

Introduction to Categorical Logic

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Contents

1	Algebraic Theories	5
1.1	Syntax and semantics	5
1.1.1	Models of algebraic theories	8
1.1.2	Theories as categories	12
1.1.3	Models as functors	14
1.1.4	Soundness and completeness	19
1.1.5	Functorial semantics	22
1.2	Lawvere duality	24
1.2.1	Logical duality	24
1.2.2	Lawvere algebraic theories	32
1.2.3	Algebraic categories	35
1.2.4	Algebraic functors	40
1.2.5	Dualities for algebraic theories	46
1.2.6	Definability*	47
	Bibliography	49

Chapter 1

Algebraic Theories

Algebraic theories are descriptions of structures that are given entirely in terms of operations and equations. All such algebraic notions have in common some quite deep and general properties, from the existence of free algebras to Lawvere’s duality theory. The most basic of these are presented in this chapter. The development also serves as a first example and template for the general scheme of *functorial semantics*, to be applied to other logical notions in later chapters.

1.1 Syntax and semantics

We begin with a general approach to algebraic structures such as groups, rings, and lattices. These are characterized by axiomatizations which involve only a single sort of variables and constants, operations, and equations. It is important that the operations are defined everywhere, which excludes two important examples: fields, because the inverse of 0 is undefined, and categories because composition is defined only for certain pairs of morphisms.

Let us start with the quintessential algebraic theory: the theory of groups. In first-order logic, a group can be described as a set G with a binary operation $\cdot : G \times G \rightarrow G$, satisfying the two first-order axioms:

$$\begin{aligned} &\forall x, y, z \in G. (x \cdot y) \cdot z = x \cdot (y \cdot z) \\ &\exists e \in G. \forall x \in G. \exists y \in G. (e \cdot x = x \cdot e = x \wedge x \cdot y = y \cdot x = e) \end{aligned}$$

Taking a closer look at the logical form of these axioms, we see that the second one, which expresses the existence of a unit and inverse elements, is somewhat unsatisfactory because it involves nested quantifiers. Not only does this complicate the interpretation, but it is not really necessary, since the unit element and inverse operation in a group are uniquely determined. Thus we can add them to the structure and reformulate as follows. The unit is to be represented by a distinguished *constant* $e \in G$, and the inverse is to be a unary *operation* $^{-1} : G \rightarrow G$. We then obtain an equivalent formulation in which all axioms can

be expressed as (universally quantified) *equations*:

$$\begin{aligned} x \cdot (y \cdot z) &= (x \cdot y) \cdot z \\ x \cdot e &= x & e \cdot x &= x \\ x \cdot x^{-1} &= e & x^{-1} \cdot x &= e \end{aligned}$$

The universal quantifiers $\forall x \in G, \forall y \in G$, etc. are no longer needed in stating the axioms, since we can interpret all variables as ranging over all elements of G (because of our restriction to totally defined operations). Nor do we really need to explicitly mention the particular set G in the specification. Finally, since the constant e can be regarded as a nullary operation, i.e., a function $e : 1 \rightarrow G$, the specification of the group concept consists solely of operations and equations. This leads to the following general definition of an algebraic theory.

Definition 1.1.1. A *signature* Σ for an algebraic theory consists of a family of sets $\{\Sigma_k\}_{k \in \mathbb{N}}$. The elements of Σ_k are called the *k-ary operations*. In particular, the elements of Σ_0 are the *nullary operations* or *constants*.

The *terms* of a signature Σ are the expressions constructed inductively by the following rules:

1. variables x, y, z, \dots , are terms,
2. if t_1, \dots, t_k are terms and $f \in \Sigma_k$ is a *k-ary operation* then $f(t_1, \dots, t_k)$ is a term.

Definition 1.1.2 (cf. Definition 1.2.10). An *algebraic theory* $\mathbb{T} = (\Sigma_{\mathbb{T}}, A_{\mathbb{T}})$ is given by a signature $\Sigma_{\mathbb{T}}$ and a set $A_{\mathbb{T}}$ of *axioms*, which are equations between terms (formally, pairs of terms).

Algebraic theories are also called *equational theories*. We do not assume that the sets Σ_k or $A_{\mathbb{T}}$ are finite, but the individual terms and equations always involve only finitely many variables.

Example 1.1.3. The theory of a commutative ring with unit is an algebraic theory. There are two nullary operations (constants) 0 and 1, a unary operation $-$, and two binary operations $+$ and \cdot . The equations are:

$$\begin{aligned} (x + y) + z &= x + (y + z) & (x \cdot y) \cdot z &= x \cdot (y \cdot z) \\ x + 0 &= x & x \cdot 1 &= x \\ 0 + x &= x & 1 \cdot x &= x \\ x + (-x) &= 0 & (x + y) \cdot z &= x \cdot z + y \cdot z \\ (-x) + x &= 0 & z \cdot (x + y) &= z \cdot x + z \cdot y \\ x + y &= y + x & x \cdot y &= y \cdot x \end{aligned}$$

Example 1.1.4. The “empty” or trivial theory \mathbb{T}_0 with no operations and no equations is the theory of a set.

Example 1.1.5. The theory with one constant and no equations is the theory of a *pointed set*, cf. Example ??.

Example 1.1.6. Let R be a ring. There is an algebraic theory of left R -modules. It has one constant 0 , a unary operation $-$, a binary operation $+$, and for each $a \in R$ a unary operation \bar{a} , called *scalar multiplication by a* . The following equations hold:

$$\begin{aligned} (x + y) + z &= x + (y + z) , & x + y &= y + x , \\ x + 0 &= x , & 0 + x &= x , \\ x + (-x) &= 0 , & (-x) + x &= 0 . \end{aligned}$$

For every $a, b \in R$ we also have the equations

$$\bar{a}(x + y) = \bar{a}x + \bar{a}y , \quad \bar{a}(\bar{b}x) = \overline{(ab)}x , \quad \overline{(a + b)}x = \bar{a}x + \bar{b}x .$$

Scalar multiplication by a is usually written as $a \cdot x$ instead of $\bar{a}x$. If we replace the ring R by a field \mathbb{F} we obtain the algebraic theory of a vector space over \mathbb{F} (even though the theory of fields is not algebraic!).

Example 1.1.7. In computer science, inductive datatypes are examples of algebraic theories. For example, the datatype of binary trees with leaves labeled by integers might be defined as follows in a programming language:

```
type tree = Leaf of int | Node of tree * tree
```

This corresponds to the algebraic theory with a constant `Leaf n` for each integer n and a binary operation `Node`. There are no equations. Actually, when computer scientists define a datatype like this, they have in mind a particular model of the theory, namely the *free* one.

Example 1.1.8. An obvious non-example is the theory of posets, formulated with a binary relation symbol $x \leq y$ and the usual axioms of reflexivity, transitivity and anti-symmetry, namely:

$$\begin{aligned} x &\leq x \\ x \leq y , y \leq z &\Rightarrow x \leq z \\ x \leq y , y \leq x &\Rightarrow x = y \end{aligned}$$

On the other hand, using an operation of greatest lower bound or “meet” $x \wedge y$, one can make the equational theory of “ \wedge -semilattices”:

$$\begin{aligned} x \wedge x &= x \\ x \wedge y &= y \wedge x \\ x \wedge (y \wedge z) &= (x \wedge y) \wedge z \end{aligned}$$

Then, defining a partial ordering by $x \leq y \Leftrightarrow x = (x \wedge y)$ we arrive at the notion of a “poset with meets”, which *is* equational (of course, the same can be done with joins $x \vee y$ as well). We will show later (in section ??) that there is no reformulation of the general theory of posets into an equivalent equational one by considering the *category of models* of the theory, *i.e.* the category of posets, and showing that it lacks a general property enjoyed by all categories of algebras.

Exercise 1.1.9. Let G be a group. Formulate the notion of a (left) G -set (*i.e.* a functor $G \rightarrow \mathbf{Set}$) as an algebraic theory.

1.1.1 Models of algebraic theories

Let us now consider *models* of an algebraic theory, *i.e.* *algebras*. Classically, a group can be given by a set G , an element $e \in G$, a function $m : G \times G \rightarrow G$ and a function $i : G \rightarrow G$, satisfying the group axioms:

$$\begin{aligned} m(x, m(y, z)) &= m(m(x, y), z) \\ m(x, ix) &= m(ix, x) = e \\ m(x, e) &= m(e, x) = x \end{aligned}$$

for any $x, y, z \in G$. Observe, however, that this notion can easily be generalized so that we can speak of models of group theory in categories other than \mathbf{Set} . This is accomplished simply by translating the equations between arbitrary elements into equations between the operations themselves: thus a group is given, first, by an object $G \in \mathbf{Set}$ and three morphisms

$$e : 1 \rightarrow G, \quad m : G \times G \rightarrow G, \quad i : G \rightarrow G.$$

The associativity axiom is then expressed by the commutativity of the following diagram:

$$\begin{array}{ccc} G \times G \times G & \xrightarrow{m \times \pi_2} & G \times G \\ \pi_0 \times m \downarrow & & \downarrow m \\ G \times G & \xrightarrow{m} & G \end{array} \quad (1.1)$$

Note that we have omitted the canonical associativity function $G \times (G \times G) \cong (G \times G) \times G$, which should be inserted into the top left corner of the diagram. The equations for the

unit and the inverse are similarly expressed by commutativity of the following diagrams:

$$\begin{array}{ccc}
 G \times 1 & \xrightarrow{1_G \times e} & G \times G \xleftarrow{e \times 1_G} 1 \times G \\
 \searrow \pi_0 & & \downarrow m \swarrow \pi_1 \\
 & G &
 \end{array}
 \qquad
 \begin{array}{ccccc}
 G & \xrightarrow{\langle 1_G, i \rangle} & G \times G & \xleftarrow{\langle i, 1_G \rangle} & G \\
 \downarrow !_G & & \downarrow m & & \downarrow !_G \\
 1 & \xrightarrow{e} & G & \xleftarrow{e} & 1
 \end{array}
 \quad (1.2)$$

This formulation makes sense in any category \mathcal{C} with finite products.

Definition 1.1.10. Let \mathcal{C} be a category with finite products. A *group in \mathcal{C}* consists of an object G equipped with arrows:

$$\begin{array}{ccc}
 G \times G & \xrightarrow{m} & G \xleftarrow{i} G \\
 & \uparrow e & \\
 & 1 &
 \end{array}$$

such that the above diagrams (1.1) and (1.2) expressing the group equations commute.

There is also an obvious corresponding generalization of a group homomorphism in **Set** to homomorphisms of groups in \mathcal{C} . Namely, an arrow in \mathcal{C} between (the underlying objects of) groups, say $h : M \rightarrow N$, is a homomorphism if it commutes with the interpretations of the basic operations m , i , and e ,

$$h \circ m^M = m^N \circ h^2 \qquad h \circ i^M = i^N \circ h \qquad h \circ e^M = e^N$$

as indicated in:

$$\begin{array}{ccc}
 M^2 & \xrightarrow{h^2} & N^2 \\
 m^M \downarrow & & \downarrow m^N \\
 M & \xrightarrow{h} & N
 \end{array}
 \qquad
 \begin{array}{ccc}
 M & \xrightarrow{h} & N \\
 i^M \downarrow & & \downarrow i^N \\
 M & \xrightarrow{h} & N
 \end{array}
 \qquad
 \begin{array}{ccc}
 1 & \xrightarrow{=} & 1 \\
 e^M \downarrow & & \downarrow e^N \\
 M & \xrightarrow{h} & N
 \end{array}$$

Together with the evident composition and identity arrows inherited from \mathcal{C} , this gives a category of groups in \mathcal{C} , which we denote:

$$\mathbf{Group}(\mathcal{C})$$

In general, we define an *interpretation* I of a theory \mathbb{T} in a category \mathcal{C} with finite products to consist of an object $I \in \mathcal{C}$ and, for each basic operation f of arity k , a morphism $f^I : I^k \rightarrow I$. (More formally, I is the tuple consisting of an underlying object $|I|$ and the interpretations f^I , but we shall write simply I for $|I|$.) In particular, basic constants are interpreted as morphisms $1 \rightarrow I$. The interpretation is then extended to all

terms as follows: a general term t will be interpreted together with a *context of variables* x_1, \dots, x_n (a list without repetitions), where the variables appearing in t are among those appearing in the context. We write

$$x_1, \dots, x_n \mid t \quad (1.3)$$

for a term t in context x_1, \dots, x_n . The interpretation of such a term in context (1.3) is a morphism $t^I : I^n \rightarrow I$, determined by the following specification:

1. The interpretation of a variable x_i among the x_1, \dots, x_n is the i -th projection $\pi_i : I^n \rightarrow I$.
2. A term of the form $f(t_1, \dots, t_k)$ is interpreted as the composite:

$$I^n \xrightarrow{(t_1^I, \dots, t_k^I)} I^k \xrightarrow{f^I} I$$

where $t_i^I : I^n \rightarrow I$ is the interpretation of the subterm t_i , for $i = 1, \dots, k$, and f^I is the interpretation of the basic operation f .

It is clear that the interpretation of a term really depends on the context, and when necessary we shall write $t^I = [x_1, \dots, x_n \mid t]^I$. For example, the term $f x_1$ is interpreted as a morphism $f^I : I \rightarrow I$ in context x_1 , and as the morphism $f^I \circ \pi_1 : I^2 \rightarrow I$ in the context x_1, x_2 .

Suppose u and v are terms in context x_1, \dots, x_n . Then we say that the equation in context $x_1, \dots, x_n \mid u = v$ is *satisfied* by the interpretation I if u^I and v^I are the same morphism in \mathcal{C} . In particular, if $u = v$ is an axiom of the theory, and x_1, \dots, x_n are all the variables appearing in either u or v , we say that I *satisfies the axiom* $u = v$, written

$$I \models u = v,$$

if $[x_1, \dots, x_n \mid u]^I$ and $[x_1, \dots, x_n \mid v]^I$ are the same morphism,

$$I^n \xrightarrow{\begin{array}{c} [x_1, \dots, x_n \mid u]^I \\ [x_1, \dots, x_n \mid v]^I \end{array}} I. \quad (1.4)$$

We can then define, as expected:

Definition 1.1.11 (cf. Definition 1.2.10). A *model* M of an algebraic theory \mathbb{T} in a category \mathcal{C} with finite products (also called a \mathbb{T} -*algebra*) is an interpretation of the signature $\Sigma_{\mathbb{T}}$,

$$f^I : I^k \longrightarrow I \quad \text{in } \mathcal{C},$$

for all $f \in \Sigma_{\mathbb{T}}$, that satisfies the axioms $A_{\mathbb{T}}$,

$$I \models u = v,$$

for all $(u = v) \in A_{\mathbb{T}}$.

A *homomorphism* of models $h : M \rightarrow N$ is an arrow in \mathcal{C} that commutes with the interpretations of the basic operations,

$$h \circ f^M = f^N \circ h^k$$

for all $f \in \Sigma_{\mathbb{T}}$, as indicated in:

$$\begin{array}{ccc} M^k & \xrightarrow{h^k} & N^k \\ f^M \downarrow & & \downarrow f^N \\ M & \xrightarrow{h} & N \end{array}$$

The category of \mathbb{T} -models in \mathcal{C} is written,

$$\mathbf{Mod}(\mathbb{T}, \mathcal{C}).$$

A model of the trivial theory \mathbb{T}_0 in \mathcal{C} is therefore just an object A in \mathcal{C} , and a homomorphism is just a map, so

$$\mathbf{Mod}(\mathbb{T}_0, \mathcal{C}) = \mathcal{C}.$$

A model of the theory $\mathbb{T}_{\text{Group}}$ of groups in \mathcal{C} is a group in \mathcal{C} , in the above sense, and similarly for homomorphisms, so:

$$\mathbf{Mod}(\mathbb{T}_{\text{Group}}, \mathcal{C}) = \mathbf{Group}(\mathcal{C})$$

as defined above. In particular, a model in \mathbf{Set} is just a group in the usual sense, so we have:

$$\mathbf{Mod}(\mathbb{T}_{\text{Group}}, \mathbf{Set}) = \mathbf{Group}(\mathbf{Set}) = \mathbf{Group}.$$

An example of a new kind is provided by the following.

Example 1.1.12. A model of the theory of groups in a functor category $\mathbf{Set}^{\mathbb{C}}$ is the same thing as a functor from \mathbb{C} into the category groups,

$$\mathbf{Group}(\mathbf{Set}^{\mathbb{C}}) = \mathbf{Group}(\mathbf{Set})^{\mathbb{C}} \cong \mathbf{Group}^{\mathbb{C}}.$$

Indeed, for each object $C \in \mathbb{C}$ there is an evaluation functor,

$$\mathbf{eval}_C : \mathbf{Set}^{\mathbb{C}} \rightarrow \mathbf{Set}$$

with $\mathbf{eval}_C(F) = F(C)$, and evaluation preserves products since these are computed point-wise in the functor category. Moreover, every arrow $h : C \rightarrow D$ in \mathbb{C} gives rise to an obvious natural transformation $h : \mathbf{eval}_C \rightarrow \mathbf{eval}_D$. Thus for any group G in $\mathbf{Set}^{\mathbb{C}}$, we have groups $\mathbf{eval}_C(G) = G(C)$ for each $C \in \mathbb{C}$ and group homomorphisms $h_G : G(C) \rightarrow G(D)$ for each $h : C \rightarrow D$, comprising a functor $G : \mathbb{C} \rightarrow \mathbf{Group}$. Conversely, it is clear that a functor $H : \mathbb{C} \rightarrow \mathbf{Group}$ determines a group H in $\mathbf{Set}^{\mathbb{C}}$ with underlying object $U \circ H$, where $U : \mathbf{Group} \rightarrow \mathbf{Set}$ is the forgetful functor, so that for each $C \in \mathbb{C}$ we have a group HC with underlying set $UHC = |HC|$. These constructions are clearly mutually inverse (up to canonical isomorphisms determined by the choice of products). Thus, briefly, *a group in the category of variable sets may be regarded as a variable group*.

Exercise 1.1.13. Verify the details of the isomorphism of categories

$$\mathbf{Mod}(\mathbb{T}, \mathbf{Set}^{\mathbb{C}}) \cong \mathbf{Mod}(\mathbb{T}, \mathbf{Set})^{\mathbb{C}},$$

as example 1.1.12, for an arbitrary algebraic theory \mathbb{T} .

Exercise 1.1.14. Determine what a group is in the following categories: the category of graphs **Graph**, the category of topological spaces **Top**, and the category of groups **Group**. (Hint: Only the last case is tricky. Before thinking too hard about it, prove the following lemma [Bor94, Lemma 3.11.6], known as the Eckmann-Hilton argument. Let G be a set provided with two binary operations \cdot and \star and a common unit e , so that $x \cdot e = e \cdot x = x \star e = e \star x = x$. Suppose the two operations commute, i.e., $(x \star y) \cdot (z \star w) = (x \cdot z) \star (y \cdot w)$. Then they coincide, and are *commutative* and associative.)

1.1.2 Theories as categories

The syntactically presented notion of an algebraic theory is a practical convenience, but as a specification of a mathematical concept, say that of a group, it has some defects. We would prefer a *presentation-free* notion that captures the group concept without tying it to a specific syntactic presentation (the example below indicates why). One such notion can be given by a category with a certain universal property, which determines it uniquely, up to equivalence of categories.

Let us consider group theory again. The algebraic axiomatization in terms of unit, multiplication and inverse is not the only possible one. For example, an alternative formulation uses the unit e and a binary operation \odot , called *double division*, along with a single axiom [McC93]:

$$(x \odot (((x \odot y) \odot z) \odot (y \odot e))) \odot (e \odot e) = z.$$

The usual group operations are related to double division as follows:

$$x \odot y = x^{-1} \cdot y^{-1}, \quad x^{-1} = x \odot e, \quad x \cdot y = (x \odot e) \odot (y \odot e).$$

There may be practical reasons for preferring one formulation of group theory over another, but this should not determine what the general concept of a group is. For example, we would like to avoid particular choices of basic constants, operations, and axioms. This is akin to the situation where an algebra is presented by generators and relations: the algebra itself is regarded as independent of any particular such presentation. Similarly, one usually prefers a basis-free theory of vector spaces: it is better to formulate the general idea of a vector space without referring explicitly to a basis, even though every vector space has one.

As a first step, one could simply take *all* operations built from unit, multiplication, and inverse as basic, and *all* valid equations of group theory as axioms. But we can go a step further and collect all the operations into a category, thus forgetting about which ones were “basic”, and which equalities were “axioms”. We first describe this construction of a “syntactic category” $\mathbf{Syn}(\mathbb{T})$ for an algebraic theory \mathbb{T} , and then determine a universal characterization of it.

As objects of $\mathbf{Syn}(\mathbb{T})$ we take the *contexts*, i.e. sequences of distinct variables,

$$[x_1, \dots, x_n] . \quad (n \geq 0)$$

Actually, it will be more convenient to take equivalence classes under renaming of variables, so that $[x_1, x_3] = [x_2, x_1]$. That is to say, the objects are just natural numbers; but it will be useful to continue to write them as contexts.

A morphism from $[x_1, \dots, x_m]$ to $[x_1, \dots, x_n]$ is then an n -tuple (t_1, \dots, t_n) , where each t_k is a term in the context x_1, \dots, x_m , possibly after renaming the variables. Two such morphisms (t_1, \dots, t_n) and (s_1, \dots, s_n) are equal if, and only if, the axioms of the theory formally imply that $t_k = s_k$ for every $k = 1, \dots, n$,

$$\mathbb{T} \vdash t_k = s_k .$$

Here we are using the usual notion of equational deduction $\mathbb{T} \vdash$ (see Section ??). Strictly speaking, morphisms are thus *equivalence classes* of tuples of terms in context,

$$[x_1, \dots, x_m \mid t_1, \dots, t_n] : [x_1, \dots, x_m] \longrightarrow [x_1, \dots, x_n],$$

where two terms are equivalent when the theory proves them to be equal (after renaming the variables). Since it is rather cumbersome to work with such equivalence classes, we shall work with the terms directly, but keeping in mind that equality between them is this equivalence. Note also that the context of the morphism agrees with its domain, so we can omit it from the notation when that domain is clear. The composition of two morphisms

$$\begin{aligned} (t_1, \dots, t_m) &: [x_1, \dots, x_k] \longrightarrow [x_1, \dots, x_m] \\ (s_1, \dots, s_n) &: [x_1, \dots, x_m] \longrightarrow [x_1, \dots, x_n] \end{aligned}$$

is the morphism (r_1, \dots, r_n) whose i -th component is obtained by simultaneously substituting in s_i the terms t_1, \dots, t_m for the variables x_1, \dots, x_m :

$$r_i = s_i[t_1/x_1, \dots, t_m/x_m] \quad (1 \leq i \leq n)$$

The identity morphism on the object $[x_1, \dots, x_n]$ is the equivalence class of (x_1, \dots, x_n) .

Using the usual rules of deduction for equational logic (Section ??), it is easy to verify that these specifications are well-defined on equivalence classes, and therefore make $\mathbf{Syn}(\mathbb{T})$ a category.

Definition 1.1.15. The category $\mathbf{Syn}(\mathbb{T})$ just defined is called the *syntactic category* of the algebraic theory \mathbb{T} .

The syntactic category $\mathbf{Syn}(\mathbb{T})$ (which may be thought of as the “Lindenbaum-Tarski category” of \mathbb{T} , see ??) contains the same “algebraic” information as the theory \mathbb{T} from which it was built, but in a syntax-invariant way. Two different syntactic presentations of \mathbb{T} — like the ones for groups mentioned above — will give rise to essentially the same category $\mathbf{Syn}(\mathbb{T})$ (i.e. up to isomorphism). In this sense, the category $\mathbf{Syn}(\mathbb{T})$ is the abstract, algebraic object presented by the “generators and relations” (the operations and equations) of \mathbb{T} . But there is another, more important, sense in which $\mathbf{Syn}(\mathbb{T})$ represents \mathbb{T} , as we next show.

Exercise 1.1.16. Show that the syntactic category $\mathbf{Syn}(\mathbb{T})$ has all finite products.

1.1.3 Models as functors

Having represented an algebraic theory \mathbb{T} by the syntactic category $\mathbf{Syn}(\mathbb{T})$ constructed from it, we next show that $\mathbf{Syn}(\mathbb{T})$ has the universal property that models of \mathbb{T} correspond uniquely to certain functors from $\mathbf{Syn}(\mathbb{T})$. More precisely, given any category with finite products \mathcal{C} (which we shall call an *FP-category*), there is a natural (in \mathcal{C}) equivalence,

$$\frac{\mathcal{M} \in \mathbf{Mod}(\mathbb{T}, \mathcal{C})}{M : \mathbf{Syn}(\mathbb{T}) \rightarrow \mathcal{C}} \quad (1.5)$$

between models \mathcal{M} of \mathbb{T} in \mathcal{C} and finite product preserving functors (“*FP-functors*”) $M : \mathbf{Syn}(\mathbb{T}) \rightarrow \mathcal{C}$. The equivalence is mediated by a “universal model” \mathcal{U} in $\mathbf{Syn}(\mathbb{T})$, corresponding to the identity functor $1_{\mathbf{Syn}(\mathbb{T})} : \mathbf{Syn}(\mathbb{T}) \rightarrow \mathbf{Syn}(\mathbb{T})$ under the above displayed equivalence. By naturality, every model \mathcal{M} then arises as the functorial image $M(\mathcal{U}) \cong \mathcal{M}$ of \mathcal{U} under an essentially unique FP-functor $M : \mathbf{Syn}(\mathbb{T}) \rightarrow \mathcal{C}$.

To give the details of the correspondence (1.5), let \mathbb{T} be an arbitrary algebraic theory and $\mathbf{Syn}(\mathbb{T})$ the syntactic category constructed from \mathbb{T} as in Definition 1.1.15. It is easy to show that the product in $\mathbf{Syn}(\mathbb{T})$ of two objects $[x_1, \dots, x_n]$ and $[x_1, \dots, x_m]$ is the object $[x_1, \dots, x_{n+m}]$, and that $\mathbf{Syn}(\mathbb{T})$ has all finite products, including $\mathbf{1} = [-]$, the empty context (see Exercise 1.1.16). Moreover, there is a distinguished \mathbb{T} -model \mathcal{U} in $\mathbf{Syn}(\mathbb{T})$ essentially consisting of the signature $\Sigma_{\mathbb{T}}$ itself, which we call the *syntactic model*: the underlying object $U = |\mathcal{U}|$ is the context $[x_1]$ of length one, and each operation symbol f , of say arity k , is interpreted as “itself”, namely:

$$\begin{array}{ccc} U^k & \xrightarrow{f^{\mathcal{U}}} & U \\ \downarrow = & & \downarrow = \\ [x_1, \dots, x_k] & \xrightarrow{[f(x_1, \dots, x_k)]} & [x_1] \end{array} \quad (1.6)$$

The axioms are then satisfied, because the equivalence relation on terms is just \mathbb{T} -provable equality (see Section ??). Explicitly, for all terms s, t we have:

$$\mathcal{U} \models s = t \quad \Longleftrightarrow \quad \mathbb{T} \vdash s = t. \quad (1.7)$$

We record this fact as the following.

Proposition 1.1.17. *The syntactic model \mathcal{U} in $\mathbf{Syn}(\mathbb{T})$ is “logically generic” in the sense that it satisfies all and only the \mathbb{T} -provable equations, as in (1.7).*

Proof. For the proof, one shows that every term t is interpreted in \mathcal{U} by “itself”, i.e. by its own equivalence class under \mathbb{T} -provable equality,

$$(x_1, \dots, x_m \mid t)^{\mathcal{U}} = [x_1, \dots, x_m \mid t]$$

This is a simple induction on the construction of t , where the base case is given by (1.6). \square

Even more important than being logically generic, though, is the following *universal property* of the syntactic model \mathcal{U} in $\mathbf{Syn}(\mathbb{T})$.

Any model \mathcal{M} in any finite product category \mathcal{C} is the image of \mathcal{U} under an essentially unique, finite product preserving functor $\mathcal{M}^\sharp : \mathbf{Syn}(\mathbb{T}) \rightarrow \mathcal{C}$,

$$\mathcal{M}^\sharp(\mathcal{U}) \cong \mathcal{M}.$$

(See Definition 1.1.20 below for a more precise formulation.) In this sense, the syntactic category $\mathbf{Syn}(\mathbb{T})$ may be thought of as the “free finite product category with a model of \mathbb{T} ”. To show this formally, first observe that any FP-functor $F : \mathbf{Syn}(\mathbb{T}) \rightarrow \mathcal{C}$ takes the syntactic model \mathcal{U} in $\mathbf{Syn}(\mathbb{T})$ to a model $F\mathcal{U}$ in \mathcal{C} , with underlying interpretations

$$f^{F\mathcal{U}} = F f^{\mathcal{U}} : F U^k \rightarrow F U \quad \text{for each } f \in \Sigma_k.$$

Indeed, that is true for any FP-category \mathcal{S} in place of $\mathbf{Syn}(\mathbb{T})$ and any model in \mathcal{S} . Similarly, any natural transformation $\vartheta : F \rightarrow G$ between FP-functors determines a homomorphism of models $h = \vartheta_{\mathcal{U}} : F\mathcal{U} \rightarrow G\mathcal{U}$. In more detail, suppose $f : U \times U \rightarrow U$ is a basic operation, then there is a commutative diagram,

$$\begin{array}{ccc}
 FU \times FU & \xrightarrow{h \times h} & GU \times GU \\
 \downarrow \cong & & \downarrow \cong \\
 f^{FU} \left(F(U \times U) \right) & \xrightarrow{\vartheta_{U \times U}} & G(U \times U) \\
 \downarrow Ff & & \downarrow Gf \\
 FU & \xrightarrow{h = \vartheta_U} & GU
 \end{array}
 \begin{array}{l}
 \nearrow f^{FU} \\
 \searrow f^{GU}
 \end{array}$$

where the upper square commutes by preservation of products, and the lower one by naturality. Thus the operation “evaluation at \mathcal{U} ” always determines a functor,

$$\text{eval}_{\mathcal{U}} : \text{Hom}_{\text{FP}}(\mathbf{Syn}(\mathbb{T}), \mathcal{C}) \longrightarrow \text{Mod}(\mathbb{T}, \mathcal{C}) \quad (1.8)$$

from the category of finite product preserving functors $\mathbf{Syn}(\mathbb{T}) \rightarrow \mathcal{C}$, with natural transformations as arrows, into the category of \mathbb{T} -models in \mathcal{C} . Indeed, this much is also true for any model in any FP-category \mathcal{S} ; what is special about \mathcal{U} is the following.

Proposition 1.1.18. *The functor (1.8) is an equivalence of categories, natural in \mathcal{C} .*

Proof. Let \mathcal{M} be any model in an FP-category \mathcal{C} . Then the underlying interpretation of \mathcal{M} is an assignment $f \mapsto f^{\mathcal{M}}$ for $f \in \Sigma$, which determines a functor $\mathcal{M}^\# : \text{Syn}(\mathbb{T}) \rightarrow \mathcal{C}$, defined on objects by

$$\mathcal{M}^\#[x_1, \dots, x_k] = |\mathcal{M}|^k$$

and on morphisms by

$$\mathcal{M}^\#[t_1, \dots, t_n] = (t_1^{\mathcal{M}}, \dots, t_n^{\mathcal{M}}).$$

In more detail, $\mathcal{M}^\#$ is defined on a morphism

$$[x_1, \dots, x_k \mid t] : [x_1, \dots, x_k] \rightarrow [x_1, \dots, x_n]$$

in $\text{Syn}(\mathbb{T})$ by the following rules:

1. The morphism

$$[x_1, \dots, x_k \mid x_i] : [x_1, \dots, x_k] \rightarrow [x_1]$$

is mapped to the i -th projection

$$\pi_i : M^k \rightarrow M.$$

2. The morphism

$$[x_1, \dots, x_k \mid f(t_1, \dots, t_m)] : [x_1, \dots, x_k] \rightarrow [x_1]$$

is mapped to the composite

$$M^k \xrightarrow{(\mathcal{M}^\#t_1, \dots, \mathcal{M}^\#t_m)} M^m \xrightarrow{f^{\mathcal{M}}} M$$

where the $\mathcal{M}^\#t_i : M^k \rightarrow M$ are the values of $\mathcal{M}^\#$ on the morphisms $[t_i] : [x_1, \dots, x_k] \rightarrow [x_i]$, for $i = 1, \dots, m$, and $f^{\mathcal{M}}$ is the interpretation of the basic operation f .

3. The morphism

$$[t_1, \dots, t_n] : [x_1, \dots, x_k] \rightarrow [x_1, \dots, x_n]$$

is mapped to the morphism $(\mathcal{M}^\#t_1, \dots, \mathcal{M}^\#t_n)$ where the $\mathcal{M}^\#t_i$ are the values of $\mathcal{M}^\#$ on the morphisms $[t_i] : [x_1, \dots, x_k] \rightarrow [x_i]$, and

$$(\mathcal{M}^\#t_1, \dots, \mathcal{M}^\#t_n) : M^k \longrightarrow M^n$$

is the evident n -tuple in the FP-category \mathcal{C} .

That $\mathcal{M}^\# : \text{Syn}(\mathbb{T}) \rightarrow \mathcal{C}$ really is a functor follows from the assumption that the interpretation M is a model, meaning that all the equations of the theory are satisfied by it, so that these specifications are well-defined on equivalence classes. Here we use the *soundness* of equational deduction with respect to models in FP categories.

Note that the functor $\mathcal{M}^\#$ is defined in such a way that it obviously preserves finite products, and that there is an isomorphism of models,

$$\mathcal{M}^\#(\mathcal{U}) \cong \mathcal{M}.$$

Thus we have shown that the functor “evaluation at \mathcal{U} ”,

$$\text{eval}_{\mathcal{U}} : \text{Hom}_{\text{FP}}(\text{Syn}(\mathbb{T}), \mathcal{C}) \longrightarrow \text{Mod}(\mathbb{T}, \mathcal{C}) \quad (1.9)$$

is essentially surjective on objects, since $\text{eval}_{\mathcal{U}}(\mathcal{M}^{\sharp}) = \mathcal{M}^{\sharp}(\mathcal{U}) \cong \mathcal{M}$.

We leave the verification that it is full and faithful as an easy exercise.

Exercise 1.1.19. Verify this. (Hint: A homomorphism is entirely determined by what it does to the underlying object, and a natural transformation between FP functors is similarly determined by its component at $[x_1]$.)

Finally, naturality in \mathcal{C} means the following. Suppose \mathcal{M} is a model of \mathbb{T} in any FP-category \mathcal{C} . Any FP-functor $F : \mathcal{C} \rightarrow \mathcal{D}$ to another FP-category \mathcal{D} then takes \mathcal{M} to a model $F(\mathcal{M})$ in \mathcal{D} . Just as for the special case of \mathcal{U} , the interpretation is given by setting $f^{F(\mathcal{M})} = F(f^{\mathcal{M}})$ for the basic operations f (and composing with the canonical isos coming from preservation of products, $F(M) \times F(M) \cong F(M \times M)$, etc.). Since equations are described by commuting diagrams, F takes a model to a model, and the same is true for homomorphisms. Thus $F : \mathcal{C} \rightarrow \mathcal{D}$ induces a functor on \mathbb{T} -models,

$$\text{Mod}(\mathbb{T}, F) : \text{Mod}(\mathbb{T}, \mathcal{C}) \longrightarrow \text{Mod}(\mathbb{T}, \mathcal{D}).$$

By naturality of (1.8), we mean that the following square commutes up to natural isomorphism:

$$\begin{array}{ccc} \text{Hom}_{\text{FP}}(\text{Syn}(\mathbb{T}), \mathcal{C}) & \xrightarrow{\text{eval}_{\mathcal{U}}} & \text{Mod}(\mathbb{T}, \mathcal{C}) \\ \text{Hom}_{\text{FP}}(\text{Syn}(\mathbb{T}), F) \downarrow & & \downarrow \text{Mod}(\mathbb{T}, F) \\ \text{Hom}_{\text{FP}}(\text{Syn}(\mathbb{T}), \mathcal{D}) & \xrightarrow{\text{eval}_{\mathcal{U}}} & \text{Mod}(\mathbb{T}, \mathcal{D}) \end{array} \quad (1.10)$$

But this is clear, since for any FP-functor $M : \text{Syn}(\mathbb{T}) \rightarrow \mathcal{C}$ we have:

$$\begin{aligned} \text{eval}_{\mathcal{U}} \circ \text{Hom}_{\text{FP}}(\text{Syn}(\mathbb{T}), F)(M) &= (\text{Hom}_{\text{FP}}(\text{Syn}(\mathbb{T}), F)(M))(\mathcal{U}) \\ &= (F \circ M)(\mathcal{U}) \\ &= F(M(\mathcal{U})) \\ &= F(\text{eval}_{\mathcal{U}}(M)) \\ &\cong \text{Mod}(\mathbb{T}, F)(\text{eval}_{\mathcal{U}}(M)) \\ &= \text{Mod}(\mathbb{T}, F) \circ \text{eval}_{\mathcal{U}}(M). \end{aligned}$$

□

The equivalence of categories

$$\mathrm{Hom}_{\mathrm{FP}}(\mathrm{Syn}(\mathbb{T}), \mathcal{C}) \simeq \mathrm{Mod}(\mathbb{T}, \mathcal{C}) \quad (1.11)$$

actually determines $\mathrm{Syn}(\mathbb{T})$ and the universal model \mathcal{U} uniquely, up to equivalence of categories and isomorphism of models. Indeed, to recover \mathcal{U} , just put $\mathrm{Syn}(\mathbb{T})$ for \mathcal{C} and the identity functor $1_{\mathrm{Syn}(\mathbb{T})}$ on the left, to get \mathcal{U} in $\mathrm{Mod}(\mathbb{T}, \mathrm{Syn}(\mathbb{T}))$ on the right! To see that $\mathrm{Syn}(\mathbb{T})$ itself is also determined, observe that (1.11) says that the functor $\mathrm{Mod}(\mathbb{T}, \mathcal{C})$ is *representable*, with representing object $\mathrm{Syn}(\mathbb{T})$, in an appropriate (i.e. bicategorical) sense. As usual, this fact can also be formulated in elementary terms as a universal mapping property of $\mathrm{Syn}(\mathbb{T})$, as follows:

Definition 1.1.20. The *classifying category* of an algebraic theory \mathbb{T} is an FP-category $\mathcal{C}_{\mathbb{T}}$ with a distinguished model \mathcal{U} , called the *universal model*, such that:

- (i) for any model \mathcal{M} in any FP-category \mathcal{C} , there is an FP-functor

$$\mathcal{M}^{\sharp} : \mathcal{C}_{\mathbb{T}} \rightarrow \mathcal{C}$$

and an isomorphism of models $\mathcal{M} \cong \mathcal{M}^{\sharp}(\mathcal{U})$.

- (ii) for any FP-functors $F, G : \mathcal{C}_{\mathbb{T}} \rightarrow \mathcal{C}$ and model homomorphism $h : F(\mathcal{U}) \rightarrow G(\mathcal{U})$, there is a unique natural transformation $\vartheta : F \rightarrow G$ with

$$\vartheta_{\mathcal{U}} = h.$$

Observe that (i) says that the evaluation functor (1.8) is essentially surjective, and (ii) that it is full and faithful. The category $\mathcal{C}_{\mathbb{T}}$ is then determined, up to equivalence, by this universal mapping property. Specifically, if $(\mathcal{C}, \mathcal{U})$ and $(\mathcal{D}, \mathcal{V})$ are both classifying categories for the same theory, then there are classifying functors,

$$\begin{array}{ccc} & \mathcal{V}^{\sharp} & \\ \mathcal{C} & \xleftrightarrow{\quad} & \mathcal{D} \\ & \mathcal{U}^{\sharp} & \end{array}$$

the composites of which are necessarily isomorphic to the respective identity functors, since e.g. $\mathcal{U}^{\sharp}(\mathcal{V}^{\sharp}(\mathcal{U})) \cong \mathcal{U}^{\sharp}(\mathcal{V}) \cong \mathcal{U}$.

We have now shown not only that every algebraic theory has a classifying category $\mathcal{C}_{\mathbb{T}}$, but also that the syntactic category $\mathrm{Syn}(\mathbb{T})$ is such a classifying category, and that it is essentially determined by that property. We record this as the following.

Theorem 1.1.21. *Every algebraic theory \mathbb{T} has a classifying category $\mathcal{C}_{\mathbb{T}}$, which can be constructed as the syntactic category $\mathrm{Syn}(\mathbb{T})$ of \mathbb{T} , in the sense of Definition 1.1.15.*

Example 1.1.22. Let us see explicitly what the foregoing definitions give us in the case of the theory of groups $\mathbb{T}_{\text{Group}}$. Let us write $\mathbb{G} = \text{syn}(\mathbb{T}_{\text{Group}})$ for the syntactic category, which has contexts $[x_1, \dots, x_n]$ as objects, and terms built from variables and the group operations (modulo renaming of variables and provability from the group laws) as arrows. A finite product preserving functor $G : \mathbb{G} \rightarrow \mathbf{Set}$ is determined uniquely, up to natural isomorphism, by its action on the context $[x_1]$ and the terms representing the basic operations. If we set

$$\begin{aligned} |\mathcal{G}| &:= G[x_1] , & u^{\mathcal{G}} &:= G(\cdot \mid e) , \\ i^{\mathcal{G}} &:= G(x_1 \mid x_1^{-1}) , & m_G &= G(x_1, x_2 \mid x_1 \cdot x_2) , \end{aligned}$$

then $\mathcal{G} = (|\mathcal{G}|, u^{\mathcal{G}}, i^{\mathcal{G}}, m^{\mathcal{G}})$ is just a group, with unit $u^{\mathcal{G}}$, inverse $i^{\mathcal{G}}$, and multiplication $m^{\mathcal{G}}$. That the interpretation \mathcal{G} satisfies the group equaitons follows from the fact that \mathcal{G} does (it is generic by Proposition 1.1.17), the preservation of finite products by G , and its functoriality, which implies preservation of the corresponding commutative diagrams.

Conversely, any group $\mathcal{G} = (G, u, i, m)$ determines a finite product preserving functor $\mathcal{G}^{\#} : \mathbb{G} \rightarrow \mathbf{Set}$, by setting $\mathcal{G}^{\#}[x_1] = G$, etc. Thus $\mathbf{Mod}(\mathbb{G}, \mathbf{Set})$ will indeed be equivalent to \mathbf{Group} once we show that both categories have the same notion of morphisms. This is shown just as in the general case above.

Example 1.1.23. Recall from 1.1.12 that a group G in the functor category $\mathbf{Set}^{\mathbb{C}}$ is essentially the same thing as a functor $G : \mathbb{C} \rightarrow \mathbf{Group}$. From the point of view of algebras as functors, this amounts to the observation that product-preserving functors $\mathbb{G} \rightarrow \mathbf{Hom}(\mathbb{C}, \mathbf{Set})$ correspond (by exponential transposition) to functors $\mathbb{C} \rightarrow \mathbf{Hom}_{\text{FP}}(\mathbb{G}, \mathbf{Set})$, where the latter \mathbf{Hom} -set consists just of product-preserving functors (since products in functor categories are computed pointwise). The correspondence extends to natural transformations, giving the previously observed (Example 1.1.12) equivalence of categories,

$$\mathbf{Group}(\mathbf{Set}^{\mathbb{C}}) \simeq \mathbf{Group}(\mathbf{Set})^{\mathbb{C}} = \mathbf{Group}^{\mathbb{C}}.$$

1.1.4 Soundness and completeness

Consider an algebraic theory \mathbb{T} and an equation $s = t$ between terms of the theory. If the equation can be proved from the axioms of the theory, $\mathbb{T} \vdash s = t$, then every model \mathcal{M} of the theory in any FP-category satisfies the equation, $\mathcal{M} \models s = t$. This is called the *soundness* of the equational calculus with respect to categorical models, and it can be shown by a straightforward induction on the equational proof that establishes $\mathbb{T} \vdash s = t$. The converse statement reads:

$$\mathcal{M} \models s = t, \text{ for all } \mathcal{M} \quad \Rightarrow \quad \mathbb{T} \vdash s = t .$$

This is called *completeness*, and (together with soundness) it says that the equational calculus suffices for proving all (and only) the equations that hold generally in the semantics. For functorial semantics, this condition holds in an especially strong way: by Proposition

1.1.17, we already know that the syntactic model \mathcal{U} in $\mathbf{Syn}(\mathbb{T})$ is logically generic, in the sense that satisfaction by \mathcal{U} is equivalent to provability in \mathbb{T} ,

$$\mathcal{U} \models s = t \iff \mathbb{T} \vdash s = t.$$

But since $\mathbf{Syn}(\mathbb{T})$ is a classifying category for \mathbb{T} and \mathcal{U} is universal in the sense of Definition 1.1.20 it follows that we also have completeness:

Theorem 1.1.24 (Soundness and completeness of equational logic). *For any terms s, t we have $\mathbb{T} \vdash s = t$ if and only if every model \mathcal{M} in every FP-category \mathcal{C} satisfies $s = t$.*

Proof. We have a classifying category $\mathcal{C}_{\mathbb{T}} \simeq \mathbf{Syn}(\mathbb{T})$ with universal model \mathcal{U} . If $\mathbb{T} \vdash s = t$, then by Proposition 1.1.17 we have $\mathcal{U} \models s = t$, meaning that $s^{\mathcal{U}} = t^{\mathcal{U}}$. But then for any model \mathcal{M} in an FP-category \mathcal{C} , we obtain $\mathcal{M} \models s = t$ by applying the classifying functor $\mathcal{M}^{\#} : \mathcal{C}_{\mathbb{T}} \rightarrow \mathcal{C}$, which preserves the interpretations of s and t ,

$$\mathcal{M}^{\#}(s^{\mathcal{U}}) = s^{\mathcal{M}^{\#}(\mathcal{U})} = s^{\mathcal{M}}$$

and so from $s^{\mathcal{U}} = t^{\mathcal{U}}$ we get $s^{\mathcal{M}} = t^{\mathcal{M}}$.

Conversely, if $\mathcal{M} \models s = t$ for every model \mathcal{M} , then in particular $\mathcal{U} \models s = t$, and so $\mathbb{T} \vdash s = t$, since \mathcal{U} is generic. \square

Classically, it is seldom the case that there exists a generic model; instead, one usually considers completeness with respect to a class of special models, say, those in \mathbf{Set} . Completeness with respect to a restricted class of models is of course a stronger statement than completeness with respect to all models in all categories; indeed, one need only test an equation in the restricted class to know that it can be proved, and therefore holds in all models. Toward the classical result, we can first consider completeness with respect to just “variable models” in \mathbf{Set} , i.e. in arbitrary functor categories $\mathbf{Set}^{\mathcal{C}}$. That result follows immediately from the next lemma.

Lemma 1.1.25. *Let \mathbb{T} be an algebraic theory. The Yoneda embedding*

$$y : \mathcal{C}_{\mathbb{T}} \rightarrow \widehat{\mathcal{C}_{\mathbb{T}}} = \mathbf{Set}^{\mathcal{C}_{\mathbb{T}}^{\text{op}}}$$

is a generic model for \mathbb{T} .

Proof. The Yoneda embedding $y : \mathcal{C}_{\mathbb{T}} \rightarrow \widehat{\mathcal{C}_{\mathbb{T}}}$ preserves all limits, and in particular finite products, hence it determines a model $\mathcal{Y} = y(\mathcal{U})$ in the category of presheaves $\widehat{\mathcal{C}_{\mathbb{T}}}$. Like all models, \mathcal{Y} satisfies all the equations that hold in \mathcal{U} , simply because y is an FP functor. But because y is also faithful, any equation that holds in \mathcal{Y} must already hold in \mathcal{U} , and is therefore provable, since \mathcal{U} is generic. \square

Example 1.1.26. We consider group theory one more time. We again write simply \mathbb{G} for the syntactic (classifying) category of the theory $\mathbb{T}_{\text{Group}}$ of groups. As a presheaf on \mathbb{G} , the generic group $\mathcal{Y} \in \widehat{\mathbb{G}}$ satisfies every equation that is satisfied by all groups, and no others.

Let us describe its underlying object $Y = |\mathcal{Y}|$ explicitly as a “variable set”. By definition, the presheaf Y is represented by the underlying object $U = |\mathcal{U}|$ of the universal group in \mathbb{G} , which in syntactic terms is the context with one variable,

$$Y = \mathbf{y}[x_1] = \mathbb{G}(-, [x_1]) .$$

The values of this functor thus comprise a family of sets parametrized by the objects $[x_1, \dots, x_n]$ of \mathbb{G} ; namely, for every $n \in \mathbb{N}$, we have the set

$$Y_n = \mathbb{G}([x_1, \dots, x_n], [x_1])$$

consisting of all (equivalence classes of) terms $[x_1, \dots, x_n \mid t]$ in n variables (modulo the equations of group theory); but this is just the set of elements of the *free group* $F(n)$ on n generators! Thus we have

$$Y_n = \mathbb{G}([x_1, \dots, x_n], [x_1]) \cong |F(n)| \cong \mathbf{Set}(1, |F(n)|) \cong \mathbf{Group}(F(1), F(n)).$$

Moreover, the action of the functor Y on a map

$$s : [x_1, \dots, x_m] \longrightarrow [x_1, \dots, x_n] \quad \text{in } \mathbb{G}$$

can be described by substitution of the terms $s = (s_1, \dots, s_n)$ into the elements $t \in Y_n$,

$$Y(s)(t) = \mathbb{G}(s, [x_1])(t) = t[s_1/x_1, \dots, s_n/x_n] .$$

In terms of the free groups $F(n)$, the terms s_1, \dots, s_n in the context x_1, \dots, x_m are elements of the free group $F(m)$, and so they determine a unique homomorphism

$$\bar{s} : F(n) \cong F(1) + \dots + F(1) \longrightarrow F(m)$$

such that $\bar{s}(x_i) = s_i$ for $i = 1, \dots, n$. Composition with $\bar{s} : F(n) \rightarrow F(m)$ then encodes the corresponding substitution, in the sense that the following diagram commutes (as the reader should verify!).

$$\begin{array}{ccccc}
 [x_1, \dots, x_n] & & \mathbb{G}([x_1, \dots, x_n], [x_1]) & \xrightarrow{\cong} & \mathbf{Group}(F(1), F(n)) & & F(n) \\
 \uparrow s & & \downarrow \mathbb{G}(s, [x_1]) & & \downarrow \mathbf{Group}(F(1), \bar{s}) & & \downarrow \bar{s} \\
 [x_1, \dots, x_m] & & \mathbb{G}([x_1, \dots, x_m], [x_1]) & \xrightarrow{\cong} & \mathbf{Group}(F(1), F(m)) & & F(m)
 \end{array} \tag{1.12}$$

Finally, the unit, inverse, and multiplication operations of the internal group \mathcal{Y} are determined at each stage Y_n by the corresponding operations on the free group $F(n)$ (as the reader should verify!). We will discover a deeper reason for this in Section 1.2.1.

Finally, we can consider the completeness of equational logic with respect to all **Set**-valued models $\mathcal{M} : \mathcal{C}_{\mathbb{T}} \rightarrow \mathbf{Set}$, which of course correspond to classical \mathbb{T} -algebras. We need the following:

Lemma 1.1.27. *For any small category \mathbb{C} , there is a jointly faithful family $(E_i)_{i \in I}$ of FP-functors $E_i : \mathbf{Set}^{\mathbb{C}} \rightarrow \mathbf{Set}$, with I a set. That is, for any maps $f, g : A \rightarrow B$ in $\mathbf{Set}^{\mathbb{C}}$, if $E_i(f) = E_i(g)$ for all $i \in I$, then $f = g$.*

Proof. We can take $I = \mathbb{C}_0$, the set of objects of \mathbb{C} , and the evaluation functors

$$E_c = \text{eval}_c : \mathbf{Set}^{\mathbb{C}} \rightarrow \mathbf{Set},$$

for all $c \in \mathbb{C}$. These are clearly jointly faithful. Note that they also preserve all limits and colimits, since these are constructed pointwise in functor categories. \square

Proposition 1.1.28. *Suppose \mathbb{T} is an algebraic theory. For any terms s, t ,*

$$\mathcal{M} \models s = t \quad \text{for all models } \mathcal{M} \text{ in } \mathbf{Set} \quad \Longleftrightarrow \quad \mathbb{T} \vdash s = t.$$

Thus the equational logic of algebraic theories is sound and complete with respect to Set-valued semantics.

Proof. Combine the foregoing lemma with the fact, from Lemma 1.1.25, that the Yoneda embedding is a generic model. \square

The completeness of equational reasoning was originally proved by Birkhoff [Bir35]. The proof is not particularly difficult; we have chosen to redo it in this way because the method will generalize to other systems of logic in later chapters.

Exercise 1.1.29. We described the functor $Y = \mathbf{y}U : \mathbb{G}^{\text{op}} \rightarrow \mathbf{Set}$ represented by the underlying object $U = [x_1]$ of the universal group \mathcal{U} in terms of the free groups $F(n)$. Verify that the action of Y on the arrows of \mathbb{G} is indeed given by substitution of terms by checking that diagram (1.12) commutes. Also describe the group structure on Y in $\widehat{\mathbb{G}}$ explicitly in terms of that on the free groups.

Exercise 1.1.30. Let $t = t(x_1, \dots, x_n)$ be a term of group theory in the variables x_1, \dots, x_n . On the one hand we can think of t as an element of the free group $F(n)$, and on the other we can consider the interpretation of t with respect to the representable group \mathcal{Y} in $\widehat{\mathbb{G}}$, namely as a natural transformation $t^{\mathcal{Y}} : Y^n \rightarrow Y$. Suppose $s = s(x_1, \dots, x_n)$ is another such term in the same variables x_1, \dots, x_n . Show that $s^{\mathcal{Y}} = t^{\mathcal{Y}}$ if, and only if, $s = t$ in the free group $F(n)$.

1.1.5 Functorial semantics

Let us summarize our treatment of algebraic theories so far. We have reformulated certain traditional *logical* notions in terms of *categorical* ones. The traditional approach may be described as involving the following four different parts:

Terms

There is an underlying *type theory* consisting of types and terms. For algebraic theories there is only one type, which is not even explicitly mentioned. The terms are built from variables and a *signature* consisting of some basic operation symbols.

Equations

Algebraic theories have a particularly simple *logic* that involves only equations between terms and equational reasoning, which is basically *substitution* of equals for equals and the laws of an *equivalence relation*.

Theories

An *algebraic theory* then consists of a signature and a set of *axioms*, which are just equations between terms. Such theories are regarded as *logical syntax*: sets of uninterpreted, formal expressions, generated inductively by rules of inference.

Models

An algebraic theory can be modeled by a *set* equipped with some *operations* interpreting the signature. Such an interpretation is a *model* if it satisfies the axioms of the theory, meaning that the functions interpreting the terms that occur in the equational axioms are actually equal.

The alternative approach of *functorial semantics* may be summarized as follows:

Theories are categories

From a given theory we construct a structured category that captures the same information in a way that is independent of a particular presentation by basic operations and axioms.

Models are functors

A model is a structure-preserving functor from the theory to a category with the same structure. For algebraic theories, a model is a functor that preserves finite products, which ensures that all valid equations of the theory are preserved, and the axioms are therefore satisfied.

Homomorphisms are natural transformations

We obtain the notion of a homomorphism of models for free: since models are functors, the homomorphisms between them are just the natural transformations. Such homomorphisms agree with the usual notion, consisting of a function on the underlying sets that “respects” the algebraic structure.

Universal models

By allowing for models in categories other than **Set**, functorial semantics admits *universal models*: a model \mathcal{U} in the classifying category $\mathcal{C}_{\mathbb{T}}$, such that any model anywhere is a functorial image of \mathcal{U} by an essentially unique, structure-preserving functor. Thus \mathcal{U} has all and only those logical properties that are had by all models, since such properties are preserved by the functors in question.

Logical completeness

The construction of the classifying category $\mathcal{C}_{\mathbb{T}}$ from the syntax of the theory \mathbb{T} shows that the universal model is also *generic*: it has exactly those properties that are provable in the theory \mathbb{T} . This implies the *soundness and completeness* of the logic with respect to general categorical semantics. Completeness with respect to a restricted class of models, such as those in **Set**, then results from an embedding theorem for the classifying category.

1.2 Lawvere duality

The scheme of functorial semantics outlined in the previous section applies to many other systems of logic than algebraic theories, some of which will be considered in later chapters. A further aspect of this approach is especially transparent in the case of algebraic theories; namely, a deep and fascinating *duality* relating syntax and semantics. We devote the rest of this chapter to its investigation.

1.2.1 Logical duality

There is a remarkable and far-reaching duality in logic of the form

$$\text{Syntax} \simeq \text{Semantics}^{\text{op}}.$$

It was discovered by F.W. Lawvere in the 1960s and presented in some early papers, [Law63a, Law63b, Law65, Law69], but it has still hardly been noticed in conventional logic—perhaps because its recognition requires the tools of category theory.

We can see this duality quite clearly in the case of algebraic theories. Let $\mathcal{C}_{\mathbb{T}}$ be the classifying category for an equational theory \mathbb{T} , like the theory of groups, constructed syntactically as in section 1.1.2 above. So the objects of $\mathcal{C}_{\mathbb{T}}$ are contexts of variables $[x_1 \dots, x_n]$, up to renaming, and the arrows $(t_1, \dots, t_n) : [x_1 \dots, x_m] \rightarrow [x_1 \dots, x_n]$ are n -tuples of terms in context $[x_1 \dots, x_m \mid t_i]$, up to \mathbb{T} -provable equality. We will see that this syntactic category $\mathcal{C}_{\mathbb{T}}$ is in fact dual to a certain subcategory of *models* of \mathbb{T} (in **Set**). Specifically, there is a small, full subcategory $\mathbf{mod}(\mathbb{T}) \hookrightarrow \mathbf{Mod}(\mathbb{T})$ and an equivalence of categories,

$$\mathcal{C}_{\mathbb{T}} \simeq \mathbf{mod}(\mathbb{T})^{\text{op}},$$

making the *syntactic* category $\mathcal{C}_{\mathbb{T}}$ dual to a subcategory of the *semantic* category $\mathbf{Mod}(\mathbb{T})$. Thus, in particular, there is an invariant representation of the syntax of the theory \mathbb{T} “hidden” inside the category of models of \mathbb{T} .

Indeed, it is quite easy to specify $\mathbf{mod}(\mathbb{T})$ explicitly: it is the full subcategory of $\mathbf{Mod}(\mathbb{T})$ on the *finitely generated free models* $F(n)$,

$$\mathbf{mod}(\mathbb{T})_0 = \{F(n) \mid n \in \mathbb{N}\}.$$

We will have a more intrinsic characterization by the end of this chapter.

Theorem 1.2.1. *Let \mathbb{T} be an algebraic theory, and let*

$$\mathbf{mod}(\mathbb{T}) \hookrightarrow \mathbf{Mod}(\mathbb{T})$$

be the full subcategory of finitely generated free models of \mathbb{T} . Then $\mathbf{mod}(\mathbb{T})^{\mathrm{op}}$ classifies \mathbb{T} models. That is to say, for any FP-category \mathcal{C} , there is an equivalence of categories,

$$\mathbf{Hom}_{\mathrm{FP}}(\mathbf{mod}(\mathbb{T})^{\mathrm{op}}, \mathcal{C}) \simeq \mathbf{Mod}(\mathbb{T}, \mathcal{C}), \quad (1.13)$$

which is natural in \mathcal{C} .

Before giving the (somewhat lengthy, but straightforward) proof of the theorem, let us observe that the syntax-semantics duality follows immediately. Indeed, given (1.13), there is then an equivalence,

$$\mathcal{C}_{\mathbb{T}} \simeq \mathbf{mod}(\mathbb{T})^{\mathrm{op}} \quad (1.14)$$

between the (syntactically constructed) classifying category $\mathcal{C}_{\mathbb{T}}$ and the opposite of the (semantic) category $\mathbf{mod}(\mathbb{T})$ of finitely generated free models, because by Proposition 1.1.18, both categories $\mathcal{C}_{\mathbb{T}}$ and $\mathbf{mod}(\mathbb{T})^{\mathrm{op}}$ represent the same functor $\mathbf{Mod}(\mathbb{T}, \mathcal{C})$.

Proof of Theorem 1.2.1. First, observe that $\mathbf{mod}(\mathbb{T})^{\mathrm{op}}$ has all finite products, since $\mathbf{mod}(\mathbb{T})$ has all finite coproducts. Indeed, for the finitely generated free algebras $F(n)$ we have

$$\begin{aligned} F(n) + F(m) &\cong F(n + m), \\ 0 &\cong F(0), \end{aligned}$$

in $\mathbf{Mod}(\mathbb{T})$, since the left adjoint F preserves all colimits.

For the universal \mathbb{T} -algebra \mathcal{U} in $\mathbf{mod}(\mathbb{T})^{\mathrm{op}}$, let

$$U = F(1),$$

so that every object in $\mathbf{mod}(\mathbb{T})^{\mathrm{op}}$ is indeed a power of U ,

$$F(n) \cong U^n.$$

We next interpret the signature $\Sigma_{\mathbb{T}}$. For each basic operation symbol $f \in \Sigma_{\mathbb{T}}$, with arity k , there is an element of the free algebra $F(k)$ built from the operation $f^{F(k)} : F(k)^k \rightarrow F(k)$ and the k generators $x_1, \dots, x_k \in F(k)$, namely

$$f^{F(k)}(x_1, \dots, x_k).$$

E.g. in the theory of groups, there is the element $x \cdot y$ in the free group on the two generators x, y . By freeness of $F(1)$, each element $t \in F(k)$ determines a unique homomorphism $\bar{t} : F(1) \rightarrow F(k)$ in $\mathbf{mod}(\mathbb{T})$ taking the generator $x \in F(1)$ to $t = \bar{t}(x)$. Thus associated to the element $f^{F(k)}(x_1, \dots, x_k) \in F(k)$ there is a homomorphism

$$\overline{f^{F(k)}(x_1, \dots, x_k)} : F(1) \longrightarrow F(k) \quad \text{in } \mathbf{mod}(\mathbb{T}).$$

We take this map, regarded as an arrow in $\mathbf{mod}(\mathbb{T})^{\text{op}}$, as the \mathcal{U} -interpretation of the basic operation symbol f ,

$$f^{\mathcal{U}} := \overline{f^{F(k)}(x_1, \dots, x_k)} : U^k \longrightarrow U \quad \text{in } \mathbf{mod}(\mathbb{T})^{\text{op}}.$$

It then follows easily that for any term in context $(x_1 \dots, x_k \mid t)$, the interpretation

$$[x_1 \dots, x_k \mid t]^{\mathcal{U}} : U^k \longrightarrow U$$

will be the unique homomorphism $\overline{t^{F(k)}} : F(1) \rightarrow F(k)$ corresponding to the element $t^{F(k)} \in F(k)$ (proof by induction!).

Moreover, for every axiom $(s = t)$ of \mathbb{T} , we then have $\mathcal{U} \models s = t$. Indeed,

$$[x_1 \dots, x_k \mid s]^{\mathcal{U}} = [x_1 \dots, x_k \mid t]^{\mathcal{U}} : U^k \longrightarrow U$$

if, and only if, the corresponding homomorphisms $\bar{s}, \bar{t} : F(1) \rightarrow F(k)$ agree, which they do just if the associated elements of the free algebra $F(k)$ agree, by the freeness of $F(1)$. And the latter holds, in turn, simply because $F(k)$ is a \mathbb{T} -algebra. Indeed, consider the example of the two generators x, y of the free *abelian* group $F(2)$, for which we have $x \cdot y = y \cdot x$ simply because $F(2)$ is abelian. Thus we indeed have a \mathbb{T} -model \mathcal{U} in $\mathbf{mod}(\mathbb{T})^{\text{op}}$, consisting of the free algebras.

We next show that \mathcal{U} has the required universal property, in three steps:

Step 1. Let \mathcal{A} be any \mathbb{T} -algebra in **Set**. Then there is a product-preserving functor,

$$\mathcal{A}^{\sharp} : \mathbf{mod}(\mathbb{T})^{\text{op}} \rightarrow \mathbf{Set}$$

with $\mathcal{A}^{\sharp}(\mathcal{U}) \cong \mathcal{A}$ (as \mathbb{T} -models), namely:

$$\mathcal{A}^{\sharp}(-) = \mathbf{Hom}_{\mathbf{Mod}(\mathbb{T})}(-, \mathcal{A}),$$

where we of course restrict the representable functor $\mathbf{Hom}_{\mathbf{Mod}(\mathbb{T})}(-, \mathcal{A}) : \mathbf{Mod}(\mathbb{T})^{\text{op}} \rightarrow \mathbf{Set}$ along the (full) inclusion

$$\mathbf{mod}(\mathbb{T}) \hookrightarrow \mathbf{Mod}(\mathbb{T})$$

of the finitely generated, free algebras. The (restricted) functor

$$\mathcal{A}^{\sharp} : \mathbf{mod}(\mathbb{T})^{\text{op}} \rightarrow \mathbf{Set}$$

clearly preserves products: for each object $U^n \in \mathbf{mod}(\mathbb{T})^{\text{op}}$, we have

$$\mathcal{A}^{\sharp}(U^n) = \mathbf{Hom}_{\mathbf{Mod}(\mathbb{T})}(F(n), \mathcal{A}) \cong \mathbf{Hom}_{\mathbf{Set}}(n, |\mathcal{A}|) \cong A^n$$

and, in particular, $\mathcal{A}^{\sharp}(U) \cong A$.

Finally, let us show that for any basic operation symbol f , we have $\mathcal{A}^\sharp(f^\mathcal{U}) = f^\mathcal{A}$, up to isomorphism. Indeed, given any algebra \mathcal{A} and operation $f^\mathcal{A} : A^n \rightarrow A$, we have a commutative diagram,

$$\begin{array}{ccc} A^n & \xrightarrow{f^\mathcal{A}} & A \\ \cong \downarrow & & \downarrow \cong \\ \mathrm{Hom}(F(n), \mathcal{A}) & \xrightarrow{f^*} & \mathrm{Hom}(F(1), \mathcal{A}) \end{array} \quad (1.15)$$

where f^* is precomposition with the homomorphism

$$F(n) \xleftarrow{\overline{f^{F(n)}(x_1, \dots, x_n)}} F(1)$$

To see that (1.15) commutes, take any $(a_1, \dots, a_n) \in A^n$ with associated homomorphism $\overline{(a_1, \dots, a_n)} : F(n) \rightarrow \mathcal{A}$ and precompose with $\overline{f^{F(n)}(x_1, \dots, x_n)}$ to get a map $F(1) \rightarrow \mathcal{A}$, picking out the element

$$\begin{aligned} \overline{(a_1, \dots, a_n)} \circ \overline{f^{F(n)}(x_1, \dots, x_n)}(x) &= \overline{(a_1, \dots, a_n)}(f^{F(n)}(x_1, \dots, x_n)) \\ &= \overline{(a_1, \dots, a_n)} \circ f^{F(n)}(x_1, \dots, x_n) \\ &= f^\mathcal{A} \circ \overline{(a_1, \dots, a_n)}(x_1, \dots, x_n) \\ &= f^\mathcal{A}(a_1, \dots, a_n) \end{aligned}$$

where x is the generator of $F(1)$, and we have used the fact that $\overline{(a_1, \dots, a_n)}$ is a homomorphism and therefore commutes with the respective interpretations of f .

But now note that

$$F(n) \xleftarrow{\overline{f^{F(n)}(x_1, \dots, x_n)}} F(1)$$

in $\mathrm{mod}(\mathbb{T})$ is

$$U^n \xrightarrow{f^U} U$$

in $\mathrm{mod}(\mathbb{T})^{\mathrm{op}}$, and that $\mathrm{Hom}(F(n), \mathcal{A}) = \mathcal{A}^\sharp(U^n)$ and $f^* = \mathcal{A}^\sharp(f^U)$. Thus (1.15) shows that indeed $\mathcal{A}^\sharp(f^\mathcal{U}) = f^\mathcal{A}$, up to isomorphism. Thus we indeed have $\mathcal{A}^\sharp(\mathcal{U}) \cong \mathcal{A}$ as algebras, as required.

We leave it to the reader to verify that any homomorphism $h : F(\mathcal{U}) \rightarrow G(\mathcal{U})$ of \mathbb{T} -algebras $F(\mathcal{U}), G(\mathcal{U})$ arising from FP-functors $F, G : \mathrm{mod}(\mathbb{T})^{\mathrm{op}} \rightarrow \mathrm{Set}$ is of the form $h = \vartheta_\mathcal{U}$ for a unique natural transformation $\vartheta : F \rightarrow G$.

Exercise 1.2.2. Show this.

Step 2. Let \mathbb{C} be any (locally small) category, and \mathcal{A} a \mathbb{T} -algebra in $\mathbf{Set}^{\mathbb{C}}$. Using the isomorphism

$$\mathbf{Mod}(\mathbb{T}, \mathbf{Set}^{\mathbb{C}}) \cong \mathbf{Mod}(\mathbb{T})^{\mathbb{C}},$$

each $\mathcal{A}(C)$ is a \mathbb{T} -algebra (in \mathbf{Set}), which by Step 1 has a classifying functor,

$$\mathcal{A}(C)^{\sharp} : \mathbf{mod}(\mathbb{T})^{\mathrm{op}} \rightarrow \mathbf{Set}.$$

Together, these determine a single functor $\mathcal{A}^{\sharp} : \mathbf{mod}(\mathbb{T})^{\mathrm{op}} \rightarrow \mathbf{Set}^{\mathbb{C}}$, defined on any $U^n \in \mathbf{mod}(\mathbb{T})^{\mathrm{op}}$ by

$$(\mathcal{A}^{\sharp}(U^n))(C) \cong \mathcal{A}(C)^{\sharp}(U^n) \cong (AC)^n.$$

The action on arrows $U^n \rightarrow U^m$ in $\mathbf{mod}(\mathbb{T})^{\mathrm{op}}$ is similarly determined pointwise by the components

$$(\mathcal{A}^{\sharp}(U^n))(C) \cong \mathcal{A}(C)^{\sharp}(U^n) \rightarrow \mathcal{A}(C)^{\sharp}(U^m) = (\mathcal{A}^{\sharp}(U^m))(C),$$

for all $C \in \mathbb{C}$.

In this way, we have an FP-functor $\mathcal{A}^{\sharp} : \mathbf{mod}(\mathbb{T})^{\mathrm{op}} \rightarrow \mathbf{Set}^{\mathbb{C}}$, and an isomorphism of models $\mathcal{A}^{\sharp}(\mathcal{U}) \cong \mathcal{A}$ in $\mathbf{Set}^{\mathbb{C}}$. It is then clear that any natural transformation $\mathcal{A}^{\sharp} \rightarrow \mathcal{B}^{\sharp}$ gives rise to a homomorphism $\mathcal{A}^{\sharp}(\mathcal{U}) \rightarrow \mathcal{B}^{\sharp}(\mathcal{U})$, and that the resulting functor

$$\mathbf{Hom}_{\mathbf{FP}}(\mathbf{mod}(\mathbb{T})^{\mathrm{op}}, \mathbf{Set}^{\mathbb{C}}) \rightarrow \mathbf{Mod}(\mathbb{T}, \mathbf{Set}^{\mathbb{C}})$$

is an equivalence.

Step 3. For the general case, let \mathcal{C} be any (locally small) FP-category, and \mathbf{A} a \mathbb{T} -algebra in \mathcal{C} . Use the Yoneda embedding

$$y : \mathcal{C} \hookrightarrow \mathbf{Set}^{\mathcal{C}^{\mathrm{op}}}$$

to send \mathbf{A} to an algebra $\mathcal{A} = y(\mathbf{A})$ in $\mathbf{Set}^{\mathcal{C}^{\mathrm{op}}}$ (since y preserves finite products). Now apply Step 2 to get a classifying functor,

$$\mathcal{A}^{\sharp} : \mathbf{mod}(\mathbb{T})^{\mathrm{op}} \rightarrow \mathbf{Set}^{\mathcal{C}^{\mathrm{op}}}.$$

We claim that \mathcal{A}^{\sharp} factors through the Yoneda embedding by an FP-functor \mathbf{A}^{\sharp} ,

$$\begin{array}{ccc} & & \mathbf{Set}^{\mathcal{C}^{\mathrm{op}}} \\ & \nearrow \mathcal{A}^{\sharp} & \uparrow y \\ \mathbf{mod}(\mathbb{T})^{\mathrm{op}} & \xrightarrow{\mathbf{A}^{\sharp}} & \mathcal{C}. \end{array}$$

Indeed, we know that the objects of $\mathbf{mod}(\mathbb{T})^{\mathrm{op}}$ all have the form U^n , and for their images we have

$$\mathcal{A}^{\sharp}(U^n) \cong \mathcal{A}^{\sharp}(U)^n \cong y(\mathbf{A})^n \cong y(\mathbf{A}^n).$$

Thus the images of the objects of $\mathbf{mod}(\mathbb{T})^{\text{op}}$ are all representable. Since \mathbf{y} is full and faithful, the claim is established, and the resulting functor $\mathbf{A}^\sharp : \mathbf{mod}(\mathbb{T})^{\text{op}} \rightarrow \mathcal{C}$ preserves finite products because \mathcal{A}^\sharp does so, and \mathbf{y} creates them. Clearly,

$$\mathbf{A}^\sharp(\mathcal{U}) \cong \mathbf{A},$$

since \mathbf{y} reflects isos.

Naturality of the equivalence

$$\mathbf{Hom}_{\mathbf{FP}}(\mathbf{mod}(\mathbb{T})^{\text{op}}, \mathcal{C}) \simeq \mathbf{Mod}(\mathbb{T}, \mathcal{C}),$$

in \mathcal{C} is essentially automatic, using the fact that it is induced by evaluating an FP functor $F : \mathbf{mod}(\mathbb{T})^{\text{op}} \rightarrow \mathcal{C}$ at the universal model \mathcal{U} in $\mathbf{mod}(\mathbb{T})^{\text{op}}$. \square

As already mentioned, since the classifying category is uniquely determined, up to equivalence, by its universal property, combining the foregoing theorem with the syntactic construction of $\mathcal{C}_{\mathbb{T}}$ given in theorem 1.1.18 yields the following:

Corollary 1.2.3 (Logical duality for algebraic theories). *For any algebraic theory \mathbb{T} , there is an equivalence of categories,*

$$\mathbf{Syn}(\mathbb{T}) \simeq \mathcal{C}_{\mathbb{T}} \simeq \mathbf{mod}(\mathbb{T})^{\text{op}} \tag{1.16}$$

between the classifying category $\mathcal{C}_{\mathbb{T}}$ constructed syntactically as $\mathbf{Syn}(\mathbb{T})$ and the semantic construction as the opposite of the category $\mathbf{mod}(\mathbb{T})$ of finitely generated, free models.

Thus, as claimed, the construction of the classifying category $\mathcal{C}_{\mathbb{T}}$ from the syntax of \mathbb{T} , on the one hand, and its semantic construction as $\mathbf{mod}(\mathbb{T})$, taken together, imply that there is an invariant representation of the *syntax* of \mathbb{T} hidden, as it were, in the opposite of the *semantics*, namely the category $\mathbf{Mod}(\mathbb{T})$ of all \mathbb{T} -models. The reader may wish to reflect on the importance of (i) considering the *category* of all models, rather than the mere collection of them, and (ii) generalizing from set-theoretic to categorical models, in arriving at the fundamental logical duality expressed by (1.16).

In section 1.2.5 below, we shall consider how to actually *recover* this syntactic category $\mathcal{C}_{\mathbb{T}}$ from the semantic category $\mathbf{Mod}(\mathbb{T})$ by identifying the subcategory $\mathbf{mod}(\mathbb{T})$ intrinsically; indeed, it will be seen to consist of certain continuous functors $\mathbf{Mod}(\mathbb{T}) \rightarrow \mathbf{Set}$. Before doing this, however, let us examine the fundamental equivalence (1.16) explicitly in a few special cases.

Example 1.2.4. Consider the trivial theory \mathbb{T}_0 of Example 1.1.4, with no basic operations or equations. A model of \mathbb{T}_0 in \mathbf{Set} is just a set X , equipped with no operations, and satisfying no further conditions (and similarly in any other FP category). All \mathbb{T}_0 -algebras are free, and the finitely generated ones are just the finite sets, thus

$$\mathbf{mod}(\mathbb{T}_0) = \mathbf{Set}_{\text{fin}}$$

is the category of finite sets (to be more specific, let us take a skeleton, with one n -element set $[n]$ for each $n \in \mathbb{N}$). Theorem 1.2.1 tells us that, for any FP category \mathcal{C} , there is an equivalence

$$\mathrm{Hom}_{\mathrm{FP}}(\mathrm{Set}_{\mathrm{fin}}^{\mathrm{op}}, \mathcal{C}) \simeq \mathrm{Mod}(\mathbb{T}_0, \mathcal{C}) \simeq \mathcal{C}.$$

This simply says that $\mathrm{Set}_{\mathrm{fin}}^{\mathrm{op}}$ is the free FP category on one object. Equivalently, $\mathrm{Set}_{\mathrm{fin}}$ is the free finite *coproduct* category on one object. And this is indeed the case, as one can easily see directly (the objects are the finite cardinal numbers $[0], [1], [2] = [1] + [1], \dots$).

The logical duality of corollary 1.2.3 now tells us that the dual of the category of finite sets is the *syntactic category* of \mathbb{T}_0 ,

$$\mathcal{C}_{\mathbb{T}_0} \simeq \mathrm{Set}_{\mathrm{fin}}^{\mathrm{op}}.$$

Let us see how the syntax of the pure theory of equality \mathbb{T}_0 is “hidden” in the opposite of the category of finite sets. The only terms in context are the variables $(x_1, \dots, x_n \mid x_i)$, representing the product projections, and the provable equations are just those that are true of them *as terms*, so $x_i = x_j$ just if $i = j$. The maps $[n] \rightarrow [k]$ in $\mathcal{C}_{\mathbb{T}_0}$ are therefore just tuples of variables,

$$(x_{i_1}, \dots, x_{i_k}) : [x_1, \dots, x_n] \longrightarrow [x_1, \dots, x_k]$$

Our corollary tells us that this is the category of finite sets, which we can see immediately by reading the contexts $[x_1, \dots, x_n]$ as coproducts $1 + \dots + 1$ and a tuple such as $(x_2, x_5) : [x_1, \dots, x_5] \rightarrow [x_1, x_2]$ as a *cotuple* like $[i_2, i_5] : 1_1 + 1_2 \rightarrow 1_1 + \dots + 1_5$.

Example 1.2.5. For a less trivial example, consider the theory \mathbb{T}_{Ab} of abelian groups. Duality tells us that the syntactic category $\mathcal{C}_{\mathbb{T}_{\mathrm{Ab}}}$ is dual to the category of finitely generated, free abelian groups $\mathbf{Ab}_{\mathrm{fg}}$,

$$\mathcal{C}_{\mathbb{T}_{\mathrm{Ab}}} \simeq \mathbf{Ab}_{\mathrm{fgf}}^{\mathrm{op}}.$$

This gives us a representation of the syntax of (abelian) group theory in the category of abelian groups, which can be described concretely as follows, using fact that for Abelian groups A, B we have an isomorphism $A + B \cong A \times B$.

- The basic types of variables $[-] = 1$, $[x_1] = U$, $[x_1, x_2] = U \times U, \dots$ are represented by the free abelian groups $\{0\}$, \mathbb{Z} , $\mathbb{Z} + \mathbb{Z} = \mathbb{Z}^2$, \mathbb{Z}^3, \dots
- The group unit $u : 1 \rightarrow U$ is the zero homomorphism $0 : \mathbb{Z} \rightarrow \{0\}$.
- The inverse operation $i : U \rightarrow U$ is the unique homomorphism $\mathbb{Z} \rightarrow \mathbb{Z}$ taking 1 to -1 (and therefore n to $-n$).
- The group operation $m : U \times U \rightarrow U$ is the homomorphism $\bar{+} : \mathbb{Z} \rightarrow \mathbb{Z} + \mathbb{Z}$ taking 1 to $\langle 1, 0 \rangle + \langle 0, 1 \rangle = \langle 1, 1 \rangle$, (using $\mathbb{Z} + \mathbb{Z} \cong \mathbb{Z} \times \mathbb{Z}$).

- The laws of abelian groups (and no further ones!) hold under this interpretation, because by (1.15) the group structure on any abelian group A is induced by precomposing with these “co-operations”. For instance, the multiplication $+^A : |A| \times |A| \rightarrow |A|$ works by first “classifying” a pair of elements $a, b \in |A|$ by the homomorphism $\overline{(a, b)} : \mathbb{Z} + \mathbb{Z} \rightarrow A$ and then precomposing with the comultiplication $\overline{+} : \mathbb{Z} \rightarrow \mathbb{Z} + \mathbb{Z}$ to obtain the homomorphism $\overline{a + b} : \mathbb{Z} \rightarrow A$, which classifies the element $a + b \in |A|$.

$$\begin{array}{ccc}
 \mathbb{Z} + \mathbb{Z} & \xrightarrow{\overline{(a, b)}} & A \\
 \uparrow \overline{+} & \nearrow \overline{a + b} & \\
 \mathbb{Z} & & \\
 \text{hom}(\mathbb{Z} + \mathbb{Z}, A) & \xrightarrow{\cong} & |A| \times |A| \\
 \downarrow \text{hom}(\overline{+}, A) & & \downarrow +^A \\
 \text{hom}(\mathbb{Z}, A) & \xrightarrow{\cong} & |A|
 \end{array}$$

Example 1.2.6. The category of *affine schemes* is, by definition, the dual of the category of commutative rings with unit,

$$\mathbf{Scheme}_{\text{aff}} = \mathbf{Ring}^{\text{op}}$$

There is therefore a ring object in affine schemes – called the *affine line* – based on the finitely generated free algebra $F(1) = \mathbb{Z}[x]$, the ring of polynomials in one variable x with integer coefficients. The “co-operations” of $+$ and \cdot are given in rings by the homomorphisms $\mathbb{Z}[x] \rightarrow \mathbb{Z}[x, y]$ taking the generator x to the elements $x + y$ and $x \cdot y$.

Exercise 1.2.7. Prove directly that $\mathbf{Set}_{\text{fin}}$ is the free finite coproduct category on one object.

Exercise 1.2.8. Show that for any algebraic theory \mathbb{T} , the forgetful functor $V : \mathbf{Mod}(\mathbb{T}) \rightarrow \mathbf{Set}$ underlies an algebra \mathcal{V} in the functor category $\mathbf{Set}^{\mathbf{Mod}(\mathbb{T})}$. In more detail, each n -ary operation symbol f determines a natural transformation $f^{\mathcal{V}} : V^n \rightarrow V$, since the homomorphisms in $\mathbf{Mod}(\mathbb{T})$ commute with the respective operations interpreting f . Indeed, given any algebra \mathcal{A} we have the underlying set $V(\mathcal{A}) = A$ and an operation $f^{\mathcal{A}} : A^n \rightarrow A$, and for every homomorphism $h : \mathcal{A} \rightarrow \mathcal{B}$ to another algebra \mathcal{B} , there is a commutative square,

$$\begin{array}{ccc}
 A^n & \xrightarrow{h^n} & B^n \\
 f^{\mathcal{A}} \downarrow & & \downarrow f^{\mathcal{B}} \\
 A & \xrightarrow{h} & B.
 \end{array} \tag{1.17}$$

So we can set $(f^{\mathcal{V}})_{\mathcal{A}} = f^{\mathcal{A}}$ to get a natural transformation $f^{\mathcal{V}} : V^n \rightarrow V$. Now check that this really is an algebra \mathcal{V} in $\mathbf{Set}^{\mathbf{Mod}(\mathbb{T})}$.

Exercise 1.2.9. * Show that the algebra described in the previous exercise is represented by the universal one \mathcal{U} in $\mathbf{mod}(\mathbb{T})^{\text{op}} \hookrightarrow \mathbf{Mod}(\mathbb{T})^{\text{op}}$ under the (covariant) Yoneda embedding,

$$y : \mathbf{Mod}(\mathbb{T})^{\text{op}} \longrightarrow \mathbf{Set}^{\mathbf{Mod}(\mathbb{T})}.$$

1.2.2 Lawvere algebraic theories

Nothing in the foregoing account of the functorial semantics for algebraic theories really depended on the primarily syntactic nature of such theories, i.e. their specification in terms of operations and equations. We can thus generalize it to “abstract” algebraic theories, which can be regarded as a *presentation-free* notion of an algebraic theory.

Definition 1.2.10 (cf. Definition 1.1.2). A *Lawvere algebraic theory* \mathbb{A} is a small category with finite products, the objects of which form a sequence A^0, A^1, A^2, \dots with $A^0 = 1$ terminal and $A^{n+1} = A^n \times A^1$ for all $n \in \mathbb{N}$. Thus every object is a product of finitely many copies of the *generating object* $A := A^1$.

A *model* of a Lawvere algebraic theory \mathbb{A} in any category \mathcal{C} with finite products is simply an FP functor $M : \mathbb{A} \rightarrow \mathcal{C}$, and a *homomorphism of models* is just a natural transformation $\vartheta : M \rightarrow M'$ between such functors.

As was the case for the syntactic categories $\text{Syn}(\mathbb{T})$, we could just as well have taken the natural numbers $0, 1, 2, \dots$ themselves as the objects of a Lawvere algebraic theory \mathbb{A} , but the notation A^n is more suggestive. A Lawvere algebraic theory \mathbb{A} in the sense of the above definition determines an algebraic theory in the sense of Definition 1.1.2 as follows. As basic operations with arity k we take all of the morphisms $A^k \rightarrow A$:

$$\Sigma(\mathbb{A})_k = \text{Hom}_{\mathbb{A}}(A^k, A) \quad (1.18)$$

There is a canonical interpretation in \mathbb{A} of terms built from variables and morphisms $A^k \rightarrow A$, namely each morphism is interpreted by itself, and variables are interpreted as product projects, as usual. An equation $u = v$ is taken as an axiom of the theory \mathbb{A} just if the canonical interpretations of u and v coincide. Of course, the conventional logical notions of a model 1.1.11 and a homomorphism of models then also correspond to the new, functorial ones in the obvious way.

This more abstract view of algebraic theories immediately suggests some interesting new examples.

Example 1.2.11. The *algebraic theory of smooth maps* \mathcal{C}^∞ is the category whose objects are n -dimensional Euclidean spaces $1, \mathbb{R}, \mathbb{R}^2, \dots$, and whose morphisms are \mathcal{C}^∞ -maps between them. Recall that a \mathcal{C}^∞ -map $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is a function which has all higher partial derivatives, and that a function $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is a \mathcal{C}^∞ -map exactly when all of its composites $\pi_k \circ f : \mathbb{R}^n \rightarrow \mathbb{R}$ with the projections $\pi_k : \mathbb{R}^m \rightarrow \mathbb{R}$ are \mathcal{C}^∞ -maps.

A model of this theory in **Set** is (by definition) a finite product preserving functor $A : \mathcal{C}^\infty \rightarrow \text{Set}$. Up to natural isomorphism, such a model can be described as follows. A \mathcal{C}^∞ -*algebra* is given by a set A and for every smooth map $f : \mathbb{R}^n \rightarrow \mathbb{R}$ a function $Af : A^n \rightarrow A$ such that if $f : \mathbb{R}^n \rightarrow \mathbb{R}$ and $g_i : \mathbb{R}^m \rightarrow \mathbb{R}$, $i = 1, \dots, n$, are smooth maps then, for all $a_1, \dots, a_m \in A$,

$$Af((Ag_1)\langle a_1, \dots, a_m \rangle, \dots, (Ag_n)\langle a_1, \dots, a_m \rangle) = A(f \circ \langle g_1, \dots, g_n \rangle)\langle a_1, \dots, a_m \rangle.$$

In particular, since multiplication and addition are smooth maps, A is a commutative ring with unit. Such structures are known as \mathcal{C}^∞ -rings. Therefore, the models in **Set** of the theory of smooth maps are the \mathcal{C}^∞ -rings (cf. [MR91]).

Example 1.2.12. Recall that a (*total*) *recursive function* $f : \mathbb{N}^m \rightarrow \mathbb{N}^n$ is one that can be computed by a Turing machine. This means that there exists a Turing machine which on input $\langle a_1, \dots, a_m \rangle$ outputs the value of $f\langle a_1, \dots, a_m \rangle$. The algebraic theory **Rec** of recursive functions is the category whose objects are finite powers of the natural numbers $1, \mathbb{N}, \mathbb{N}^2, \dots$, and whose morphisms are recursive functions between them. The models of this theory in a category \mathcal{C} with finite products give a notion of computability in \mathcal{C} .

Let us consider the category of all set-theoretic models $\mathcal{R} = \mathbf{Mod}(\mathbf{Rec})$. First, there is the “identity” model $I \in \mathcal{R}$, defined by $IN^k = \mathbb{N}^k$ and $If = f$. Given any model $S \in \mathcal{R}$, its object part is determined by $S_1 = S\mathbb{N}$ since $S\mathbb{N}^k = S_1^k$. For every $n \in \mathbb{N}$ there is a morphism $1 \rightarrow \mathbb{N}$ in **Rec** defined by $\star \mapsto n$. Thus we have for each $n \in \mathbb{N}$ an element $s_n = S(\star \mapsto n) : 1 \rightarrow S_1$. This defines a function $s : \mathbb{N} \rightarrow S_1$ which in turn determines a natural transformation $\sigma : I \Rightarrow S$ whose component at \mathbb{N}^k is $s \times \dots \times s : \mathbb{N}^k \rightarrow S_1^k$.

Example 1.2.13. In a category \mathcal{C} with finite products every object $A \in \mathcal{C}$ determines a full subcategory consisting of the finite powers $1, A, A^2, A^3, \dots$ and all morphisms between them. This is the *total theory* \mathbb{T}_A of the object A in \mathcal{C} .

Free algebras

In order to extend the logical duality of the foregoing section to the abstract case, we will require the notion of a *free model* of an abstract algebraic theory. Of course, we already have the conventional notion of free models determined in terms of the associated conventional algebraic theory given by (1.18). But we can also determine free models directly in terms of the abstract theory, in a way which then agrees with the conventional ones.

Let \mathbb{A} be a Lawvere algebraic theory, with objects $1, A, A^2, \dots$. We have the category of models,

$$\mathbf{Mod}(\mathbb{A}) = \mathbf{Hom}_{\mathbf{FP}}(\mathbb{A}, \mathbf{Set}).$$

Let us first define the *forgetful functor* by evaluating at the generating object $A \in \mathbb{A}$,

$$U := \mathbf{eval}_A : \mathbf{Mod}(\mathbb{A}) \rightarrow \mathbf{Set} \tag{1.19}$$

$$(M : \mathbb{A} \rightarrow \mathbf{Set}) \mapsto M(A). \tag{1.20}$$

As before, we shall also write

$$|M| = U(M) = M(A). \tag{1.21}$$

Now for the *finitary* free functor $F : \mathbf{Set}_{\text{fin}} \rightarrow \mathbf{Mod}(\mathbb{A})$, we set:

$$\begin{aligned} F(0) &= \mathbf{Hom}_{\mathbb{A}}(1, -) \\ F(1) &= \mathbf{Hom}_{\mathbb{A}}(A, -) \\ &\vdots \\ F(n) &= \mathbf{Hom}_{\mathbb{A}}(A^n, -). \end{aligned}$$

Note that this is a composite of the two (contravariant) functors,

$$\mathbf{Set}_{\text{fin}} \rightarrow \mathbb{A}^{\text{op}} \rightarrow \mathbf{Mod}(\mathbb{A}),$$

given by $n \mapsto A^n$ and $X \mapsto \mathbf{Hom}_{\mathbb{A}}(X, -)$, and is therefore (covariantly) functorial. Note also that the representables $\mathbf{Hom}_{\mathbb{A}}(A^n, -)$ do indeed preserve finite products, and are therefore in the full subcategory $\mathbf{Mod}(\mathbb{A}) \hookrightarrow \mathbf{Set}^{\mathbb{A}}$ of models.

For adjointness we need to check that for any FP-functor $M : \mathbb{A} \rightarrow \mathbf{Set}$ there is a natural (in both arguments) bijection,

$$\mathbf{Hom}_{\mathbf{Mod}(\mathbb{A})}(F(n), M) \cong \mathbf{Hom}_{\mathbf{Set}}(n, U(M)). \quad (1.22)$$

The right-hand side is plainly just $|M|^n$. For the left-hand side we have:

$$\begin{aligned} \mathbf{Hom}_{\mathbf{Mod}(\mathbb{A})}(F(n), M) &= \mathbf{Hom}_{\mathbf{Mod}(\mathbb{A})}(\mathbf{Hom}_{\mathbb{A}}(A^n, -), M) \\ &= \mathbf{Hom}_{\mathbf{Set}^{\mathbb{A}}}(\mathbf{Hom}_{\mathbb{A}}(A^n, -), M) && (\mathbf{Mod}(\mathbb{A}) \text{ is full}) \\ &\cong M(A^n) && (\text{by Yoneda}) \\ &\cong M(A)^n && (M \text{ is FP}) \\ &= |M|^n && (1.21). \end{aligned}$$

The full definition of the free functor

$$F : \mathbf{Set} \rightarrow \mathbf{Mod}(\mathbb{A})$$

is then given by writing an arbitrary set X as a (filtered) colimit of its finite subsets $X_i \subseteq X$, and setting $F(X) = \text{colim}_i F(X_i)$ in the category $\mathbf{Set}^{\mathbb{A}}$. Since filtered colimits commute with finite products, these colimits taken in $\mathbf{Set}^{\mathbb{A}}$ will remain in $\mathbf{Mod}(\mathbb{A})$.

Theorem 1.2.14. *For any set X with free algebra $F(X)$ as just defined, and any \mathbb{A} -model M , there is a natural isomorphism,*

$$\mathbf{Hom}_{\mathbf{Mod}(\mathbb{A})}(F(X), M) \cong \mathbf{Hom}_{\mathbf{Set}}(X, U(M)). \quad (1.23)$$

Proof. The rest of the proof is now an easy exercise. □

By definition, the finitely generated free models $F(n)$ are just the representables $\mathbf{Hom}_{\mathbb{A}}(A^n, -)$; therefore as the “semantic dual” $\mathbf{mod}(\mathbb{A}) \hookrightarrow \mathbf{Mod}(\mathbb{A})$ of the theory \mathbb{A} , in the sense of corollary 1.2.3, we simply have (the full subcategory of $\mathbf{Hom}_{\mathbf{FP}}(\mathbb{A}, \mathbf{Set})$ on) the image of the Yoneda embedding,

$$\begin{array}{ccccc} \mathbf{mod}(\mathbb{A}) & \hookrightarrow & \mathbf{Mod}(\mathbb{A}) = \mathbf{Hom}_{\mathbf{FP}}(\mathbb{A}, \mathbf{Set}) & \hookrightarrow & \mathbf{Set}^{\mathbb{A}} \\ \uparrow \simeq & & & & \uparrow \mathbf{y} \\ \mathbb{A}^{\mathrm{op}} & \xrightarrow{\quad = \quad} & & & \mathbb{A}^{\mathrm{op}}. \end{array}$$

So in the abstract case, the logical duality

$$\mathbb{A} \simeq \mathbf{mod}(\mathbb{A})^{\mathrm{op}}$$

comes down to the fact that the (contravariant) Yoneda embedding

$$\mathbb{A}^{\mathrm{op}} \hookrightarrow \mathbf{Set}^{\mathbb{A}}$$

represents \mathbb{A} as (the dual of) a full subcategory of (product-preserving!) functors.

Summarizing, we have now shown:

Theorem 1.2.15. *For any Lawvere algebraic theory \mathbb{A} , there is an equivalence,*

$$\mathbb{A} \simeq \mathbf{mod}(\mathbb{A})^{\mathrm{op}}$$

between \mathbb{A} and the full subcategory of finitely generated free models.

Exercise 1.2.16. Prove theorem 1.2.14.

1.2.3 Algebraic categories

Given an *arbitrary* category \mathcal{A} , we may ask: *When is \mathcal{A} the category of models for some algebraic theory?* Such categories are sometimes called *varieties*, at least in universal algebra, and there are well-known *recognition theorems* such as Birkhoff’s famous HSP-theorem, which says that a class of interpretations for some fixed signature are all those satisfying a set of equations if the class is closed under Products, Subalgebras, and Homomorphic images (i.e. quotients by an algebra congruence). Toward the goal of “recognizing” a *category* of algebras (without being given the signature!), let us define:

Definition 1.2.17. An *algebraic category* \mathcal{A} is a (locally small) category equivalent to one of the form

$$\mathbf{Hom}_{\mathbf{FP}}(\mathbb{A}, \mathbf{Set}) \hookrightarrow \mathbf{Set}^{\mathbb{A}}$$

where \mathbb{A} is any small finite product category and $\mathbf{Hom}_{\mathbf{FP}}(\mathbb{A}, \mathbf{Set})$ is the full subcategory of finite product preserving functors. If \mathbb{A} is a Lawvere algebraic theory (i.e. the objects are generated under finite products by a single object), then we will say that \mathcal{A} is a *Lawvere algebraic category*.

If $\mathcal{A} \simeq \text{Hom}_{\text{FP}}(\mathbb{A}, \text{Set})$ is a Lawvere algebraic category, then in particular there will be a forgetful functor, determined by evaluation at the generating object A of \mathbb{A} ,

$$U = \text{eval}_A : \mathcal{A} \rightarrow \text{Set}. \quad (1.24)$$

It follows immediately that U preserves all limits, and one can show without difficulty that it also preserves all filtered colimits (cf. exercise 1.2.23). We require only one further condition to “recognize” \mathcal{A} as algebraic, namely creation of “ U -absolute coequalizers”.

Definition 1.2.18. In any category \mathcal{D} , a coequalizer $c : Y \rightarrow Z$ of maps $a, b : X \rightrightarrows Y$ is *absolute* if, for every category \mathcal{D}' and functor $G : \mathcal{D} \rightarrow \mathcal{D}'$, the map $Gc : GY \rightarrow GZ$ is a coequalizer of the maps $Ga, Gb : GX \rightrightarrows GY$. A functor $F : \mathcal{C} \rightarrow \mathcal{D}$ may be said to *create F -absolute coequalizers* if for every parallel pair of maps $a, b : X \rightrightarrows Y$ in \mathcal{C} and absolute coequalizer $q : FY \rightarrow Q$ of $Fa, Fb : FX \rightrightarrows FY$ in \mathcal{D} , there is a unique object Z and map $c : Y \rightarrow Z$ in \mathcal{C} with $FZ = Q$ and $Fc = q$, which, moreover, is a coequalizer in \mathcal{C} .

$$\begin{array}{ccc} \mathcal{C} & & X \xrightarrow{a} Y \xrightarrow{c} Z \\ \downarrow F & & \downarrow b \\ \mathcal{D} & & FX \xrightarrow{Fa} FY \xrightarrow{q} Q \end{array} \quad (1.25)$$

Thus, roughly, F creates those coequalizers in \mathcal{C} that are absolute in \mathcal{D} .

Theorem 1.2.19. *Given a category \mathcal{A} equipped with a functor $U : \mathcal{A} \rightarrow \text{Set}$, the following conditions are equivalent.*

1. \mathcal{A} is a Lawvere algebraic category, and $U \cong \text{eval}_A : \mathcal{A} \rightarrow \text{Set}$. In more detail, there is a Lawvere algebraic theory \mathbb{A} , and an equivalence,

$$\mathcal{A} \simeq \text{Hom}_{\text{FP}}(\mathbb{A}, \text{Set}) \hookrightarrow \text{Set}^{\mathbb{A}},$$

associating $U : \mathcal{A} \rightarrow \text{Set}$ to the evaluation at the generating object of $A \in \mathbb{A}$.

2. $U : \mathcal{A} \rightarrow \text{Set}$ has a left adjoint $F : \text{Set} \rightarrow \mathcal{A}$, preserves all filtered colimits, and creates U -absolute coequalizers.
3. \mathcal{A} is monadic over Set (via $U : \mathcal{A} \rightarrow \text{Set}$),

$$\mathcal{A} \simeq \text{Set}^T$$

for a finitary monad $T : \text{Set} \rightarrow \text{Set}$.

Proof. (1 \Rightarrow 2) Suppose first that \mathcal{A} is Lawvere algebraic, so

$$\mathcal{A} \simeq \text{Mod}(\mathbb{A}) = \text{Hom}_{\text{FP}}(\mathbb{A}, \text{Set}) \hookrightarrow \text{Set}^{\mathbb{A}}$$

for a Lawvere algebraic theory \mathbb{A} . By theorem 1.2.14 we know that U has a left adjoint $F : \text{Set} \rightarrow \mathcal{A}$. It also preserves filtered colimits because they commute with finite products, and so a filtered colimit of FP functors, calculated in $\text{Set}^{\mathbb{A}}$, is again an FP functor. This suffices, since colimits are computed pointwise in $\text{Set}^{\mathbb{A}}$ and U is an evaluation functor.

For creation of U -absolute coequalizers, suppose we have maps $f, g : A \rightrightarrows B$ in \mathcal{A} and an absolute coequalizer $c : UB \rightarrow C$ for $Uf, Ug : UA \rightrightarrows UB$ in Set ; we want to put an algebra structure on C making c a homomorphism $c : B \rightarrow C$, and a coequalizer of f and g in \mathcal{A} .

$$\begin{array}{ccccc} UA^n & \xrightarrow{Uf^n} & UB^n & \xrightarrow{c^n} & C^n \\ \sigma^A \downarrow & \xrightarrow{Ug^n} & \downarrow \sigma^B & & \downarrow \sigma^C \\ UA & \xrightarrow{Uf} & UB & \xrightarrow{c} & C \\ & \xrightarrow{Ug} & & & \end{array} \quad (1.26)$$

For each function symbol $\sigma \in \Sigma$ we have commutative squares as on the left in the above diagram, because f and g are homomorphisms. It follows by a simple diagram chase that $c \circ \sigma^B$ coequalizes the pair $Uf^n, Ug^n : UA^n \rightrightarrows UB^n$. Since $c : UB \rightarrow C$ is absolute, it is preserved by the functor $(-)^n$, and therefore $c^n : UB^n \rightarrow C^n$ is a coequalizer of Uf^n, Ug^n . There is therefore a unique map $\sigma^C : C^n \rightarrow C$ as indicated, making the right hand square commute. Doing this for each $\sigma \in \Sigma$ gives an interpretation of Σ on C . This is seen to be an algebra structure because the maps c^n are surjections. Thus $c : B \rightarrow C$ becomes a homomorphism, which is easily seen to be a coequalizer in \mathcal{A} .

(2 \Rightarrow 3) Taking the standard monad (T, η, μ) on Set with underlying functor $T = U \circ F$, we want to show that the canonical comparison map

$$\mathcal{A} \rightarrow \text{Set}^T$$

to the category of T -algebras is an isomorphism. This follows by Beck's theorem (see [Lan71, VI.7]) from the condition that U creates absolute coequalizers. Moreover, T preserves filtered colimits (i.e. is “finitary”) because each of F and U do so.

(3 \Rightarrow 1) Let (T, η, μ) be a finitary monad on Set and $U : \text{Set}^T \rightarrow \text{Set}$ the forgetful functor from the category of T -algebras. We want an algebraic theory \mathbb{A} and an equivalence

$$\text{Set}^T \simeq \text{Mod}(\mathbb{A})$$

commuting with U and evaluation at the generator of \mathbb{A} , where recall $\text{Mod}(\mathbb{A}) = \text{Hom}_{\text{FP}}(\mathbb{A}, \text{Set})$. Let

$$\mathbb{A} = (\text{Set}^T)_{\text{fgf}}^{\text{op}} \quad (1.27)$$

be the dual of the full subcategory of finitely generated free T -algebras. The objects of \mathbb{A} are thus of the form T_0, T_1, T_2, \dots where $T_n = T(n)$, equipped with the multiplication $\mu_n : T^2(n) \rightarrow T(n)$ as algebra structure map. Since, as free algebras, $T(n+m) \cong T(n) + T(m)$ we indeed have $T_n \times T_m \cong T_{n+m}$ as objects of \mathbb{A} , and T_1 as the generating object.

By the first two steps of this proof, we know that the algebraic category $\mathbf{Mod}(\mathbb{A})$ is also (finitary) monadic,

$$\mathbf{Mod}(\mathbb{A}) \simeq \mathbf{Set}^M,$$

with monad $M = U_M \circ F_M$, where $F_M \dashv U_M$ is the free-forgetful adjunction for $\mathbf{Mod}(\mathbb{A}) = \mathbf{Hom}_{\mathbf{FP}}(\mathbb{A}, \mathbf{Set})$, and $U_M \cong \mathbf{eval}_{T_1}$. Thus it will suffice to show that $M \cong T$, as monads, in order to conclude that

$$\mathbf{Mod}(\mathbb{A}) \simeq \mathbf{Set}^M \simeq \mathbf{Set}^T.$$

Moreover, since both M and T are finitary, it suffices to show that their respective restrictions to the dense subcategory $\mathbf{Set}_{\text{fin}} \hookrightarrow \mathbf{Set}$ are isomorphic. By (1.22), we know that the finite free functor $F_M(n)$ has the form

$$F_M(n) = \mathbf{Hom}_{\mathbb{A}}(T_n, -) = \mathbf{Hom}_{(\mathbf{Set}^T)_{\text{fgf}}}(-, \langle T(n), \mu_n \rangle)$$

thus using the fact that $U_M \cong \mathbf{eval}_{T_1}$ we see that

$$\begin{aligned} M(n) &= U_M(F_M(n)) = U_M(\mathbf{Hom}_{(\mathbf{Set}^T)_{\text{fgf}}}(-, \langle T(n), \mu_n \rangle)) \\ &\cong \mathbf{Hom}_{(\mathbf{Set}^T)_{\text{fgf}}}(\langle T(1), \mu_1 \rangle, \langle T(n), \mu_n \rangle) \\ &\cong \mathbf{Hom}_{\mathbf{Set}}(1, T(n)) \cong T(n). \end{aligned}$$

□

This theorem can be used to show, for example, that the theory of posets cannot be given an equational reformulation (unlike \wedge -semilattices, which can), by showing that the category \mathbf{Pos} is not Lawvere algebraic (via the underlying set functor $U : \mathbf{Pos} \rightarrow \mathbf{Set}$).

Exercise 1.2.20. Show this. (*Hint:* determine the left adjoint of U , and the resulting monad $U \circ F : \mathbf{Set} \rightarrow \mathbf{Set}$.)

Remark 1.2.21. Another “recognition theorem” that can be found in [Bor94] is the following:

Theorem (Borceux II.3.9). *Given a category \mathcal{A} , equipped with a functor $U : \mathcal{A} \rightarrow \mathbf{Set}$, the following conditions are equivalent.*

1. \mathcal{A} is equivalent to the category of models of some Lawvere algebraic theory \mathbb{T} ,

$$\mathcal{A} \simeq \mathbf{Mod}(\mathbb{T})$$

with $U : \mathcal{A} \rightarrow \mathbf{Set}$ the corresponding forgetful functor.

2. \mathcal{A} has coequalizers and kernel pairs, and $U : \mathcal{A} \rightarrow \mathbf{Set}$ has a left adjoint $F : \mathbf{Set} \rightarrow \mathcal{A}$, preserves all filtered colimits and regular epimorphisms, and reflects isomorphisms.

Exercise 1.2.22. A *split coequalizer* for maps $f, g : A \rightrightarrows B$ is a map $e : B \rightarrow C$ together with s and t as indicated below,

$$\begin{array}{ccccc} A & \xrightarrow{f} & B & \xrightarrow{e} & C \\ & \searrow g & \swarrow & \searrow s & \\ & & & & \\ & \swarrow t & \nwarrow & \swarrow & \end{array} \quad (1.28)$$

satisfying the equations

$$ef = eg, \quad ft = 1_B, \quad gt = se, \quad es = 1_C.$$

Show that a split coequalizer is an absolute coequalizer.

Exercise 1.2.23. A filtered colimit of algebras can be described directly as follows: First consider the case of sets. Let the index category \mathbb{J} be filtered and $D : \mathbb{J} \rightarrow \mathbf{Set}$ a diagram. The colimiting set $\text{colim}_j D_j$ can be described as the quotient of the coproduct $(\coprod_j D_j)/\sim$, where the equivalence relation \sim is defined by:

$$(d_i \in D_i) \sim (d_j \in D_j) \Leftrightarrow t_{ik}(d_i) = t_{jk}(d_j) \text{ for some } t_{ik} : i \rightarrow k \text{ and } t_{jk} : j \rightarrow k \text{ in } \mathbb{J}.$$

1. Show that this is an equivalence relation using the filteredness of \mathbb{J} .
2. Now assume that the D_j all have an algebra structure and that all the transition maps $t_{ik} : D_i \rightarrow D_k$ are homomorphisms. Show that the colimit set $D_\infty = \text{colim}_j D_j$ is also an algebra of the same kind by defining each of the operations $\sigma_\infty : D_\infty \times \dots \times D_\infty \rightarrow D_\infty$ on equivalence classes as

$$\sigma_\infty \langle [d_i], \dots, [d'_j] \rangle = [\sigma_k \langle t_{ik}(d_i), \dots, t_{jk}(d'_j) \rangle]$$

for suitable k . Show that this is well-defined, and that D_∞ , so equipped, also satisfies the equations satisfied by the D_j .

Example 1.2.24. A field is a ring in which every non-zero element has a multiplicative inverse. The theory of fields is (apparently) not algebraic, because the axiom

$$x \neq 0 \Rightarrow \exists y(x \cdot y = 1)$$

is not simply an equation. But in principle there could be an equivalent algebraic formulation of the theory which would somehow circumvent this problem. We can show that this is not the case by proving that the category **Field** of fields and field homomorphisms is not algebraic.

First observe that a category of models $\mathbf{Mod}(\mathbb{A})$ always has a terminal object because \mathbf{Set} has a terminal object 1 , and the constant functor $\Delta_1 : \mathbb{A} \rightarrow \mathbf{Set}$ which maps everything to 1 is a model. The functor Δ_1 is the terminal object in $\mathbf{Mod}(\mathbb{A})$ because it is the terminal functor in the functor category $\mathbf{Set}^{\mathbb{A}}$. In order to see that **Field** is not algebraic it thus suffices to show that there is no terminal field.

Exercise 1.2.25. Show that the category \mathbf{Field} does not have a terminal object. (Hint: suppose that T is the terminal field and use the unique homomorphism $\mathbb{Z}_2 \rightarrow T$ to see that $1 + 1 = 0$ in T , then reason similarly using the unique homomorphism $\mathbb{Z}_3 \rightarrow T$.)

1.2.4 Algebraic functors

Now that we know by Theorem 1.2.19 what the algebraic categories are, we would like to know what the “algebraic functors” between them are. These will be the functors induced by “syntactic translations” between theories, in the following sense. Classically, a *syntactic translation* of one algebraic theory into another may be defined as an assignment of types to types and terms to terms, respecting the tupling operations and substitutions of terms for variables. Such a translation can of course be described abstractly as a finite product preserving functor,

$$T : \mathbb{A} \rightarrow \mathbb{B}$$

between the associated (Lawvere) algebraic theories. Every such translation then induces a functor on the semantics, just by precomposition:

$$T^*(M) = M \circ T.$$

$$\mathbf{Mod}(\mathbb{A}) \xleftarrow{T^*} \mathbf{Mod}(\mathbb{B}) \tag{1.29}$$

$$\begin{array}{ccc} \mathbb{A} & \xrightarrow{T} & \mathbb{B} \\ & \searrow T^*(M) & \downarrow M \\ & & \mathbf{Set} \end{array}$$

Such a functor may be regarded as being “definable” by the translation.

For instance, let $\mathbb{A}_0 = (\mathbf{Set}_{\mathbf{fin}})^{\mathbf{op}}$ be (the classifying category of) the trivial theory \mathbb{T}_0 of an object (so $\mathbb{A}_0 \simeq \mathcal{C}_{\mathbb{T}_0}$), so that $\mathbf{Mod}(\mathbb{A}_0) \simeq \mathbf{Set}$. Then for any Lawvere algebraic theory \mathbb{A} , the generating object $A \in \mathbb{A}$ has a classifying functor

$$A : \mathbb{A}_0 \rightarrow \mathbb{A}$$

which induces the forgetful functor by precomposition:

$$\mathbf{Set} \simeq \mathbf{Mod}(\mathbb{A}_0) \xleftarrow{A^*} \mathbf{Mod}(\mathbb{A})$$

$$\begin{array}{ccc} \mathbb{A}_0 & \xrightarrow{A} & \mathbb{A} \\ & \searrow A^* M & \downarrow M \\ & & \mathbf{Set} \end{array}$$

More generally, by the universal property of \mathbb{A} , a translation $T : \mathbb{A} \rightarrow \mathbb{B}$ corresponds to a “model of \mathbb{A} in the syntax of \mathbb{B} ”:

$$\frac{T : \mathbb{A} \rightarrow \mathbb{B}}{\hat{T} \in \mathbf{Mod}(\mathbb{A}, \mathbb{B})}$$

For instance, since every ring R has an underlying group $|R|_{\mathbf{Grp}}$, the universal ring $\mathcal{U}_{\mathbb{R}}$ in the theory of rings \mathbb{R} also has one $|\mathcal{U}_{\mathbb{R}}|_{\mathbf{Grp}}$, which is therefore classified by an essentially unique functor from the theory of groups,

$$|\mathcal{U}_{\mathbb{R}}|_{\mathbf{Grp}}^{\sharp} : \mathbb{G} \longrightarrow \mathbb{R},$$

which is essentially determined by taking the universal group $\mathcal{U}_{\mathbb{G}}$ to $|\mathcal{U}_{\mathbb{R}}|_{\mathbf{Grp}}$:

$$|\mathcal{U}_{\mathbb{R}}|_{\mathbf{Grp}}^{\sharp}(\mathcal{U}_{\mathbb{G}}) = |\mathcal{U}_{\mathbb{R}}|_{\mathbf{Grp}}.$$

This translation induces a functor in the opposite direction on the corresponding categories of models,

$$(|\mathcal{U}_{\mathbb{R}}|_{\mathbf{Grp}}^{\sharp})^* : \mathbf{Ring} \longrightarrow \mathbf{Group}, \quad (1.30)$$

taking a ring $R : \mathbb{R} \rightarrow \mathbf{Set}$ to the group,

$$(|\mathcal{U}_{\mathbb{R}}|_{\mathbf{Grp}}^{\sharp})^*(R) = R \circ (|\mathcal{U}_{\mathbb{R}}|_{\mathbf{Grp}}^{\sharp}) : \mathbb{G} \longrightarrow \mathbf{Set}$$

which takes the universal group $\mathcal{U}_{\mathbb{G}}$ to :

$$(R \circ (|\mathcal{U}_{\mathbb{R}}|_{\mathbf{Grp}}^{\sharp}))\mathcal{U}_{\mathbb{G}} = R(|\mathcal{U}_{\mathbb{R}}|_{\mathbf{Grp}}) = |R|_{\mathbf{Grp}},$$

This is of course just the underlying group functor $| - |_{\mathbf{Grp}} : \mathbf{Ring} \rightarrow \mathbf{Group}$.

More simply put, the underlying group functor $| - |_{\text{Grp}} : \text{Ring} \rightarrow \text{Group}$ is *represented* by the translation induced by the “universal underlying group of a ring” $|\mathcal{U}_{\mathbb{R}}|_{\text{Grp}}$,

$$\begin{array}{ccc}
 \text{Ring} & \xrightarrow{| - |_{\text{Grp}}} & \text{Group} \\
 \downarrow \simeq & & \downarrow \simeq \\
 \text{Mod}(\mathbb{R}) & & \text{Mod}(\mathbb{G}) \\
 \downarrow \simeq & & \downarrow \simeq \\
 \text{Hom}_{\text{FP}}(\mathbb{R}, \text{Set}) & \xrightarrow{|\mathcal{U}_{\mathbb{R}}|_{\text{Grp}}^*} & \text{Hom}_{\text{FP}}(\mathbb{G}, \text{Set})
 \end{array} \tag{1.31}$$

$$\begin{array}{ccc}
 & & \mathbb{G} \\
 & \xleftarrow{|\mathcal{U}_{\mathbb{R}}|_{\text{Grp}}} & \\
 \mathbb{R} & & \\
 \downarrow R & \swarrow |R| & \\
 \text{Set} & &
 \end{array}$$

We can now ask: *Which functors $f : \text{Mod}(\mathbb{B}) \rightarrow \text{Mod}(\mathbb{A})$ between algebraic categories are of the form $f = T^*$ for a translation $T : \mathbb{A} \rightarrow \mathbb{B}$ of theories?* Let us call these *algebraic functors*. We consider first the case where \mathbb{A} and \mathbb{B} are Lawvere algebraic and T takes the generator A of \mathbb{A} to the generator B of \mathbb{B} ,

$$T(A) \cong B$$

as in the foregoing example. Then T^* commutes with the forgetful functors, which, recall, are evaluation at the generators, $U_{\mathbb{A}}(M) = M(A)$:

$$\begin{array}{ccc}
 \text{Mod}(\mathbb{B}) & \xrightarrow{T^*} & \text{Mod}(\mathbb{A}) \\
 & \searrow U_{\mathbb{B}} & \swarrow U_{\mathbb{A}} \\
 & \text{Set} &
 \end{array}$$

This is simply because

$$(U_{\mathbb{A}} \circ T^*)(M) = U_{\mathbb{A}}(M \circ T) = (M \circ T)(A) \cong M(T(A)) \cong M(B) = U_{\mathbb{B}}(M).$$

We shall see that this condition is in fact already sufficient! We first require the following.

Lemma 1.2.26. *Let \mathcal{A} be Lawvere algebraic. The forgetful functor $U : \mathcal{A} \rightarrow \text{Set}$ not only preserves, but also creates all small limits, filtered colimits, and regular epimorphisms.*

Proof. This is a standard fact, and not difficult to prove; the reader can either prove it as an exercise, or look it up in [ALR03]. \square

Proposition 1.2.27. *For Lawvere algebraic theories \mathbb{A} and \mathbb{B} , every functor $f : \mathbf{Mod}(\mathbb{B}) \rightarrow \mathbf{Mod}(\mathbb{A})$ with*

$$U_{\mathbb{B}} \cong U_{\mathbb{A}} \circ f,$$

is of the form $f \cong T^$ for a unique (up to iso) FP-functor $T : \mathbb{A} \rightarrow \mathbb{B}$.*

Proof 1. Consider the diagram

$$\begin{array}{ccc} \mathbf{Mod}(\mathbb{B}) & \xrightarrow{f} & \mathbf{Mod}(\mathbb{A}) \\ & \searrow U_{\mathbb{B}} & \nearrow U_{\mathbb{A}} \\ & \mathbf{Set} & \end{array} \quad \begin{array}{ccc} & \nwarrow F_{\mathbb{B}} & \\ & \nwarrow F_{\mathbb{A}} & \end{array}$$

where, in each pair, we have an adjunction $F \dashv U$ by Theorem 1.2.19, and the central triangle commutes up to iso. We seek an FP-functor $T : \mathbb{A} \rightarrow \mathbb{B}$ such that $f \cong T^*$.

Since by Lemma 1.2.26, $U_{\mathbb{A}}$ creates limits, and $U_{\mathbb{A}} \circ f \cong U_{\mathbb{B}}$ preserves them, it follows that f also preserves them. In more detail, given a diagram $D : J \rightarrow \mathbf{Mod}(\mathbb{B})$ with limit $\lim_j D_j$, we have $f \lim_j D_j \cong \lim_j f D_j$ just if $U_{\mathbb{A}} f \lim_j D_j \cong \lim_j U_{\mathbb{A}} f D_j$, since $U_{\mathbb{A}}$ creates limits. But

$$U_{\mathbb{A}} f \lim_j D_j \cong U_{\mathbb{B}} \lim_j D_j \cong \lim_j U_{\mathbb{B}} D_j \cong \lim_j U_{\mathbb{A}} f D_j$$

since $U_{\mathbb{A}} f \cong U_{\mathbb{B}}$ and $U_{\mathbb{B}}$ preserves limits. The same argument applies to filtered colimits (and regular epis).

Now both $\mathbf{Mod}(\mathbb{A})$ and $\mathbf{Mod}(\mathbb{B})$ are *locally finitely presentable* (LFP): a cocomplete category \mathcal{C} is LFP if it has a small subcategory \mathbb{K} of finitely presentable objects k such that every object c in \mathcal{C} is a filtered colimit of all the maps $k \rightarrow c$.¹ A category of algebras like $\mathbf{Mod}(\mathbb{A})$ is LFP because it is a reflective subcategory of a functor category $\mathbf{Set}^{\mathbb{A}}$, with a filtered-colimit preserving inclusion (cf. [AR94]). Thus, since $f : \mathbf{Mod}(\mathbb{B}) \rightarrow \mathbf{Mod}(\mathbb{A})$ preserves (small) limits and filtered colimits, it therefore has a left adjoint

$$f_! : \mathbf{Mod}(\mathbb{A}) \rightarrow \mathbf{Mod}(\mathbb{B})$$

by the Adjoint Functor Theorem. Indeed, one can check the solution set condition directly (see [Lan71, AR94]). From $U_{\mathbb{B}} \cong U_{\mathbb{A}} \circ f$, it then follows that $F_{\mathbb{B}} \cong f_! \circ F_{\mathbb{A}}$. In particular, for the generators $A = F_{\mathbb{A}}(1)$ and $B = F_{\mathbb{B}}(1)$ we have $f_!(A) = f_! F_{\mathbb{A}}(1) \cong F_{\mathbb{B}}(1) = B$, and then $f_!(\coprod_n A) = \coprod_n B$ since $f_!$ preserves coproducts.

Since we know by Theorem 1.2.15 that $\mathbb{A} \simeq \mathbf{mod}(\mathbb{A})^{\mathrm{op}}$, the dual of the subcategory of finitely generated free models, and the same holds for \mathbb{B} , the left adjoint $f_! : \mathbf{Mod}(\mathbb{A}) \rightarrow$

¹An object k is called *finitely presentable* if $\mathbf{Hom}(k, -)$ preserves filtered colimits, see [AR94]

$\mathbf{Mod}(\mathbb{B})$ restricts and dualizes to an FP “translation of theories” $T : \mathbb{A} \rightarrow \mathbb{B}$ as in,

$$\begin{array}{ccc} \mathbb{A} & \xrightarrow{\quad T \quad} & \mathbb{B} \\ \downarrow y^{\text{op}} & & \downarrow y^{\text{op}} \\ \mathbf{Mod}(\mathbb{A})^{\text{op}} & \xrightarrow{\quad f_!^{\text{op}} \quad} & \mathbf{Mod}(\mathbb{B})^{\text{op}} \end{array}$$

such that

$$T(A^n) = T(F_{\mathbb{A}}(n)) = f_!^{\text{op}}(F_{\mathbb{A}}(n)) \cong F_{\mathbb{B}}(n) = B^n. \quad (1.32)$$

It remains to see that $f \cong T^* : \mathbf{Mod}(\mathbb{B}) \rightarrow \mathbf{Mod}(\mathbb{A})$. Indeed, for any model $M : \mathbb{B} \rightarrow \mathbf{Set}$, we have

$$\begin{aligned} f(M)(A) &\cong \mathbf{Set}^{\mathbb{A}}(yA, f(M)) && \text{Yoneda} \\ &\cong \mathbf{Mod}(\mathbb{A})(yA, f(M)) && \mathbf{Mod}(\mathbb{A}) \hookrightarrow \mathbf{Set}^{\mathbb{A}} \\ &\cong \mathbf{Mod}(\mathbb{B})(f_!(yA), M) && f_! \dashv f \\ &\cong \mathbf{Mod}(\mathbb{B})(y(TA), M) && (1.32) \\ &\cong \mathbf{Set}^{\mathbb{B}}(y(TA), M) && \mathbf{Mod}(\mathbb{A}) \hookrightarrow \mathbf{Set}^{\mathbb{A}} \\ &\cong M(TA) && \text{Yoneda} \\ &\cong T^*(M)(A), \end{aligned}$$

naturally in M . The case of an arbitrary object $A^n \in \mathbb{A}$ follows, since the models $f(M)$ and $T^*(M)$ preserve products. \square

Corollary 1.2.28. *For a functor $f : \mathbf{Mod}(\mathbb{B}) \rightarrow \mathbf{Mod}(\mathbb{A})$ between Lawvere algebraic categories, the following are equivalent.*

1. f commutes with the forgetful functors, $U_{\mathbb{A}} \circ f \cong U_{\mathbb{B}}$.
2. f is algebraic: $f = T^*$, for an FP functor $T : \mathbb{A} \rightarrow \mathbb{B}$ that preserves the generator, $T(A) \cong B$.

\square

The corollary tells us that functors between the (semantic) categories of algebraic structures that respect the underlying sets correspond to translations of their syntactic presentations. In fact, even more is true: there is a *biequivalence* of categories

$$\mathbf{LAlgCat}/\mathbf{Set} \simeq (\mathbf{Set}_{\text{fin}}^{\text{op}}/\mathbf{LAlgTh})^{\text{op}} \simeq (\mathbf{LAlgTh}_{\bullet})^{\text{op}}, \quad (1.33)$$

where on the left we have the category of Lawvere algebraic categories \mathcal{A} , equipped with their canonical forgetful functors $U_{\mathbb{A}} : \mathcal{A} \rightarrow \mathbf{Set}$, and algebraic functors between them that commute up to natural isomorphism over the base, and on the right (the dual of) the category of Lawvere algebraic theories and FP functors that preserve the generator.

A “biequivalence” is like an equivalence, but only up to equivalence! Observe that the left-hand side of (1.33) is not even locally small, while the entire category on the right is small. (See e.g. [ARV10] for details.) This “global” Syntax-Semantics duality can be extended even further, as sketched in the following exercises.

Exercise 1.2.29. Show that for any Lawvere algebraic theory \mathbb{A} , the full inclusion $\mathbf{Mod}(\mathbb{A}) \hookrightarrow \mathbf{Set}^{\mathbb{A}}$ has a left adjoint. (*Hint:* use the Adjoint Functor Theorem.)

Exercise 1.2.30. Assuming the result of the previous exercise, show that the precomposition functor $T^* : \mathbf{Mod}(\mathbb{B}) \rightarrow \mathbf{Mod}(\mathbb{A})$ induced by *any* translation $T : \mathbb{A} \rightarrow \mathbb{B}$ (not necessarily preserving the generator) always has a left adjoint $T_! : \mathbf{Mod}(\mathbb{A}) \rightarrow \mathbf{Mod}(\mathbb{B})$.

Exercise 1.2.31. Assuming the results of the previous two exercises, show that an algebraic functor $f : \mathbf{Mod}(\mathbb{B}) \rightarrow \mathbf{Mod}(\mathbb{A})$, induced by a translation $T : \mathbb{A} \rightarrow \mathbb{B}$ as $f = T^*$, satisfies the following conditions:

- (i) f preserves limits.
- (ii) f preserves filtered colimits.
- (iii) f preserves regular epimorphisms.

Hint: Since f has a left adjoint $f_! : \mathbf{Mod}(\mathbb{A}) \rightarrow \mathbf{Mod}(\mathbb{B})$, we know that $f_!(A) \cong B^n$ for some $0 \leq n$. Now use $\mathbb{B} \simeq \mathbf{mod}(\mathbb{B})^{\mathrm{op}}$.

Remark 1.2.32. The converse of Exercise 1.2.31 holds as well, under a certain condition on the syntactic categories, to be explained below. We then obtain a duality of the form

$$\mathbf{LAlgCat} \simeq \mathbf{LAlgTh}^{\mathrm{op}}, \quad (1.34)$$

generalizing (1.33) by eliminating the “base point”. This generalizes even further to “many-sorted” algebraic theories \mathbb{A} not assumed to be generated by a single object, and thus given simply by small FP categories. The corresponding semantic category $\mathbf{Mod}(\mathbb{A})$ still consists of all FP-functors $\mathbb{A} \rightarrow \mathbf{Set}$, and is still locally finitely presentable. The question, when is a “semantic functor”

$$f : \mathbf{Mod}(\mathbb{B}) \rightarrow \mathbf{Mod}(\mathbb{A})$$

between such algebraic categories induced by a “syntactic translation” $T : \mathbb{A} \rightarrow \mathbb{B}$ of such algebraic theories can also be answered in this more general setting, determining a general notion of an *algebraic functor*: it is again one that preserves all limits, filtered colimits, and regular epimorphisms. The resulting duality

$$\mathbf{AlgCat} \simeq \mathbf{AlgTh}^{\mathrm{op}}, \quad (1.35)$$

requires a technical condition on the syntactic side, however; namely, that the algebraic theories are closed under retracts—as does (1.34). See [ALR03] for details.

1.2.5 Dualities for algebraic theories

Let us now summarize, and generalize, the different dualities for algebraic theories that arose in this chapter. See the references [ALR03, ARV10] for the details.

In Section 1.2.1, we had what we called the *logical duality* relating an individual algebraic theory \mathbb{T} and its category of models $\mathbf{Mod}(\mathbb{T})$, given by an equivalence of categories

$$\mathcal{C}_{\mathbb{T}}^{\text{op}} \simeq \mathbf{mod}(\mathbb{T}) \hookrightarrow \mathbf{Mod}(\mathbb{T}),$$

between the classifying category $\mathcal{C}_{\mathbb{T}}$ (which can be constructed syntactically) and a full subcategory of the semantics $\mathbf{mod}(\mathbb{T}) \hookrightarrow \mathbf{Mod}(\mathbb{T})$, consisting of the finitely generated free models.

The “semantics” functor \mathbf{Mod} is represented by assigning to each model M an essentially unique FP functor $M^{\sharp} : \mathcal{C}_{\mathbb{T}} \rightarrow \mathbf{Set}$, providing an equivalence of categories,

$$\mathbf{Mod}(\mathbb{T}) \simeq \mathbf{Hom}_{\mathbf{FP}}(\mathcal{C}_{\mathbb{T}}, \mathbf{Set}). \quad (1.36)$$

By (1.36), the assignment $\mathbb{T} \mapsto \mathbf{Mod}(\mathbb{T})$ is then *contravariantly functorial* in the theory \mathbb{T} . Regarding a theory abstractly as a small finite product category \mathbb{A} , and a syntactic translation as an FP functor $T : \mathbb{A} \rightarrow \mathbb{B}$, this provides a global semantic representation of the syntax of algebraic theories,

$$\mathbf{Mod} : \mathbf{AlgTh}^{\text{op}} \rightarrow \mathbf{Cat}.$$

We can recognize the essential image of the semantics functor \mathbf{Mod} as consisting of certain *locally finitely presentable* categories $\mathcal{A} = \mathbf{Mod}(\mathbb{A})$, which may be called *algebraic categories*.²

An algebraic theory \mathbb{A} can then be recovered functorially from its algebraic category of models $\mathcal{A} = \mathbf{Mod}(\mathbb{A})$ as the finitely generated free models. As remarked earlier, these can now also be determined “intrinsically”, by considering the category of all *algebraic functors*

$$f : \mathcal{A} \rightarrow \mathbf{Set},$$

defined as functors preserving limits, filtered colimits, and regular epimorphisms. Indeed, this follows from the duality

$$\mathbf{AlgTh}^{\text{op}} \simeq \mathbf{AlgCat}, \quad (1.37)$$

by taking $\mathbf{Set} = \mathbf{Mod}(\mathbb{A}_0)$, where $\mathbb{A}_0 = \mathbf{Set}_{\mathbf{fin}}^{\text{op}}$ is the free FP category on one object (which we recognized in Example 1.2.4 as the classifying category $\mathcal{C}_{\mathbb{T}_0}$ of the trivial theory \mathbb{T}_0), so that we have a sequence of equivalences:

$$\begin{array}{ccc} \mathcal{A} & \longrightarrow & \mathbf{Set} \\ \hline \mathbf{Mod}(\mathbb{A}) & \longrightarrow & \mathbf{Mod}(\mathbb{A}_0) \\ \hline \mathbb{A}_0 & \longrightarrow & \mathbb{A} \\ \hline & & \mathbb{A} \end{array} \quad \begin{array}{c} \mathbf{AlgCat} \\ \mathbf{AlgCat} \\ \mathbf{AlgTh} \end{array}$$

²These can be characterized as cocomplete categories \mathcal{A} having a set \mathbf{G} of objects such that every $A \in \mathcal{A}$ is a *sifted* colimit of objects $G \in \mathbf{G}$, for each of which $\mathbf{Hom}(G, -)$ preserves sifted colimits. See [ARV10].

In this way, the category **Set** serves as a “dualizing object”, representing both the semantics **Mod** and the syntax **Theory** as contravariant functors,

$$\begin{array}{ccc} & \text{Mod} & \\ \text{AlgTh}^{\text{op}} & \xrightarrow{\quad} & \text{AlgCat} \\ & \xleftarrow{\quad \text{Theory}} & \end{array} \quad (1.38)$$

using the two different structures on **Set**,

$$\begin{aligned} \text{Mod}(\mathbb{A}) &\simeq \text{Hom}_{\text{AlgTh}}(\mathbb{A}, \text{Set}), \\ \text{Theory}(\mathcal{A}) &\simeq \text{Hom}_{\text{AlgCat}}(\mathcal{A}, \text{Set}). \end{aligned}$$

The functors in (1.38) do *not* yet form a biequivalence, however, but only an adjunction. The syntax-semantics duality of (1.37) results by cutting down the syntax side **AlgTh** to just those theories in the image of the **Theory** functor. These can be described as those \mathbb{A} for which the unit of the adjunction

$$\eta : \mathbb{A} \rightarrow \text{Theory}(\text{Mod}(\mathbb{A}))$$

is an equivalence. One can show that this holds just if the finite product category \mathbb{A} is closed under retracts, and that this is always the case for $\text{Theory}(\text{Mod}(\mathbb{A}))$, which is then the so-called *Cauchy completion* of \mathbb{A} . See [ARV10].

1.2.6 Definability*

Suppose we have a (conventional, single-sorted) algebraic theory \mathbb{T} . Then a term in context $(x_1, \dots, x_n \mid t)$ determines, for each \mathbb{T} -algebra A (in **Set**), an operation

$$t^A : A^n \rightarrow A,$$

that commutes with every homomorphism $h : A \rightarrow B$,

$$\begin{array}{ccc} A^n & \xrightarrow{h^n} & B^n \\ t^A \downarrow & & \downarrow t^B \\ A & \xrightarrow{h} & B. \end{array} \quad (1.39)$$

Suppose we are just given a family of operations $(f_A : A^n \rightarrow A)_{A \in \text{Mod}(\mathbb{T})}$ commuting with all homomorphisms, in the sense of (1.39). Are they necessarily the interpretations of some term t built up from the signature $\Sigma_{\mathbb{T}}$? The answer is yes, and it’s now easy to show.

Proposition 1.2.33. *Given a family $(f_A : A^n \rightarrow A)_{A \in \mathbf{Mod}(\mathbb{T})}$ of operations on \mathbb{T} -algebras commuting with all homomorphisms $h : A \rightarrow B$,*

$$\begin{array}{ccc} A^n & \xrightarrow{h^n} & B^n \\ f_A \downarrow & & \downarrow f_B \\ A & \xrightarrow{h} & B \end{array} \quad (1.40)$$

there is a term in context $(x_1, \dots, x_n \mid t)$ such that $f_A = t^A$ for each algebra A . Moreover, t is unique up to \mathbb{T} -provable equality.

Proof. Such a family is exactly a natural transformation $f : U^n \rightarrow U$ for the underlying set functor $U : \mathbf{Mod}(\mathbb{T}) \rightarrow \mathbf{Set}$. But both U and its n -fold power U^n are representable, by finitely generated free algebras, namely $U \cong \mathbf{Mod}(\mathbb{T})(F(1), -)$ and $U^n \cong \mathbf{Mod}(\mathbb{T})(F(n), -)$, and these finitely generated free algebras are objects of the classifying category $\mathcal{C}_{\mathbb{T}} \simeq \mathbf{mod}(\mathbb{T})^{\text{op}}$. Since the composite functor

$$\mathbf{mod}(\mathbb{T})^{\text{op}} \hookrightarrow \mathbf{Mod}(\mathbb{T})^{\text{op}} \hookrightarrow \mathbf{Set}^{\mathbf{Mod}(\mathbb{T})}$$

is full and faithful, the natural transformation $f : U^n \rightarrow U$ comes from a unique arrow $F(n) \rightarrow F(1)$ in $\mathbf{mod}(\mathbb{T})^{\text{op}}$, which therefore corresponds to (the equivalence class of) a term

$$(x_1, \dots, x_n \mid t) : [x_1, \dots, x_n] \rightarrow [x_1]$$

in the syntax of \mathbb{T} , which is unique up to \mathbb{T} -provable equality. \square

A more difficult question to answer, but one to which our machinery also applies, is the following. Suppose we extend \mathbb{T} to a new theory \mathbb{T}' by adding a single function symbol f , together with some new equations between terms of \mathbb{T}' (but not so many that new equations are implied between terms of \mathbb{T}). Consider the resulting FP-functor $e : \mathcal{C}_{\mathbb{T}} \rightarrow \mathcal{C}_{\mathbb{T}'}$ classifying the underlying \mathbb{T} -model of the universal \mathbb{T}' -model. Precomposition with e determines a (relative) forgetful functor $E = e^* : \mathbf{Mod}(\mathbb{T}') \rightarrow \mathbf{Mod}(\mathbb{T})$. Under what conditions on the “syntactic extension” $e : \mathcal{C}_{\mathbb{T}} \rightarrow \mathcal{C}_{\mathbb{T}'}$ is this functor $E : \mathbf{Mod}(\mathbb{T}') \rightarrow \mathbf{Mod}(\mathbb{T})$ full? faithful? essentially surjective? By the foregoing proposition it is all three—*i.e.* an equivalence of categories of models—if the new operation f is already *definable* by a term t in \mathbb{T} , in the sense that $\mathbb{T}' \vdash f(x_1, \dots, x_n) = t(x_1, \dots, x_n)$. The individual questions are good ones for further study. (See [Makzz] for related results.)

Bibliography

- [AGH21] S. Awodey, N. Gambino, and S. Hazratpour. Kripke-Joyal forcing for type theory and uniform fibrations, October 2021. Preprint available as <https://arxiv.org/abs/2110.14576>.
- [AK08] Steve Awodey and Kohei Kishida. Topology and modality: Topological semantics for first-order modal logic. *The Review of Symbolic Logic*, 1:146–166, 2008.
- [ALR03] J. Adamek, F. W. Lawvere, and J. Rosiky. On the duality between varieties and algebraic theories. *Algebra Universalis*, 49:35–49, 2003.
- [AR94] Jiri Adamek and Jiri Rosicky. *Locally Presentable and Accessible Categories*. Number 189 in London Mathematical Society Lecture Notes. Cambridge University Press, 1994.
- [AR11] S. Awodey and F. Rabe. Kripke semantics for Martin-Löf’s extensional type theory. *Logical Methods in Computer Science*, 7(3):1–25, 2011.
- [ARV10] J. Adamek, J. Rosicky, and E.M. Vitale. *Algebraic Theories*. Cambridge University Press, 2010.
- [Awo00] Steve Awodey. Topological representation of the λ -calculus. *Mathematical Structures in Computer Science*, 10:81–96, 2000.
- [Awo10] Steve Awodey. *Category Theory*. Number 52 in Oxford Logic Guides. Oxford University Press, 2010.
- [Awo21] Steve Awodey. Sheaf representations and duality in logic. In C. Casadio and P.J. Scott, editors, *Joachim Lambek: The Interplay of Mathematics, Logic, and Linguistics*. Springer, 2021. arXiv:2001.09195.
- [Bir35] Garrett Birkhoff. On the structure of abstract algebras. *Proc. Camb. Philos. Soc.*, 31:433–454, 1935.
- [Bor94] F. Borceux. *Handbook of Categorical Algebra II. Categories and Structures*, volume 51 of *Encyclopedia of Mathematics and Its Applications*. Cambridge University Press, 1994.

- [But98] C. Butz. Regular categories and regular logic. BRICS Lecture Series, 1998.
- [Fre72] Peter Freyd. Aspects of topoi. *Bulletin of the Australian Mathematical Society*, 7:1–76, 1972.
- [GER96] Housman Zolfaghari Gonzalo E. Reyes. Bi-heyting algebras, toposes and modalities. *J. Phi. Logic*, 25:25–43, 1996.
- [Joh82] P.T. Johnstone. *Stone Spaces*. Number 3 in Cambridge studies in advanced mathematics. Cambridge University Press, 1982.
- [Joh03] P.T. Johnstone. *Sketches of an Elephant: A Topos Theory Compendium*, 2 vol.s. Number 43 in Oxford Logic Guides. Oxford University Press, 2003.
- [Lan71] Saunders Mac Lane. *Categories for the Working Mathematician*. Springer-Verlag, New York, 1971.
- [Law63a] F. W. Lawvere. Functorial semantics of algebraic theories. Ph.D. thesis, Columbia University, 1963.
- [Law63b] F. W. Lawvere. Functorial semantics of algebraic theories. *Proc. Nat. Acad. Sci.*, 50:869–872, 1963.
- [Law65] F. W. Lawvere. Algebraic theories, algebraic categories, and algebraic functors. In *The Theory of Models*, pages 413–418. North-Holland, 1965.
- [Law69] F.W. Lawvere. Adjointness in foundations. *Dialectica*, 23:281–296, 1969.
- [Law70] F.W. Lawvere. Equality in hyperdoctrines and comprehension schema as an adjoint functor. *Proceedings of the AMS Symposium on Pure Mathematics XVII*, pages 1–14, 1970.
- [Law91] F. W. Lawvere. Intrinsic co-heyting boundaries and the leibniz rule in certain toposes. In G. Rosolini A. Carboni, M. Pedicchio, editor, *Category Theory - Como 1990*, number 1488 in LNM. Springer-Verlag, Heidelberg, 1991.
- [Makzz] Michael Makkai. Duality and definability. *Memiors of the AMS*, nn:xx–yy, zzzz.
- [McC93] W. McCune. Single axioms for groups and abelian groups with various operations. *Journal of Automated Reasoning*, 10(1):1–13, 1993.
- [MH92] Michael Makkai and Victor Harnik. Lambek’s categorical proof theory and Läuchli’s abstract realizability. *Journal of Symbolic Logic*, 57(1):200–230, 1992.
- [ML84] Per Martin-Löf. *Intuitionistic type theory*, volume 1 of *Studies in Proof Theory*. Bibliopolis, 1984.

- [MM92] S. Mac Lane and I. Moerdijk. *Sheaves in Geometry and Logic. A First Introduction to Topos Theory*. Springer-Verlag, New York, 1992.
- [MR91] Ieke Moerdijk and Gonzalo Reyes. *Models for Smooth Infinitesimal Analysis*. Springer-Verlag, New York, 1991.
- [MR95] Michael Makkai and Gonzalo Reyes. Completeness results for intuitionistic and modal logic in a categorical setting. *Annals of Pure and Applied Logic*, 72:25–101, 1995.
- [PV07] E. Palmgren and S.J. Vickers. Partial horn logic and cartesian categories. *Annals of Pure and Applied Logic*, 145(3):314–353, 2007.
- [Sco70] Dana Scott. Constructive validity. In M. Laudet, D. Lacombe, L. Nolin, and M. Schützenberger, editors, *Symposium on Automatic Demonstration*, volume 125, pages 237–275. Springer-Verlag, 1970.
- [Tai68] William W. Tait. Constructive reasoning. In *Logic, Methodology and Philos. Sci. III (Proc. Third Internat. Congr., Amsterdam, 1967)*, pages 185–199. North-Holland, Amsterdam, 1968.