

# Monads and their applications

Dr. Daniel Schächli's course lecture notes

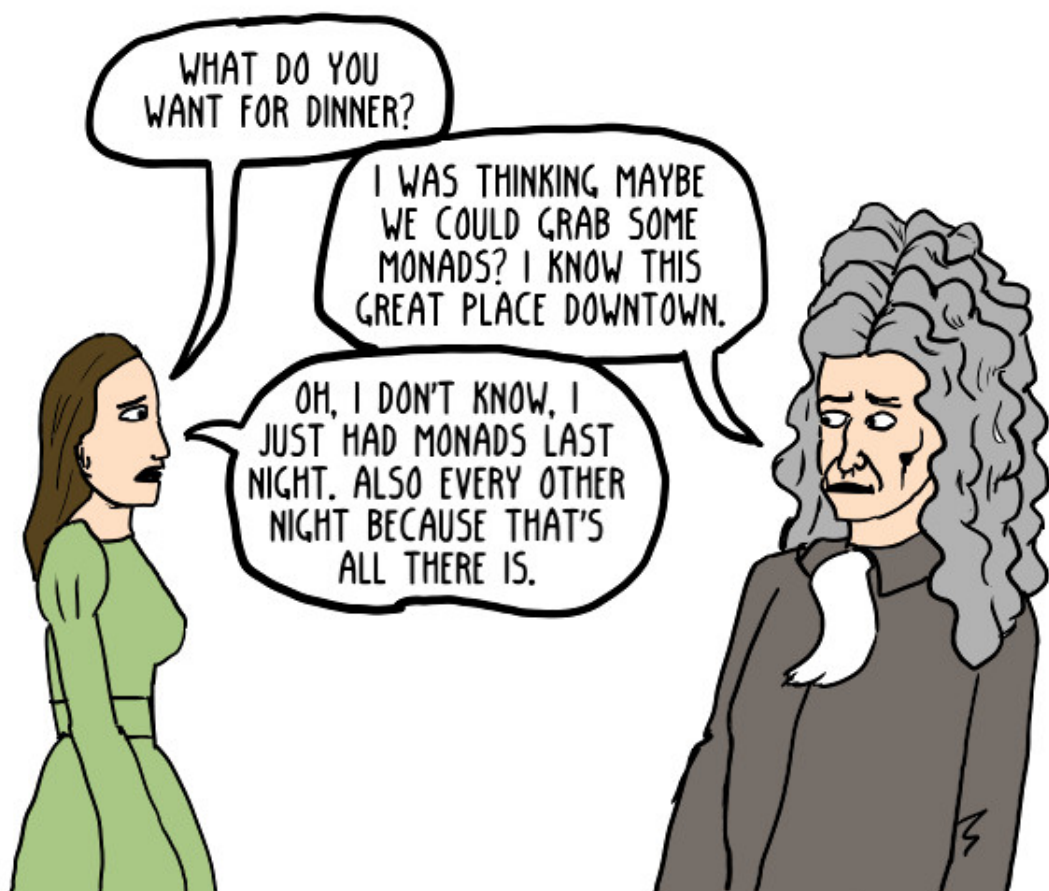
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# Categorical preliminaries

**Definition 0.0.1** (Categories). A *category*  $\mathcal{C}$  consists of:

1. a collection of objects  $\text{Ob}(\mathcal{C})$ ;
2. a collection of arrows  $\text{Ar}(\mathcal{C})$ ;
3. two maps  $\text{dom}, \text{cod}: \text{Ar}(\mathcal{C}) \rightarrow \text{Ob}(\mathcal{C})$ ;
4. a map  $\text{id}_-: \text{Ob}(\mathcal{C}) \rightarrow \text{Ar}(\mathcal{C})$  with  $\text{dom}(\text{id}_c) = c = \text{cod}(\text{id}_c)$ ;
5. for every  $f, g \in \text{Ar}(\mathcal{C})$  such that  $\text{cod}(f) = \text{dom}(g)$  a unique composite morphism  $gf$  such that  $\text{cod}(gf) = \text{cod}(g)$ ,  $\text{dom}(gf) = \text{dom}(f)$ .

This data has to satisfy the following axioms

1. given  $f \in \text{Ar}(\mathcal{C})$ ,  $c = \text{dom}(f)$  and  $c' = \text{cod}(f)$ ,  $\text{id}_{c'} f = f = f \text{id}_c$ , that is the composition is unital;
2. given a composable triple  $f, g, h \in \text{Ar}(\mathcal{C})$ ,  $h(gf) = (hg)f$ , that is the composition is associative.

An arrow  $f$  such that  $c = \text{dom}(f)$  and  $c' = \text{cod}(f)$  is denoted  $f: c \rightarrow c'$ .

**Definition 0.0.2** (Functors).

**Definition 0.0.3** (Full functors, faithful functor).

**Definition 0.0.4** (Natural transformations).

**Definition 0.0.5** (Equivalent functors).

**Definition 0.0.6** (Representable Functors).

**Definition 0.0.7** (Whiskering).

**Definition 0.0.8** (Horizontal and vertical composition of nat.transf.).

**Definition 0.0.9** (adjunctions).

**Lemma 0.0.10** (Yoneda).

*Proof.*

□

We will denote by  $\mathcal{Y}$  (the kana for “Yo”) the Yoneda embedding  $\mathcal{C} \hookrightarrow \mathbf{Set}^{\mathcal{C}^{\text{op}}}$ .

# 1 Monads and adjunctions

Throughout mathematics we encounter structures defined by some action morphisms. Here we give some examples.

- Example 1.0.1.**
1. Given a group  $G$ , we may consider a  $G$ -set  $X$  described by an action map  $G \times X \rightarrow X$ .
  2. Given an abelian group  $M$  and a ring  $R$ , we can get an  $R$ -module  $M$  by fixing a group homomorphism  $R \otimes_{\mathbb{Z}} M \rightarrow M$ .
  3. Given a monoid  $M$  in **Set**, we get a map  $\prod_{k=1}^n M \rightarrow M$ ,  $(m_1, \dots, m_n) \mapsto ((\dots((m_1 m_2) m_3) \dots) m_{n-1}) m_n$ . This induces an action map from  $WM = \prod_{n \in \mathbb{N}} \prod_{k=1}^n M$ , the set of words on  $M$ , to  $M$ .
  4. Given a set  $X$ , let  $\mathcal{U}X$  be the set of ultrafilters on it. Any compact Hausdorff topology on  $X$  allows us to see each ultrafilter as a system of neighborhoods of a unique point in  $X$ , hence it gives us a unique map  $\mathcal{U}X \rightarrow X$  sending each ultrafilter to the respective point.
  5. Given a directed graph  $D = (V, E, E \xrightarrow{s} V, E \xrightarrow{t} V)$ , we can create its free category  $FD$ , where the objects are the vertices and  $FD(v, w) = \{\text{finite paths } v \rightarrow \dots \rightarrow w\}$ . We set  $\text{id}_v$  to be the path of length 0, while composition is just the concatenation of paths.

In particular, if  $D$  is the directed graph with  $V = \{0, \dots, n\}$  and an edge  $j \rightarrow k$  if and only if  $k = j + 1$ , we have  $FD \cong [n]$ .

If  $D = \{*\}$  and  $E = \{* \rightarrow *\}$ , then  $FD(*, *) \cong \mathbb{N}$ .

Given a small category  $\mathcal{C}$ , we may consider the underlying directed graph  $U\mathcal{C} = D$  with  $V = \text{Ob}(\mathcal{C})$ ,  $E = \text{Ar}(\mathcal{C})$ ,  $s = \text{dom}$  and  $t = \text{cod}$ . We get then an action map  $UFU\mathcal{C} \rightarrow U\mathcal{C}$  sending a finite path to its composite. This map is a morphism of directed graphs.

Notice that we always have a category  $\mathcal{C}$  and some functor  $T: \mathcal{C} \rightarrow \mathcal{C}$  with an action map  $T\mathcal{C} \rightarrow \mathcal{C}$ . How can we see all of these examples as specific instances of a general phenomenon?

**Definition 1.0.2.** A *monad* on a category  $\mathcal{C}$  is a triple  $(T, \mu, \eta)$  where  $T: \mathcal{C} \rightarrow \mathcal{C}$  is a functor, while  $\mu: T^2 \Rightarrow T$  and  $\eta: \text{id}_{\mathcal{C}} \Rightarrow T$  are natural transformations such that the diagrams

$$\begin{array}{ccc} T^3 & \xrightarrow{T\mu} & T^2 \\ \mu T \downarrow & & \downarrow \mu \\ T^2 & \xrightarrow{\mu} & T \end{array} \quad \begin{array}{ccc} T & \xrightarrow{\eta T} & T^2 & \xleftarrow{T\eta} & T \\ & \searrow & \downarrow \mu & \swarrow & \\ & & T & & \end{array}$$

commute.  $\mu$  is called the *multiplicative map*, while  $\eta$  is the *unit* of  $T$ .

The commutativity of the first diagram is equivalent to stating that the following two diagrams are equal.

$$\begin{array}{ccccc} & & \mathcal{C} & \xrightarrow{T} & \mathcal{C} \\ & \nearrow T & \downarrow \mu & \searrow T & \\ \mathcal{C} & & & & \mathcal{C} \\ & \searrow T & \downarrow \mu & \swarrow T & \\ & & \mathcal{C} & \xrightarrow{T} & \mathcal{C} \end{array} = \begin{array}{ccccc} & & \mathcal{C} & \xrightarrow{T} & \mathcal{C} \\ & \nearrow T & \downarrow \mu & \searrow T & \\ \mathcal{C} & & & & \mathcal{C} \\ & \searrow T & \downarrow \mu & \swarrow T & \\ & & \mathcal{C} & \xrightarrow{T} & \mathcal{C} \end{array}$$

On the other hand, the second diagram can be rephrased as follows:

$$\begin{array}{c} \mathcal{C} \\ \downarrow \eta \quad \downarrow \mu \\ \mathcal{C} \xrightarrow{T} \mathcal{C} \end{array} \quad = \quad T \left( \begin{array}{c} \mathcal{C} \\ \downarrow \mu \\ \mathcal{C} \end{array} \right) T \quad = \quad \begin{array}{c} \mathcal{C} \\ \downarrow \mu \quad \downarrow \eta \\ \mathcal{C} \xrightarrow{T} \mathcal{C} \end{array}$$

A monad naturally defines other algebraic structures, which we now introduce.

**Definition 1.0.3.** Given a monad  $(T, \mu, \eta)$ , a  $T$ -algebra or  $T$ -module is a pair  $(a, \alpha)$ , where  $a \in \text{Ob}(\mathcal{C})$  and  $\alpha: Ta \rightarrow a$  is such that the diagrams

$$\begin{array}{ccc} T^2a & \xrightarrow{T\alpha} & Ta \\ \mu_a \downarrow & & \downarrow \alpha \\ Ta & \xrightarrow{\alpha} & a \end{array} \quad \begin{array}{ccc} a & \xrightarrow{\eta_a} & Ta \\ & \searrow & \downarrow \alpha \\ & & a \end{array}$$

commute.

**Definition 1.0.4.** A morphism of  $T$ -algebras  $(a, \alpha) \rightarrow (b, \beta)$  is a morphism  $f: a \rightarrow b$  such that the diagram

$$\begin{array}{ccc} Ta & \xrightarrow{Tf} & Tb \\ \alpha \downarrow & & \downarrow \beta \\ a & \xrightarrow{f} & b \end{array}$$

commutes.

$T$ -algebras form a category  $T\text{-Alg}$ , which has a natural forgetful functor  $U^T: T\text{-Alg} \rightarrow \mathcal{C}$ .

We now show how to recover the examples previously given with this language.

**Example 1.0.5.** 1.

$$\begin{aligned} T &= G \times -: \mathbf{Set} \rightarrow \mathbf{Set} \\ \mu_A &: G \times (G \times A) \rightarrow G \times A \\ &\quad (g, (h, a)) \mapsto (gh, a) \\ \eta_A &: A \rightarrow G \times A \\ &\quad a \mapsto (e, a) \end{aligned}$$

is a monad and  $(A, \alpha)$  is a  $T$ -algebra if and only if  $A$  is a  $G$ -set. It follows that  $T\text{-Alg} \cong G\text{-Set}$ .

2. Given a ring  $R$ ,  $T = R \otimes_{\mathbb{Z}} -: \mathbf{Ab} \rightarrow \mathbf{Ab}$  is a monad when considered with the following natural transformations:

$$\begin{aligned} \mu_- &: R \otimes_{\mathbb{Z}} (R \otimes_{\mathbb{Z}} -) \cong (R \otimes_{\mathbb{Z}} R) \otimes_{\mathbb{Z}} - \Rightarrow R \otimes_{\mathbb{Z}} - \\ \eta_- &: - \cong \mathbb{Z} \otimes_{\mathbb{Z}} - \Rightarrow R \otimes_{\mathbb{Z}} - \end{aligned}$$

We have that  $(R \otimes_{\mathbb{Z}} -)\text{-Alg} \cong \mathbf{Mod}_R$ .

3. Consider  $W: \mathbf{Set} \rightarrow \mathbf{Set}$  given by  $WX = \coprod_{n \in \mathbb{N}} \coprod_{k=1}^n X$ . Multiplication  $\mu_X: WWX \rightarrow WX$  is given by concatenation of words, while the unit  $\eta_X: X \rightarrow WX$  is just  $x \mapsto (x)$ . With this,  $W\text{-Alg} \cong \mathbf{Mon}(\mathbf{Set})$ .

4. The functor  $\mathcal{U}$  defined in Example ??, equipped with suitable natural transformations, is a monad on **Set** and  $\mathcal{U}\text{-Alg} \cong \mathbf{CHTop}$ , the category of compact Hausdorff spaces.
5. The free-forgetful adjunction  $F \dashv U$  between categories and directed graphs induces a monad on the latter, with  $UF\text{-Alg} \cong \mathbf{Cat}$ .

There is a deep connection between monads and adjunctions, which we now make explicit.

**Proposition 1.0.6.** The functor  $U^T: T\text{-Alg} \rightarrow \mathcal{C}$  has a left adjoint  $F^T: \mathcal{C} \rightarrow T\text{-Alg}$  such that  $F^T c = (Tc, \mu_c)$ ,  $F^T f = Tf: (Tc, \mu_c) \rightarrow (Td, \mu_d)$  and  $U^T F^T = T$ . Furthermore, the unit of this adjunction is given by  $\eta$  and the counit has components  $\epsilon_{(a, \alpha)} = \alpha: (Ta, \mu_a) \rightarrow (a, \alpha)$ .

*Proof.* (i) To show that  $(Tc, \mu_c)$  is a  $T$ -algebra we need the following diagrams to be commutative.

$$\begin{array}{ccc} T^3 c & \xrightarrow{T\mu_c} & T^2 c \\ \mu_{Tc} \downarrow & & \downarrow \mu_c \\ T^2 c & \xrightarrow{\mu_c} & Tc \end{array} \quad \begin{array}{ccc} Tc & \xrightarrow{\eta_{Tc}} & T^2 c \\ & \searrow & \downarrow \mu_c \\ & & Tc \end{array}$$

These are exactly the associativity and one of the unit laws for  $(T, \mu, \eta)$ .

- (ii) For every  $f: c \rightarrow c'$ ,  $Tf$  is a morphism of algebras  $(Tc, \mu_c) \rightarrow (Tc', \mu_{c'})$  because the diagram

$$\begin{array}{ccc} T^2 c & \xrightarrow{T^2 f} & T^2 c' \\ \mu_c \downarrow & & \downarrow \mu_{c'} \\ Tc & \xrightarrow{Tf} & Tc' \end{array}$$

is commutative by naturality of  $\mu$ , hence  $F^T$  is defined on morphisms. It is a functor by functoriality of  $T$ .

- (iii) The unit is natural by assumption. We claim that  $\epsilon_{(a, \alpha)} = \alpha$  is a morphism of algebras

$$F^T U^T(a, \alpha) = F^T a = (Ta, \mu_a) \rightarrow \text{id}_{T\text{-Alg}}(a, \alpha) = (a, \alpha)$$

and  $\epsilon$  is a natural transformation  $F^T U^T \Rightarrow \text{id}_{T\text{-Alg}}$ . Let's check it. We know that  $\alpha$  is a morphism of algebras if and only if

$$\begin{array}{ccc} T^2 a & \xrightarrow{T\alpha} & Ta \\ \mu_a \downarrow & & \downarrow \alpha \\ Ta & \xrightarrow{\alpha} & a \end{array}$$

is commutative, but this is one of the two  $T$ -algebra axioms! Moreover, to prove that  $\epsilon$  is natural, we need to show that

$$\begin{array}{ccc} (Ta, \mu_a) & \xrightarrow{\alpha = \epsilon_{(a, \alpha)}} & (a, \alpha) \\ Tf \downarrow & & \downarrow f \\ (Tb, \mu_b) & \xrightarrow{\beta = \epsilon_{(b, \beta)}} & (b, \beta) \end{array}$$

is commutative, but this is the axiom for  $f$  to be a morphism of  $T$ -algebras!

- (iv) It remains to check the two triangular identities  $\epsilon F^T \cdot F^T \eta = \text{id}_{F^T}$  and  $U^T \epsilon \cdot \eta U^T = \text{id}_{U^T}$ . These are to be checked on the components at  $c$  and  $(a, \alpha)$ , respectively.

$$\begin{array}{ccc}
 (Tc, \mu_c) & \xrightarrow{T\eta_c} & (T^2c, \mu_{Tc}) \\
 \parallel & & \downarrow \mu_{Tc} \\
 & & (Tc, \mu_c)
 \end{array}
 \qquad
 \begin{array}{ccc}
 a & \xrightarrow{\eta_a} & Ta \\
 \parallel & & \downarrow \alpha \\
 & & a
 \end{array}$$

The commutativity of these diagrams is ensured by the second unit law for a monad and the unit law for the  $T$ -algebra  $(a, \alpha)$  respectively.  $\square$

**Definition 1.0.7.** Given a monad  $(T, \mu, \eta)$ ,  $T$ -algebras of the form  $(Tc, \mu_c)$  are called *free  $T$ -algebras*.

Thanks to the proposition above we can prove that, given a monad  $T$ , we can always find an adjunction that generates it. Actually, the converse holds too.

**Proposition 1.0.8.** If  $U: \mathcal{D} \rightarrow \mathcal{C}$  has a left adjoint  $F$  with unit  $\eta$  and counit  $\epsilon$ , then  $(UF, U\epsilon F, \eta)$  is a monad on  $\mathcal{C}$ . Also, if  $(T, \mu, \eta)$  is a monad on  $\mathcal{C}$ , then  $(U^T F^T, U^T \epsilon F^T, \eta) = (T, \mu, \eta)$ .

*Proof.* Let us check the axioms. First of all, associativity holds due to the naturality of the vertical natural transformation  $U\epsilon: UFU \Rightarrow U$ .

$$\begin{array}{ccc}
 UFUFUF & \xrightarrow{UFU\epsilon F} & UFUF \\
 \downarrow U\epsilon FUF & & \downarrow U\epsilon F \\
 UFUF & \xrightarrow{U\epsilon F} & UF
 \end{array}$$

One could also write down the 2-cells and check that they are equal by making use of the explicit definition of the horizontal composition.

On the other end, the unit laws hold by the triangular identities of the adjunction.

$$\begin{array}{ccccc}
 UF & \xrightarrow{\eta UF} & UFUF & \xleftarrow{UF\eta} & UF \\
 & \searrow & \downarrow U\epsilon F & \swarrow & \\
 & & UF & & 
 \end{array}$$

$\square$

**Example 1.0.9.** 1. Let us consider the adjunction  $U: \mathbf{Top} \rightleftarrows \mathbf{Set}: \text{Disc} =: F$ , whose left adjoint assigns to every set  $X$  the discrete topological space  $FX = (X, 2^X)$ . It's immediate to see that  $UF X = X$ , hence  $UF = \text{id}_{\mathbf{Set}}$ . How many natural transformations  $\text{id}_{\mathbf{Set}} = UF \xrightarrow{\alpha} UF = \text{id}_{\mathbf{Set}}$  are there? We know that  $\text{id}_{\mathbf{Set}} \cong \text{Hom}(*, -)$ , so  $\text{Nat}(\text{id}_{\mathbf{Set}}, \text{id}_{\mathbf{Set}}) \cong \text{Nat}(\text{Hom}(*, -), \text{Hom}(*, -)) \cong \text{Hom}(*, *) = \{\text{id}_*\}$  by Yoneda, hence  $\alpha = \text{id}_{\mathbf{Set}}$  necessarily. It follows that  $(UF, U\epsilon F, \eta) = (\text{id}_{\mathbf{Set}}, \text{id}, \text{id})$ .

2. If  $S$  is a set, then  $\mathbf{Set}(S, -): \mathbf{Set} \rightarrow \mathbf{Set}$  is right adjoint to  $S \times -: \mathbf{Set} \rightarrow \mathbf{Set}$ , so we get a monad  $X \mapsto \mathbf{Set}(S, S \times X)$ . This is called the *state monad* and it is important in Computer Science.



## 1.1 $T$ -actions and monadic functors

Given an adjunction  $F: \mathcal{C} \xrightleftharpoons[\perp]{} \mathcal{D}: U$ , there is always a comparison morphism  $\mathcal{D} \xrightarrow{\bar{U}} UF\text{-Alg}$  such that

$$\begin{array}{ccc} \mathcal{D} & \xrightarrow{\bar{U}} & UF\text{-Alg} \\ & \searrow U & \swarrow U^{UF} \\ & \mathcal{C} & \end{array}$$

commutes. We set  $\bar{U}d = (Ud, UFUd \xrightarrow{U\epsilon_d} Ud) = (Ud, U\epsilon_d)$ . More generally, for a given functor  $G: \mathcal{D} \rightarrow \mathcal{C}$  we can ask what do we need to get a lift  $\bar{G}: \mathcal{D} \rightarrow T\text{-Alg}$ . To get there, we will need a few more definitions.

Just like a monad  $(T, \mu, \eta)$  defines a category  $T\text{-Alg}$ , it also allows us to construct another category from functors  $\mathcal{D} \rightarrow \mathcal{C}$ .

**Definition 1.1.1.** Given a monad  $(T, \mu, \eta)$  on a category  $\mathcal{C}$  and fixed another category  $\mathcal{D}$ , a  $T$ -action on a functor  $G: \mathcal{D} \rightarrow \mathcal{C}$  is a natural transformation  $\gamma: TG \Rightarrow G$  such that the diagrams

$$\begin{array}{ccc} T^2G & \xrightarrow{T\gamma} & TG \\ \mu G \Downarrow & & \Downarrow \gamma \\ TG & \xrightarrow{\gamma} & G \end{array} \quad \begin{array}{ccc} G & \xrightarrow{\eta G} & TG \\ & \searrow & \Downarrow \gamma \\ & & G \end{array}$$

commute.

A *morphism of  $T$ -actions*  $(G, \gamma) \xrightarrow{\varphi} (K, \kappa)$  is a natural transformation  $\varphi: G \Rightarrow K$  such that

$$\begin{array}{ccc} TG & \xrightarrow{T\varphi} & TK \\ \gamma \Downarrow & & \Downarrow \kappa \\ G & \xrightarrow{\varphi} & K \end{array}$$

commutes.

Up to size issues,  $T$ -actions and their morphisms assemble into a category  $T\text{-Act}(\mathcal{D})$ .

**Example 1.1.2.** 1. The functor  $U^T: T\text{-Alg} \rightarrow \mathcal{C}$  has a  $T$ -action given by  $\alpha: TU^T \Rightarrow U^T$ , where  $\alpha_{(b, \beta)} := \beta: Tb \rightarrow b$ .

2. Given an adjunction  $F: \mathcal{C} \xrightleftharpoons[\perp]{} \mathcal{D}: U$  with unit  $\eta: \text{id}_{\mathcal{C}} \Rightarrow UF$  and counit  $\epsilon: FU \Rightarrow \text{id}_{\mathcal{D}}$ , we get a monad on  $(UF, U\epsilon F, \eta)$  on  $\mathcal{C}$ . We have then a  $UF$ -action  $U\epsilon: UFU \Rightarrow U$ , where the axioms follow from the triangular identities and the naturality of  $U\epsilon$ .

**Proposition 1.1.3.**  $(U^T, \alpha)$  is the universal  $T$ -action, that is for any category  $\mathcal{D}$  the functor  $\mathbf{Cat}(\mathcal{D}, T\text{-Alg}) \rightarrow T\text{-Act}(\mathcal{D})$  sending  $G$  to  $(U^T G, \alpha G)$  and  $\beta: G \Rightarrow H$  to  $U^T \beta: (U^T G, \alpha G) \Rightarrow (U^T H, \alpha H)$  is an isomorphism of categories.

*Proof.* In other words, for every  $T$ -action  $(G, \gamma)$  there exists a unique lift  $\bar{G}: \mathcal{D} \rightarrow T\text{-Alg}$  such that  $(U^T \bar{G}, \alpha \bar{G}) = (G, \gamma)$  and for every  $\phi: (G, \gamma) \Rightarrow (K, \kappa)$  there is a unique  $\bar{\phi}: \bar{G} \Rightarrow \bar{K}$  with  $U^T \bar{\phi} = \phi$ .

It is enough to set  $\overline{G}d := (Gd, \gamma_d)$  on objects,  $\overline{G}f := Gf$  on morphisms,  $\overline{\phi}_d := \phi_d$  and check the axioms.

$$\begin{array}{ccc} \mathcal{D} & \xrightarrow{\exists! \overline{G}} & T\text{-Alg} \\ & \searrow G & \downarrow U^T \\ & & \mathcal{C} \end{array}$$

□

**Remark 1.1.4.** Following the construction in this proof, from the last example we get the comparison functor for the adjunction  $F \dashv U$ . In particular,  $\overline{U}d = (Ud, U\epsilon_d)$ . Furthermore,  $U: \mathbf{Top} \rightarrow \mathbf{Set}$  factors through identities.

We conclude this section by introducing the concept of *monadic functor*.

**Definition 1.1.5.** An adjunction  $F: \mathcal{C} \xrightarrow{\perp} \mathcal{D}: U$  is said to be a *monadic adjunction* if the canonical comparison functor  $\overline{G}: \mathcal{D} \rightarrow GF\text{-Alg}$  is an equivalence of categories. A functor  $G$  is said to be monadic if it admits a left adjoint  $F$  such that the pair defines a monadic adjunction.

We want to give a characterization of such functors, which we will have once we prove Beck's theorem. For the moment, notice that  $U^T$  is faithful by construction, hence  $U$  must be faithful, but more is true.

**Lemma 1.1.6.** The functor  $U^T$  is conservative, that is if  $U^T f$  is an isomorphism then  $f$  is an isomorphism of  $T$ -algebras.

*Proof.* Suppose that  $g$  is the inverse of  $f: a \rightarrow b$  and  $f$  induces a morphism  $(a, \alpha) \rightarrow (b, \beta)$ . We only need to prove that in the diagram

$$\begin{array}{ccccc} Tb & \xrightarrow{Tg} & Ta & \xrightarrow{Tf} & Tb \\ \beta \downarrow & & \alpha \downarrow & & \downarrow \beta \\ b & \xrightarrow{g} & a & \xrightarrow{f} & b \end{array}$$

the square on the left commutes, that is  $g \cdot \beta = \alpha \cdot Tg$ . We see that  $f \cdot g \cdot \beta = \beta$  and  $f \cdot \alpha \cdot Tg = \beta \cdot Tf \cdot Tg = \beta \cdot T(f \cdot g) = \beta \cdot T\text{id}_b = \beta$ , hence the thesis. □

**Remark 1.1.7.** Notice that the forgetful functor  $U: \mathbf{Top} \rightarrow \mathbf{Set}$  can't be monadic since it does not reflect isomorphisms. However, if we restrict it to the full subcategory of  $\mathbf{Top}$  spanned by compact Hausdorff spaces we indeed obtain a monadic functor.

## 1.2 Limits and colimits in the category of $T$ -algebras

We have shown that the forgetful functor  $U^T: T\text{-Alg} \rightarrow \mathcal{C}$  is a right adjoint and as such it preserves limits, however we have another result concerning them.

**Proposition 1.2.1.** For any monad  $(T, \mu, \eta)$  on  $\mathcal{C}$ , the forgetful functor  $U^T: T\text{-Alg} \rightarrow \mathcal{C}$  strictly creates limits.

*Proof.* This statement means that, for any diagram  $D: \mathcal{J} \rightarrow T\text{-Alg}$  such that  $U^T D: \mathcal{J} \rightarrow \mathcal{C}$  has a limit  $(l, \kappa_i)$  in  $\mathcal{C}$ , there is a unique  $T$ -algebra structure  $\lambda: Tl \rightarrow l$  such that  $\kappa_i$  is a morphism of  $T$ -algebras for all  $i \in \mathcal{J}$  and this makes  $((l, \lambda), \kappa_i)$  into a limit of  $D$ .

Now we begin the proof.

First of all, remember that  $D\phi: D_i \rightarrow D_j$  is a morphism of  $T$ -algebras for all  $\phi: i \rightarrow j$  by assumption, hence the morphisms  $\delta_i \cdot T\kappa_i: Tl \rightarrow D_i$  define a cone over  $D$ , where  $\delta_i$  is the  $T$ -algebra structure on  $D_i$  (notice that here we are abusing the notation since our cone is in  $\mathcal{C}$  and over  $U^T D$ ). By the universal property of the limit, there is a unique morphism  $\lambda: Tl \rightarrow l$  making the following diagram commute for all  $i$ .

$$\begin{array}{ccc} Tl & \xrightarrow{T\kappa_i} & TD_i \\ \lambda \downarrow & & \downarrow \delta_i \\ l & \xrightarrow{\kappa_i} & D_i \end{array}$$

This tells us that, if the limit  $((l, \lambda), \kappa_i)$  of  $D$  exists, it is unique. We have to check that  $(l, \lambda)$  is a  $T$ -algebra.

Notice that for all  $i$  all of the faces of the following diagrams, except for possibly the top ones, commute.

The left diagram is a complex commutative diagram with nodes  $T^2l$ ,  $Tl$ ,  $T^2D_i$ ,  $TD_i$ , and  $l$ . The nodes are arranged in a 3D-like structure. The top face is a triangle with nodes  $T^2l$ ,  $Tl$ , and  $l$ . The bottom face is a triangle with nodes  $T^2D_i$ ,  $TD_i$ , and  $l$ . The left face is a square with nodes  $T^2l$ ,  $Tl$ ,  $T^2D_i$ , and  $TD_i$ . The right face is a square with nodes  $Tl$ ,  $l$ ,  $TD_i$ , and  $D_i$ . The front face is a square with nodes  $T^2l$ ,  $T^2D_i$ ,  $TD_i$ , and  $l$ . The back face is a square with nodes  $Tl$ ,  $TD_i$ ,  $D_i$ , and  $l$ . The top face is a triangle with nodes  $T^2l$ ,  $Tl$ , and  $l$ . The bottom face is a triangle with nodes  $T^2D_i$ ,  $TD_i$ , and  $l$ . The left face is a square with nodes  $T^2l$ ,  $Tl$ ,  $T^2D_i$ , and  $TD_i$ . The right face is a square with nodes  $Tl$ ,  $l$ ,  $TD_i$ , and  $D_i$ . The front face is a square with nodes  $T^2l$ ,  $T^2D_i$ ,  $TD_i$ , and  $l$ . The back face is a square with nodes  $Tl$ ,  $TD_i$ ,  $D_i$ , and  $l$ . The top face is a triangle with nodes  $T^2l$ ,  $Tl$ , and  $l$ . The bottom face is a triangle with nodes  $T^2D_i$ ,  $TD_i$ , and  $l$ . The left face is a square with nodes  $T^2l$ ,  $Tl$ ,  $T^2D_i$ , and  $TD_i$ . The right face is a square with nodes  $Tl$ ,  $l$ ,  $TD_i$ , and  $D_i$ . The front face is a square with nodes  $T^2l$ ,  $T^2D_i$ ,  $TD_i$ , and  $l$ . The back face is a square with nodes  $Tl$ ,  $TD_i$ ,  $D_i$ , and  $l$ .

The right diagram is a commutative diagram with nodes  $l$ ,  $Tl$ ,  $TD_i$ , and  $D_i$ . The top face is a triangle with nodes  $l$ ,  $Tl$ , and  $l$ . The bottom face is a triangle with nodes  $l$ ,  $TD_i$ , and  $D_i$ . The left face is a square with nodes  $l$ ,  $Tl$ ,  $TD_i$ , and  $D_i$ . The right face is a square with nodes  $Tl$ ,  $l$ ,  $TD_i$ , and  $D_i$ . The front face is a square with nodes  $l$ ,  $TD_i$ ,  $D_i$ , and  $l$ . The back face is a square with nodes  $Tl$ ,  $TD_i$ ,  $D_i$ , and  $l$ . The top face is a triangle with nodes  $l$ ,  $Tl$ , and  $l$ . The bottom face is a triangle with nodes  $l$ ,  $TD_i$ , and  $D_i$ . The left face is a square with nodes  $l$ ,  $Tl$ ,  $TD_i$ , and  $D_i$ . The right face is a square with nodes  $Tl$ ,  $l$ ,  $TD_i$ , and  $D_i$ . The front face is a square with nodes  $l$ ,  $TD_i$ ,  $D_i$ , and  $l$ . The back face is a square with nodes  $Tl$ ,  $TD_i$ ,  $D_i$ , and  $l$ .

Since the  $\kappa_i$  are jointly monic, the upper face commutes and therefore  $(l, \lambda)$  is a  $T$ -algebra. It remains to check that  $((l, \lambda), \kappa_i)$  factors every other cone over  $D$ .

Let  $\gamma_i: (x, \zeta) \rightarrow (D_i, \delta_i)$  be a cone over  $D$ . Then, there is a unique  $f: x \rightarrow l$  in  $\mathcal{C}$  such that  $\kappa_i f = \gamma_i$ . We only have to show that  $f$  is a morphism of  $T$ -algebras  $(x, \zeta) \rightarrow (l, \lambda)$ .

Consider the following diagram and notice that the outer square, the one on the right and the two triangles commute, hence the square on the left commutes as well since the  $\kappa_i$  are jointly monic.

$$\begin{array}{ccccc}
& & T\gamma_i & & \\
& \nearrow & & \searrow & \\
Tx & \xrightarrow{Tf} & Tl & \xrightarrow{T\kappa_i} & TD_i \\
\downarrow \zeta & & \downarrow \lambda & & \downarrow \delta_i \\
x & \xrightarrow{f} & l & \xrightarrow{\kappa_i} & D_i \\
& \searrow & & \nearrow & \\
& & \gamma_i & & 
\end{array}$$

□

A similar statement holds for colimits.

**Proposition 1.2.2.** Given a monad  $(T, \mu, \eta)$  on  $\mathcal{C}$ , the forgetful functor  $U^T: T\text{-Alg} \rightarrow \mathcal{C}$  strictly creates any colimit preserved by both  $T$  and  $T^2$ .

*Proof.* Similarly to the dual situation, this means that for any diagram  $D: \mathcal{J} \rightarrow T\text{-Alg}$  such that  $U^T D: \mathcal{J} \rightarrow \mathcal{C}$  has a colimit  $(c, \kappa_i)$  preserved by both  $T$  and  $T^2$  there is a unique  $T$ -algebra structure  $\lambda: Tc \rightarrow c$  such that  $\kappa_i$  is a morphism of  $T$ -algebras for all  $i \in \mathcal{J}$ . This makes  $((c, \lambda), \kappa_i)$  into a colimit of  $D$ .

The proof is essentially dual to the one given earlier, in the sense that we find again a unique  $\lambda: Tc \rightarrow c$  using the universal property of the colimit  $(Tc, T\kappa_i)$  of  $TU^T D$ .

$$\begin{array}{ccc}
TD_i & \xrightarrow{T\kappa_i} & Tc \\
\delta_i \downarrow & & \downarrow \lambda \\
D_i & \xrightarrow{\kappa_i} & c
\end{array}$$

To check that  $(c, \lambda)$  is an algebra we use the universal property of  $(T^2c, T^2\kappa_i)$ , for  $\mu$ , and the one of  $(c, \kappa_i)$ , for  $\eta$ . □

**Remark 1.2.3.** • The same statements hold for monadic functors, except for the fact that they might not create limits and colimits strictly since they are just equivalent to a  $U^T$ .

- If  $T$  is a monad on a complete category  $\mathcal{C}$ , then  $T\text{-Alg}$  is complete. If  $\mathcal{C}$  is cocomplete and  $T$  is cocontinuous, then  $T\text{-Alg}$  is cocomplete.

**Example 1.2.4.** Let  $\mathcal{C}$  be a small category. There is a cocontinuous monad on the category of  $\text{Ob}(\mathcal{C})$ -indexed collections of sets whose category of algebras is the functor category  $[\mathcal{C}, \mathbf{Set}]$ . The underlying endofunctor of this monad is defined as

$$\begin{aligned}
T: [\text{Ob}(\mathcal{C}), \mathbf{Set}] &\rightarrow [\text{Ob}(\mathcal{C}), \mathbf{Set}] \\
(X_c)_{c \in \mathcal{C}} &\mapsto \left( \coprod_{d \in \mathcal{C}} \mathcal{C}(d, c) \times X_d \right)_{c \in \mathcal{C}}
\end{aligned}$$

Since  $[\text{Ob}(\mathcal{C}), \mathbf{Set}]$  is complete and cocomplete, so is  $[\mathcal{C}, \mathbf{Set}]$  (with limits and colimits computed pointwise).

### 1.3 Beck's monadicity theorem

The final ingredient we need to give a characterization of monadic functors is the observation that  $T$ -algebras admit canonical presentations using free algebras.

**Example 1.3.1.** Pick an epimorphism  $F \twoheadrightarrow G$  in the category of groups **Grp**, where  $F$  is a free group. The kernel of this homomorphism defines a (normal) subgroup  $K$  of  $F$ , giving rise to the sequence  $K \twoheadrightarrow F \twoheadrightarrow G$ . We can take another epimorphism  $F' \twoheadrightarrow K$ , with  $F'$  again a free group, which presents  $G$  as the cokernel of some morphism  $F' \rightarrow F$  between free groups. This argument applies to rings, algebras, etc.

It is natural to ask if we can do this systematically for general  $T$ -algebras. Given  $(a, \alpha)$  in  $T\text{-Alg}$ , we have  $F^T U^T(a, \alpha) \rightarrow (a, \alpha)$ , that is  $(Ta, \mu_a) \xrightarrow{\alpha} (a, \alpha)$ . A candidate<sup>1</sup> for  $F'$  would be  $F^T U^T(Ta, \mu_a) = (T^2a, \mu_{Ta})$ . Notice that

$$(T^2a, \mu_{Ta}) \xrightarrow[\mu_a]{T\alpha} (Ta, \mu_a) \xrightarrow{\alpha} (a, \alpha)$$

is a well defined diagram in  $T\text{-Alg}$ , with  $\alpha \cdot \mu_a = \alpha \cdot T\alpha$ . Moreover, this is a coequalizer. In order to prove it using Proposition ?? we need to check whether  $U^T$  sends the diagram above to a coequalizer preserved by  $T$  and  $T^2$ . In  $\mathcal{C}$ , we extend the diagram to

$$\begin{array}{ccccc} T^2a & \xrightarrow[\mu_a]{T\alpha} & Ta & \xrightarrow{\alpha} & a \\ \eta_{Ta} \swarrow & & \nwarrow \eta_a & & \\ & & & & \end{array}$$

where the following equations hold true by naturality or axioms:  $\alpha \cdot T\alpha = \alpha \cdot \mu_a$ ,  $\alpha \cdot \eta_a = \text{id}_a$ ,  $\mu_a \cdot \eta_{Ta} = \text{id}_{Ta}$  and  $\eta_a \cdot \alpha = T\alpha \cdot \eta_{Ta}$ . It is a particular case of a more general concept.

**Definition 1.3.2.** A *split coequalizer* is a diagram of the form

$$\begin{array}{ccccc} a & \xrightarrow[f]{g} & b & \xrightarrow[h]{s} & c \\ & \nwarrow t & \swarrow s & & \end{array}$$

so that  $hf = hg$ ,  $hs = \text{id}_c$ ,  $gt = \text{id}_b$ , and  $ft = sh$ .

**Proposition 1.3.3.** In the above situation,

$$a \xrightarrow[g]{f} b \xrightarrow{h} c$$

is a coequalizer. In particular, any functor preserves this coequalizer.

*Proof.* Take  $k: b \rightarrow d$  such that  $kf = kg$  and define  $\bar{k} := ks$ . Then we have

$$\bar{k}h = ksh = kft = kgt = k.$$

Uniqueness is clear since  $h$  is a (split) epimorphism. □

$T$  and  $T^2$  preserve split coequalizers, hence they preserve our coequalizer.

---

<sup>1</sup>Think about free groups: in that case we take words on  $Ta$ .

**Corollary 1.3.4.** Let  $T$  be a monad on  $\mathcal{C}$  and  $(a, \alpha)$  a  $T$ -algebra. Then

$$(T^2a, \mu_{Ta}) \xrightarrow[\mu_a]{T\alpha} (Ta, \mu_a) \xrightarrow{\alpha} (a, \alpha)$$

is a coequalizer in  $T\text{-Alg}$ , which  $U^T: T\text{-Alg} \rightarrow \mathcal{C}$  sends to a split coequalizer in  $\mathcal{C}$ .

*Proof.* We have already observed that the second statement holds, so that  $\text{coeq}(U^T T\alpha, U^T \mu_a)$  is preserved by  $T$  and  $T^2$ , hence there exists a unique lift of the (split) coequalizer in  $\mathcal{C}$  to a coequalizer in  $T\text{-Alg}$ .  $\square$

Results like the previous one inspire us to look at the parallel pairs of morphisms in a category which are sent to split coequalizers or, to say it better, to a parallel pair of morphisms that can be extended to a split coequalizer diagram. This kind of pairs will be of crucial importance when characterizing monadic functors.

**Definition 1.3.5.** Let  $U: \mathcal{D} \rightarrow \mathcal{C}$  be a functor. A pair of morphisms  $f, g: d \rightrightarrows d'$  in  $\mathcal{D}$  is  *$U$ -split* if  $Uf, Ug: Ud \rightrightarrows Ud'$  is part of a split coequalizer in  $\mathcal{C}$ .

**Remark 1.3.6.** Given a  $T$ -algebra  $(a, \alpha)$ , the morphisms  $T\alpha, \mu_a: (T^2a, \mu_{Ta}) \rightrightarrows (Ta, \mu_a)$  form a  $U^T$ -split pair. Moreover,  $T\text{-Alg}$  has coequalizers of  $U^T$ -split pairs and  $U^T$  preserves them. This implies that functors equivalent to  $U^T$  satisfy three conditions:

1. they have a left adjoint;
2. they are conservative;
3.  $U$ -split pairs have coequalizers which are preserved by  $U$ .

As it turns out, these properties are enough for  $U$  to be monadic.

**Theorem 1** (Beck). Let  $U: \mathcal{D} \rightarrow \mathcal{C}$  be a right adjoint to  $F$ . Let  $(T = UF, U\epsilon F, \eta)$  be the induced monad and  $\bar{U}: \mathcal{D} \rightarrow T\text{-Alg}$  be the comparison functor.

1. If  $\mathcal{D}$  has coequalizers of  $U$ -split pairs, then  $\bar{U}$  has a left adjoint  $\bar{F}: T\text{-Alg} \rightarrow \mathcal{D}$ ;
2. if, in addition,  $U$  preserves coequalizers of  $U$ -split pairs, the unit  $\bar{\eta}: \text{id}_{T\text{-Alg}} \Rightarrow \bar{U}\bar{F}$  is an isomorphism;
3. if  $U$  is also conservative, then  $\bar{U}$  is an equivalence of categories.

*Proof.* 1. For each free  $T$ -algebra  $(Ta, \mu_a)$  we have

$$\begin{aligned} T\text{-Alg}((Ta, \mu_a), \bar{U}-) &= T\text{-Alg}(F^T a, \bar{U}-) \\ &\cong \mathcal{C}(a, U^T \bar{U}-) \\ &= \mathcal{C}(a, U-) \\ &\cong \mathcal{D}(Fa, -), \end{aligned}$$

therefore the value of  $\bar{F}$  at  $(Ta, \mu_a)$  has to be  $Fa$ . Since every  $T$ -algebra is a coequalizer of free algebras which is preserved by  $U^T$ , we may define  $\bar{F}(a, \alpha)$  as the coequalizer of a

pair of morphisms  $FTa \rightrightarrows Fa$ . We write this as  $FUFUT(a, \alpha) \rightrightarrows FUT(a, \alpha)$ . Consider the following pair of morphisms of functors

$$FUFUT \xrightleftharpoons[\epsilon FUT]{F\alpha} FUT$$

in the functor category  $[T\text{-Alg}, \mathcal{D}]$ . We claim that this pair has a coequalizer and  $\bar{F}: T\text{-Alg} \rightarrow \mathcal{D}$  is left adjoint to  $\bar{U}$ . Note that the pair of morphisms just above becomes split after the composition with  $U: \mathcal{D} \rightarrow \mathcal{C}$ . In fact

$$\begin{array}{ccccc} U F U F U T & \xrightleftharpoons[U \epsilon F U T]{U F \alpha} & U F U T & \xrightarrow{\alpha} & U T \\ & \nwarrow \eta U F U T & \nwarrow \eta U T & & \\ & & & & \end{array}$$

is a split coequalizer in  $[T\text{-Alg}, \mathcal{C}]$ , given that it holds pointwise since  $UF = T$ . Let us denote by  $\beta: FUT \rightarrow \bar{F}$  the colimit (computed pointwise) of the pair  $F\alpha, \epsilon FUT: FUFUT \rightrightarrows FUT$ . Precomposing this pair with  $\bar{U}$  and recalling that  $\alpha\bar{U} = U\epsilon$ ,  $U^T\bar{U} = U$ , we get the pair

$$FUFU \xrightleftharpoons[\epsilon FU]{FU\epsilon} FU,$$

which is coequalized by  $\epsilon: FU \Rightarrow \text{id}_{\mathcal{D}}$ .

$$\begin{array}{ccc} FUFU & \xrightleftharpoons[\epsilon FU]{FU\epsilon} & FU \\ & \searrow \epsilon & \downarrow \exists! \bar{\epsilon} \\ & & \text{id}_{\mathcal{D}} \end{array}$$

Since  $\bar{F}\bar{U}$  is the coequalizer of the diagram above, there exists a unique  $\bar{\epsilon}: \bar{F}\bar{U} \Rightarrow \text{id}_{\mathcal{D}}$  such that  $\bar{\epsilon} \cdot \beta\bar{U} = \epsilon$ . To get the unit  $\bar{\eta}: \text{id}_{T\text{-Alg}} \Rightarrow \bar{U}\bar{F}$  we need to describe a morphism of  $T$ -actions  $(U^T, \alpha) \rightarrow (U^T\bar{U}\bar{F}, \alpha\bar{U}\bar{F})$ . We claim that the natural transformation induced by the universal property of the split coequalizer in the first row

$$\begin{array}{ccccc} U F U F U T & \xrightleftharpoons[U \epsilon F U T]{U F \alpha} & U F U T & \xrightarrow{\alpha} & U T \\ \parallel & & \parallel & & \downarrow \exists! \bar{\eta} \\ U^T \bar{U} F U F U T & \xrightleftharpoons[U^T \bar{U} \epsilon F U T]{U^T \bar{U} F \alpha} & U^T \bar{U} F U T & \xrightarrow{U^T \bar{U} \beta} & U^T \bar{U} \bar{F} \end{array}$$

is a morphism of  $T$ -actions<sup>2</sup>.

Unraveling what this means, we have to check that the diagram

$$\begin{array}{ccc} U F a & \xrightarrow{U F \bar{\eta}_{(a, \alpha)}} & U F U \bar{F}(a, \alpha) \\ \alpha \downarrow & & \downarrow U \epsilon_{\bar{F}(a, \alpha)} \\ a & \xrightarrow{\bar{\eta}_{(a, \alpha)}} & U \bar{F}(a, \alpha) \end{array}$$

<sup>2</sup>In fact, this tells us that the morphism  $\bar{\eta}_{(a, \alpha)}: a \rightarrow U^T \bar{U} \bar{F}(a, \alpha)$  in  $\mathcal{C}$  lifts uniquely to a morphism of  $T$ -algebras  $\bar{\eta}_{(a, \alpha)}: (a, \alpha) \rightarrow \bar{U} \bar{F}(a, \alpha)$ .

is commutative. We know that  $\bar{\eta} \cdot \alpha = U\beta$  by the definition of  $\bar{\eta}$ . Moreover,  $\alpha$  is a split epimorphism in  $\mathcal{C}$ , hence we can precompose with  $UF\alpha$  (again a split epi) and check the commutativity of the resulting diagram. We get the diagram

$$\begin{array}{ccccc}
 & & & & U\epsilon_{Fa} \\
 & & & & \swarrow \\
 UFUFa & & & & \\
 \downarrow UF\alpha & & & & \searrow \\
 UFa & \xrightarrow{UF\bar{\eta}(a,\alpha)} & UFUF(a,\alpha) & \xrightarrow{U\epsilon_{F(a,\alpha)}} & UFa \\
 \downarrow \alpha & \searrow U\beta(a,\alpha) & \downarrow U\epsilon_{F(a,\alpha)} & & \swarrow U\beta(a,\alpha) \\
 a & \xrightarrow{\bar{\eta}(a,\alpha)} & U\bar{F}(a,\alpha) & \xleftarrow{U\beta(a,\alpha)} & 
 \end{array}$$

nat. of  $\epsilon$

The definition of  $\beta$  as a coequalizer implies that  $\beta_{(a,\alpha)} \cdot F\alpha = \beta_{(a,\alpha)} \cdot \epsilon_{Fa}$ , so we get the natural transformation  $\bar{\eta}: \text{id}_{T\text{-Alg}} \Rightarrow \bar{U}\bar{F}$ . The only thing left to do is checking the triangular identities, which is left to the reader.

2. If  $U$  preserves coequalizers of  $U$ -split pairs, both  $U\bar{F}$  and  $U^T$  are coequalizers of the above diagram, hence  $\bar{\eta}$  is an isomorphism.
3. From the triangular identities,  $\bar{U}\bar{\epsilon} \cdot \bar{\eta}\bar{U} = \text{id}_{\bar{U}}$ , hence  $\bar{U}\bar{\epsilon}$  is an isomorphism. Being  $U^T\bar{U} = U$  conservative,  $\bar{\epsilon}$  is an isomorphism as well.  $\square$

**Definition 1.3.7.** A pair  $f, g: c \rightrightarrows d$  in a category  $\mathcal{C}$  is *reflexive* if there exists a common section  $i: d \rightarrow c$ , that is  $f \cdot i = g \cdot i = \text{id}_d$ . A coequalizer of a reflexive pair is a *reflexive coequalizer*.

**Remark 1.3.8.** To give a cone of a reflexive pair it is enough to give a map  $h: d \rightarrow x$  such that  $h \cdot f = h \cdot g$ , hence  $\text{colim}(c \rightrightarrows d) \cong \text{colim}(c \rightarrow d)$ .

**Proposition 1.3.9.** In Beck's monadicity theorem it suffices for (1) that coequalizers of reflexive  $U$ -split pairs exist, while in (2) and (3) we only need for them to be preserved.

*Proof.* The pair

$$FUFUT \xrightarrow[\epsilon_{FUT}]{F\alpha} FUT$$

has  $F\eta U^T$  as common section. In fact,  $\alpha \cdot \eta U^T = \text{id}_{UT}$  by the unit law of the  $T$ -action  $\alpha: TU^T \Rightarrow U^T$  and  $\epsilon F \cdot F\eta = \text{id}_F$  by the triangular identities.  $\square$

**Example 1.3.10.** Let  $\mathcal{A}$  and  $\mathcal{B}$  be small categories,  $\mathcal{C}$  a category which is both complete and cocomplete and  $G: \mathcal{A} \rightarrow \mathcal{B}$  a functor. The restriction along  $G$ ,  $G^*$ , has both adjoints, given by left and right Kan extensions. Notice that the induced monad on  $[\mathcal{A}, \mathcal{C}]$  is cocontinuous since  $G^*$  is a left adjoint. Moreover,  $G^*$  is conservative if  $G$  is essentially surjective, thus any essentially surjective functor  $G$  induces a monadic adjunction as follows:

$$\begin{array}{ccc}
 [\mathcal{B}, \mathcal{C}] & \xrightarrow{\bar{G}^*} & G^* \text{Lan}_G\text{-Alg} \\
 & \Downarrow \cong & \swarrow \\
 & G^* & \searrow \\
 & & [\mathcal{A}, \mathcal{C}]
 \end{array}$$



## 2 Categories of algebras

### 2.1 Sifted colimits

In this chapter we are going to show how various categories emerging in algebra can be studied naturally using the theory of monads. We will begin by introducing the notion of *algebraic theory*, but first we need some preliminary definitions and results.

**Definition 2.1.1.** A functor  $F: \mathcal{J} \rightarrow \mathcal{J}$  between small categories is called *final* if for any diagram  $D: \mathcal{J} \rightarrow \mathcal{C}$  the comparison morphism  $\text{colim}_{\mathcal{J}} DF \rightarrow \text{colim}_{\mathcal{J}} D$  is an isomorphism whenever both colimits exist.

**Proposition 2.1.2.** Let  $F: \mathcal{J} \rightarrow \mathcal{J}$  be a functor between small categories. The following are equivalent:

- (i)  $F$  is final;
- (ii) the unique isomorphism

$$\begin{array}{ccc} \mathcal{J}^{\text{op}} & \xrightarrow{F^{\text{op}}} & \mathcal{J}^{\text{op}} \\ & \Downarrow \cong & \\ * & & * \\ & \text{Set} & \end{array}$$

exhibits  $*$  as  $\text{Lan}_{F^{\text{op}}} *$ ;

- (iii) for each  $j \in \mathcal{J}$ , the category  $(j \downarrow F)$  is connected.

*Proof.* (ii)  $\iff$  (iii) We have  $\text{Lan}_{F^{\text{op}}} *(j) \cong \text{colim}_{(j \downarrow F)} *$  by the formula for Kan extensions. A cone of  $(j \downarrow F) \rightarrow \mathbf{Set}$ ,  $(\phi, j') \mapsto *$ , is terminal if and only if  $(j \downarrow F)$  is connected, hence the thesis.

- (ii)  $\implies$  (i) Let  $D: \mathcal{J} \rightarrow \mathcal{C}$  be a diagram. We can then write  $\text{Cocone}(D, -)$  as follows:

$$\text{Cocone}(D, X) \cong \text{Nat}(*, \mathcal{C}(D, X)) \cong [\mathcal{J}^{\text{op}}, \mathbf{Set}](*, \mathcal{C}(D, X))$$

By definition of left Kan extension, we also have

$$\text{Cocone}(DF, X) \cong [\mathcal{J}^{\text{op}}, \mathbf{Set}](*, \mathcal{C}(DF, X)) \cong [\mathcal{J}^{\text{op}}, \mathbf{Set}](\text{Lan}_{F^{\text{op}}} *, \mathcal{C}(D, X))$$

If  $\text{Lan}_{F^{\text{op}}} * \cong *$ , this shows that  $\text{colim}_{\mathcal{J}} DF \cong \text{colim}_{\mathcal{J}} D$ .

- (i)  $\implies$  (iii) Left as an exercise. □

**Definition 2.1.3.** A small category  $\mathcal{J}$  is *sifted* if the diagonal  $\Delta: \mathcal{J} \rightarrow \mathcal{J} \times \mathcal{J}$  is final. A colimit is sifted if the domain category is.

**Example 2.1.4.** 1. For any filtered category  $\mathcal{J}$ , the category  $((i, i') \downarrow \Delta)$  is again filtered for any  $(i, i') \in \mathcal{J} \times \mathcal{J}$  and hence connected, thus filtered colimits are sifted.

2. Coequalizers are not sifted. Indeed, their indexing category  $\mathcal{J} = \{1 \rightrightarrows 0\}$  is such that  $((0, 1) \downarrow \Delta)$  is not connected. However, reflexive coequalizers are sifted. Checking it for yourself may be a tedious yet useful exercise.

3. Initial objects and coproducts are not sifted, for their slice categories are either empty or have several connected components.

4. Pushouts are not sifted.

**Proposition 2.1.5.** If  $F: \mathcal{A} \times \mathcal{B} \rightarrow \mathcal{C}$  is a functor preserving reflexive coequalizers in each variable, that is for any  $a \in \mathcal{A}$ ,  $b \in \mathcal{B}$  the functors  $F(a, -): \mathcal{B} \rightarrow \mathcal{C}$  and  $F(-, b): \mathcal{A} \rightarrow \mathcal{C}$  preserve reflexive coequalizers, then  $F$  preserves reflexive coequalizers as well.

*Proof.* We need to check that, given a reflexive coequalizer  $a_0 \rightrightarrows a_1 \longrightarrow a_2$  in  $\mathcal{A}$  and  $b_0 \rightrightarrows b_1 \longrightarrow b_2$  in  $\mathcal{B}$ , the diagonal of the following diagram is a coequalizer diagram in  $\mathcal{C}$ .

$$\begin{array}{ccccc}
 F(a_0, b_0) & \rightrightarrows & F(a_1, b_0) & \longrightarrow & F(a_2, b_0) \\
 \Downarrow & \nearrow & \Downarrow & & \Downarrow \\
 F(a_0, b_1) & \rightrightarrows & F(a_1, b_1) & \longrightarrow & F(a_2, b_1) \\
 \downarrow & & \downarrow & \searrow & \downarrow \\
 F(a_0, b_2) & \rightrightarrows & F(a_1, b_2) & \longrightarrow & F(a_2, b_2)
 \end{array}$$

From general facts,  $F(a_2, b_2)$  is the colimit of the square in the top left. We may prove this using the sections, however in this case we can use the fact that a reflexive coequalizer is sifted and apply the last proposition.  $\square$

**Example 2.1.6.** The functor  $\mathbf{Set} \times \mathbf{Set} \xrightarrow{- \times -} \mathbf{Set}$  satisfies the hypothesis of the theorem since  $\mathbf{Set}$  is cartesian closed, hence  $X \mapsto X \times X$  preserves reflexive coequalizers by the proposition. This shows that  $\mathbf{Set}(X, -) \cong \prod_{x \in X} \mathbf{Set}(*, -)$  preserves reflexive coequalizers if  $X$  is finite, hence the functor  $\mathbf{Set}(X, -): \mathbf{Set} \rightarrow \mathbf{Set}$  is monadic with  $T = \mathbf{Set}(X, X \times -)$  for  $X$  finite.

$$\begin{array}{ccc}
 \mathbf{Set} & \xrightarrow{\cong} & T\text{-Alg} \\
 \searrow \mathbf{Set}(X, -) & & \swarrow U^T \\
 & \mathbf{Set} &
 \end{array}$$

We also have the following result.

**Proposition 2.1.7.** If  $F: \mathcal{B} \times \mathcal{C} \rightarrow \mathcal{D}$  is a functor preserving sifted colimits in each variable, then it preserves them as a functor  $\mathcal{B} \times \mathcal{C} \rightarrow \mathcal{D}$ .

**Remark 2.1.8.** This proposition is false if we drop the siftedness condition, for under the functor  $\mathbf{Set} \times \mathbf{Set} \xrightarrow{- \times -} \mathbf{Set}$  we have  $(* + *) \times (* + *) \not\cong * + * \cong (* \times *) + (* \times *)$ .

## 2.2 Algebraic Theories and Finitary Monads

Many objects in algebra can be described as sets  $X$  with some finitary operations  $X^{n_i} \xrightarrow{m_i} X$  subject to a list of axioms involving the  $m_i$  and their products.

**Example 2.2.1.** (Commutative) monoids and groups, rings and, fixed a ring  $R$ ,  $R$ -modules, where for each  $r \in R$  we specify an operation  $X \xrightarrow{r} X$ .

We can construct categories whose objects are sets paired with operations fulfilling the axioms and functions commuting with the operations as morphisms. These are called models for single-sorted finitary theories.

**Proposition 2.2.2.** The forgetful functor from a category  $\mathcal{C}$  of models of a single-sorted finitary theory to **Set** creates sifted colimits.

*Proof.* Notice that the  $n$ -fold product  $\mathbf{Set} \xrightarrow{(-)^n} \mathbf{Set}$  factors as  $\mathbf{Set} \xrightarrow{\Delta} \mathbf{Set}^n \xrightarrow{- \times \cdots \times -} \mathbf{Set}$ , hence it preserves sifted colimits. This gives us unique candidates for operations on the colimit such that the cocone in **Set** is a morphism of models. These operations satisfy the axioms because the domain is in each case again of the form  $\text{colim}^n$ .

$$\begin{array}{ccccc} X^{n_i} & \xrightleftharpoons{\quad} & Y^{n_i} & \longrightarrow & Z^{n_i} \\ \downarrow m_i & & \downarrow m_i & & \downarrow \exists! m_i \\ X & \xrightleftharpoons{\quad} & Y & \longrightarrow & Z \end{array}$$

□

**Corollary 2.2.3.** Let  $\mathcal{C}, \mathcal{D}$  be categories of models of single sorted finitary theories. Any functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  which commutes with the forgetful functor to **Set** preserves reflexive coequalizers. If  $F$  has a left adjoint, then it is monadic.

*Proof.* The forgetful functors  $\mathcal{C} \rightarrow \mathbf{Set}, \mathcal{D} \rightarrow \mathbf{Set}$  are both conservative, hence  $F$  is as well. The statement about reflexive coequalizers was just proved and the last claim follows from Beck's theorem. □

**Example 2.2.4.** The forgetful functor  $\mathbf{CAlg}_R \rightarrow \mathbf{Mod}_R$  is monadic for any commutative ring  $R$ . The same goes for the forgetful functors from **Grp**, **Ab**,  $\mathbf{Mod}_R$ , **Rng**, **CRng**, **Ring** and **CRing** to **Set**.

**Definition 2.2.5.** A functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  is *finitary* if it commutes with filtered colimits. A monad is *finitary* if its underlying endofunctor  $T$  is finitary.

**Remark 2.2.6.** Asking for the underlying endofunctor  $T$  to be finitary is equivalent to asking for its forgetful functor  $U^T$  to be finitary.

**Example 2.2.7.** All the forgetful functors from single sorted finitary theories which have a left adjoint (fact: all of them do) come from finitary monads on **Set**.

In general, preserving filtered colimits is a weaker condition than preserving sifted colimits. However, for endofunctors on **Set** the two coincide.

In order to prove this, we need to know how such an endofunctor is determined by its action on sets and the idea is to check its behaviour on finite sets, since every set is a directed union of its finite subsets. We write  $[\mathcal{C}, \mathcal{D}]_{\text{fin}}$  for the full subcategory of  $[\mathcal{C}, \mathcal{D}]$  whose objects are finitary functors,  $\mathbf{Set}_{\text{fin}}$  for the category of finite sets.

**Theorem 2.2.8.** Restriction along the inclusion  $K: \mathbf{Set}_{\text{fin}} \rightarrow \mathbf{Set}$  induces an equivalence  $[\mathbf{Set}, \mathbf{Set}]_{\text{fin}} \rightarrow [\mathbf{Set}_{\text{fin}}, \mathbf{Set}]$  whose inverse sends  $F$  to  $\text{Lan}_K F$ .

Before proving this theorem, we present some consequences.

**Corollary 2.2.9.** Any finitary functor  $\mathbf{Set} \rightarrow \mathbf{Set}$  preserves sifted colimits. In particular, if  $T: \mathbf{Set} \rightarrow \mathbf{Set}$  is the underlying endofunctor of a finitary monad, then  $U^T: T\text{-Alg} \rightarrow \mathbf{Set}$  strictly creates sifted colimits.

*Proof.* Recall that  $\text{Lan}_K: [\mathbf{Set}_{\text{fin}}, \mathbf{Set}] \rightarrow [\mathbf{Set}, \mathbf{Set}]_{\text{fin}}$  is a left adjoint and on both sides colimits are computed pointwise. Moreover, functors preserving colimits of a given class are closed under formation of pointwise colimits, hence it is enough to check on a generating set.

If for all  $F_i: \mathbf{Set}_{\text{fin}} \rightarrow \mathbf{Set}$  we have that  $\text{Lan}_K F_i$  preserves sifted colimits, then the functor  $\text{colim}_j \text{Lan}_K F_i \cong \text{Lan}_K \text{colim}_j F_i$  preserves sifted colimits as well.

Any functor  $F: \mathbf{Set}_{\text{fin}} \rightarrow \mathbf{Set}$  is a colimit of representable functors  $\mathbf{Set}_{\text{fin}}(X, -)$ . Indeed, it is enough to consider  $(\mathcal{J} \downarrow F) \rightarrow [\mathbf{Set}_{\text{fin}}, \mathbf{Set}]$ ,  $(\mathbf{Set}_{\text{fin}}(X, -) \Rightarrow F) \mapsto \mathbf{Set}_{\text{fin}}(X, -)$  and notice that this being a colimit diagram essentially follows from Yoneda as  $F \cong \text{colim}_{(\mathcal{J} \downarrow F)} \mathcal{J}_a$ .

By the previous theorem, it is enough to check now that the functor  $\text{Lan}_K \mathbf{Set}_{\text{fin}}(X, -)$  preserves sifted colimits.

Observe the following diagram:

$$\begin{array}{ccc} \mathbf{Set}_{\text{fin}} & \xrightarrow{K} & \mathbf{Set} \\ \mathbf{Set}_{\text{fin}}(X, -) \searrow & \xRightarrow{\quad} & \swarrow \text{Lan}_K \mathbf{Set}_{\text{fin}}(X, -) \\ & \mathbf{Set} & \end{array}$$

A natural transformation  $\text{Lan}_K \mathbf{Set}_{\text{fin}}(X, -) \Rightarrow G$  by definition is equivalent to a natural transformation  $\mathbf{Set}_{\text{fin}}(X, -) \Rightarrow GK$ , which by Yoneda is equivalent to a map  $* \rightarrow GKX$ , which again by Yoneda corresponds to a natural transformation  $\mathbf{Set}(KX, -) \Rightarrow G$ , hence  $\text{Lan}_K \mathbf{Set}_{\text{fin}}(X, -) \cong \mathbf{Set}(KX, -)$ .

We only have to check now that  $\mathbf{Set}(KX, -) \cong \prod_{x \in X} \mathbf{Set}(*, -)$  preserves sifted colimits, but this is just the functor  $Y \mapsto \prod_{x \in X} Y$ , which as we know commutes with sifted colimits.  $\square$

**Proposition 2.2.10.** A category  $\mathcal{C}$  with sifted colimits is cocomplete if and only if it has an initial object and binary coproducts.

*Proof.* One implication is obvious. For the other one, notice that we get finite coproducts immediately and an infinite coproduct can be written as a filtered colimit of finite coproducts. We are only missing coequalizers. If  $f, g: a \rightrightarrows b$  is a pair, then  $f + \text{id}_b, g + \text{id}_b: a + b \rightrightarrows b: \text{in}_b$  (where  $\text{in}_b$  is the inclusion of  $b$  in the coproduct) is a reflexive pair, hence the coequalizer  $c = \text{coeq}(a + b \rightrightarrows b)$  exists and coequalizes the original pair. The universal arrow  $h: b \rightarrow c$  is also a coequalizer of  $f, g: a \rightrightarrows b$ .  $\square$

**Theorem 2.2.11.** Let  $X$  be a finite set,  $T: \prod_{x \in X} \mathbf{Set} \rightarrow \prod_{x \in X} \mathbf{Set}$  a finitary monad. Then  $T\text{-Alg}$  is cocomplete.

*Proof.* The category  $T\text{-Alg}$  has always an initial object, namely the free algebra of the initial object  $(T \prod_{x \in X} \emptyset, \mu_{\prod_{x \in X} \emptyset})$ . Similarly, for  $a, b \in \prod_{x \in X} \mathbf{Set}$ , using that  $F^T$  is a left adjoint (hence it preserves colimits) we find that  $(T(a \amalg b), \mu_a \amalg b)$  is a coproduct of  $(Ta, \mu_a)$  and

$(Tb, \mu_b)$ . Therefore  $T\text{-Alg}$  has coproducts of free algebras. We want to check that we have binary coproducts of  $T$ -algebras  $(a, \alpha)$  and  $(b, \beta)$ . We have reflexive coequalizers

$$\begin{array}{ccc} (T^2a, \mu_{Ta}) & \begin{array}{c} \xrightarrow{T\alpha} \\ \xleftarrow{T\eta_a} \\ \xrightarrow{\mu_a} \end{array} & (Ta, \mu_a) \xrightarrow{\alpha} (a, \alpha) \\ (T^2b, \mu_{Tb}) & \begin{array}{c} \xrightarrow{T\beta} \\ \xleftarrow{T\eta_b} \\ \xrightarrow{\mu_b} \end{array} & (Tb, \mu_b) \xrightarrow{\beta} (b, \beta) \end{array}$$

so we get a new reflexive pair by taking coproducts of the free algebras

$$(T^2a, \mu_{Ta}) + (T^2b, \mu_{Tb}) \begin{array}{c} \xrightarrow{T\alpha+T\beta} \\ \xleftarrow{T\eta_a+T\eta_b} \\ \xrightarrow{\mu_a+\mu_b} \end{array} (Ta, \mu_a) + (Tb, \mu_b)$$

From the corollary,  $T$  preserves sifted colimits, hence  $T\text{-Alg}$  has reflexive coequalizers. Then the diagram above has a coequalizer, which is a coproduct of  $(a, \alpha)$  and  $(b, \beta)$ .  $\square$

**Remark 2.2.12.** 1. This shows that **Ab**, **Grp**, **Rng**, etc. are cocomplete.

2. We only used the fact that  $T$  preserves sifted colimits, hence a monad on a cocomplete category  $\mathcal{C}$  preserving sifted colimits has a cocomplete category of algebras. In fact, we only need that reflexive coequalizers and filtered colimits exist in  $T\text{-Alg}$ .

## 2.3 Dense generators

The aim of this section is to prove the theorem about finitary endofunctors of **Set**. We want to identify “nice” generating subcategories like  $\mathbf{Set}_{\text{fin}} \rightarrow \mathbf{Set}$ .

**Definition 2.3.1.** Let  $K: \mathcal{A} \rightarrow \mathcal{C}$  be the inclusion of a full subcategory or, equivalently, a fully faithful functor. We define the *restricted Yoneda functor*  $\tilde{K}: \mathcal{C} \rightarrow [\mathcal{A}^{\text{op}}, \mathbf{Set}]$  as the functor sending  $c \in \mathcal{C}$  to  $\mathcal{C}(K, c)$ .

The *canonical cocone* on the domain functor

$$\begin{aligned} \text{dom}: (K \downarrow c) &\rightarrow \mathcal{C} \\ (a, \varphi) &\mapsto Ka \end{aligned}$$

has components  $\varphi: \text{dom}(a, \varphi) = Ka \xrightarrow{\varphi} c$ .

**Definition 2.3.2.** A colimit of a diagram  $D: \mathcal{J} \rightarrow \mathcal{C}$  is *K-absolute* if it is preserved by  $\tilde{K}: \mathcal{C} \rightarrow [\mathcal{A}^{\text{op}}, \mathbf{Set}]$ .

**Definition 2.3.3.** A fully faithful functor  $K: \mathcal{A} \rightarrow \mathcal{C}$  is called *dense* if  $\tilde{K}$  is fully faithful. A full subcategory  $\mathcal{A}$  of  $\mathcal{C}$  is *dense* if the full embedding  $K: \mathcal{A} \rightarrow \mathcal{C}$  is.

**Theorem 2.3.4** (Kan). Let  $\mathcal{C}$  be a locally small cocomplete category,  $\mathcal{A}$  a small category and  $K: \mathcal{A} \rightarrow \mathcal{C}$  a functor. Then,  $\tilde{K}$  has a left adjoint given by  $\text{Lan}_{\mathcal{A}} K: [\mathcal{A}, \mathbf{Set}] \rightarrow \mathcal{C}$  such that the diagram

$$\begin{array}{ccc} \mathcal{A} & \xrightarrow{\mathcal{A}} & [\mathcal{A}^{\text{op}}, \mathbf{Set}] \\ & \searrow K & \swarrow \text{Lan}_{\mathcal{A}} K \\ & \mathcal{C} & \end{array}$$

commutes up to natural isomorphism.

*Proof.* We have  $\text{Lan}_{\mathcal{J}} K(F) = \text{colim}_{(\mathcal{J} \downarrow F)} Ka$ , hence

$$\begin{aligned} \mathcal{C}(\text{Lan}_{\mathcal{J}} K(F), c) &\cong \lim_{(\mathcal{J} \downarrow F)} \mathcal{C}(Ka, c) \\ &\stackrel{\text{Yoneda}}{\cong} \lim_{(\mathcal{J} \downarrow F)} [\mathcal{A}^{\text{op}}, \mathbf{Set}] (\mathcal{J}_a, \tilde{K}c) \\ &\cong [\mathcal{A}^{\text{op}}, \mathbf{Set}] \left( \text{colim}_{(\mathcal{J} \downarrow F)} \mathcal{J}_a, \tilde{K}c \right) \\ &\cong [\mathcal{A}^{\text{op}}, \mathbf{Set}](F, \tilde{K}c). \end{aligned}$$

Notice that for  $F = \mathcal{J}_a$  the category  $(\mathcal{J} \downarrow F)$  has a terminal object  $(a, \text{id}_a)$ , thus  $\text{Lan}_{\mathcal{J}} K(\mathcal{J}_a) \cong Ka$  naturally.  $\square$

**Theorem 2.3.5.** Let  $\mathcal{C}$  be a locally small cocomplete category,  $\mathcal{A}$  a small category and  $K: \mathcal{A} \rightarrow \mathcal{C}$  a fully faithful functor. The following conditions are equivalent:

1.  $\tilde{K}$  is fully faithful;
2. for every  $c \in \mathcal{C}$ , the canonical cocone on  $\text{dom}: (K \downarrow c) \rightarrow \mathcal{C}$  exhibits  $c$  as colimit of the diagram  $\text{dom}: (K \downarrow c) \rightarrow \mathcal{C}$ ;
3. every object  $c \in \mathcal{C}$  is a  $K$ -absolute colimit of a diagram of the form  $\mathcal{J} \xrightarrow{D} \mathcal{A} \xrightarrow{K} \mathcal{C}$ ;
4. there exists some family of diagrams  $D_i: \mathcal{J}_i \rightarrow \mathcal{C}$  which have  $K$ -absolute colimits and  $\mathcal{C}$  is the closure<sup>1</sup> of  $\mathcal{A}$  under the colimits of the  $D_i$ ;
5. the counit of  $\text{Lan}_{\mathcal{J}} K \dashv \tilde{K}$  is an isomorphism.

*Proof.* (1)  $\implies$  (2) If  $\tilde{K}$  is fully faithful, it suffices to check that the image of the canonical cocone under  $\tilde{K}$  is a colimit. Since  $K$  is fully faithful, this image is precisely the diagram given by the natural transformations  $\mathcal{J}_a = \mathcal{A}(-, a) \cong \mathcal{C}(K, Ka) \Rightarrow \mathcal{C}(K, c) = \tilde{K}c$ . Then

$$\text{colim}_{(K \downarrow c)} \tilde{K} \text{dom} = \text{colim}_{(\mathcal{J} \downarrow \tilde{K}c)} \mathcal{J}_a \cong \tilde{K}c.$$

This proves (2) and the fact that the colimit of  $(K \downarrow c) \rightarrow \mathcal{C}$  is preserved by  $\tilde{K}: \mathcal{C} \rightarrow [\mathcal{A}^{\text{op}}, \mathbf{Set}]$ .

(2)  $\implies$  (3) As we just observed,  $\text{colim}_{(K \downarrow c)} \text{dom}$  is  $\tilde{K}$ -absolute and  $\text{dom}: (K \downarrow c) \rightarrow \mathcal{C}$  factors through  $\mathcal{A}$ .

(3)  $\implies$  (4) Clear.

(4)  $\implies$  (5) Let  $\mathcal{B}$  be full subcategory spanned by the elements  $b \in \mathcal{C}$  such that  $\epsilon_b: \text{Lan}_{\mathcal{J}} K(\tilde{K}b) \rightarrow b$  is an isomorphism. It is closed under  $K$ -absolute colimits since they are preserved by  $\tilde{K}$  (by definition), by the left adjoint  $\text{Lan}_{\mathcal{J}} K$  and by  $\text{id}_{\mathcal{C}}$ . It remains to check that the counit at  $Ka \in \mathcal{C}$  is an isomorphism. But  $\tilde{K}Ka = \mathcal{C}(K, Ka) \cong \mathcal{A}(-, a) = \mathcal{J}_a$ , so  $\text{Lan}_{\mathcal{J}} K(\tilde{K}Ka) = \text{Lan}_{\mathcal{J}} K(\mathcal{J}_a) \cong Ka$ .

<sup>1</sup>That is, the smallest full subcategory  $\mathcal{B}$  of  $\mathcal{C}$  which contains  $\mathcal{A}$  and which satisfies the following

if some diagram  $D_i: \mathcal{J}_i \rightarrow \mathcal{C}$  factors through  $\mathcal{B}$ , then  $\text{colim } D_i \in \mathcal{B}$

is  $\mathcal{C}$  itself.

(5)  $\implies$  (1) Any right adjoint whose counit is an isomorphism is fully faithful.  $\square$

**Remark 2.3.6.** Notice that the first four points of the Theorem ?? are equivalent even when  $\mathcal{C}$  is not cocomplete. In fact, we also have the implication (4)  $\implies$  (1) without assumptions on the cocompleteness of  $\mathcal{C}$ .

*Proof.* We give an alternative proof which holds without the cocompleteness hypothesis of the implication (4)  $\implies$  (1).

Consider the full subcategory  $\mathcal{B}$  of  $\mathcal{C}$  with objects

$$\{b \in \mathcal{C} \mid \tilde{K}_{Ka,b}: \mathcal{C}(Ka, b) \rightarrow [\mathcal{A}^{\text{op}}, \mathbf{Set}] (\tilde{K}Ka, \tilde{K}b) \text{ is bijective } \forall a \in \mathcal{A}\}$$

Since  $\tilde{K}Ka = \mathcal{A}(-, a)$ , by Yoneda, the target is given by  $\text{ev}_a \circ \tilde{K}b$ . Therefore it preserves  $K$ -absolute colimits. The domain is also equal to  $\text{ev}_a \circ \tilde{K}(b)$ , by definition. Hence it preserves  $K$ -absolute colimits and contains  $Ka'$  for every  $a'$ , therefore  $\mathcal{B} = \mathcal{C}$ . Consider now

$$\mathcal{B}' = \{b' \mid \mathcal{C}(b', b) \xrightarrow{\tilde{K}} [\mathcal{A}^{\text{op}}, \mathbf{Set}] (\tilde{K}b', \tilde{K}b) \text{ is bijective}\}$$

This is closed under all  $K$ -absolute colimits and contains  $Ka$  by the above argument, hence it is all of  $\mathcal{C}$ .  $\square$

**Definition 2.3.7.** A fully faithful functor  $K: \mathcal{A} \rightarrow \mathcal{C}$  is *dense* if  $\tilde{K}$  is fully faithful. A collection of diagrams  $\{D_j: J_j \rightarrow \mathcal{C}\}$  such that  $\mathcal{C}$  is the closure of  $\mathcal{A}$  under colimits of  $D_j$  and the colim  $D_j$  are  $K$ -absolute is a *density presentation*.

**Remark 2.3.8.** The definition of density makes sense for arbitrary  $K$ , but the implication (4)  $\implies$  (1) does not work in general.

**Example 2.3.9.** 1.  $\mathcal{Y}: \mathcal{A} \rightarrow [\mathcal{A}^{\text{op}}, \mathbf{Set}]$  is dense: we have

$$\tilde{\mathcal{Y}}(G) = [\mathcal{A}^{\text{op}}, \mathbf{Set}] (\mathcal{Y}, G) \overset{\text{Yoneda}}{\cong} G,$$

thus  $\tilde{\mathcal{Y}} \cong \text{id}$  preserves all colimits. The colimits indexed by the slices  $(\mathcal{Y} \downarrow F)$  give a density presentation.

2.  $K: \mathbf{Set}_{\text{fin}} \hookrightarrow \mathbf{Set}$  is dense:  $S$  finite implies that  $\mathbf{Set}(S, -)$  preserves sifted, hence filtered, colimits. Filtered (and sifted) colimits are  $K$ -absolute and a density presentation for  $K$  can be found once one writes an arbitrary set as a union of its finite subset.
3.  $K: \{*\} \rightarrow \mathbf{Set}$  is dense:  $\tilde{K}: \mathbf{Set} \rightarrow [*, \mathbf{Set}] \cong \mathbf{Set}$ ,  $S \mapsto \mathbf{Set}(*, S) \cong S$ , hence we find that  $\tilde{K}$  preserves all colimits. We can use coproducts to get a density presentation.
4.  $K: \{k\} \rightarrow \mathbf{Vect}_k$  is not dense even though every vector space is a coproduct of copies of  $k$ .

**Definition 2.3.10.** Given *any* functor  $F: \mathcal{A} \rightarrow \mathcal{D}$ , we can talk about the *restricted Yoneda embedding*  $\tilde{F}: \mathcal{D} \rightarrow [\mathcal{A}^{\text{op}}, \mathbf{Set}]$ , sending  $d \in \mathcal{D}$  to  $\mathcal{D}(F, d)$ .

**Proposition 2.3.11.** Let  $K: \mathcal{A} \rightarrow \mathcal{C}$  be fully faithful and  $F: \mathcal{A} \rightarrow \mathcal{D}$  any functor. Suppose there exists  $L: \mathcal{C} \rightarrow \mathcal{D}$  and bijections  $\mathcal{D}(Lc, d) \rightarrow [\mathcal{A}^{\text{op}}, \mathbf{Set}] (\tilde{K}c, \tilde{F}d)$  natural both in  $c$  and  $d$ . Then there is an isomorphism  $\eta: F \xrightarrow{\sim} LK$  exhibiting  $L$  as left Kan extension of  $F$  along  $K$ .

*Proof.* The presheaf  $\tilde{K}c$  is the colimit of the canonical cocone on  $(\mathcal{A} \downarrow \tilde{K}c)$ . By Yoneda, this is equivalent to  $(K \downarrow c)$  with objects  $(a \in \mathcal{A}, \varphi: Ka \rightarrow c)$  and the evident morphisms. If  $c \cong Ka$ , this has  $(a, \text{id}_a)$  as terminal object, in which case the colimit is  $\mathcal{C}(K, Ka) \cong \mathcal{A}(-, a) = \mathcal{A}_a$ . Moreover, the formula above in this case gives

$$\mathcal{D}(LKa, d) \cong [\mathcal{A}^{\text{op}}, \mathbf{Set}](\tilde{K}Ka, \tilde{F}d) \cong [\mathcal{A}^{\text{op}}, \mathbf{Set}](\mathcal{A}_a, \tilde{F}d) \cong \mathcal{D}(Fa, d).$$

This shows that  $LK \cong F$  naturally. Then  $Lc = \text{colim}_{(K \downarrow c)} Fa$ , which is the classical formula for left Kan extensions.  $\square$

**Definition 2.3.12.** Any such Kan extension is called pointwise.

**Theorem 2.3.13.** Let  $K: \mathcal{A} \rightarrow \mathcal{C}$  be a fully faithful dense functor with density presentation  $\{D_j: \mathcal{J}_j \rightarrow \mathcal{C}\}_{j \in \mathcal{J}}$ . Let  $\mathcal{D}$  be a locally small category,  $F: \mathcal{A} \rightarrow \mathcal{D}$  a functor and assume that  $\mathcal{D}$  has colimits of shape  $\mathcal{J}_j$  for all  $j \in \mathcal{J}$ . Then the pointwise left Kan extension of  $F$  along  $K$  exists. In particular, the unit  $F \Rightarrow \text{Lan}_K F \circ K$  is an isomorphism.

*Proof.* We want a  $L$  as above, that is such that  $\mathcal{D}(Lc, d) \cong [\mathcal{A}^{\text{op}}, \mathbf{Set}](\tilde{K}c, \tilde{F}d)$  naturally in  $c, d$ . This simply says that for all  $c \in \mathcal{C}$  the functor  $[\mathcal{A}^{\text{op}}, \mathbf{Set}](\tilde{K}c, \tilde{F}): \mathcal{D} \rightarrow \mathbf{Set}$  is representable. Take  $\mathcal{B} := \{c \in \mathcal{C} \mid [\mathcal{A}^{\text{op}}, \mathbf{Set}](\tilde{K}c, \tilde{F}) \text{ is representable}\}$ . If  $c = Ka$ , then  $\tilde{K}c = \mathcal{C}(K, Ka) \cong \mathcal{A}(-, a) = \mathcal{A}_a$ , therefore

$$\begin{aligned} [\mathcal{A}^{\text{op}}, \mathbf{Set}](\tilde{K}Ka, \tilde{F}d) &\cong [\mathcal{A}^{\text{op}}, \mathbf{Set}](\mathcal{A}_a, \tilde{F}d) \\ &\stackrel{\text{Yoneda}}{\cong} \tilde{F}d(a) \\ &\cong \mathcal{D}(Fa, d), \end{aligned}$$

hence it is represented by  $Fa$  and  $Ka \in \mathcal{B}$ . Furthermore,  $\mathcal{B}$  is closed under  $\tilde{K}$ -absolute colimits of shape  $\mathcal{J}_j$ , thus, letting  $D: \mathcal{J}_j \rightarrow \mathcal{B}$  be a diagram such that  $\text{colim}_{\mathcal{J}_j} D$  exists in  $\mathcal{C}$  and is preserved by  $\tilde{K}$ , we claim that  $\text{colim}_{\mathcal{J}_j} D \in \mathcal{B}$ .

$$\begin{aligned} [\mathcal{A}^{\text{op}}, \mathbf{Set}](\tilde{K} \text{colim}_{\mathcal{J}_j} D, \tilde{F}d) &\cong [\mathcal{A}^{\text{op}}, \mathbf{Set}](\text{colim}_{\mathcal{J}_j} \tilde{K}D, \tilde{F}d) \\ &\cong \lim_{\mathcal{J}_j} [\mathcal{A}^{\text{op}}, \mathbf{Set}](\tilde{K}D, \tilde{F}d) \\ &\cong \lim_{\mathcal{J}_j} \mathcal{D}(LD, d) \\ &\cong \mathcal{D}(\text{colim}_{\mathcal{J}_j} LD, d), \end{aligned}$$

therefore  $\mathcal{B} = \mathcal{C}$  and we get the functor  $L = \text{Lan}_K F$ .  $\square$

**Lemma 2.3.14.** Under the same conditions as before, pointwise Kan extensions along  $K$  preserve  $K$ -absolute colimits.

*Proof.* By definition,  $\mathcal{D}(\text{Lan}_K F(c), d) \cong [\mathcal{A}^{\text{op}}, \mathbf{Set}](\tilde{K}c, \tilde{F}d)$ . Let  $\text{colim}_{\mathcal{J}} D$  be  $K$ -absolute. Then



the claim is shown by the following chain of isomorphisms.

$$\begin{aligned}
\mathcal{D}(\mathrm{Lan}_K F(\mathrm{colim}_j D), d) &\cong [\mathcal{A}^{\mathrm{op}}, \mathbf{Set}] (\tilde{K} \mathrm{colim}_j D, \tilde{F}d) \\
&\cong [\mathcal{A}^{\mathrm{op}}, \mathbf{Set}] (\mathrm{colim}_j \tilde{K}D, \tilde{F}d) \\
&\cong \lim_j [\mathcal{A}^{\mathrm{op}}, \mathbf{Set}] (\tilde{K}D, \tilde{F}d) \\
&\cong \lim_j \mathcal{D}(\mathrm{Lan}_K F(D), d) \\
&\cong \mathcal{D}(\mathrm{colim}_j \mathrm{Lan}_K F(D), d). \quad \square
\end{aligned}$$

**Theorem 2.3.15.** Let  $K: \mathcal{A} \rightarrow \mathcal{C}$  be fully faithful,  $\Phi$  a class of colimit shapes and assume there exists a density presentation for  $K$  with colimits of shape  $J_j \in \Phi$ . Let  $\mathcal{D}$  be a category with colimits of shape  $\Phi$ . We write  $\Phi\text{-Cocts}(\mathcal{C}, \mathcal{D})$  for the category of functors  $\mathcal{C} \rightarrow \mathcal{D}$  which preserve  $\Phi$ -colimits. If all colimits of shape  $\Phi$  are  $K$ -absolute, then

$$[\mathcal{A}, \mathcal{D}] \xrightleftharpoons[\begin{smallmatrix} \perp \\ K^* \end{smallmatrix}]{\mathrm{Lan}_K} \Phi\text{-Cocts}(\mathcal{C}, \mathcal{D})$$

is an equivalence.

*Proof.* The existence of  $\mathrm{Lan}_K$  is guaranteed by the fact that  $\mathcal{D}$  has  $\Phi$ -colimits and  $K$  has density presentation with colimits of shape  $J_j \in \Phi$ . By definition,  $\mathrm{Lan}_K$  is left adjoint to  $K^*: [\mathcal{C}, \mathcal{D}] \rightarrow [\mathcal{A}, \mathcal{D}]$  and by the lemma it lands in  $\Phi\text{-Cocts}(\mathcal{C}, \mathcal{D})$ . Then  $\mathrm{Lan}_K$  is a left adjoint to the restriction. The unit is an isomorphism since  $\mathrm{Lan}_K F$  is pointwise, so it suffices to check that  $K^*$  is conservative. Let  $G, H: \mathcal{C} \rightarrow \mathcal{D}$  be  $\Phi$ -cocontinuous,  $\alpha: G \Rightarrow H$  natural transformation such that  $\alpha K$  is an isomorphism. Then,  $\{c \mid \alpha_c \text{ is an isomorphism}\}$  contains  $Ka$  for every  $a$  and is closed under colimits of density presentations, hence  $\alpha$  is an isomorphism.  $\square$

**Corollary 2.3.16.** For  $K: \mathbf{Set}_{\mathrm{fin}} \hookrightarrow \mathbf{Set}$ , we get that

$$[\mathbf{Set}_{\mathrm{fin}}, \mathbf{Set}] \xrightleftharpoons[\begin{smallmatrix} \perp \\ K^* \end{smallmatrix}]{\mathrm{Lan}_K} [\mathbf{Set}, \mathbf{Set}]_{\mathrm{fin}}$$

is an equivalence.

**Definition 2.3.17.** Let  $\Phi$  be a class of colimit shapes and  $\mathcal{A}$  be a small category. We write  $\Phi(\mathcal{A})$  for the closure of the representable presheaves in  $[\mathcal{A}^{\mathrm{op}}, \mathbf{Set}]$  under  $\Phi$ -colimits. We have a functor  $\mathfrak{J}: \mathcal{A} \rightarrow \Phi(\mathcal{A})$ .

**Remark 2.3.18.** By construction, there exists a density presentation for  $\mathfrak{J}: \mathcal{A} \rightarrow \Phi(\mathcal{A})$  consisting of  $\Phi$ -colimits. This follows from  $\tilde{\mathfrak{J}}: \Phi(\mathcal{A}) \rightarrow [\mathcal{A}^{\mathrm{op}}, \mathbf{Set}]$  being simply the inclusion.

**Theorem 2.3.19.** Let  $\Phi$  be a class of small colimit shapes,  $\mathcal{A}$  a small category. Then  $\mathcal{A} \xrightarrow{\mathfrak{J}} \Phi(\mathcal{A})$  is the *free cocompletion* of  $\mathcal{A}$  under  $\Phi$ -colimits, that is

$$[\mathcal{A}, \mathcal{C}] \xrightleftharpoons[\begin{smallmatrix} \perp \\ \mathfrak{J}^* \end{smallmatrix}]{\mathrm{Lan}_{\mathfrak{J}}} \Phi\text{-Cocts}(\Phi(\mathcal{A}), \mathcal{C})$$

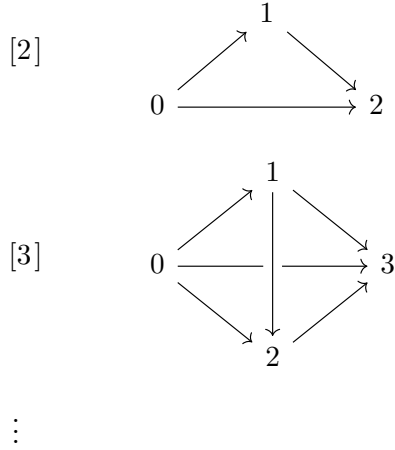
is an equivalence for every  $\Phi$ -cocomplete  $\mathcal{C}$ . In particular, if  $\Phi$  is the class of all small colimit shapes, then  $\Phi(\mathcal{A}) = [\mathcal{A}^{\mathrm{op}}, \mathbf{Set}]$  is the free cocompletion of  $\mathcal{A}$ . In this case, every  $L \cong \mathrm{Lan}_{\mathfrak{J}} F \in \mathrm{Cocts}([\mathcal{A}^{\mathrm{op}}, \mathbf{Set}], \mathcal{C})$  has a right adjoint, that is  $\mathrm{Lan}_{\mathfrak{J}} F \dashv \tilde{F}$ .

*Proof.* Since  $\mathfrak{J}: \mathcal{A} \rightarrow \Phi(\mathcal{A})$  has density presentation consisting of  $\Phi$ -colimits, the two equivalences follow from the previous theorem. To exhibit the right adjoint of  $L$ , we see that

$$\mathcal{C}(\text{Lan}_{\mathfrak{J}} F(G), c) \cong [\mathcal{A}^{\text{op}}, \mathbf{Set}] (\tilde{\mathfrak{J}}(G), \tilde{F}c) \cong [\mathcal{A}^{\text{op}}, \mathbf{Set}] (G, \tilde{F}c)$$

since  $\text{Lan}_{\mathfrak{J}} F$  is pointwise.  $\square$

**Example 2.3.20.** Let  $\Delta$  be the category of finite non-empty ordinals  $[0], [1], \dots$  and order preserving maps. We have a functor  $\Delta_{\bullet}: \Delta \rightarrow \mathbf{Top}$ , sending  $[n]$  to the standard (geometric)  $n$ -simplex  $\Delta_n$  so we get an adjunction  $\text{Lan}_{\mathfrak{J}} \Delta_{\bullet}: [\mathcal{A}^{\text{op}}, \mathbf{Set}] \rightleftarrows \mathbf{Top}: \Delta_{\bullet}^*$ .  $\text{Lan}_{\mathfrak{J}} \Delta_{\bullet}$  is called the *geometric realization* and  $\Delta_{\bullet}^* =: \text{Sing}(-)$  is called the *singular complex*. In pictures:



$[\Delta^{\text{op}}, \mathbf{Set}]$  is called the category of *simplicial sets* and it is denoted by  $\mathbf{sSet}$ .  $\text{Lan}_{\mathfrak{J}} \Delta_{\bullet}$  is denoted by  $|\cdot|$ .

## 2.4 Locally presentable categories

From now on we fix a regular cardinal  $\kappa^2$ .

**Definition 2.4.1.** A category  $\mathcal{C}$  is  $\kappa$ -*filtered* if any diagram in  $\mathcal{C}$  of size  $< \kappa$  has a cocone. Equivalently, if it is non-empty and for any set of objects  $\{x_i\}$  of cardinality  $< \kappa$  there exists  $x \in \mathcal{C}$  and  $x_i \rightarrow x$  such that

$$\begin{array}{ccc} & \xrightarrow{\quad} & \\ x_i & \begin{array}{c} \xrightarrow{\quad} \\ \vdots \\ \xrightarrow{\quad} \end{array} & x_j \longrightarrow x \\ & \xrightarrow{\quad} & \end{array} \quad \text{with } \text{cardinality} < \kappa$$

is coequalizing. If  $\kappa = \aleph_0$ , then a  $\kappa$ -filtered category is just a filtered one.

**Definition 2.4.2.** An object  $c \in \mathcal{C}$  is called  $\kappa$ -*presentable* if  $\mathcal{C}(c, -)$  preserves  $\kappa$ -filtered colimits. If  $\kappa = \aleph_0$ ,  $c$  is called *finitely presentable*.

**Definition 2.4.3.** A category  $\mathcal{A}$  is called  $\kappa$ -*accessible* if there exists a small subcategory  $\mathcal{A}_0$  of  $\kappa$ -presentable objects such that  $\mathcal{A}$  is the closure of  $\mathcal{A}_0$  under  $\kappa$ -filtered colimits. The category  $\mathcal{A}$  is called *locally  $\kappa$ -presentable* if it is  $\kappa$ -accessible and cocomplete.

<sup>2</sup>Namely, a union of  $< \kappa$  sets of cardinality  $< \kappa$  has cardinality  $< \kappa$ .

**Example 2.4.4.** Take  $\mathcal{A} = \mathbf{Set}$ ,  $\mathcal{A}_0 = \mathbf{Set}_{\text{fin}}$  and  $S \in \mathbf{Set}_{\text{fin}}$ . Then

$$\mathbf{Set}(S, -) = \prod_{|S| \text{ finite}} \mathbf{Set}(*, -)$$

preserves sifted, hence filtered, colimits, thus  $\mathbf{Set}$  is locally finitely presentable.

**Remark 2.4.5.** For  $\mathcal{A}_0$  as in the definition,  $K: \mathcal{A}_0 \rightarrow \mathcal{A}$  the inclusion, we find that  $\kappa$ -filtered colimits are  $K$ -absolute.

$$\begin{aligned} \mathcal{A} &\xrightarrow{\tilde{K}} [\mathcal{A}_0^{\text{op}}, \mathbf{Set}] \xrightarrow{\text{ev}_a} \mathbf{Set} \\ a' &\longmapsto \mathcal{A}(K, a') \longmapsto \mathcal{A}(a, a') \end{aligned}$$

so that  $\mathcal{A}_0 \xrightarrow{K} \mathcal{A}$  has a density presentation consisting of  $\kappa$ -filtered colimits. Thus  $\tilde{K}: \mathcal{A} \rightarrow [\mathcal{A}_0^{\text{op}}, \mathbf{Set}]$  is fully faithful and preserves  $\kappa$ -filtered colimits.

**Definition 2.4.6.** A functor is  $\kappa$ -accessible if it commutes with  $\kappa$ -filtered colimits. We write  $[\mathcal{A}, \mathcal{C}]_{\kappa}$  for the subcategory of  $\kappa$ -accessible functors ( $[\mathcal{A}, \mathcal{C}]_{\text{fin}}$  if  $\kappa = \aleph_0$ ).

It follows that we have an adjunction

$$[\mathcal{A}_0, \mathcal{C}] \begin{array}{c} \xrightarrow{\text{Lan}_K} \\ \perp \\ \xleftarrow{K^*} \end{array} [\mathcal{A}, \mathcal{C}]_{\kappa}$$

if  $\mathcal{A}, \mathcal{A}_0$  are as above and  $\mathcal{C}$  has  $\kappa$ -filtered colimits.

**Remark 2.4.7.** A  $\kappa$ -accessible category  $\mathcal{A}$  is locally  $\kappa$ -presentable if and only if  $\mathcal{A} \xrightarrow{\tilde{K}} [\mathcal{A}_0^{\text{op}}, \mathbf{Set}]$  has a left adjoint for any choice of  $\mathcal{A}_0 \subseteq \mathcal{A}$  that defines it as the closure under  $\kappa$ -filtered colimits.

**Definition 2.4.8.** A monad  $(T, \mu, \eta)$  is said to have rank  $\kappa$  if  $T$  is a  $\kappa$ -accessible endofunctor.

**Definition 2.4.9.** A category  $\mathcal{A}$  is called *accessible* (resp. *locally presentable*) if it is  $\kappa$ -accessible (resp. locally  $\kappa$ -presentable) for some regular cardinal  $\kappa$ . A functor is accessible if it is  $\kappa$ -accessible for some  $\kappa$ . A monad has rank if it is accessible.

Our next goal is to prove that if  $(T, \mu, \eta)$  is an accessible monad on a locally presentable category, then  $T\text{-Alg}$  is locally presentable.

**Proposition 2.4.10.** Let  $\mathcal{A}$  be  $\kappa$ -accessible,  $\mathcal{A}_0 \subseteq \mathcal{A}$  be the small subcategory of  $\kappa$ -presentable objects such that  $\mathcal{A}$  is the closure of  $\mathcal{A}_0$  under  $\kappa$ -filtered colimits, and  $(T, \mu, \eta)$  be a monad of rank  $\kappa$  on  $\mathcal{A}$ . Then  $\mathcal{B} = \{(Ta_0, \mu_{a_0}) \mid a_0 \in \mathcal{A}_0\}$  is a dense generator of  $T\text{-Alg}$ .

*Proof.* First note that  $(Ta_0, \mu_{a_0})$  is  $\kappa$ -presentable. Indeed, we have  $T\text{-Alg}((Ta_0, \mu_{a_0}), -) \cong \mathcal{A}(a_0, U^T -)$  and  $U^T$  creates all colimits that  $T$  preserves, in particular  $\kappa$ -filtered ones. Hence,  $U^T$  preserves  $\kappa$ -filtered colimits and for this reason  $(Ta_0, \mu_{a_0})$  is  $\kappa$ -presentable. Let  $\Phi_1$  be the class of  $\kappa$ -filtered diagrams. Writing  $K: \mathcal{B} \rightarrow T\text{-Alg}$  for the inclusion, we have just shown that  $\Phi_1$ -colimits are  $K$ -absolute. Note that the closure of  $\mathcal{B}$  under  $\Phi_1$  contains all free algebras  $(Ta, \mu_a)$  since  $\mathcal{A}$  is the closure of  $\mathcal{A}_0$  under  $\Phi_1$ -colimits. Let  $\Phi_2$  be the class of diagrams

$(T^2a, \mu_{Ta}) \rightrightarrows (Ta, \mu_a)$  for all  $(a, \alpha) \in T\text{-Alg}$ . The closure under  $\Phi_1 \cup \Phi_2$  is clearly all of  $T\text{-Alg}$ , so we just need to show that  $\Phi_2$ -colimits are  $K$ -absolute, that is preserved by each  $T\text{-Alg}((Ta_0, \mu_{a_0}), -)$ . Since  $T\text{-Alg}((Ta_0, \mu_{a_0}), -) \cong \mathcal{A}(a_0, U^T -)$  and  $U^T$  sends a coequalizer in question to a split coequalizer, the colimit is indeed  $K$ -absolute.  $\square$

**Example 2.4.11.** *Finite* free groups, abelian groups, commutative rings etc. form dense generators of **Grp**, **Ab**, **CRng** etc.

Recall that the category of  $T$ -algebras of a finitary monad  $T: \mathbf{Set} \rightarrow \mathbf{Set}$  is cocomplete. We would like to know that  $T\text{-Alg}$  is locally finitely presentable. This result can be proved using the following fact (which is in turn an easy consequence of the result about the commutativity of  $\kappa$ -filtered colimits with  $\kappa$ -small limits in **Set**):

$\kappa$ -presentable objects are closed under  $\kappa$ -small colimits.

**Proposition 2.4.12.** Let  $\mathcal{C}$  be a locally small cocomplete category which has a *small* dense subcategory consisting of  $\kappa$ -presentable objects. Then  $\mathcal{C}$  is locally  $\kappa$ -presentable.

*Proof.* Let  $\mathcal{A}'$  be the closure of  $\mathcal{A}$  under  $\kappa$ -small colimits. This is constructed as follows:  $\mathcal{A}_0 = \mathcal{A}$ . For any ordinal  $i$  we set

$$\mathcal{A}_{i+1} = \{\text{colimits of } \kappa\text{-small diagrams in } \mathcal{A}_i\}$$

and for a limit-ordinal  $\lambda$  we set  $\mathcal{A}_\lambda = \bigcup_{\mu < \lambda} \mathcal{A}_\mu$ . This terminates when  $\lambda = \kappa$ , so  $\mathcal{A}_\kappa$  is the colimit closure and thus small. From the above mentioned fact we know that  $\mathcal{A}'$  consists of  $\kappa$ -presentable objects. Since it contains  $\mathcal{A}$ , the inclusion  $K: \mathcal{A}' \rightarrow \mathcal{C}$  is dense. If  $\mathcal{A}'$  is dense, then each object in  $\mathcal{C}$  is a colimit of  $(K \downarrow c) \rightarrow \mathcal{C}$  which is a  $\kappa$ -filtered diagram by construction.  $\square$

**Corollary 2.4.13.** For each finitary monad  $T$  on **Set**, the category  $T\text{-Alg}$  is locally finitely presentable. Moreover, if  $T$  is a monad of rank  $\kappa$  on a locally  $\kappa$ -presentable category, then  $T\text{-Alg}$  is locally  $\kappa$ -presentable if and only if it is cocomplete.

**Theorem 2.4.14.** Let  $\mathcal{J}$  be a filtered category and

$$X: \mathcal{J} \rightarrow \mathbf{Set}, \quad i \mapsto X_i$$

a diagram and  $(X_i \xrightarrow{n_i} X)_i$  a cocone. Then  $(X_i \rightarrow X)_i$  is a colimit cocone if and only if

- i) For all  $x \in X$  there exists an  $i \in \mathcal{J}$  and an  $\tilde{x} \in X_i$  such that  $x = n_i(\tilde{x})$ .
- ii) If  $x, y \in X_i$  satisfy  $n_i(x) = n_i(y)$ , then there is some  $\phi: i \rightarrow j$  such that  $X_\phi(x) = X_\phi(y)$ .  
(Informally: “all equalities that hold in  $X$  hold in some  $X_j$ .”)

*Proof.* Given any other cocone  $\lambda_i: X_i \rightarrow Y$  we define  $f: X \rightarrow Y$  as  $x \mapsto \lambda_i(\tilde{x})$  for any, with  $\tilde{x}$  constructed as in (i). This is well defined by (ii) and filteredness. It only remains to show that there exists such a cocone. Take  $X = (\coprod X_i) / \sim$  with  $(x, i) \sim (y, j)$  if there is some diagram  $i \xrightarrow{\phi} k \xleftarrow{\psi} j$  in  $\mathcal{J}$  with  $X_\phi(x) = X_\psi(y)$ .  $\square$

**Corollary 2.4.15.** In **Set** filtered colimits commute with finite limits and  $\kappa$ -filtered colimits commute with  $\kappa$ -small limits.

*Proof.* Check that a levelwise equalizer of cones satisfying i) and ii) above still satisfies i) and ii). This can be done by chasing through the following diagram

$$\begin{array}{ccccc} X_i & \hookrightarrow & Y_i & \rightrightarrows & Z_i \\ \downarrow & & \downarrow & & \downarrow \\ X & \hookrightarrow & Y & \rightrightarrows & Z \end{array}$$

For  $< \kappa$ -fold products, we use  $\kappa$ -filteredness to extend ii) to any set of pairs of size  $< \kappa$ . Then check that the product of cones satisfying i) and ii) of size  $< \kappa$  still satisfies i) and ii).  $\square$

**Corollary 2.4.16.** In any category,  $\kappa$ -presentable objects are closed under  $\kappa$ -small colimits.

*Proof.* Let  $C: \mathcal{J} \rightarrow \mathcal{C}$  be a  $\kappa$ -filtered diagram and  $D: \mathcal{J} \rightarrow \mathcal{C}$  a  $\kappa$ -small diagram of  $\kappa$ -presentable objects  $D_j$ .

$$\begin{aligned} \mathcal{C}(\operatorname{colim}_{\mathcal{J}} D_j, \operatorname{colim}_{\mathcal{J}} C_i) &\cong \lim_{\mathcal{J}} \mathcal{C}(D_j, \operatorname{colim}_{\mathcal{J}} C_i) \\ &\cong \lim_{\mathcal{J}} \operatorname{colim}_{\mathcal{J}} \mathcal{C}(D_j, C_i) \\ \text{Previous corollary} &\cong \operatorname{colim}_{\mathcal{J}} \lim_{\mathcal{J}} \mathcal{C}(D_j, C_i) \\ &\cong \operatorname{colim}_{\mathcal{J}} \mathcal{C}(\operatorname{colim}_{\mathcal{J}} D_j, C_i). \end{aligned} \quad \square$$

**Proposition 2.4.17.** Each object in a locally presentable category is  $\lambda$ -presentable for  $\lambda \gg 0$ .

*Proof.* Let  $\mathcal{C}$  be locally  $\kappa$ -presentable, choose a small dense subcategory  $\mathcal{A}$  of  $\kappa$ -presentable objects. So, any object  $c \in \mathcal{C}$  we have is a colimit of  $\operatorname{dom}: (K \downarrow c) \rightarrow \mathcal{C}$ , where  $K$  is the inclusion  $\mathcal{A} \rightarrow \mathcal{C}$ . Choose  $\lambda$  such that  $\lambda > \kappa$  and  $\lambda > |\operatorname{Arr}(K \downarrow c)|$ .  $\square$

The characterization of filtered colimits in **Set** gives the following characterization of finitely presentable objects:  $a$  is finitely presentable if for all filtered colimits  $k_i: c_i \rightarrow c$  in  $\mathcal{C}$  and all  $f: a \rightarrow c$  there exists a factorization

$$\begin{array}{ccc} & c_i & \\ f' \nearrow & & \searrow k_i \\ a & \xrightarrow{f} & c \end{array}$$

and any two such lifts  $f', f''$  satisfying  $k_i \cdot f' = k_i \cdot f''$  become equal after composing with some  $c_\phi: c_i \rightarrow c_j$ .

**Corollary 2.4.18.** Let  $\mathcal{C}$  be a locally  $\kappa$ -presentable category. We have that  $\kappa$ -filtered colimits commute with  $\kappa$ -small limits in  $\mathcal{C}$ .

*Proof.* Choose a small dense subcategory  $\mathcal{A} \subset \mathcal{C}$  of  $\kappa$ -presentable objects. The inclusion  $K: \mathcal{A} \rightarrow \mathcal{C}$  induces a fully faithful functor  $\tilde{K}: \mathcal{C} \rightarrow [\mathcal{A}^{\operatorname{op}}, \mathbf{Set}]$  with left adjoint  $\operatorname{Lan}_{\mathcal{A}} K$ , hence it preserves all limits. This implies that  $\mathcal{C}$  is complete as a reflective subcategory of the complete category  $[\mathcal{A}^{\operatorname{op}}, \mathbf{Set}]^3$ . Moreover,  $\tilde{K}$  preserves  $\kappa$ -filtered colimits because  $\operatorname{ev}_a \circ \tilde{K} = \mathcal{C}(Ka, -)$ , which reduces the problem to  $\kappa$ -small limits and  $\kappa$ -filtered colimits in  $[\mathcal{A}^{\operatorname{op}}, \mathbf{Set}]$ , where both are computed levelwise.  $\square$

**Proposition 2.4.19.** Let  $\mathcal{C}, \mathcal{D}$  be locally  $\kappa$ -presentable,  $\lambda \geq \kappa$  a regular cardinal. Then the category  $[\mathcal{C}, \mathcal{D}]_\lambda$  of  $\lambda$ -accessible functors and natural transformations is locally small, cocomplete and the inclusion  $[\mathcal{C}, \mathcal{D}]_\lambda \rightarrow [\mathcal{C}, \mathcal{D}]$  preserves colimits. In fact,  $[\mathcal{C}, \mathcal{D}]_\lambda$  is locally presentable.

*Proof.* The category  $\mathcal{C}_\lambda$  of  $\lambda$ -presentable objects in  $\mathcal{C}$  is essentially small and each  $(\mathcal{C}_\lambda \downarrow c)$  is  $\lambda$ -filtered, so  $\mathcal{C}_\lambda \hookrightarrow \mathcal{C}$  is dense with density presentation consisting of  $\lambda$ -filtered colimits. From a general fact, the left adjoint of

$$[\mathcal{C}_\lambda, \mathcal{D}] \xrightleftharpoons[\operatorname{K}^*]{\operatorname{Lan}_K} [\mathcal{C}, \mathcal{D}]$$

<sup>3</sup>Note, that one also could define a locally  $\kappa$ -presentable category to be a reflexive subcategory of a presheaf category, such that the inclusion commutes with  $\kappa$ -filtered colimits

induces an equivalence onto its essential image, which is precisely  $[\mathcal{C}, \mathcal{D}]_\lambda$ . In other words,  $[\mathcal{C}, \mathcal{D}]_\lambda \cong [\mathcal{C}_\lambda, \mathcal{D}]$  is locally small and the inclusion preserves all colimits. Furthermore,  $[\mathcal{C}, \mathcal{D}]_\lambda$  is locally presentable since  $[\mathcal{C}_\lambda, \mathcal{D}]$  is locally  $\kappa$ -presentable.  $\square$

**Corollary 2.4.20.** The category of accessible functors  $[\mathcal{C}, \mathcal{D}]_{\text{acc}}$  is closed under small colimits in  $[\mathcal{C}, \mathcal{D}]$ .

*Proof.* This is clear, since  $[\mathcal{C}, \mathcal{D}]_{\text{acc}} = \bigcup_\lambda [\mathcal{C}, \mathcal{D}]_\lambda$ .  $\square$

The following theorem about dense functors has already been secretly used previously. Let us prove it once and for all.

**Theorem 2.4.21.** Consider two small categories  $\mathcal{A}$  and  $\mathcal{A}'$  and two fully faithful functors  $\mathcal{A} \xrightarrow{P} \mathcal{A}' \xrightarrow{J} \mathcal{C}$ . If the composite  $K = JP$  is dense, then both  $P$  and  $J$  are dense.

*Proof.* It is immediate for  $P$ , since  $\tilde{P} = \tilde{K}|_{\mathcal{A}'}$ . Let us show that  $J$  is dense. Note that we have

$$\begin{aligned} \mathcal{C}(Jd, c) &\xrightarrow[\sim]{\tilde{JP}} [\mathcal{A}^{\text{op}}, \mathbf{Set}] (\mathcal{C}(JP, Jd), \mathcal{C}(JP, c)) \\ &\xrightarrow[\sim]{(JP, d)^*} [\mathcal{A}^{\text{op}}, \mathbf{Set}] (\mathcal{A}'(P, d), \mathcal{C}(JP, c)) \end{aligned}$$

where the first isomorphism holds because  $JP$  is dense and the second one because  $J$  is fully faithful. Consequently  $J$  is the pointwise left Kan extension of  $JP$  along  $P$ .

$$\begin{array}{ccc} \mathcal{A} & \xrightarrow{P} & \mathcal{A}' \\ & \searrow \scriptstyle JP & \swarrow \scriptstyle J \\ & \mathcal{C} & \end{array}$$

Since the left Kan extension is pointwise, it is preserved by any cocontinuous functor out of  $\mathcal{C}$ . In particular, for every  $c \in \mathcal{C}$  we can apply  $\mathcal{C}(-, c): \mathcal{C} \rightarrow \mathbf{Set}^{\text{op}}$  and we get that

$$\begin{array}{ccc} \mathcal{A}^{\text{op}} & \xrightarrow{P^{\text{op}}} & (\mathcal{A}')^{\text{op}} \\ & \searrow \scriptstyle \mathcal{C}(JP, c) & \swarrow \scriptstyle \mathcal{C}(J, c) \\ & \mathbf{Set} & \end{array}$$

is a right Kan extension for every  $c \in \mathcal{C}$ . In particular, each  $\alpha: \mathcal{C}(J, c) \Rightarrow \mathcal{C}(J, c')$  is uniquely given by  $\alpha P^{\text{op}}: \mathcal{C}(JP, c) \Rightarrow \mathcal{C}(JP, c')$ . By density of  $JP = K$ ,  $\alpha P^{\text{op}}$  must be of the form  $g_*$  for a unique  $g: c \rightarrow c'$ . By uniqueness,  $\alpha = \mathcal{C}(J, g)$ , hence  $\tilde{J}$  is full. Moreover,  $\tilde{JP}$  is equal to the composition  $\mathcal{C} \xrightarrow{\tilde{J}} [(\mathcal{A}')^{\text{op}}, \mathbf{Set}] \xrightarrow{(P^{\text{op}})^*} [\mathcal{A}^{\text{op}}, \mathbf{Set}]$  and then  $\tilde{J}$  is also faithful.  $\square$

## 2.5 Cocompleteness of categories of algebras

The goal of this section is to show that, if  $T$  is a monad on a locally presentable category  $\mathcal{C}$  and  $T$  has rank (it is accessible), then  $T\text{-Alg}$  is cocomplete and thus locally presentable (the last bit is a consequence of a previous result).

There exists a single construction which admits the following as special cases:

- free monad on an endofunctor,

- free monad on a pointed endofunctor,
- free monoid on an object in a monoidal category,
- orthogonal factorization system generated by a set of morphisms,
- reflectiveness of a small orthogonality class,
- cocompletion of  $T\text{-Alg}$  for suitable monads  $T$ ,
- existence of colimits of diagrams of accessible monads.

This was observed by G. M. Kelly in [kelly1980unified], which is “hard to read” but simplifies greatly in the context of locally presentable categories.

Throughout this section we will work with locally presentable categories and accessible functors.

Kelly’s main observation is that all above constructions can be reduced to the case of algebras for a well-pointed endofunctor.

**Definition 2.5.1.** Let  $S: \mathcal{C} \rightarrow \mathcal{C}$  be a functor. We call  $S$  *pointed* if there exists  $\sigma: \text{id}_{\mathcal{C}} \Rightarrow S$ . The pair  $(S, \sigma)$  is *well-pointed*<sup>4</sup> if  $S\sigma = \sigma S: S \Rightarrow S^2$ .

**Definition 2.5.2.** Given a pointed endofunctor  $(S, \sigma)$ , a  $(S, \sigma)$ -algebra is a pair  $(a, \alpha)$ , where  $\alpha: Sa \rightarrow a$  is a morphism in  $\mathcal{C}$  s.t.  $\alpha \cdot \sigma_a = \text{id}_a$  (basically a monad without multiplication gives an example). A morphism of algebras  $(a, \alpha) \rightarrow (b, \beta)$  is a morphism  $f: a \rightarrow b$  in  $\mathcal{C}$  such that

$$\begin{array}{ccc} Sa & \xrightarrow{Sf} & Sb \\ \alpha \downarrow & & \downarrow \beta \\ a & \xrightarrow{f} & b \end{array}$$

commutes. We write  $(S, \sigma)\text{-Alg}$  for the resulting category and  $U^S: (S, \sigma)\text{-Alg} \rightarrow \mathcal{C}$  for the forgetful functor.

**Lemma 2.5.3.** If  $(S, \sigma)$  is a well-pointed endofunctor, then there exists at most one algebra structure for any object and it exists if and only if  $\sigma_a$  is invertible, in which case  $\alpha = \sigma_a^{-1}$ . Moreover,  $U^S: (S, \sigma)\text{-Alg} \rightarrow \mathcal{C}$  is fully faithful. In other words,  $(S, \sigma)\text{-Alg}$  is isomorphic to the full subcategory of  $\mathcal{C}$  given by  $\{a \in \mathcal{C} \mid \sigma_a \text{ is invertible}\}$ .

*Proof.* For fixed  $(a, \alpha) \in (S, \sigma)\text{-Alg}$ , the diagram

$$\begin{array}{ccc} Sa & \xrightarrow{\sigma_{Sa}} & S^2a \\ \alpha \downarrow & & \downarrow S\alpha \\ a & \xrightarrow{\sigma_a} & Sa \end{array}$$

commutes by the naturality of  $\sigma$ . Since  $S$  is well-pointed, this implies  $\sigma_a \cdot \alpha = S\alpha \cdot \sigma_{Sa} = S\alpha \cdot S\sigma_a = S(\alpha \cdot \sigma_a) = S\text{id}_a = \text{id}_{Sa}$ , therefore  $\alpha = \sigma_a^{-1}$ . On the other hand, if  $\sigma_a$  is invertible then  $(a, \sigma_a^{-1})$  is a  $(S, \sigma)$ -algebra.

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<sup>4</sup>Note that, as soon as one defines a monad to be idempotent if the multiplication is an isomorphism, being idempotent is equivalent to being well-pointed.

If  $f: a \rightarrow b$  is any morphism and both  $\sigma_a$  and  $\sigma_b$  are invertible, then

$$\begin{array}{ccc} Sa & \xrightarrow{Sf} & Sb \\ \sigma_a^{-1} \downarrow & & \downarrow \sigma_b^{-1} \\ a & \xrightarrow{f} & b \end{array}$$

commutes by naturality of  $\sigma$ , so  $U^S$  is full (being faithful by construction). It follows that  $U^S: (S, \sigma)\text{-Alg} \rightarrow \{a \in \mathcal{C} \mid \sigma_a \text{ is invertible}\}$  is bijective on objects and fully faithful, so it is an isomorphism.  $\square$

**Lemma 2.5.4.** If  $(S, \sigma)$  is a pointed endofunctor, then  $U^S: (S, \sigma)\text{-Alg} \rightarrow \mathcal{C}$  is monadic if and only if it has a left adjoint.

*Proof.*  $U^S$  is conservative and creates all colimits preserved by  $S$ . In particular, it preserves coequalizers of  $U^S$ -split pairs.  $\square$

**Definition 2.5.5.** For an endofunctor  $F: \mathcal{C} \rightarrow \mathcal{C}$  (or a pointed endofunctor  $(S, \sigma)$ ), we say that the *algebraically free monad* on  $F$  (respectively  $(S, \sigma)$ ) exists if  $U^F: F\text{-Alg} \rightarrow \mathcal{C}$  (or  $U^S: (S, \sigma)\text{-Alg} \rightarrow \mathcal{C}$ ) has a left adjoint.

We will denote by **Ord** the category of ordinals. Furthermore, using the well-ordering principle, we can associate an ordinal to any cardinal. Note that, given a regular cardinal  $\kappa$ , its associated ordinal (which also will be denoted by  $\kappa$ ) will be a limit ordinal.

**Theorem 2.5.6.** Let  $\mathcal{C}$  be a category with colimits of chains (that is the domain of the diagram is an ordinal). Let  $(S, \sigma)$  be a well-pointed endofunctor such that  $S$  preserves  $\kappa$ -filtered colimits. Then, the algebraically free monad on  $(S, \sigma)$  exists. In particular,  $\{c \in \mathcal{C} \mid \sigma_c \text{ is an isomorphism}\}$  is a reflective subcategory.

*Proof.* For a given object  $c \in \mathcal{C}$  we define a functor  $S^\bullet c: \mathbf{Ord} \rightarrow \mathcal{C}$  by setting  $S^0 c := c$ , while  $S^{\lambda+1} c := S(S^\lambda c)$ , with  $S^\lambda c \rightarrow S^{\lambda+1} c$  given by  $\sigma_{S^\lambda c}$  for  $\lambda \in \mathbf{Ord}$ . Given a limit ordinal  $\mu$ , we set  $S^\mu c = \text{colim}_{\lambda < \mu} S^\lambda c$ .

We claim that  $S^\kappa c$  lies in  $(S, \sigma)\text{-Alg}$ , that is  $\sigma_{S^\kappa c}$  is an isomorphism. We will prove this by constructing an inverse  $\alpha: S(S^\kappa c) \rightarrow S^\kappa c$ .

Since  $S$  is  $\kappa$ -accessible,  $S^{\kappa+1} c = S(S^\kappa c) = \text{colim}_{\lambda < \kappa} S(S^\lambda c)$ . We construct a cocone on  $S(S^\bullet c)$  by considering the maps  $l_{\lambda+1}: S(S^\lambda c) = S^{\lambda+1} c \rightarrow S^\kappa c$  exhibiting  $S^\kappa c$  as a colimit.

$$\begin{array}{ccc} S(S^\lambda c) & \xrightarrow{S\sigma_{S^\lambda c} = \sigma_{S^{\lambda+1} c}} & S(S^{\lambda+1} c) \\ \downarrow l_{\lambda+1} & & \downarrow l_{\lambda+2} \\ S^\kappa c & \xlongequal{\quad} & S^\kappa c \end{array}$$

Well pointedness gives us the upper equality and the diagram commutes, hence we get a cocone culminating in  $S^\kappa c$ , which will then factor uniquely through the cocone culminating in  $S(S^\kappa c)$  as  $\alpha: S(S^\kappa c) \rightarrow S^\kappa c$ . By construction, the following diagram commutes and  $l_{\mu+1} \cdot \sigma_{S^\mu c} = l_\mu$  by the definition of the cocone.

$$\begin{array}{ccccc} S^\mu c & \xrightarrow{\sigma_{S^\mu c}} & S(S^\mu c) & & \\ \downarrow l_\mu & & \downarrow Sl_\mu & \searrow l_{\mu+1} & \\ S^\kappa c & \xrightarrow{\sigma_{S^\kappa c}} & S(S^\kappa c) & \xrightarrow{\alpha} & S^\kappa c \end{array}$$



Passing to the colimit, this implies that  $\alpha \cdot \sigma_{S^\kappa c} = \text{id}_{S^\kappa c}$  because the  $l_\mu$  on the left and therefore  $l_{\mu+1} \cdot \sigma_{S^\mu c} = l_\mu$  become identities, hence  $(S^\kappa c, \alpha)$  is indeed a  $(S, \sigma)$ -algebra.

We now claim that  $l_0: c \rightarrow S^\kappa c$  defines a reflection into the full subcategory given by  $\mathcal{B} := \{c \in \mathcal{C} \mid \sigma_c \text{ is an isomorphism}\}$ . Firstly, we have shown that  $S^\kappa c \in \mathcal{B}$ , hence we only need  $l_0^*: \mathcal{C}(S^\kappa c, b) \rightarrow \mathcal{C}(c, b)$  to be a bijection for all  $b \in \mathcal{B}$ .

Since representable functors  $\mathcal{C}(-, b)$  send colimits to limits, this immediately reduces to the following: given  $b \in \mathcal{B}$ ,  $c \in \mathcal{C}$ , the map  $\sigma_c^*: \mathcal{C}(Sc, b) \rightarrow \mathcal{C}(c, b)$  is a bijection.

Using well-pointedness, we can write the inverse to  $\sigma_c^*$  as  $\mathcal{C}(c, b) \rightarrow \mathcal{C}(Sc, b)$ ,  $f \mapsto \sigma_b^{-1} \cdot Sf$ .  $\square$

**Theorem 2.5.7.** Let  $\mathcal{C}$  be a cocomplete category,  $F: \mathcal{C} \rightarrow \mathcal{C}$  an endofunctor. The comma category  $(F \downarrow \mathcal{C})$  is cocomplete. Moreover, all colimits preserved by  $F$  are computed pointwise, that is  $\text{colim}_{\mathcal{J}}(a_i, b_i, \alpha_i: Fa_i \rightarrow b_i) = (\text{colim}_{\mathcal{J}} a_i, \text{colim}_{\mathcal{J}} b_i, \text{colim}_{\mathcal{J}} \alpha_i: F(\text{colim}_{\mathcal{J}} a_i) \rightarrow \text{colim}_{\mathcal{J}} b_i)$ .

*Proof.* Giving a diagram  $D: \mathcal{J} \rightarrow (F \downarrow \mathcal{C})$  amounts to giving diagrams  $a_\bullet: \mathcal{J} \rightarrow \mathcal{C}$ ,  $b_\bullet: \mathcal{J} \rightarrow \mathcal{C}$  and a natural transformation  $\alpha_\bullet: Fa_\bullet \Rightarrow b_\bullet$ .

Giving a cocone on this with vertex  $(c, d, \gamma: Fc \rightarrow d)$  is equivalent to giving morphisms  $\text{colim}_{\mathcal{J}} a_i \rightarrow c$ ,  $\text{colim}_{\mathcal{J}} b_i \rightarrow c$  such that the diagram

$$\begin{array}{ccccc} Fa_i & \longrightarrow & F(\text{colim}_{\mathcal{J}} a_i) & \longrightarrow & Fc \\ \downarrow & & \downarrow & & \downarrow \gamma \\ b_i & \longrightarrow & \text{colim}_{\mathcal{J}} b_i & \longrightarrow & d \end{array}$$

commutes for all  $i$ .

Equivalently, we can give a morphism  $\text{colim}_{\mathcal{J}} a_i \rightarrow c$  and a morphism from the pushout  $p$  to  $d$  making the following diagram commute.

$$\begin{array}{ccccc} \text{colim}_{\mathcal{J}} Fa_i & \longrightarrow & F(\text{colim}_{\mathcal{J}} a_i) & \longrightarrow & Fc \\ \downarrow \text{colim}_{\mathcal{J}} \alpha_i & & \downarrow & & \downarrow \gamma \\ \text{colim}_{\mathcal{J}} b_i & \longrightarrow & p & \longrightarrow & d \end{array}$$

We have then the colimit  $(\text{colim}_{\mathcal{J}} a_i, p, F(\text{colim}_{\mathcal{J}} a_i) \rightarrow p)$  in  $(F \downarrow \mathcal{C})$ . In particular, if  $F$  preserves this colimit, then the top map  $\text{colim}_{\mathcal{J}} Fa_i \rightarrow F(\text{colim}_{\mathcal{J}} a_i)$  is an isomorphism, in which case we may take  $p = \text{colim}_{\mathcal{J}} b_i$  and the identity as the map from  $\text{colim}_{\mathcal{J}} b_i$  to  $p$ .  $\square$

**Proposition 2.5.8.** If in the theorem above  $\mathcal{C}$  is locally presentable and  $F$  is accessible, then  $(F \downarrow \mathcal{C})$  is locally presentable.

*Proof.* There exists a regular cardinal  $\kappa$  such that  $\mathcal{C}$  is locally  $\kappa$ -presentable and  $F(\mathcal{C}_\lambda) \subset \mathcal{C}_\kappa$ , with  $F$   $\lambda$ -accessible and  $\lambda \leq \kappa$ . We claim that the full subcategory  $\mathcal{A} := \{(a, b, \alpha: Fa \rightarrow b) \mid a \in \mathcal{C}_\lambda, b \in \mathcal{C}_\kappa\}$  is dense and consists of  $\kappa$ -presentable objects in  $(F \downarrow \mathcal{C})$ .

The fact that it consists of  $\kappa$ -presentable objects follows from the facts that  $\kappa$ -filtered colimits in  $(F \downarrow \mathcal{C})$  are computed pointwise.

To prove density, we want that for each  $(c, d, \gamma: Fc \rightarrow d)$  the canonical cocone of  $(\mathcal{A} \downarrow (c, d, \gamma)) \rightarrow (F \downarrow \mathcal{C})$  exhibits  $(c, d, \gamma)$  as a colimit. In the arrow category  $\mathcal{C}^{[1]}$ ,  $Fc \rightarrow d$  is a colimit of all  $\kappa$ -presentable pairs  $c_0, c_1 \in \mathcal{C}_\lambda$  with a morphism  $c_0 \rightarrow c_1$  such that there exists a pair of morphisms making the diagram

$$\begin{array}{ccc} c_0 & \longrightarrow & Fc \\ \downarrow & & \downarrow \\ c_1 & \longrightarrow & d \end{array}$$

commute.

We need to check that the natural functor  $(\mathcal{A} \downarrow (c, d, \gamma)) \rightarrow ((\mathcal{C}^{[1]})_\lambda \downarrow \gamma)$  is final.

Check for yourself that the category  $((\mathcal{C}^{[1]})_\lambda \downarrow \gamma)$  we are considering is actually filtered and specifically can always find a pair of morphisms completing the following commutative diagram, where  $Fa \rightarrow b$  comes from  $\mathcal{A}$ .

$$\begin{array}{ccccc}
 & & Fa & & \\
 & \nearrow & \downarrow & \searrow & \\
 c_0 & \xrightarrow{\quad} & & & Fc \\
 \downarrow & & \downarrow & & \downarrow \\
 & \nearrow & b & \searrow & \\
 c_1 & \xrightarrow{\quad} & & & d
 \end{array}$$

The codomains form a colimit diagram in  $\mathcal{C}$ , hence we are left with checking that the domains form a colimit diagram as well. To do this, we use the fact that  $(\mathcal{C}_\lambda \downarrow c) \rightarrow \mathcal{C}$  has colimit  $c$  and an argument similar to the previous one.  $\square$

## 2.6 Algebraically free Monads on a pointed Endofunctor

Let  $T: \mathcal{C} \rightarrow \mathcal{C}$  a  $\kappa$ -accessible endofunctor, with  $\mathcal{C}$  cocomplete. As we have already shown, the category  $(T \downarrow \mathcal{C})$  is cocomplete and  $\kappa$ -filtered colimits in  $(T \downarrow \mathcal{C})$  are computed objectwise. Given a natural transformation  $\alpha: T' \Rightarrow T$ , we get an adjunction

$$(T' \downarrow \mathcal{C}) \begin{array}{c} \xrightarrow{\alpha_!} \\ \perp \\ \xleftarrow{\alpha^*} \end{array} (T \downarrow \mathcal{C})$$

where  $\alpha^*(a, b, Ta \xrightarrow{\gamma} b) = (a, b, T'a \xrightarrow{\alpha_a} Ta \xrightarrow{\gamma} b)$  and  $\alpha_!$  is given by the pushout

$$\begin{array}{ccc}
 T'a & \xrightarrow{\beta} & b \\
 \downarrow \alpha_a & & \downarrow \\
 Ta & \xrightarrow{\gamma} & c
 \end{array},$$

that is  $\alpha_!(a, b, \beta) = (Ta \xrightarrow{\gamma} c)$ . If  $T, T'$  are  $\kappa$ -accessible, then  $\alpha^*$  is  $\kappa$ -accessible. If we apply this to the case  $T' = \text{id}_{\mathcal{C}}$ ,  $\alpha = \tau: \text{id}_{\mathcal{C}} \rightarrow T$ , then  $(\text{id}_{\mathcal{C}} \downarrow \mathcal{C}) = \mathcal{C}^{[1]}$  is the arrow category, and  $\tau^*$  sends  $(a, b, Ta \xrightarrow{\gamma} b)$  to  $a \xrightarrow{\alpha_a} Ta \xrightarrow{\gamma} b$ . Now use exercise 5.1.

**Proposition 2.6.1.** If

$$\mathcal{D} \begin{array}{c} \xrightarrow{F} \\ \perp \\ \xleftarrow{U} \end{array} \mathcal{C}$$

is an adjunction,  $(S, \sigma)$  is a well-pointed endofunctor on  $\mathcal{D}$  and  $\mathcal{C}$  has pushouts, then

$$\begin{array}{ccc}
 FU & \xrightarrow{F\sigma U} & FSU \\
 \downarrow \epsilon & & \downarrow \\
 \text{id}_{\mathcal{C}} & \xrightarrow{\sigma'} & S'
 \end{array}$$

defines a well-pointed endofunctor  $(S', \sigma')$  on  $\mathcal{C}$  such that the square

$$\begin{array}{ccc} (S', \sigma')\text{-Alg} & \xrightarrow{\bar{U}} & (S, \sigma)\text{-Alg} \\ \downarrow & & \downarrow \\ \mathcal{C} & \xrightarrow{U} & \mathcal{D} \end{array}$$

is a pullback.  $\square$

**Theorem 2.6.2.** Let  $\mathcal{C}$  be a cocomplete category,  $(T, \tau)$  a pointed endofunctor on  $\mathcal{C}$  with  $T$   $\kappa$ -accessible. Then  $(T, \tau)\text{-Alg}$  is a reflective subcategory of  $(T \downarrow \mathcal{C})$  and the algebraically free monad on  $(T, \tau)$  exists. In particular, by reflexivity,  $(T, \tau)\text{-Alg}$  is cocomplete.

*Proof.* Notice that the functor

$$(T, \tau)\text{-Alg} \rightarrow (T \downarrow \mathcal{C}), \quad (a, \alpha) \mapsto (a, a, Ta \xrightarrow{\alpha} a), \quad f \mapsto (f, f)$$

is fully faithful. It is clearly faithful, and if  $(f, g): (a, a, \alpha) \rightarrow (b, b, \beta)$  is a morphism in  $(T \downarrow \mathcal{C})$ , then we have a commutative diagram

$$\begin{array}{ccccc} a & \xrightarrow{\tau_a} & Ta & \xrightarrow{\alpha} & a \\ \downarrow f & & \downarrow Tf & & \downarrow g \\ b & \xrightarrow{\tau_b} & Tb & \xrightarrow{\beta} & b \end{array}$$

Since  $(a, \alpha)$  and  $(b, \beta)$  are algebras, we have  $\beta \cdot \tau_b = \text{id}_b$  and  $\alpha \cdot \tau_a = \text{id}_a$ . It immediately follows that  $f = g$ . Moreover, the essential image of this functor is

$$\{(a, b, \gamma) \in (T \downarrow \mathcal{C}) \mid \gamma \cdot \tau_a \text{ is an isomorphism}\}$$

Apply the previous proposition to the pullback

$$\begin{array}{ccc} (T, \tau)\text{-Alg} & \longrightarrow & \text{Iso}(\mathcal{C}) \\ \downarrow & & \downarrow \\ (T \downarrow \mathcal{C}) & \xrightarrow{\tau^*} & \mathcal{C}^{[1]} \\ (a, b, \gamma) & \longmapsto & \gamma \tau_a \end{array}$$

and the well-pointed endofunctor  $S: \mathcal{C}^{[1]} \rightarrow \mathcal{C}^{[1]}$  given by  $S(c \rightarrow d) = \text{id}_d$  with  $(S, \sigma)\text{-Alg} = \text{Iso}(\mathcal{C})$ . We obtain  $(S', \sigma')$  such that  $(T, \tau)\text{-Alg} \cong (S', \sigma')\text{-Alg}$ . Since the pushout from the previous proposition consists of  $\kappa$ -accessible functors (here we use that  $\tau^*$  is  $\kappa$ -accessible),  $(S', \sigma')$  is  $\kappa$ -accessible. It follows that  $(S', \sigma')\text{-Alg}$  is reflexive in  $(T \downarrow \mathcal{C})$ , as claimed.

Thus  $(T, \tau)\text{-Alg}$  is cocomplete. Note that the forgetful functor  $U^T: (T, \tau)\text{-Alg} \rightarrow \mathcal{C}$  factors as

$$\begin{array}{ccc} (T, \tau)\text{-Alg} & \longrightarrow & (T \downarrow \mathcal{C}) \xrightarrow{\text{dom}} \mathcal{C} \\ (a, \alpha) & \longmapsto & (a, a, \alpha) \mapsto a \end{array}$$

and  $(T, \tau)\text{-Alg} \rightarrow \mathcal{C}$  has a left adjoint. To show this, we only need to find a left adjoint to  $\text{dom}$  which is given by  $c \mapsto (c, Tc, \text{id}_{Tc})$ .  $\square$

**Theorem 2.6.3.** Let  $\mathcal{C}$  be a cocomplete category and  $F$  a  $\kappa$ -accessible endofunctor. The category  $F\text{-Alg}$  is cocomplete and the algebraically free monad on  $F$  exists, that is the functor  $U^F: F\text{-Alg} \rightarrow \mathcal{C}$  has a left adjoint.

*Proof.* Let  $T$  be the coproduct  $F + \text{id}_{\mathcal{C}}$  and  $\tau: \text{id}_{\mathcal{C}} \Rightarrow F + \text{id}_{\mathcal{C}}$  the inclusion. Then  $(T, \tau)\text{-Alg} \cong F\text{-Alg}$  is an isomorphism which is compatible with the forgetful functors.  $\square$

For example, we can easily prove the following.

**Proposition 2.6.4.** Let  $\mathcal{C}$  be a locally  $\kappa$ -presentable category and  $T: \mathcal{C} \rightarrow \mathcal{C}$   $\kappa$ -accessible. Then  $(T \downarrow \mathcal{C})$  is locally  $\kappa$ -presentable.

*Proof.* Consider the functor  $\mathcal{C} \times \mathcal{C} \xrightarrow{F} \mathcal{C} \times \mathcal{C}$ ,  $(a, b) \mapsto (\emptyset, Ta)$ . Then  $F\text{-Alg} \cong (T \downarrow \mathcal{C})$  and  $U^F$  is  $\kappa$ -accessible. Since  $U^F$  is monadic, the free objects on the  $\kappa$ -presentable objects form a dense generating set consisting of  $\kappa$ -presentable objects in  $F\text{-Alg} \cong (T \downarrow \mathcal{C})$ .  $\square$

**Remark 2.6.5.** An analysis of the construction of  $(S', \sigma')$  in the proof of the previous theorem shows that  $S': (T \downarrow \mathcal{C}) \rightarrow (T \downarrow \mathcal{C})$  sends  $(a, b, \alpha: Ta \rightarrow b)$  to  $(b, c, \gamma: Tb \rightarrow c)$  where

$$Ta \xrightarrow[\tau_{Ta}]{T\tau_a} T^2a \xrightarrow{T\alpha} Tb \xrightarrow{\beta} c \quad (1)$$

is a coequalizer diagram in  $\mathcal{C}$ . Notice that  $\beta$  is a coequalizer of  $T\alpha \cdot T\tau_a$  and  $T\alpha \cdot \tau_{Ta}$  (see the exercises for more details).

**Proposition 2.6.6.** Let  $(S, \sigma)$  be a well-pointed endofunctor on  $\mathcal{C}$  and let  $L: \mathcal{C} \rightarrow \mathcal{C}$  be a functor. If  $\pi: S \rightarrow L$  is a natural transformation such that  $\pi_c: Sc \rightarrow Lc$  is epic for all  $c \in \mathcal{C}$ , then  $(L, \pi \cdot \sigma)$  is a well-pointed endofunctor and  $(L, \pi \sigma)\text{-Alg}$  is equivalent to the full subcategory of  $(S, \sigma)\text{-Alg}$  on objects  $(a, \alpha)$  such that  $\pi_a: Sa \rightarrow La$  is an isomorphism.

*Proof.* Exercise.  $\square$

Now let  $(T, \mu, \eta)$  be a monad on a cocomplete category  $\mathcal{C}$  and assume  $T$  is  $\kappa$ -accessible. We define an endofunctor  $L: (T \downarrow \mathcal{C}) \rightarrow (T \downarrow \mathcal{C})$  as follows: given  $(a, b, \alpha: Ta \rightarrow b)$  we set  $L(a, b, \alpha) = (b, d, \gamma: Tb \rightarrow d)$  with  $\gamma$  defined by the following pushout in  $\mathcal{C}$ .

$$\begin{array}{ccc} T^2a & \xrightarrow{\mu_a} & Ta \\ T\alpha \downarrow & & \downarrow \delta \\ Tb & \xrightarrow{\gamma} & d \end{array}$$

Using this construction we can finally prove the following.

**Theorem 2.6.7.** Let  $\mathcal{C}$  be a complete category,  $(T, \mu, \eta)$  a monad over  $\mathcal{C}$  with  $T$   $\kappa$ -accessible. Then  $T\text{-Alg}$  is reflexive in  $(T \downarrow \mathcal{C})$  and cocomplete.

*Proof.* Recall that  $(T, \eta)\text{-Alg}$  is reflexive in  $(T \downarrow \mathcal{C})$  and we have a well-pointed endofunctor given by  $S'$  described in (??). Remember the functor  $L$  just defined.

Since  $\mu_a$  has a section  $T\eta_a$ , it is the coequalizer of  $\text{id}_a$  and  $T\eta_a \cdot \mu_a$ . For that reason one also could define  $\gamma$  to be given by the following coequalizer.

$$\begin{array}{ccccc} T^2a & \xlongequal{\quad} & T^2a & \xrightarrow{T\alpha} & Tb \xrightarrow{\gamma} d \\ & \searrow \mu_a & \nearrow T\eta_a & & \\ & & Ta & & \end{array} \quad (2)$$

Given that  $\mu_a \cdot T\eta_a = \text{id}_{Ta}$ , we have  $\delta = \delta \cdot \mu_a \cdot T\eta_a = \gamma \cdot T\alpha \cdot T\eta_a$ . Moreover,  $\gamma$  coequalizes  $T\alpha \cdot T\eta_a$  and  $T\alpha \cdot \eta_{Ta}$ , hence there exists a unique  $\pi: c \rightarrow d$  making the following diagram commute.

$$\begin{array}{ccc} Tb & \xrightarrow{\beta} & c \\ \parallel & & \downarrow \pi \\ Tb & \xrightarrow{\gamma} & d \end{array}$$

This defines a natural transformation  $(\text{id}, \pi): S'(a, b, \alpha) \rightarrow L(a, b, \alpha)$ , where the components are epimorphisms because  $\gamma$  is a coequalizer of the diagram in (??) and therefore an epimorphism.

We get then a well-pointed endofunctor  $(L, \pi\sigma')$  over  $(T \downarrow \mathcal{C})$  with  $(L, \pi\sigma')$ -Alg equivalent to the full subcategory of  $(S', \sigma')$ -Alg given by the objects  $b$  such that  $(\text{id}_b, \pi)$  is an isomorphism. We also have an equivalence  $(T, \eta)\text{-Alg} \rightarrow (S', \sigma')\text{-Alg}$ ,  $(a, \alpha) \mapsto (a, a, \alpha)$ , hence we get that  $(S', \sigma')\text{-Alg}$  is isomorphic to the full subcategory of  $(T, \eta)\text{-Alg}$  given by  $\{(a, \alpha) \in (T, \eta)\text{-Alg} \mid (\text{id}_a, \pi): S'(a, a, \alpha) \rightarrow L(a, a, \alpha) \text{ is an isomorphism}\}$ .

In this case, the coequalizer of (??) is actually  $\alpha: Ta \rightarrow a$  (we have a split given by  $\eta_a$  and  $\text{id}_{Ta}$ ), hence our  $\pi$  looks as follows.

$$\begin{array}{ccc} Ta & \xrightarrow{\alpha} & a \\ \parallel & & \downarrow \pi \\ Ta & \xrightarrow{\gamma} & d \end{array}$$

Having  $\pi$  invertible is then equivalent to  $\alpha$  being the coequalizer of (??), where  $b = a$ . If it is a coequalizer diagram,  $\alpha\mu_a = \alpha T\alpha$ , which implies that  $(a, \alpha)$  is a  $T$ -algebra. Conversely, if  $(a, \alpha)$  is a  $T$ -algebra, then this is a split coequalizer in  $\mathcal{C}$ . It follows that  $T\text{-Alg}$  is equivalent to  $(L, \pi\sigma')\text{-Alg}$ .

$L$  is accessible since  $T$  is and  $\kappa$ -filtered colimits in  $(T \downarrow \mathcal{C})$  are computed as in  $\mathcal{C}$ , thus  $(L, \pi\sigma')\text{-Alg} \rightarrow (T \downarrow \mathcal{C})$  has a left adjoint and therefore  $T\text{-Alg} \rightarrow (T \downarrow \mathcal{C})$ ,  $(a, \alpha) \mapsto (a, a, \alpha)$  is fully faithful and has a left adjoint.  $\square$

We have the following result as a consequence.

**Theorem 2.6.8.** Given a locally  $\kappa$ -presentable category  $\mathcal{C}$  and a monad  $(T, \mu, \eta)$  of rank  $\kappa$ ,  $T\text{-Alg}$  is locally  $\kappa$ -presentable.

*Proof.* We have shown that  $\{(Ta, \mu_a) \mid a \in \mathcal{C}_\kappa\}$  is a dense generating system of  $\kappa$ -presentable objects, hence the claim follows from the fact that  $T\text{-Alg}$  is cocomplete.  $\square$

## 2.7 Monads are monadic

Given an endofunctor  $F: \mathcal{C} \rightarrow \mathcal{C}$ , an algebraically free monad on  $F$  exists if  $U^F: F\text{-Alg} \rightarrow \mathcal{C}$  has a left adjoint  $F^F: \mathcal{C} \rightarrow F\text{-Alg}$ . We write then  $T(F) = (U^F F^F, U^F \epsilon F^F, \eta)$  for the resulting monad. From Beck's theorem, we know that  $J: F\text{-Alg} \rightarrow T(F)\text{-Alg}$ ,  $(a, \alpha) \mapsto (U^F(a, \alpha) = a, U^F \epsilon_{(a, \alpha)})$  is an equivalence of categories. We also have a natural transformation  $\psi: F \Rightarrow T(F)$  corresponding via adjunction to  $\alpha: F U^F \Rightarrow U^F$ . This gives us a functor  $\psi^*: T(F)\text{-Alg} \rightarrow F\text{-Alg}$ ,  $(a, \alpha) \mapsto (a, \alpha\psi_a)$  such that  $\psi^* J = \text{id}_{F\text{-Alg}}$ . We have the following result.

**Proposition 2.7.1.** In the described situation,  $\psi^*$  is an isomorphism of categories.

*Proof.* We still have to show that  $J$  is surjective on objects, which follows from the fact that both  $U^F$  and  $U^{T(F)}$  are isofibrations and the fact that two  $T(F)$ -algebras isomorphic via  $\text{id}_a$  are equal.  $\square$

**Definition 2.7.2.** A *morphism of monads*  $(T, \mu, \eta) \rightarrow (T', \mu', \eta')$  over a category  $\mathcal{C}$  is a natural transformation  $\phi: T \Rightarrow T'$  making the following diagrams commute.

$$\begin{array}{ccc} T^2 & \xrightarrow{\phi^2} & (T')^2 \\ \Downarrow \mu & & \Downarrow \mu' \\ T & \xrightarrow{\phi} & T' \end{array} \quad \begin{array}{ccc} \text{id}_{\mathcal{C}} & \xrightarrow{\eta} & T \\ & \searrow \eta' & \Downarrow \phi \\ & & T' \end{array}$$

The first diagram is equivalent to equating the following 2-cells.

$$\begin{array}{c} \begin{array}{ccc} T & \xrightarrow{\quad} & \mathcal{C} \\ \downarrow \mu & & \downarrow \phi \\ \mathcal{C} & \xrightarrow{T} & \mathcal{C} \\ \uparrow \phi & & \uparrow \mu \\ T' & \xrightarrow{\quad} & \mathcal{C} \end{array} \\ = \\ \begin{array}{ccc} T & \xrightarrow{\quad} & \mathcal{C} \\ \downarrow \phi & & \downarrow \mu' \\ \mathcal{C} & \xrightarrow{T'} & \mathcal{C} \\ \uparrow \mu' & & \uparrow \phi \\ T' & \xrightarrow{\quad} & \mathcal{C} \end{array} \end{array}$$

Likewise, the second diagram amounts saying that the following two 2-cells are equal.

$$\begin{array}{ccc} \begin{array}{ccc} \mathcal{C} & \xrightarrow{\quad} & \mathcal{C} \\ \downarrow \eta & & \downarrow \phi \\ \mathcal{C} & \xrightarrow{T} & \mathcal{C} \\ \uparrow \phi & & \uparrow \eta \\ \mathcal{C} & \xrightarrow{T'} & \mathcal{C} \end{array} & = & \begin{array}{ccc} \mathcal{C} & \xrightarrow{\quad} & \mathcal{C} \\ \downarrow \eta' & & \downarrow \phi \\ \mathcal{C} & \xrightarrow{T'} & \mathcal{C} \\ \uparrow \phi & & \uparrow \eta' \\ \mathcal{C} & \xrightarrow{T'} & \mathcal{C} \end{array} \end{array}$$

We denote the category of monads over  $\mathcal{C}$  by  $\mathbf{Mnd}(\mathcal{C})$ .

**Proposition 2.7.3.** The functor

$$\begin{aligned} \mathbf{Mnd}(\mathcal{C})^{\text{op}} &\rightarrow (\mathbf{CAT} \downarrow \mathcal{C}) \\ (T, \mu, \eta) &\mapsto (U^F: T\text{-Alg} \rightarrow \mathcal{C}) \\ \phi &\mapsto \left( \begin{array}{l} \phi^*: T'\text{-Alg} \rightarrow T\text{-Alg} \\ (a, \alpha) \mapsto (a, \alpha \cdot \phi_a) \end{array} \right) \end{aligned}$$

is fully faithful.

*Proof.* Prove by yourself that this is a functor. Consider then two monads  $T, T'$  over  $\mathcal{C}$ . Giving a functor making the following diagram commute amounts to giving a  $T$ -action on  $U^{T'}$ , that is a natural transformation  $\rho: TU^{T'} \Rightarrow U^{T'}$  making the known diagrams commute.

$$\begin{array}{ccc} T'\text{-Alg} & \longrightarrow & T\text{-Alg} \\ & \searrow U^{T'} & \swarrow U^T \\ & \mathcal{C} & \end{array}$$

Using the adjunction  $F^{T'} \dashv U^{T'}$ , this corresponds to a unique natural transformation  $T \Rightarrow U^{T'} F^{T'} = T'$ . Notice that the  $T$ -action axioms for  $\rho$  correspond precisely to axioms for morphisms of monads, hence we are done.  $\square$

**Proposition 2.7.4** (Algebraically free monads are free). Let  $F: \mathcal{C} \rightarrow \mathcal{C}$  be an endofunctor such that the algebraically free monad  $T(F)$  exists. Then, for every monad  $T$  over  $\mathcal{C}$ , the natural transformation  $\psi: F \Rightarrow T(F)$  induces a bijection  $\psi^*: \mathbf{Mnd}(\mathcal{C}) \rightarrow [\mathcal{C}, \mathcal{C}](F, T)$ .

*Proof.* Consider the diagram

$$\begin{array}{ccc}
 \mathbf{Mnd}(\mathcal{C})^{\text{op}}(T(F), T) & \xrightarrow{\cong} & \left\{ \begin{array}{ccc} T\text{-Alg} & \longrightarrow & T(F)\text{-Alg} \\ & \searrow & \swarrow \\ & \mathcal{C} & \end{array} \right\} \\
 \downarrow \psi^* & & \downarrow \cong \text{compose with } \psi^*: T(F)\text{-Alg} \xrightarrow{\sim} F\text{-Alg} \\
 [\mathcal{C}, \mathcal{C}]^{\text{op}}(F, T) & \longrightarrow & \left\{ \begin{array}{ccc} T\text{-Alg} & \longrightarrow & F\text{-Alg} \\ & \searrow U^T & \swarrow U^F \\ & \mathcal{C} & \end{array} \right\} \\
 \\ 
 \beta: F \Rightarrow T & \longmapsto & \begin{array}{ccc} T\text{-Alg} & \longrightarrow & F\text{-Alg} \\ (a, \alpha) & \mapsto & (a, \alpha\beta_a) \end{array}
 \end{array}$$

which commutes by Yoneda. We want to prove that the horizontal arrows and the one on the right are bijective, which will give us the thesis. The top map is a bijection by the previous proposition and the one on the right is a bijection given by composing with  $\psi^*: T(F)\text{-Alg} \xrightarrow{\sim} F\text{-Alg}$ .

Notice that giving the following commutative diagram amounts to giving a natural transformation  $\rho: FG \Rightarrow G$  without requiring any additional property.

$$\begin{array}{ccc}
 \mathcal{A} & \longrightarrow & F\text{-Alg} \\
 & \searrow G & \swarrow U^F \\
 & \mathcal{C} &
 \end{array}$$

Here the natural transformations  $FU^T \Rightarrow U^T$  correspond bijectively to natural transformations  $F \Rightarrow U^T F^T = T$  by adjunction, hence the bottom map is bijective as well.  $\square$

**Theorem 2.7.5.** Let  $\mathcal{C}$  be a locally  $\kappa$ -presentable category. We write  $\mathbf{Mnd}_\kappa(\mathcal{C})$  for the full subcategory of  $\mathbf{Mnd}(\mathcal{C})$  given by  $\kappa$ -accessible monads. Then, the forgetful functor  $U: \mathbf{Mnd}_\kappa(\mathcal{C}) \rightarrow [\mathcal{C}, \mathcal{C}]_\kappa$  is monadic and  $\kappa$ -accessible. In particular,  $\mathbf{Mnd}_\kappa(\mathcal{C})$  is locally  $\kappa$ -presentable.

*Proof.* We already have seen that, given a  $\kappa$ -accessible  $F$ , the algebraically free monad  $T(F)$  exists and is  $\kappa$ -accessible. Now, since  $\phi: F \Rightarrow T(F)$  is a universal morphism to a monad, the functor  $T(-): [\mathcal{C}, \mathcal{C}]_\kappa \rightarrow \mathbf{Mnd}_\kappa(\mathcal{C})$  is left adjoint to  $U$ . It is also easy to see that  $U$  is conservative: indeed, the inverse of a natural isomorphism, which is a morphism of monads, is a morphism of monads again. It remains to show that  $U$  creates coequalizers of  $U$ -split reflexive pairs. Note first that for any  $F \in [\mathcal{C}, \mathcal{C}]_\kappa$  both pre and post-composition with  $F$  preserve coequalizers of such pairs. In particular those are preserved by the functors  $[\mathcal{C}, \mathcal{C}]_\kappa \rightarrow [\mathcal{C}, \mathcal{C}]_\kappa$  given by the assignments  $F \mapsto F \circ F$  and  $F \mapsto F \circ F \circ F$ . Now for a coequalizer

$$UT_1 \rightrightarrows UT_2 \longrightarrow T'$$

of such a  $U$ -split reflexive pair, the diagram

$$UT_1 \circ UT_1 \rightrightarrows UT_2 \circ UT_2 \longrightarrow T' \circ T'$$

is coequalizer diagram as well. So we get unique natural transformation  $\mu': T' \circ T' \Rightarrow T'$ . Using the same argument, one can identify  $T' \circ T' \circ T'$  as a coequalizer and verify the associativity. Also the unit  $\eta: \text{id} \Rightarrow T'$  can be constructed this way, such that the unit law holds. Thus we have constructed a coequalizer in  $\mathbf{Mnd}_\kappa(\mathcal{C})$  and  $U$  is monadic.

To get the second claim, it remains to show that  $U$  preserves  $\kappa$ -filtered colimits. Note again, that for any  $F \in [\mathcal{C}, \mathcal{C}]_\kappa$  pre-composition with  $F$  preserves all colimits, since those are computed point wise, and post-composition preserves  $\kappa$ -filtered colimits, since  $F$  is  $\kappa$ -accessible. Thus, since  $\kappa$ -filtered colimits are sifted, the functor  $[\mathcal{C}, \mathcal{C}]_\kappa \times [\mathcal{C}, \mathcal{C}]_\kappa \rightarrow [\mathcal{C}, \mathcal{C}]_\kappa$  given by composition preserves them, hence we conclude that the functors given by the assignments  $F \mapsto F \circ F$  and  $F \mapsto F \circ F \circ F$  preserve  $\kappa$ -filtered colimits and use the same arguments as above to see that  $U$  creates  $\kappa$ -filtered colimits.  $\square$

**Proposition 2.7.6.** Let  $\mathcal{C}$  be locally  $\kappa$ -presentable. Then the functor

$$(-)\text{-Alg}: \mathbf{Mnd}_\kappa(\mathcal{C})^{\text{op}} \rightarrow (\mathbf{CAT} \downarrow \mathcal{C})$$

preserves limits. That is, it sends colimits in  $\mathbf{Mnd}_\kappa(\mathcal{C})$  to limits.

The following proof uses a generalisation of the endomorphism monad  $\langle b, b \rangle$  on an object  $b \in \mathcal{C}$ , which was discussed in the exercise class. We will prove the details in use later, but give an idea why the statement holds.

*Proof.* Recall that this endomorphism monad was given by  $\text{Ran}_b b: \mathcal{C} \rightarrow \mathcal{C}$ . Similarly, given two objects  $a, b \in \mathcal{C}$ , one can construct a monad  $\langle a, b \rangle$  given by the right Kan extension of  $b$  along  $a$ .

$$\begin{array}{ccc} \mathcal{C} & & \\ \downarrow & \swarrow a & \\ \mathcal{C} & \Rightarrow & * \\ & \nwarrow b & \end{array}$$

Furthermore a morphism  $f: a \rightarrow b$  gives natural transformations  $\langle a, f \rangle: \langle a, a \rangle \rightarrow \langle a, b \rangle$  and  $\langle f, b \rangle: \langle b, b \rangle \rightarrow \langle a, b \rangle$ . Now, just by unveiling the definitions, one checks that giving a morphism of monads  $T \Rightarrow \langle a, a \rangle$  is equivalent to giving a  $T$ -algebra structure on  $a$ . Moreover, the pullback

$$\begin{array}{ccc} \langle f, f \rangle & \longrightarrow & \langle b, b \rangle \\ \downarrow & & \downarrow \\ \langle a, a \rangle & \longrightarrow & \langle a, b \rangle \end{array}$$

induced by a morphism  $f: a \rightarrow b$  also gives a monad such that, for fixed  $T$ -algebra structures  $T \Rightarrow \langle a, a \rangle$  and  $T \Rightarrow \langle b, b \rangle$ , there exists a morphism of monads  $T \Rightarrow \langle f, f \rangle$  if and only if  $f$  is a morphism of  $T$ -algebras. Now we claim there also exist  $\kappa$ -accessible monads  $\langle a, a \rangle_\kappa$  and  $\langle f, f \rangle_\kappa$  having the property that for any  $\kappa$ -accessible monad  $T$  there is a natural isomorphism

$$\mathbf{Mnd}_\kappa(\mathcal{C})(T, \langle a, a \rangle_\kappa) \cong \mathbf{Mnd}(\mathcal{C})(T, \langle a, a \rangle)$$

(similarly for  $\langle f, f \rangle_\kappa$ ). The construction of those will be given later in the lecture. Unraveling the constructions given above, one sees that giving an object in  $(\text{colim}_j T_j)\text{-Alg}$  is equivalent to



giving a compatible system of  $T_i$ -algebra structures on a fixed object  $a \in \mathcal{C}$ . This shows that  $(\text{colim}_{\mathcal{J}} T_i)\text{-Alg} \cong \lim_{\mathcal{J}} (T_i\text{-Alg})$  in  $(\mathbf{CAT} \downarrow \mathcal{C})$ .  $\square$

Now we can use this proposition to construct monads via presentations.

**Example 2.7.7.** Let  $\mathcal{E}$  be a locally presentable cartesian closed category, that is there is a product functor  $\times X: \mathcal{E} \rightarrow \mathcal{E}$  which has a right adjoint for all  $X \in \mathcal{E}$ . Now we start with the endofunctor  $F_1: \mathcal{E} \rightarrow \mathcal{E}$  given by the assignment  $X \mapsto X \times X + X$ . So the category of  $F_1\text{-Alg}$  is given by the following data

$$T(F_1)\text{-Alg} \cong F_1\text{-Alg} = \{ (X, m, e): m: X \times X \rightarrow X, e: * \rightarrow X \}$$

satisfying no axioms. Furthermore we take another endofunctor  $F_2: \mathcal{E} \rightarrow \mathcal{E}$  given by  $X \mapsto X \times X \times X + X + X$  and obtain the data

$$T(F_2)\text{-Alg} \cong F_2\text{-Alg} = \{ (X, f_1, f_2, f_3): f_1: X \times X \times X \rightarrow X, f_2, f_3: X \rightarrow X \}$$

Note that  $F_1$  and  $F_2$  both are  $\kappa$ -accessible by the usual sifted colimit argument, thus the algebraically free monads  $T(F_1)$  and  $T(F_2)$  exist and are  $\kappa$ -accessible. We now define two functors

$$F_1\text{-Alg} \begin{array}{c} \xrightarrow{G_1} \\ \xrightarrow{G_2} \end{array} F_2\text{-Alg}$$

by the formulas

$$\begin{aligned} G_1(X, m, e) &= (X, m \circ m \times X, m \circ e \times X, m \circ X \times e) \\ G_2(X, m, e) &= (X, m \circ X \times m, \text{id}_X, \text{id}_X) \end{aligned}$$

By fullness and faithfulness of  $(\text{ })\text{-Alg}$ , we get monad morphisms  $\varphi_1, \varphi_2: T(F_2) \rightarrow T(F_1)$ , inducing  $G_1$  and  $G_2$  up to isomorphism ( $G_1 = \varphi_1^*, G_2 = \varphi_2^*$ ). Now the coequalizer  $T_{\text{mon}}$  of  $\varphi_1$  and  $\varphi_2$  has algebras isomorphic to the equalizer of  $G_1$  and  $G_2$ , thus this gives the data of a monoid object in  $\mathcal{E}$

$$T_{\text{mon}}\text{-Alg} = \{ (X, m, e): m \circ m \times X = m \circ X \times e, m \circ e \times X = \text{id}_X, m \circ X \times e = \text{id}_X \}.$$

**Example 2.7.8.** In the exercise classes we will see  $\mathbf{Cat}$  is locally finitely presentable. Let  $\mathcal{D} = \{0 \rightrightarrows 1\}$  be the category with two objects and two non trivial parallel morphisms. We now want to show that small categories with chosen coequalizers are monadic. First we take the endofunctor  $F_1: \mathbf{Cat} \rightarrow \mathbf{Cat}$  given by  $\mathcal{C} \mapsto [\mathcal{C}, \mathcal{D}]$  and obtain

$$F_1\text{-Alg} = \{ (\mathcal{C}, l: [\mathcal{C}, \mathcal{D}] \rightarrow \mathcal{C}) \}$$

We want to say that such a  $l$  is left adjoint to the constant diagram functor  $c: \mathcal{C} \rightarrow [\mathcal{C}, \mathcal{D}]$ . For this we need unit  $\eta$  and counit  $\varepsilon$ . To construct them we use the arrow category  $[1]$ , since giving a natural transformation

$$\begin{array}{ccc} & f & \\ \mathcal{C} & \Downarrow & \mathcal{D} \\ & g & \end{array}$$

amounts to giving a commutative diagram

$$\begin{array}{ccc}
 \mathcal{C} & & \\
 \downarrow & \searrow f & \\
 \mathcal{C} \times [1] & \longrightarrow & \mathcal{D} \\
 \uparrow & \nearrow g & \\
 \mathcal{C} & & 
 \end{array}$$

so we can get the counit  $\varepsilon: l \circ c \rightarrow \text{id}$  using the endofunctor  $F_2(\mathcal{C}) = \mathcal{C} \times [1]$ . Since the unit has to be of the form  $\eta: [\mathcal{D}, \mathcal{C}] \times [1] \rightarrow [\mathcal{D}, \mathcal{C}]$ , there has to be done a bit more. But the functor  $[\mathcal{D}, -]$  is right adjoint to  $-\times \mathcal{D}$  and via this adjunction such a morphism corresponds to  $[\mathcal{D}, \mathcal{C}] \times [1] \times \mathcal{D} \rightarrow \mathcal{C}$ . So we can get the unit using the endofunctor given by  $F_3(\mathcal{C}) = [\mathcal{D}, \mathcal{C}] \times [1] \times \mathcal{D}$ . Now we can express, having "same" natural transformations with desired source and target via equalizers of  $(-)\text{-Alg}$ . Also the  $\Delta$ -identities then can be expressed in a second coequalizer step. But in this construction the following problem appears: since the morphisms preserve the chosen coequalizers on the nose, they will rarely arise in nature.

## 3 Monads in 2-category theory

### 3.1 Symmetric monoidal categories

**Definition 3.1.1.** A *monoidal category* is a tuple  $(\mathcal{V}, \otimes, I, \alpha, \lambda, \rho)$ , where  $\mathcal{V}$  is a category,  $\otimes: \mathcal{V} \times \mathcal{V} \rightarrow \mathcal{V}$  a functor,  $I \in \mathcal{V}$  an object,  $\alpha: (- \otimes -) \otimes - \Rightarrow - \otimes (- \otimes -)$ ,  $\lambda: I \otimes - \Rightarrow \text{id}$  and  $\rho: - \otimes I \Rightarrow \text{id}$  natural isomorphisms such that for every  $W, X, Y, Z \in \mathcal{V}$  the diagrams

$$\begin{array}{ccccc}
 & & (W \otimes X) \otimes (Y \otimes Z) & & \\
 \alpha_{W \otimes X, Y, Z} \nearrow & & & \searrow \alpha_{W, X, Y \otimes Z} & \\
 ((W \otimes X) \otimes Y) \otimes Z & & & & W \otimes (X \otimes (Y \otimes Z)) \\
 \alpha_{W, X, Y} \otimes \text{id}_Z \searrow & & & \nearrow \text{id}_W \otimes \alpha_{X, Y, Z} & \\
 (W \otimes (X \otimes Y)) \otimes Z & \xrightarrow{\alpha_{W, X \otimes Y, Z}} & W \otimes ((X \otimes Y) \otimes Z) & & \\
 & & & & \\
 & & (X \otimes I) \otimes Y & \xrightarrow{\alpha_{X, I, Y}} & X \otimes (I \otimes Y) \\
 & \searrow \rho_X \otimes \text{id}_Y & & \nearrow \text{id}_X \otimes \lambda_Y & \\
 & & X \otimes Y & & 
 \end{array}$$

commute. We call  $\otimes$  the *tensor product*,  $I$  the *unit object* or *tensor unit*,  $\alpha$  the *associator*,  $\lambda$  the *left unitor* and  $\rho$  the *right unitor*. For convenience, we shall denote  $- \otimes \text{id}_X$  and  $\text{id}_X \otimes -$  by  $- \otimes X$  and  $X \otimes -$  respectively.

**Example 3.1.2.** We now list some monoidal categories.

1. If  $\mathcal{E}$  is a category with finite products, then  $(\mathcal{E}, \times, *)$  is monoidal, with  $\alpha$ ,  $\lambda$  and  $\rho$  induced by the universal property. Instances of this are **Set**, **Cat**, **Grp**, **sSet**, **Top**, **CGTop** and **CGHTop**.
2.  $(\mathbf{Ab}, \otimes_{\mathbb{Z}}, \mathbb{Z})$  and, given a commutative ring  $R$ ,  $(\mathbf{Mod}_R, \otimes_R, R)$  and  $(\mathbf{dgMod}_R, \otimes_R, R)$ .
3. The order  $\overline{\mathbb{R}}_+ = [0, \infty]$  with  $\otimes = +$ ,  $I = 0$ .
4. A monoid in **Cat** or **CAT** is a monoidal category such that  $\alpha$ ,  $\lambda$  and  $\rho$  are identities. This is the case of  $[\mathcal{C}, \mathcal{C}]$ ,  $[\mathcal{C}, \mathcal{C}]_{\kappa}$  and  $\Phi\text{-Cocts}[\mathcal{C}, \mathcal{C}]$ .

We mention without proof the following fundamental theorem.

**Theorem 3.1.3** (Mac Lane). Any diagram built from  $\otimes$ ,  $I$ ,  $\alpha$ ,  $\lambda$ ,  $\rho$  and their iterations is commutative.

Given a word of objects tensored among them, any two choices of bracketing are uniquely isomorphic. This result is plausible if  $\otimes$  is derived from an universal property as in (1) – (3) and clear if  $\mathcal{V}$  is strict (that is the natural isomorphisms are identities), like in (3) and (4), while the general proof uses a rewriting argument which can be found in [MacLane2].

**Definition 3.1.4.** A *lax monoidal functor* from  $\mathcal{V}$  to  $\mathcal{W}$  is a triple  $(F, \phi_0, \phi)$ , where  $F: \mathcal{V} \rightarrow \mathcal{W}$  is a functor,  $\phi_0: I_{\mathcal{W}} \rightarrow FI_{\mathcal{V}}$  a morphism and  $\phi: \otimes_{\mathcal{W}} \circ (F \times F) \Rightarrow F \circ \otimes_{\mathcal{V}}$  a natural transformation such that for all  $X, Y, Z \in \mathcal{V}$  the diagrams

$$\begin{array}{ccc}
 (FX \otimes_{\mathcal{W}} FY) \otimes_{\mathcal{W}} FZ & \xrightarrow{\alpha^{\mathcal{W}}} & FX \otimes_{\mathcal{W}} (FY \otimes_{\mathcal{W}} FZ) \\
 \downarrow \phi_{X,Y} \otimes_{\mathcal{W}} FZ & & \downarrow FX \otimes_{\mathcal{W}} \phi_{X,Z} \\
 F(X \otimes_{\mathcal{V}} Y) \otimes_{\mathcal{W}} FZ & & FX \otimes_{\mathcal{W}} F(Y \otimes_{\mathcal{V}} Z) \\
 \downarrow \phi_{X \otimes_{\mathcal{V}} Y, Z} & & \downarrow \phi_{X,Y} \otimes_{\mathcal{W}} Z \\
 F((X \otimes_{\mathcal{V}} Y) \otimes_{\mathcal{V}} Z) & \xrightarrow{F\alpha^{\mathcal{V}}} & F(X \otimes_{\mathcal{V}} (Y \otimes_{\mathcal{V}} Z))
 \end{array}$$
  

$$\begin{array}{ccc}
 I_{\mathcal{W}} \otimes_{\mathcal{W}} FX & \xrightarrow{\phi_0 \otimes_{\mathcal{W}} FX} & FI_{\mathcal{V}} \otimes_{\mathcal{W}} FX \\
 \downarrow \lambda_X^{\mathcal{W}} & & \downarrow \phi_{I_{\mathcal{V}}, X} \\
 FX & \xleftarrow{F\lambda_X^{\mathcal{V}}} & F(I_{\mathcal{V}} \otimes_{\mathcal{V}} X)
 \end{array}
 \quad
 \begin{array}{ccc}
 FX \otimes_{\mathcal{W}} I_{\mathcal{W}} & \xrightarrow{FX \otimes_{\mathcal{W}} \phi_0} & FI_{\mathcal{V}} \otimes_{\mathcal{W}} FX \\
 \downarrow \rho_X^{\mathcal{W}} & & \downarrow \phi_{X, I_{\mathcal{V}}} \\
 FX & \xleftarrow{F\rho_X^{\mathcal{V}}} & F(I_{\mathcal{V}} \otimes_{\mathcal{V}} X)
 \end{array}$$

are commutative.

If we reverse the direction of  $\phi_0$  and  $\phi$  we get *oplax monoidal functors*.

A *strong (strict) monoidal functor* is a lax monoidal functor such that  $\phi_0$  and  $\phi$  are isomorphisms (identities).

A *monoidal natural transformation* from  $(F, \phi_0, \phi)$  to  $(G, \psi_0, \psi)$  is a natural transformation  $\gamma: F \Rightarrow G$  such that the diagrams

$$\begin{array}{ccc}
 FX \otimes_{\mathcal{W}} FY & \xrightarrow{\gamma_X \otimes_{\mathcal{W}} \gamma_Y} & GX \otimes_{\mathcal{W}} GY \\
 \downarrow \phi_{X,Y} & & \downarrow \psi_{X,Y} \\
 F(X \otimes_{\mathcal{V}} Y) & \xrightarrow{\gamma_{X \otimes_{\mathcal{V}} Y}} & G(X \otimes_{\mathcal{V}} Y)
 \end{array}
 \quad
 \begin{array}{ccc}
 & I_{\mathcal{W}} & \\
 \phi_0 \swarrow & & \searrow \psi_0 \\
 FI_{\mathcal{V}} & \xrightarrow{\gamma_{I_{\mathcal{V}}}} & GI_{\mathcal{V}}
 \end{array}$$

commute.

**Proposition 3.1.5.** Lax monoidal functors compose and monoidal natural transformations whisker.

**Proposition 3.1.6.** There is a finitary monad  $T$  on  $\mathbf{Cat}$  such that  $T\text{-Alg}$  is the category of monoidal categories and strict monoidal functors.

*Proof.* We can write down a presentation of this monad using the finitary endofunctors  $X \mapsto X \times X$ ,  $X \mapsto X \times X \times X \times X$ .  $\square$

**Example 3.1.7.** Given a locally small monoidal category  $\mathcal{V}$ , the functor  $\mathcal{V}(I, -): \mathcal{V} \rightarrow \mathbf{Set}$  is lax monoidal, with  $\phi_0: \{*\} \rightarrow \mathcal{V}(I, I)$ ,  $*$   $\mapsto \text{id}_I$  and  $\phi_{X,Y}$  sending  $(f, g) \in \mathcal{V}(I, X) \times \mathcal{V}(I, Y)$  to  $(f \otimes g) \circ \lambda_I^{-1} = (f \otimes g) \circ \rho_I^{-1}: I \xrightarrow{\sim} I \otimes I \rightarrow X \otimes Y$ . It is universally denoted by  $V: \mathcal{V} \rightarrow \mathbf{Set}$  and, if  $\mathcal{V}$  has coproducts, it has a left adjoint given by  $F: \mathbf{Set} \rightarrow \mathcal{V}$ ,  $S \mapsto \amalg_S I$ .

Assuming for simplicity that  $\mathcal{V}$  is cocomplete, it is easy to show that  $F$  is strong monoidal if  $\otimes$  preserves colimits in each variable by using that  $\mathbf{Set}$  is the free cocomplete category on  $\{*\}$ .

The previous example is an instance of a more general phenomenon, as shown by the following result.

**Theorem 3.1.8.** Let  $F: \mathcal{V} \rightarrow \mathcal{W}$  be a left adjoint to  $U$ . If  $\mathcal{V}, \mathcal{W}$  are monoidal,  $F, U$  lax and  $\eta, \epsilon$  monoidal natural transformations, then  $F$  is strong monoidal. Conversely, if  $(F, \phi_0, \phi)$  is strong monoidal and  $U$  is any right adjoint, then

$$\begin{array}{ccc}
 I_{\mathcal{V}} \xrightarrow{\eta_{I_{\mathcal{V}}}} UFI_{\mathcal{V}} & UX \otimes_{\mathcal{V}} UY & \xrightarrow{\psi_{X,Y}} U(X \otimes_{\mathcal{V}} Y) \\
 \searrow \psi_0 & \downarrow U\phi_0^{-1} & \uparrow U(\epsilon_X \otimes_{\mathcal{W}} \epsilon_Y) \\
 & UI_{\mathcal{W}} & \\
 & UF(UX \otimes_{\mathcal{V}} UY) & \xrightarrow{U\phi_{UX,UY}^{-1}} U(FUX \otimes_{\mathcal{W}} FUY)
 \end{array}$$

define a lax monoidal structure on  $U$  which is unique with the property that  $\eta, \epsilon$  are monoidal.

*Proof.* Exercise.  $\square$

**Example 3.1.9.** Given a homomorphism of commutative rings  $R \rightarrow S$ , then  $- \otimes_R S \dashv U$ , where  $U$  is the restriction on scalars, and  $- \otimes_R S: \mathbf{Mod}_R \rightarrow \mathbf{Mod}_S$  is a monoidal adjunction.

The free module functor  $\mathbf{Set} \rightarrow \mathbf{Mod}_R$  is strong monoidal by the previous example.

**Remark 3.1.10.** The last example still holds if we substitute to  $\mathbf{Mod}_R$  any cocomplete monoidal category  $\mathcal{V}$  with  $- \otimes V, V \otimes -$  cocontinuous.

**Definition 3.1.11.** A monoid in a monoidal category  $\mathcal{V}$  is a triple  $(M, m, u)$  where  $m: M \otimes M \rightarrow M$  is the *multiplication*,  $u: I \rightarrow M$  the *unit* and the diagrams

$$\begin{array}{ccccc}
 & (M \otimes M) \otimes M & \xrightarrow{\alpha_{M,M,M}} & M \otimes (M \otimes M) & \\
 m \otimes M \swarrow & & & & \searrow M \otimes m \\
 M \otimes M & & & & M \otimes M \\
 & m \searrow & & m \swarrow & \\
 & M & & M & \\
 I \otimes M & \xrightarrow{u \otimes M} & M \otimes M & \xleftarrow{M \otimes u} & M \otimes I \\
 \lambda_M \searrow & & \downarrow m & & \swarrow \rho_M \\
 & M & & & 
 \end{array}$$

commute.

Morphisms of monoids are maps  $f: M \rightarrow M'$  such that  $m' \cdot (f \otimes f) = f \cdot m$ ,  $f \cdot u = u'$ .

We write  $\mathbf{Mon}(\mathcal{V})$  for the category of monoids over  $\mathcal{V}$ .

**Remark 3.1.12.** If  $\mathcal{V}$  is additive, monoids are often called algebras as well because  $\mathbf{Mon}(\mathbf{Mod}_R) = \mathbf{Alg}_R$  and  $\mathbf{Mon}(\mathbf{dgMod}_R) = \mathbf{dgAlg}_R$ .

**Example 3.1.13.** For  $R$  a commutative ring,  $\mathbf{Alg}_R$  is locally finitely presentable

**Proposition 3.1.14.** If  $F: \mathcal{V} \rightarrow \mathcal{W}: U$  is a monoidal adjunction ( $F$  strong,  $U$  monoidal), then  $F \dashv U$  lifts to an adjunction of monoids

$$\begin{array}{ccc}
 \mathbf{Mon}(\mathcal{V}) & \begin{array}{c} \xrightarrow{\bar{F}} \\ \perp \\ \xleftarrow{\bar{U}} \end{array} & \mathbf{Mon}(\mathcal{W}) \\
 \downarrow & & \downarrow \\
 \mathcal{V} & \begin{array}{c} \xrightarrow{F} \\ \perp \\ \xleftarrow{U} \end{array} & \mathcal{W}
 \end{array}$$

where  $\overline{F}(M, m, n) = (FM, Fm \circ \phi_{M,M}^F, Fn \circ \phi_0^F)$  and  $\overline{U}(M', m', n') = (UM, Um' \circ \phi_{M,M}, Un' \circ \phi_{U_0})$ .

*Proof.* The axioms for lax monoidal functors show that these are indeed monoids, naturality of  $\phi^F, \phi^U$  shows that  $Ff$  is a monoid morphism if  $f$  is. It follows that  $\overline{F}, \overline{U}$  are indeed functors. Axioms for monoidal transformations show  $\eta, \epsilon$  are monoid morphisms, hence  $\overline{F} \dashv \overline{U}$ .  $\square$

**Example 3.1.15.** i) A ring homomorphism  $R \rightarrow S$  of commutative rings induces base change functors  $\mathbf{Alg}_R \xrightleftharpoons[\text{forget}]{S \otimes_R -} \mathbf{Alg}_S$ . This also works for commutative algebras, etc.

ii) Let  $\mathcal{C}$  be locally  $\kappa$ -presentable. Then  $[\mathcal{C}, \mathcal{C}]_\kappa \rightarrow [\mathcal{C}, \mathcal{C}]$  is strict monoidal and a left adjoint, so it lifts to a left adjoint  $\mathbf{Mod}_\kappa(\mathcal{C}) \rightarrow \mathbf{Mod}(\mathcal{C})$ . Why is it left adjoint? Let  $K: \mathcal{C}_\kappa \rightarrow \mathcal{C}$  be the inclusion. Since  $\Phi$  is cocontinuous we have

$$\begin{array}{ccc} [\mathcal{C}, \mathcal{C}]_\kappa & \xrightarrow{\simeq} & [\mathcal{C}_\kappa, \mathcal{C}] \\ \downarrow & \swarrow \text{Lan}_K & \uparrow \\ [\mathcal{C}, \mathcal{C}] & \xleftarrow{K^*} & \end{array}$$

From this it follows that the inclusion is indeed a left adjoint.

**Remark 3.1.16.** This completes the proof that  $(-)\text{-Alg}: \mathbf{Mnd}_\kappa(\mathcal{C})^{\text{op}} \rightarrow (\mathbf{Cat} \downarrow \mathcal{C})$  is full and faithful and sends colimits of monads to limits of categories.

Let  $(\mathcal{V}, \otimes, I)$  be a monoidal category such that  $x \otimes -$  and  $- \otimes x$  preserve coproducts for all  $x \in \mathcal{V}$ . The category of  $\mathcal{V}$ -matrices with index set  $S$  is  $[S \times S, \mathcal{V}] = \prod_{S \times S} \mathcal{V}$  and denoted by  $\text{Mat}(\mathcal{V}, S)$ . There is a natural monoidal structure on  $\text{Mat}(\mathcal{V}, S)$  given by matrix multiplication

$$M(x, y)_{(x,y) \in S^2} \otimes N(x, y)_{(x,y) \in S^2} = \left( \sum_{z \in S} M(z, y) \otimes N(x, z) \right)_{(x,y) \in S^2}$$

and the unit  $(I_{x,y})_{(x,y) \in S^2}$  where  $I_{x,y} = I$  if  $x = y$  and  $I_{x,y} = \emptyset$  otherwise. The triple  $(\alpha, \lambda, \rho)$  on  $\text{Mat}(\mathcal{V}, S)$  is induced by the one on  $\mathcal{V}$  via the universal properties of coproducts.

**Definition 3.1.17.** A  $\mathcal{V}$ -category  $\mathcal{A}$  with object set  $S$  is a monoid in  $\text{Mat}(\mathcal{V}, S)$ , i.e. for each pair  $(a, b) \in S^2$  there is a unique object  $\mathcal{A}(a, b) \in \mathcal{V}$ , called the  $\mathcal{V}$ -object of homomorphisms. Moreover we have units  $I \xrightarrow{\text{id}_a} \mathcal{A}(a, a)$  and composition homomorphisms

$$\mathcal{A}(b, c) \otimes \mathcal{A}(a, b) \xrightarrow{C_{a,b,c}} \mathcal{A}(a, c)$$

such that the diagram

$$\begin{array}{ccc} (\mathcal{A}(c, d) \otimes \mathcal{A}(b, c)) \otimes \mathcal{A}(a, b) & \xrightarrow{\cong} & \mathcal{A}(c, d) \otimes (\mathcal{A}(b, c) \otimes \mathcal{A}(a, b)) \\ \downarrow C \otimes \mathcal{A}(a, b) & & \downarrow \mathcal{A}(c, d) \otimes C \\ \mathcal{A}(b, d) \otimes \mathcal{A}(a, b) & & \mathcal{A}(c, d) \otimes \mathcal{A}(a, c) \\ & \searrow C \quad \swarrow C & \\ & \mathcal{A}(a, d) & \end{array}$$

commutes and the two unit axioms hold. This is in fact the definition if  $\mathcal{V}$  does not have all coproducts or  $x \otimes -$  does not preserve them.

**Example 3.1.18.** •  $\mathcal{V} = \mathbf{Top} \rightsquigarrow$  topological categories

- $\mathcal{V} = \mathbf{Ab} \rightsquigarrow$  additive categories
- $\mathcal{V} = \mathbf{Mod}_R \rightsquigarrow$  linear categories
- $\mathcal{V} = \mathbf{Mod}_R^{\text{d.g.}} \rightsquigarrow$  graded categories
- $\mathcal{V} = \mathbf{Cat} \rightsquigarrow$  2-categories
- $\mathcal{V} = n\text{-}\mathbf{Cat} \rightsquigarrow$  strict  $(n + 1)$ -categories

**Proposition 3.1.19.** If  $\mathcal{V}$  is presentable and both  $x \otimes -$  and  $- \otimes x$  are  $\kappa$ -accessible for all  $x \in \mathcal{D}$  and preserve coproducts, then the category of  $\mathcal{V}$ -categories with fixed object set  $S$  is locally  $\kappa$ -presentable.

*Proof.* It suffices to show that the matrices are  $\kappa$ -accessible in each variable, which follows from the fact that colimits commute.  $\square$

**Definition 3.1.20.** Let  $\mathcal{V}$  be a monoidal category with coproducts, and such that  $x \otimes -$  and  $- \otimes x$  preserve coproducts for each  $x \in \mathcal{V}$ . Let  $f: S \rightarrow T$  be a map of sets. We write

$$\begin{aligned} f^*: \text{Mat}(\mathcal{V}, T) &\rightarrow \text{Mat}(\mathcal{V}, S) \\ (T \times T \xrightarrow{M} \mathcal{V}) &\mapsto (S \times S \xrightarrow{f \times f} T \times T \xrightarrow{M} \mathcal{V}) \end{aligned}$$

and  $f_*: \text{Mat}(\mathcal{V}, S) \rightarrow \text{Mat}(\mathcal{V}, T)$  for its left adjoint, given by

$$(f_* M)(a, b) = \sum_{\{(x, y): fx=a, fy=b\}} M(x, y).$$

**Proposition 3.1.21.** The left adjoint is strong monoidal.

**Definition 3.1.22.** A  $\mathcal{V}$ -functor  $(S, \mathcal{A}) \rightarrow (T, \mathcal{B})$  is a pair  $(F, (F_{a,b})_{(a,b) \in S^2})$  where  $F: S \rightarrow T$  is a function and  $(F_{a,b})_{(a,b) \in S^2}$  is a monoid morphism  $\mathcal{A} \rightarrow F^* \mathcal{B}$ , that is  $F_{a,b}: \mathcal{A}(a, b) \rightarrow \mathcal{B}(Fa, Fb)$  is a morphism in  $\mathcal{V}$  for any  $a, b \in S$ .

We denote the resulting category of small  $\mathcal{V}$ -categories by  $\mathcal{V}\text{-}\mathbf{Cat}$ . We may also define  $\mathcal{V}\text{-}\mathbf{CAT}$  as the category of all  $\mathcal{V}$ -categories. We may define the category of  $\mathcal{V}$ -graphs analogously. We have an obvious forgetful functor from  $\mathcal{V}$ -categories to  $\mathcal{V}$ -graphs.

**Example 3.1.23.** We now want to see what happens if we take  $\mathcal{V} = \mathbf{Cat}$ . That is unveiling the data of a 2-category. First we have a class of objects  $\text{Ob}(\mathcal{K})$ , called 0-cells, and for any two  $A, B \in \text{Ob}(\mathcal{K})$ , we have a category  $\mathcal{K}(A, B)$ . We call the objects of  $\mathcal{K}(A, B)$  1-cells from  $A$  to  $B$  and denote them  $f: A \rightarrow B$ . The morphisms in  $\mathcal{K}(A, B)$  are called 2-cells, denoted by

$$\begin{array}{ccc} & f & \\ A & \xrightarrow{\quad} & B \\ & \Downarrow \alpha & \\ & g & \end{array}$$

The categorical structure of  $\mathcal{K}(A, B)$  now tells us that we have a vertical composition operation

$$\begin{array}{ccc} & \Downarrow \alpha & \\ A & \xrightarrow{\quad} & B \\ & \Downarrow \beta & \end{array}$$

which is associative and has a unit  $\text{id}_f: f \Rightarrow f$ . We also have identities  $\text{id}_A: * \rightarrow \mathcal{K}(A, A)$ , written  $\text{id}_A: A \rightarrow A$ , and composition functors  $\mathcal{K}(B, C) \times \mathcal{K}(A, B) \rightarrow \mathcal{K}(A, C)$  which give in particular horizontal composition of 1-cells  $A \rightarrow B \rightarrow C$  and whiskering operations

$$(B \begin{array}{c} \xrightarrow{g} \\ \Downarrow \alpha \\ \xrightarrow{h} \end{array} C, A \xrightarrow{f} B) \longmapsto A \begin{array}{c} \xrightarrow{gf} \\ \Downarrow \alpha_f \\ \xrightarrow{hf} \end{array} B$$

and similarly on the other side. Saying that this defines a functor means that these operations satisfy the interchange law: That is, given a diagram of the form

$$A \begin{array}{c} \xrightarrow{f} \\ \Downarrow \alpha \\ \xrightarrow{g} \end{array} B \begin{array}{c} \xrightarrow{h} \\ \Downarrow \beta \\ \xrightarrow{k} \end{array} C$$

we have  $\beta_g \cdot h\alpha = k\alpha \cdot \beta_f$  or in pictures

$$\begin{array}{ccc} \cdot \begin{array}{c} \xrightarrow{\psi} \\ \Downarrow \end{array} \cdot \longrightarrow \cdot & = & \cdot \longrightarrow \cdot \begin{array}{c} \xrightarrow{\psi} \\ \Downarrow \end{array} \cdot \\ \cdot \longrightarrow \cdot \begin{array}{c} \xrightarrow{\psi} \\ \Downarrow \end{array} \cdot & = & \cdot \begin{array}{c} \xrightarrow{\psi} \\ \Downarrow \end{array} \cdot \longrightarrow \cdot \end{array}$$

This follows from the fact that giving a functor  $F: \mathcal{C} \times \mathcal{D} \rightarrow \mathcal{E}$  amounts to giving a compatible collection of functors  $F(-, d)$  and  $F(c, -)$  for all  $(c, d) \in \mathcal{C} \times \mathcal{D}$ .

**Example 3.1.24.** Examples of 2-categories are

- (i) **Cat** and **CAT** with small or locally small categories as 0-cells, functors as 1-cells and natural transformations as 2-cells.
- (ii) Locally  $\kappa$ -presentable categories,  $\kappa$ -accessible functors and natural transformations.
- (iii) Monoidal categories, lax monoidal functors and monoidal natural transformations.
- (iv) For  $\mathcal{V}$  a monoidal category,  $\mathcal{V}\text{-Cat}$  and  $\mathcal{V}\text{-CAT}$  are 2-categories. 0-cells are small/locally small  $\mathcal{V}$ -categories, 1-cells are  $\mathcal{V}$ -functors and 2-cells are  $\mathcal{V}$ -natural transformations.

**Definition 3.1.25.** Let  $\mathcal{A}$  and  $\mathcal{B}$  be two  $\mathcal{V}$ -categories and  $F, G: \mathcal{A} \rightarrow \mathcal{B}$  be two  $\mathcal{V}$ -functors. Then a  $\mathcal{V}$ -natural transformation  $F \Rightarrow G$  is a collection of morphisms  $(\alpha_A: I \rightarrow \mathcal{B}(FA, GA))_{A \in \mathcal{A}}$  in  $\mathcal{V}$  (note that this collection can be indexed by a class of objects), such that for all objects  $A, B$  in  $\mathcal{A}$  the diagram

$$\begin{array}{ccccc} & & I \otimes \mathcal{A}(A, B) & \xrightarrow{\alpha_B \otimes F} & \mathcal{B}(FB, GB) \otimes \mathcal{B}(FA, FB) \\ & \nearrow \lambda^{-1} & & & \searrow \circ \\ \mathcal{A}(A, B) & & & & \mathcal{B}(FA, GB) \\ & \searrow \rho^{-1} & & & \nearrow \circ \\ & & \mathcal{A}(A, B) \otimes I & \xrightarrow{G \otimes \alpha_A} & \mathcal{B}(GA, GB) \otimes \mathcal{B}(FA, GA) \end{array}$$

is commutative. We then first define the whiskering operations. consider the diagram

$$\mathcal{A}' \xrightarrow{K} \mathcal{A} \begin{array}{c} \xrightarrow{F} \\ \Downarrow \alpha \\ \xrightarrow{G} \end{array} \mathcal{B} \xrightarrow{L} \mathcal{B}'$$



then we define  $(L, \alpha)_{A \in \mathcal{A}}$  via the composition

$$I \xrightarrow{\alpha_A} \mathcal{B}(FA, GA) \xrightarrow{L} \mathcal{B}'(LFB, LGB)$$

and  $(\alpha, K)_{A' \in \mathcal{A}'}$  by  $\alpha_{KA'}: I \rightarrow \mathcal{B}(FKA', GKA')$ . Clearly  $\alpha_K$  is a  $\mathcal{V}$ -natural transformation  $FK \Rightarrow GK$ . To see this for  $L\alpha$  compare the needed diagram with

$$\begin{array}{ccc} \mathcal{B}(FB, GB) \otimes \mathcal{B}(FA, FB) & \xrightarrow{L \otimes L} & \mathcal{B}'(LFB, LGB) \otimes \mathcal{B}'(LFA, LFB) \\ \downarrow \circ & & \downarrow \circ \\ \mathcal{B}(FA, GB) & \xrightarrow{L} & \mathcal{B}'(LFA, LGB) \\ \uparrow \circ & & \uparrow \circ \\ \mathcal{B}(GA, GB) \otimes \mathcal{B}(FA, GA) & \xrightarrow{L \otimes L} & \mathcal{B}'(LGA, LGB) \otimes \mathcal{B}'(LFA, LGA) \end{array}$$

Now given a diagram of the form

$$\begin{array}{ccc} & F & \\ \curvearrowright & \Downarrow \alpha & \curvearrowright \\ \mathcal{A} & \xrightarrow{G} & \mathcal{B} \\ \curvearrowleft & \Downarrow \beta & \curvearrowleft \\ & H & \end{array}$$

we define the vertical composition  $(\beta \cdot \alpha)_A$  by

$$I \cong I \otimes I \xrightarrow{\beta_A \otimes \alpha_A} \mathcal{B}(GA, HA) \otimes \mathcal{B}(FA, GA) \xrightarrow{\circ} \mathcal{B}(FA, HA)$$

with unit natural transformation  $\text{id}_{FA}: I \rightarrow \mathcal{B}(FA, FA)$ . We leave it to the reader to check associativity and the interchange law.

**Example 3.1.26.** For  $\mathcal{V} = \mathbf{Set}$ , we get precisely the 2-categories of categories, functors and natural transformations. What happens if instead we take **Cat** or even **CAT**. 0-cells are 2-categories? 1-cells are 2-functors or **Cat**-functors, that is: given two 2-categories  $\mathcal{K}, \mathcal{K}'$ , we have an assignment  $\text{Ob}(\mathcal{K}) \rightarrow \text{Ob}(\mathcal{K}')$  of the form  $A \mapsto FA$  and for any two objects  $A, B$  in  $\text{Ob}(\mathcal{K})$  there is a functor  $F_{A,B}: \mathcal{K}(A, B) \rightarrow \mathcal{K}'(FA, FB)$

$$\begin{array}{ccc} A & \xrightarrow{f} & B \\ \Downarrow \alpha & & \Downarrow F\alpha \\ & \xrightarrow{g} & \end{array} \longmapsto \begin{array}{ccc} FA & \xrightarrow{Ff} & FB \\ \Downarrow F\alpha & & \Downarrow F\alpha \\ & \xrightarrow{Fg} & \end{array}$$

to say that this defines a functor is exactly to say that this assignment respects vertical composition. The first  $\mathcal{V}$ -functor axiom says that  $F \text{id}_A = \text{id}_{FA}$  and the second that the diagram

$$\begin{array}{ccc} \mathcal{K}(B, C) \times \mathcal{K}(A, B) & \xrightarrow{\circ} & \mathcal{K}(A, C) \\ F \times F \downarrow & & \downarrow F \\ \mathcal{K}'(FB, FC) \times \mathcal{K}'(FA, FB) & \xrightarrow{\circ} & \mathcal{K}'(FA, FC) \end{array}$$

commutes, so  $F$  preserves the whiskering operation. What is a 2-natural transformation?

$$\begin{array}{ccc} & F & \\ \curvearrowright & \Downarrow \alpha & \curvearrowright \\ \mathcal{K} & \xrightarrow{G} & \mathcal{K}' \\ \curvearrowleft & & \curvearrowleft \end{array}$$

For all objects  $A$  in  $\text{Ob}(\mathcal{K})$  we have a morphism  $\alpha_A: * \rightarrow \mathcal{K}'(FA, GA)$ , i.e. a 1-cell  $\alpha_A: FA \rightarrow GA$ , such that the **Cat**-naturality axioms hold. That is the diagram

$$\begin{array}{ccc}
 & \mathcal{K}'(FB, GB) \times \mathcal{K}'(FA, FB) & \\
 \alpha_B \times F \nearrow & & \circ \searrow \\
 \mathcal{K}(A, B) & & \mathcal{K}'(FA, GB) \\
 G \times \alpha_A \searrow & & \circ \nearrow \\
 & \mathcal{K}'(GA, GB) \times \mathcal{K}'(FA, GA) &
 \end{array}$$

commutes. On objects that says, that for any 1-cell  $f: A \rightarrow B$  the diagram

$$\begin{array}{ccc}
 FA & \xrightarrow{Ff} & FB \\
 \alpha_A \downarrow & & \downarrow \alpha_B \\
 GA & \xrightarrow{Gf} & GB
 \end{array}$$

commutes and on morphisms it says that for all 2-cells  $\varphi: f \Rightarrow g$ , we have

$$\begin{array}{ccc}
 \begin{array}{ccc}
 FA & \xrightarrow{Ff} & FB \\
 \alpha_A \downarrow & \Downarrow F\varphi & \downarrow \alpha_B \\
 GA & \xrightarrow{Gg} & GB
 \end{array} & = & \begin{array}{ccc}
 FA & \xrightarrow{Ff} & FB \\
 \alpha_A \downarrow & \Downarrow G\varphi & \downarrow \alpha_B \\
 GA & \xrightarrow{Gg} & GB
 \end{array}
 \end{array}$$

Such transformations are called (strict) 2-natural transformations. The constructed categories will be denoted by **2-Cat** and **2-CAT**.

**Definition 3.1.27.** Let  $\mathcal{V}$  be a monoidal category. A  $\mathcal{V}$ -*monad* is a monad in  $\mathcal{V}\text{-Cat}$  or  $\mathcal{V}\text{-CAT}$ . In other words, a  $\mathcal{V}$ -monad on a  $\mathcal{V}$ -category  $\mathcal{C}$  (a 0-cell in  $\mathcal{V}\text{-CAT}$ ) is a  $\mathcal{V}$ -functor  $T: \mathcal{C} \rightarrow \mathcal{C}$  equipped with  $\mathcal{V}$ -natural transformations  $\mu$  and  $\eta$  filling the usual pasting diagrams.

The goal of the following section is to use them to define new  $\mathcal{V}$ -categories from old ones and develop enriched category theory. Namely, we will construct a new  $\mathcal{V}$ -category of  $T$ -algebras out of a  $\mathcal{V}$ -monad  $T$ . For this we need the underlying *ordinary* or *unenriched* category of a  $\mathcal{V}$ -category  $\mathcal{C}$ . We have a lax monoidal functor  $V: \mathcal{V} \rightarrow \mathbf{Set}$  which induces the functor

$$\begin{aligned}
 \mathcal{V}\text{-CAT} &\longrightarrow \mathbf{Set}\text{-CAT} = \mathbf{CAT} \\
 \mathcal{C} &\longmapsto V_* \mathcal{C}
 \end{aligned}$$

Here  $V_* \mathcal{C}$  has the same object class as  $\mathcal{C}$  and  $V_* \mathcal{C}(a, b) = V(\mathcal{C}(a, b))$ . For the composition we use the lax monoidal structure of  $\mathcal{V}$ , i.e. the morphisms in  $V_* \mathcal{C}$  from  $a$  to  $b$  are given by morphisms  $I \xrightarrow{f} \mathcal{C}(a, b)$ . The composition of the morphisms  $f: a \rightarrow b$  and  $g: b \rightarrow c$  is the morphism defined as

$$g \circ f = I \xrightarrow{\sim} I \otimes I \xrightarrow{g \otimes f} \mathcal{C}(b, c) \otimes \mathcal{C}(a, b) \xrightarrow{\circ} \mathcal{C}(a, c).$$

We write  $\mathcal{C}_0$  for the underlying unenriched category of  $\mathcal{C}$ . It would be good if  $(T\text{-Alg})_0 \cong T_0\text{-Alg}$  in the sense we defined before. The objects should be  $T_0$ -algebras, i.e. pairs  $(A, \alpha)$ ,  $\alpha: TA \rightarrow A \cong I \xrightarrow{\alpha} \mathcal{C}(TA, A)$  such that the two algebra axioms hold.

**Example 3.1.28.** A few examples of the action of the functor  $\mathcal{V}\text{-}\mathbf{CAT} \rightarrow \mathbf{CAT}$ :

1. when  $\mathcal{V} = \mathbf{Mod}_R$  we just forget the additive structure of the hom-sets;
2. if  $\mathcal{V} = \mathbf{Top}$  we forget the topology;
3. for  $\mathcal{V} = \mathbf{dgMod}_R$  we consider cycles of degree zero;
4. if  $\mathcal{V} = (\mathbf{sSet}, \times)$  then  $V_*\mathcal{C}$  forgets all the simplices in  $\mathcal{C}(a, b)$  except the 0-simplices, i.e. the vertices;
5. if  $\mathcal{V} = \overline{\mathbb{R}}_+$ , a  $\mathcal{V}$ -enriched category is a metric space (in the sense of Lawvere) and the composition is given by the triangle inequality. The functor above just sees the poset of real numbers as a set.

From now on we assume that  $\mathcal{V}$  has equalizers.

**Proposition 3.1.29.** Let  $\mathcal{C}$  be a  $\mathcal{V}$ -category and  $(T, \mu, \eta)$  a  $\mathcal{V}$ -monad on  $\mathcal{C}$ . For algebras  $(A, \alpha), (B, \beta) \in T_0\text{-Alg}$  let

$$T\text{-Alg}((A, \alpha), (B, \beta)) \xrightarrow{U} \mathcal{C}(A, B) \begin{array}{c} \xrightarrow{T} \mathcal{C}(TA, TB) \\ \xrightarrow{\alpha^*} \mathcal{C}(TA, B) \end{array} \begin{array}{c} \xleftarrow{\beta_*} \mathcal{C}(TA, TB) \end{array}$$

be an equalizer in  $\mathcal{V}$ , where  $\beta_*$  is the composition

$$\mathcal{C}(TA, TB) \cong I \otimes \mathcal{C}(TA, TB) \xrightarrow{\beta \otimes \text{id}} \mathcal{C}(TB, B) \otimes \mathcal{C}(TA, TB) \xrightarrow{\circ} \mathcal{C}(TA, B)$$

and similarly  $\alpha^* = \circ \cdot \text{id} \otimes \alpha$ . Then there is a unique way to define a structure of  $\mathcal{V}$ -category with objects equal to  $T_0\text{-Alg}$  and hom-object  $T\text{-Alg}((A, \alpha), (B, \beta)) \in \mathcal{V}$  such that  $U$  becomes a  $\mathcal{V}$ -functor.

*Proof.* For the identities note that  $\text{id}_A: I \rightarrow \mathcal{C}(A, A)$  equalizes the two arrows if  $(A, \alpha) = (B, \beta)$ . Namely, we have  $\text{id}_A \cdot \alpha = \alpha \cdot T\text{id}_A$ , thus we get a factorization

$$T\text{-Alg}((A, \alpha), (A, \alpha)) \xrightarrow{U} \mathcal{C}(A, A) \begin{array}{c} \xleftarrow{\exists! \text{id}_{(A, \alpha)}} I \\ \xrightarrow{\text{id}_A} \end{array}$$

and by  $U$  being regular monic we have to define  $\text{id}_{(A, \alpha)}$  as this dashed arrow if we want  $U$  to be a  $\mathcal{V}$ -functor. Similarly we want to define composition s.t. the diagram

$$\begin{array}{ccc} T\text{-Alg}((B, \beta), (C, \gamma)) \otimes T\text{-Alg}((A, \alpha), (B, \beta)) & \xrightarrow{U \otimes U} & \mathcal{C}(B, C) \otimes \mathcal{C}(A, C) \\ \downarrow & & \downarrow \circ \\ T\text{-Alg}((A, \alpha), (C, \gamma)) & \xrightarrow{U} & \mathcal{C}(A, C) \end{array}$$

commutes. So one has to check that  $\circ \cdot U \otimes U$  equalizes the two arrows defining the equalizer at the bottom of the diagram. One checks that this is the case by translating the usual proof that morphisms of  $T$ -algebras compose first into a proof just using the hom-sets (not their elements)

and then into a proof in the monoidal category  $\mathcal{V}$ . It remains to check that this defines a  $\mathcal{V}$ -category and that  $U$  is indeed a  $\mathcal{V}$ -functor. The first follows from the fact that each  $U_{((A,\alpha),(B,\beta))}$  is a monomorphism and the fact that  $\mathcal{C}$  is a  $\mathcal{V}$ -category. By design, the diagrams above are exactly the  $\mathcal{V}$ -functor axioms for  $U$ . This also shows uniqueness.  $\square$

**Example 3.1.30.** If  $\mathcal{V}$  = “sets with structure” we just get the corresponding substructure on the morphism set, e.g. subspace topology, submodules etc.

1. If  $G$  is a topological group then  $G \times - : \mathbf{Top} \rightarrow \mathbf{Top}$  is a **Top**-monad if **Top** is a cartesian closed category of topological spaces such as compactly generated weak Hausdorff spaces. From that we get the topological category of  $G$ -spaces.
2. If  $\mathcal{V} = \mathbf{Ab}$  and  $R$  is a ring, then **Ab** is an **Ab**-category since we can sum morphisms of abelian groups and this is  $\mathbb{Z}$ -bilinear. Moreover  $- \otimes_{\mathbb{Z}} R : \mathbf{Ab} \rightarrow \mathbf{Ab}$  is an additive monad.  $T\text{-Alg}$  is simply **Mod** $_R$  with addition of  $R$ -module homomorphisms.
3. For  $\mathcal{V} = \mathbf{Cat}$  we have 2-monads  $T$  in 2-CAT. From a 2-category  $\mathcal{K}$  with a 2-monad  $T : \mathcal{K} \rightarrow \mathcal{K}$  we get a new 2-category  $T\text{-Alg}$ . 0-cells are elements of  $T_0\text{-Alg}$ , namely pairs  $(A, \alpha)$  s.t.

$$\begin{array}{ccc} T^2 A & \xrightarrow{T\alpha} & TA \\ \mu_A \downarrow & & \downarrow \alpha \\ TA & \xrightarrow{\alpha} & A \end{array} \quad \begin{array}{ccc} A & \xrightarrow{\eta_A} & TA \\ & \searrow & \downarrow \alpha \\ & & A \end{array}$$

are commutative. A 1-cell in  $T\text{-Alg}$  is simply a morphism in  $T_0\text{-Alg}$ , that is, a 1-cell  $A \xrightarrow{f} B$  in  $\mathcal{K}$  s.t. the diagram

$$\begin{array}{ccc} TA & \xrightarrow{Tf} & TB \\ \alpha \downarrow & & \downarrow \beta \\ A & \xrightarrow{f} & B \end{array}$$

is commutative. A 2-cell in  $T\text{-Alg}$  is a morphism in the equalizer

$$\begin{array}{ccccc} & & \mathcal{K}(TA, TB) & & \\ & \nearrow T & & \searrow \beta_* & \\ T\text{-Alg}((A, \alpha), (B, \beta)) & \xrightarrow{U} & \mathcal{K}(A, B) & \xrightarrow{\alpha^*} & \mathcal{K}(TA, B) \end{array}$$

i.e. a 2-cell  $\varphi : f \Rightarrow g$  such that

$$\begin{array}{ccc} TA & \xrightarrow{\quad} & TB \\ \alpha \downarrow & \text{\scriptsize $T\varphi \Downarrow$} & \downarrow \beta \\ A & \xrightarrow{g} & B \end{array} = \begin{array}{ccc} TA & \xrightarrow{\quad} & TB \\ \alpha \downarrow & & \downarrow \beta \\ A & \xrightarrow{\quad} & B \\ & \text{\scriptsize $\varphi \Downarrow$} & \end{array}$$

In this case we can talk about pseudomorphisms and lax/oplax morphisms. For lax morphisms those are the squares

$$\begin{array}{ccc} TA & \xrightarrow{Tf} & TB \\ \downarrow & \text{\scriptsize $\bar{f}$} & \downarrow \\ A & \xrightarrow{f} & B \end{array}$$

( $\bar{f}$  is an isomorphism in the pseudo case) subject to some axioms.

We get four 2-categories from  $T$ : the original  $T\text{-Alg}$  is called  $T\text{-Alg}_S$  and its 1-cells are the *strict* morphisms of algebras. We have non-full inclusions

$$\begin{array}{ccc} & & T\text{-Alg}_L \\ & \nearrow & \\ T\text{-Alg}_S & \longrightarrow & T\text{-Alg}_P \\ & \searrow & \\ & & T\text{-Alg}^L \end{array}$$

There is a 2-monad  $T$  on  $\mathbf{Cat}$  s.t.  $T\text{-Alg}_P = \mathbf{Mon}_{str}(\mathbf{Cat})$  with strong morphisms.

Now we want to define opposite  $\mathcal{V}$ -categories and  $\mathcal{V}$ -functors of several variables using the tensor product of  $\mathcal{V}$ -categories. This is similar to the product of categories  $\mathcal{C} \times \mathcal{D}$ , however there  $(f, f') \cdot (g, g') = (fg, f'g')$ , which changes the order of  $f'$  and  $g$ . The following definition allows us to fix this.

**Definition 3.1.31.** Let  $\mathcal{V}$  be a monoidal category. A *braiding* on  $\mathcal{V}$  is a natural isomorphism

$$\begin{array}{ccc} \mathcal{V} \times \mathcal{V} & \xrightarrow{\tau} & \mathcal{V} \times \mathcal{V} \\ \otimes \searrow & \xrightarrow[\gamma]{\sim} & \swarrow \otimes \\ & \mathcal{V} & \end{array},$$

where  $\tau$  is the switch functor and for all  $A, B, C \in \mathcal{V}$  the diagram

$$\begin{array}{ccccc} & A \otimes (B \otimes C) & \xrightarrow{\gamma} & (B \otimes C) \otimes A & \\ \alpha \nearrow & & & & \searrow \alpha \\ (A \otimes B) \otimes C & & & & B \otimes (C \otimes A) \\ \gamma \otimes \text{id} \searrow & & & & \nearrow \text{id} \otimes \gamma \\ & (B \otimes A) \otimes C & \xrightarrow{\alpha} & B \otimes (A \otimes C) & \end{array}$$

and the one obtained by inverting the  $\alpha$  commute.

A braiding is called a *simmetry* if  $\gamma_{A,B} \circ \gamma_{B,A} = \text{id}$  for all  $A, B \in \mathcal{V}$ .

**Remark 3.1.32.** If  $\gamma$  is a simmetry, then either one of the above hexagons implies the other. Moreover, the diagram

$$\begin{array}{ccc} I \otimes A & \xrightarrow{\gamma_{I,A}} & A \otimes I \\ \lambda_A \searrow & & \swarrow \rho_A \\ & A & \end{array}$$

commutes.

**Example 3.1.33.**

- (i) If  $\mathcal{E} = (\mathcal{E}, \times, *)$  is cartesian, then the switch  $\tau: \mathcal{E} \times \mathcal{E} \rightarrow \mathcal{E}$  defines a simmetry. This is the case of **Set**, categories of presheaves, **sSet**, **Top**, **Cat**, etc.

- (ii) If  $R$  is a unital commutative ring,  $\mathbf{Mod}_R$  is a symmetric monoidal category with  $\gamma: M \otimes_R N \rightarrow N \otimes_R M$  the canonical isomorphism.
- (iii) If  $A$  is an abelian group, write  $A\text{-}\mathbf{Mod}_R$  for the category of  $A$ -graded  $R$ -modules, that is  $\Pi_A \mathbf{Mod}_R$ . We have a functor  $A\text{-}\mathbf{Mod}_R \times A\text{-}\mathbf{Mod}_R \rightarrow A\text{-}\mathbf{Mod}_R$ ,  $((V_i), (W_i)) \mapsto (\bigoplus_{i+j=k} V_i \otimes_R W_j)$ . This has a monoidal structure with unit  $R$  concentrated in degree  $0 \in A$ . There are obvious choices for  $\lambda$  and  $\rho$ .

A *normalized 3-cocycle* on  $A$  with values in  $R^\times$  is a function  $h: A \times A \times A \rightarrow R^\times$  such that, for any tuple  $(i, j, k, l) \in A^4$

$$\begin{aligned} h(i, 0, j) &= 1, \\ h(j, k, l) \cdot h(i, j + l, k) \cdot h(i, j, k) &= h(i, j, k + l) \cdot h(i + j, k, l). \end{aligned}$$

We define  $\alpha^h: ((U_\bullet) \otimes (V_\bullet)) \otimes (W_\bullet) \rightarrow (U_\bullet) \otimes ((V_\bullet) \otimes (W_\bullet))$  on the component given by the triple  $(i, j, k)$  as

$$\begin{aligned} (U_i \otimes V_j) \otimes W_k &\rightarrow U_i \otimes (V_j \otimes W_k) \\ (a \otimes b) \otimes c &\mapsto h(i, j, k) \cdot a \otimes (b \otimes c) \end{aligned}$$

The two axioms for normalized 3-cocycles say precisely that this is a monoidal structure on  $A\text{-}\mathbf{Mod}_R$ . Also, by considering modules concentrated in a single degree, one finds that all associators are of this form.

A *normalized abelian 3-cocycle* is an arrow  $h$  as above plus a map  $c: A \times A \rightarrow R^\times$  such that, for any triple  $(i, j, k) \in A^3$ ,

$$\begin{aligned} h(j, k, i) \cdot c(i, j + k) \cdot h(i, j, k) &= c(i, k) \cdot h(j, i, k) \cdot c(i, j), \\ h(k, i, j)^{-1} \cdot c(i + j, k) \cdot h(i, j, k)^{-1} &= c(i, k) \cdot h(i, j, k)^{-1} \cdot c(j, k). \end{aligned}$$

Given such  $(h, c)$ , we get a braiding defined by

$$\begin{aligned} V_i \otimes W_j &\rightarrow W_j \otimes V_i \\ a \otimes b &\mapsto c(i, j) \cdot b \otimes a \end{aligned}$$

and this is a symmetry if and only if  $c(i, j) = c(j, i) = 1$  for all  $i, j$ .

If we take the constant map  $h \equiv 1$ , then the two axioms say exactly that  $c$  is bilinear.

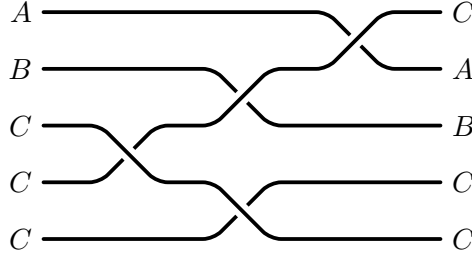
For  $A = \mathbb{Z}$ , given any  $u \in R^\times$  we can define  $c(i, j) = u^{|ij|}$ , which gives a symmetry if  $u^2 = 1$ . In particular, if  $R$  is a domain we have  $R^\times = \{\pm 1\}$  and the condition is always satisfied.

There are then only two symmetric monoidal structures on  $\mathbb{Z}\text{-}\mathbf{Mod}_R$ , the trivial one and the one given by  $V_i \otimes W_j \rightarrow W_j \otimes V_i$ ,  $a \otimes b \mapsto (-1)^{|ij|} \cdot b \otimes a$ . The latter is the symmetry given by the *Koszul sign rule*.

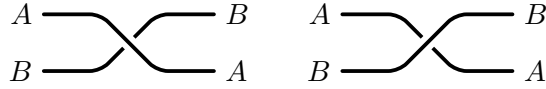
- (iv) The symmetry given by the Koszul sign rule lifts to a symmetry on  $\mathbf{dgMod}_R$ , while the trivial one does not.

**Remark 3.1.34.** The coherence theorem for braided (symmetric) monoidal categories does not say that “all diagrams commute”, in particular  $\gamma_{X,X}: X \otimes X \rightarrow X \otimes X$  in general is not the identity on  $X \otimes X$ . Instead, it tells us that the morphism is completely given by a labelled

braid, for example



completely describes a map  $A \otimes B \otimes C \otimes C \otimes C \rightarrow C \otimes A \otimes B \otimes C \otimes C$ . If  $\gamma$  is a symmetry, then only the permutation of the objects matters, hence the following braids induce the same morphism.



**Definition 3.1.35.** Let  $\mathcal{V}$  and  $\mathcal{W}$  be braided monoidal categories,  $F: \mathcal{V} \rightarrow \mathcal{W}$  a lax/strong/strict monoidal functor. We call  $F$  a *braided lax/strong/strict monoidal functor* if the diagram

$$\begin{array}{ccc} FA \otimes_{\mathcal{W}} FB & \xrightarrow{\gamma_{\mathcal{W}}} & FB \otimes_{\mathcal{W}} FA \\ \downarrow \phi & & \downarrow \phi \\ F(A \otimes_{\mathcal{V}} B) & \xrightarrow{F\gamma_{\mathcal{V}}} & F(B \otimes_{\mathcal{V}} A) \end{array}$$

commutes.

A *braided natural transformation* is just a monoidal natural transformation between braided monoidal functors.

If  $\mathcal{V}$  and  $\mathcal{W}$  are braided symmetric monoidal categories, then the braided functors and natural transformations are also called *symmetric*.

**Example 3.1.36.**

- (i) If  $\phi: R \rightarrow S$  is a map of commutative rings, then  $- \otimes_R S: \mathbf{Mod}_R \rightarrow \mathbf{Mod}_S$  is a symmetric strong monoidal functor.
- (ii) If  $A$  is an abelian group,  $(h, c)$  a normalized abelian 3-cocycle on  $A$  with values in  $R^\times$  and  $\phi: R \rightarrow S$  a ring homomorphism, we have that  $S \otimes_R -: A\text{-}\mathbf{Mod}_R^{(h,c)} \rightarrow A\text{-}\mathbf{Mod}_S^{(\phi h, \phi c)}$  is a braided strong monoidal functor. In particular, base change is a symmetric strong monoidal functor for both the trivial and the Koszul symmetry on  $\mathbb{Z}\text{-}\mathbf{Mod}_R$ .
- (iii) If  $F$  is a braided strong monoidal left adjoint, then the right adjoint is braided lax monoidal.

**Definition 3.1.37.** Let  $\mathcal{V}$  be a braided monoidal category. A monoid  $(M, \mu, \eta)$  in  $\mathcal{V}$  is *commutative* if

$$\begin{array}{ccc} M \otimes M & \xrightarrow{\gamma_{M,M}} & M \otimes M \\ \mu \searrow & & \swarrow \mu \\ & M & \end{array}$$

commutes.

A *morphism of commutative monoids* is just a morphism of monoids.

**Remark 3.1.38.** In general, a lax monoidal functor will not lift to commutative monoids, but a braided lax monoidal functor will. It follows that we have a 2-functor  $\mathbf{CMon}: \mathbf{BrMonCAT} \rightarrow \mathbf{CAT}$ ,  $\mathcal{V} \mapsto \mathbf{CMon}(\mathcal{V})$ , sending braided monoidal categories to their categories of commutative monoids.

**Theorem 3.1.39.** If  $\mathcal{V}$  is a locally presentable monoidal category with  $- \otimes -$  cocontinuous in both variables, then  $\mathbf{CMon}(\mathcal{V}) \rightarrow \mathcal{V}$  is monadic and accessible. Also,  $\mathbf{CMon}(\mathcal{V})$  is locally  $\kappa$ -presentable if  $\mathcal{V}$  is.

*Proof.* Adapt the one for all monoids with an additional action.  $\square$

**Definition 3.1.40.** Let  $\mathcal{V}$  be a braided monoidal category. Define the *opposite* of a  $\mathcal{V}$ -category  $\mathcal{A}$  by:

- $\mathrm{Ob}(\mathcal{A}^{\mathrm{op}}) = \mathrm{Ob}(\mathcal{A})$ ,
- $\mathcal{A}^{\mathrm{op}}(A, B) = \mathcal{A}(B, A)$ ,
- $\mathrm{id}_A$  the same morphism as for  $\mathcal{A}$  and
- composition by the diagram

$$\begin{array}{ccc} \mathcal{A}^{\mathrm{op}}(B, C) \otimes \mathcal{A}^{\mathrm{op}}(A, B) & \xlongequal{\quad} & \mathcal{A}(C, B) \otimes \mathcal{A}(B, A) \\ \downarrow \circ_{\mathcal{A}^{\mathrm{op}}} & & \downarrow \gamma \\ \mathcal{A}^{\mathrm{op}}(A, C) = \mathcal{A}(C, A) & \xleftarrow{\quad \circ_{\mathcal{A}} \quad} & \mathcal{A}(B, A) \otimes \mathcal{A}(C, B) \end{array}$$

We want to talk about  $\mathcal{V}$ -functors of “several variables.” For this we need  $\mathcal{A} \otimes \mathcal{B}$ .

**Definition 3.1.41.** Let  $\mathcal{A}, \mathcal{B}$  be  $\mathcal{V}$ -categories. Define the  $\mathcal{V}$ -category  $\mathcal{A} \otimes \mathcal{B}$  by

- $\mathrm{Ob}(\mathcal{A} \otimes \mathcal{B}) = \mathrm{Ob}(\mathcal{A}) \times \mathrm{Ob}(\mathcal{B})$
- $(\mathcal{A} \otimes \mathcal{B})((A, B), (A', B')) = \mathcal{A}(A, A') \otimes \mathcal{B}(B, B')$
- identities:  $I \cong I \otimes I \xrightarrow{\mathrm{id}_A \otimes \mathrm{id}_B} \mathcal{A} \otimes \mathcal{B}((A, B), (A, B))$  and
- compositions

$$\begin{array}{c} (\mathcal{A}(A', A'') \otimes \mathcal{B}(B', B'')) \otimes (\mathcal{A}(A, A') \otimes \mathcal{B}(B, B')) \\ \downarrow \text{isomorphism built from } \gamma\text{'s} \\ \mathcal{A}(A', A'') \otimes \mathcal{A}(A, A') \otimes \mathcal{B}(B', B'') \otimes \mathcal{B}(B, B') \\ \downarrow \circ_{\otimes} \\ \mathcal{A}(A, A'') \otimes \mathcal{B}(B, B'') \end{array}$$

Note: The first isomorphism is unique, if  $\mathcal{V}$  is symmetric.

The final ingredient for Yoneda is the enrichment of  $\mathcal{V}$  over itself. For this we need an internal Hom-functor.



**Definition 3.1.42.** A monoidal category  $\mathcal{V}$  is *closed monoidal* if for any  $X \in \mathcal{V}$  the functors  $X \otimes -$  and  $- \otimes X$  have right adjoints  $[X, -]_l$  and  $[X, -]_r$ . We denote the unit and counit by  $\text{coev}$  and  $\text{ev}$  respectively. For example

$$\text{ev}_Y^X: [X, Y]_r \otimes X \rightarrow Y.$$

**Remark 3.1.43.** If  $\mathcal{V}$  is braided, we have  $- \otimes X \cong X \otimes -$ , so  $[-, -]_l$  exists if and only  $[-, -]_r$  does and they are isomorphic. We simply write  $[-, -] = [-, -]_r$  in this case. In other words  $\mathcal{V}(X \otimes Y, Z) \cong \mathcal{V}(X, [Y, Z])$ .

**Remark 3.1.44.** If  $- \otimes X$  and  $X \otimes -$  have right adjoints, the monoidal natural transformations may *not* define a braiding  $\gamma$ ! We need more compatibility.

**Proposition 3.1.45.** Let  $\mathcal{V}$  be a right-closed (that is  $[-, -]_r$  exists) monoidal category. Then the morphisms

$$[Y, Z]_r \otimes [X, Y]_r \rightarrow [X, Z]_r \quad \text{and} \quad I \rightarrow [X, X]_r$$

corresponding to

$$\begin{array}{ccc} ([Y, Z]_r \otimes [X, Y]_r) \otimes X & \longrightarrow & Z \\ \alpha \downarrow & & \uparrow \text{ev}^Y \\ [Y, Z]_r \otimes ([X, Y]_r \otimes X) & \xrightarrow{\text{id} \otimes \text{ev}^X} & [Y, Z]_r \otimes Y \end{array} \quad \text{and} \quad I \otimes X \xrightarrow{\lambda_X} X$$

give a  $\mathcal{V}$ -category structure on  $\text{Ob}(\mathcal{V})$  with underlying category isomorphic to  $\mathcal{V}$ .

*Proof.* The proof is slightly tedious and we refer to Kelly's book.

A more abstract argument is possible if  $\mathcal{V}$  is locally presentable and biclosed. Then we have a monoidal left adjoint

$$\begin{array}{ccc} \mathcal{V} & \xrightarrow{\quad \top \quad} & [\mathcal{V}, \mathcal{V}]_\kappa \xrightarrow{\quad \top \quad} [\mathcal{V}, \mathcal{V}] \\ X & \longmapsto & - \otimes X \end{array}$$

Use the  $[\mathcal{V}, \mathcal{V}]$ -enrichment on  $\text{Ob}(\mathcal{V})$  given by  $\langle \mathcal{V}, \mathcal{W} \rangle$  (previous exercise). Pull this back along the right adjoint and get  $R\langle \mathcal{V}, \mathcal{W} \rangle = [V, W]_r$ .  $\square$

**Example 3.1.46.** 1) If  $\mathcal{V}$  is a category of “sets with structure,” that is if  $V: \mathcal{V} \rightarrow \mathbf{Set}$  is monadic (for example  $\mathcal{V} = \mathbf{Mod}_R, \mathbf{Ab}$  or  $\mathcal{V} = \mathbf{Top}_{\text{CGWH}}$ ), then  $[-, -]$  is just the obvious structure on Hom-sets of  $\mathcal{V}$ . Specifically if  $M, N$  are  $R$ -modules, then  $\text{Hom}_R(M, N)$  has the natural  $R$ -modules structure.

2) For  $\mathcal{V} = \mathbf{Cat}$ ,  $[A, B]$  is just the category of functors from  $A$  to  $B$ . Note that this is not just structure on the Hom-sets, we need the additional data of natural transformations.

3) Even more involved:  $\mathbf{dgMod}_R, \mathbf{sSet}$ :

If we have all these structures, that is a symmetric monoidal closed category, we can define a  $\mathcal{V}$ -functor

$$\mathcal{C}(-, -): \mathcal{C}^{\text{op}} \otimes \mathcal{C} \rightarrow \mathcal{V}.$$

In order to do this, we use the following way of constructing functors  $\mathcal{A} \otimes \mathcal{B} \rightarrow \mathcal{C}$ :

**Proposition 3.1.47.** To give a  $\mathcal{V}$ -functor  $T: \mathcal{A} \otimes \mathcal{B} \rightarrow \mathcal{C}$  amounts to giving families of functors  $(T(A, -): \mathcal{B} \rightarrow \mathcal{C})_{A \in \mathcal{A}}$  and  $(T(-, B): \mathcal{A} \rightarrow \mathcal{C})_{B \in \mathcal{B}}$  such that

- i) On objects  $T(A, -)(B) = T(-, B)(A)$ , which we denote by  $T(A, B)$ .
- ii)  $A, A' \in \mathcal{A}$  and  $B, B' \in \mathcal{B}$  the diagram

$$\begin{array}{ccc}
 & \xrightarrow{T(-, B') \otimes T(A, -)} & \\
 \mathcal{A}(A, A') \otimes \mathcal{B}(B, B') & & \mathcal{C}(T(A, B'), T(A', B')) \otimes \mathcal{C}(T(A, B), T(A', B')) \\
 \downarrow \gamma & & \downarrow \circ \\
 & & \mathcal{C}(T(A, B), T(A', B')) \\
 & & \uparrow \circ \\
 \mathcal{B}(B, B') \otimes \mathcal{A}(A, A') & & \mathcal{C}(T(A', B), T(A', B')) \otimes \mathcal{C}(T(A, B), T(A', B)) \\
 & \xrightarrow{T(A', -) \otimes T(-, B)} &
 \end{array}$$

commutes. This means that “it does not matter in which way we compose.” In this case,  $T_{(A, B), (A', B')}$  is given by the now well defined composite in the above diagram.

*Proof.* Long exercise. □

Now we need to define  $\mathcal{C}(c, -): \mathcal{C} \rightarrow \mathcal{V}$ ,  $\mathcal{C}(-, c): \mathcal{C}^{\text{op}} \rightarrow \mathcal{V}$ . But  $\mathcal{C}(-, c)$  is just  $\mathcal{C}^{\text{op}}(c, -)$ , so we only need to prove that the covariant one is a well defined functor. On objects we define  $\mathcal{C}(c, -)(c') = \mathcal{C}(c, c') \in \mathcal{V}$ . The action on morphisms is given by the morphism

$$\mathcal{C}(c, -)_{c', c'': \mathcal{C}(c', c'') \rightarrow [\mathcal{C}(c, c'), \mathcal{C}(c, c'')]$$

corresponding under adjunction to the composition

$$\mathcal{C}(c', c'') \otimes \mathcal{C}(c, c') \xrightarrow{\circ} \mathcal{C}(c, c'')$$

The diagram in the above proposition commutes by adjunction since composition is associative.

**Example 3.1.48.** 1) For  $\mathcal{V}$  = “sets with structure,” the functor  $\mathcal{C}(-, -)$  simply defines a lift

$$\begin{array}{ccc}
 & & \mathcal{V} \\
 & \nearrow \mathcal{C}(-, -) & \downarrow V \\
 \mathcal{C}^{\text{op}} \otimes \mathcal{C} & & \mathbf{Set} \\
 & \searrow \mathcal{C}_0(-, -) &
 \end{array}$$

we remember that  $\mathcal{C}(-, -)$  is an  $R$ -module, a topological space, etc.

- 2) For  $\mathcal{C} = \mathbf{Cat}$ , we get  $\mathcal{K}(-, -): \mathcal{K}^{\text{op}} \times \mathcal{K} \rightarrow \mathbf{Cat}$ ,  $(x, y) \mapsto \mathcal{K}(x, y)$ , a 2-functor, where the action on 1-cells is given by whiskering on either side.
- 3) For  $\mathcal{V}$  itself, we get  $\mathcal{V}(-, -): \mathcal{V}^{\text{op}} \otimes \mathcal{V} \rightarrow \mathcal{V}$ ,  $(V, W) \mapsto [V, W]$ . The underlying set of this is  $\mathcal{V}(I, [V, W]) \cong \mathcal{V}(V, W)$ . To avoid confusion, we will write  $\mathcal{V}_0(V, W)$  for the *set* of morphisms in  $\mathcal{V}$ .

**Proposition 3.1.49.** There is a  $\mathcal{V}$ -functor  $- \otimes -: \mathcal{V} \otimes \mathcal{V} \rightarrow \mathcal{V}$  which on Hom-objects is the morphism

$$[X, X'] \otimes [Y, Y'] \rightarrow [X \otimes Y, X' \otimes Y']$$

corresponding by adjunction to the morphism

$$([X, X'] \otimes [Y, Y']) \otimes (X \otimes Y) \cong ([X, X'] \otimes X) \otimes ([Y, Y'] \otimes Y) \xrightarrow{\text{ev}^X \otimes \text{ev}^Y} X' \otimes Y'.$$

For this functor,  $\alpha, \lambda, \rho$  are  $\mathcal{V}$ -natural transformations. Moreover for each  $X$ , the maps  $\text{ev}^X$  and  $\text{coev}^X$  are  $\mathcal{V}$ -natural, so  $- \otimes X$  is a left adjoint to the functor  $[X, -]$  in  $\mathcal{V}\text{-CAT}$ .

*Proof.* By adjunction. Straightforward, but tedious (see Kelly).  $\square$

**Remark 3.1.50.** One can check that all “reasonable” morphisms built from the canonical ones are  $\mathcal{V}$ -natural. For example, if  $f: A \rightarrow B$  is a morphism in  $\mathcal{A}_0$ , we get  $\mathcal{V}$ -natural transformations

$$\mathcal{A}(f, -): \mathcal{A}(B, -) \Rightarrow \mathcal{A}(A, -) \quad \text{and} \quad \mathcal{A}(-, f): \mathcal{A}(-, A) \Rightarrow \mathcal{A}(-, B)$$

defined by applying

$$\mathcal{A}_0^{\text{op}} \times \mathcal{A}_0 \rightarrow \mathcal{A}^{\text{op}} \otimes \mathcal{A} \xrightarrow{\mathcal{A}(-, -)_0} \mathcal{V}_0$$

to  $(f, \text{id})$  and  $(\text{id}, f)$  respectively.

Further details - or more precisely a good list of instructions on how to proceed efficiently - can be found in [Kelly].

## 3.2 The weak Yoneda Lemma

**Remark 3.2.1.** With the morphism just defined, we can express  $\mathcal{V}$ -naturality of  $\alpha: F \Rightarrow G$ , where  $F, G: \mathcal{C} \rightarrow \mathcal{D}$  are  $\mathcal{V}$ -functors, by saying that the following diagram commutes for all  $c, c' \in \mathcal{C}$ .

$$\begin{array}{ccc} \mathcal{C}(c, c') & \xrightarrow{F} & \mathcal{D}(Fc, Fc') \\ \downarrow G & & \downarrow \mathcal{D}(Fc, \alpha_{c'}) \\ \mathcal{D}(Gc, Gc') & \xrightarrow{\mathcal{D}(\alpha_c, Gc')} & \mathcal{D}(Fc, Gc') \end{array}$$

**Theorem 3.2.2** (Weak Yoneda lemma). Let  $\mathcal{V}$  be a symmetric monoidal category,  $\mathcal{A}$  a  $\mathcal{V}$ -category,  $F: \mathcal{A} \rightarrow \mathcal{V}$  a  $\mathcal{V}$ -functor,  $A \in \mathcal{A}$ . Given a  $\mathcal{V}$ -natural transformation  $\alpha: \mathcal{A}(A, -) \Rightarrow F$ , let  $\phi(\alpha)$  be the map

$$I \xrightarrow{\text{id}_A} \mathcal{A}(A, A) \xrightarrow{\alpha_A} FA.$$

The assignment

$$\begin{aligned} \mathcal{V}\text{-Nat}(\mathcal{A}(A, -), F) &\rightarrow \mathcal{V}_0(I, FA) \\ \alpha &\mapsto \phi(\alpha) \end{aligned}$$

is a bijection whose inverse map  $\psi$  is given by sending  $\eta: I \rightarrow FA$  to the  $\mathcal{V}$ -natural transformation

$$\mathcal{A}(A, B) \xrightarrow{F_{A, B}} [FA, FB] \xrightarrow{[\eta, \text{id}_{FB}]} [I, FB] \cong FB$$

*Proof.*  $\mathcal{V}$ -naturality follows from the general principle previously mentioned that “all” morphisms coming from the monoidal structure are  $\mathcal{V}$ -natural. Since  $F_{A,A}(\text{id}_A) = \text{id}_{FA}$ , we get  $\phi \cdot \psi = \text{id}$  by construction. We still have to prove that  $\psi \cdot \phi = \text{id}$ .

Consider the diagram

$$\begin{array}{ccccccc}
 \mathcal{A}(A, B) & \xrightarrow{\mathcal{A}(A, -)} & [\mathcal{A}(A, A), \mathcal{A}(A, B)] & \xrightarrow{[\text{id}_A, I]} & [I, \mathcal{A}(A, B)] & \xrightarrow{\sim} & \mathcal{A}(A, B) \\
 \downarrow F & & \downarrow [I, \alpha_B] & & \downarrow [I, \alpha_B] & & \downarrow \alpha_B \\
 [FA, FB] & \xrightarrow{[\alpha_A, I]} & [\mathcal{A}(A, A), FB] & \xrightarrow{[\text{id}_A, I]} & [I, FB] & \xrightarrow{\sim} & FB \\
 & & & \searrow [\phi(B), I] & & & 
 \end{array}$$

where the left and right squares on extremes commute by  $\mathcal{V}$ -naturality, while for the one in the middle we consider the functor  $[-, -]: \mathcal{V}^{\text{op}} \otimes \mathcal{V} \rightarrow \mathcal{V}$ .

The claim follows by checking that the composition is the identity.  $\square$

**Theorem 3.2.3** (Parametrized Yoneda). Let  $T: \mathcal{B}^{\text{op}} \otimes \mathcal{A} \rightarrow \mathcal{V}$  be a  $\mathcal{V}$ -functor and suppose that for all  $B \in \mathcal{B}$  there exists a  $KB \in \mathcal{A}$  and a  $\mathcal{V}$ -natural isomorphism  $\alpha_B: \mathcal{A}(KB, -) \xrightarrow{\sim} T(B, -)$ . Then there is a unique way to define  $K_{B,C}: \mathcal{B}(B, C) \rightarrow \mathcal{A}(KB, KC)$  in  $\mathcal{V}$  such that  $K$  is a  $\mathcal{V}$ -functor and  $(\alpha_B)_A: \mathcal{A}(KB, A) \rightarrow T(B, A)$  is  $\mathcal{V}$ -natural in both variables as a  $\mathcal{V}$ -functor  $\mathcal{B}^{\text{op}} \otimes \mathcal{A} \rightarrow \mathcal{V}$ .

*Proof.* One checks that  $\mathcal{V}$ -naturality of  $(\alpha_A)_B$  amounts to commutativity of the diagram

$$\begin{array}{ccccc}
 \mathcal{B}(B, C) & \xrightarrow{\quad K_{B,C} \quad} & \mathcal{A}(KB, KC) & \xrightarrow{T(B, -)} & [T(B, KB), T(B, KC)] \\
 \downarrow T(-, KC) & & & \searrow \sim & \downarrow [\eta_B, I] \\
 [T(C, KC), T(B, KC)] & \xrightarrow{[\eta_C, I]} & [I, T(B, KC)] & & 
 \end{array}$$

where  $\eta_B = \phi(\alpha_B)$  and the triangle commutes by Yoneda. Since  $(\alpha_B)_{KC}$  is an isomorphism there exists a unique candidate  $K_{B,C}$  and one only has to check that it works.  $\square$

**Remark 3.2.4.** This is really useful as a way of constructing  $\mathcal{V}$ -functors via universal properties and representability results.

### 3.3 Weighted colimits and enriched presheaf categories

We want to define the  $\mathcal{V}$ -category  $[\mathcal{A}^{\text{op}}, \mathcal{V}]$  of  $\mathcal{V}$ -presheaves or  $\mathcal{V}$ -functors for  $\mathcal{A}$  small. We will do this by defining a suitable  $\mathcal{V}$ -monad  $T$  such that  $[\mathcal{A}^{\text{op}}, \mathcal{V}] := T\text{-Alg}$ . We want our category to have at least coproducts and equalizers, so from now on we assume that  $\mathcal{V}$  is a (co)complete, symmetric monoidal and closed. Such an object is called *cosmos*, after *Bénabou cosmos*.

**Definition 3.3.1.** Let  $\mathcal{C}$  be a  $\mathcal{V}$ -category,  $(C_j)_{j \in J} \in \text{Ob}(\mathcal{C})^J$  a family of objects in  $\mathcal{C}$ . We say that a collection  $j_j: C_j \rightarrow C$  exhibits  $C$  as a  $\mathcal{V}$ -coproduct of the  $(C_j)_{j \in J}$  if

$$\mathcal{C}(j_j, D): \mathcal{C}(C, D) \rightarrow \mathcal{C}(C_j, D)$$

is a product diagram in  $\mathcal{V}_0$  for all  $D \in \mathcal{C}$ .

Similarly, we define a  $\mathcal{V}$ -coequalizer

$$A \rightrightarrows B \rightarrow C$$

by requiring that

$$\mathcal{C}(C, D) \rightarrow \mathcal{C}(B, D) \rightrightarrows \mathcal{C}(A, D)$$

is a coequalizer in  $\mathcal{V}_0$ .

Dualizing the definitions, we find the notions of  $\mathcal{V}$ -product and  $\mathcal{V}$ -equalizer.

**Remark 3.3.2.** If we apply  $\mathcal{C}_0(-, A): \mathcal{C}_0 \rightarrow \mathbf{Set}$  for every  $A \in \mathcal{C}$ , we see that  $\mathcal{V}$ -coproducts and  $\mathcal{V}$ -coequalizers are in particular coproducts and coequalizers in  $\mathcal{C}_0$ .

**Example 3.3.3.** For  $\mathcal{V} = \mathbf{Cat}$ , a  $\mathcal{V}$ -coequalizer also has a 2-dimensional universal property, that is given one  $A \rightrightarrows B \rightarrow C$  and a 2-cell from  $B$  to  $D$  there is a unique 2-cell from  $C$  to  $D$  making the following diagram commute.

For enriched categories, there is an important third kind of colimit called *copower* or *tensor*.

**Definition 3.3.4.** Let  $\mathcal{C}$  be a  $\mathcal{V}$ -category,  $V \in \mathcal{V}$ ,  $C \in \mathcal{C}$ . We say that the copower of  $C$  by  $V$  exists if the  $\mathcal{V}$ -functor  $[V, \mathcal{C}(C, -)]: \mathcal{C} \rightarrow \mathcal{V}$  is representable by some object  $V \odot C \in \mathcal{C}$ , the copower, that is we have a  $\mathcal{V}$ -natural isomorphism  $\mathcal{C}(V \odot C, -) \xrightarrow{\sim} [V, \mathcal{C}(C, -)]$ .

Dualizing the definition, we find the notion of *power* or *cotensor*.

**Remark 3.3.5.** By parametrized Yoneda, we get a  $\mathcal{V}$ -functor

$$- \odot -: \mathcal{V} \otimes \mathcal{C} \rightarrow \mathcal{C}$$

if all copowers exist. It is associative up to coherent isomorphism, so it defines a kind of weak action of  $\mathcal{V}$  on  $\mathcal{C}$ .

**Example 3.3.6.** For  $\mathcal{V} = \mathcal{C} = \mathbf{Cat}$ ,  $C \times [1]$  is the copower of  $C \in \mathcal{C}$  by  $[1] \in \mathcal{V}$ . Indeed, we have a pair of bijective correspondences inducing the one we want as follows:

$$C \times [1] \rightarrow D \quad \leftrightarrow \quad C \begin{array}{c} \xrightarrow{\quad} \\ \Downarrow \alpha \\ \xrightarrow{\quad} \end{array} D \quad \leftrightarrow \quad C \rightarrow D^{[1]}.$$

**Proposition 3.3.7.** A  $\mathcal{V}$ -category  $\mathcal{C}$  has  $\mathcal{V}$ -coproducts and  $\mathcal{V}$ -coequalizers if  $\mathcal{C}_0$  has coproducts and coequalizers and these are preserved by the functor  $\mathcal{C}_0(-, D): \mathcal{C}_0 \rightarrow \mathcal{V}^{\text{op}}$  for every  $D \in \mathcal{C}$ .

*Proof.* It follows from the definition. □

**Corollary 3.3.8.** The  $\mathcal{V}$ -categories  $\mathcal{V}$  and  $\mathcal{V}^{\text{op}}$  have all  $\mathcal{V}$ -coproducts and  $\mathcal{V}$ -coequalizers.

*Proof.* We need to check that  $[-, V]_0: \mathcal{C}_0 \rightarrow \mathcal{V}_0^{\text{op}}$  preserves coproducts and coequalizers, but this is just  $[-, V]: \mathcal{V}_0 \rightarrow \mathcal{V}_0^{\text{op}}$  and we have  $[-, V] \dashv [-, V]: \mathcal{V}_0^{\text{op}} \rightarrow \mathcal{V}_0$  because

$$\mathcal{V}_0(X, [Y, V]) \cong \mathcal{V}_0(X \otimes Y, V) \cong \mathcal{V}_0(Y \otimes X, V) \cong \mathcal{V}_0(Y, [X, V]).$$

For  $\mathcal{V}^{\text{op}}$ , we need to check that  $[V, -]_0: \mathcal{V}_0 \rightarrow \mathcal{V}_0^{\text{op}}$  preserves limits, which follows from  $- \otimes V \dashv [V, -]$ . □

**Proposition 3.3.9.** The  $\mathcal{V}$ -category  $\mathcal{V}$  has all powers and copowers given by  $[V, C]$  and  $V \otimes C$  respectively.

*Proof.* We need  $\mathcal{V}$ -natural isomorphisms  $[V, [C, D]] \cong [V \otimes C, D]$ , which follows from the fact that we have a  $\mathcal{V}$ -adjunction  $- \otimes C \dashv [C, -]$ . Similarly, use the symmetry isomorphism to get a  $\mathcal{V}$ -natural isomorphism  $[D, [V, C]] \cong [V, [D, C]]$ .  $\square$

**Definition 3.3.10.** A  $\mathcal{V}$ -category  $\mathcal{C}$  is  $\mathcal{V}$ -cocomplete if it has all  $\mathcal{V}$ -coequalizers,  $\mathcal{V}$ -coproducts and copowers. If it satisfies the dual conditions, then it is  $\mathcal{V}$ -complete.

**Example 3.3.11.** If  $(\mathcal{C}_j)_{j \in J}$  is a family of  $\mathcal{V}$ -(co)complete  $\mathcal{V}$ -categories, then  $\prod_{j \in J} \mathcal{C}_j$  is a  $\mathcal{V}$ -(co)complete  $\mathcal{V}$ -category.

**Proposition 3.3.12.** If  $\mathcal{C}$  has powers (cotensors), then  $\mathcal{C}$  is cocomplete if and only if  $\mathcal{C}_0$  is cocomplete and  $\mathcal{C}$  has copowers.

*Proof.* " $\Rightarrow$ " : We have already seen this.

" $\Leftarrow$ " : We need to show that ordinary coequalizers and coproducts in  $\mathcal{C}_0$  are automatically  $\mathcal{V}$ -coequalizers and  $\mathcal{V}$ -coproducts. We will just check the case of coequalizers and leave the other case for the reader. We know that we have a natural bijection of sets between equalizers

$$\mathcal{C}_0(K, D) \xrightarrow{\cong} \text{Eq}(\mathcal{C}_0(B, D) \xrightarrow{f^*} \mathcal{C}_0(A, D))$$

in **Set** and coequalizers

$$A \xrightarrow[f]{g} B \xrightarrow{k} K$$

in  $\mathcal{C}_0$ . For each  $E \in \mathcal{C}$  and  $V \in \mathcal{V}_0$  we have then the commutative diagram

$$\begin{array}{ccccc} \mathcal{C}_0(K, E^V) & \longrightarrow & \mathcal{C}_0(B, E^V) & \rightrightarrows & \mathcal{C}_0(A, E^V) \\ \cong \downarrow & & \downarrow \cong & & \downarrow \cong \\ \mathcal{V}_0(V, \mathcal{C}(K, E)) & \longrightarrow & \mathcal{V}_0(V, \mathcal{C}(B, E)) & \rightrightarrows & \mathcal{V}_0(V, \mathcal{C}(A, E)) \end{array}$$

and since this holds for all  $V \in \mathcal{V}_0$ , this implies that  $\mathcal{C}(K, E) \cong \text{Eq}(f^*, g^*)$  in  $\mathcal{V}$ , as claimed.  $\square$

**Corollary 3.3.13.**  $\mathcal{V}$  is complete and cocomplete as  $\mathcal{V}$ -category.

**Remark 3.3.14.** Note, that the existence of powers for a strong generating set suffices.

**Definition 3.3.15.** We say that a  $\mathcal{V}$ -functor  $F: \mathcal{C} \rightarrow \mathcal{D}$  preserves (certain)  $\mathcal{V}$ -coequalizers or  $\mathcal{V}$ -coproducts if  $F_0: \mathcal{C}_0 \rightarrow \mathcal{D}_0$  preserves coequalizers or coproducts.

To talk about preservation of copowers, we need a canonical comparison morphism  $\bar{F}: V \odot FC \rightarrow F(V \odot C)$ , which we define to be

$$\begin{array}{ccc} I & \longrightarrow & \mathcal{D}(V \odot FC, F(V \odot C)) \\ \eta \downarrow & & \uparrow \cong \\ [V, \mathcal{C}(C, V \odot C)] & \longrightarrow & [V, \mathcal{D}(FC, F(V \odot C))] \end{array}$$

where the lower horizontal morphism is  $[V, F]$  and  $\eta$  corresponds via weak Yoneda to the  $\mathcal{V}$ -natural isomorphism  $\mathcal{C}(V \odot C, -) \cong [V, \mathcal{C}(C, -)]$ .

**Definition 3.3.16.** We say, that  $F$  preserves the copower  $V \odot C$  if  $\bar{F}: V \odot FC \rightarrow F(V \odot C)$  is an isomorphism in  $\mathcal{D}_0$ .

**Lemma 3.3.17.** Let  $\mathcal{C}$  be a  $\mathcal{V}$ -category and  $\mathcal{B} \subset \mathcal{C}$  the full subcategory generated by those object  $B \in \mathcal{C}$  such that  $V \odot B$  exists (in  $\mathcal{C}$ ) for all  $V \in \mathcal{V}$ . Then  $\mathcal{B}$  is closed in  $\mathcal{C}$  under  $\mathcal{V}$ -coequalizers and  $\mathcal{V}$ -coproducts.

*Proof.* Let

$$A \xrightarrow[f]{g} B \xrightarrow{k} K$$

be a  $\mathcal{V}$ -coequalizer such that  $A, B \in \mathcal{B}$ . We need to show that the  $\mathcal{V}$ -coequalizer of

$$V \odot A \xrightarrow[V \odot g]{V \odot f} V \odot B$$

is given by  $V \odot K$ . Indeed we have an induced isomorphism

$$\begin{array}{ccccc} \mathcal{C}(V \odot K, D) & \xrightarrow{eq} & \mathcal{C}(V \odot, D) & \rightrightarrows & \mathcal{C}(V \odot A, D) \\ \cong \downarrow \exists! & & \downarrow \cong & & \downarrow \cong \\ [V, \mathcal{C}(K, D)] & \xrightarrow{eq} & [V, \mathcal{C}(B, D)] & \rightrightarrows & [V, \mathcal{C}(A, D)] \end{array}$$

and the proof for coproducts is similar.  $\square$

**Theorem 3.3.18.** Let  $\mathcal{C}$  be a complete  $\mathcal{V}$ -category and let  $T: \mathcal{C} \rightarrow \mathcal{C}$  be a  $\mathcal{V}$ -monad. Then  $T\text{-Alg}$  is complete and  $U: T\text{-Alg} \rightarrow \mathcal{C}$  preserves  $\mathcal{V}$ -powers,  $\mathcal{V}$ -products and  $\mathcal{V}$ -equalizers. If  $\mathcal{C}$  is also cocomplete, then  $T\text{-Alg}$  is cocomplete if and only if the underlying unenriched category  $(T\text{-Alg})_0 \cong T_0\text{-Alg}$  is cocomplete.

*Proof.* We know that  $T_0\text{-Alg}$  is complete, so we need to show that equalizers and products are  $\mathcal{V}$ -equalizers and  $\mathcal{V}$ -products. But hom-objects are defined as equalizers in  $\mathcal{V}$

$$T\text{-Alg}((A, a), (B, b)) \longrightarrow \mathcal{C}(A, B) \rightrightarrows \mathcal{C}(TA, B)$$

and we thus get the claim for  $\mathcal{V}$ -equalizers and  $\mathcal{V}$ -products, since equalizers and products commute with equalizers in  $\mathcal{V}_0$ . We will leave the claim for powers as an exercise. Once we have the powers, we get from the cocompleteness of  $T_0\text{-Alg}$  that  $T\text{-Alg}$  has  $\mathcal{V}$ -coequalizers and  $\mathcal{V}$ -coproducts. It remains to show that  $T\text{-Alg}$  has copowers. For this we use the lemma above: since every object is a coequalizer of free algebras, hence a  $\mathcal{V}$ -coequalizer, it suffices to check this for free algebras, i.e. algebras in the image of the left  $\mathcal{V}$ -adjoint  $F: \mathcal{C} \rightarrow T\text{-Alg}$ . So we are done if we can show that left  $\mathcal{V}$ -adjoints preserve copowers. This follows from the next proposition.  $\square$

**Proposition 3.3.19.** Left  $\mathcal{V}$ -adjoints preserve  $\mathcal{V}$ -coequalizers,  $\mathcal{V}$ -coproducts and copowers.

*Proof.* Let  $F: \mathcal{C} \rightarrow \mathcal{D}$  be a left  $\mathcal{V}$ -adjoint  $F \dashv U$ . The claims all follow as in the unenriched case. For copowers we have the isomorphisms

$$\mathcal{D}(F(V \odot C), D) \cong \mathcal{C}(V \odot C, UD) \cong [V, \mathcal{C}(C, UD)] \cong [V, \mathcal{D}(FC, D)]$$

and one checks that this is the counit morphism if the target has copowers.  $\square$

We are now ready to define enriched presheaf categories. Let  $\mathcal{A}$  be a small  $\mathcal{V}$ -category. Then  $\prod_{A \in \text{Ob}(\mathcal{A})} \mathcal{V}$  is clearly a complete and cocomplete  $\mathcal{V}$ -category with everything computed pointwise. We define the  $\mathcal{V}$ -monad for presheaves as

$$T((FA)_{A \in \text{Ob}(\mathcal{A})}) = \left( \coprod_{A \in \text{Ob}(\mathcal{A})} \mathcal{A}(B, A) \odot FA \right)_{B \in \text{Ob}(\mathcal{A})}$$

with unit given by identities and multiplication given by composition. A  $T$ -algebra is thus a collection  $(FA)_{A \in \text{Ob}(\mathcal{A})} \in \prod_{A \in \text{Ob}(\mathcal{A})} \mathcal{V}$  with action  $\coprod \mathcal{A}(B, A) \odot FA \rightarrow FB$ , which amounts precisely to a  $\mathcal{V}$ -functor  $\mathcal{A}(B, A) \rightarrow [FA, FB]$  i.e. a  $\mathcal{V}$ -functor  $\mathcal{A}^{\text{op}} \rightarrow \mathcal{V}$ .

**Definition 3.3.20.** We write  $[\mathcal{A}^{\text{op}}, \mathcal{V}]$  for  $T\text{-Alg}$  and call it the  $\mathcal{V}$ -category of  $\mathcal{V}$ -presheaves on  $\mathcal{A}$ . By construction we have  $[\mathcal{A}^{\text{op}}, \mathcal{V}]_0 = \mathcal{V}\text{-CAT}(\mathcal{A}^{\text{op}}, \mathcal{V})$ .

**Remark 3.3.21.** (1) The same construction works for any cocomplete  $\mathcal{V}$ -category  $\mathcal{C}$  and we get  $\mathcal{V}$ -categories  $[\mathcal{A}^{\text{op}}, \mathcal{C}]$  and  $[\mathcal{A}, \mathcal{C}]$ .

(2) The statement “ $T$  is a  $\mathcal{V}$ -monad” actually needs to be checked. It can be done using Kelly (1.7,1.8) and the universal properties of  $\coprod$  and  $\odot$  (see also later exercise).

(3) We have the enriched Yoneda lemma basically by definition: the free algebra of the collection  $(I_B)_{B \in \text{Ob}(\mathcal{A})}$ , given by  $I$  if  $B = A$  and  $\emptyset$  else, is precisely  $\mathcal{A}(-, A)$ . So we get isomorphisms

$$[\mathcal{A}^{\text{op}}, \mathcal{V}](\mathcal{A}(-, A), F) \cong T\text{-Alg}((FI_B)_{B \in \text{Ob}(\mathcal{A})}, F) \cong \prod \mathcal{V}(I_B, (FB)_{B \in \mathcal{A}}) \cong FA$$

(4) The hom-object is by definition the equalizer

$$[\mathcal{A}^{\text{op}}, \mathcal{V}](F, G) \longrightarrow \prod_A [FA, GA] \rightrightarrows \prod_{A, B} [\mathcal{A}(A, B) \odot FA, GB]$$

**Proposition 3.3.22.** The  $\mathcal{V}$ -categories  $[\mathcal{A}^{\text{op}}, \mathcal{C}]$  and  $[\mathcal{A}, \mathcal{C}]$  are complete (resp. cocomplete), if  $\mathcal{A}$  is small and  $\mathcal{C}$  is complete (resp. cocomplete).

*Proof.* This follows, since  $T_0$  is cocontinuous. □

**Definition 3.3.23.** Given a  $\mathcal{V}$ -category  $\mathcal{C}$  and a  $\mathcal{V}$ -functor  $K: \mathcal{A} \rightarrow \mathcal{C}$ , where  $\mathcal{A}$  is small, we have a natural  $T$ -action on the  $\mathcal{V}$ -functor  $\mathcal{C} \rightarrow \prod_{\text{Ob}(\mathcal{A})} \mathcal{V}$  given by the assignment  $c \mapsto \mathcal{C}(Ka, c)$ . Now we write

$$\mathcal{C}(K, -): \mathcal{C} \rightarrow [\mathcal{A}^{\text{op}}, \mathcal{V}]$$

for the induced  $\mathcal{V}$ -functor given by sending  $c$  to  $\mathcal{C}(K-, c)$ . This is also written as  $\tilde{K}$ .

**Definition 3.3.24.** Given a  $\mathcal{V}$ -presheaf  $W: \mathcal{A}^{\text{op}} \rightarrow \mathcal{V}$  and a  $\mathcal{V}$ -functor  $K: \mathcal{A} \rightarrow \mathcal{C}$ , we say that the  $W$ -weighted colimit of  $K$  exists if

$$[\mathcal{A}^{\text{op}}, \mathcal{V}](W, \mathcal{C}(K, -)): \mathcal{C} \rightarrow \mathbf{Set}$$

is corepresentable, that is there is a corepresenting object denoted by  $W \odot_{\mathcal{A}} K$ , such that

$$\mathcal{C}(W \odot_{\mathcal{A}} K, c) \cong [\mathcal{A}^{\text{op}}, \mathcal{V}](W, \mathcal{C}(K-, c))$$

naturally in  $c \in \mathcal{C}$ .



We can think of  $Wa \rightarrow \mathcal{C}(Ka, c)$  as a bunch of enriched cocones.

**Example 3.3.25.** (i) If  $\mathcal{A} = \mathcal{J}$  with  $\text{Ob}(\mathcal{J}) = \{*\}$  and  $\mathcal{J}(*, *) = \{\text{id}_*\}$ , then  $[\mathcal{J}^{\text{op}}, \mathcal{V}] \cong \mathcal{V}$  and every  $\mathcal{J} \rightarrow \mathcal{C}$  amounts to giving an object  $c \in \mathcal{C}$ . Hence  $v \odot_{\mathcal{J}} c$  is simply the copower  $v \odot c$ .

(ii) If  $\mathcal{D}$  is an unenriched small category, we can consider the free  $\mathcal{V}$ -category  $(I)_* \mathcal{D}$ . Then giving a  $\mathcal{V}$ -functor  $(I)_* \mathcal{D} \rightarrow \mathcal{C}$  is the same as giving a functor  $\mathcal{D} \rightarrow \mathcal{C}_0$ . The conical weight  $\Delta_I: (I)_* \mathcal{D}^{\text{op}} \rightarrow \mathcal{V}$  gives us a functor  $\mathcal{D}^{\text{op}} \rightarrow \mathcal{V}_0$  sending the whole category to the identity of the monoidal category  $\mathcal{V}$ . Then  $\Delta_I \odot_{(I)_* \mathcal{D}} F$  is really the same as a colimit of  $\tilde{F}: \mathcal{D} \rightarrow \mathcal{C}_0$  with the additional property that  $\mathcal{C}(\text{colim } \tilde{F}d, c) \cong \lim \mathcal{C}(Fd, c)$  in  $\mathcal{V}$  (rather than just a bijection of sets). In particular, when  $\mathcal{C}$  has powers there is no distinction between colimits in  $\mathcal{C}_0$  and  $\Delta_I$ -weighted colimits. Powers make it possible to lift the bijection of sets to an isomorphism in  $\mathcal{V}$  via (unenriched) Yoneda for  $\mathcal{V}_0$ . The  $\Delta_I$ -weighted colimits are called *conical* colimits. In particular,  $\mathcal{V}$ -coequalizers and  $\mathcal{V}$ -coproducts are conical colimits.

**Theorem 3.3.26.** Let  $\mathcal{C}$  be a  $\mathcal{V}$ -category. TFAE:

1. The  $\mathcal{V}$ -category  $\mathcal{C}$  is cocomplete.
2. For each small  $\mathcal{V}$ -category  $\mathcal{A}$  and each  $\mathcal{V}$ -functor  $K: \mathcal{A} \rightarrow \mathcal{C}$ , the functor  $\mathcal{C}(K, -): \mathcal{C} \rightarrow [\mathcal{A}^{\text{op}}, \mathcal{V}]$  has a left  $\mathcal{V}$ -adjoint  $- \odot_{\mathcal{A}} K: [\mathcal{A}^{\text{op}}, \mathcal{V}] \rightarrow \mathcal{C}$ .
3. The category  $\mathcal{C}$  has all weighted colimits.

*Proof.* In the example we saw  $3 \Rightarrow 1$  and clearly  $2 \Rightarrow 3$  by definition. It remains to show  $1 \Rightarrow 2$ . By the parametrized Yoneda lemma, we need to show that

$$W \mapsto [\mathcal{A}^{\text{op}}, \mathcal{V}](W, \mathcal{C}(K, -))$$

is representable for every  $W \in [\mathcal{A}^{\text{op}}, \mathcal{V}]$ . Every such  $W$  is canonically a  $\mathcal{V}$ -coequalizer of free objects (recall that  $[\mathcal{A}^{\text{op}}, \mathcal{V}] = T\text{-Alg}$ ). Let  $\mathcal{B} \subseteq [\mathcal{A}^{\text{op}}, \mathcal{V}]$  be the subcategory of the  $W$  such that  $[\mathcal{A}^{\text{op}}, \mathcal{V}](W, \mathcal{C}(K, -))$  is representable. By assumption,  $\mathcal{B}$  is closed under copowers,  $\mathcal{V}$ -coproducts and  $\mathcal{V}$ -coequalizers. Thus it suffices to show that if  $W$  is a free  $T$ -algebra, then  $W \in \mathcal{B}$ . Using copowers and coproducts, we can reduce the case  $W = T(V_A)_{A \in \mathcal{A}}$  to  $T(I_A)$  where

$$(I_A) = \begin{cases} \emptyset, & \text{if } \mathcal{B} \neq \mathcal{A} \\ I, & \text{if } \mathcal{B} = \mathcal{A} \end{cases}$$

Therefore

$$(V_A)_{A \in \mathcal{A}} = \coprod_{A \in \mathcal{A}} V_A \odot I_A \in \prod_{A \in \mathcal{A}} \mathcal{V}$$

so that we are reduced to checking  $T(I_A) \in \mathcal{B}$ . But  $T(I_A) = \mathcal{A}(-, A)$  by definition of  $T$ . Here we have

$$[\mathcal{A}^{\text{op}}, \mathcal{V}](T(I_A), \mathcal{C}(K, -)) \cong \prod \mathcal{V}(I_A, (\mathcal{C}(KB, -))_{B \in \mathcal{A}}) \cong \mathcal{C}(KA, -)$$

so this is corepresented by  $KA \in \mathcal{C}$ . □

**Remark 3.3.27.** We may extract a formula from the proof above. Then we find

$$\mathcal{A}(-, A) \odot_{\mathcal{A}} K = KA$$

and

$$W \odot_{\mathcal{A}} K = \text{coeq} \left( \prod_{A, B} (WB \otimes \mathcal{A}(A, B)) \odot KA \rightrightarrows \prod_A WA \otimes KA \right)$$

**Corollary 3.3.28.** For all small  $\mathcal{A}$ ,  $[\mathcal{A}, \mathcal{V}]$  has weighted colimits.

**Example 3.3.29.** Take  $\mathcal{V} = \mathbf{Cat}$  and  $\mathcal{K}$  a (cocomplete) 2-category. In this case,  $[\mathcal{A}, \mathcal{K}]$  is the 2-category with 0-cells the 2-functors, 1-cells the 2-natural transformations and 2-cells the so-called *modifications*.

**Definition 3.3.30.** Let  $\alpha, \beta: F \Rightarrow G$  be 2-natural transformations between 2-functors  $\mathcal{A} \rightarrow \mathcal{K}$ . A modification  $\varphi: \alpha \Rightarrow \beta$  is a collection of 2-cells  $(\varphi_A: \alpha_A \Rightarrow \beta_A)_{A \in \mathcal{A}}$  in  $\mathcal{K}$ , such that

$$\begin{array}{ccc} FA & \xrightarrow{\alpha_A} & GA \\ \varphi_A \Downarrow & & \downarrow Gf \\ Ff \downarrow & & \downarrow Gf \\ FB & \xrightarrow{\beta_B} & GB \end{array} = \begin{array}{ccc} FA & \xrightarrow{\alpha_A} & GA \\ Ff \downarrow & & \downarrow Gf \\ FB & \xrightarrow{\varphi_B \Downarrow} & GB \\ & \beta_B & \end{array}$$

holds for every  $f: A \rightarrow B$

Take  $\mathcal{A} = \{f_0, f_1: 0 \rightrightarrows 1\}$  and  $W: \mathcal{A} \rightarrow \mathbf{Cat}$  sending 0 to the terminal category  $*$ , 1 to the category  $[1] = \{0 \rightarrow 1\}$  and such that  $Wf_i = \text{in}_i: * \rightarrow [1]$  are the inclusions of the domain and the target in the walking arrow. The  $W$ -weighted limit represents  $[\mathcal{A}, \mathbf{Cat}](W, \mathcal{C}(c, F-))$  for  $F: \mathcal{A} \rightarrow \mathcal{C}$ . This amounts to a morphism  $c \xrightarrow{c} F_0$  and a 2-cell

$$\begin{array}{ccc} & F_0 & \\ c \nearrow & & \searrow Ff_0 \\ c & & F_1 \\ c \searrow & & \nearrow Ff_1 \\ & F_0 & \end{array} \quad \Downarrow \gamma$$

as objects, while morphisms are modifications. A priori, these are two natural transformations

$$\begin{array}{ccc} & (c, \gamma) & \\ W_i & \xrightarrow{\varphi_i \Downarrow} & \mathcal{C}(c, F-) \\ & (d, \delta) & \end{array}$$

but  $\varphi_i$  is determined by  $\varphi_0$ , so we are left with a single equation.

$$\begin{array}{ccc} & F_0 & \xrightarrow{Ff_0} F_1 \\ c \nearrow & & \downarrow \delta \\ c & & F_0 \\ d \searrow & & \uparrow Ff_1 \end{array} \quad \Downarrow \varphi_0 \quad = \quad \begin{array}{ccc} & c & \xrightarrow{c} F_0 \\ d \nearrow & & \downarrow \gamma \\ F_0 & & F_1 \\ & \xleftarrow{Ff_1} & \end{array}$$

The limit is called the *insertor* of  $Ff_0$  and  $Ff_1$ , since it freely inserts a 2-cell. If we set  $W(1) =$  “walking isomorphism” we get an *iso-insertor*, that is an invertible inserter. As in the unenriched case, we can define  $\mathcal{V}$ -dense functors and density presentations.

**Definition 3.3.31.** Let  $\mathcal{A}$  be a small  $\mathcal{V}$ -category. A  $\mathcal{V}$ -functor  $K: \mathcal{A} \rightarrow \mathcal{C}$  is called *dense* if  $\mathcal{C}(K, -): \mathcal{C} \rightarrow [\mathcal{A}^{\text{op}}, \mathcal{V}]$  is full and faithful. A weighted colimit in  $\mathcal{C}$  is called *K-absolute* if it is preserved by  $\mathcal{C}(K, -)$  that is, the canonical morphism

$$W \odot_{\mathcal{A}} \mathcal{C}(K, F-) \xrightarrow{\mathcal{C}(K, -)} \mathcal{C}(K, W \odot_{\mathcal{A}} F)$$

is an isomorphism.

**Definition 3.3.32.** If  $K$  is full and faithful, a  $\mathcal{V}$ -density presentation is a collection of weights and diagrams  $\{W_\gamma: \mathcal{A}_\gamma^{\text{op}} \rightarrow \mathcal{V}, F_\gamma: \mathcal{A}_\gamma \rightarrow \mathcal{C}\}_{\gamma \in \Gamma}$  such that  $W_\gamma \odot_{\mathcal{A}_\gamma} F_\gamma$  exists, is  $K$ -absolute and  $\mathcal{C}$  is the closure of  $\{KA \mid A \in \mathcal{A}\}$  under colimits in  $\Gamma$ .

**Proposition 3.3.33.** If a full and faithful functor  $K: \mathcal{A} \rightarrow \mathcal{C}$  has a  $\mathcal{V}$ -density presentation, then it is  $\mathcal{V}$ -dense.

*Proof.* Consider the full subcategory  $\mathcal{B} \subseteq \mathcal{C}$  spanned by the objects  $B$  s.t.

$$\mathcal{C}(K, -)_{B, C}: \mathcal{C}(B, C) \rightarrow [\mathcal{A}^{\text{op}}, \mathcal{V}](\mathcal{C}(K-, B), \mathcal{C}(K-, C))$$

is an iso in  $\mathcal{V}$  for all  $c \in \mathcal{C}$ . By definition of  $K$ -absoluteness,  $\mathcal{B}$  is closed under  $K$ -absolute colimits, both sides preserve  $K$ -absolute colimits, i.e.  $\mathcal{C}(-, c)$  and  $[\mathcal{A}^{\text{op}}, \mathcal{V}](\mathcal{C}(K-, -), \mathcal{C}(K-, c)): \mathcal{C} \rightarrow \mathcal{V}^{\text{op}}$  preserve them. It only remains to show that  $KA \in \mathcal{B} \ \forall A \in \mathcal{A}$ . To see this one needs to observe that the diagram

$$\begin{array}{ccc} \mathcal{C}(KA, C) & \xrightarrow{\mathcal{C}(K, -)} & [\mathcal{A}^{\text{op}}, \mathcal{V}](\mathcal{C}(K-, KA), \mathcal{C}(K-, C)) \\ & \searrow \text{Yoneda} \cong & \downarrow \\ & & [\mathcal{A}^{\text{op}}, \mathcal{V}](\mathcal{A}(-, A), \mathcal{C}(K-, C)) \end{array}$$

is commutative<sup>1</sup>. The claim follows since we assumed that  $\mathcal{C}(K-, KA) \cong \mathcal{A}(-, A)$ .  $\square$

**Example 3.3.34.**  $I \in \mathcal{V}$  is always dense, but rarely **Set**-dense.

**Definition 3.3.35.** Given a small  $\mathcal{V}$ -category  $\mathcal{A}$  and  $\mathcal{V}$ -functors  $K: \mathcal{A} \rightarrow \mathcal{C}$  and  $F: \mathcal{A} \rightarrow \mathcal{D}$ , we say that the *pointwise Kan extension* of  $F$  along  $K$  exists if the  $\mathcal{V}$ -functor

$$[\mathcal{A}^{\text{op}}, \mathcal{V}]\left(\mathcal{C}(K, -), \mathcal{C}(F, -)\right): \mathcal{C}^{\text{op}} \times \mathcal{D} \rightarrow \mathcal{V}$$

is representable in the first variable. By parameterized Yoneda, we get a functor  $\mathcal{C} \rightarrow \mathcal{D}$  which we denote by  $\text{Lan}_K F$ . In other words  $\text{Lan}_K F = (- \odot_{\mathcal{A}} F) \circ \mathcal{C}(K, -)$  and  $\text{Lan}_K F(c) = \mathcal{C}(K-, c) \odot_{\mathcal{A}} F$ .

**Proposition 3.3.36.** If the pointwise Kan extension exists, then it is in particular a left Kan extension in  $\mathcal{V}\text{-CAT}$ , i.e.

$$\begin{array}{ccc} \mathcal{A} & \xrightarrow{K} & \mathcal{C} \\ & \searrow F \Rightarrow & \downarrow \text{Lan}_K F \\ & & \mathcal{D} \end{array}$$

is the universal natural transformation in this diagram. Also we have  $\text{Lan}_K \dashv K^*$ .

*Proof.* We need to show that

$$\frac{\text{Lan}_K F \Rightarrow G}{F \Rightarrow GK}$$

By definition we have  $\text{Lan}_K F = (- \odot F) \circ \mathcal{C}(K, -)$  so by (partial) adjunction we have

$$\frac{\text{Lan}_K F \rightarrow G}{\mathcal{C}(K, -) \rightarrow \mathcal{C}(F, -) \circ G}$$

<sup>1</sup>Compare this result with faithfulness of  $[\mathcal{A}^{\text{op}}, \mathcal{V}] \rightarrow \prod \mathcal{V}$

Both  $\mathcal{C}(K, -)$  and  $\mathcal{C}(F, -)$  are defined by lifting  $T$ -action on collections ( $T$  the presheaf monad) so this amounts to giving a collection of  $\mathcal{V}$ -natural transformations  $\mathcal{C}(Ka, -) \xrightarrow{\alpha_{a,-}} \mathcal{D}(Fa, G-)$  compatible with the action, i.e.

$$\begin{array}{ccc} \mathcal{A}(a', a) \otimes \mathcal{C}(Ka, c) & \xrightarrow{1 \otimes \alpha_{a,-}} & \mathcal{A}(a', a) \otimes \mathcal{D}(Fa, G-) \\ \downarrow \text{action} & & \downarrow \\ \mathcal{C}(Ka', c) & \xrightarrow{\alpha_{a',-}} & \mathcal{D}(Fa', G-) \end{array}$$

By weak Yoneda, the  $\alpha_{a,-}$  are uniquely determined by  $\alpha_{a,Ka}(\text{id}_{Ka}) =: \beta: Fa \rightarrow GKa$ . In fact (again by Yoneda) we have

$$\alpha_{a,-} = \mathcal{C}(Ka, -) \xrightarrow{G_{Ka,-}} \mathcal{D}(GKa, -) \xrightarrow{\mathcal{D}(\beta_a, G-)} \mathcal{D}(Fa, G-)$$

Plugging this into the square above and precomposing with

$$1 \otimes \text{id}_{Ka}: \mathcal{A}(a, a') \rightarrow \mathcal{A}(a, a') \otimes \mathcal{C}(Ka, Ka)$$

we find that  $\beta$  is  $\mathcal{V}$ -natural, i.e. the  $\alpha_{a,-}$  are compatible with the  $\mathcal{V}$ -action as above.  $\square$

**Lemma 3.3.37.** If the pointwise left Kan extension exists and  $K$  is fully faithful, then the unit

$$\begin{array}{ccc} \mathcal{A} & \xrightarrow{K} & \mathcal{C} \\ & \searrow \eta_F & \downarrow \text{Lan}_K F \\ & F & \mathcal{D} \end{array}$$

is a natural isomorphism.

*Proof.* One checks that the unit is

$$\begin{array}{ccc} \mathcal{A} & \xrightarrow{F} & \mathcal{D} \\ \downarrow K & \searrow Y & \uparrow - \odot_{\mathcal{A}} F \\ \mathcal{C} & \xrightarrow{\text{Hom}_{\mathcal{A}}(K, -)} & [\mathcal{A}^{\text{op}}, \mathcal{V}] \end{array} \quad \begin{array}{c} \cong \\ \Downarrow \end{array}$$

i.e. a composition of natural isomorphisms since  $K$  is fully faithful.  $\square$

**Definition 3.3.38.** Give a class of weights  $\Phi$  we write  $\Phi\text{-Cocts}_0[\mathcal{C}, \mathcal{D}]$  for the category of  $\mathcal{V}$ -functors which preserve  $\Phi$ -colimits and  $\mathcal{V}$  natural transformations, i.e.

$$W \odot_{\mathcal{A}} FD \xrightarrow{F} F(W \odot_{\mathcal{A}} D)$$

is an isomorphism for all  $W: \mathcal{A}^{\text{op}} \rightarrow \mathcal{V}$  and  $D: \mathcal{A} \rightarrow \mathcal{C}$ .

**Theorem 3.3.39.** Let  $\Phi$  be a class of weights,  $K: \mathcal{A} \rightarrow \mathcal{C}$  full and faithful. Suppose all  $\Phi$ -colimits are  $K$ -absolute and  $K$  has a density presentation using  $\Phi$ -colimits. Then for every  $\Phi$ -cocomplete  $\mathcal{V}$ -category  $\mathcal{D}$  the pointwise left Kan extension  $\text{Lan}_K F$  exists and is  $\Phi$ -cocontinuous. Moreover, the functors

$$\text{Lan}_K: \mathcal{V}\text{-CAT}(\mathcal{A}, \mathcal{D}) \rightarrow \Phi\text{-Cocts}_0(\mathcal{C}, \mathcal{D}) \quad \text{and} \quad K^*: \Phi\text{-Cocts}_0(\mathcal{C}, \mathcal{D}) \rightarrow \mathcal{V}\text{-CAT}(\mathcal{A}, \mathcal{D})$$

are inverse equivalences.

*Proof.* The full subcategory  $\mathcal{B} \subseteq \mathcal{C}$  of objects  $B$  such that  $\mathcal{C}(K-, B) \odot_{\mathcal{A}} F$  exists is closed under  $\Phi$ -colimits, since they are  $K$ -absolute and contains representables  $\{KA \mid A \in \mathcal{A}\}$ . Therefore  $\mathcal{B} = \mathcal{C}$  and so  $\text{Lan}_K F$  exists and is clearly  $\Phi$ -cocontinuous, since

$$(- \odot_{\mathcal{A}} F) \circ \mathcal{C}(K, -)$$

preserves  $\Phi$ -colimits.

For the second statement we already know that the unit is an isomorphism, so we only need to show that the right adjoint  $K^*$  is conservative. The same colimit-closure argument shows this is the case, hence  $\epsilon$  is an iso by the triangle identities.  $\square$

**Corollary 3.3.40.** Let  $\mathcal{A}$  be a small  $\mathcal{V}$ -category,  $\Phi$  a class of weights and  $\Phi(\mathcal{A}) \subseteq [\mathcal{A}^{\text{op}}, \mathcal{V}]$  the closure of the representables under  $\Phi$ -colimits. Then  $\Phi(\mathcal{A})$  is the free  $\Phi$ -cocomplete  $\mathcal{V}$ -category on  $\mathcal{A}$ , i.e. we have

$$\mathcal{V}\text{-}\mathbf{CAT} \xrightarrow[\text{Lan}_{\mathcal{V}}]{\sim} \Phi\text{-}\mathbf{Cocts}_0(\Phi(\mathcal{A}), \mathcal{D})$$

for any  $\Phi$ -cocomplete  $\mathcal{D}$ .

*Proof.* As in the unenriched case, one shows that there is a  $\mathcal{V}$ -natural isomorphism  $\mathcal{C}(Y, -) \cong \text{id}_{[\mathcal{A}^{\text{op}}, \mathcal{V}]}$  (check on collections), so all colimits are  $Y$ -absolute.  $\square$

We are now ready to define locally presentable  $\mathcal{V}$ -categories. For this it is convenient to assume that  $\mathcal{V}_0$  is locally finitely presentable. This ensures that all filtered colimits in  $\mathcal{V}_0$  behave “the same” as in **Set**.

**Definition 3.3.41.** Let  $\mathcal{C}$  be a  $\mathcal{V}$ -category. An object  $c \in \mathcal{C}$  is called  $\kappa$ -presentable, if  $\mathcal{C}(c, -): \mathcal{C} \rightarrow \mathcal{V}$  preserves conical  $\kappa$ -filtered colimits. Note that this is equivalent to saying that  $\mathcal{C}(c, -): \mathcal{C}_0 \rightarrow \mathcal{V}_0$  is  $\kappa$ -accessible.

Note that this imposes a condition even for  $\mathcal{C} = \mathcal{V}$ . An object  $V \in \mathcal{V}$  is finitely presentable if and only if  $[V, -]$  preserves filtered colimits, or equivalently if and only if  $- \otimes V$  preserves finitely presentable objects.

So, finitely presentable in  $\mathcal{V}$  is equivalent to finitely presentable in  $\mathcal{V}_0$  if  $(\mathcal{V}_0)_{\text{fp}}$  is closed under finite  $\otimes$ -products.

**Definition 3.3.42.**  $\mathcal{V}$  is *locally finitely presentable* as a closed category if  $(\mathcal{V})_0$  is closed under finite  $\otimes$ -products.

**Example 3.3.43.** **Set**, **Cat**, **sSet**, **Mod** $_R$ , **dgMod** $_R$  are all locally finitely presentable (lfp) as a closed category. We call such  $\mathcal{V}$  a *locally finitely presentable cosmos*.

**Proposition 3.3.44.** If  $\mathcal{V}$  is an lfp cosmos and  $\mathcal{C}$  has copowers, then  $c \in \mathcal{C}$  is  $\kappa$ -presentable if and only if  $V \odot c \in \mathcal{C}_0$  is  $\kappa$ -presentable for each  $V \in \mathcal{V}_{\text{fp}}$ .

*Proof.* By definition of copowers we have in particular, that

$$\mathcal{C}_0(V \odot c, -) \cong \mathcal{V}_0(V, \mathcal{C}(c, -))$$

So, if  $c$  is  $\kappa$ -presentable in  $\mathcal{C}$ , then  $\mathcal{C}_0(V \odot c, -)$  preserves  $\kappa$ -filtered colimits for any  $V \in \mathcal{V}_{\text{fp}}$ .

Conversely the  $\mathcal{V}_0(V, -)$  define the full and faithful embedding  $\mathcal{V}_0 \rightarrow [\mathcal{V}_{\text{fp}}^{\text{op}}, \mathbf{Set}]$  which preserves filtered colimits so they jointly detect  $\kappa$ -filtered colimits.  $\square$

**Definition 3.3.45.** Let  $\mathcal{V}$  be an lfp cosmos. Then a  $\mathcal{V}$ -category  $\mathcal{C}$  is called locally  $\kappa$ -presentable if it has a small subcategory  $\mathcal{A} \subseteq \mathcal{C}$  consisting of  $\kappa$ -presentable objects in  $\mathcal{C}$ ,  $\mathcal{C}$  is cocomplete and the inclusion  $K: \mathcal{A} \rightarrow \mathcal{C}$  has a density presentation consisting of conical  $\kappa$ -filtered colimits.

**Theorem 3.3.46.** Let  $\mathcal{V}$  an lfp cosmos. For an  $\mathcal{V}$ -category  $\mathcal{C}$ , the following are equivalent:

- 1)  $\mathcal{C}$  is locally  $\kappa$ -presentable.
- 2)  $\mathcal{C}$  is a reflective subcategory of  $[\mathcal{A}^{\text{op}}, \mathcal{V}]$  for some small  $\mathcal{A}$  such that the inclusion preserves  $\kappa$ -filtered colimits.
- 3) The underlying category  $\mathcal{C}_0$  is locally  $\kappa$ -presentable,  $\mathcal{C}$  has copowers and  $(\mathcal{C}_0)_\kappa$  is closed under  $V \odot -$  for all  $V \in \mathcal{V}_{\text{fp}}$ .

*Proof.*

- 1)  $\Rightarrow$  2) Use the  $\mathcal{V}$ -dense  $K: \mathcal{A} \rightarrow \mathcal{C}$  from the definition. The functor

$$\mathcal{C}(K, -): \mathcal{C} \rightarrow [\mathcal{A}^{\text{op}}, \mathcal{V}]$$

is fully faithful and preserves  $\kappa$ -filtered colimits.

- 2)  $\Rightarrow$  3) Clear from the above proposition.

- 3)  $\Rightarrow$  1) Consider  $\mathcal{A}$  the full subcategory on  $(\mathcal{C}_0)_\kappa$ . By assumption  $(\mathcal{C}_0)_\kappa$  consists of  $\kappa$ -presentable objects in  $\mathcal{C}$ . Every object  $C \in \mathcal{C}_0$  is a filtered colimit of  $(\mathcal{C}_0)_\kappa/C$ . Since we have powers, these are actually  $\mathcal{V}$ -colimits.  $\square$

**Corollary 3.3.47.** Let  $\mathcal{C}$  be a locally  $\kappa$ -presentable  $\mathcal{V}$ -category and  $T$  a  $\kappa$ -accessible  $\mathcal{V}$ -monad on  $\mathcal{C}$ . Then  $T\text{-Alg}$  is a locally  $\kappa$ -presentable  $\mathcal{V}$ -category.

*Proof.* We have powers in  $T\text{-Alg}$  since  $\mathcal{C}$  has powers. It also has copowers. Indeed, this is clear for free algebras since left adjoints preserve copowers. Using coequalizers we find that all objects have copowers. The category  $(T\text{-Alg})_0 \cong T_0\text{-Alg}$  is locally  $\kappa$ -presentable by previous results. We only need to check that  $(T_0\text{-Alg})_\kappa$  is closed under  $V \odot -$  for all  $V \in (\mathcal{V}_0)_{\text{fp}} = \mathcal{V}_{\text{fp}}$ . This is again trivial for free algebras on  $\kappa$ -presentable objects  $A \in \mathcal{C}_\kappa$ . The general case follows since  $(T_0\text{-Alg})_\kappa$  is closed under coequalizers.  $\square$

**Corollary 3.3.48.** If  $\mathcal{C}$  is a locally  $\kappa$ -presentable  $\mathcal{V}$ -category and  $\mathcal{A}$  is small, then  $[\mathcal{A}, \mathcal{C}]$  is a locally  $\kappa$ -presentable  $\mathcal{V}$ -category. In particular,  $[\mathcal{C}_\kappa, \mathcal{C}]$  is locally  $\kappa$ -presentable. Moreover, since  $[\mathcal{C}_\kappa, \mathcal{C}]_0 = \mathcal{V}\text{-CAT}(\mathcal{C}_\kappa, \mathcal{C})$ , this category is locally  $\kappa$ -presentable (as a **Set**-category). Thus,  $\mathcal{V}\text{-CAT}_\kappa(\mathcal{C}, \mathcal{C})$ , the category of  $\kappa$ -accessible  $\mathcal{V}$ -endofunctors and  $\mathcal{V}$ -natural transformations, is locally  $\kappa$ -presentable.

*Proof.*  $\mathcal{V}\text{-CAT}_\kappa(\mathcal{C}, \mathcal{C}) = \Phi\text{-Cocts}_0(\mathcal{C}, \mathcal{C})$ , where  $\Phi$  is the class of conical filtered weights. The category of functors with a small domain is the category of algebras for a cocontinuous, in particular  $\kappa$ -accessible,  $\mathcal{V}$ -monad on  $\prod_{A \in \mathcal{A}} \mathcal{C}$ .  $\square$

**Theorem 3.3.49.** Let  $\mathcal{V}$  be a lfp cosmos,  $\mathcal{C}$  a locally presentable  $\mathcal{V}$ -category. Then

$$\mathcal{V}\text{-Mnd}_\kappa(\mathcal{C}) \xrightarrow{\text{forget}} \mathcal{V}\text{-CAT}_\kappa(\mathcal{C}, \mathcal{C})$$

is  $\kappa$ -accessible and monadic. Moreover, the inclusion  $\mathcal{V}\text{-Mnd}_\kappa(\mathcal{C}) \rightarrow \mathcal{V}\text{-Mnd}(\mathcal{C})$  preserves colimits.

*Proof.* The composition functor  $- \circ -$  preserves  $\kappa$ -filtered colimits in each variable, so that the endofunctor  $F \mapsto F \circ F$  is  $\kappa$ -accessible. Thus we can write down a presentation for the “monad for  $\kappa$ -accessible monads”. The second part follows again as in the unenriched case: we are lifting the monoidal adjunction  $\mathcal{V}\text{-}\mathbf{CAT}_\kappa(\mathcal{C}, \mathcal{C}) \xrightleftharpoons[\leftarrow]{\rightarrow} \mathcal{V}\text{-}\mathbf{CAT}(\mathcal{C}, \mathcal{C})$  to an adjunction of categories of monoids, as in the following diagram

$$\begin{array}{ccc}
 \mathcal{V}\text{-}\mathbf{CAT}_\kappa(\mathcal{C}, \mathcal{C}) & \xrightleftharpoons[\leftarrow]{\rightarrow} & \mathcal{V}\text{-}\mathbf{CAT}(\mathcal{C}, \mathcal{C}) \\
 \uparrow \cong & \nearrow \text{Lan}_K & \nearrow \\
 [\mathcal{C}_\kappa, \mathcal{C}]_0 & \xleftarrow{K^*} & 
 \end{array}$$

hence the inclusion of  $\kappa$ -accessible monoids is a left adjoint.  $\square$

**Remark 3.3.50.** These are “just” ordinary categories. In general  $\mathcal{V}\text{-}\mathbf{Mnd}_\kappa(\mathcal{C})$  is **not** a  $\mathcal{V}$ -category in a natural way.

**Corollary 3.3.51.** Take  $\mathcal{V}$  a lfp cosmos and  $\mathcal{C}$  locally  $\kappa$ -presentable. The functor

$$\mathcal{V}\text{-}\mathbf{Mnd}_\kappa(\mathcal{C})^{\text{op}} \xrightarrow{(-)\text{-Alg}} \mathcal{V}\text{-}\mathbf{CAT}/\mathcal{C}$$

sends colimits to limits.

*Proof.* We combine the above with the semantics-structure adjunction  $\mathcal{K}'/\mathcal{C} \xrightleftharpoons[\leftarrow]{\rightarrow} \mathbf{Mnd}(\mathcal{C})^{\text{op}}$  for arbitrary 2-categories with Eilenberg-Mac Lane objects (do it as an exercise). Since  $\mathcal{C}$  is complete,  $\text{Ran}_F F$  exists for all  $F$  with *small* domain. Therefore<sup>2</sup>  $\mathcal{V}\text{-}\mathbf{Cat}/\mathcal{C} \subseteq \mathcal{V}\text{-}\mathbf{CAT}'/\mathcal{C}$  and thus  $\mathcal{V}\text{-}\mathbf{CAT}'/\mathcal{C} \hookrightarrow \mathcal{V}\text{-}\mathbf{CAT}/\mathcal{C}$  preserves limits.  $\square$

We will apply this to the case  $\mathcal{V} = \mathbf{Cat}$ , that is to the theory of 2-monads. For this, we would like to have lots of examples of locally presentable 2-categories.

**Theorem 3.3.52.** If  $\mathcal{V}$  is a locally  $\kappa$ -presentable symmetric monoidal closed category and  $(\mathcal{V}_0)_\kappa$  is closed under finite  $\otimes$ , then  $\mathcal{V}\text{-}\mathbf{Cat}$  is locally  $\kappa$ -presentable and  $(\mathcal{V}\text{-}\mathbf{Cat})_\kappa$  is closed under finite  $\otimes$  (this construction is stable under enrichment).

**Remark 3.3.53.** It follows that  $\mathcal{V}\text{-}\mathbf{Cat}$  is a lfp 2-category whenever  $\mathcal{V}$  is a lfp cosmos. We need to check that for  $\mathcal{A} \in (\mathcal{V}\text{-}\mathbf{Cat}_0)_{\text{fp}}$ ,  $\mathcal{C} \in (\mathbf{Cat}_0)_{\text{fp}}$ , we have  $\mathcal{C} \odot \mathcal{A} \in (\mathcal{V}\text{-}\mathbf{Cat})_{\text{fp}}$ . This immediately reduces to the case  $\mathcal{C} = [1]$ . We will prove by inspection that  $F_*[1] \in \mathcal{V}\text{-}\mathbf{Cat}$  is finitely presentable only if  $\mathcal{C} \odot \mathcal{A} = F_* \mathcal{C} \otimes \mathcal{A}$ .

We prove the theorem in two steps. First we prove that  $\mathcal{V}\text{-}\mathbf{Cat}$  is finitary monadic over  $\mathcal{V}\text{-}\mathbf{Grph}$  and then that  $\mathcal{V}\text{-}\mathbf{Grph}$  is locally  $\kappa$ -presentable.

Recall that a  $\mathcal{V}$ -matrix on a set  $S$  is an object of  $\mathcal{V}\text{-}\mathbf{Mat}(S) = \prod_{S \times S} \mathcal{V} = \mathcal{V}^{S \times S}$  and a  $\mathcal{V}$ -graph is a pair  $(S, M)$  of a set  $S$  and  $M \in \mathcal{V}^{S \times S}$ . A morphism of  $\mathcal{V}$ -graphs is a pair composed of a morphism  $f: S \rightarrow T$  and a collection  $(f_{a,b}: M(a,b) \rightarrow N(fa,fb)) \iff f_{-, -}: M \rightarrow f^*N$ . If  $\mathcal{V}$  is symmetric monoidal closed and cocomplete, this is equivalent to a morphism  $f_*M \rightarrow N$  in  $\mathcal{V}^{T \times T}$ .

<sup>2</sup> $\mathcal{V}\text{-}\mathbf{Cat}/\mathcal{C}$  is a generating set for  $\mathcal{V}\text{-}\mathbf{CAT}'/\mathcal{C}$ , so if it's a limit from its perspective it still is in  $\mathcal{V}\text{-}\mathbf{Cat}/\mathcal{C}$ .

**Theorem 3.3.54.** If  $\mathcal{V}$  is symmetric monoidal closed and locally  $\kappa$ -presentable, then

$$\begin{aligned} U: \mathcal{V}\text{-}\mathbf{Cat} &\rightarrow \mathcal{V}\text{-}\mathbf{Grph} \\ \mathcal{A} &\mapsto (\mathrm{Ob}(\mathcal{A}), \mathcal{A}) \end{aligned}$$

is monadic and preserves sifted colimits.

*Proof.* We first prove the claim about sifted colimits. Recall that we have a tensor product on  $\mathcal{V}^{S \times S}$  s.t.  $\mathrm{Mon}(\mathcal{V}^{S \times S}) = \mathcal{V}\text{-}\mathbf{Cat}(S)$ , the category of  $\mathcal{V}$ -categories with object set  $S$  and morphisms identity-on-objects  $\mathcal{V}$ -functors. Moreover,  $f: S \rightarrow T$  induces an adjunction

$$\begin{array}{ccc} & f^* & \\ \mathrm{Mon}(\mathcal{V}^{S \times S}) & \xrightarrow{\quad} & \mathrm{Mon}(\mathcal{V}^{T \times T}) \\ & f_* & \end{array} \quad \perp$$

where

$$f_*(\mathcal{A})_{x,y} = \sum_{\{(a,b): fa=x, fb=y\}} \mathcal{A}(a,b) \in \mathcal{V}.$$

Note that  $\mathrm{Mon}(\mathcal{V}^{S \times S})$  is a locally  $\kappa$ -presentable category because the tensor of matrices preserves filtered colimits in each variable. In fact,  $\mathrm{Mon}(\mathcal{V}^{S \times S}) \rightarrow \mathcal{V}^{S \times S}$  is *monadic*.

The left adjoint of  $U$  sends  $(S, M)$  to the free monoid for the matrix tensor product, that is it doesn't change the set of objects (check it as an exercise). The functor  $U$  is conservative since a  $\mathcal{V}$ -functor is an isomorphism if and only if it is bijective on objects and  $\forall a, b \ f_{a,b}: \mathcal{A}(a, b) \rightarrow \mathcal{B}(fa, fb)$  is an isomorphism in  $\mathcal{V}$  if and only if it is an isomorphism of  $\mathcal{V}$ -graphs. To apply Beck, we only need that certain reflexive coequalizers are preserved. This follows from the claim on sifted colimits. We can compute colimits of  $\mathcal{V}$ -categories  $(S_i, \mathcal{A}_i)$ , where  $S_i = \mathrm{Ob}(\mathcal{A}_i)$ , as follows.

First, let  $S = \mathrm{colim} S_i$  with universal cocone  $\iota_i: S_i \rightarrow S$  in  $\mathbf{Set}$ . Then  $(\iota_i)_* \mathcal{A}_i$  defines a diagonal of the same shape in  $\mathrm{Mon}(\mathcal{V}^{S \times S})$ . Let  $\mathcal{A} = \mathrm{colim}_i (\iota_i)_* \mathcal{A}_i$ . Then  $\mathrm{colim}(S_i, \mathcal{A}_i) = (S, \mathcal{A})$ . The same recipe works for colimits of  $\mathcal{V}$ -graphs  $\mathrm{colim}(S_i, M_i) = (S, \mathrm{colim}_{\mathcal{V}^{S \times S}} (\iota_i)_* M_i)$ . It follows that  $U: \mathcal{V}\text{-}\mathbf{Cat} \rightarrow \mathcal{V}\text{-}\mathbf{Grph}$  preserves all the colimits that are preserved by each forgetful functor  $\mathrm{Mon}(\mathcal{V}^{S \times S}) \rightarrow \mathcal{V}^{S \times S}$ ,  $S \in \mathbf{Set}$ . Now we use the fact that the tensor product of matrices preserves sifted colimits in each variable. Hence sifted colimits of monoids are preserved by  $\mathrm{Mon}(\mathcal{V}^{S \times S}) \xrightarrow{\mathrm{forget}} \mathcal{V}^{S \times S}$ .  $\square$

**Remark 3.3.55.** We don't really need locally  $\kappa$ -presentable here: any cosmos  $\mathcal{V}$  suffices by Kelly's "transfinite construction".

It remains to show that  $\mathcal{V}\text{-}\mathbf{Grph}$  is locally  $\kappa$ -presentable if  $\mathcal{V}$  is. We consider the  $\mathcal{V}$ -graph  $(2, \bar{V})$ , for  $V \in \mathcal{V}$  denoted as follows: The set is given by  $\{0, 1\}$  and  $\bar{V}(i, j) = V$  if  $(i, j) = (0, 1)$  and  $\bar{V}(i, j) = \emptyset$  else. Note that this is a strong generator of  $\mathcal{V}\text{-}\mathbf{Grph}$ , if we let  $\mathcal{V}$  sum through objects of  $\mathcal{V}_\kappa$ . Then to give a  $(2, \bar{V}) \rightarrow (S, M)$  is equivalent to picking  $x, y \in S$  and  $\varphi: V \rightarrow M(x, y)$ .

**Proposition 3.3.56.** Let  $\mathcal{V}$  be locally  $\kappa$ -presentable. Then for all  $V \in (\mathcal{V}_0)_\kappa$  the object  $(2, \bar{V})$  is  $\kappa$ -presentable in  $\mathcal{V}\text{-}\mathbf{Grph}$ .

*Proof.* Consider a  $\kappa$ -filtered colimit  $(X, M) = \mathrm{colim}_i (X_i, M_i)$  in  $\mathcal{V}\text{-}\mathbf{Grph}$  with universal cocone  $\iota_i: X_i \rightarrow X$  in  $\mathbf{Set}$ . Then we have  $M = \mathrm{colim}(\iota_i)_* M_i$  in  $\mathcal{V}^{X \times X}$ . We have to show, that  $\mathcal{V}\text{-}\mathbf{Grph}((2, \bar{V}), -)$  preserves this  $\kappa$ -filtered colimit. That is for any  $f: (2, \bar{V}) \rightarrow (X, M)$ , we find a factorisation



$$\begin{array}{ccc}
 & (X_i, M_i) & \\
 f' \nearrow & \downarrow & \\
 (2, \bar{V}) & \xrightarrow{f} & (X, M)
 \end{array}$$

and any two such morphisms, which become equal in the colimit become already equal at a common stage in the diagram. Recall that

$$(\iota_i)_* M_i(x, y) = \sum_{\{(a,b): \iota_i(a)=x, \iota_i(b)=y\}} M_i(a, b)$$

Our  $f: (2, \bar{V}) \rightarrow (X, M)$  is given by the elements  $x, y \in X$  and  $\varphi: V \rightarrow (\text{colim}(\iota_i)_*)(x, y)$ . Both  $x, y$  are in the image of  $\iota_i: X_i \rightarrow X$  for some  $i$ . Since  $V$  is  $\kappa$ -presentable  $\varphi$  factors through one of the inclusions  $(\iota_i)_* M_i(x, y) \rightarrow \text{colim}(\iota_i)_* M_i(x, y)$ . Thus we obtain a morphism

$$\varphi: V \rightarrow \sum_{\{(a,b): \iota_i(a)=x, \iota_i(b)=y\}} M_i(a, b)$$

Since  $V$  is  $\kappa$ -presentable, there exist sets  $A \subset \iota_i^{-1}(x)$  and  $B \subset \iota_i^{-1}(y)$  with  $|A|, |B| \prec \kappa$ , such that  $\varphi$  factors through  $\sum_{(a,b) \in A \times B} M_i(a, b)$ . But the diagram  $X_i \rightarrow X$  is a  $\kappa$ -filtered colimit diagram in **Set**. So we can find a stage  $j$

$$\begin{array}{ccc}
 X_i & \xrightarrow{X_\varphi} & X_j \\
 & \searrow & \downarrow \\
 & & X
 \end{array}$$

such that  $X_\varphi(A) = \{x_0\}$  and  $X_\varphi(B) = \{y_0\}$ . Now by picking  $x_0, y_0$ , we get the desired lift  $f': (2, \bar{V}) \rightarrow (X_j, M_j)$ . It remains to check, that given a other commutative square

$$\begin{array}{ccccc}
 & (X_i, M_i) & & & \\
 & \nearrow & \searrow & & \\
 (2, \bar{V}) & & & (X_k, M_k) & \longrightarrow (X, M) \\
 & \searrow & \nearrow & \nearrow & \\
 & (X_j, M_j) & & & 
 \end{array}$$

we find a stage  $k$  and dashed arrows making the inner square commute. Without loss of generality we can assume  $i = j$  and that 0 and 1 go to the same element in  $X_i$  (since 2 is finitely presentable in **Set**). The remaining data are morphisms

$$V \begin{array}{c} \xrightarrow{\varphi} \\ \xrightarrow{\psi} \end{array} M_i(a, b)$$

such that they become equal when comparing with  $(X_i, M_i) \rightarrow (X, M)$ .

$$\begin{array}{ccccc}
 V & \xrightarrow{\varphi} & M_i(a, b) & \longrightarrow & \sum_{\{(a,b): \iota_i(a)=x, \iota_i(b)=y\}} M_i(a, b) \\
 & \searrow \psi & & & \searrow \\
 & & M_i(a, b) & \longrightarrow & \sum_{\{(a,b): \iota_i(a)=x, \iota_i(b)=y\}} M_i(a, b) \\
 & & & & \searrow \\
 & & & & \text{colim}(\iota_i)_* M_i(x, y)
 \end{array}$$

But the colimit in the target is a filtered colimit in  $\mathcal{V}$  and  $V$  is  $\kappa$ -presentable. So they factor through some  $(\iota_j)_* M_i \rightarrow \text{colim}$ . This  $j$  gives the desired diagram by looking at composition of maps in  $\mathcal{V}\text{-}\mathbf{Graph}$ .  $\square$

This now proves the theorem, that  $\mathcal{V}\text{-}\mathbf{Cat}$  is locally  $\kappa$ -presentable if  $\mathcal{V}$  is so. It remains to check, that if  $I \in (\mathcal{V}_0)_\kappa$  and  $(\mathcal{V}_0)_\kappa$  is closed under  $- \otimes -$ , then the same is true in  $\mathcal{V}\text{-}\mathbf{Cat}$ .

**Proposition 3.3.57.** Under the above assumptions,  $J \in \mathcal{V}\text{-}\mathbf{Cat}$  is locally finitely presentable and for  $V, W \in (\mathcal{V}_0)_\kappa$ ,  $\mathcal{R}[V] \otimes \mathcal{R}[W]$  is locally  $\kappa$ -presentable, where  $\mathcal{R}[V]$  is the free  $\mathcal{V}\text{-}\mathbf{Cat}$  on  $(2, \bar{V})$ .

*Proof.* The tensor product has four objects  $\{(i, j) : i, j \in \{0, 1\}\}$  and looks like

$$\begin{array}{ccc} (0, 0) & \xrightarrow{\sim}^V & (0, 1) \\ \downarrow W & & \downarrow W \\ (1, 0) & \xrightarrow{\sim}^V & (1, 1) \end{array}$$

Now let  $\mathcal{B}[V, W]$  be the pushout

$$\begin{array}{ccc} J & \longrightarrow & \mathcal{R}[V] \\ \downarrow & & \downarrow \\ \mathcal{R}[W] & \longrightarrow & \mathcal{B}[V, W] \end{array}$$

Then one checks, that  $\mathcal{R}[V] \otimes \mathcal{R}[W]$  is precisely the pushout

$$\begin{array}{ccc} \mathcal{R}[V \otimes W] & \longrightarrow & \mathcal{B}[V, W] \\ \downarrow & & \downarrow \\ \mathcal{B}[W, V] & \longrightarrow & \mathcal{R}[V] \otimes \mathcal{R}[W] \end{array}$$

So since  $\mathcal{R}[V]$  and  $\mathcal{R}[W]$  are free on  $V, W$  they are locally  $\kappa$ -presentable. It only remains to show, that  $J$  is locally  $\kappa$ -presentable. But we have  $\mathcal{V}\text{-}\mathbf{Cat}(J, -) \cong \text{Ob}(-) : \mathcal{V}\text{-}\mathbf{Cat} \rightarrow \mathbf{Set}$  so this preserves all small colimits.  $\square$

**Example 3.3.58.**  $2\text{-}\mathbf{Cat}$ , simplicial categories and dg-categories form locally finitely presentable cosmoi.

**Remark 3.3.59.** Since  $F_*[1] = \mathcal{R}[I]$  we get  $\mathcal{V}\text{-}\mathbf{Cat}$  is a locally  $\kappa$ -presentable 2-category.

## 3.4 Two-dimensional monad theory

In the case  $\mathcal{V} = \mathbf{Cat}$  the (large) categories  $\mathcal{V}\text{-}\mathbf{CAT}(\mathcal{K}, \mathcal{L})$  are again 2-categories (modifications can be defined as for small  $\mathcal{K}$ ). We denote them by  $[\mathcal{K}, \mathcal{L}]$ . Moreover, we have 2-functors  $[\mathcal{L}, \mathcal{M}] \times [\mathcal{K}, \mathcal{L}] \rightarrow [\mathcal{K}, \mathcal{M}]$ . Since  $\mathbf{Cat}$  is cartesian, we also have a diagonal  $[\mathcal{K}, \mathcal{K}] \rightarrow [\mathcal{K}, \mathcal{K}] \times [\mathcal{K}, \mathcal{K}]$  given by the assignment  $F \mapsto (F, F)$ . This allows us to present the 2-monad for  $\kappa$ -accessible 2-monads on a locally  $\kappa$ -presentable 2-cat  $\mathcal{K}$ . This way we can study 2-monads by studying the algebras of 2-monads. Moreover  $2\text{-}\mathbf{Cat}_{/\mathcal{K}}$  is a 2-category and  $(-)\text{-}\mathbf{Alg} : 2\text{-}\mathbf{Mnd}_\kappa(\mathcal{K}) \rightarrow 2\text{-}\mathbf{Cat}_{/\mathcal{K}}$  preserves all weighted limits (sends  $\mathbf{Cat}$ -weighted colimits to limits). This can be seen via the following construction. Given a  $c \in \mathcal{K}$  we have the 2-monad  $\langle c, c \rangle : \mathcal{K} \rightarrow \mathcal{K}$ , which satisfies the property, that giving  $T \rightarrow \langle c, c \rangle$  is the same as defining a  $T$ -algebra structure on  $c$ . Now given a 1-cell  $f : c \rightarrow d$ , we can form the pullback

$$\begin{array}{ccc}
\{f, f\} & \longrightarrow & \langle c, c \rangle \\
\downarrow & & \downarrow \\
\langle d, d \rangle & \longrightarrow & \langle c, d \rangle
\end{array}$$

Then given a 2-cell  $\sigma: f \Rightarrow g: c \rightarrow d$  we form the pullback

$$\begin{array}{ccc}
\|\sigma, \sigma\| & \longrightarrow & \{f, f\} \\
\downarrow & & \downarrow \\
\{g, g\} & \longrightarrow & \{f, g\}
\end{array}$$

By construction giving  $T \rightarrow \|\sigma, \sigma\|$  amounts to lifting  $\sigma$  to a 2-cell in  $T\text{-Alg}$

$$\begin{array}{ccc}
& f & \\
(A, \alpha) & \xrightarrow{\quad} & (B, \beta) \\
& g & \\
& \Downarrow \sigma &
\end{array}$$

**Example 3.4.1.** We can present the 2-monad on  $\mathcal{V}\text{-Cat}$  for a monoidal (small)  $\mathcal{V}$ -category by starting with the endo-2-functor given by the assignment  $\mathcal{A} \mapsto \mathcal{A} \otimes \mathcal{A}$ .  $F\text{-Alg}$  then has objects  $(\mathcal{A}, \mathcal{A} \otimes \mathcal{A} \rightarrow \mathcal{A})$  and the use inserts to get

$$\begin{array}{ccccc}
& & m \otimes 1 & & \\
& & \curvearrowright & & \\
(\mathcal{A} \otimes \mathcal{A}) \otimes \mathcal{A} & & & \mathcal{A} \otimes \mathcal{A} & \xrightarrow{m} \mathcal{A} \\
\downarrow \cong & & & \downarrow \alpha & \\
\mathcal{A} \otimes (\mathcal{A} \otimes \mathcal{A}) & & & \mathcal{A} \otimes \mathcal{A} & \xrightarrow{m} \mathcal{A} \\
& & 1 \otimes m & &
\end{array}$$

and then equifier for the pentagon and also add limits etc. The resulting category  $T\text{-Alg}$  has the right objects, but the 1-cells preserve the structure strictly.

**Definition 3.4.2.** Let  $T$  be a 2-monad on a 2-category  $\mathcal{K}$ . A *lax  $T$ -morphism* between  $T$ -algebras  $(A, a), (B, b)$  is a pair  $(f, \bar{f})$  together with a 1-cell  $f: A \rightarrow B$  and a 2-cell

$$\begin{array}{ccc}
TA & \xrightarrow{Tf} & TB \\
a \downarrow & \swarrow \bar{f} & \downarrow b \\
A & \xrightarrow{f} & B
\end{array}$$

such that

$$\begin{array}{ccc}
T^2 A & \xrightarrow{T^2 f} & T^2 B \\
Ta \downarrow & \swarrow T\bar{f} & \downarrow Tb \\
TA & \xrightarrow{Tf} & TB \\
a \downarrow & \swarrow \bar{f} & \downarrow b \\
A & \xrightarrow{f} & B
\end{array}
=
\begin{array}{ccc}
T^2 A & \xrightarrow{T^2 f} & T^2 B \\
\mu_A \downarrow & \swarrow & \downarrow \mu_B \\
TA & \xrightarrow{Tf} & TB \\
a \downarrow & \swarrow \bar{f} & \downarrow b \\
A & \xrightarrow{f} & B
\end{array}$$

$$\begin{array}{ccc}
 A & \xrightarrow{f} & B \\
 \eta_A \downarrow & \swarrow & \downarrow \eta_B \\
 TA & \xrightarrow{Tf} & TB \\
 a \downarrow & \swarrow \bar{f} & \downarrow b \\
 A & \xrightarrow{f} & B
 \end{array} = \text{id}_f$$

We call  $(f, \bar{f})$  a *pseudo  $T$ -morphism* if  $\bar{f}$  is invertible. A 2-cell of lax or pseudo-morphisms  $(f, \bar{f}) \Rightarrow (g, \bar{g})$  is a 2-cell  $\sigma: f \Rightarrow g$  in  $\mathcal{K}$  such that

$$\begin{array}{ccc}
 TA & \xrightarrow{Tf} & TB \\
 \Downarrow T\sigma & & \\
 TA & \xrightarrow{Tg} & TB \\
 a \downarrow & \swarrow \bar{g} & \downarrow b \\
 A & \xrightarrow{g} & B
 \end{array} = \begin{array}{ccc}
 TA & \xrightarrow{Tf} & TB \\
 a \downarrow & \swarrow \bar{f} & \downarrow b \\
 A & \xrightarrow{f} & B \\
 \Downarrow \sigma & & \\
 A & \xrightarrow{g} & B
 \end{array}$$

Finally a *colax* morphism is one with the direction of  $\bar{f}$  reversed (also called *oplax*).

- Example 3.4.3.** 1. The pseudo/lax morphisms for the 2-monad for monoidal  $\mathcal{V}$ -categories are precisely the strong monoidal/lax monoidal  $\mathcal{V}$ -functors. 2-cells are the monoidal 2-cells.
2. For the 2-monad of presheaves  $T: \prod_{\text{Ob}(\mathcal{A})} \mathbf{Cat} \rightarrow \prod_{\text{Ob}(\mathcal{A})} \mathbf{Cat}$  on a small 2-category  $\mathcal{A}$  the pseudo- $T$ -morphisms are the pseudo-natural transformations, the lax morphisms are the lax-natural transformations between (strict) 2-functors. One way to prove this is to use the corresponding pseudo/lax version of  $\{f, f\}$

$$\begin{array}{ccc}
 \{f, f\}_l & \longrightarrow & \langle B, B \rangle \\
 \downarrow & \swarrow & \downarrow \\
 \langle A, A \rangle & \longrightarrow & \langle A, B \rangle
 \end{array}$$

the comma object with the universal 2-cell an iso for  $\{f, f\}_p$  for a complete 2-category and check that there are 2-monads such that 2-monad morphisms  $T \rightarrow \{f, f\}_l$  are precisely lax  $T$ -morphisms  $(f, \bar{f}): (A, a) \rightarrow (B, b)$ .

We thus have 2-categories and 2-functors

$$\begin{array}{ccccc}
 & & & & T\text{-Alg}_l \\
 & & & \nearrow & \\
 T\text{-Alg}_s & \longrightarrow & T\text{-Alg}_p & & \\
 & \searrow & \downarrow & \searrow & \\
 & & \mathcal{K} & \nearrow & T\text{-Alg}_c
 \end{array}$$

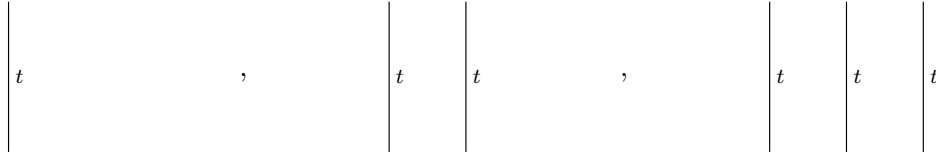
Where  $T\text{-Alg}$  denotes the category of algebras of a  $\mathbf{Cat}$ -enriched monad,  $s$  stands for strict,  $p$  for pseudo,  $l$  for lax and  $c$  for colax. As we saw in the examples we often care about  $T\text{-Alg}_l$  or  $T\text{-Alg}_p$  but we know a lot about  $T\text{-Alg}_s$ . For example  $T\text{-Alg}_s$  is a locally presentable 2-category if  $\mathcal{K}$  is such and  $T$  is accessible. In this case the inclusions  $T\text{-Alg}_s \rightarrow T\text{-Alg}_{p,l}$  have left adjoint 2-functors. These are sometimes denoted by  $(-)'$ ,  $Q$  or  $Q_l$ . It turns out, that  $T\text{-Alg}_p$  is biequivalent to a certain subcategory of  $T\text{-Alg}_s$  consisting of the *flexible* algebras (i.e. those such that the counit  $Q(A.a) \rightarrow (A, a)$  is an equivalence in  $T\text{-Alg}_s$ ). This can for example be used to show that  $T\text{-Alg}_p$  is bicategorically complete and cocomplete if  $\mathcal{K}$  is a locally presentable 2-category and  $T$  is accessible.

To summarize: The philosophy is that enriched things are easy, weak things are hard, so use strictly enriched categories to study weakly enriched categories, to study weak things. To illustrate this, we consider one definition of monads and algebras in higher categories. Before we do that, we need to monad in 2-categories. We have shown that  $2\text{-Cat}$  is a locally finitely presentable cosmos. This means in particular that we can talk about the “free 2-category” with a monad  $\mathcal{M}$ :

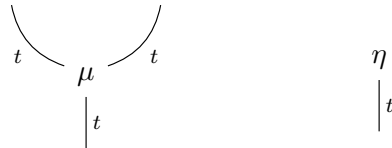
Start with a single object  $*$ , a 1-cell  $t: * \rightarrow *$  and two 2-cells  $\mu: t^2 \Rightarrow t$ ,  $\eta: \text{id}_* \Rightarrow t$  and impose the monad axioms. Then a 2-functor  $\mathcal{M} \rightarrow \mathcal{K}$  is precisely given by pairs of an object  $C \in \text{Ob}(\mathcal{K})$  and a monad  $t: C \rightarrow C$ . Since  $\mathcal{M}$  clearly has a single object, it is simply a monoid in  $\mathbf{Cat}$ .

**Proposition 3.4.4.** The monoid  $(\mathcal{M}(*, *), \circ)$  is isomorphic to  $(\Delta_+, +)$  the category of finite posets and  $+$  the ordinal sum (i.e. the join).

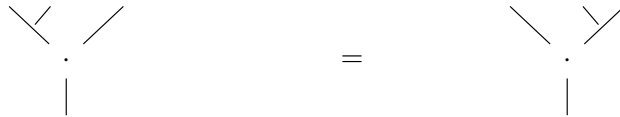
*Proof.* Do this using string diagrams: The string diagrams for  $\mathcal{M}$  are the following. 1-cells for  $t^n$  for some integer are



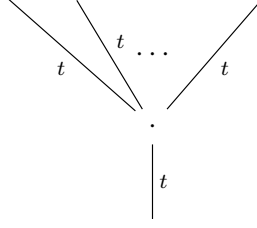
and so on. 2-cells are:



Now from



we get that there is a unique 2-cell



□

From the defining isomorphism  $\mathcal{K}(X, [W, F]) \cong [\mathcal{A}^{\text{op}}, \mathbf{Cat}](W, \mathcal{K}(X, F-))$  we see that  $[-, F]$  sends colimits to limits. From the isomorphism  $[\mathcal{A}(a, -), F] \cong F(a)$  it follows that we have to compute the corresponding colimit of the Yoneda diagram  $\mathcal{A}^{\text{op}} \rightarrow [\mathcal{A}, \mathbf{Cat}]$ . So  $W \cong Y \odot_{\mathcal{A}} W$ . For this we need to compute the Kleisli object of the monad in  $[\Delta_+, \mathbf{Cat}]$ . If it really is a weighted colimit, this would be computed pointwise in  $\mathbf{Cat}$ . So we need to compute the Kleisli object of  $- + [0]: \Delta_+ \rightarrow \Delta_+$  in  $\mathbf{Cat}$ .

By an exercise, the collection of objects of the category  $\mathbf{Kl}(- + [0])$  is  $\{[n] \mid n \geq -1\}$  and the morphisms  $[m] \rightarrow [n]$  are morphisms  $[m] \rightarrow [n] + [0]$  in  $\Delta_+$ .

— Insert pic —

We write  $\Delta_{\infty}$  for this category.

The structure of  $\Delta_+$ -module is given by ordinal — Insert pic —

$W$  is  $\Delta_{\infty}$  with this  $\Delta_+$ -action. By construction, we get  $[[\Delta_+, \mathbf{Cat}]](W, \mathcal{K}(X, (C, t))) \cong t\text{-Act}(X)$ .

One can also see this more directly. Indeed, a morphism of  $\Delta_+$ -modules out of  $W$  is completely determined by where it sends — Insert pic —, that is a 1-cell  $g: X \rightarrow C$  and a 2-cell  $\rho: tg \Rightarrow g$ .

**Corollary 3.4.5.** Any complete 2-category has EM-objects and they are preserved by right adjoint 2-functors (horrible name, what about right 2-adjoints?)

*Proof.* EM-objects are weighted limits. □

As observed by Riehl-Verity, this can be used to define and study monads of  $(\infty, n)$ -categories. In many cases we have *simplicial* categories of  $(\infty, n)$ -categories with good properties, like the simplicial category of quasi-categories  $\mathbf{qCat}$ .

We have a 2-functor  $\tau: \mathbf{sSet} \rightarrow \mathbf{Cat}$  which is left adjoint to the nerve and preserves products, hence it is strong monoidal. We get then  $\tau_*: \mathbf{sSet-Cat} \rightarrow \mathbf{2-Cat}$ . This defines the homotopy  $\mathbf{2-Cat}$  of a simplicial category, that is  $\mathbf{qCat}$ , and can be used to define categorical structures. In this context, adjoints are those which are mapped to adjoints under  $\tau_*$  or something like that (wtf does this mean?).

The nerve functor  $N: \mathbf{Cat} \rightarrow \mathbf{sSet}$  is also strong monoidal and defines  $N_*: \mathbf{2-Cat} \rightarrow \mathbf{sSet-Cat}$ .

**Definition 3.4.6.** A homotopy-coherent monad on an object  $C$  in a simplicial category  $\mathcal{C}$  is a simplicial functor  $N_*\Delta_+ \rightarrow \mathcal{C}$ ,  $* \mapsto C$ , that is a morphism of simplicial monoids  $N\Delta_+ \rightarrow \mathcal{C}(c, c)$ .

The object of homotopy-coherent algebras of such a monad is the  $N\Delta_{\infty}$ -weighted limit of  $(C, t)$ .

This concept is highly non-trivial and we refer to [riehl2016homotopy].

### 3.5 Outlook

In many monoidal categories  $\mathcal{V}$  we have a notion of weak equivalence, for example:

- **Cat**: equivalence;
- **Top**: homotopy equivalence;
- **Ch**: quasi-isomorphism.

There are further classes of maps, which allow one to talk about cellular constructions, homotopies and lifting of homotopies called fibrations and cofibrations. A model structure on  $\mathcal{V}$  is a choice of such classes  $\mathcal{W}$ ,  $\mathcal{F}$ ,  $\mathcal{C}$  subject to some axioms. If this is compatible with the monoidal structure, we can also talk about  $\mathcal{V}$ -model categories, like:

- $\mathcal{V} = \mathbf{Top}$ , **sSet**  $\rightsquigarrow$  homotopy theory;
- $\mathcal{V} = \mathbf{Sp}$  (spectra in the sense of algebraic topology)  $\rightsquigarrow$  stable homotopy theory;
- $\mathcal{V} = \mathbf{Ch}(\mathcal{A})$   $\rightsquigarrow$  homological algebra, where  $\mathcal{A}$  is an abelian category (often **Ab**);
- $\mathcal{V} = \mathbf{Cat}$   $\rightsquigarrow$  2-category theory (instead of plain **Cat**-enriched category theory);
- $\mathcal{V} = \mathbf{sSet}_{\text{Joyal}}$ , Segal categories, Rezk's complete Segal spaces, complicial sets, etc.  $\rightsquigarrow$  higher category theory.

Many of the techniques discussed are also useful to study and construct model categories. For example, one of their axioms is the existence of factorizations of morphisms  $f: X \rightarrow Y$  as  $X \rightarrow E \xrightarrow{\sim} Y$ , where the first map is a cofibration and the second one an acyclic fibration. To construct these, one often uses transfinite constructions similar to Kelly's proper *small object argument*. If one actually uses Kelly's construction, one gets particularly nice factorizations systems called *algebraic weak factorization systems* (Garner). These actually form a pair of a comonad and a monad on the arrow category  $\mathcal{C}^{[1]}$ , which are particularly useful if  $\mathcal{C}$  is locally presentable and the model category is combinatorial.

For further reading, we refer to the following:

- $\mathcal{C} = \mathbf{Cat}$  and 2-monad theory: [lack20102];
- $\mathcal{C} = \mathbf{sSet}, \mathbf{Top}, \mathbf{Ch}$ : [hovey2007model];
- use of these ideas in higher category theory: Riehl-Verity's papers and their book [riehl2018elements].

# Monads and their applications 1

## Exercise 1.

Let  $(T, \mu, \eta)$  be a monad on  $\mathcal{C}$  and let  $(A, \alpha)$  be a  $T$ -algebra. Show that for any isomorphism  $g: B \rightarrow A$  there exists a unique  $T$ -algebra structure  $\beta: TB \rightarrow B$  on  $B$  such that  $g$  is a morphism of  $T$ -algebras  $(B, \beta) \rightarrow (A, \alpha)$ .

## Exercise 2.

A monad  $(T, \mu, \eta)$  on  $\mathcal{C}$  is called *idempotent* if the multiplication  $\mu: T^2 \Rightarrow T$  is an isomorphism. Show that for any idempotent monad  $T: \mathcal{C} \rightarrow \mathcal{C}$  and any object  $A \in \mathcal{C}$ , there exists at most one  $T$ -algebra structure on  $A$ . Moreover, show that for any pair of  $T$ -algebras  $(A, \alpha)$  and  $(B, \beta)$ , every morphism  $f: A \rightarrow B$  in  $\mathcal{C}$  is a morphism of  $T$ -algebras (in other words, the forgetful functor  $U^T: T\text{-}\mathbf{Alg} \rightarrow \mathcal{C}$  is full).

## Exercise 3.

Let  $R$  be a commutative ring. Show that the functor  $\mathbf{Mod}_R \rightarrow \mathbf{Mod}_R$ , which sends  $M$  to  $\bigoplus_{n \in \mathbb{N}} M^{\otimes n}$  can be endowed with the structure of a monad whose category of algebras is (isomorphic to) the category of  $R$ -algebras. Find a monad on  $\mathbf{Mod}_R$  whose category of algebras is the category of *commutative*  $R$ -algebras.

## Exercise 4. ??

Let  $F: \mathcal{C} \rightarrow \mathcal{D}$  and  $U: \mathcal{D} \rightarrow \mathcal{C}$  be two functors.

- (a) Show that there is a bijection between the set of pairs natural transformations  $\eta: \text{id}_{\mathcal{D}} \Rightarrow UF$  and  $\varepsilon: FU \rightarrow \text{id}_{\mathcal{C}}$  which satisfy the triangle identities ( $\varepsilon F \cdot F\eta = 1_F$ ,  $U\varepsilon \cdot \eta U = 1_U$ ) on the one hand and the set of natural isomorphisms

$$\varphi: \mathcal{D}(F-, -) \Rightarrow \mathcal{C}(-, U-): \mathcal{D}^{\text{op}} \times \mathcal{C} \rightarrow \mathbf{Set}$$

on the other.

- (b) Assume that for each  $c \in \mathcal{C}$ , the functor  $\mathcal{C}(c, U-)$  is representable. Suppose that there is an explicit choice of representing object  $d_c \in \mathcal{D}$ , that is, a choice of a natural isomorphism  $\mathcal{D}(d_c, -) \cong \mathcal{C}(c, U-)$ . Show that there exists a functor  $G: \mathcal{C} \rightarrow \mathcal{D}$  with  $Gc = d_c$  such that  $G$  is left adjoint to  $U$ .
- (c) Show that if both  $F$  and  $G$  are left adjoint to  $U$ , then there exists a natural isomorphism  $F \cong G$ .



**Exercise 5.** ??

An *ultrafilter* on a set  $X$  is a set  $\mathcal{F}$  of subsets of  $X$  such that the following axiom holds: for all subsets  $A \subseteq X$ ,  $A$  belongs to  $\mathcal{F}$  if and only if for all  $B_1, \dots, B_n \in \mathcal{F}$ , the intersection  $A \cap B_1 \cap \dots \cap B_n$  is non-empty. The *principal ultrafilter* of  $x \in X$  is  $\mathcal{F}_x = \{A \subseteq X \mid x \in A\}$ . Given a subset  $A \subseteq X$ , we write  $[A]$  for the set of ultrafilters  $\mathcal{F}$  which contain  $A$ . We write  $UX$  for the set of ultrafilters on  $X$ . Given a function  $f: X \rightarrow Y$  and an ultrafilter  $\mathcal{F}$  on  $X$ , we call

$$f_*\mathcal{F} := \{B \subseteq Y \mid f^{-1}(B) \in \mathcal{F}\}$$

the pushforward of  $\mathcal{F}$ .

- (a) Show that  $UX$  defines an endofunctor of **Set** via the pushforward.
- (b) Show that  $\eta_X: X \rightarrow UX$ ,  $x \mapsto \mathcal{F}_x$  and  $\mu_X: UUX \rightarrow UX$  defined by

$$\mu(\mathcal{F}) = \{A \subseteq X \mid [A] \in \mathcal{F}\}$$

endow  $U$  with the structure of a monad.

- (c) Let  $\xi: UX \rightarrow X$  be an algebra for the ultrafilter monad. We call a subset  $U \subseteq X$  *open* if

$$\forall x \in X \forall \mathcal{F} \in UX: (x \in U \text{ and } \xi(\mathcal{F}) = x) \Rightarrow U \in \mathcal{F}$$

holds. Show that these open sets form a topology on  $X$ .

## Monads and their applications 2

### Exercise 1.

Let  $\mathcal{C}$  be a category with finite coproducts. For an object  $c \in \mathcal{C}$ , let  $c/\mathcal{C}$  denote the slice category, whose objects are morphisms with domain  $c$  and whose morphisms are commutative triangles. Show that the forgetful functor  $c/\mathcal{C} \rightarrow \mathcal{C}$  is monadic (using Beck's theorem) and describe the monad in question.

### Exercise 2.

Let  $\mathcal{C}$  be the category of torsion free abelian groups.

- (a) Show that the inclusion  $\mathcal{C} \rightarrow \mathbf{Ab}$  is monadic (using the monadicity theorem).
- (b) Show that the forgetful functor  $\mathbf{Ab} \rightarrow \mathbf{Set}$  is monadic.
- (c) Show that the composite  $\mathcal{C} \rightarrow \mathbf{Set}$  of the above two functors is *not* monadic. (Hint: what happens to the canonical presentation of a finite abelian group?)

### Exercise 3.

An object  $g \in \mathcal{C}$  is called a *strong generator* if  $\mathcal{C}(g, -): \mathcal{C} \rightarrow \mathbf{Set}$  is conservative.

- (a) Assume that  $\mathcal{C}$  has small colimits and that  $g$  is a strong generator such that  $\mathcal{C}(g, -)$  preserves small colimits (an object satisfying the latter condition is sometimes called *small projective*). Show that there exists a monoid  $M$  such that  $\mathcal{C}$  is equivalent to the category of  $M$ -sets. (Hint: is  $\mathcal{C}(g, -)$  monadic?)
- (b) Show that the monoid  $M$  above is isomorphic to the endomorphism monoid  $\mathcal{C}(g, g)$  of  $g$ .

### Exercise 4.

Let  $F: \mathcal{C} \rightarrow \mathcal{C}$  be an endofunctor. An *F-algebra* is a pair  $(c, \gamma)$  of an object  $c \in \mathcal{C}$  and a morphism  $\gamma: Fc \rightarrow c$  (not subject to any axioms). A morphism of algebras  $(c, \gamma) \rightarrow (d, \delta)$  is a morphism  $f: c \rightarrow d$  making the evident square commutative. We denote the category of  $F$ -algebras by  $F\text{-}\mathbf{Alg}$ . Show that the forgetful functor  $F\text{-}\mathbf{Alg} \rightarrow \mathcal{C}$  is monadic if and only if it has a left adjoint.

**Exercise 5.**

Complete the proof of the monadicity theorem by showing that the natural transformations  $\bar{\eta}$  and  $\bar{\varepsilon}$  described in the lecture satisfy the triangle identities.

## Monads and their applications 3

### Exercise 1.

Let  $F: \mathcal{A} \rightarrow \mathcal{C}$ ,  $K: \mathcal{A} \rightarrow \mathcal{B}$  and  $L: \mathcal{B} \rightarrow \mathcal{C}$  be functors. A natural transformation  $\eta: F \Rightarrow L \circ K$  is said to exhibit  $L$  as left Kan extension of  $F$  along  $K$  if the composite

$$[\mathcal{B}, \mathcal{C}](L, G) \xrightarrow{- \circ K} [\mathcal{A}, \mathcal{C}](LK, G) \xrightarrow{\eta^*} [\mathcal{A}, \mathcal{C}](F, G)$$

is a bijection for all functors  $G: \mathcal{B} \rightarrow \mathcal{C}$ . If a left Kan extension of  $F$  along  $K$  exists, then it is unique up to unique natural isomorphism and it is denoted by  $\text{Lan}_K F$ .

- (a) Show that left adjoints preserve left Kan extensions in the following sense: if  $\eta: F \Rightarrow LK$  exhibits  $L$  as left Kan extension of  $F$  along  $K$  and  $H: \mathcal{C} \rightarrow \mathcal{D}$  is a left adjoint, then  $H\eta$  exhibits  $HL$  as left Kan extension of  $HF$  along  $K$ .
- (b) Show that left Kan extensions compose: if  $\text{Lan}_K F$  exists and

$$K': \mathcal{B} \rightarrow \mathcal{B}'$$

is any functor, then  $\text{Lan}_{K'} \text{Lan}_K F$  exists if and only if  $\text{Lan}_{K'K} F$  exists. Moreover, show that in this case there is a natural isomorphism  $\text{Lan}_{K'} \text{Lan}_K F \cong \text{Lan}_{K'K} F$ .

### Exercise 2.

The notion of *right* Kan extension is dual to left Kan extension: it is given by a universal natural transformation  $\gamma: RK \Rightarrow F$  and denoted by  $\text{Ran}_K F$ .

- (a) Let  $F: \mathcal{A} \rightarrow \mathcal{C}$  be a functor such that the right Kan extension

$$\text{Ran}_F F: \mathcal{C} \rightarrow \mathcal{C}$$

of  $F$  along itself exists. Show that  $\text{Ran}_F F$  has the structure of a monad in a natural way. This monad is called the *codensity monad* of  $F$ .

- (b) If  $\mathcal{A} = *$  is the terminal category, then giving a functor  $F: \mathcal{A} \rightarrow \mathcal{C}$  amounts to picking an object  $c \in \mathcal{C}$ ,  $c = F(*)$ . Show that, in this case,  $\text{Ran}_F F$  exists if  $\mathcal{C}$  has products. The resulting codensity monad is called the *endomorphism monad* of  $c$  and denoted by  $\langle c, c \rangle$ .

**Exercise 3.**

Let  $k$  be a field and  $\mathbf{Vect}_k$  the category of  $k$ -vector spaces. Let  $\mathcal{A} = \{k\}$  be the full subcategory on the one-dimensional vector space  $k$ . Note that every object of  $\mathbf{Vect}_k$  is a colimit of some diagram that factors through  $\mathcal{A}$  (since all vector spaces are free).

- (a) Show that, nevertheless, the inclusion  $\mathcal{A} \rightarrow \mathbf{Vect}_k$  is *not* dense.
- (b) Let  $\mathcal{B} = \{k \oplus k\}$  be the full subcategory on the two-dimensional vector space. Show that the inclusion  $\mathcal{B} \rightarrow \mathbf{Vect}_k$  is dense.

**Exercise 4.**

Let  $\mathcal{A}$  be a small category and let  $Y: \mathcal{A} \rightarrow [\mathcal{A}^{\text{op}}, \mathbf{Set}]$  be the Yoneda embedding.

- (a) Use the Yoneda lemma to show that the canonical cocone on  $Y/F$  exhibits  $F$  as colimit of the domain functor  $\text{dom}: Y/F \rightarrow [\mathcal{A}^{\text{op}}, \mathbf{Set}]$ ,  $(\varphi: \mathcal{A}(-, a) \Rightarrow F) \mapsto \mathcal{A}(-, a)$ .
- (b) The category  $\text{el}(F)$  of elements of  $F$  has objects the pairs  $(a, x)$  where  $a \in \mathcal{A}$  and  $x \in Fa$  and morphisms  $(a, x) \rightarrow (b, y)$  the morphisms  $f: a \rightarrow b$  in  $\mathcal{A}$  which satisfy  $Ff(y) = x$ . Show that there is an isomorphism  $Y/F \cong \text{el}(F)^{\text{op}}$ .

**Exercise 5.** (*bonus*)

An object  $c \in \mathcal{C}$  is called *strongly finitely presentable* if the representable functor  $\mathcal{C}(c, -): \mathcal{C} \rightarrow \mathbf{Set}$  preserves sifted colimits. A cocomplete category  $\mathcal{C}$  is called *locally strongly finitely presentable* if there exists a small dense subcategory  $\mathcal{A}$  of  $\mathcal{C}$  which consists of strongly finitely presentable objects.

- (a) Show that finite coproducts of strongly finitely presentable objects are strongly finitely presentable.
- (b) Let  $U: \mathcal{D} \rightarrow \mathcal{C}$  have a left adjoint  $F: \mathcal{C} \rightarrow \mathcal{D}$ . Show the following claim: if  $U$  preserves sifted colimits, then  $F$  preserves strongly finitely presentable objects.
- (c) Let  $\mathcal{C}$  be a strongly finitely presentable category and let  $T: \mathcal{C} \rightarrow \mathcal{C}$  be a monad which commutes with sifted colimits. Show that  $T\text{-}\mathbf{Alg}$  is locally strongly finitely presentable. (Hint: let  $\mathcal{A}$  be a dense subcategory of  $\mathcal{C}$  consisting of strongly finitely presentable objects. Show that the objects  $(Ta, \mu_a)$  form a dense subcategory of  $T\text{-}\mathbf{Alg}$ ).

## Monads and their applications 4

### Exercise 1.

Let  $F: \mathcal{A} \rightarrow \mathcal{C}$ ,  $K: \mathcal{A} \rightarrow \mathcal{B}$  be two functors where  $\mathcal{A}$  is essentially small. Note that  $K$  is not assumed to be full and faithful.

- (a) Show that  $[\mathcal{A}^{\text{op}}, \mathbf{Set}](\tilde{K}c, \tilde{F}-): \mathcal{D} \rightarrow \mathbf{Set}$  is representable if and only if the colimit of the diagram  $K/c \rightarrow \mathcal{D}$  which sends  $(a, \varphi: Ka \rightarrow c)$  to  $Fa \in \mathcal{D}$  has a colimit.
- (a) Assume that the colimit of part (a) always exist. By Yoneda, there exists a functor  $L: \mathcal{C} \rightarrow \mathcal{D}$  with bijections

$$\mathcal{D}(Lc, d) \cong [\mathcal{A}^{\text{op}}, \mathbf{Set}](\tilde{K}c, \tilde{F}d)$$

which are natural in  $c$  and  $d$ . Show that, in this case, there exists a natural transformation  $\eta: F \Rightarrow LK$  which exhibits  $L$  as left Kan extension of  $F$  along  $K$ .

### Exercise 2.

- (a) Let  $(\mathcal{C}_i)_{i \in I}$  be a family of locally finitely presentable categories. Show that the product  $\prod_{i \in I} \mathcal{C}_i$  is locally finitely presentable.
- (b) Let  $\mathcal{A}$  be a small category and  $\mathcal{C}$  locally finitely presentable. Show that  $[\mathcal{A}, \mathcal{C}]$  is locally finitely presentable.

### Exercise 3.

Let  $\mathcal{C}$  be a cocomplete category. An object  $a \in \mathcal{C}$  is called *small projective* if  $\mathcal{C}(a, -)$  preserves *all* small colimits. Suppose there exists a small subcategory  $\mathcal{A} \subseteq \mathcal{C}$  such that the closure of  $\mathcal{A}$  under colimits is all of  $\mathcal{C}$ . Show that  $\mathcal{C} \simeq [\mathcal{A}^{\text{op}}, \mathbf{Set}]$ . (Hint: start by showing that the inclusion  $K: \mathcal{A} \rightarrow \mathcal{C}$  is dense.

### Exercise 4.

Let  $\mathcal{C}$  be locally finitely presentable,  $\mathcal{A}$  a small dense subcategory consisting of finitely presentable objects. Let  $\mathcal{A}'$  be the closure of  $\mathcal{A}$  under finite colimits. Let  $\mathcal{C}_{\text{fp}}$  denote the full subcategory consisting of finitely presentable objects. From the lecture, we know that  $\mathcal{A}' \subseteq \mathcal{C}_{\text{fp}}$ . Show that this in fact an equality: every finitely presentable object lies in the closure of  $\mathcal{A}$  under finite colimits.

**Exercise 5.** ??

Show that the finitely presentable objects in the category of topological spaces are precisely the finite discrete spaces, and that they do not form a dense generator. Thus **Top** is not finitely presentable.

## Monads and their applications 5

### Exercise 1.

Let  $(S, \sigma)$  be a well-pointed endofunctor of  $\mathcal{D}$ . Let  $\mathcal{C}$  be a finitely cocomplete category and let  $F: \mathcal{D} \rightarrow \mathcal{C}$  be left adjoint to  $U: \mathcal{C} \rightarrow \mathcal{D}$ . Show that the endofunctor  $(S', \sigma')$  of  $\mathcal{C}$  defined by the pushout diagram

$$\begin{array}{ccc} FU & \xrightarrow{F\sigma U} & FSU \\ \varepsilon \downarrow & & \downarrow \\ \text{id} & \xrightarrow{\sigma'} & S' \end{array}$$

in  $[\mathcal{C}, \mathcal{C}]$  is a well-pointed endofunctor and that there is an induced diagram

$$\begin{array}{ccc} (S', \sigma')\text{-}\mathbf{Alg} & \xrightarrow{\bar{U}} & (S, \sigma)\text{-}\mathbf{Alg} \\ \downarrow & & \downarrow \\ \mathcal{C} & \xrightarrow{U} & \mathcal{D} \end{array}$$

which is a (strict) pullback diagram of categories.

### Exercise 2.

Let  $((S_i, \sigma_i))_{i \in I}$  be a family of accessible well-pointed endofunctors of a locally presentable category  $\mathcal{C}$ . Let  $S$  be the colimit in  $[\mathcal{C}, \mathcal{C}]$  of the “star-shaped” diagram  $\sigma_i: \text{id}_{\mathcal{C}} \Rightarrow S_i$  (that is, a star with center  $\text{id}_{\mathcal{C}}$ ). Write  $\sigma$  for the induced composite  $\text{id} \Rightarrow S_i \Rightarrow S$  (which is by construction independent of  $i$ ). Show that  $(S, \sigma)$  is an accessible well-pointed endofunctor and that  $(S, \sigma)\text{-}\mathbf{Alg}$  is the intersection  $\bigcap_{i \in I} (S_i, \sigma_i)\text{-}\mathbf{Alg}$ .

### Exercise 3.

Let  $k: a \rightarrow b$  be a morphism of a category  $\mathcal{C}$ . An object  $c \in \mathcal{C}$  is called *orthogonal* to  $k$  if for any  $f: a \rightarrow c$ , there exists a unique dashed arrow making the triangle

$$\begin{array}{ccc} a & \xrightarrow{f} & c \\ k \downarrow & \nearrow & \\ b & & \end{array}$$

commutative. The full subcategory of objects orthogonal to  $k$  is denoted by  $\{k\}^\perp \subseteq \mathcal{C}$ . Similarly, given a set  $\Sigma$  of morphisms in  $\mathcal{C}$ , we write  $\Sigma^\perp \subseteq \mathcal{C}$  for the class of objects which are orthogonal to all the morphisms in  $\Sigma$ .



- (a) Let  $\mathcal{C}$  be locally presentable and let  $k: a \rightarrow b$  be a morphism in  $\mathcal{C}$ . This defines a functor  $k: [1] \rightarrow \mathcal{C}$ , where  $[1] = \{0 \rightarrow 1\}$  denotes the category consisting of a single non-trivial morphism. Show that the right adjoint of the induced adjunction  $\text{Lan}_Y k: \mathbf{Set}^{[1]^{\text{op}}} \rightleftarrows \mathcal{C}: \tilde{k}$  is accessible.
- (b) Show that there exists an accessible well-pointed endofunctor  $(S_k, \sigma_k)$  of  $\mathcal{C}$  such that  $(S_k, \sigma_k)\text{-Alg}$  is equal to the full subcategory  $\{k\}^\perp \subseteq \mathcal{C}$  of objects orthogonal to  $k$ . (Hint: apply Exercise 1 to the adjunction of (a).)
- (c) Let  $\Sigma$  be a set of morphisms in  $\mathcal{C}$ . Show that there exists an accessible well-pointed endofunctor of  $\mathcal{C}$  whose category of algebras is  $\Sigma^\perp \subseteq \mathcal{C}$ .

**Exercise 4.**

Let  $\mathcal{A}$  be a small category and consider a set  $(D^k: \mathcal{I}_k \rightarrow \mathcal{A})_{k \in K}$  of diagrams in  $\mathcal{A}$ . For each diagram  $D^k$ , fix a cocone  $\kappa_i: D_i^k \rightarrow a_k$  in  $\mathcal{A}$ . Let  $\mathcal{C} \subseteq [\mathcal{A}^{\text{op}}, \mathbf{Set}]$  be the full subcategory of presheaves  $F: \mathcal{A}^{\text{op}} \rightarrow \mathbf{Set}$  with the property that  $F\kappa_i: Fa_k \rightarrow FD_i^k$  is a limit cone for each  $k \in K$ . Show that there exists a set  $\Sigma$  of morphisms in  $[\mathcal{A}^{\text{op}}, \mathbf{Set}]$  such that  $\mathcal{C} = \Sigma^\perp$ .

**Exercise 5.** ??

From the lecture, we know that the category  $\mathcal{C}$  in Exercise 4 is reflective. Show that the composite

$$\mathcal{A} \xrightarrow{Y} [\mathcal{A}^{\text{op}}, \mathbf{Set}] \longrightarrow \mathcal{C}$$

of the Yoneda embedding and the left adjoint of the inclusion is the universal functor to a cocomplete category which sends the given cones to colimit cones.

## Monads and their applications 6

### Exercise 1.

Let  $(S, \sigma)$  be a well-pointed endofunctor of  $\mathcal{C}$ . Let  $L: \mathcal{C} \rightarrow \mathcal{C}$  be an endofunctor of  $\mathcal{C}$  and  $\pi: S \Rightarrow L$  a natural transformation such that  $\pi_c: Sc \rightarrow Lc$  is an epimorphism for all  $c \in \mathcal{C}$ . Show that  $(L, \pi\sigma)$  is a well-pointed endofunctor and that  $(L, \pi\sigma)\text{-}\mathbf{Alg}$  is equivalent to the full subcategory of  $(S, \sigma)\text{-}\mathbf{Alg}$  consisting of objects  $(a, \alpha)$  such that  $\pi_a: Sa \rightarrow La$  is an isomorphism.

### Exercise 2.

Let  $\mathcal{C}$  be a cocomplete category and let  $(T, \tau)$  be a pointed endofunctor of  $\mathcal{C}$ . Let  $(S, \sigma)$  be the well-pointed endofunctor of the arrow category  $\mathcal{C}^{[1]}$  whose algebras are the isomorphisms:  $S(c \rightarrow c') = \text{id}_{c'}$ . Recall that we defined a well-pointed endofunctor  $(S', \sigma')$  on the slice category  $T/\mathcal{C}$  by the pushout

$$\begin{array}{ccc} \tau_! \tau^* & \xrightarrow{\tau_! \sigma \tau^*} & \tau_! S \tau^* \\ \varepsilon \downarrow & & \downarrow \\ \text{id} & \xrightarrow{\sigma'} & S' \end{array}$$

in  $[T/\mathcal{C}, T/\mathcal{C}]$ . Show that  $S'$  sends  $(a, b, \alpha: Ta \rightarrow b)$  to  $(b, c, \beta: Tb \rightarrow c)$ , where  $\beta$  denotes the coequalizer

$$T^2 a \xrightarrow[\tau_{Ta}]{T\tau_a} T^2 a \xrightarrow{T\alpha} Tb \xrightarrow{\beta} c$$

in  $\mathcal{C}$ . (Hint: if you get stuck, this is discussed in Kelly's "transfinite constructions," §17).

### Exercise 3.

Let  $\mathcal{C}$  be a locally  $\lambda$ -presentable category,  $F: \mathcal{C} \rightarrow \mathcal{D}$   $\lambda$ -accessible, and let  $G: \mathcal{C} \rightarrow \mathcal{D}$  be a right adjoint. Recall that the slice category  $F/G$  has objects the triples  $(a, b, \gamma: Fa \rightarrow Gb)$ , with morphisms given by pairs of morphisms in  $\mathcal{C}$  making the evident square commutative.

- (a) Show that the slice category  $F/G$  is locally  $\lambda$ -presentable.
- (b) Suppose that  $G$  is also  $\lambda$ -accessible. Show that, in this case, both the domain functor and the codomain functor  $F/G \rightarrow \mathcal{C}$  which send  $(a, b, \gamma)$  to  $a$  respectively  $b$  are  $\lambda$ -accessible.

**Exercise 4.**

Let  $\mathcal{C}$ ,  $\mathcal{D}$  be locally  $\lambda$ -presentable,  $F: \mathcal{C} \rightarrow \mathcal{D}$  left adjoint to  $U: \mathcal{D} \rightarrow \mathcal{C}$ . Let  $\kappa \geq \lambda$  be a regular cardinal.

- (a) Show that if  $U$  is  $\kappa$ -accessible, then  $F(\mathcal{C}_\kappa) \subseteq \mathcal{D}_\kappa$ . (Recall that  $\mathcal{C}_\kappa$  denotes the full subcategory of  $\kappa$ -presentable objects in  $\mathcal{C}$ .)
- (b) Show that there exists a regular cardinal  $\mu \geq \lambda$  such that  $U$  is  $\mu$ -accessible. (Hint: consider the composite of  $U$  with the full and faithful  $\tilde{K}: \mathcal{C} \rightarrow [\mathcal{C}_\lambda^{\text{op}}, \mathbf{Set}]$ , where  $K: \mathcal{C}_\lambda \rightarrow \mathcal{C}$  denotes the inclusion.)
- (c) Conclude that for any left adjoint  $F$  between locally  $\lambda$ -presentable categories, there exists a regular cardinal  $\mu \geq \lambda$  such that  $F(\mathcal{C}_\mu) \subseteq \mathcal{D}_\mu$ .

**Exercise 5.** ??

Show that left adjoint functors between locally presentable categories are precisely the cocontinuous functors and that right adjoints between locally presentable categories are precisely the continuous functors which are also accessible.

## Monads and their applications 7

### Exercise 1.

Complete the proof that  $(-)\text{-}\mathbf{Alg}: \mathbf{Mnd}(\mathcal{C})^{\mathrm{op}} \rightarrow \mathbf{CAT}/\mathcal{C}$  is a functor and that it is full and faithful.

### Exercise 2.

Recall that the *codensity monad*  $\mathrm{Ran}_F F$  of  $F: \mathcal{A} \rightarrow \mathcal{C}$  is the right Kan extension of  $F$  along itself.

- (a) Show that the right Kan extension of any functor  $G$  along a right adjoint  $U$  always exists and is given by  $GL$  (“by adjunction”).
- (b) Show that the codensity monad of a right adjoint is precisely the monad  $(UL, \eta, U\varepsilon L)$  associated to the adjunction.

### Exercise 3.

We call a functor  $F: \mathcal{A} \rightarrow \mathcal{C}$  *admissible* if  $\mathrm{Ran}_F F$  exists and we write  $\mathbf{CAT}'/\mathcal{C}$  for the full subcategory of admissible functors. From Exercise 2 it follows that  $(-)\text{-}\mathbf{Alg}$  factors through the admissible functors. We denote the codensity monad of  $F$  by  $S(F)$ .

- (a) Show that

$$(-)\text{-}\mathbf{Alg}: \mathbf{Mnd}(\mathcal{C})^{\mathrm{op}} \rightarrow \mathbf{CAT}'/\mathcal{C}$$

is right adjoint to

$$S: \mathbf{CAT}'/\mathcal{C} \rightarrow \mathbf{Mnd}(\mathcal{C})^{\mathrm{op}}$$

(this is called the *semantics-structure adjunction*).

- (b) Use this adjunction to give a rigorous argument that the algebra functor

$$(-)\text{-}\mathbf{Alg}: \mathbf{Mnd}(\mathcal{C})^{\mathrm{op}} \rightarrow \mathbf{CAT}/\mathcal{C}$$

with target the full slice category sends colimits to limits if  $\mathcal{C}$  is complete.

- (c) Use the adjunction to give an alternative proof that  $(-)\text{-}\mathbf{Alg}$  is full and faithful.

**Exercise 4.**

Directed graphs are presheaves on  $G = \{ 0 \rightrightarrows 1 \}$ , that is, pairs of sets  $E$  and  $V$  with source and target maps  $s: E \rightarrow V$  and  $t: E \rightarrow V$ . Use finitary endofunctors of the presheaf category such as  $(E, V, s, t) \mapsto (V, V, \text{id}, \text{id})$  or the functor which sends a graph to the graph consisting of paths of length two in the original (that is, the edges in the new graph are given by the pullback of  $s$  along  $t$ ) to construct a finitary monad on  $[G^{\text{op}}, \mathbf{Set}]$  whose category of algebras is isomorphic to **Cat**.

**Exercise 5.** ??

Let  $\mathcal{C}$  be the category whose objects are small categories with a choice of colimit for each finite diagram and whose morphisms are the functors which preserve these colimits strictly. Use free finitary monads and colimits of such to show that  $\mathcal{C}$  is finitarily monadic over **Cat**.

## Monads and their applications 8

### Exercise 1.

Let  $\mathcal{V}, \mathcal{W}, \mathcal{U}$  be monoidal categories and let  $(F, \varphi_0, \varphi): \mathcal{V} \rightarrow \mathcal{W}$  and  $(G, \psi_0, \psi): \mathcal{W} \rightarrow \mathcal{U}$  is lax monoidal with structure morphisms  $\gamma_0 = G(\varphi_0) \cdot \psi_0$  and  $\gamma_{X,Y} = G(\varphi_{X,Y}) \cdot \psi_{FX,FY}$ . Show that monoidal natural transformations can be whiskered on either side with lax monoidal functors.

### Exercise 2.

Let  $(F, \varphi_0, \varphi): \mathcal{V} \rightarrow \mathcal{W}$  be strong monoidal and suppose that the underlying functor  $F$  has a right adjoint  $U$ . Show that the composites

$$I_{\mathcal{V}} \xrightarrow{\eta_{I_{\mathcal{V}}}} UF(I) \xrightarrow{U(\varphi_0^{-1})} U(I_{\mathcal{W}})$$

and

$$\begin{array}{ccc} UX \otimes_{\mathcal{V}} UY & \xrightarrow{\eta_{UX \otimes_{\mathcal{V}} UY}} & UF(UX \otimes_{\mathcal{V}} UY) \\ \downarrow & & \downarrow U\varphi_{UX,UY}^{-1} \\ U(X \otimes_{\mathcal{W}} Y) & \xleftarrow{U(\varepsilon_X \otimes_{\mathcal{W}} \varepsilon_Y)} & U(FUX \otimes_{\mathcal{W}} FUY) \end{array}$$

endow  $U$  with the structure of a lax monoidal functor, and that  $\eta, \varepsilon$  are monoidal natural transformations for this structure if the composites  $UF$  and  $FU$  are given the lax monoidal structure of Exercise 1.

### Exercise 3.

Let  $\mathcal{V}, \mathcal{W}$  be monoidal categories,  $(F, \varphi_0, \varphi): \mathcal{V} \rightarrow \mathcal{W}$  a strong monoidal left adjoint, and  $f: S \rightarrow T$  a function of sets.

- (a) Show that  $f$  induces a strong monoidal  $f_*: \mathbf{Mat}(\mathcal{V}, S) \rightarrow \mathbf{Mat}(\mathcal{W}, T)$ .
- (b) Show that  $F$  induces a strong monoidal  $F: \mathbf{Mat}(\mathcal{V}, S) \rightarrow \mathbf{Mat}(\mathcal{W}, S)$ .
- (c) Use Exercise 2 to show that these are both monoidal adjunctions.

### Exercise 4.

Let  $\mathcal{C}$  be a complete category,  $a, b$  objects of  $\mathcal{C}$ . Recall that  $\langle a, b \rangle$  is defined to be the right Kan extension of  $b: * \rightarrow \mathcal{C}$  along  $a: * \rightarrow \mathcal{C}$ . Show that

$$(\mathrm{Ob}(\mathcal{C}), (\langle a, b \rangle)_{(a,b) \in \mathrm{Ob} \mathcal{C} \times \mathrm{Ob}(\mathcal{C})})$$

defines a category enriched in the monoidal category  $[\mathcal{C}, \mathcal{C}]$  of endofunctors.

**Exercise 5.** ??

There are two natural monoidal functors  $\mathcal{V} \rightarrow [\mathcal{V}, \mathcal{V}]$  given by tensoring in either side. Under what conditions do these have a right adjoint? (For example, is locally presentable enough?) Applying Exercise 3(b) to the enriched category of Exercise 4, we get two  $\mathcal{V}$ -category structures on  $\mathcal{V}$ . Describe them explicitly. (Hint: you only need to know what the right adjoint does to functors of the form  $\langle V, W \rangle$ ).

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### Exercise 1.

Show that the interchange law holds in  $\mathcal{V}$ -**CAT**.

### Exercise 2.

Let  $F: \mathcal{V} \rightarrow \mathcal{W}$  be a lax monoidal functor. Show that  $F$  induces a 2-functor

$$F_*: \mathcal{V}\text{-}\mathbf{CAT} \rightarrow \mathcal{W}\text{-}\mathbf{CAT}$$

which sends a  $\mathcal{V}$ -category  $\mathcal{A}$  to the  $\mathcal{W}$ -category  $F_*\mathcal{A}$  with the same objects as  $\mathcal{A}$ , and hom-objects between  $a$  and  $b$  given by  $F(\mathcal{A}(a, b))$ .

### Exercise 3.

Let **Mon(CAT)** denote the 2-category of monoidal categories, lax monoidal functors, and monoidal natural transformations. Show that the assignment

$$(-)\text{-}\mathbf{Cat}: \mathbf{Mon}(\mathbf{CAT}) \rightarrow 2\text{-}\mathbf{CAT}$$

which sends  $\mathcal{V}$  to the 2-category  $\mathcal{V}\text{-}\mathbf{Cat}$  extends to a 2-functor, with action on 1-cells given by the 2-functor of Exercise 2.

### Exercise 4.

Let  $T: \mathcal{C} \rightarrow \mathcal{C}$  be a  $\mathcal{V}$ -monad. Complete the proof the  $T\text{-}\mathbf{Alg}$  has the structure of a  $\mathcal{V}$ -category. Hint: at some point in the proof that algebra morphisms compose in the unenriched case, we use associativity, namely when we consider the composite

$$\begin{array}{ccccc} TA & \xrightarrow{Tf} & TB & \dashrightarrow & \cdot \\ \downarrow & & \downarrow \beta & & \downarrow \\ \cdot & \dashrightarrow & B & \xrightarrow{g} & C \end{array}$$

in  $\mathcal{C}$ . This switches the operations “precompose with  $\beta$ ” to “postcompose with  $\beta$ ” and when translating the proof to  $\mathcal{V}$ -categories, one has to use the associator at this point.

### Exercise 5.

Show that  $T\text{-}\mathbf{Alg}$  has the same universal property in  $\mathcal{V}\text{-}\mathbf{CAT}$  as the ordinary category of algebras for an unenriched monad has in **CAT**. Namely, for each  $\mathcal{V}$ -category  $\mathcal{A}$ , define the category  $T\text{-}\mathbf{Act}(\mathcal{A}, \mathcal{C})$  of  $T$ -actions (now given by  $\mathcal{V}$ -functors with a  $\mathcal{V}$ -natural transformation  $\rho: TG \Rightarrow G$ ) and show that  $U^T: T\text{-}\mathbf{Alg} \rightarrow \mathcal{C}$  is the universal  $T$ -action.



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### Exercise 1.

Let  $\mathcal{V}$  be a braided monoidal category. Show that the monoidal structure of  $\mathcal{V}$  lifts to a monoidal structure of  $\mathbf{Mon}(\mathcal{V})$  (that is, put a monoid structure on  $M \otimes M'$  so that  $\alpha, \rho, \lambda$  become monoid morphisms). If  $\mathcal{V}$  is symmetric, show that  $\gamma$  lifts to a symmetry on  $\mathbf{Mon}(\mathcal{V})$ .

### Exercise 2.

Show that a monoid in  $\mathbf{Mon}(\mathcal{V})$  is a commutative monoid (this is known as the “Eckmann-Hilton argument”). More precisely, if  $((M, \mu, \eta), \mu', \eta')$  is a monoid in  $\mathbf{Mon}(\mathcal{V})$ , show that  $\eta' = \eta$ ,  $\mu' = \mu$  and  $\mu\gamma_{M,M} = \mu$ . (Hint: it is best to first prove this for  $\mathcal{V} = \mathbf{Set}$  and then translate to general monoidal categories. First show that the two units  $\eta = \eta'$  are the same and then turn the following pictorial “proof” into a precise argument, where we write one multiplication vertically, one horizontally:

$$\begin{bmatrix} a & b \end{bmatrix} = \begin{bmatrix} a & \eta \\ \eta & b \end{bmatrix} = \begin{bmatrix} \eta & a \\ b & \eta \end{bmatrix} = \begin{bmatrix} b & a \end{bmatrix}$$

for all  $a, b \in M$ .

### Exercise 3.

Let  $\mathcal{V}$  be a symmetric monoidal closed category,  $\mathcal{C}$  a  $\mathcal{V}$ -category, and  $C \in \mathcal{C}$ . Show that the functor  $\mathcal{C}(C, -): \mathcal{C} \rightarrow \mathcal{V}$  defined in class is indeed a  $\mathcal{V}$ -functor.

### Exercise 4.

Let  $\mathcal{V}$  be a symmetric monoidal category. If  $A \in \mathcal{V}$  is a monoid, then  $A \otimes -$  is a monad. The  $(A \otimes -)$ -algebras are called *A-modules* and we write  $\mathcal{V}_A$  for  $(A \otimes -)$ -**Alg**. Now suppose that  $A$  is commutative, that  $\mathcal{V}$  has reflexive coequalizers, and that  $V \otimes -$  preserves these for all  $V \in \mathcal{V}$ . Given  $A$ -modules  $M$  and  $N$ , define  $M \otimes_A N$  by the reflexive coequalizer

$$M \otimes A \otimes N \begin{matrix} \xrightarrow{\quad} \\ \xleftarrow{\quad} \end{matrix} M \otimes N \longrightarrow M \otimes_A N$$

in  $\mathcal{V}$ . Show that this lifts to a functor  $- \otimes_A -: \mathcal{V}_A \otimes \mathcal{V}_A \rightarrow \mathcal{V}_A$  making  $\mathcal{V}_A$  into a symmetric monoidal category with unit  $A$  (Hint: use the fact that reflexive coequalizers are sifted and split coequalizers are absolute).

### Exercise 5. ??

Give an example of a braided monoidal category  $\mathcal{V}$  such that the braiding does not lift to  $\mathbf{Mon}(\mathcal{V})$ .

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## Exercise 1.

Let  $\mathcal{V}$  be the category  $\mathbf{Ch}(\mathbf{Ab})$  of chain complexes over abelian groups (“differential graded  $\mathbb{Z}$ -modules”). The tensor product of  $X_\bullet$  and  $Y_\bullet$  is given in degree  $n$  by  $\oplus_{i+j=n} X_i \otimes Y_j$ , with differential  $d(x \otimes y) = dx \otimes y + (-1)^i x \otimes dy$  for  $x \otimes y \in X_i \otimes Y_j$ . Show that this is a symmetric monoidal closed category and explicitly describe the self-enrichment of  $\mathcal{V}$  (specifically, the composition morphism).

## Exercise 2.

Let  $\mathcal{C}$  be a  $\mathcal{V}$ -category with powers,  $T: \mathcal{C} \rightarrow \mathcal{C}$  a  $\mathcal{V}$ -monad. Show that the forgetful  $\mathcal{V}$ -functor  $T\text{-}\mathbf{Alg} \rightarrow \mathcal{C}$  creates powers (that is, for every  $T$ -algebra  $(A, a)$  and  $V \in \mathcal{V}$  one can put a unique  $T$ -algebra structure on  $A^V$  making it a power of  $(A, a)$  in  $T\text{-}\mathbf{Alg}$ ).

## Exercise 3.

Let  $t: C \rightarrow C$  be a monad in the 2-category  $\mathcal{K}$ . A  $t$ -action on a 1-cell  $g: A \rightarrow C$  is a 2-cell  $\alpha: tg \Rightarrow g$  satisfying the laws for a  $t$ -algebra. This defines a 2-functor

$$t\text{-act}(-): \mathcal{K}^{\text{op}} \rightarrow \mathbf{Cat}$$

and we say that the *Eilenberg–Moore* object of  $t$  exists if this 2-functor is representable, that is, there exists a *universal*  $t$ -action  $(u, \alpha): C_t \rightarrow C$ .

- (a) Show that  $U: T\text{-}\mathbf{Alg} \rightarrow \mathcal{C}$  is an Eilenberg–Moore object in  $\mathcal{V}\text{-}\mathbf{Cat}$ .
- (b) Given any Eilenberg–More object  $u: C_t \rightarrow C$ , show that there exists a left adjoint  $f$  of  $u$  such that the monad  $uf$  is  $t$ . (Hint: define a suitable  $t$ -action on  $t$  itself).

## Exercise 4.

- (a) Let  $\mathcal{V} = \mathbf{Set}$  and consider the discrete category  $2 = \{0, 1\}$  on two objects. A weight  $W$  on this category amounts to a choice of two sets. What is the  $W$ -weighted colimit on a diagram  $2 \rightarrow \mathcal{C}$ ?
- (b) Let  $\mathcal{V} = \mathbf{Ab}$  and let  $R$  be a ring, considered as a 1-object  $\mathcal{V}$ -category. Let  $\mathcal{C} = \mathbf{Ab}$  as well. Show that weighted colimits over  $R$  correspond to the usual tensor product of a right and a left  $R$ -module.
- (c) Let  $\mathcal{V} = \mathbf{Cat}$  and consider the category  $\mathcal{J} = 0 \longrightarrow 2 \longleftarrow 1$ . Let  $W$  be the weight with  $W(0) = *$ ,  $W(1) = *$ , and  $W(2) = [1]$ , with

the morphisms  $W(i) \rightarrow [1]$  picking out  $i \in [1] = \{0 \rightarrow 1\}$ . Show that  $W$ -weighted limits in a 2-category  $\mathcal{K}$  are precisely comma-objects.

**Exercise 5.** ??

Show that  $\prod_{j \in J} \mathcal{V}$  is the free cocomplete  $\mathcal{V}$ -category on the discrete category  $j$ . More precisely, given a cocomplete  $\mathcal{V}$ -categories  $\mathcal{C}, \mathcal{D}$ , write  $\mathbf{Cocts}_0[\mathcal{C}, \mathcal{D}]$  for the category of cocontinuous  $\mathcal{V}$ -functors and  $\mathcal{V}$ -natural transformations. Show that the functor  $\mathbf{Cocts}_0[\prod_{j \in J} \mathcal{V}, \mathcal{C}] \rightarrow \prod_{j \in J} \mathcal{C}_0$  given by  $F \mapsto (FI_j)_{j \in J}$  is an equivalence of categories. Here  $I_j$  stands for the object which is given by  $I$  in degree  $j$  and by the initial object everywhere else. You need to be careful when showing that the functor is full!

If one checks all the requirements by only referring to copowers,  $\mathcal{V}$ -coproducts, and  $\mathcal{V}$ -coequalizers, (the latter is not even necessary), then one can use this to show that cocontinuous endofunctors of the product are equivalent, as a monoidal category, to  $\mathcal{V}$ -matrices on  $J$ . This can then be used to give a rigorous proof that any  $\mathcal{V}$ -category with object set  $J$  gives rise to the cocontinuous  $\mathcal{V}$ -monad  $T$  defined in the lecture.

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### Exercise 1.

Let  $\mathcal{V}$  be a cosmos,  $A$  and  $B$  monoids in  $\mathcal{V}$ . The category  $\mathcal{V}_A$  of left  $A$ -modules is precisely the functor category  $[A, \mathcal{V}]$ . Show that the category of left  $\mathcal{V}$ -adjoints  $\mathcal{V}_A \rightarrow \mathcal{V}_B$  is equivalent to the category of  $A$ - $B$ -bimodules (Hint: use the theory of free cocompletions). Apply this to the case of equivalences to show that the module categories are equivalent as  $\mathcal{V}$ -categories if and only if there exists an  $A$ - $B$  bimodule  $M$  and a  $B$ - $A$ -bimodule  $N$  with  $N \otimes_B M \cong A$  and  $M \otimes_A N \cong B$  (this is called *Morita equivalence* of monoids).

### Exercise 2.

Recall that an Eilenberg–Moore object (EM-object for short) represents actions of a monad in a 2-category  $\mathcal{K}$ . A *Kleisli-object* is the dual notion, that is, an EM-object in  $\mathcal{K}^{\text{op}}$ : given a monad  $t: C \rightarrow C$ , the Kleisli-object is the universal morphism  $f: C \rightarrow C^t$  with an action  $ft \Rightarrow f$ .

Show that **CAT** has Kleisli-objects, described as follows: for a monad  $T: \mathcal{C} \rightarrow \mathcal{C}$ , the category  $\mathcal{C}^T$  has the same objects as  $\mathcal{C}$  and  $\mathcal{C}^T(A, B) := \mathcal{C}(A, TB)$ . The composition is defined using the monad multiplication. Show that  $\mathcal{C}^T$  is equivalent to the full subcategory of  $T$ -**Alg** consisting of the free algebras.

### Exercise 3.

Let  $\mathcal{K}$  be a 2-category with EM-objects and let  $C \in \mathcal{K}$ . Write  $\text{Mnd}(C)$  for the category of monads on  $C$ . Call a 1-cell  $g: A \rightarrow C$  *tractable* if the right Kan extension of  $g$  along itself exists. Write  $\mathcal{K}'_0/C$  for the full subcategory of the slice (1-)category consisting of tractable 1-cells. Show that the functor

$$(-)\text{-}\mathbf{Alg}: \text{Mnd}(C)^{\text{op}} \rightarrow \mathcal{K}'_0/C$$

which sends  $t$  to its EM-object is right adjoint to the functor which sends  $g$  to the density monad  $\text{Ran}_g g$ .

### Exercise 4.

Let  $\mathcal{C}$  be an unenriched cocomplete category. Let  $\mathcal{G}$  be a full subcategory consisting of  $\kappa$ -presentable objects and suppose that  $\mathcal{G}$  is a *strong* generator: the functor

$$\tilde{K} = \text{Hom}_{\mathcal{G}}(K, -): \mathcal{C} \rightarrow [\mathcal{G}^{\text{op}}, \mathbf{Set}]$$

is conservative. The goal of this exercise is to show that  $\mathcal{C}$  is locally  $\kappa$ -presentable, that is, there automatically exists a *dense* generator of  $\kappa$ -small

objects. More precisely, let  $\mathcal{A}$  be the closure of  $\mathcal{G}$  under  $\kappa$ -small colimits. Show that  $\mathcal{A}$  is dense using the following steps.

- (a) Show that the category  $\mathcal{A}/C$  is  $\kappa$ -filtered and that the canonical diagram  $\mathcal{A}/C \rightarrow \mathcal{C}$  is sent to a colimit diagram by the functor  $\tilde{K}$ .
- (b) Show the following fact about conservative functors  $F: \mathcal{A} \rightarrow \mathcal{B}$ : if  $\mathcal{A}$  has colimits of a given shape,  $F$  preserves colimits of that shape, and a specific cocone is sent to a colimit cocone by  $F$ , then the cocone in question is already a colimit cocone. In other words, a conservative functor *detects* all the colimits that exist in the domain and that it preserves.
- (c) Conclude that  $\mathcal{A}$  is dense and thus that  $\mathcal{C}$  is locally  $\kappa$ -presentable.

**Exercise 5.** ??

Let  $\mathcal{V}$  be a cosmos. Given two *small*  $\mathcal{V}$ -categories, show that there exists a  $\mathcal{V}$ -category  $[\mathcal{A}, \mathcal{B}]$  whose underlying category is  $\mathcal{V}\text{-}\mathbf{Cat}(\mathcal{A}, \mathcal{B})$ . The hom-object can be defined using the usual equalizer in  $\mathcal{V}$  which would give natural transformations for  $\mathcal{V} = \mathbf{Set}$ . Show that this defines an internal hom-object in the monoidal category  $\mathcal{V}\text{-}\mathbf{Cat}$ , that is,  $- \otimes \mathcal{A} \dashv [\mathcal{A}, -]$ .