

## WHAT ARE SIFTED COLIMITS?

J. ADÁMEK, J. ROSICKÝ, E. M. VITALE

*Dedicated to Dominique Bourn on the occasion of his sixtieth birthday*

ABSTRACT. Sifted colimits, important for algebraic theories, are “almost” just the combination of filtered colimits and reflexive coequalizers. For example, given a finitely cocomplete category  $\mathcal{A}$ , then a functor with domain  $\mathcal{A}$  preserves sifted colimits iff it preserves filtered colimits and reflexive coequalizers. But for general categories  $\mathcal{A}$  that statement is not true: we provide a counter-example.

### Introduction

Sifted colimits play for the doctrine of finite products precisely the role which filtered colimits play for the doctrine of finite limits. Recall that a small category  $\mathcal{D}$  which is filtered has the property that  $\mathcal{D}$ -colimits commute with finite limits in *Set*. The converse is less well known (but trivial to prove using representable functors as diagrams): if  $\mathcal{D}$ -colimits commute with finite limits in *Set*, then  $\mathcal{D}$  is filtered. Now sifted categories are defined as those small categories  $\mathcal{D}$  such that  $\mathcal{D}$ -colimits commute with finite products in *Set*. They were first studied (without any name) in the classical lecture notes of P. Gabriel and F. Ulmer [6] who proved that  $\mathcal{D}$  is sifted iff the diagonal  $\Delta: \mathcal{D} \rightarrow \mathcal{D} \times \mathcal{D}$  is a final functor; this nicely corresponds to the fact that  $\mathcal{D}$  is filtered iff the diagonals  $\Delta: \mathcal{D} \rightarrow \mathcal{D}^{\mathcal{J}}$  are final for all finite graphs  $\mathcal{J}$ . Sifted colimits are colimits whose schemes are sifted categories; they were studied (independently of [6]) by C. Lair [9] who called them “tamisante”, later P. T. Johnstone suggested the translation to “sifted”. Besides filtered colimits, prime examples of sifted colimits are reflexive coequalizers, that is, coequalizers of parallel pairs of epimorphisms with a joint splitting.

Sifted colimits are of major importance in general algebra. Recall that an algebraic theory (in the sense of F. W. Lawvere [10]) is a small category  $\mathcal{T}$  with finite products and an algebra for  $\mathcal{T}$  is a functor  $A: \mathcal{T} \rightarrow \mathit{Set}$  preserving finite products. The category  $\mathit{Alg}\mathcal{T}$  of algebras is a full subcategory of the functor category  $\mathit{Set}^{\mathcal{T}}$ . Now, let us denote by  $\mathit{Sind}\mathcal{A}$  the free completion of a category  $\mathcal{A}$  under sifted colimits (resembling the name

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$Ind\mathcal{A}$  for Grothendieck's completion under filtered colimits, see [4]). Then for every algebraic theory  $\mathcal{T}$  the category of algebras is just the above completion of  $\mathcal{T}^{op}$ :

$$Alg\mathcal{T} = Sind\mathcal{T}^{op}$$

see [2]. And algebraic functors, that is functors between algebraic categories induced by morphisms of algebraic theories, are precisely the functors preserving limits and sifted colimits, see [1].

The aim of our paper is to discuss the slogan

“filtered colimits = filtered colimits + reflexive coequalizers.”

This could mean the existence:

A category  $\mathcal{A}$  has sifted colimits iff it has filtered colimits and reflexive coequalizers.

Or the preservation:

A functor  $F : \mathcal{A} \rightarrow \mathcal{B}$  preserves sifted colimits iff it preserves filtered colimits and reflexive coequalizers.

Unfortunately, none of these two statements holds in general, as we demonstrate by counter-examples. However, both statements are true whenever  $\mathcal{A}$  is finitely cocomplete. Whereas the first one is trivial, since filtered colimits imply cocompleteness, the latter one concerning preservation is not. Let us mention that this result, assuming  $\mathcal{A}$  is cocomplete, was proved by A. Joyal (his proof even works for quasicategories, see [7]) and by S. Lack (see [8]). Their proofs are different, and more elegant than our proof below, however, for our proof we only assume the existence of finite colimits. (Another proof assuming cocompleteness is presented in [3].)

Let us also remark that there is another interpretation of the above slogan: the free completion of a category  $\mathcal{A}$  under sifted colimits can be constructed as a free completion of  $Ind\mathcal{A}$  under reflexive coequalizers. This is true if  $\mathcal{A}$  has finite coproducts and false in general, see [2].

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## 1. Existence of Sifted Colimits

As mentioned in the Introduction, a small category  $\mathcal{D}$  is called sifted iff  $\mathcal{D}$ -colimits commute in  $Set$  with finite products. That is, given a diagram

$$\mathcal{D} \times \mathcal{J} \rightarrow Set$$

where  $\mathcal{J}$  is a finite discrete category, then the canonical morphism

$$colim_{\mathcal{D}} \left( \prod_{\mathcal{J}} D(d, j) \right) \rightarrow \prod_{\mathcal{J}} \left( colim_{\mathcal{D}} D(d, j) \right)$$

is an isomorphism.

Colimits of diagrams over sifted categories are called sifted colimits.

1.1. REMARK.

(i) As proved by P. Gabriel and F. Ulmer [6], a small, nonempty category  $\mathcal{D}$  is sifted if and only if the diagonal functor  $\Delta: \mathcal{D} \rightarrow \mathcal{D} \times \mathcal{D}$  is final. This means that for every pair of objects  $A, B$  of  $\mathcal{D}$  the category  $(A, B) \downarrow \Delta$  of cospans on  $A, B$  is connected. That is:

- (a) a cospan  $A \rightarrow X \leftarrow B$  exists, and
- (b) every pair of cospans on  $A, B$  is connected by a zig-zag of cospans.

This characterization was later re-discovered by C. Lair [9].

(ii) P. Gabriel and F. Ulmer [6] also proved that a small category  $\mathcal{D}$  is sifted if and only if  $\mathcal{D}$  is final in its free completion  $\text{Fam } \mathcal{D}$  under finite coproducts. In fact, (a) and (b) above clearly imply the same property for finite families of objects too. This is precisely the finality of  $\mathcal{D} \rightarrow \text{Fam } \mathcal{D}$ .

(iii) Every small category with finite coproducts is sifted. This immediately follows from (i).

1.2. EXAMPLE. ([2]) Reflexive coequalizers are sifted colimits. That is, the category  $\mathcal{D}$  given by the graph

$$\begin{array}{ccc}
 & \xrightarrow{a_1} & \\
 P & \xleftarrow{d} & Q \\
 & \xrightarrow{a_2} & 
 \end{array}$$

and the equations

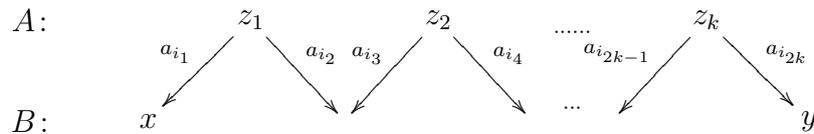
$$a_1 \cdot d = \text{id}_B = a_2 \cdot d$$

is sifted. This follows from the characterization of sifted colimits mentioned in the Introduction. We present a full proof here because we are going to use it again below. Let us add that this fact was already realized by Y. Diers [5] but remained unnoticed. Another proof is given in [12], Lemma 1.2.3.

In fact, suppose that

$$A \begin{array}{c} \xrightarrow{a_1} \\ \xrightarrow{a_2} \end{array} B \xrightarrow{c} C \quad \text{and} \quad A' \begin{array}{c} \xrightarrow{a'_1} \\ \xrightarrow{a'_2} \end{array} B' \xrightarrow{c'} C'$$

are reflexive coequalizers in *Set*. We can assume, without loss of generality, that  $c$  is the canonical function of the quotient  $C = B / \sim$  modulo the equivalence relation described as follows: two elements  $x, y \in B$  are equivalent iff there exists a zig-zag



where  $i_1, i_2, \dots, i_{2k}$  are 1 or 2. For reflexive pairs  $a_1, a_2$  these zig-zags can always be chosen to have the following form

$$\begin{array}{c}
 A: \\
 B:
 \end{array}
 \begin{array}{c}
 z_1 \qquad z_2 \qquad \dots \qquad z_{2k} \\
 \begin{array}{c}
 \swarrow a_1 \quad \searrow a_2 \\
 \swarrow a_2 \quad \searrow a_1 \\
 \dots \\
 \swarrow a_2 \quad \searrow a_1
 \end{array}
 \end{array}
 \qquad (*)$$

where for the elements  $z_{2i}$  of  $A$  we use  $a_1, a_2$  and for the elements  $z_{2i+1}$  we use  $a_2, a_1$ . In fact, let  $d: B \rightarrow A$  be a joint splitting of  $a_1, a_2$ . Thus given a zig-zag, say,

$$\begin{array}{c}
 z \\
 \swarrow a_2 \quad \searrow a_1 \\
 x \qquad y
 \end{array}$$

we can modify it as follows: put  $z_1 = d(x)$  and  $z_2 = z$  to get

$$\begin{array}{c}
 z_1 \qquad z_2 \\
 \swarrow a_1 \quad \searrow a_2 \quad \swarrow a_2 \quad \searrow a_1 \\
 x \qquad x \qquad y
 \end{array}$$

Moreover, the length  $2k$  of the zig-zag  $(*)$  can be prolonged to  $2k + 2$  or  $2k + 4$  etc. by using  $d$ . Analogously, we can assume  $C' = B'/ \sim'$  where  $\sim'$  is the equivalence relation given by zig-zags of  $a'_1$  and  $a'_2$  of the above form  $(*)$ . Now we form the parallel pair

$$A \times A' \begin{array}{c} \xrightarrow{a_1 \times a'_1} \\ \xrightarrow{a_2 \times a'_2} \end{array} B \times B'$$

and obtain its coequalizer by the zig-zag equivalence  $\approx$  on  $B \times B'$ . Given  $(x, x') \approx (y, y')$  in  $B \times B'$ , we obviously have zig-zags both for  $x \sim y$  and for  $x' \sim' y'$  (use projections of the given zig-zag). But also the other way round: whenever  $x \sim y$  and  $x' \sim' y'$ , then we choose the two zig-zags so that they both have the above type  $(*)$  and have the same lengths. They create an obvious zig-zag for  $(x, x') \approx (y, y')$ . From this it follows that the map

$$A \times A' \begin{array}{c} \xrightarrow{a_1 \times a'_1} \\ \xrightarrow{a_2 \times a'_2} \end{array} B \times B' \xrightarrow{c \times c'} (B / \sim) \times (B' / \sim')$$

is a coequalizer, as required.

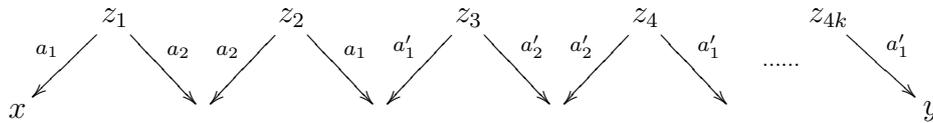
1.3. EXAMPLE. By merging two copies of reflexive pairs we also obtain a sifted category  $\mathcal{D}$ : let  $\mathcal{D}$  be given by the graph

$$\begin{array}{c}
 \begin{array}{ccc}
 A & \begin{array}{c} \xrightarrow{a_1} \\ \xleftarrow{d} \\ \xrightarrow{a_2} \end{array} & B \\
 & & \begin{array}{c} \xleftarrow{a'_1} \\ \xrightarrow{d'} \\ \xleftarrow{a'_2} \end{array} & A'
 \end{array}
 \end{array}$$

and the equations making both parallel pairs reflexive:

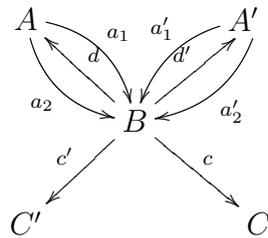
$$a_i \cdot d = \text{id}_B = a'_i \cdot d' \quad \text{for } i = 1, 2$$

The proof that  $\mathcal{D}$  is sifted is completely analogous to the proof of Example 1.2: we verify that colimits over  $\mathcal{D}$  in *Set* commute with finite products. Assume that the above graph depicts sets  $A, B$  and  $A'$  and functions between them. Then a colimit can be described as the canonical function  $c: B \rightarrow C = B/\sim$  where two elements  $x, y \in B$  are equivalent iff they are connected by a zig-zag formed by  $a_1, a_2, a'_1$  and  $a'_2$ . Since the two pairs are reflexive, the length of the zig-zag can be arbitrarily prolonged. And the type can be chosen to be



From that it is easy to derive that  $\mathcal{D}$  is sifted.

1.4. EXAMPLE. A category  $\mathcal{A}$  which does not have sifted colimits although it has both filtered colimits and reflexive coequalizers:  $\mathcal{A}$  is the free completion of  $\mathcal{D}$  from 1.3 under filtered colimits and reflexive coequalizers. We claim that  $\mathcal{A}$  is obtained from  $\mathcal{D}$  by simply adding the coequalizer  $c$  of  $a_1, a_2$  and the coequalizer  $c'$  of  $a'_1, a'_2$ . That is, we consider the graph



and the equations

$$c \cdot a_1 = c \cdot a_2 \quad c' \cdot a'_1 = c' \cdot a'_2.$$

In fact, the category  $\mathcal{A}$  is clearly finite. Therefore, its only filtered diagrams are its idempotents:

$$e_i = d \cdot a_i \quad \text{and} \quad e'_i = d' \cdot a'_i \quad (i = 1, 2).$$

We claim that  $a_1$  is the colimit of  $e_1$ . In fact,  $a_1 \cdot e_1 = a_1$ , and given a morphism  $f$  with

$$f \cdot e_1 = f,$$

then we see that  $f \cdot d \cdot a_1 = f$ , consequently,  $f$  factorizes through  $a_1$ . Since  $a_1$  is an epimorphism, this factorization is unique. Analogously for  $e_2, e'_1$  and  $e'_2$ . Thus,  $\mathcal{A}$  has filtered colimits. And it has reflexive coequalizers because its only reflexive pairs of distinct morphisms are  $a_1, a_2$  whose coequalizer is  $c$ , and  $a'_1, a'_2$  whose coequalizer is  $c'$ . It is obvious that the (sifted) embedding  $D: \mathcal{D} \rightarrow \mathcal{A}$  does not have a colimit.

## 2. Preservation of Sifted Colimits

2.1. THEOREM. *A functor  $F: \mathcal{A} \rightarrow \mathcal{B}$  with  $\mathcal{A}$  finitely cocomplete preserves sifted colimits iff it preserves filtered colimits and reflexive coequalizers.*

PROOF. Given a sifted diagram  $D: \mathcal{D} \rightarrow \mathcal{A}$  with a colimit in  $\mathcal{A}$ , we prove that  $F \cdot D$  has colimit  $F(\text{colim } D)$  in  $\mathcal{D}$ .

Recall from 1.1(ii) that  $D: \mathcal{D} \rightarrow \text{Fam}\mathcal{D}$  is final, thus,  $D$  has the same colimit as its extension  $\bar{D}: \text{Fam}\mathcal{D} \rightarrow \mathcal{A}$  preserving finite coproducts. Therefore, without loss of generality we can assume that  $\mathcal{D}$  has finite coproducts and  $D$  preserves them (if not, substitute  $\bar{D}$  for  $D$ ). Recall also the construction of finite colimits via finite coproducts and coequalizers from [11]: given a finite graph  $M$  and a functor  $F: M \rightarrow \mathcal{A}$  we form coproducts

$$\coprod_i F(i)$$

indexed by objects  $i$  of  $M$  and with injections.

$$\alpha_i: F(i) \rightarrow \coprod_i F(i).$$

Analogously, we form coproducts

$$\coprod_{f:i \rightarrow i'} F(i)$$

indexed by morphisms  $f$  of  $M$  and with injections

$$\beta_f: F(i) \rightarrow \coprod_{f:i \rightarrow i'} F(i).$$

Consider morphisms

$$a, b: \coprod_{f:i \rightarrow i'} F(i) \rightarrow \coprod_i F(i)$$

such that  $a \cdot \beta_f = \alpha_i$  and  $b \cdot \beta_f = \alpha_{i'} \cdot Ff$  for each morphism  $f: i \rightarrow i'$  in  $M$ . If  $q: \coprod_i F(i) \rightarrow Q$  is the coequalizer of  $a$  and  $b$ , then  $Q = \text{colim } F$  with the colimit cocone  $q \cdot \alpha_i$ .

We now prove the theorem:

(1) For every finite reflexive subgraph  $M$  of  $\mathcal{D}$  we form coproducts in  $\mathcal{D}$

$$i_M = \coprod_i i \quad j_M = \coprod_{f:i \rightarrow i'} i$$

and morphisms

$$a_M, b_M: j_M \rightarrow i_M$$

analogous to those considered above. Since  $D$  preserves the two coproducts, we have  $a = Da_M$  and  $b = Db_M$  and the colimit  $Q_M$  of the domain restriction  $D/M$  of  $D$  on  $M$  is given by the coequalizer

$$Dj_M \begin{array}{c} \xrightarrow{Da_M} \\ \xrightarrow{Db_M} \end{array} Di_M \xrightarrow{q_M} Q_M = \text{colim } D/M$$

Since the graph  $M$  is reflexive,  $a_M, b_M$  is a reflexive pair, thus, so is  $Da_M, Db_M$ . Let  $\mathcal{M}$  be the directed family of all finite reflexive subgraphs of  $\mathcal{D}$ .

(2) Let  $k_i: Di \rightarrow K$  ( $i \in \text{obj } \mathcal{D}$ ) be a colimit of  $D$ , then we prove that  $(Fk_i)$  is a colimit of  $FD$ . We express  $D$  as the directed union of all  $D/M$  for  $M \in \mathcal{M}$  and for each  $M \in \mathcal{M}$  we see that

$$k_{i_M} \cdot Da_M = k_{j_M} = k_{i_M} \cdot Db_M \tag{1}$$

from which we derive that  $k_{i_M}$  factors through the coequalizer

$$k_{i_M} = r_M \cdot q_M \quad \text{for some } r_M: Q_M \rightarrow K. \tag{2}$$

Then  $K$  is the filtered colimit of all  $Q_M$  with the colimit cocone  $(r_M)_{M \in \mathcal{M}}$  (since every colimit is a filtered colimits of all finite subcolimits). We conclude that

(i)  $FK$  is a colimit of  $FQ_M$  with the cocone  $Fr_M$  ( $M \in \mathcal{M}$ ),

and

(ii) for every  $M \in \mathcal{M}$  the coequalizer of  $FDa_M$  and  $FDb_M$  is  $Fq_M$ .

(3) Given a cocone

$$x_i: FD_i \rightarrow X \quad (i \in \text{obj } \mathcal{D})$$

of  $FD$ , we are to find a factorization through  $(Fk_i)$ . Analogously to (1) above we have, for every  $M \in \mathcal{M}$

$$x_{i_M} \cdot FDa_M = x_{j_M} = x_{i_M} \cdot FDb_M$$

thus, there exists a unique

$$y_M: FQ_M \rightarrow C \quad \text{with} \quad x_{i_M} = y_M \cdot Fq_M. \tag{3}$$

These morphisms form a cocone of the filtered diagram of all  $FQ_M$ 's: in fact, the connecting morphisms

$$q_{M,M'}: Q_M \rightarrow Q_{M'} \quad (M, M' \in \mathcal{M}, M \subseteq M')$$

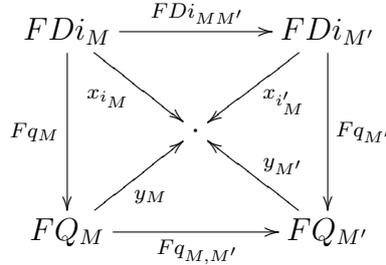
are defined by the commutative squares

$$\begin{array}{ccc} Di_M & \xrightarrow{Di_{MM'}} & Di_{M'} \\ q_M \downarrow & & \downarrow q_{M'} \\ Q_M & \xrightarrow{q_{M,M'}} & Q_{M'} \end{array}$$

where  $i_{MM'}: i_M \rightarrow i_{M'}$  is the coproduct injection in  $\mathcal{D}$ . The desired equality

$$y_M = y_{M'} \cdot Fq_{MM'}$$

easily follows since, by (ii),  $Fq_M$  is an epimorphism:



Consequently, we obtain the unique

$$y: FK \rightarrow X \quad \text{with} \quad y \cdot Fr_M = y_M.$$

This is the desired factorization: for every  $i \in I$  we have

$$y \cdot Fk_i = x_i.$$

In fact, consider the singleton subgraph  $M$  with one object  $i$  and its identity morphism. Obviously

$$i_M = i \quad \text{and} \quad q_M = \text{id}, \quad \text{thus,} \quad r_M = k_i$$

which yields by (3)

$$y_M \cdot Fk_i = y_M = y_M \cdot Fq_M = x_{i_M} = x_i.$$

The uniqueness is clear: since each  $Fq_M$  is an epimorphism, from (2) we see that  $(Fr_M \cdot Fq_M)$  is collectively epic, and then (1) implies that  $(Fk_i)$  is collectively epic. ■

2.2. EXAMPLE. A functor  $F$  which

- (1) does not preserve sifted colimits

but

- (2) preserves filtered colimits and reflexive coequalizers

can be constructed as follows.

By adding to the category  $\mathcal{A}$  of 1.4 a terminal object  $T$  we obtain a category  $\mathcal{A}'$  in which the sifted diagram  $D: \mathcal{D} \rightarrow \mathcal{A}$  has colimit

$$\text{colim } D = T.$$

Let  $\mathcal{B}$  be the category obtained from  $\mathcal{A}'$  by adding a new terminal object  $S$ . The functor  $F: \mathcal{A}' \rightarrow \mathcal{B}$  with  $F(T) = S$  which is the identity map on objects and morphisms of  $\mathcal{A}$  does not preserve sifted colimits because  $\text{colim } F \cdot D = T$  but  $F(\text{colim } D) = S$ . It is easy to verify that  $F$  preserves filtered colimits and reflexive coequalizers.

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