\text{inv}}(x) = F \circ G(x) = F_{\text{inv}} \circ G_{\text{inv}}(x)$$

$$(F \circ G)_{\text{inv}}(f) = F \circ G(f) = F_{\text{inv}} \circ G_{\text{inv}}(f)$$

and so the assignment  $F \mapsto F_{\text{inv}}$  is clearly functorial. Next, let  $\theta : F \Rightarrow G$  be an EG-monoidal natural transformation. Choose an invertible object  $x$  from  $X$ , and consider the component map of its inverse,  $\theta_{x^*} : F(x^*) \rightarrow G(x^*)$ . Since  $\theta$  is monoidal, we have  $\theta_{x^*} \otimes \theta_x = \theta_I = I$  and  $\theta_x \otimes \theta_{x^*} = I$ , or in other words that  $\theta_{x^*}$  is the monoidal inverse of  $\theta_x$ . We can use this fact to construct a compositional inverse as well, namely  $\text{id}_{F(x)} \otimes \theta_{x^*} \otimes \text{id}_{G(x)}$ , which can be seen as follows:

$$\begin{aligned} (\text{id}_{F(x)} \otimes \theta_{x^*} \otimes \text{id}_{G(x)}) \circ \theta_x &= \theta_x \otimes \theta_{x^*} \otimes \text{id}_{G(x)} \\ &= \text{id}_{G(x)} \\ \theta_x \circ (\text{id}_{F(x)} \otimes \theta_{x^*} \otimes \text{id}_{G(x)}) &= \text{id}_{F(x)} \otimes \theta_{x^*} \otimes \theta_x \\ &= \text{id}_{F(x)} \end{aligned}$$

Therefore, we see that all the components of our transformation on invertible objects are isomorphisms, and hence we can define a new transformation  $\theta_{\text{inv}} : F_{\text{inv}} \Rightarrow G_{\text{inv}}$  whose components are just  $(\theta_{\text{inv}})_x = \theta_x$ . The assignment  $\theta \mapsto \theta_{\text{inv}}$  is also clearly functorial, and thus we have a complete 2-functor  $(-)_{\text{inv}} : \text{EGAlg}_S \rightarrow \text{EGAlg}_S$ .  $\square$

**Proposition 2.3.** *The 2-functor  $(-)_{\text{inv}} : \text{EGAlg}_S \rightarrow \text{EGAlg}_S$  has a left adjoint,  $L : \text{EGAlg}_S \rightarrow \text{EGAlg}_S$ .*

*Proof.* To begin, consider the 2-monad  $\text{EG}(-)$ . This is a finitary monad, that is it preserves all filtered colimits, and it is a 2-monad over  $\text{Cat}$ , which is locally finitely presentable. It follows from this that  $\text{EGAlg}_S$  is itself locally finitely presentable. Thus if we want to prove  $(-)_{\text{inv}}$  has a left adjoint, we can use the Adjoint Functor Theorem for locally finitely presentable categories, which amounts to showing that  $(-)_{\text{inv}}$  preserves both limits and filtered colimits.

- Given an indexed collection of EG-algebras  $X_i$ , the EG-action of their product  $\prod X_i$  is defined componentwise. In particular, this means that the tensor product of two objects in  $\prod X_i$  is just the collection of the tensor products of their components in each of the  $X_i$ . An invertible object in  $\prod X_i$  is thus simply a family of invertible objects from the  $X_i$  — in other words,  $(\prod X_i)_{\text{inv}} = \prod (X_i)_{\text{inv}}$ .
- Given maps of EG-algebras  $F : X \rightarrow Z$ ,  $G : Y \rightarrow Z$ , the EG-action of their pullback  $X \times_Z Y$  is also defined componentwise. It follows that an invertible object in  $X \times_Z Y$  is just a pair of invertible objects  $(x, y)$  from  $X$  and  $Y$ , such that  $F(x) = G(y)$ . But this is the same as asking for a pair of objects  $(x, y)$  from  $X_{\text{inv}}$  and  $Y_{\text{inv}}$  such that  $F_{\text{inv}}(x) = G_{\text{inv}}(y)$ , and hence  $(X \times_Z Y)_{\text{inv}} = X_{\text{inv}} \times_{Z_{\text{inv}}} Y_{\text{inv}}$ .
- Given a filtered diagram  $D$  of EG-algebras, the EG-action of their colimit  $\text{colim}(D_n)$  is defined in the following way: use filteredness to find an algebra which contains (representatives of the classes of) all the things you want to act on, then apply the action of that algebra. In the case of tensor products this means that  $[x] \otimes [y] = [x \otimes y]$ , and thus an invertible object in  $\text{colim}(D_n)$  is just (the class of) an invertible object in one of the algebras of  $D$ . In other words,  $\text{colim}(D_n)_{\text{inv}} = \text{colim}(D_{\text{inv}})$ .

Preservation of products and pullbacks gives preservation of limits, and preservation of limits and filtered colimits gives the result.  $\square$



With this new 2-functor  $L : \mathbf{EGAlg}_S \rightarrow \mathbf{EGAlg}_S$ , we now have the ability to ‘freely add inverses to objects’ in any EG-algebra we want. The algebra  $L\mathbb{G}_n$  is then a clear candidate for our free algebra on  $n$  invertible objects, and indeed the proof of this is very simple.

**Theorem 2.4.** *There exists a free EG-algebra on  $n$  invertible objects. Specifically, the algebra  $L\mathbb{G}_n$  is such that for any other EG-algebra  $X$ , we have an isomorphism of categories*

$$\mathbf{EGAlg}_S(L\mathbb{G}_n, X) \cong (X_{\text{inv}})^n$$

*Proof.* Using the adjunction from the previous Proposition along with the one from Proposition 1.15, we see that

$$\begin{aligned} U(X_{\text{inv}})^n &= \text{Cat}(\{z_1, \dots, z_n\}, U(X_{\text{inv}})) \\ &\cong \mathbf{EGAlg}_S(F(\{z_1, \dots, z_n\}), X_{\text{inv}}) \\ &\cong \mathbf{EGAlg}_S(LF(\{z_1, \dots, z_n\}), X) \end{aligned}$$

As before,  $X_{\text{inv}}$  and  $U(X_{\text{inv}})$  are obviously isomorphic as categories, and so  $LF(\{z_1, \dots, z_n\}) = L\mathbb{G}_n$  satisfies the requirements for the free algebra on  $n$  invertible objects.  $\square$

**2.2.  $L\mathbb{G}_n$  as an initial algebra.** We have now proven that a free EG-algebra on  $n$  invertible objects does indeed exist. But this fact on its own is not very helpful. To be able to actually use the free algebra  $L\mathbb{G}_n$ , we need to know how to construct it explicitly, in terms of its objects and morphisms. We could do this by finding a detailed characterisation of the 2-functor  $L$ , and then applying this to our explicit description of  $\mathbb{G}_n$  from Definition 1.16. However, this would probably be much more effort than is required, since it would involve determining the behaviour of  $L$  in many situations we aren’t interested in, and we also wouldn’t be leveraging  $\mathbb{G}_n$ ’s status as a free algebra to make the calculations any easier. We will try a different strategy instead. We begin by noticing a special property of the functor  $L$ .

**Proposition 2.5.** *For any EG-algebra  $X$ , we have  $L(X)_{\text{inv}} = L(X)$ .*

*Proof.* From the definition of adjunctions, the isomorphisms

$$\mathbf{EGAlg}_S(LX, Y) \cong \mathbf{EGAlg}_S(X, Y_{\text{inv}})$$

are subject to certain naturality conditions. Specifically, given  $F : X' \rightarrow X$  and  $G : Y \rightarrow Y'$  we get a commutative diagram

$$\begin{array}{ccc} \mathbf{EGAlg}_S(LX, Y) & \xrightarrow{\sim} & \mathbf{EGAlg}_S(X, Y_{\text{inv}}) \\ \downarrow G \circ L F & & \downarrow G_{\text{inv}} \circ F \\ \mathbf{EGAlg}_S(LX', Y') & \xrightarrow{\sim} & \mathbf{EGAlg}_S(X', Y'_{\text{inv}}) \end{array}$$

Consider the case where  $F$  is the identity map  $\text{id}_X : X \rightarrow X$  and  $G$  is the inclusion  $j : L(X)_{\text{inv}} \rightarrow L(X)$ . Note that because  $j$  is an inclusion, the restriction  $j_{\text{inv}} : (L(X)_{\text{inv}})_{\text{inv}} \rightarrow L(X)_{\text{inv}}$  is also an inclusion, but since  $((-)_{\text{inv}})_{\text{inv}} = (-)_{\text{inv}}$ , we

have that  $j_{\text{inv}} = \text{id}$ . It follows that

$$\begin{array}{ccc} \text{EGAlg}_S(LX, LX_{\text{inv}}) & \xrightarrow{\sim} & \text{EGAlg}_S(X, LX_{\text{inv}}) \\ \downarrow j \circ - & & \parallel \\ \text{EGAlg}_S(LX, LX) & \xrightarrow{\sim} & \text{EGAlg}_S(X, LX_{\text{inv}}) \end{array}$$

Therefore, for any map  $f : LX \rightarrow LX$  there exists a unique  $g : LX \rightarrow LX_{\text{inv}}$  such that  $j \circ g = f$ . But this means that for any such  $f$ , we must have  $\text{im}(f) \subseteq L(X)_{\text{inv}}$ , and so in particular  $L(X) = \text{im}(\text{id}_{LX}) \subseteq L(X)_{\text{inv}}$ . Since  $L(X)_{\text{inv}} \subseteq L(X)$  by definition, we obtain the result.  $\square$

This result is not especially surprising. Intuitively, it just says that when you freely add inverses to an algebra, every object ends up with an inverse. But the upshot of this is that we now have another way of thinking about  $L(X)$ : as the target object of the unit of our adjunction,  $\eta_X : X \rightarrow L(X)_{\text{inv}}$ . This means that we don't really need to know the entirety of  $L$  in order to determine the free algebra  $L\mathbb{G}_n$ , just its unit. To find this unit directly, we can turn to the following fact about adjunctions, for which a proof can be found in Lemma 2.3.5 of Leinster's *Basic Category Theory* [6].

**Proposition 2.6.** *Let  $F \dashv G : A \rightarrow B$  be an adjunction with unit  $\eta$ . For any object  $a$  in  $A$ , let  $(a \downarrow G)$  denote the comma category whose objects are pairs  $(b, f)$  consisting of an object  $b$  from  $B$  and a morphism  $f : a \rightarrow G(b)$  from  $A$ , and whose morphisms  $h : (b, f) \rightarrow (b', f')$  are morphisms  $f : b \rightarrow b'$  from  $B$  such that  $G(f) \circ f = f'$ . Then the pair  $(F(a), \eta_a : a \rightarrow GF(a))$  is an initial object of  $(a \downarrow G)$ .*

**Corollary 2.7.** *If  $\phi : \mathbb{G}_n \rightarrow Z$  is an initial object of  $(\mathbb{G}_n \downarrow \text{inv})$ , then*

$$Z \cong (L\mathbb{G}_n)_{\text{inv}} = L\mathbb{G}_n$$

Being able to view  $L\mathbb{G}_n$  as the initial object in the comma category  $(\mathbb{G}_n \downarrow \text{inv})$  will prove immensely useful in the coming sections. This is because it lets us think about the properties of  $L\mathbb{G}_n$  in terms of maps  $\psi : \mathbb{G}_n \rightarrow X_{\text{inv}}$ , and this is exactly the context where we can exploit  $\mathbb{G}_n$ 's status as a free algebra.

Before moving on, we'll make a small change in notation. From now on, rather than writing objects in  $(\mathbb{G}_n \downarrow \text{inv})$  as maps  $\psi : \mathbb{G}_n \rightarrow Y_{\text{inv}}$ , we will instead just let  $X = Y_{\text{inv}}$  and speak of maps  $\psi : \mathbb{G}_n \rightarrow X$ . This is purely to prevent the notation from becoming cluttered, and shouldn't be a problem so long as we always remember that the targets of these maps only ever contain invertible objects and morphisms.

**2.3. The objects of  $L\mathbb{G}_n$ .** So now we know that  $L\mathbb{G}_n$  is an initial object in the category  $(\mathbb{G}_n \downarrow \text{inv})$ . But what does this actually tell us? After all, we do not currently have a method for finding initial objects in an arbitrary collection of EG-algebra maps. Because of this, we'll have to approach the problem step-by-step, using the initiality of  $\eta$  to extract different pieces of information about the algebra  $L\mathbb{G}_n$  as we go. We'll begin by trying to find its objects.

**Definition 2.8.** Denote by  $\text{Ob} : \text{EGAlg}_S \rightarrow \text{Mon}$  be the functor that sends EG-algebras  $X$  to their monoid of objects  $\text{Ob}(X)$ , and algebra maps  $F : X \rightarrow Y$  to their underlying monoid homomorphism  $\text{Ob}(F) : \text{Ob}(X) \rightarrow \text{Ob}(Y)$ .

In order to find  $\text{Ob}(L\mathbb{G}_n)$ , we'll need to make use of an important result about the nature of  $\text{Ob}$ .

**Definition 2.9.** Recall that given a monoid  $M$ , the monoidal category  $EM$  is the one whose monoid of objects is  $M$  and which has a unique isomorphism between any two objects. We can view  $EM$  as not just a category but an  $EG$ -algebra, by letting the action on morphisms take the only possible values it can, given the required source and target. Similarly, for any monoid homomorphisms  $h : M \rightarrow M'$  we can define a map of  $EG$ -algebras

$$\begin{aligned} Eh & : & EM & \rightarrow & EM' \\ & : & m & \mapsto & h(m) \\ & : & m \rightarrow m' & \mapsto & h(m) \rightarrow h(m') \end{aligned}$$

This definition of  $Eh$  respects composition and identities, and so together with  $EM$  it describes a functor  $E : \text{Mon} \rightarrow \text{EGAlg}_S$ .

**Proposition 2.10.**  *$E$  is a right adjoint to the functor  $\text{Ob}$ .*

*Proof.* For any  $EG$ -algebra  $X$ , a map  $F : X \rightarrow EM$  is determined entirely by its restriction to objects, the monoid homomorphism  $\text{Ob}(F) : \text{Ob}(X) \rightarrow M$ . This is because functoriality of  $F$  ensures that any map  $x \rightarrow x'$  in  $X$  must be sent to a map  $F(x) \rightarrow F(x')$  in  $EM$ , and by the definition of  $E$  there is always exactly one of these to choose from. In other words, we have an isomorphism between the homsets

$$\text{EGAlg}_S(X, EM) \cong \text{Mon}(\text{Ob}(X), M)$$

Additionally, this isomorphism is natural in both coordinates. That is, for any  $G : X \rightarrow X'$  in  $\text{EGAlg}_S$  and  $h : M \rightarrow M'$  in  $\text{Mon}$ , the diagram

$$\begin{array}{ccc} \text{EGAlg}_S(X, EM) & \xrightarrow{\sim} & \text{Mon}(\text{Ob}(X), M) \\ \text{Eh} \circ \circ G \downarrow & & \downarrow h \circ \circ \text{Ob}(G) \\ \text{EGAlg}_S(X', EM') & \xrightarrow{\sim} & \text{Mon}(\text{Ob}(X'), M') \end{array}$$

commutes, because

$$\text{Ob}(Eh \circ F \circ G) = \text{Ob}(Eh) \circ \text{Ob}(F) \circ \text{Ob}(G) = h \circ \text{Ob}(F) \circ \text{Ob}(G)$$

Therefore,  $\text{Ob} \dashv E$ . □

What Proposition 2.10 is essentially saying is that the functor  $\text{Ob}$  provides a way for us to move back and forth between the categories  $\text{EGAlg}_S$  and  $\text{Mon}$ . By applying this reasoning to the universal property of the initial object  $\eta$ , we can then determine the value of  $\text{Ob}(L\mathbb{G}_n)$  in terms of a new universal property of  $\text{Ob}(\eta)$  in the category  $\text{Mon}$ . In particular, the algebras in  $(\mathbb{G}_n \downarrow \text{inv})$  are those whose objects are all invertible, and so the induced property of  $\text{Ob}(\eta)$  will end up saying something about the relationship between  $\text{Ob}(\mathbb{G}_n)$  and groups — those monoids whose elements are all invertible.

**Definition 2.11.** Let  $M$  be a monoid,  $M^{\text{gp}}$  a group, and  $i : M \rightarrow M^{\text{gp}}$  a monoid homomorphism between them. Then we say that  $M^{\text{gp}}$  is the *group completion* of  $M$  if for any other group  $H$  and homomorphism  $h : M \rightarrow H$ , there exists a unique homomorphism  $u : M^{\text{gp}} \rightarrow H$  such that  $u \circ i = h$ .

In practice,  $M^{\text{gp}}$  is the group whose group presentation is the same as the monoid presentation of  $M$ . That is, if  $M$  is the quotient of the free monoid on generators  $\mathcal{G}$  by the relations  $\mathcal{R}$ , then  $M^{\text{gp}}$  is the quotient of the free *group* on generators  $\mathcal{G}$  by relations  $\mathcal{R}$ .

**Proposition 2.12.** *The object monoid of  $L\mathbb{G}_n$  is  $\mathbb{Z}^{*n}$ , and the restriction of  $\eta$  to objects  $\text{Ob}(\eta)$  is the obvious inclusion  $\mathbb{N}^{*n} \hookrightarrow \mathbb{Z}^{*n}$ .*

*Proof.* Let  $H$  be a group, and  $h : \text{Ob}(\mathbb{G}_n) \rightarrow H$  a monoid homomorphism. By Proposition 2.10 we have an isomorphism of homsets

$$\text{EGAlg}_S(\mathbb{G}_n, EH) \cong \text{Mon}(\text{Ob}(\mathbb{G}_n), H)$$

Denote by  $h' : \mathbb{G}_n \rightarrow EH$  the map of EG-algebras corresponding to  $h$  under this isomorphism. Since  $H$  is a group, every object in  $EH$  is invertible, and so  $h'$  is an object of  $(\mathbb{G}_n \downarrow \text{inv})$ . Thus, by initiality of  $\eta$ , there must exist a unique map  $u : L\mathbb{G}_n \rightarrow EH$  making the lefthand triangle below commute:

$$\begin{array}{ccc} \mathbb{G}_n & & \text{Ob}(\mathbb{G}_n) \\ \eta \downarrow & \searrow h' & \downarrow \text{Ob}(\eta) \\ L\mathbb{G}_n & \xrightarrow{u} & EH \\ & & \downarrow \text{Ob}(u) \\ & & H \end{array}$$

It follows that the righthand triangle — which is the image of the first under  $\text{Ob}$  — also commutes. Hence for any group  $H$  and homomorphism  $h : \text{Ob}(\mathbb{G}_n) \rightarrow H$ , there is at least one map which factors  $h$  through  $\text{Ob}(\eta)$ .

But now let  $v : \text{Ob}(L\mathbb{G}_n) \rightarrow H$  be any homomorphism such that  $v \circ \text{Ob}(\eta) = h$ . If  $v' : L\mathbb{G}_n \rightarrow EH$  is the image of  $v$  under the adjunction isomorphism, then by naturality  $v' \circ \eta = h'$ , a property that was supposed to be unique to  $u$ . Thus  $v = \text{Ob}(u)$ , and so there is actually only one possible map which factors  $h$  through  $\text{Ob}(\eta)$ .

Therefore every homomorphism from  $\text{Ob}(\mathbb{G}_n)$  onto a group factors uniquely through the  $\text{Ob}(L\mathbb{G}_n)$ , or in other words  $\text{Ob}(L\mathbb{G}_n)$  is the group completion of the monoid  $\text{Ob}(\mathbb{G}_n)$ . Since by Lemma 1.18 the object monoid of  $\mathbb{G}_n$  is  $\mathbb{N}^{*n}$ , the free monoid on  $n$  generators, we can conclude that

$$\text{Ob}(L\mathbb{G}_n) = \text{Ob}(\mathbb{G}_n)^{\text{gp}} = (\mathbb{N}^{*n})^{\text{gp}} = \mathbb{Z}^{*n}$$

the free group on  $n$  generators. Moreover, the map  $\text{Ob}(\eta)$  is then the inclusion of  $\text{Ob}(\mathbb{G}_n)$  into its completion, which is just  $\mathbb{N}^{*n} \hookrightarrow \mathbb{Z}^{*n}$ .  $\square$

This result makes concrete the sense in which the functor  $L$  represents ‘freely adding inverses’ to objects. Extending this same logic to connected components as well, it seems reasonable to expect that  $\pi_0(L\mathbb{G}_n)$  should be  $\mathbb{Z}^n$ , the group completion of  $\pi_0(\mathbb{G}_n) = \mathbb{N}^n$ . This is indeed the case, and the proof proceeds in a way completely analogous to Proposition 2.12. First, we show that the process of taking connected components is part of an adjunction.

**Definition 2.13.** Denote by  $\pi_0 : \text{EGAlg}_S \rightarrow \text{CMon}$  be the functor that sends each algebra  $X$  to its commutative monoid of connected components,  $\pi_0(X)$ , and sends each map of algebras  $F : X \rightarrow Y$  to its restriction to connected components  $\pi_0(F) : \pi_0(X) \rightarrow \pi_0(Y)$ .

**Definition 2.14.** There exists an inclusion of 2-categories  $\text{Set} \hookrightarrow \text{Cat}$  which allows us to view any set  $S$  as a discrete category, one whose objects are just the elements of  $S$  and whose morphisms are all identities. If the given set also happens to be a monoid then there is an obvious way to see this discrete category as a monoidal category, and so we have a similar inclusion  $\text{Mon} \hookrightarrow \text{MonCat}$ . Finally, if a given monoid happens to be commutative then there is a unique way to assign an EG-action to its discrete category. This works because for any elements  $c_i$  of a commutative monoid  $C$ , the morphism  $\alpha(g; \text{id}_{c_1}, \dots, \text{id}_{c_m})$  must have source and target  $c_1 \otimes \dots \otimes c_m = c_{\pi(g^{-1})(1)} \otimes \dots \otimes c_{\pi(g^{-1})(m)}$ , and therefore it can only be  $\text{id}_{c_1 \otimes \dots \otimes c_m}$ . This choice of action yields one last inclusion  $\text{CMon} \hookrightarrow \text{EGAlg}_S$ , which we shall call  $D$ .

**Proposition 2.15.**  $D$  is a right adjoint to the functor  $\pi_0$ .

*Proof.* Consider a map  $F : X \rightarrow DC$  from some EG-algebra  $X$  to the discrete EG-algebra on a commutative monoid  $C$ . For any  $f : x \rightarrow x'$  in  $X$ , the morphism  $F(f)$  must be an identity map in  $DC$ , since these are the only morphisms that  $DC$  has. It follows that  $x$  and  $x'$  being in the same connected component implies  $F(x) = F(x')$ , and so  $F$  is determined entirely by its restriction to connected components, the monoid homomorphism  $\pi_0(F) : \pi_0(X) \rightarrow C$ . In other words, we have an isomorphism between the homsets

$$\text{EGAlg}_S(X, DC) \cong \text{CMon}(\pi_0(X), C)$$

This isomorphism is natural in both coordinates, since for any  $G : X \rightarrow X'$  in  $\text{EGAlg}_S$  and  $h : C \rightarrow C'$  in  $\text{CMon}$ ,

$$\pi_0(Dh \circ F \circ G) = \pi_0(Dh) \circ \pi_0(F) \circ \pi_0(G) = h \circ \pi_0(F) \circ \pi_0(G)$$

and so the diagram

$$\begin{array}{ccc} \text{EGAlg}_S(X, DC) & \xrightarrow{\sim} & \text{CMon}(\pi_0(X), C) \\ \text{Dh} \circ \_ \circ G \downarrow & & \downarrow h \circ \_ \circ \pi_0(G) \\ \text{EGAlg}_S(X', DC') & \xrightarrow{\sim} & \text{CMon}(\pi_0(X'), C') \end{array}$$

commutes. Therefore,  $\pi_0 \dashv D$ .  $\square$

Now we can utilise Proposition 2.15 to draw out a universal property of  $\pi_0(L\mathbb{G}_n)$ , just as we did with Proposition 2.10 and  $\text{Ob}(L\mathbb{G}_n)$ . This time, since we are dealing with commutative monoids, the requirement that everything be invertible will lead us to consider abelian groups.

**Proposition 2.16.** *The connected components of  $L\mathbb{G}_n$  are  $\mathbb{Z}^n$ , with the restriction of  $\eta$  to components  $\pi_0(\eta)$  being the obvious inclusion  $\mathbb{N}^n \hookrightarrow \mathbb{Z}^n$ , and the assignment of objects to their component  $[-] : \text{Ob}(L\mathbb{G}_n) \rightarrow \pi_0(L\mathbb{G}_n)$  being the quotient map of abelianisation  $\mathbb{Z}^{*n} \rightarrow \mathbb{Z}^n$ .*

*Proof.* Let  $A$  be an abelian group and  $h : \pi_0(\mathbb{G}_n) \rightarrow A$  a monoid homomorphism. By Proposition 2.15 there is a homset isomorphism

$$\text{EGAlg}_S(\mathbb{G}_n, DA) \cong \text{Mon}(\pi_0(\mathbb{G}_n), A)$$

and thus some EG-algebra map  $h' : \mathbb{G}_n \rightarrow DA$  corresponding to  $h$ . As every object of  $DA$  is invertible,  $h'$  is in  $(\mathbb{G}_n \downarrow \text{inv})$ , and hence there exists a unique map

$u : L\mathbb{G}_n \rightarrow DA$  factoring  $h'$  through the initial object  $\eta$ :

$$\begin{array}{ccc} \mathbb{G}_n & & \pi_0(\mathbb{G}_n) \\ \eta \downarrow & \searrow h' & \downarrow \pi_0(\eta) \\ L\mathbb{G}_n & \xrightarrow{u} & DA \end{array} \quad \begin{array}{ccc} \pi_0(\mathbb{G}_n) & & \pi_0(L\mathbb{G}_n) \\ \downarrow \pi_0(\eta) & \searrow h & \downarrow \pi_0(u) \\ \pi_0(L\mathbb{G}_n) & \xrightarrow{\pi_0(u)} & A \end{array}$$

Applying the functor  $\pi_0$  everywhere, we see that  $\pi_0(u)$  must also factor  $h$  through the homomorphism  $\pi_0(\eta)$ . Moreover,  $\pi_0(u)$  is the only map with this property, since for any other map  $v : \pi_0(L\mathbb{G}_n) \rightarrow A$  with  $v \circ \pi_0(\eta) = h$ , its image under the adjunction isomorphism  $v' : L\mathbb{G}_n \rightarrow DA$  would have  $v' \circ \eta = h'$  by naturality, which would mean that it was actually  $u$ . Therefore, any homomorphism  $\text{Ob}(\mathbb{G}_n) \rightarrow A$  will factor uniquely through  $\text{Ob}(L\mathbb{G}_n)$ , so long as  $A$  is an abelian group.

Now assume that  $h : \text{Ob}(\mathbb{G}_n) \rightarrow H$  is more general sort of homomorphism, where  $H$  is a group but not necessarily an abelian one. Since  $\pi_0(L\mathbb{G}_n)$  is a commutative monoid, it follows that its image  $\langle \text{im}(h) \rangle$  will be commutative too:

$$h(x)h(y) = h(xy) = h(yx) = h(y)h(x)$$

But then  $\langle \text{im}(h) \rangle$  is a commutative submonoid of the group  $H$ , and so it is really an abelian group. If we denote by  $h_{\text{im}} : \text{Ob}(\mathbb{G}_n) \rightarrow \langle \text{im}(h) \rangle$  the restriction of  $h$  to it image, then from what we have already shown we can conclude that there will be a unique homomorphism  $v : \text{Ob}(L\mathbb{G}_n) \rightarrow \langle \text{im}(h) \rangle$  with the property  $v \circ \pi_0(\eta) = h_{\text{im}}$ . Composing this  $v$  with the inclusion  $i : \langle \text{im}(h) \rangle \hookrightarrow A$ , we see that

$$i \circ v \circ \pi_0(\eta) = i \circ h_{\text{im}} = h$$

and  $i \circ v$  must be the only map for which this is true, for restricting this equation back on  $\langle \text{im}(h) \rangle$  yields the unique property of  $v$  again. Thus  $\pi_0(L\mathbb{G}_n)$  will actually factor any homomorphism  $\text{Ob}(\mathbb{G}_n) \rightarrow H$  in a unique way, and hence by Proposition 1.20 it is the group completion

$$\pi_0(L\mathbb{G}_n) = \pi_0(\mathbb{G}_n)^{\text{gp}} = (\mathbb{N}^n)^{\text{gp}} = \mathbb{Z}^n$$

The map  $\text{Ob}(\eta)$  is then the inclusion of  $\text{Ob}(\mathbb{G}_n)$  into its completion,  $\mathbb{N}^{*n} \hookrightarrow \mathbb{Z}^{*n}$ .

Something else we previously saw in Proposition 1.20 was that that the map  $[-] : \text{Ob}(\mathbb{G}_n) \rightarrow \pi_0(\mathbb{G}_n)$  sending objects of  $\mathbb{G}_n$  to their connected component is the quotient map of abelianisation,  $\mathbb{N}^{*n} \rightarrow (\mathbb{N}^{*n})^{\text{ab}} = \mathbb{N}^n$ . If we also use  $[-]$  to denote the map sending objects of  $L\mathbb{G}_n$  to their components, then functoriality of  $\eta$  tells us that

$$\begin{array}{ccc} \mathbb{N}^{*n} & \xrightarrow{\text{Ob}(\eta)} & \mathbb{Z}^{*n} \\ [-] \downarrow & & \downarrow [-] \\ \mathbb{N}^n & \xrightarrow{\pi_0(\eta)} & \mathbb{Z}^n \end{array}$$

commutes. Using the values of  $[-]$  from Proposition 1.20,  $\text{Ob}(\eta)$  from Proposition 2.12, and  $\pi_0(\eta)$  from the earlier parts of this proposition, it follows that for any generator  $z_i$  of  $\mathbb{Z}^{*n}$ ,

$$[z_i] = [\text{Ob}(\eta)(z_i)] = \pi_0(\eta)([z_i]) = \pi_0(\eta)(z_i) = z_i$$

But this description of  $[-] : \text{Ob}(L\mathbb{G}_n) \rightarrow \pi_0(L\mathbb{G}_n)$  on generators is then just the definition of the quotient map of abelianisation  $\mathbb{Z}^{*n} \rightarrow (\mathbb{Z}^{*n})^{\text{ab}}$ , as required  $\square$

**2.4. The morphisms of  $L\mathbb{G}_n$ .** Now that we understand the objects of the algebra  $L\mathbb{G}_n$ , the next most obvious thing to look at are its morphisms,  $\text{Mor}(L\mathbb{G}_n)$ . We will attempt to construct this collection in a similar way to how we constructed  $\text{Ob}(L\mathbb{G}_n)$  and  $\pi_0(L\mathbb{G}_n)$ , via an adjunction. Before we begin though, we need to ask ourselves a question. What sort of mathematical object is  $\text{Mor}(L\mathbb{G}_n)$ , exactly?

Given a pair of morphisms  $f : x \rightarrow y, f' : x' \rightarrow y'$  in an EG-algebra  $X$ , there are two basic binary operations we can perform. First, we can take their tensor product  $f \otimes f'$ , and this together with the unit map  $\text{id}_I$  imbues  $\text{Mor}(X)$  with the structure of a monoid. Second, if we have  $y = x'$  then we can form the composite morphism  $f' \circ f$ . However, consider the following fact: if  $y$  is an invertible object, then

$$\begin{aligned} f' \circ f &= (f' \otimes \text{id}_I) \circ (\text{id}_I \otimes f) \\ &= (f' \otimes \text{id}_{y*} \otimes \text{id}_y) \circ (\text{id}_y \otimes \text{id}_{y*} \otimes f) \\ &= (f' \circ \text{id}_y) \otimes (\text{id}_{y*} \circ \text{id}_{y*}) \otimes (\text{id}_y \circ f) \\ &= f' \otimes \text{id}_{y*} \otimes f \end{aligned}$$

In other words, composition along invertible objects in  $X$  is determined completely by the monoidal structure of  $X$ . In the case of  $L\mathbb{G}_n$ , where every object is invertible, this means that if we understand  $\text{Mor}(L\mathbb{G}_n)$  as a monoid then we will be able to recover the operation  $\circ$  in its entirety. For that reason, we will choose to ignore composition of elements of  $\text{Mor}(X)$  for the time being, and focus on its status as a monoid.

Now we proceed as we did before, by showing that  $\text{Mor}(X)$  is part of an adjunction.

**Definition 2.17.** Let  $\text{Mor} : \text{MonCat} \rightarrow \text{Mon}$  be the functor which sends algebras  $X$  to their monoid of morphisms  $\text{Mor}(X)$ , and sends algebra maps  $F : X \rightarrow Y$  to the monoid homomorphism

$$\begin{aligned} \text{Mor}(F) &: \text{Mor}(X) \rightarrow \text{Mor}(Y) \\ &: f : x \rightarrow x' \mapsto F(f) : F(x) \rightarrow F(x') \end{aligned}$$

**Definition 2.18.** For a given abelian group  $A$ , let  $C(A)$  represent the monoidal category defined as follows:

- The objects of  $C(A)$  are the monoid  $A$ , with the monoid multiplication as the tensor product and the identity element  $e$  as the monoidal unit.
- For any two objects  $a, a' \in A$ , the homset  $C(A)(a, a')$  is isomorphic to the underlying set of  $A$ .
- From the above, the morphisms of  $C(A)$  will clearly be

$$\text{Mor}(C(A)) = A \times A^2 = A^3$$

when viewed as a set, but this equality also holds as monoids, so that the tensor product is defined componentwise using the monoid multiplication of  $A$ .

- For any two composable morphisms  $(a, b, b'), (a', b', b'')$  of  $C(A)$ , their composite is the morphism

$$(a', b', b'') \circ (a, b, b') = (a(b')^* a', b, b'')$$

Likewise, for any group homomorphism  $h : A \rightarrow A'$  between abelian groups, denote by  $C(h) : C(A) \rightarrow C(A')$  the obvious monoidal functor which acts like  $h$  on objects

and  $h^3$  on morphisms. This defines a functor  $C : \text{Ab} \rightarrow \text{MonCat}$  from the category of abelian groups onto the category of monoidal categories.

Intuitively,  $C(A)$  is the monoidal category that we can build out of  $A$  by using the trick we discussed before for extracting composition from the tensor product,  $f' \circ f = f' \otimes \text{id}_{y*} \otimes f$ . This is why we had to choose  $A$  to be a group, as this can only work when all of the objects of  $C(A)$  are invertible. Notice also that commutativity is required in order for  $C(A)$  to be a well-defined monoidal category, since we need its operations to obey an interchange law, and thus

$$\begin{aligned} (aa', e, e) &= (a, e, e) \otimes (a', e, e) \\ &= (\text{id}_e \circ (a, e, e)) \otimes ((a', e, e) \circ \text{id}_e) \\ &= ((a', e, e) \otimes \text{id}_e) \circ (\text{id}_e \otimes (a, e, e)) \\ &= (a', e, e) \circ (a, e, e) \\ &= (a'a, e, e) \end{aligned}$$

This is the classic Eckmann-Hilton argument.

**Proposition 2.19.** *The functor  $C$  is a right adjoint to the functor  $\text{Mor}(-)^{\text{gp,ab}} : \text{MonCat} \rightarrow \text{Ab}$ .*

*Proof.* Let  $X$  be a monoidal category,  $A$  an abelian group, and  $F : X \rightarrow C(A)$  a monoidal functor. For any morphism  $f : x \rightarrow y$  in  $X$ , by functoriality  $F$  will send it onto some morphism  $F(f)$  in the homset  $C(A)(F(x), F(y))$ . However, every homset of  $C(A)$  is isomorphic to a copy of  $A$ , and so clearly there is a way to extract from  $F$  a map  $\text{Mor}(X) \rightarrow A$ . Specifically, if we define the map  $\epsilon_A$  to be the projection

$$\begin{aligned} \epsilon_A &: \text{Mor}(C(A)) \rightarrow A \\ &: A^3 \rightarrow A \\ &: (a, b, b') \mapsto a \end{aligned}$$

then we can use the functor  $\text{Mor}$  and the map  $\epsilon_A$  to form the following composite map:

$$\text{Mor}(X) \xrightarrow{\text{Mor}(F)} \text{Mor}(C(A)) \xrightarrow{\epsilon_A} A$$

Then, since  $A$  is not just a monoid but an abelian group, we can factor the homomorphism  $\text{Mor}(F)$  through the group completion of  $\text{Mor}(X)$ , and then through the abelianisation of that group, at last yielding a map

$$F' := \epsilon_A \circ (\text{Mor}(F)^{\text{gp}})^{\text{ab}} : (\text{Mor}(X)^{\text{gp}})^{\text{ab}} \rightarrow A$$

This  $\epsilon$  will be the counit of our adjunction, with the assignment  $F \mapsto F'$  being one direction of the eventual homset adjunction.

Conversely, let  $\eta_X$  be the monoidal functor defined by

$$\begin{aligned} \eta_X &: X \rightarrow C(\text{Mor}(X)^{\text{gp,ab}}) \\ &: x \mapsto [\text{id}_x] \\ &: f : x \rightarrow y \mapsto ([f], [\text{id}_x], [\text{id}_y]) \end{aligned}$$

where  $[-]$  is the quotient of abelianisation  $\text{Mor}(X) \rightarrow \text{Mor}(X)^{\text{gp,ab}}$ . Then any homomorphism  $h : \text{Mor}(X)^{\text{gp,ab}} \rightarrow A$  can be used to construct a monoidal functor  $h' : X \rightarrow C(A)$  as follows:

$$X \xrightarrow{\eta_X} C(\text{Mor}(X)) \xrightarrow{C([-])} C(\text{Mor}(X)^{\text{gp,ab}}) \xrightarrow{C(h)} C(A)$$



Moreover, if we compare this  $\eta$  with  $\epsilon$  then we see that the composites

$$\begin{array}{ccc}
\text{Mor}(X)^{\text{gp,ab}} & & C(A) \\
\downarrow \text{Mor}(\eta_X)^{\text{gp,ab}} & & \downarrow \eta_{C(A)} \\
\text{Mor}\left(C\left(\text{Mor}(X)^{\text{gp,ab}}\right)\right)^{\text{gp,ab}} & & C\left(\text{Mor}\left(C(A)^{\text{gp,ab}}\right)\right) \\
\parallel & & \parallel \\
\text{Mor}\left(C\left(\text{Mor}(X)^{\text{gp,ab}}\right)\right) & & C\left(\text{Mor}\left(C(A)\right)\right) \\
\downarrow \epsilon_{\text{Mor}(X)^{\text{gp,ab}}} & & \downarrow C(\epsilon_A) \\
\text{Mor}(X)^{\text{gp,ab}} & & C(A)
\end{array}$$

must be the respective identity maps:

$$\begin{aligned}
\epsilon_{\text{Mor}(X)^{\text{gp,ab}}} \circ \text{Mor}(\eta_X)^{\text{gp,ab}}([f : x \rightarrow y]) &= \epsilon_{\text{Mor}(X)^{\text{gp,ab}}}([f], [\text{id}_x], [\text{id}_y]) \\
&= [f] \\
C(\epsilon_A) \circ \epsilon_{\text{Mor}(X)^{\text{gp,ab}}}(a) &= C(\epsilon_A)(a, a, a) \\
&= a \\
C(\epsilon_A) \circ \epsilon_{\text{Mor}(X)^{\text{gp,ab}}}(a, b, b') &= C(\epsilon_A)((a, b, b'), (b, b, b'), (b', b', b')) \\
&= (a, b, b')
\end{aligned}$$

In other words,  $\eta_X$  and  $\epsilon_A$  really are the unit and counit of an adjunction  $\text{Mor}(-)^{\text{gp,ab}} \dashv C$ , whose isomorphism of homsets

$$\text{MonCat}(X, C(A)) \cong \text{Ab}(\text{Mor}(X)^{\text{gp,ab}}, A)$$

is given by the assignments  $F \mapsto F'$  and  $h \mapsto h'$ .  $\square$

Proposition 2.19 is very similar to Propositions 2.10 and 2.15, but it falls short in a very important way. We want to use the map  $\eta$  to relate the morphisms of  $\mathbb{G}_n$  and  $L\mathbb{G}_n$ , like what we did in Propositions 2.12 and 2.16, but in order to do this what we need is an adjunction involving  $\text{EGAlg}_S$ , not  $\text{MonCat}$ . Unfortunately this is the best we can do. Given an arbitrary abelian group that we want to see as the morphisms of some algebra, there is an obvious way to define a tensor product and even composition on it, but there is no general method for assigning it an EG-action. Likewise,  $L\mathbb{G}_n$  cannot be used to factor an arbitrary monoidal functor out of  $\mathbb{G}_n$  as it can with algebra maps. If we are to use the adjunction we have to extract some information about  $L\mathbb{G}_n$ , we will need to try a less straightforward approach.

**2.5. The pure morphisms of  $L\mathbb{G}_n$ .** To that end, recall from Lemma 1.19 that every morphism in  $\mathbb{G}_n$  can be expressed in a canonical way as an action morphism. Since maps between EG-algebras preserve the action, this means that for any surjective algebra map  $F : \mathbb{G}_n \rightarrow X$ , the action on  $X$  can always be recovered in full from the underlying monoidal functor of  $F$ . That is, for any morphisms  $f_1, \dots, f_m$  of  $X$  we can choose some morphisms  $f'_1, \dots, f'_m$  of  $\mathbb{G}_n$  with  $F(f'_i) = f_i$ , and then for each  $g \in G(m)$  we'll have

$$\alpha_X(g; f_1, \dots, f_m) = \alpha_X(g; F(f'_1), \dots, F(f'_m)) = F(\alpha(g; f'_1, \dots, f'_m))$$

This indicates how we can get around having to work with monoidal categories rather than algebras.

**Proposition 2.20.** *Let  $X$  be a monoidal category whose objects are all invertible, and let  $\psi : \mathbb{G}_n \rightarrow X$  be a monoidal functor which is surjective on objects. Then there exists another monoidal functor  $\psi' : L\mathbb{G}_n \rightarrow X$ , not necessarily unique, for which  $\psi' \circ \eta = \psi$ .*

*Proof.*

□

**Definition 2.21.** Pure morphism subcategory  $PX$

**Proposition 2.22.**

$$\text{Mor}(PL\mathbb{G}_n) = L\mathbb{G}_n(I, I) \times \text{Ob}(L\mathbb{G}_n)$$

**Corollary 2.23.**

$$L\mathbb{G}_n(I, I) = \text{Mor}(PL\mathbb{G}_n)^{\text{gp, ab}} / \text{Ob}(L\mathbb{G}_n)^{\text{gp, ab}}$$

**Proposition 2.24.**

$$\text{Mor}(P\mathbb{G}_n)^{\text{gp, ab}} / \text{Ob}(\mathbb{G}_n)^{\text{gp, ab}} = \text{Mor}(PL\mathbb{G}_n)^{\text{gp, ab}} / \text{Ob}(L\mathbb{G}_n)^{\text{gp, ab}}$$

**Definition 2.25.** Let  $G$  be an action operad. Then we will also use the notation  $G$  to denote the *underlying monoid* of this action operad. This is the natural way to consider  $G$  as a monoid, with its element set being all of its elements together,  $\bigsqcup_m G(m)$ , and with tensor product as its binary operation,  $g \otimes h = \mu(e_2; g, h)$ .

Also, note that this monoid comes equipped with a homomorphism  $|-| : G \rightarrow \mathbb{N}$ , sending each  $g \in G$  to the natural number  $m$  if and only if  $g$  is an element of the group  $G(m)$ . We'll call this number  $|g|$  the *length* of  $g$ .

**Definition 2.26.** Let  $S$  be a set and  $F(S)$  the free monoid on  $S$ , the monoid whose elements are strings of elements of  $S$  and whose binary operation is concatenation. Then we will denote by

$$|-| : F(S) \rightarrow \mathbb{N}$$

the monoid homomorphism defined by sending each element of  $S \subseteq F(S)$  to 1, and therefore also each concatenation of  $n$  elements of  $S$  to the natural number  $n$ . Again, we will call  $|x|$  the *length* of  $x \in F(S)$ .

**Proposition 2.27.** *The monoid of morphisms of the algebra  $\mathbb{G}_n$  is*

$$\text{Mor}(\mathbb{G}_n) \cong G \times_{\mathbb{N}} \mathbb{N}^{*n}$$

*where this pullback is taken over the respective length homomorphisms,*

$$\begin{array}{ccc} G \times_{\mathbb{N}} F(\{z_1, \dots, z_n\}) & \longrightarrow & F(\{z_1, \dots, z_n\}) \\ \downarrow & & \downarrow |-| \\ G & \xrightarrow{\quad |-| \quad} & \mathbb{N} \end{array}$$

*using the fact that  $\mathbb{N}^{*n}$  is the free monoid  $F(\{z_1, \dots, z_n\})$ .*

*Proof.* An element of  $G \times_{\mathbb{N}} F(\{z_1, \dots, z_n\})$  is just an element  $g \in G(m)$  for some  $m$ , together with an  $m$ -tuple of objects  $(x_1, \dots, x_m)$  from the set of generators  $\{z_1, \dots, z_n\}$ . Thus the action on  $\mathbb{G}_n$  defines an obvious function  $\alpha : G \times_{\mathbb{N}} F(\{z_1, \dots, z_n\}) \rightarrow \text{Mor}(\mathbb{G}_n)$  by sending each  $(g; x_1, \dots, x_m)$  to the map  $\alpha(g; \text{id}_{x_1}, \dots, \text{id}_{x_m})$ . But by Lemma 1.19, each element of  $\text{Mor}(\mathbb{G}_n)$  can be expressed as  $\alpha(g; \text{id}_{x_1}, \dots, \text{id}_{x_m})$  for some unique collection  $(g; x_1, \dots, x_m)$ , and so this function  $\alpha$  is actually a bijection of sets. Furthermore, this function preserves tensor product, since

$$\begin{aligned} \alpha((g; f_1, \dots, f_m) \otimes (g'; f'_1, \dots, f'_m)) &= \alpha(g \otimes g'; f_1, \dots, f_m, f'_1, \dots, f'_m) \\ &= \alpha(g; f_1, \dots, f_m) \otimes \alpha(g'; f'_1, \dots, f'_m) \end{aligned}$$

and hence it is a monoid isomorphism, as required.  $\square$

**Proposition 2.28.** *Morphism monoid of  $P\mathbb{G}_n$*

**Proposition 2.29.** *Full description of  $L\mathbb{G}_n(I, I)$  and  $\text{Mor}(PL\mathbb{G}_n)$*

**2.6. The tree subcategory of  $L\mathbb{G}_n$ .**

**Definition 2.30.** Tree category  $TX$

**Proposition 2.31.**

$$\text{Mor}(T\mathbb{G}_n) \cong \mathbb{N}^{*n} \times_{\mathbb{N}^n} \mathbb{N}^{*n}$$

**Proposition 2.32.**  $\mathbb{N}^{*n} \times_{\mathbb{N}^n} \mathbb{N}^{*n}$  is a free monoid.

**Proposition 2.33.**  $T\mathbb{G}_n$  is a subcategory of  $\mathbb{G}_n$

**Proposition 2.34.**  $T\mathbb{G}_n^{gp} = TL\mathbb{G}_n$

**Proposition 2.35.**  $TL\mathbb{G}_n$  is a subcategory of  $L\mathbb{G}_n$

**Proposition 2.36.**

$$\text{Mor}(L\mathbb{G}_n) = L\mathbb{G}_n(I, I) \times \text{Mor}(TL\mathbb{G}_n)$$

**Corollary 2.37.**

$$\text{Mor}(L\mathbb{G}_n) = ??? \times \mathbb{Z}^{*n} \times_{\mathbb{Z}^n} \mathbb{Z}^{*n}$$

### 3. FREE INVERTIBLE ALGEBRAS AS COEQUALIZERS

In order to describe an EG-algebra like  $L\mathbb{G}_n$  in full, we must have an understanding three things: its objects, its morphisms, and its EG-action. We achieved the first of these in Proposition 2.12, where we learnt that  $\text{Ob}(L\mathbb{G}_n) = \mathbb{Z}^{*n}$ , and we just found the second in Corollary 2.37. In order to find the last part, the action  $\alpha_{L\mathbb{G}_n}$ , we can build upon a trick we used last chapter.

Recall that in Proposition 2.20, we were able to use the surjectivity of a monoidal functor  $\psi : \mathbb{G}_n \rightarrow X$  to factor it through our initial map  $\eta : \mathbb{G}_n \rightarrow L\mathbb{G}_n$ . We did this by defining supposed ‘action morphisms’ in  $X$ , so that we had something to map the genuine action morphisms of  $L\mathbb{G}_n$  onto. But if the functor  $\psi$  had actually been a map of EG-algebras, then this method would have allowed us to recover the real action on  $X$ :

$$\alpha_X(g; \text{id}_{\psi(x_1)}, \dots, \text{id}_{\psi(x_m)}) = \psi(\alpha_{\mathbb{G}_n}(g; \text{id}_{x_1}, \dots, \text{id}_{x_m}))$$

Therefore our aim going forward will be to find a surjective map of EG-algebras whose target is  $L\mathbb{G}_n$ , from which we will be able to recover the whole of its EG-algebra structure.

**3.1.  $L\mathbb{G}_n$  as a coequalizer.** In the previous chapter, we proved that the algebra  $L\mathbb{G}_n$  is an initial objects in a certain comma category under  $\mathbb{G}_n$ . However, this not the only way of thinking about  $L\mathbb{G}_n$ . Consider for a moment the free EG-algebra on  $2n$  objects,  $\mathbb{G}_{2n}$ . Intuitively, if we were to take this algebra and then enforce upon it the extra relations  $z_{n+1} = z_1^*, \dots, z_{2n} = z_n^*$ , we would be changing it from a structure with  $2n$  independent generators into one with  $n$  indepedent generators and their inverses. That is, there seems to be a natural way to think about  $L\mathbb{G}_n$  as a quotient of the larger algebra  $\mathbb{G}_{2n}$ . In this section we will work towards making this idea precise, and then examine some of its consequences. We'll begin with some definitions.

**Definition 3.1.** Let  $\delta$  be the map of EG-algebras defined on generators by

$$\begin{aligned} \delta &: \mathbb{G}_{4n} \rightarrow \mathbb{G}_{2n} \\ &: z_i \mapsto z_i \\ &: z_{n+i} \mapsto z_{n+i} \\ &: z_{2n+i} \mapsto z_i \otimes z_{n+i} \\ &: z_{3n+i} \mapsto z_{n+i} \otimes z_i \end{aligned}$$

for  $1 \leq i \leq n$ . Similarly, let  $\zeta$  be the EG-algebra map defined by

$$\begin{aligned} \zeta &: \mathbb{G}_{4n} \rightarrow \mathbb{G}_{2n} \\ &: z_i \mapsto z_i \\ &: z_{n+i} \mapsto z_{n+i} \\ &: z_{2n+i} \mapsto I \\ &: z_{3n+i} \mapsto I \end{aligned}$$

We will denote by  $q : \mathbb{G}_{2n} \rightarrow Q$  the coequalizer these two maps.

Note that the above definitions do actually make sense. The given descriptions of  $\delta$  and  $\zeta$  are enough to specify those maps uniquely because  $\mathbb{G}_k$  is the free EG-algebra on  $k$  objects, and hence algebra maps  $\mathbb{G}_k \rightarrow \mathbb{G}_{k'}$  are canonically isomorphic to functors  $\{z_1, \dots, z_k\} \rightarrow \mathbb{G}_{k'}$ . Also we can be sure that the map  $q$  exists, because  $\text{EGAlg}_S$  is a locally finitely presentable category and thus has all finite colimits.

The goal of this approach will be show that  $Q$  is in fact that same algebra as  $L\mathbb{G}_n$ . In order to do this, it would help if we could easily compare  $q : \mathbb{G}_{2n} \rightarrow Q$  to our initial object  $\eta : \mathbb{G}_{2n} \rightarrow L\mathbb{G}_n$ . In other words, we really want to show that  $q$  is an object of  $(\mathbb{G}_n \downarrow \text{inv})$  — that  $Q$  has only invertible objects. This can be done using the adjunction we found in Proposition 2.10.

**Lemma 3.2.** *The object monoid of  $Q$  is  $\mathbb{Z}^{*n}$ , and the restriction of  $q$  to objects  $\text{Ob}(q) : \text{Ob}(\mathbb{G}_{2n}) \rightarrow \text{Ob}(Q)$  is the monoid homomorphism defined on generators as*

$$\begin{aligned} \text{Ob}(q) &: \mathbb{N}^{*2n} \rightarrow \mathbb{Z}^{*n} \\ &: z_i \mapsto z_i \\ &: z_{n+i} \mapsto z_i^* \end{aligned}$$

*Proof.* Consider  $\text{Ob}(\delta)$  and  $\text{Ob}(\zeta)$ , the restrictions on objects of the algebra maps  $\delta, \zeta : \mathbb{G}_{4n} \rightarrow \mathbb{G}_{2n}$ . By Lemma 1.18, these are monoid homomorphisms  $\mathbb{N}^{*4n} \rightarrow \mathbb{N}^{*2n}$ , and since  $\text{Mon}$  is cocomplete we can take their coequalizer in that category. This will give us a new homomorphism, whose source is  $\mathbb{N}^{*2n}$  and whose target is the quotient of  $\mathbb{N}^{*2n}$  by the relations  $\text{Ob}(\delta)(x) = \text{Ob}(\zeta)(x)$ . Remembering Definition 3.1, and that  $\mathbb{N}^{*2n}$  is the free monoid on  $2n$  generators, this quotient monoid will have the

following presentation:

$$\begin{aligned} \text{Generators: } & z_1, \dots, z_{2n} \\ \text{Relations: } & z_i \otimes z_{n+i} = I, \\ & z_{n+i} \otimes z_i = I \end{aligned}$$

This is just the same as

$$\begin{aligned} \text{Generators: } & z_1, \dots, z_{2n} \\ \text{Relations: } & z_{n+i} = z_i^*, \end{aligned}$$

which is the presentation of  $\mathbb{Z}^{*n}$ .

But by Proposition 2.10,  $\text{Ob}$  is a left adjoint and hence preserves all colimits. Thus the coequalizer of  $\text{Ob}(\delta)$  and  $\text{Ob}(\zeta)$  is just the underlying homomorphism  $\text{Ob}(q)$  of the coequalizer  $q$  of  $\delta, \zeta$ . Therefore  $\text{Ob}(Q) = \mathbb{Z}^{*n}$ , and  $\text{Ob}(q)$  is the quotient map  $\mathbb{N}^{*2n} \rightarrow \mathbb{Z}^{*n}$  sending  $z_i \mapsto z_i$  and  $z_{n+i} \mapsto z_i^*$  for  $1 \leq i \leq n$ .  $\square$

An immediate corollary of Lemma 3.2 is that every object of the coequalizer algebra  $Q$  is invertible. Thus  $q : \mathbb{G}_{2n} \rightarrow Q$  is an object of the category  $(\mathbb{G}_n \downarrow \text{inv})$ , and hence we can use the initiality of  $\eta$  to determine the following result:

**Proposition 3.3.** *Let  $i : \mathbb{G}_n \rightarrow \mathbb{G}_{2n}$  be the inclusion of EG-algebras defined on generators by*

$$i(z_i) = z_i$$

*Then  $i \circ q$  is an initial object of  $(\mathbb{G}_n \downarrow \text{inv})$ . In particular, this means that*

$$Q \cong L\mathbb{G}_n$$

*Proof.* Let  $\psi : \mathbb{G}_n \rightarrow X$  be an arbitrary object of  $(\mathbb{G}_n \downarrow \text{inv})$ . The map  $\psi^* : \mathbb{G}_n \rightarrow X$  which takes values

$$\psi^*(z_i) = \psi(z_i)^*$$

is also an object of  $(\mathbb{G}_n \downarrow \text{inv})$ , and using these two we can define a new map,  $\psi + \psi^*$ , using the universal property of the colimit:

$$\begin{array}{ccc} & \mathbb{G}_n + \mathbb{G}_n & \\ i \swarrow & \uparrow & \nwarrow i' \\ \mathbb{G}_n & & \mathbb{G}_n \\ \searrow \psi & \downarrow \psi + \psi^* & \swarrow \psi^* \\ & X & \end{array}$$

But  $\mathbb{G}_n$  is the free EG-algebra on  $n$  objects, and the free functor  $F : \text{Cat} \rightarrow \text{EGAlgs}$  preserves colimits because it is a left adjoint, so clearly

$$\begin{aligned} \mathbb{G}_n + \mathbb{G}_n &= F(\{z_1, \dots, z_n\}) + F(\{z'_1, \dots, z'_n\}) \\ &= F(\{z_1, \dots, z_n\} + \{z'_1, \dots, z'_n\}) \\ &= F(\{z_1, \dots, z_{2n}\}) \\ &= \mathbb{G}_{2n} \end{aligned}$$

This means that we can compose  $\psi + \psi^* : \mathbb{G}_{2n} \rightarrow X$  with the maps  $\delta, \zeta : \mathbb{G}_{4n} \rightarrow \mathbb{G}_{2n}$ , though we need to be careful to specify which inclusions we really used in the definition of  $\psi + \psi^*$ . Suppose that the lefthand inclusion is  $i$ , the one given in the

statement of the proposition, and the other is defined by the assignment  $z_i \mapsto z_{i+n}$ . Then for  $1 \leq i \leq n$ ,

$$\begin{aligned}
(\psi + \psi^*)\delta(z_i) &= (\psi + \psi^*)(z_i) \\
&= (\psi + \psi^*)\zeta(z_i) \\
(\psi + \psi^*)\delta(z_{n+i}) &= (\psi + \psi^*)(z_{n+i}) \\
&= (\psi + \psi^*)\zeta(z_i) \\
(\psi + \psi^*)\delta(z_{2n+i}) &= (\psi + \psi^*)(z_i \otimes z_{n+i}) \\
&= \psi(z_i) \otimes \psi(z_i)^* \\
&= I \\
&= (\psi + \psi^*)(I) \\
&= (\psi + \psi^*)\zeta(z_{2n+i}) \\
(\psi + \psi^*)\delta(z_{3n+i}) &= (\psi + \psi^*)(z_{n+i} \otimes z_i) \\
&= \psi(z_i)^* \otimes \psi(z_i) \\
&= I \\
&= (\psi + \psi^*)(I) \\
&= (\psi + \psi^*)\zeta(z_{3n+i})
\end{aligned}$$

That is,  $(\psi + \psi^*) \circ \delta = (\psi + \psi^*) \circ \zeta$ . However, we've already defined  $q : \mathbb{G}_{2n} \rightarrow Q$  to be the coequalizer of  $\delta$  and  $\zeta$ , the universal map such that its composites with them are equal. Therefore, there must exist a unique EG-algebra map  $u : Q \rightarrow X$  making the righthand triangle below diagram commute:

$$\begin{array}{ccccc}
\mathbb{G}_n & \xrightarrow{i} & \mathbb{G}_{2n} & \xrightarrow{q} & Q \\
& \searrow \psi & \downarrow \psi + \psi^* & \swarrow u & \\
& & X & & 
\end{array}$$

The other triangle commutes by the definition of  $\psi + \psi^*$ , and so together the diagram tells us that for any object  $\psi$  of  $(\mathbb{G}_n \downarrow \text{inv})$ , there exists at least one morphism  $u$  in  $(\mathbb{G}_n \downarrow \text{inv})$  going from  $q \circ i$  to  $\psi$ .

Next, let  $v : Q \rightarrow X$  be an arbitrary morphism  $q \circ i \rightarrow \psi$  in  $(\mathbb{G}_n \downarrow \text{inv})$ . By definition, this means that

$$\begin{aligned}
\psi &= vqi \\
\implies \psi + \psi^* &= vqi + (vqi)^*
\end{aligned}$$

Also, for  $1 \leq i \leq n$  we have

$$\begin{aligned}
q(z_i) \otimes q(z_{n+i}) &= q(z_{i-n} \otimes z_i) = q\delta(z_{2n+i}) = q\zeta(z_{2n+i}) = I \\
q(z_{n+i}) \otimes q(z_i) &= q(z_i \otimes z_{n+i}) = q\delta(z_{3n+i}) = q\zeta(z_{3n+i}) = I \\
\implies q(z_{n+i}) &= q(z_i)^*
\end{aligned}$$

Therefore,

$$\begin{aligned}
(\psi + \psi^*)(z_i) &= (vqi + (vqi)^*)(z_i) \\
&= vqi(z_i) \\
&= vq(z_i) \\
(\psi + \psi^*)(z_{n+i}) &= (vqi + (vqi)^*)(z_{n+i}) \\
&= vqi(z_i)^* \\
&= v(q(z_i)^*) \\
&= vq(z_{n+i})
\end{aligned}$$

or in other words  $\psi + \psi^* = v \circ q$  for any morphism  $v : q \circ i \rightarrow \psi$  in  $(\mathbb{G}_n \downarrow \text{inv})$ . But this is the property that the map  $u$  was supposed to satisfy uniquely, and thus it must be the only morphism  $q \circ i \rightarrow \psi$  in  $(\mathbb{G}_n \downarrow \text{inv})$ . Therefore  $q \circ i$  is an initial object, and hence it is isomorphic in  $(\mathbb{G}_n \downarrow \text{inv})$  to any other initial object, such as  $\eta$ . It follows that the targets of these two maps,  $Q$  and  $L\mathbb{G}_n$  respectively, are isomorphic as EG-algebras.  $\square$

It's worth noting that we have not given a method for actually taking coequalizers in  $\text{EGAlg}_S$ , and so Proposition 3.3 doesn't immediately provide an explicit description of  $L\mathbb{G}_n$ . Nevertheless, we will be able to use this new perspective to fix the last few ways that our current description is incomplete.

**3.2.  $L\mathbb{G}_n$  as a reflexive coequalizer.** Since left adjoint functors preserve colimits, Propositions 2.10 and 2.15 both imply results about the partial surjectivity of this new map  $q$ . The former says that since  $\text{Ob}(q)$  is a coequalizer map of monoids, and hence that every object of  $L\mathbb{G}_n$  is the image under  $q$  of some object of  $\mathbb{G}_{2n}$ ; the latter says a similar thing for connected components. From this one might guess that  $q$  will just turn out to be a surjective map of EG-algebras, and indeed this is the case. Moreover, much as Propositions 2.12 and 2.16 are analogues of Lemma 1.18 and Proposition 1.20 respectively, the fact that  $q$  is surjective on morphisms means that there is a result analogous to Lemma 1.19 as well. That is, since every morphism of  $\mathbb{G}_{2n}$  is an action morphism, and since EG-algebra maps always send action morphisms to action morphisms, if  $q$  is surjective then every morphism of  $L\mathbb{G}_n$  is also an action morphism.

However, the proof of this is not so simple. Unfortunately, we can not go about proving that  $q$  is surjective on morphisms by using the adjunction from Proposition 2.19, since this will only tell us about the map  $\text{Mor}(q)^{gp,ab}$ . Without this, it is not obvious how the morphisms of some algebras should be related to the morphisms of their coequalizer in this way. In particular, for it to make sense that  $q$  is surjective, we would need the image of  $q$  to be closed under composition, since it is supposed to be the whole algebra  $L\mathbb{G}_n$ . Again by Lemma 1.19, this is equivalent to saying that the set of all action morphisms of  $L\mathbb{G}_n$  would have to be closed under composition, a statement which is not at all obvious. In the case of  $\mathbb{G}_{2n}$ , we know that the action morphisms are closed because maps  $\alpha(g; \text{id}_{x_1}, \dots, \text{id}_{x_m})$ ,  $\alpha(g'; \text{id}_{x'_1}, \dots, \text{id}_{x'_m})$ ,  $x_i, x'_i \in \{z_1, \dots, z_{2n}\}$  are composable only if the target of the first is equal to the source of the second, and hence

$$\begin{aligned}
& x_{\pi(g^{-1})(1)} \otimes \dots \otimes x_{\pi(g^{-1})(m)} = x'_1 \otimes \dots \otimes x'_m, & x_i, x'_i \in \{z_1, \dots, z_{2n}\} \\
\implies & x_{\pi(g^{-1})(i)} = x'_i, & 1 \leq i \leq m \\
\implies & \alpha(gg'; \text{id}_{x_1}, \dots, \text{id}_{x_m}) = \alpha(g; \text{id}_{x_1}, \dots, \text{id}_{x_m}) \circ \alpha(g'; \text{id}_{x'_1}, \dots, \text{id}_{x'_m})
\end{aligned}$$

However, in  $L\mathbb{G}_n$  this line of reasoning does not work, because for example

$$z_1 \otimes z_1^* = I = z_2 \otimes z_2^*$$

but this does not imply that  $z_1 = z_2$ .

The key to solving this problem is noticing that the maps  $\delta$  and  $\zeta$  form a reflexive pair — parallel maps which share a right-inverse.

**Lemma 3.4.** *Let  $\iota : \mathbb{G}_{2n} \rightarrow \mathbb{G}_{4n}$  be the inclusion defined on generators by  $z_i \mapsto z_i$ . Then  $\iota$  is a right-inverse of both  $\delta$  and  $\zeta$ .*

*Proof.* For  $1 \leq i \leq 2n$ ,

$$\begin{aligned} \delta \iota(z_i) &= \delta(z_i) = z_i \\ \zeta \iota(z_i) &= \zeta(z_i) = z_i \\ \implies \delta \circ \iota &= \text{id}_{\mathbb{G}_{2n}} = \zeta \circ \iota \end{aligned}$$

□

In other words,  $q$  is a reflexive coequalizer. Using this property of  $q$ , we will eventually be able to prove that the image of  $q$  is closed under composition. First though, we need some intermediate results.

**Definition 3.5.** Let  $x$  be an object of  $\mathbb{G}_m$  for some  $m \in \mathbb{N}$ , and hence an element of  $\mathbb{N}^{*m}$ , the free monoid on  $m$  generators  $\{z_1, \dots, z_m\}$ . Then by the definition of the free product of monoids,  $x$  will have a unique decomposition of the form

$$x = \bigotimes_{i=1}^{|x|} g(x, i)$$

where the upper bound  $|x|$  is the length of the element  $x$  as in Definition 2.26, and each  $g(x, i)$  is a generator of one of the  $m$  copies of  $\mathbb{N}$ , so  $g(x, i) \in \{z_1, \dots, z_m\}$ .

Note that this decomposition shows that the length of  $x$  is just the sum of all of the coordinates of its connected component,  $[x] \in \mathbb{N}^m$ :

**Lemma 3.6.**

$$|x| = \sum_{i=1}^m [x]_i$$

*Proof.* For any generator  $z_j$  its connected component has coordinates

$$[z_j]_i = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{otherwise} \end{cases}$$

and hence

$$\begin{aligned} \sum_{i=1}^m [x]_i &= \sum_{i=1}^m \left[ \bigotimes_{j=1}^{|x|} g(x, j) \right]_i \\ &= \sum_{i=1}^m \sum_{j=1}^{|x|} [g(x, j)]_i \\ &= \sum_{j=1}^{|x|} \sum_{i=1}^m [g(x, j)]_i \\ &= \sum_{j=1}^{|x|} 1 \\ &= |x| \end{aligned}$$

□



**Proposition 3.7.** *Let  $w$  be an object of  $\mathbb{G}_{2n}$ . Then there exist objects  $w_1, \dots, w_k$  in  $\mathbb{G}_{2n}$  and  $u_1, \dots, u_k$  in  $\mathbb{G}_{4n}$ , for some value of  $k \in \mathbb{N}$ , such that*

$$w_1 = w, \quad \zeta(u_{i-1}) = w_i = \delta(u_i), \quad u_k = \iota(w_k)$$

*for  $1 \leq i \leq k$ , and for any object  $u$  of  $\mathbb{G}_{4n}$ ,*

$$\delta(u) = w_k \implies u = u_k$$

*Proof.* From ?? and Definition 3.1, we know that for any generator  $z_i$  of  $\mathbb{G}_{4n}$ ,

$$|\delta(z_i)| = \begin{cases} 1 & \text{if } 1 \leq i \leq 2n \\ 2 & \text{if } 2n+1 \leq i \leq 4n \end{cases} \geq 1$$

$$|\zeta(z_i)| = \begin{cases} 1 & \text{if } 1 \leq i \leq 2n \\ 0 & \text{if } 2n+1 \leq i \leq 4n \end{cases} \leq 1$$

Also, length is additive on tensor products, because

$$|x \otimes y| = \sum [x \otimes y]_i = \sum ([x]_i + [y]_i) = \sum [x]_i + \sum [y]_i = |x| + |y|$$

Thus for any object  $u$  in  $\mathbb{G}_{4n}$ , we can conclude that

$$\begin{aligned} |\delta(u)| &= \left| \delta \left( \bigotimes_{i=1}^{|u|} g(u, i) \right) \right| = \left| \bigotimes_{i=1}^{|u|} \delta(g(u, i)) \right| = \sum_{i=1}^{|u|} |\delta(g(u, i))| \geq |u| \\ |\zeta(u)| &= \left| \zeta \left( \bigotimes_{i=1}^{|u|} g(u, i) \right) \right| = \left| \bigotimes_{i=1}^{|u|} \zeta(g(u, i)) \right| = \sum_{i=1}^{|u|} |\zeta(g(u, i))| \leq |u| \end{aligned}$$

Also, since the only generators that have  $|\delta(z_i)| = |\zeta(z_i)| = 1$  are those from the  $\mathbb{G}_{2n}$  subalgebra associated with  $\iota$ , the inequality above becomes an equality if and only if  $u$  is in the image of  $\iota$ . That is,

$$|\zeta(u)| = |u| = |\delta(u)| \iff \exists v \in \mathbb{N}^{*2n} : u = \iota(v)$$

Next, consider the set

$$\delta^{-1}(w) = \{u \in \mathbb{N}^{*4n} : \delta(u) = w\}$$

of all objects in  $\mathbb{G}_{4n}$  which  $\delta$  sends to  $w$ . This set is always nonempty, since by Lemma 3.4  $\iota$  is a right-inverse of  $\delta$ :

$$\delta \iota(w) = w \implies \iota(w) \in \delta^{-1}(w)$$

Moreover,  $\iota(w)$  is the only element of  $\delta^{-1}(w)$  which can be expressed as  $\iota(v)$  for some object  $v$  in  $\mathbb{G}_{2n}$ , because

$$\delta(\iota(v)) = w \implies v = w$$

With all of this now in place, we can begin constructing the sequences  $w_1, \dots, w_k$  and  $u_1, \dots, u_k$ . Start by setting  $w_1 = w$  and  $i = 1$ , then apply the following algorithm:

- (1) If  $\delta^{-1}(w_i)$  is just the set  $\{\iota(w_i)\}$ , choose  $u_i = \iota(w_i)$ , set  $k$  to be the current value of  $i$ , and terminate.
- (2) Otherwise, choose  $u_i$  to be any element of  $\delta^{-1}(w_i)$  other than  $\iota(w_i)$ .
- (3) Set  $w_{i+1} = \zeta(u_i)$ .

(4) Increase the value of  $i$  by 1, then return to step 1.

By design, none of the  $u_i$  produced by this process can be expressed as  $u_i = \iota(v)$  for some  $v$  in  $\mathbb{G}_{2n}$ , with the possible exception of  $u_k$  if the algorithm terminates. This is because  $\iota(w_i)$  is the only element of  $\delta^{-1}(w_i)$  that can be expressed that way, and the above process will terminate the first time it has to pick  $u_i = \iota(w_i)$ , at which point  $i$  is set equal to  $k$ . Therefore, for any  $i \neq k$ , we will have the following strict inequalities:

$$|w_{i+1}| = |\zeta(u_i)| < |u_i| < |\delta(u_i)| = |w_i|$$

That is, the  $w_i$  generated by this algorithm form a sequence with strictly decreasing length. However, it is impossible to have a infinite sequence of strictly decreasing natural numbers, and hence we can be sure that this process will terminate at some finite  $k$ .

But in order for the algorithm to have terminate, it must be the case that

$$\delta^{-1}(w_k) = \{\iota(w_k)\}$$

and hence

$$\delta(u) = w_k \implies u = \iota(w_k) = u_k$$

Thus the sequences  $w_1, \dots, w_k$  and  $u_1, \dots, u_k$  satisfy all of the conditions in the statement of the lemma.  $\square$

The intuition behind Proposition 3.7 is that we are successively removing parts of the object  $w$ , without changing its image under  $q$ . The map  $\delta$  sends  $z_{2n+i} \mapsto z_i \otimes z_{n+i}$  and  $z_{3n+i} \mapsto z_{n+1} \otimes z_i$  while  $\zeta$  sends these all to  $I$ , and so for any  $u$  in  $\mathbb{G}_{4n}$  the object  $\zeta(u)$  will look like  $\delta(u)$  except missing some number of  $z_i \otimes z_{n+i}$  or  $z_{n+1} \otimes z_i$  substrings. But since  $q$  sends  $z_{n+i} \mapsto z_i^*$ , these are exactly the sort of omissions which the coequaliser doesn't care about. If we repeat this process then it will eventually terminate at  $u_k = \iota(w_k)$ , so we really have a method for removing *all* of the relevant substrings from objects of  $\mathbb{G}_{2n}$ . In other words,  $w_k$  has the smallest possible length while still having  $q(w_k) = q(w)$ . In fact, we will show that it is the unique shortest object of  $\mathbb{G}_{2n}$  with this property.

**Definition 3.8.** Let  $x$  be an object of  $L\mathbb{G}_m$  for some  $m \in \mathbb{N}$ , and hence an element of  $\mathbb{Z}^{*m}$ , the free monoid on  $m$  invertible generators  $\{z_1, \dots, z_m\}$ . Then as in ?? we can use the definition of the free product of monoids to write  $x$  uniquely in the form

$$x = \bigotimes_{i=1}^{|x|} g(x, i)$$

This time each  $g(x, i)$  is either a generator of one of the copies of  $\mathbb{N}$  or the inverse of a generator,  $g(x, i) \in \{z_1, \dots, z_m, z_1^*, \dots, z_m^*\}$ , and for any  $1 \leq i < |x|$  we will always have  $g(x, i+1) \neq g(x, i)^*$ . As before, we will call the upper bound  $|x|$  of this tensor product the *length* of the element  $x$ .

**Proposition 3.9.** Let  $w, w'$  be objects of  $\mathbb{G}_{2n}$  such that  $q(w) = q(w')$ . If  $w_1, \dots, w_k$  and  $u_1, \dots, u_k$  are sequences generated from  $w$  via Proposition 3.7, and likewise  $w'_1, \dots, w'_{k'}$  and  $u'_1, \dots, u'_{k'}$  from  $w'$ , then  $w_k = w'_{k'}$  and  $u_k = u'_{k'}$ .

*Proof.* Consider the decomposition of the object  $w_k \in \mathbb{N}^{*2n}$  as in ??. Assume, for the sake of contradiction, that there exist  $1 \leq j < |w_k|$  and  $1 \leq m \leq n$  such that

$$g(w_k, j) = z_m, \quad g(w_k, j+1) = z_{n+m}$$

Then we can use  $j, m$  to construct an element  $u \in \mathbb{N}^{*4n}$ , defined by

$$|u| = |w| - 1, \quad g(u, i) = \begin{cases} \iota(g(w_k, i)) & \text{if } 1 \leq i < j \\ z_{2n+m} & \text{if } i = j \\ \iota(g(w_k, i+1)) & \text{if } j < i \leq |u| \end{cases}$$

for which

$$\begin{aligned} \delta(u) &= \delta\left(\bigotimes_{i=1}^{|u|} g(u, i)\right) \\ &= \bigotimes_{i=1}^{|u|} \delta(g(u, i)) \\ &= \bigotimes_{i=1}^{j-1} \delta\iota(g(w_k, i)) \otimes \delta(z_{2n+m}) \otimes \bigotimes_{i=j+1}^{|u|} \delta\iota(g(w_k, i+1)) \\ &= \bigotimes_{i=1}^{j-1} g(w_k, i) \otimes g(w_k, j) \otimes g(w_k, j+1) \otimes \bigotimes_{i=j+2}^{|u|+1} g(w_k, i) \\ &= w_k \end{aligned}$$

But this is impossible, since by Proposition 3.7  $u_k$  is the only object of  $\mathbb{G}_{4n}$  whose image under  $\delta$  is  $w_k$ , and the  $u$  we have constructed is manifestly not  $w_k$ . Thus we can conclude that there are no values of  $j$  and  $m$  for which

$$g(w_k, j) = z_m, \quad g(w_k, j+1) = z_{n+m}$$

An analogous line of reasoning — using  $z_{3n+m}$  rather than  $z_{2n+m}$  in the definition of  $u$  — demonstrates that there are also no  $j, m$  with

$$g(w_k, j) = z_{n+m}, \quad g(w_k, j+1) = z_m$$

As a result, for all  $1 \leq i < |w_k|$

$$q(g(w_k, i+1)) \neq q(g(w_k, i))^*$$

and this combined with the fact that

$$\bigotimes_{i=1}^{|w_k|} q(g(w_k, i)) = q\left(\bigotimes_{i=1}^{|w_k|} g(w_k, i)\right) = q(w_k)$$

shows that the unique decomposition of  $q(w_k)$  as in Definition 3.8 is given by

$$|q(w_k)| = |w_k|, \quad g(q(w_k), i) = q(g(w_k, i))$$

Next, let  $s$  be the *function* which is defined by

$$\begin{aligned} s &: \mathbb{Z}^{*n} \rightarrow \mathbb{N}^{*2n} \\ &: z_i \mapsto z_i \\ &: z_i^* \mapsto z_{n+i} \\ &: x \mapsto \bigotimes_{i=1}^{|x|} s(g(x, i)) \end{aligned}$$

Then for  $1 \leq i \leq n$ ,

$$sq(z_i) = s(z_i) = z_i, \quad sq(z_{n+i}) = s(z_i^*) = z_{n+i}$$

and so it follows that

$$\begin{aligned}
 sq(w_k) &= \bigotimes_{i=1}^{|w_k|} s\left(g(q(w_k), i)\right) \\
 &= \bigotimes_{i=1}^{|w_k|} sq(g(w_k, i)) \\
 &= \bigotimes_{i=1}^{|w_k|} g(w_k, i) \\
 &= w_k
 \end{aligned}$$

Finally, notice that the exact same logic as we've used above will also work for  $w'_{k'}$ , so that  $sq(w'_{k'}) = w'_{k'}$ . Therefore,

$$\begin{aligned}
 w_k &= sq(w_k) \\
 &= sq\zeta(u_{k-1}) \\
 &= sq\delta(u_{k-1}) \\
 &= sq(w_{k-1}) \\
 &\vdots \\
 &= sq(w) \\
 &= sq(w') \\
 &= sq\delta(u'_1) \\
 &= sq\zeta(u'_1) \\
 &= sq(w'_2) \\
 &\vdots \\
 &= sq(w'_{k'}) \\
 &= w'_{k'}
 \end{aligned}$$

as required.  $\square$

Next, we need to take things one step further. We've already shown that we can find an object  $w_k$  which is like  $w$  but with all  $z_i \otimes z_{n+i}$  and  $z_{n+i} \otimes z_i$  substrings removed. In order to prove the closure of  $\text{im}(q)$ , we will need to construct a morphism of  $\mathbb{G}_{2n}$  which witnesses this removal — that is, a map  $h : w \rightarrow v \otimes w_k$  where  $v$  is made up of all of the  $z_i \otimes z_{n+i}$  that are taken out of  $w$  to make  $w_k$ . Likewise, the fact that  $q(w_k) = q(w)$  will be embodied by the fact that  $h$  becomes an identity morphism under  $q$ . This map  $h$  will need to be built out of smaller pieces, using the sequence  $u_1, \dots, u_k$  and the following proposition:

**Proposition 3.10.** *Let  $u$  be an object of  $\mathbb{G}_{4n}$ . Then there exists another object  $x$  in  $\mathbb{G}_{4n}$  and a morphism  $h : \delta(u) \rightarrow \delta(x) \otimes \zeta(u)$  in  $\mathbb{G}_{2n}$  such that  $q(h) = \text{id}_{q\delta(u)}$ .*

*Proof.* First, consider the object  $\iota\zeta(u) \in \mathbb{N}^{4n}$ . Because  $\zeta$  acts by sending the generator  $z_{2n+i}$  to  $I$  for each  $1 \leq i \leq n$ , and since  $\iota$  is an inclusion, the connected component  $[\iota\zeta(u)] \in \mathbb{N}^{4n}$  will have  $i$ th coordinate

$$[\iota\zeta(u)]_i = [\zeta(u)]_i = \begin{cases} [u]_i & \text{if } 1 \leq i \leq 2n \\ 0 & \text{if } 2n+1 \leq i \leq 4n \end{cases}$$

Intuitively,  $\iota\zeta(u)$  is what would be left if we were to remove all of the  $z_{2n+i}$  generators from  $u$ . Conversely, the object  $x \in \mathbb{G}_{4n}$  defined as

$$x = z_{2n+1}^{\otimes [u]_{2n+1}} \otimes \dots \otimes z_{4n}^{\otimes [u]_{4n}}$$

is like a reordered list of all of the  $z_{2n+i}$  that we would have to remove from  $u$  in order to make  $\iota\zeta(u)$ , and will have the property that

$$[x]_i = \begin{cases} 0 & \text{if } 1 \leq i \leq 2n \\ [u]_i & \text{if } 2n+1 \leq i \leq 4n \end{cases}$$

Thus the object  $x \otimes \iota\zeta(u)$  is simply a reordered version of  $u$ , or more concretely

$$[x \otimes \iota\zeta(u)]_i = [x]_i + [\iota\zeta(u)]_i = \begin{cases} 0 + [u]_i & \text{if } 1 \leq i \leq 2n \\ [u]_i + 0 & \text{if } 2n+1 \leq i \leq 4n \end{cases} = [u]_i$$

for all  $i$ , and hence  $u$  and  $x \otimes \iota\zeta(u)$  are part of the same connected component.

Knowing this, we can now choose an arbitrary morphism  $f : u \rightarrow x \otimes \iota\zeta(u)$  from  $\mathbb{G}_{4n}$ . The map  $\zeta(f)$  will then have source  $\zeta(u)$  and target

$$\zeta(x \otimes \iota\zeta(u)) = \zeta(x) \otimes \zeta\iota\zeta(u) = \zeta(u)$$

because  $\iota$  is a right inverse of  $\zeta$ , and  $x$  was defined in such a way that  $\zeta(x) = I$ . It follows that  $\iota\zeta(f)$  is a map  $\iota\zeta(u) \rightarrow \iota\zeta(u)$ , and therefore it is possible to form the composite

$$u \xrightarrow{f} x \otimes \iota\zeta(u) \xrightarrow{\text{id}_x \otimes \iota\zeta(f)^{-1}} x \otimes \iota\zeta(u)$$

which we'll call  $g$ . Effectively, what  $g$  does is to first apply the map  $f$ , and then 'undo' its effect on the generators  $z_1, \dots, z_{2n}$ , while leaving the  $z_{2n+1}, \dots, z_{4n}$  in  $x$  untouched. It should not be surprising then that if we take the image of  $g$  under  $\zeta$ , we get

$$\begin{aligned} \zeta(g) &= \zeta((\text{id}_x \otimes \iota\zeta(f)^{-1}) \circ f) \\ &= (\zeta(\text{id}_x) \otimes \zeta\iota\zeta(f)^{-1}) \circ \zeta(f) \\ &= \zeta(f)^{-1} \circ \zeta(f) \\ &= \text{id}_{\zeta(u)} \end{aligned}$$

Finally, consider the morphism  $\delta(g)$ . This has source  $\delta(u)$  and target

$$\delta(x \otimes \iota\zeta(u)) = \delta(x) \otimes \delta\iota\zeta(u) = \zeta(u)$$

because  $\iota$  is also the right inverse of  $\delta$ , and so we can choose  $\delta(g)$  to be the map  $h$  that we are looking for. If we do, then since  $q$  is the coequalizer of  $\delta$  and  $\zeta$  we'll have

$$q(h) = q\delta(g) = q\zeta(g) = q(\text{id}_{\zeta(u)}) = \text{id}_{q\zeta(u)} = \text{id}_{q\delta(u)}$$

as required.  $\square$

Hopefully it is clear that nothing in the proof of Proposition 3.9 really depended on the order in which we tensored together  $\delta(x) \otimes \zeta(u)$ . Consequently, the same basic proof will also work when this order is reversed:

**Corollary 3.11.** *Let  $u$  be an object of  $\mathbb{G}_{4n}$ . Then there exists another object  $x$  in  $\mathbb{G}_{4n}$  and a morphism  $h : \delta(u) \rightarrow \zeta(u) \otimes \delta(x)$  in  $\mathbb{G}_{2n}$  such that  $q(h) = \text{id}_{q\delta(u)}$ .*

Now we finally have enough results in place to show that the image of  $q$  is closed under composition.

$$\begin{array}{c}
 v \otimes \delta(x'_{k'-1}) \otimes \dots \otimes \delta(x'_1) \\
 \downarrow f \otimes \text{id} \\
 w \otimes \delta(x'_{k'-1}) \otimes \dots \otimes \delta(x'_1) \\
 \downarrow h_1 \otimes \text{id} \\
 \delta(x_1) \otimes w_2 \otimes \delta(x'_{k'-1}) \otimes \dots \otimes \delta(x'_1) \\
 \downarrow \text{id} \otimes h_2 \otimes \text{id} \\
 \delta(x_1) \otimes \delta(x_2) \otimes w_3 \otimes \delta(x'_{k'-1}) \otimes \dots \otimes \delta(x'_1) \\
 \downarrow \text{id} \otimes h_3 \otimes \text{id} \\
 \vdots \\
 \downarrow \text{id} \otimes h_{k-1} \otimes \text{id} \\
 \delta(x_1) \otimes \dots \otimes \delta(x_{k-1}) \otimes w_k \otimes \delta(x'_{k'-1}) \otimes \dots \otimes \delta(x'_1) \\
 \parallel \\
 \delta(x_1) \otimes \dots \otimes \delta(x_{k-1}) \otimes w'_{k'} \otimes \delta(x'_{k'-1}) \otimes \dots \otimes \delta(x'_1) \\
 \downarrow \text{id} \otimes h'_{k'-1} \otimes \text{id} \\
 \vdots \\
 \downarrow \text{id} \otimes h'_1 \\
 \delta(x_1) \otimes \dots \otimes \delta(x_{k-1}) \otimes w' \\
 \downarrow \text{id} \otimes f' \\
 \delta(x_1) \otimes \dots \otimes \delta(x_{k-1}) \otimes v'
 \end{array}$$

 FIGURE 1. The composite  $h$

**Proposition 3.12.** *Let  $f : v \rightarrow w$  and  $f' : w' \rightarrow v'$  be two morphisms of  $\mathbb{G}_{2n}$  such that  $q(f)$  and  $q(f')$  are composable. Then there exist objects  $y, y'$  and a morphism  $h : y \rightarrow y'$  in  $\mathbb{G}_{2n}$  such that  $q(h) = q(f') \circ q(f)$ .*

*Proof.* To begin, we'll use Proposition 3.7 to construct from  $w$  the sequences of objects  $w_1, \dots, w_k$  in  $\mathbb{G}_{2n}$  and  $u_1, \dots, u_k$  in  $\mathbb{G}_{4n}$ , for some  $k \in \mathbb{N}$ . These have

$$w_1 = w, \quad \zeta(u_{i-1}) = w_i = \delta(u_i), \quad \iota(w_k) = u_k$$

Then we can apply Proposition 3.10 to each  $u_i$  in turn, producing a new sequence of object  $x_1, \dots, x_{k-1}$  in  $\mathbb{G}_{4n}$  and morphisms

$$\begin{aligned} h_i &: \delta(u_i) \rightarrow \delta(x_i) \otimes \zeta(u_i) \\ &: w_i \rightarrow \delta(x_i) \otimes w_{i+1} \end{aligned}$$

for each  $1 \leq i < k$ , with the properties

$$\zeta(x_i) = I, \quad q(h_i) = \text{id}_{q(w_i)}$$

We can do a similar thing with  $w'$ , first using Proposition 3.7 to get sequences  $w'_1, \dots, w'_{k'}$  and  $u'_1, \dots, u'_{k'}$  with the appropriate properties, but this time applying Corollary 3.11 to find objects  $x'_1, \dots, x'_{k'-1}$  and morphisms  $h'_i : w'_i \rightarrow w_{i+1} \otimes \delta(x'_i)$ . Moreover, since the morphisms  $q(f) : q(v) \rightarrow q(w)$  and  $q(f') : q(w') \rightarrow q(v')$  are composable, it must be the case that  $q(w)$  and  $q(w')$  are equal. By Proposition 3.9, this means that  $w_k = w'_{k'}$ .

Putting all of this together, we can form the composite morphism shown in Figure 1. Here the subscripts of the identity maps have been suppressed for clarity. This morphism will be our choice of  $h : y \rightarrow y'$ . To complete the proof, notice that

$$\begin{aligned} q\delta(x_i) &= q\zeta(x_i) = I = q\zeta(x'_i) = q\delta(x'_i) \\ \implies q(\text{id}_{\delta(x_i)}) &= \text{id}_{q\delta(x_i)} = \text{id}_I = \text{id}_{q\delta(x'_i)} = q(\text{id}_{\delta(x'_i)}) \end{aligned}$$

for each value of  $i$ , and so when we take the image of the composite  $h$  under  $q$  all of the  $\text{id}_{\delta(x_i)}$  and  $\text{id}_{\delta(x'_i)}$  terms will cancel out, leaving just

$$\begin{aligned} q(h) &= q(f') \circ q(h'_1) \circ \dots \circ q(h'_{k'-1}) \circ q(h_{k-1}) \circ \dots \circ q(h_1) \circ q(f) \\ &= q(f') \circ \text{id}_{q(w)} \circ \dots \circ \text{id}_{q(w)} \circ \text{id}_{q(w)} \circ \dots \circ \text{id}_{q(w)} \circ q(f) \\ &= q(f') \circ q(f) \end{aligned}$$

as required.  $\square$

Finally, we can return to how we began this section. We wished to show that the map  $q$  is surjective, and from this conclude that all morphisms of  $L\mathbb{G}_n$  are action morphisms. However, it was not obvious that such a statement would even make sense, since the image of  $q$  would consist entirely of morphisms of the form  $\alpha_{L\mathbb{G}_n}(g; \text{id}_{x_1}, \dots, \text{id}_{x_m})$ , and these are not a priori closed under composition. But with Proposition 3.12 we now know that the image of  $q$  is indeed closed, and we can immediately use this to demonstrate surjectivity.

**Proposition 3.13.** *The quotient map  $q : \mathbb{G}_{2n} \rightarrow L\mathbb{G}_n$  is surjective. Therefore, every morphism in  $L\mathbb{G}_n$  can be expressed as  $\alpha_{L\mathbb{G}_n}(g; \text{id}_{x_1}, \dots, \text{id}_{x_m})$  for some  $g \in G(m)$  and  $x_i \in \{z_1, \dots, z_n, z_1^*, \dots, z_n^*\}$ .*

*Proof.* Consider  $q(\mathbb{G}_{2n})$ , the subcategory of  $L\mathbb{G}_n$  that contains every object  $x$  for which there exists  $x'$  in  $\mathbb{G}_{2n}$  with  $q(x') = x$ , and every morphism  $f$  for which there exists  $f'$  in  $\mathbb{G}_{2n}$  with  $q(f') = f$ . By Proposition 3.12 the morphisms of  $q(\mathbb{G}_{2n})$  are

closed under composition, and so this is a well-defined category. Moreover, since  $q$  is a map of EG-algebras then for any morphisms  $f_1, \dots, f_m$  of  $q(\mathbb{G}_{2n})$  we'll have

$$\begin{aligned} \alpha_{L\mathbb{G}_n}(g; f_1, \dots, f_m) &= \alpha_{L\mathbb{G}_n}(g; q(f'_1), \dots, q(f'_m)) \\ &= q(\alpha_{\mathbb{G}_{2n}}(g; f'_1, \dots, f'_m)) \\ &\in q(\mathbb{G}_{2n}) \end{aligned}$$

Thus  $q(\mathbb{G}_{2n})$  is also a well-defined sub-EG-algebra of  $L\mathbb{G}_n$ .

Next, let  $q' : \mathbb{G}_{2n} \rightarrow q(\mathbb{G}_{2n})$  be the surjective map which acts on objects and morphism exactly as  $q$ . Also denote by  $i$  the evident inclusion of algebras  $q(\mathbb{G}_{2n}) \hookrightarrow L\mathbb{G}_n$ , so that for instance  $i \circ q' = q$ .

$$\begin{array}{c} \mathbb{G}_{3n} \\ \delta \swarrow \quad \searrow \zeta \\ \mathbb{G}_{2n} \\ \begin{array}{ccc} q' \swarrow & q \downarrow & p \searrow \\ q(\mathbb{G}_{2n}) & \xrightarrow{i} & L\mathbb{G}_n \xrightarrow{u} X \end{array} \end{array}$$

Further, let  $p : \mathbb{G}_{2n} \rightarrow X$  be any map of EG-algebras with the property that  $p \circ \delta = p \circ \zeta$ . Since  $q$  is the coequalizer of  $\delta$  and  $\zeta$ , there will then exist a unique map  $u : L\mathbb{G}_n \rightarrow X$  such that  $p = u \circ q$ . This means that  $p = u \circ i \circ q'$ , and hence there is obviously at least one map,  $u \circ i$ , which lets us factor  $p$  through  $q'$ . But for any other map  $v' : q(\mathbb{G}_{2n}) \rightarrow X$  that factors  $p$  like this, we have

$$\begin{aligned} v' \circ q' &= p \\ &= v' \circ i \circ q' \\ \implies v' &= v' \circ i \end{aligned}$$

because  $q'$  is surjective, and thus  $u \circ i$  is the unique map with this property. That is,  $q'$  is also a coequalizer of  $\delta$  and  $\zeta$ . Since colimits are always unique up to isomorphism, this means that there exists an invertible map  $v : q(\mathbb{G}_{2n}) \rightarrow L\mathbb{G}_n$  such that  $q = v \circ q'$ . But  $q'$  is surjective, and so it immediately follows that  $q$  is too.

Finally, let  $f$  be an arbitrary morphism in  $L\mathbb{G}_n$ . By surjectivity there exists at least one morphism  $f'$  in  $\mathbb{G}_{2n}$  such that  $q(f') = f$ , and from Lemma 1.19 we know that this  $f'$  can be expressed uniquely as  $\alpha(g; \text{id}_{x'_1}, \dots, \text{id}_{x'_m})$  for some  $g \in G(m)$  and  $x'_i \in \{z_1, \dots, z_{2n}\}$ . Thus, because  $q$  is a map of EG-algebras, we will have

$$f = q(f') = q(\alpha_{\mathbb{G}_{2n}}(g; \text{id}_{x'_1}, \dots, \text{id}_{x'_m})) = \alpha_{L\mathbb{G}_n}(g; \text{id}_{q(x'_1)}, \dots, \text{id}_{q(x'_m)})$$

But by Lemma 3.2, for each generator  $x'_i \in \{z_1, \dots, z_{2n}\}$  the object  $q(x'_i)$  is either one of the generators  $z_1, \dots, z_n$  of  $L\mathbb{G}_n$  or one of their inverse  $z_1^*, \dots, z_n^*$ . Therefore, there is at least one collection of  $x_i = q(x'_i)$  for which the statement of the proposition holds.  $\square$

Proposition 3.13 formalises a certain intuition about how the functor  $L$  should act on algebras, the idea that a ‘free’ structure really shouldn’t have any ‘superfluous’ components, only whatever data is absolutely required for it to be well-defined. In the case of  $L\mathbb{G}_n$ , we have proven that the only morphisms contained in the free



EG-algebra on invertible objects are EG-action morphisms. However, while this is very similar to what we have in the non-invertible case it should be stressed that Proposition 3.13 does *not* prove that the morphisms of  $L\mathbb{G}_n$  have *unique* representations  $\alpha(g; \text{id}_{w_1}, \dots, \text{id}_{w_m})$ , as morphisms of  $\mathbb{G}_n$  do.

### 3.3. The action of $L\mathbb{G}_n$ .

**Proposition 3.14.** *The coequalizer of  $\text{Mor}(\delta)$  and  $\text{Mor}(\zeta)$  is  $\text{Mor}(L\mathbb{G}_n)$ .*

**Corollary 3.15.**  *$\text{Mor}(q)$  is the coequalizer map of  $\text{Mor}(\delta)$  and  $\text{Mor}(\zeta)$ .*

**Proposition 3.16.** *The action of  $L\mathbb{G}_n$  is given by the following map:*

With this proposition proven, the results in this chapter now collectively describe how to construct free EG-algebras on  $n$  invertible objects. Since the argument is obviously arranged in a rather piecemeal fashion, it would be best to restate the general conclusion all in one place.

**Theorem 3.17.** *Let  $\mathbb{G}_n$  be the free EG-algebra on  $n$  objects. Then the free EG-algebra on  $n$  invertible objects,  $L\mathbb{G}_n$ , is the algebra described by*

*Proof.* □

**3.4. Examples.** With Theorem 3.17 proven we can now finally achieve the primary goal of this chapter — to describe the free braided monoidal category on  $n$  invertible objects. In addition, this section will provide a few other simple applications of the theorem, in an effort to build up to the main result more gently. The definition of  $L\mathbb{G}_n$  given in 3.17 is after all a little difficult to parse on first reading, because of the fairly abstract way it is presented, and hopefully the following concrete examples should allow the braided case to be properly understood.

**Proposition 3.18.** *One object case*

**Proposition 3.19.** *Symmetric case*

**Proposition 3.20.** *Cactus group case*

. . . . .

**3.5. The free algebra on  $n$  weakly invertible objects.** Up until now, we've been working under the convention that by 'invertible' objects we mean strictly invertible —  $x \otimes x^* = I$ . As an additional exercise, we can ask ourselves how all of this would change if we permitted our objects to be only weakly invertible, that is  $x \otimes x^* \cong I$ . The situation is actually quite elegant, in that the effect of weakening in our objects can be offset completely by the effect of also weakening our algebra homomorphisms, such that we won't need to calculate any new free algebras other than those given by Theorem 3.17. Before proving this though, we first need to set out some definitions.

**Definition 3.21.** Given an EG-algebra  $X$ , we denote by  $X_{\text{wkinv}}$  the category whose

- objects are tuples  $(x, x^*, \eta, \epsilon)$ , where  $x$  and  $x^*$  are objects of  $X$  and  $\eta : I \rightarrow x^* \otimes x$  and  $\epsilon : x \otimes x^* \rightarrow I$  are morphisms such that the composites

$$x \xrightarrow{\text{id} \otimes \eta} x \otimes x^* \otimes x \xrightarrow{\epsilon \otimes \text{id}} x \qquad x^* \xrightarrow{\eta \otimes \text{id}} x^* \otimes x \otimes x^* \xrightarrow{\text{id} \otimes \epsilon} x^*$$

are identity morphisms.

- maps  $(f, f^*) : (x, x^*, \eta_x, \epsilon_x) \rightarrow (y, y^*, \eta_y, \epsilon_y)$  are pairs  $f : x \rightarrow y$ ,  $f^* : x^* \rightarrow y^*$  of morphisms such that the diagrams

$$\begin{array}{ccc} & I & \\ \eta_x \swarrow & & \searrow \eta_y \\ x^* \otimes x & \xrightarrow{f^* \otimes f} & y \otimes y^* \end{array} \qquad \begin{array}{ccc} x \otimes x^* & \xrightarrow{f \otimes f^*} & y \otimes y^* \\ \epsilon_x \searrow & & \swarrow \epsilon_y \\ & I & \end{array}$$

commute.

**Definition 3.22.** Let  $(X, \alpha)$  and  $(Y, \beta)$  be EG-algebras. A *weak EG-algebra homomorphism* between them is a weak monoidal functor  $\psi : X \rightarrow Y$  such that all diagrams of the form

$$\begin{array}{ccc} \psi(x_1 \otimes \dots \otimes x_m) & \xrightarrow{\sim} & \psi(x_1) \otimes \dots \otimes \psi(x_m) \\ \psi(\alpha(g; h_1, \dots, h_m)) \downarrow & & \downarrow \beta(g; \psi(h_1), \dots, \psi(h_m)) \\ \psi(y_{\pi(g)^{-1}(1)} \otimes \dots \otimes y_{\pi(g)^{-1}(m)}) & \xrightarrow{\sim} & \psi(y_{\pi(g)^{-1}(1)}) \otimes \dots \otimes \psi(y_{\pi(g)^{-1}(m)}) \end{array}$$

commute.

**Definition 3.23.** We denote by  $\text{EGAlg}_W$  the 2-category of EG-algebras, weak EG-algebra homomorphisms, and weak monoidal transformations.

Now we can properly express what we mean by the free algebras on weakly invertible objects being the same as those in the strict case.

**Theorem 3.24.** *The algebra  $L\mathbb{G}_n$  is also the free EG-algebra on  $n$  weakly invertible objects. Specifically, for any other EG-algebra  $X$  there is an equivalence of categories*

$$\text{EGAlg}_W(L\mathbb{G}_n, X) \simeq (X_{\text{wkinv}})^n$$

*Proof.* We begin by defining a functor  $F : \text{EGAlg}_W(L\mathbb{G}_n, X) \rightarrow (X_{\text{wkinv}})^n$ . On weak maps,  $F$  acts as

$$F(\psi : L\mathbb{G}_n \rightarrow X) = \{ (\psi(z_i), \psi(z_i^*), I \xrightarrow{\sim} \psi(I) \xrightarrow{\sim} \psi(z_i^*)\psi(z_i), \psi(z_i)\psi(z_i^*) \xrightarrow{\sim} \psi(I) \xrightarrow{\sim} I) \}_{i \in \{z_1, \dots, z_n\}}$$

where the  $z_i$  are the generators of  $\mathbb{Z}^n$  and the isomorphisms are those given by  $\psi$  being a weak monoidal functor. On weak monoidal transformations,  $F$  acts as

$$F(\theta : \psi \rightarrow \chi) = \{ (\theta_{z_i}, \theta_{z_i^*}) \}_{i \in \{z_1, \dots, z_n\}}$$

This choice does satisfy the condition on morphisms of  $(X_{\text{wkinv}})^n$ , since we can build the required commuting diagrams out of smaller ones given by  $\theta$  being a weak monoidal transformation:

$$\begin{array}{ccc} & I & \\ \sim \swarrow & & \searrow \sim \\ \psi(I) & \xrightarrow{\theta_I} & \chi(I) \\ \sim \downarrow & & \downarrow \sim \\ \psi(z_i^*) \otimes \psi(z_i) & \xrightarrow{\theta_{z_i^*} \otimes \theta_{z_i}} & \chi(z_i^*) \otimes \chi(z_i) \end{array} \qquad \begin{array}{ccc} \psi(z_i) \otimes \psi(z_i^*) & \xrightarrow{\theta_{z_i} \otimes \theta_{z_i^*}} & \chi(z_i) \otimes \chi(z_i^*) \\ \sim \downarrow & & \downarrow \sim \\ \psi(I) & \xrightarrow{\theta_I} & \chi(I) \\ \sim \swarrow & & \searrow \sim \\ & I & \end{array}$$

Now we need to check if  $F$  is an equivalence of categories. First, let  $\{(x_i, x_i^*, \eta_i, \epsilon_i)\}_{i \in \{z_1, \dots, z_n\}}$  be an arbitrary object of  $(X_{\text{wkinv}})^n$ . We can construct a weak algebra map  $\psi : L\mathbb{G}_n \rightarrow X$  from it as follows. Define

$$\psi(I) = I, \quad \psi(z_i) = x_i, \quad \psi(z_i^*) = x_i^*$$

and choose the isomorphisms

$$\begin{aligned} \psi_I &: I \rightarrow \psi(I) &= \text{id}_I &: I \rightarrow I \\ \psi_{z_i, z_i^*} &: \psi(z_i) \otimes \psi(z_i^*) \rightarrow \psi(I) &= \epsilon_i &: x_i \otimes x_i^* \rightarrow I \\ \psi_{z_i^*, z_i} &: \psi(z_i^*) \otimes \psi(z_i) \rightarrow \psi(I) &= \eta_i^{-1} &: x_i^* \otimes x_i \rightarrow I \end{aligned}$$

Then for any  $w, w' \in \text{Ob}(L\mathbb{G}_n)$  such that  $d(w \otimes w') = d(w) \otimes d(w')$ , where  $d(-)$  is the minimal generator decomposition from ??, set

$$\psi(w \otimes w') = \psi(w) \otimes \psi(w'), \quad \psi_{w, w'} = \text{id}_{\psi(w) \otimes \psi(w')}$$

This is enough to determine the value of  $\psi$  on all of the remaining objects, via successive decompositions. For the isomorphisms, first note that the ones we have already defined satisfy the associativity and unitality required of weak monoidal functors. Now consider some  $w, w'$  with  $d(w \otimes w') \neq d(w) \otimes d(w')$ . The fact that they differ implies that tensoring  $w$  with  $w'$  causes some cancellation of inverses to occur where the end of one sequence meets the beginning of another. In particular, if we let  $b$  be the last term in the minimal generator decomposition of  $w$ , and let  $c = w'$ , then we conclude that the length  $d(b \otimes c)$  is smaller than the length of  $d(c)$ . Let  $a$  be the product of the rest of  $d(w)$ , so that  $a \otimes b = w$ . Then we can use requirement for associativity,

$$\begin{array}{ccc} \psi(a) \otimes \psi(b) \otimes \psi(c) & \xrightarrow{\text{id} \otimes \psi_{b, c}} & \psi(a) \otimes \psi(b \otimes c) \\ \psi_{a, b} \otimes \text{id} \downarrow & & \downarrow \psi_{a, b \otimes c} \\ \psi(a \otimes b) \otimes \psi(c) & \xrightarrow{\psi_{a \otimes b, c}} & \psi(a \otimes b \otimes c) \end{array}$$

to define  $\psi_{w, w'} = \psi_{a \otimes b, c}$  in terms of three other isomorphisms that each have strictly smaller decompositions. Repeating this process will therefore eventually yield a definition in terms of our previous isomorphisms.

By Proposition 3.13, every morphism in  $L\mathbb{G}_n$  can be written as  $\alpha(g; \text{id}_{w_1}, \dots, \text{id}_{w_m})$  for some  $g \in G(m)$ ,  $w_i \in \mathbb{Z}^{*n}$ . The action of  $\psi$  on morphisms is thus determined by the diagram in Definition 3.22, that is

$$\psi(\alpha(g; w_1, \dots, w_m)) = \psi_{\mathbf{w}_{\pi(g)-1}} \circ \beta(g; \text{id}_{\psi(w_1)}, \dots, \text{id}_{\psi(w_m)}) \circ \psi_{\mathbf{w}}^{-1}$$

However, morphisms do not have a unique representation of this form, so we must check that whenever we have different representations of the same morphism

$$\alpha(g; \text{id}_{w_1}, \dots, \text{id}_{w_m}) = \alpha(g'; \text{id}_{w'_1}, \dots, \text{id}_{w'_m})$$

their diagrams give the same image under  $\psi$ . There are two cases to consider here;

$$\alpha(g; \text{id}_{w_1}, \dots, \text{id}_{w_m}) = \alpha(g \otimes e_k; \text{id}_{w_1}, \dots, \text{id}_{w_m}, \text{id}_{v_1}, \dots, \text{id}_{v_k})$$

when  $v_1 \otimes \dots \otimes v_k = 0$ , which comes from the edges of the colimit diagram  $D_n$  in ??; and

$$\begin{aligned} \alpha(g; \text{id}_{w_1}, \dots, \text{id}_{w_m}) &= \alpha(h; \text{id}_{w'_1}, \dots, \text{id}_{w_{m'}}) \\ &\quad \circ \alpha(j; \text{id}_{w''_1}, \dots, \text{id}_{w''_{m''}}) \\ &\quad \circ \alpha(h^{-1}; \text{id}_{w'_1}, \dots, \text{id}_{w'_{m'}}) \\ &\quad \circ \alpha(j^{-1}; \text{id}_{w''_1}, \dots, \text{id}_{w''_{m''}}) \\ &= \text{id}_{w_1 \otimes \dots \otimes w_m} \end{aligned}$$

for  $\alpha(h; \text{id}_{w'_1}, \dots, \text{id}_{w_{m'}}), \alpha(j; \text{id}_{w''_1}, \dots, \text{id}_{w''_{m''}}) \in \mathbb{G}_n(w_1 \otimes \dots \otimes w_m, w_1 \otimes \dots \otimes w_m)$ , which comes from the abelianisation of the vertices of  $D_n$ . All other ways for a morphism to have different representations must be generated by successive examples of these cases, since otherwise they wouldn't be coequalised by the colimit in ?. In the first case we just have

$$\begin{aligned} &\psi(\alpha(g \otimes e_k; \text{id}_{w_1}, \dots, \text{id}_{w_m}, \text{id}_{v_1}, \dots, \text{id}_{v_k})) \\ &= \psi_{\mathbf{w}_{\pi(g)-1}, \mathbf{v}} \circ \beta(g \otimes e_k; \text{id}_{\psi(w_1)}, \dots, \text{id}_{\psi(w_m)}, \text{id}_{\psi(v_1)}, \dots, \text{id}_{\psi(v_k)}) \circ \psi_{\mathbf{w}, \mathbf{v}}^{-1} \\ &= (\psi_{\mathbf{w}_{\pi(g)-1}} \otimes \psi_{\mathbf{v}}) \circ (\beta(g; \text{id}_{\psi(w_1)}, \dots, \text{id}_{\psi(w_m)}) \otimes \text{id}_{\psi(\mathbf{v})}) \circ (\psi_{\mathbf{w}}^{-1} \otimes \psi_{\mathbf{v}}^{-1}) \\ &= (\psi_{\mathbf{w}_{\pi(g)-1}} \circ \beta(g; \text{id}_{\psi(w_1)}, \dots, \text{id}_{\psi(w_m)}) \circ \psi_{\mathbf{w}}^{-1}) \otimes (\psi_{\mathbf{v}} \circ \text{id}_{\psi(\mathbf{v})} \circ \psi_{\mathbf{v}}^{-1}) \\ &= \psi_{\mathbf{w}_{\pi(g)-1}} \circ \beta(g; \text{id}_{\psi(w_1)}, \dots, \text{id}_{\psi(w_m)}) \circ \psi_{\mathbf{w}}^{-1} \\ &= \psi(\alpha(g; \text{id}_{w_1}, \dots, \text{id}_{w_m})) \end{aligned}$$

as required. The second case is more subtle. We begin by expanding

$$\begin{aligned} &\psi(\alpha(g; \text{id}_{w_1}, \dots, \text{id}_{w_m})) \\ &= \psi(\alpha(h; \text{id}_{w'_1}, \dots, \text{id}_{w_{m'}})) \\ &\quad \circ \psi(\alpha(j; \text{id}_{w''_1}, \dots, \text{id}_{w''_{m''}})) \\ &\quad \circ \psi(\alpha(h^{-1}; \text{id}_{w'_1}, \dots, \text{id}_{w'_{m'}})) \\ &\quad \circ \psi(\alpha(j^{-1}; \text{id}_{w''_1}, \dots, \text{id}_{w''_{m''}})) \\ &= \psi_{\mathbf{w}'} \circ \beta(h; \text{id}_{\psi(w'_1)}, \dots, \text{id}_{\psi(w_{m'})}) \circ \psi_{\mathbf{w}'}^{-1} \\ &\quad \circ \psi_{\mathbf{w}''} \circ \beta(j; \text{id}_{\psi(w''_1)}, \dots, \text{id}_{\psi(w''_{m''})}) \circ \psi_{\mathbf{w}''}^{-1} \\ &\quad \circ \psi_{\mathbf{w}'} \circ \beta(h^{-1}; \text{id}_{\psi(w'_1)}, \dots, \text{id}_{\psi(w'_{m'})}) \circ \psi_{\mathbf{w}'}^{-1} \\ &\quad \circ \psi_{\mathbf{w}''} \circ \beta(j^{-1}; \text{id}_{\psi(w''_1)}, \dots, \text{id}_{\psi(w''_{m''})}) \circ \psi_{\mathbf{w}''}^{-1} \end{aligned}$$

Here the objects  $w_i, w'_i, w''_i$  are all in  $\mathbb{G}_n \subseteq L\mathbb{G}_n$ , and so we know their minimal generator decompositions are also in  $\mathbb{G}_n$ . It follows that  $d(w_i \otimes w_j) = d(w_i) \otimes d(w_j)$  for all  $i, j$ , and hence by our definition of  $\psi$  we have  $\psi(w_i \otimes w_j) = \psi(w_i) \otimes \psi(w_j)$  and also  $\psi_{\mathbf{w}_\sigma} = \text{id}$  for any permutation  $\sigma$  — and the same for  $\mathbf{w}'$  and  $\mathbf{w}''$ . Also, note that since we are working in  $\mathbb{G}_n(w_1 \otimes \dots \otimes w_m, w_1 \otimes \dots \otimes w_m)$ , all of the action morphisms in the above composite have the same source and target,  $\psi(w_1 \otimes \dots \otimes w_m)$ . This object is weakly invertible, because each of the  $w_i$  are invertible. However, the automorphisms of any weakly invertible object are isomorphic to the automorphisms of the unit object, as in the proof of ??, and hence form an abelian group, by an Eckmann-Hilton argument like in the proof of ?. Therefore we may

permute these action morphisms freely, and so

$$\begin{aligned}
& \psi(\alpha(g; \text{id}_{w_1}, \dots, \text{id}_{w_m})) \\
&= \beta(h; \text{id}_{\psi(w'_1)}, \dots, \text{id}_{\psi(w'_{m'})}) \\
&\quad \circ \beta(h^{-1}; \text{id}_{\psi(w'_1)}, \dots, \text{id}_{\psi(w'_{m'})}) \\
&\quad \circ \beta(j; \text{id}_{\psi(w''_1)}, \dots, \text{id}_{\psi(w''_{m''})}) \\
&\quad \circ \beta(j^{-1}; \text{id}_{\psi(w''_1)}, \dots, \text{id}_{\psi(w''_{m''})}) \\
&= \text{id}_{\psi(w_1) \otimes \dots \otimes \psi(w_m)} \\
&= \psi_{\mathbf{w}} \circ \beta(e_m; \text{id}_{\psi(w_1)}, \dots, \text{id}_{\psi(w_m)}) \circ \psi_{\mathbf{w}}^{-1}
\end{aligned}$$

as required.

With  $\psi$  now fully defined, notice that

$$\begin{aligned}
F(\psi) &= \{ (\psi(z_i), \psi(z_i^*), I \xrightarrow{\sim} \psi(I) \xrightarrow{\sim} \psi(z_i^*)\psi(z_i), \psi(z_i)\psi(z_i^*) \xrightarrow{\sim} \psi(I) \xrightarrow{\sim} I) \}_{i \in \{z_1, \dots, z_n\}} \\
&= \{ (x_i, x_i^*, \eta_i, \epsilon_i) \}_{i \in \{z_1, \dots, z_n\}}
\end{aligned}$$

which was our arbitrary object in  $(X_{\text{wkinv}})^n$ . Therefore,  $F$  is surjective on objects.

Next, choose an arbitrary monoidal transformation  $\theta : \psi \rightarrow \chi$  from  $\text{EGAlg}_W(L\mathbb{G}_n, X)$ . By naturality, for any  $w, w' \in \text{Ob}(L\mathbb{G}_n)$  we have that

$$\begin{array}{ccc}
\psi(w) \otimes \psi(w') & \xrightarrow{\sim} & \psi(w \otimes w') \\
\theta_w \otimes \theta_{w'} \downarrow & & \downarrow \theta_{w \otimes w'} \\
\chi(w) \otimes \chi(w') & \xrightarrow{\sim} & \chi(w \otimes w')
\end{array}$$

or equivalently,  $\theta_{w \otimes w'} = \chi_{w, w'} \circ (\theta_w \otimes \theta_{w'}) \circ \psi_{w, w'}^{-1}$ . It follows from this that the components of  $\theta$  are generated by the components on the generators of  $\text{Ob}(L\mathbb{G}_n)$ , namely  $\{(\theta_{z_i}, \theta_{z_i^*})\}_{i \in \{z_1, \dots, z_n\}}$ . But this is just  $F(\theta)$ , and thus any monoidal transformation  $\theta$  is determined uniquely by its image under  $F$ , or in other words  $F$  is faithful.

Finally, let  $\psi, \chi$  be objects of  $\text{EGAlg}_W(L\mathbb{G}_n, X)$ , and choose an arbitrary map  $\{(f_i, f_i^*)\}_{i \in \{z_1, \dots, z_n\}} : F(\psi) \rightarrow F(\chi)$  from  $(X_{\text{wkinv}})^n$ . We can use this to construct a monoidal transformation  $\theta : \psi \rightarrow \chi$  via the reverse of process we just used. Specifically, if we define

$$\theta_I = \chi_I \circ \psi_I^{-1}, \quad \theta_{z_i} = f_i, \quad \theta_{z_i^*} = f_i^*$$

then these will automatically form the naturality squares

$$\begin{array}{ccc}
\psi(z_i) \otimes \psi(z_i^*) & \xrightarrow{\psi_{z_i, z_i^*}} & \psi(I) \\
\downarrow f_i \otimes f_i^* & & \downarrow \psi_I^{-1} \\
& & I \\
& & \downarrow \chi_I \\
\chi(z_i) \otimes \chi(z_i^*) & \xrightarrow{\chi_{z_i, z_i^*}} & \chi(I)
\end{array}
\quad
\begin{array}{ccc}
\psi(z_i^*) \otimes \psi(z_i) & \xrightarrow{\psi_{z_i^*, z_i}} & \psi(I) \\
\downarrow f_i^* \otimes f_i & & \downarrow \psi_I^{-1} \\
& & I \\
& & \downarrow \chi_I \\
\chi(z_i^*) \otimes \chi(z_i) & \xrightarrow{\chi_{z_i^*, z_i}} & \chi(I)
\end{array}$$

since these are just the conditions for  $\{(f_i, f_i^*)\}_{i \in \{z_1, \dots, z_n\}}$  to be a map  $F(\psi) \rightarrow F(\chi)$  in  $(X_{\text{wkinv}})^n$ . Repeatedly applying the naturality condition  $\theta_{w \otimes w'} = \chi_{w, w'} \circ (\theta_w \otimes \theta_{w'}) \circ \psi_{w, w'}^{-1}$  will then generate all of the other components of  $\theta$ , in a way that clearly satisfies naturality. Thus we have a well-defined monoidal transformation

$\theta : \psi \rightarrow \chi$ , and applying  $F$  to it gives

$$\begin{aligned} F(\theta) &= \{ (\theta_{z_i}, \theta_{z_i}^*) \}_{i \in \{z_1, \dots, z_n\}} \\ &= \{ (f_i, f_i^*) \}_{i \in \{z_1, \dots, z_n\}}, \end{aligned}$$

our arbitrary map. Therefore  $F$  is full and, putting this together with the previous results, is an equivalence of categories.  $\square$

#### 4. THE CLASSIFICATION OF 2-GROUPS

See [1] for more detail.

##### 4.1. $n$ -groups.

**Definition 4.1.** Weak  $n$ -categories

**Definition 4.2.**  $n$ -groupoids

**Definition 4.3.**  $n$ -groups

**Example 4.4.** Examples

##### 4.2. Classifying 2-groups.

**Definition 4.5.** 2-groups

**Definition 4.6.** Coherent 2-groups

**Theorem 4.7.** *The classification of 2-groups*

##### 4.3. Group cohomology.

**Definition 4.8.** Cochain complex of groups

**Definition 4.9.** Cocycles, coboundaries, and cohomology classes

**Definition 4.10.** Group cohomology

##### 4.4. Proof of the classification theorem.

*Proof of Theorem 4.7.*  $\square$

##### 4.5. Generalizing to 3-groups.

#### 5. 2-GROUP COHOMOLOGY

See [2] and [3] for more details.

##### 5.1. Cohomology of categories.

**Definition 5.1.** Cochain complex of categories

**Definition 5.2.** Cocycles, coboundaries, and cohomology classes

##### 5.2. Symmetric 2-group cohomology.

**Definition 5.3.** Symmetric 2-group cohomology

**Proposition 5.4.** *Coherence of symmetric 2-group cohomology*

##### 5.3. Braided 2-group cohomology.

**Definition 5.5.** Braided 2-group cohomology

**Proposition 5.6.** *Coherence of braided 2-group cohomology*

#### 6. CLASSIFYING 3-GROUPS

**Proposition 6.1.** *3-group coherence data as elements of cohomology classes*

**Theorem 6.2.** *The classification of 3-groups*

**Example 6.3.** Examples

## REFERENCES

- [1] John C. Baez; Aaron D. Lauda. *Higher-Dimensional Algebra V: 2-Groups*. <https://arxiv.org/pdf/math/0307200.pdf>
- [2] K. H. Ulbrich *Group cohomology for Picard categories* Journal of Algebra, 91 (1984), pp. 464-498 [http://dx.doi.org/10.1016/0021-8693\(84\)90114-5](http://dx.doi.org/10.1016/0021-8693(84)90114-5)
- [3] K. H. Ulbrich *Kohrenz in Kategorien mit Gruppenstruktur* Journal of Algebra, 72 (1981), pp. 279-295 [http://dx.doi.org/10.1016/0021-8693\(81\)90295-7](http://dx.doi.org/10.1016/0021-8693(81)90295-7)
- [4] Peter Selinger. *A survey of graphical languages for monoidal categories*. <http://www.mscs.dal.ca/~selinger/papers/graphical.pdf>
- [5] Nick Gurski. *Operads, tensor products, and the categorical Borel construction*. arXiv:1508.04050 [math.CT].
- [6] Tom Leinster. *Basic Category Theory* Cambridge Studies in Advanced Mathematics, Vol. 143, Cambridge University Press, Cambridge, 2014. <https://arxiv.org/pdf/1612.09375v1.pdf>
- [7] Eckmann, B.; Hilton, P. J. *Group-like structures in general categories. I. Multiplications and comultiplications* Mathematische Annalen, 145 (3), pp. 227-255