

Categories of scientific theories

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Abstract: We discuss ways in which category theory might be useful in philosophy of science, in particular for articulating the structure of scientific theories. We argue, moreover, that a categorical approach can transcend the syntax-semantics dichotomy in 20th century philosophy of science.

Keywords: received view of theories, syntactic view of theories, semantic view of theories, categorical logic

Our aim in this article is to recommend category theory to philosophers of science, in particular as a means to articulating the structure of scientific theories. We are not suggesting that we replace first-order logic, model theory, set theory, and similar formal tools with category theory — as if category theory were just one more competitor among various formal approaches to philosophy of science. Much less are we proposing to replace set theory with category theory as the foundation of mathematics. Rather, we suggest that category theory unifies various approaches to formal philosophy of science, and shows that some of the debates between various approaches have been misguided. But most importantly, our proposal is not ideological, i.e. we have no stake in the claim that category theory is the “one and only correct” approach to scientific theories, much less that, “a scientific theory *is* a category.” Rather, we are merely sketching a program of research in formal philosophy of science: we suggest that it might be interesting to think of the “universe” of scientific theories as a *category of categories*, or more precisely, as a *2-category of categories*.

Our proposal includes the idea that familiar scientific theories (e.g. Hamiltonian mechanics, special and general relativity, quantum mechanics, quantum field theory) can themselves fruitfully be described as categories.¹ If

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¹For more on this idea, including evidence of its fruitfulness, see (Weatherall, 2016).

we represent theories this way, then we can take philosophical questions — e.g. are Hamiltonian and Lagrangian mechanics equivalent theories? — make them precise, and then use mathematical tools to answer these questions. We can also suggest various explications of important notions, such as *equivalence* or *reducibility*, and can then try to prove general theorems about such notions. In short, we commend category theory to the attention of technically oriented philosophers of science.

1 Theories as categories

Before we begin to discuss scientific theories, we review some basic notions of categorical logic, in order to frame the discussion of theories as categories. There are two salient ways in which a theory can be thought of as a category — a syntactic way, and a semantic way.

1.1 The syntactic category

In this entire chapter, when we speak of first-order logic, we mean first-order logic with possibly many sorts. Allowing the flexibility of many sorts doesn't truly add to the expressive power of first-order logic; but ignoring the possibility of many sorts can lead to needless confusions (see Barrett and Halvorson, 2015c).

What we mean by “many-sorted” logic is that a signature Σ comes with a (finite) list $\sigma_1, \sigma_2, \dots$ of types, and variables, quantifiers, etc. are tagged by a particular type. For example, for each type σ , there is an equality symbol $=_\sigma$, which can be applied only to terms of type σ . Similarly, each predicate symbol $p \in \Sigma$ has an **arity** $\sigma_1 \times \dots \times \sigma_n$, where $\sigma_1, \dots, \sigma_n \in \Sigma$ are (not necessarily distinct) sort symbols. Likewise, each function symbol $f \in \Sigma$ has an **arity** $\sigma_1 \times \dots \times \sigma_n \rightarrow \sigma$, where $\sigma_1, \dots, \sigma_n, \sigma \in \Sigma$ are again (not necessarily distinct) sort symbols. Lastly, each constant symbol $c \in \Sigma$ is assigned a sort $\sigma \in \Sigma$. In addition to the elements of Σ we also have a stock of variables. We use the letters x, y , and z to denote these variables, adding subscripts when necessary. Each variable has a sort $\sigma \in \Sigma$.

Given a signature Σ , we define the terms and formulas of Σ in the normal way (see Barrett and Halvorson, 2015b). A *theory* T in Σ , is then a set of sentences (or sequents) of Σ . There are, of course, many well known examples of such theories: e.g. the theory of partially ordered sets, the theory of groups, the theory of Boolean algebras, the theory of vector spaces over a field, the theory of categories, etc..

The immediate goal is to associate a category C_T with a theory T . For several reasons, we will suppose that the theory T is formulated in the coherent fragment of first-order logic, whose only connectives are \wedge and \vee , and whose only quantifier is \exists .² There is reason to think that the coherent fragment is adequate to formulate any theory that can be formulated in full first order logic. In particular, via Morleyization, every first-order theory is Morita equivalent to a coherent theory (see Tsementzis, 2015). What’s more, we agree that coherent logic is special: “there are good reasons why it is better to take $L_{\omega\omega}^g$ [the coherent fragment of (finitary) first-order logic] as basic rather than $L_{\omega\omega}$ [full (finitary) first-order logic].” (Makkai and Reyes, 1977, p. 121). In our case, two such reasons seem especially compelling. Firstly, as emphasized by Makkai and Reyes, in coherent logic the distinction between intuitionistic and classical logic essentially disappears. Secondly, restricting ourselves to coherent logic does not practically diminish our expressive power at all: as Johnstone (2002) points out there are very few theories that are useful in mathematical practice that cannot be axiomatized by coherent sentences.

The standard way of building a “syntactic category” for T is described in many works on categorical logic — see (MacLane and Moerdijk, 2012, p. 555), (Makkai and Reyes, 1977, p. 241), (Johnstone, 2002, p. 841), and (van Oosten, 2002, p. 39). In outline: an object of the syntactic category C_T is a formula in context, i.e. if ϕ is a formula of Σ , and if \vec{x} is a string of variables containing all those free in ϕ , then $\{\vec{x}.\phi\}$ is a formula in context. (Note that the objects of C_T depend only on the signature Σ , and not on the theory T .) Defining the arrows for C_T takes a bit more work. Let $\chi(\vec{x}, \vec{y})$ be a formula of Σ , where \vec{x} and \vec{y} are mutually disjoint sequences of variables. We say that $\chi(\vec{x}, \vec{y})$ is a T -provably functional relationship from $\{\vec{x}.\phi\}$ to $\{\vec{y}.\psi\}$ just in case T entails that, “for any \vec{x} such that $\phi(\vec{x})$, there is a unique \vec{y} such that $\psi(\vec{y})$ and $\chi(\vec{x}, \vec{y})$.” (The precise definition can be found in the aforementioned works on categorical logic.) Then we define an arrow from $\{\vec{x}.\phi\}$ to $\{\vec{y}.\psi\}$ to be an equivalence class, relative to T -provable equivalence, of T -provably functional relations from $\{\vec{x}.\phi\}$ to $\{\vec{y}.\psi\}$.

²Strictly speaking this means that a theory T is a set of sequents of the form $\phi \vdash \psi$ where ϕ and ψ are coherent formulas. Alternatively, one can understand such sequents as first-order sentences of the form $\forall \vec{x}(\phi \rightarrow \psi)$ (where \vec{x} includes the unbound variables of both ϕ and ψ). In order not to deviate too much from the standard notation familiar to philosophers and logicians alike we will consider coherent theories to be sets of first-order sentences of the above-described form – this will allow us to speak of truth and satisfaction of a *sentence* rather than of a *sequent*, which is closer to the standard way of thinking about these matters.

The idea of a syntactic category might seem abstract and unfamiliar. But it is a direct generalization of the more familiar idea of a Lindenbaum algebra from propositional logic. Suppose that $\Sigma = \{p_0, p_1, \dots\}$ is propositional signature, and let T be a theory in Σ . In this case, a formula in context simplifies to a sentence; and so the objects of C_T are just sentences. In this case, there is one provably functional relation (up to T -provable equivalence) between ϕ and ψ just in case $T, \phi \vdash \psi$ and otherwise there is no such provably functional relation. In other words, in C_T for a propositional theory T , there is an arrow from ϕ to ψ just in case $T, \phi \vdash \psi$.

Thus, from a theory T (considered as a set of sentences in Σ) we have constructed a category C_T . And we can immediately note that C_T partially eliminates the “language dependence” of T , which was so bemoaned by advocates of the semantic view of theories. Indeed, while T is bound to a particular signature Σ , the syntactic category C_T is independent of signature in the following sense: two theories T and T' , in different signatures, can nonetheless have equivalent syntactic categories.

Furthermore, if our theory is coherent – as we are assuming – then this syntactic category C_T has the structure of a so-called coherent category. Coherent categories are categories that have just the right amount of structure to express models of coherent theories. In particular, they have a notion of conjunction (pullbacks), a notion of disjunction (pullback-stable disjoint coproducts) and a notion of existential closure (pullback-stable images).³ To see that the syntactic category of a coherent theory is a coherent category is straightforward: the coherent structure of C_T emerges naturally out of the coherent formulas that are used to define its objects. (For example, the finite product of two objects $\{\vec{x}.\phi\}$ and $\{\vec{y}.\psi\}$ is given by the object $\{\vec{x}, \vec{y}.\phi \wedge \psi\}$.) Moreover, there are “as many” coherent categories as there are coherent theories: as we just saw, every coherent theory gives rise to a coherent category; conversely, every coherent category is equivalent to the syntactic category of a coherent theory.

But is the syntactic category C_T an adequate representative of the original theory T ? Here we answer in the affirmative, following Makkai and Reyes:

“In Chapter 8 we will show that, in a sense made precise there, logical [i.e. coherent] categories are *the same* as theories in a finitary coherent logic $L_{\omega\omega}^g$.” (Makkai and Reyes, 1977, p. 121)

And also:

³One proper definition of a coherent category is a category that has finite limits, stable disjoint coproducts and coequalizers of kernel pairs.

“The content of 8.1.3 and 8.1.4 can be expressed by saying that for all practical purposes, T and C_T are the same.” (Makkai and Reyes, 1977, p. 241)

In what sense are T and C_T the same? Roughly: replacing one with the other involves no essential loss of information. There are a couple of ways we can make this precise. First, the theory T can be reconstructed from C_T in the following sense: each coherent category C gives rise to a canonically specified (coherent) theory T_C . T_C is (essentially) the set of sentences satisfied by C when C is understood as a model of the theory of coherent categories, i.e. the “total” theory of C qua coherent category. More precisely, for any coherent category C we have its *canonical language* Σ_C whose sorts are the objects of C and function symbols the arrows of C (sorted in the obvious way). Over this language Σ_C we can then express in a straightforward way what it is for a diagram in C to commute, what it is for a diagram to be a product diagram etc. T_C is then the collection of all those Σ_C -sentences expressing all those facts that are true of C as a coherent category. We then have that T is recoverable from C_T in the following sense:

Theorem 1. *Given a theory T , and its syntactic category C_T , the internal theory T_{C_T} of C_T is Morita equivalent to T .*

For the proof, see (Tsementzis, 2015, Corollary 4.6). We will further explain the notion of Morita equivalence in the following subsection as well as argue for its suitability as a good notion of equivalence between theories. For now, one may simply read the above result as “ T is equivalent to T_{C_T} ” and take it on faith that “Morita equivalence” is a sensible notion of equivalence between theories.

Second, the category $\text{Mod}(T)$ of models of T can be reconstructed from its syntactic category C_T .

Theorem 2. *Let T be a coherent theory, and let C_T be its syntactic category. Let $\mathbf{Coh}(C_T, \mathcal{S})$ be the category whose objects are coherent functors from C_T into the category \mathcal{S} of sets, and whose arrows are natural transformations. Let $\text{Mod}(T)$ be the category whose objects are models of T , and whose arrows are homomorphisms between models. Then $\mathbf{Coh}(C_T, \mathcal{S})$ is equivalent to $\text{Mod}(T)$.*

For the proof, see (Makkai and Reyes, 1977, p. 240).

The two preceding results show the sense in which there is no loss of essential information in passing from a theory T to its syntactic category

C_T . (In particular, the Morita equivalence class of a theory can be recovered from that theory’s syntactic category.) It is tempting now to conjecture that if T and T' are Morita equivalent, then C_T and $C_{T'}$ are equivalent categories. But that conjecture fails, since the categories C_T and $C_{T'}$ might not be “conceptually complete” in the sense of Makkai and Reyes (1977). We discuss this issue further in the following subsection.

1.2 Equivalent theories

Before proceeding to discuss the semantic category $\text{Mod}(T)$ associated with a theory T , we will briefly discuss some ideas about when two theories are *equivalent* (for further discussion and technical results, see (Barrett and Halvorson, 2015a,b; Tsementzis, 2015)). The first question to be asked here is what notion of equivalence are we intending to capture? Our answer here is that we have no intention of capturing any Platonic essence of “equivalence.” Rather, just as a group theory gives us a fruitful notion of equivalence between groups (viz. isomorphism), and just as category theory gives us a fruitful notion of equivalence between categories (viz. categorical equivalence), so when theories are treated as mathematical objects, we hope to find a notion of equivalence that will be useful and illuminating.

The strictest notion of equivalence between theories is logical equivalence: two theories T and T' are said to be *logically equivalent* just in case they are formulated in the same signature Σ , and they have the same logical consequences among the sentences of Σ . Of course, logical equivalence is of no use for theories formulated in different signatures. For that case, we look to notions of how a theory can define new concepts that do not occur in the original signature Σ . Recall that a definitional extension T^+ in Σ^+ of the theory T in Σ is the result of adding new predicate symbols, function symbols, or constant symbols that can be defined by T in terms of formulas in the original signature Σ . There is every reason, moreover, to think of a definitional extension T^+ as equivalent to the original theory T . Thus, two theories T_1 (in Σ_1) and T_2 (in Σ_2) are said to be *definitionally equivalent* just in case there are definitional extensions T_i^+ of T_i in $\Sigma_1 \cup \Sigma_2$ (for $i = 1, 2$) such that T_1^+ is logically equivalent to T_2^+ .

Nonetheless, there are reasons to think that definitional equivalence is not the most fruitful notion of equivalence between theories. One such reason is that it doesn’t match well with the notions of equivalence between the corresponding syntactic categories (two theories can have equivalent syntactic categories without being definitionally equivalent). Another reason is that definitional equivalence cannot capture the sense in which, for exam-

ple, the theory of categories can be equivalently formulated using objects and arrows, or just with arrows. In order to capture these intuitive verdicts of equivalence, the most plausible idea is *Morita equivalence*, which allows for equivalence of theories formulated not only in different signatures but also in different signatures with different sorts.

The notion of “Morita equivalence” of theories has two independent sources.⁴ On the one hand, Morita equivalence is suggested by ideas from categorical logic, in particular from topos theory. To see this, we need to introduce the notion of the *pretopos completion* $P(C)$ of a coherent category C . This notion can be described in the following equivalent ways:

1. $P(C)$ is the result of freely adjoining finite coproducts and coequalizers of equivalence relations to C (see Johnstone, 2002, A1.4).
2. $P(C)$ is the subcategory of coherent objects in the topos $\text{Sh}(C)$ of sheaves on C , where the site C is equipped with the coherent Grothendieck topology.

Recall that the *classifying topos* \mathcal{E}_T of the theory T is the unique (up to categorical equivalence) topos that contains a model of T , and such that any model of T in another topos \mathcal{E} uniquely lifts to a geometric morphism from \mathcal{E}_T into \mathcal{E} (see MacLane and Moerdijk, 2012, p. 561 and Makkai and Reyes, 1977, p. 272).

Now two coherent theories S and T are said to be *Morita equivalent* (in the categorical sense) just in case the following equivalent conditions hold (see Johnstone, 2002).

1. The classifying toposes \mathcal{E}_S and \mathcal{E}_T are equivalent.
2. The pretoposes P_S and P_T are equivalent.⁵

The equivalence between these two statements follows from the fact that $\mathcal{E}_T \simeq \text{Sh}(C_T) \simeq \text{Sh}(P_T)$. Moreover, it follows from the second fact that if C_T is equivalent to C_S , then S and T are Morita equivalent. To see that the converse is not true, it suffices to display a theory T such that its syntactic category C_T is not a pretopos. Such theories are easy to find (see Example 1 below).

⁴The name “Morita equivalence” originates in module theory, and was transmitted into category theory through the study of algebraic theories.

⁵Here we use P_T to abbreviate $P(C_T)$, the pretopos completion of the syntactic category of T .

In a completely unrelated development, ideas related to Morita equivalence began to spring up in the works of logicians. As noted by Harnik (2011), Shelah’s T^{eq} construction (also known as “elimination of imaginaries”) is closely related to the pretopos completion construction. Indeed, the pretopos completion P_T of a theory C_T is the same thing as the syntactic category of T^{eq} , i.e. Shelah’s construction applied to T . Similarly, Andr eka et al. (2001) generalize the notion of a definitional extension so as to include the possibility of defining new sort symbols. We refer the reader to those works to see the original motivations for moving to a more expansive notion of equivalence between theories. For our purposes in this paper, the following motivation suffices: the pretopos completion P_T of a syntactic category C_T represents a kind of “maximal mereological completion” of T , i.e. a theory in which not only everything implicitly defined by T receives its own name, but also every (suitable) combination of *types* of things in T receives its own name. Thus, for example, in P_T we have distinct names both for constants and for pairs consisting just of those constants (the *type* of pairs is in some sense “reified”).

But what exactly does this all mean at the level of syntax? As has been explained by Barrett and Halvorson (2015b) and Tsementzis (2015), the ideas about Morita equivalence coming from topos theory correspond to a completely natural generalization of the idea of having a common definitional extension. In particular, given a theory T in signature Σ , a *Morita extension* T^+ of T can be constructed either by defining new relation and/or function symbols, or by defining new sorts from the sorts of Σ . The operation of defining new sorts via T corresponds roughly to taking the pretopos completion of C_T . Thus, intuitively speaking, two theories T and T' are Morita equivalent just in case T can define all the sorts, relation symbols, etc. of T' , and vice versa, in a compatible fashion.⁶ And in fact it can be shown that two theories are Morita equivalent in the syntactic sense just in case the pretopos completions of their syntactic categories are equivalent – see (Tsementzis, 2015, Theorem 4.7). This merely expresses the fact that the syntactic notion of Morita equivalence developed in (Barrett and Halvorson, 2015b) coincides with – and therefore characterizes – the topos-theoretic notion defined in (Johnstone, 2002). This justifies our free use of the same term “Morita equivalence” to refer to both notions.

Clearly if two syntactic categories C_T and $C_{T'}$ are equivalent, then T

⁶For an example of how this “definitional” understanding of Morita equivalence can be applied to issues of theoretical equivalence in physics, see the discussion on classical mechanics in (Teh and Tsementzis, 2015).

and T' are Morita equivalent. The converse, however, is not true.

Example 1. An easy way to see this is to take the an empty two-sorted theory T , i.e. the theory with no axioms whose signature Σ consists only of two sort symbols σ_1, σ_2 . Then we can extend T to T' by adding a “coproduct sort” $\sigma_1 + \sigma_2$ together with function symbols $\rho_1: \sigma_1 \rightarrow \sigma_1 + \sigma_2$ and $\rho_2: \sigma_2 \rightarrow \sigma_1 + \sigma_2$ and axioms defining $\sigma_1 + \sigma_2$ as a “coproduct” with ρ_1 and ρ_2 as its coprojections. Indeed T' is exactly a Morita extension of T in the sense of (Barrett and Halvorson, 2015b) which means that T and T' are Morita equivalent. However, the syntactic categories C_T and $C_{T'}$ cannot be equivalent: the obvious embedding $C_T \hookrightarrow C_{T'}$ is full and faithful but there can be no isomorphism from $\{z: \sigma_1 + \sigma_2, \top\}$ to any object of C_T (regarded as a full subcategory of $C_{T'}$). (Given the results of Tsementzis (2015), this is also an example of two theories which have equivalent pretopos completions but inequivalent syntactic categories.) \lrcorner

As such, we are left with two distinct notions of equivalence between theories T and T' :

(SE) Equivalence of their syntactic categories, i.e. $C_T \simeq C_{T'}$

(ME) Morita Equivalence

For reasons too detailed to go into here, we believe that (SE), although weaker than logical equivalence, is still too strong a notion. As noted above, (SE) is a sufficient condition for (ME) to hold, but not a necessary one. There is a strong sense in which (ME) captures exactly the right content of a theory as long as we care about that theory only up to the structure of its category of models. In order to clarify this remark, we must now go on to say a few more words about this category of models.

1.3 The semantic category

We have already noted that there is a second category associated with a theory T , namely the category $\text{Mod}(T)$ of its models. We will call $\text{Mod}(T)$ the *semantic category* associated with T .

Before proceeding, let’s be more precise about what we mean by the category of models of T . The objects of this category are simply set-valued models of T , in the sense of Tarski. But what are the arrows of the semantic category? There are two possible choices:

- Let T be a theory in signature Σ . We let $\text{Mod}(T)$ denote the category whose objects are Σ -structures that satisfy the axioms of T , and whose

arrows are homomorphisms of Σ -structures. Recall that if M and N are Σ -structures, then a homomorphism $j : M \rightarrow N$ is a function that preserves the extensions of symbols in Σ . That is, for each relation symbol $r \in \Sigma$,

$$j(r^M) \subseteq r^N, \tag{1}$$

and so on.

In contrast to the definition found in most model theory textbooks, we do *not* require the map j to be one-to-one, nor do we require equality in (1). The reason we don't impose these requirements is because they are unmotivated when the logic at hand doesn't have a negation symbol (as in the case of coherent logic).

For example, if $\Sigma = \{\circ, e\}$, and if T is the theory of groups (written in Σ), then the notion of a homomorphism of Σ -structures is simply the notion of a group homomorphism.

- We let $\text{Mod}_e(T)$ denote the category whose objects are (again) Σ -structures that satisfy T , and whose arrows are elementary embeddings of Σ -structures. Recall that if M and N are Σ -structures, then an elementary embedding $j : M \rightarrow N$ is a function that preserves extensions of all Σ -formulas. That is, for any formula $\phi(\vec{x})$ of Σ , and for any n -tuple \vec{a} of elements of M ,

$$M \models \phi(\vec{a}) \implies N \models \phi(j(\vec{a})). \tag{2}$$

In particular, for any sentence ϕ of Σ ,

$$M \models \phi \implies N \models \phi. \tag{3}$$

We can think of $\text{Mod}(T)$ as the “thick” category of models (more arrows) and $\text{Mod}_e(T)$ as the “thin” category of models (fewer arrows) of T . Note that $\text{Mod}_e(T)$ is a subcategory of $\text{Mod}(T)$, and typically a proper subcategory.⁷ For example, let Σ be a signature with one sort and no non-logical vocabulary, and let T be the empty theory in Σ , i.e. the theory whose models are bare sets. Let m_i be a model of T with i elements. Then $\text{Mod}(T)$ has an arrow $j : m_1 \rightarrow m_2$, whereas $\text{Mod}_e(T)$ has no such arrow (since elementary embeddings preserve the truth-value of numerical statements).

⁷Indeed, $\text{Mod}_e(T) = \text{Mod}(T)$ if and only if every first-order formula ϕ (over the signature Σ of T) is T -provably equivalent to a coherent formula (over classical logic) – see Johnstone (2002, Proposition 3.4.9).

There are several questions one can ask of the relation between thin and thick categories. A well-known fact – alluded to above – is that the thin category of a full first-order theory is always equivalent to the thick category of a coherent theory, called its *Morleyization* – see (Johnstone, 2002, Lemma D1.5.13). But for now, the most important point of this subsection is that $\text{Mod}(T)$, and *a fortiori* $\text{Mod}_e(T)$, is *not* generally an adequate representative of the theory T . This means that even the thick categories of models are not “thick enough”. To be more precise, the passage from T to $\text{Mod}(T)$ loses information in the sense that neither T , nor a theory T' that is Morita equivalent to T , can be reconstructed from $\text{Mod}(T)$. Examples from propositional logic makes this fact clear.

Example 2. For full first-order theories, there is an intuitive example. Let Σ be the propositional logic signature with symbols p_0, p_1, \dots . Let T_1 be the empty theory in Σ , and let T_2 be the theory with axioms $p_0 \vdash p_i$ for all $i \in \mathbb{N}$. Clearly T_1 and T_2 are *not* Morita equivalent theories. And yet, the semantic categories $\text{Mod}(T_1)$ and $\text{Mod}(T_2)$ are equivalent — since both are discrete, and have 2^{\aleph_0} objects. Thus, T_1 and T_2 are inequivalent theories whose semantic categories are equivalent (see Halvorson, 2012, p. 191). \lrcorner

Example 3. For coherent theories, coming up with examples requires a bit more algebraic groundwork. Up to Morita equivalence, a coherent propositional theory is the same thing as the theory of prime filters of a (unique up to isomorphism) distributive lattice (see Johnstone, 2002, Remark D1.4.14). Given any such distributive lattice B the category of models of the corresponding theory can then be identified with the spectrum of B . And if B is Boolean (as a lattice) then its spectrum will be discrete. This means that up to equivalence of their categories of \mathcal{S} -models we can only recover a coherent propositional theory up to the cardinality of its spectrum. However, there are many examples of non-isomorphic Boolean lattices whose spectra have equal cardinalities. Indeed a similar idea as our previous example works again here. Let B_1 be the Boolean algebra generated by a countably infinite number of elements p_0, p_1, \dots and let B_2 be the Boolean algebra generated by the same elements plus the relation $p_0 \leq p_i$ for all $i \in \mathbb{N}$. B_1 is atomless whereas B_2 has an atom and therefore B_1 and B_2 cannot be isomorphic. However, the cardinality of both their spectra is equal to 2^{\aleph_0} a fact which can be seen by noting that homomorphisms $B_1 \rightarrow \mathbf{2}$ correspond exactly to homomorphisms $\phi: B_2 \rightarrow \mathbf{2}$ such that $\phi(p_0) = 0$. \lrcorner

The lesson here is that the semantic category of a theory — i.e. the models of that theory, and homomorphisms between models — generally contains less information than the theory itself does. *A fortiori*, the class

of models of a theory contains less information than the theory itself does. (And this is what’s wrong with the original semantic view of theories.)

It is completely natural to ask: if $\text{Mod}(T)$ does *not* contain the same amount of information as T , then what information or structure must be added to $\text{Mod}(T)$ in order to recover T ? Think of the question this way: $\text{Mod}(T)$ is a collection of models and arrows between models, including automorphisms (i.e. arrows from a model to itself). What other information about $\text{Mod}(T)$ can be extracted from the theory T ?

A classic answer to this question was given (for the propositional case) by Marshall Stone. Stone noted that T implicitly contains topological information about $\text{Mod}(T)$. In particular, let’s say that a sequence m_1, m_2, m_3, \dots of models in $\text{Mod}(T)$ converges to a model m_0 just in case for any sentence ϕ of Σ , the truth value $m_i(\phi)$ is eventually equal to $m_0(\phi)$. This notion of convergence defines a topology on $\text{Mod}(T)$. Letting $\underline{\text{Mod}}(T)$ denote the corresponding topological space, Stone’s duality theorem establishes the following:

Theorem (Stone Duality). *The collection of compact open subsets of $\underline{\text{Mod}}(T)$ forms a Boolean lattice that is equivalent, as a category, to C_T .*

In other words, from $\underline{\text{Mod}}(T)$ we can reconstruct T up to its syntactic category, i.e. up to (SE). Thus, in the case of propositional theories, the *topological* semantic category $\underline{\text{Mod}}(T)$ contains as much information as T .⁸

But what now about the case of predicate logic? Here the situation is complicated by the fact that there are typically many non-trivial arrows between models. Can the category $\text{Mod}(T)$ still be supplemented with topological information in order to recover T ? The answer here is: Yes, sort of. Although there is still no result that perfectly generalizes Stone Duality, some important partial results have been obtained by Makkai (1991) and Awodey and Forssell (2013).

Of course, philosophers of science should be eager to understand these duality results because of the important lesson they teach about the collection of models of a theory:

⁸Lest we confuse our physics-minded readers let us clarify that “dualities” such as Stone’s above are not to be thought of, from our point of view, as analogues of “dualities” in modern physics. The latter are relations *between* theories. The Stone-type dualities that we investigate here and in Section 3 are dualities that relate syntactic and semantic presentation of a *single* theory. The terminological coincidence is unfortunate (even more so since we are also interested in application of our framework to physical dualities) but, for historical reasons, unavoidable.

The category of models $\text{Mod}(T)$ of a theory T does not generally contain all the information that is contained in the original theory T . The content of T might include information, e.g., about topological relations between models.

Let’s rephrase that moral one more time, now trying to make it absolutely clear as a friendly amendment to the semantic view of theories:

The mathematical content of a scientific theory T is not exhausted by the class of models of T .

Obviously, this moral from first-order logic doesn’t generalize directly to scientific theories in the wild (e.g. classical mechanics, general relativity, quantum mechanics). However, the results from first-order categorical logic strongly suggest that in the case of scientific theories, we would similarly go wrong if we identified the mathematical content of a theory T with its category $\text{Mod}(T)$ of models⁹ — for the theory might make use of further structures on $\text{Mod}(T)$, perhaps topological (as in general relativity), or measure-theoretic (as in statistical mechanics), or perhaps some sort of monoidal or tensor structure (as in quantum mechanics and quantum field theory). For some evidence for this claim, with reference to specific scientific theories, see (Curiel, 2014) or (Fletcher, 2015), and for some related discussion see (Lal and Teh, 2015).¹⁰

⁹An important clarification: when we say here that we would go wrong if we identified the mathematical content of a theory T with its semantic category $\text{Mod}(T)$, recall that this means the semantic category *over the category of sets* \mathcal{S} . So what we are saying here is that a theory cannot be recovered up to (ME) from its category of models in \mathcal{S} . Nevertheless, conceptual completeness for coherent logic (see Johnstone (2002, Theorem D3.5.9)) says that this is very close to being true: equivalence of the semantic categories of T and T' does imply (ME) as long as this equivalence is induced by an interpretation I of T into T' at the level of syntax (i.e. a coherent functor $I: P_T \rightarrow P_{T'}$). Relatedly, there is another sense in which a theory T is actually recoverable up to (ME) from its semantic category: if we consider semantic categories over arbitrary Grothendieck toposes \mathcal{E} and stipulate that the equivalence $\mathcal{E}\text{-Mod}(T) \simeq \mathcal{E}\text{-Mod}(T')$ is *natural* in \mathcal{E} , then from this alone we can conclude that T and T' are Morita equivalent. This means that the extra structure that we need to place on $\text{Mod}(T)$ (understood as the category of \mathcal{S} -models) in order to recover T up to Morita equivalence corresponds exactly to the requirement of naturality in the class of Grothendieck toposes.

¹⁰We should also note that the question as to *how* these extra structures and topologies map on to actual “topologies” and “structures” between scientific theories remains to be explored. Clearly, the logical topologies on $\text{Mod}(T)$ encode a notion of “nearness” between models of T — does this logical topology illuminate, or correspond in any way, to the notions of “nearness” between models used by practicing scientists, e.g. when mathematical physicists topologize the solution spaces of their differential equations. Are

That said, we do not want to fall into the trap — all too common in 20th century philosophy — of being blinded by the glow of a shiny new piece of formal apparatus. We are fully aware that, from a mathematical point of view, a syntactic category is regarded merely as a technical device useful for proving other results, e.g. completeness theorems.¹¹ Yet we believe that the conceptual value of the kind of formal apparatus best encapsulated by the syntactic category of a theory goes beyond its practical use *within* mathematics. And unlike W.v.O. Quine, we have no ideological commitment to regimenting theories in first-order logic. Rather, as just explained, we see first-order logic as providing a manageable testing ground for more general ideas about theoretical structure.

Nevertheless, what we are claiming here clearly amounts to a methodology based on an analogy between the categorical metamathematics of first-order theories and the philosophy of scientific theories. Is there any reason to believe in the fruitfulness of this analogy? We believe so. Category theory brings to the table new constructions and concepts with which to study the metamathematics of first-order theories. And the metamathematics of first-order theories — if anything — is rich in concepts (“theory”, “axioms”, “interpretations” etc.) that are used heavily in the philosophy of scientific theories. So as long one is not a complete skeptic with respect to the use of logical methods to come up with idealized versions of scientific theories, there is every reason — it seems to us — to take seriously the analogy on which our method relies.

2 The category of theories

We have talked about theories *as* categories. But as the title of this paper makes clear, what we are interested in is categories *of* theories. Namely, we are interested in studying collections consisting of multiple scientific theories, and the relations between them. And since we’ve already argued that theories can be thought of as categories, the natural way to do so is to study the (2-)category of theories-as-categories. We can then apply the tools of category theory to understanding the structure of this larger category, how individual theories sit within it, and how theories are related to each other.

the logical topologies we consider here and in Section 3 good “frictionless” idealizations of these kinds of investigations? The question certainly deserves more attention and we intend to explore it in the future.

¹¹And this extends to syntax very far removed from first-order logic, e.g. the metamathematics of simple type theories or of Martin-Löf type theories are also studied via structure-bearing syntactic categories.

Why would we want to do that? To be sure, the category of “theories-as-categories” can be no more than a “frictionless” idealization of the actual zoo of scientific theories and the interactions between them that take place within it. But we are not interested in carrying out rigorous sociology – we are interested in a formal framework that is sufficiently expressive to act as such an idealization. In particular, a framework that formalizes the notions both of a scientific theory and of “structural similarities” *between* such scientific theories. Taking theories to be categories – as explained in Section 1 – and then taking functors between such categories as expressions of such a “structural similarity” gives us just such a framework. Being the first to propose such an idea, we do of course realize that the choice of category-theoretic formalism might prove inadequate in the long run; perhaps it might appear as *too* idealized already. To this we say: may others come and find better frameworks – this is the one we, at this moment in time, consider the most fruitful idealization. (In this respect we believe we are making no more arbitrary a choice than, say, what Carnap did when he thought that the predicate calculus was an adequate idealization of the language of science.)

And why do we view it as fruitful? Because we want to view scientific theories not as contenders to the throne of absolute truth but rather as creatures in an active ecosystem whose interactions are essential if more advanced life is to evolve out of it. It is this view that we take of the practice of science today – and it is this picture that we want our formal framework to be an idealization of. And we think the state of physics today justifies this view. At the very least, because talking about the relationships between scientific theories captures a critical feature of modern physics, namely the existence of dualities – most prominently in string theory. Formal frameworks in the philosophy of science of the 20th century (whether semantic or syntactic) are not, we believe, adequate to model the dualities of modern physics. Thus, our attempt to define a category of scientific theories can also be seen as our answer to the challenge of formally capturing such inter-theoretical interactions.

With that said, let us now get down to the business of introducing a suitable category of theories. As before, our initial focus is on the case of theories in first order logic. As described in the previous section, each first-order theory T corresponds to a syntactic category C_T (which we could also take to be P_T). We let the collection of all such C_T be the objects of a category \mathbf{Th} , the category of all first-order theories.

Again, we have some fine-grained control over the definition of the category \mathbf{Th} of theories. The main possibilities for \mathbf{Th} are as follows:

- **Coh** the category of coherent categories (i.e. syntactic categories of coherent theories);
- **dCoh** the category of decidable coherent categories (cf. Awodey and Forssell, 2013);
- **BCoh** the category of Boolean coherent categories (i.e. syntactic categories of first-order theories over classical logic);
- **Pretop** the category of pretoposes.

These categories are arranged roughly as follows:

$$\mathbf{BCoh} \subseteq \mathbf{dCoh} \subseteq \mathbf{Coh}$$

and

$$\mathbf{Pretop} \subseteq \mathbf{Coh}$$

where the subset symbol indicates a full inclusion of categories.

How do we choose among these (or other) options? An answer can be gotten by noting that such a choice amounts essentially to a choice of a “notion of equivalence” for our theories. This is a specific case of a very important (and far more general) observation about category-theoretic thinking, viz. that choosing the category where your objects of study live automatically determines what it means for two such objects to be “isomorphic”. This important principle is worth stating:

- (I) Choosing a notion of equivalence for our objects of study is the same thing as choosing a category of which they are the objects.

In our case, the objects of study are theories. Thus, as (I) makes clear, choosing a notion of equivalence for theories and choosing a “category of theories” are not two independent choices. Choosing one determines the other: there is only one degree of freedom here.

In our opinion, the two most natural choices for **Th** are **Coh** or **Pretop**. Given (I) and the discussion in Section 1, this shouldn’t come as a surprise: we’ve already said that the two notions of equivalence that interest us the most are (SE) and (ME) and these correspond exactly to choosing **Coh** (for (SE)) and **Pretop** (for (ME)) as our preferred categories of theories. This is because (SE) identifies theories with their syntactic categories and every coherent category is the syntactic category of some coherent theory, whereas (ME) identifies theories with the pretopos completion of their syntactic categories and every pretopos can be seen to arise in this manner

(although, of course, inequivalent coherent categories may have equivalent pretopos completions).

Furthermore there is a natural relation between these two categories: for each coherent category C , there is a unique pretopos $P(C)$ and functor $\eta_C : C \rightarrow P(C)$ satisfying a suitable universal property. In short: every coherent category has a unique pretopos completion — an operation corresponding roughly to taking a “maximal Morita extension” of the original theory. In fact, $P : \mathbf{Coh} \rightarrow \mathbf{Pretop}$ is a 2-functor (see Makkai, 1987). And even more is true: \mathbf{Pretop} is “almost” a reflective sub-2-category of \mathbf{Coh} . More precisely, \mathbf{Pretop} is a full reflective sub-2-category of \mathbf{FinSit} , the 2-category of “finitary” sites (i.e. categories equipped with finitely-generated Grothendieck topologies) — this is a special case of a far more general result proven by Shulman (2012).

For the purposes of this paper, we needn’t make a decision about the precise definition of \mathbf{Th} . However, for concreteness, let us say that we are in favor of the identification $\mathbf{Th} = \mathbf{Pretop}$. (As explained above, this means that we are effectively choosing (ME) as our preferred notion of equivalence.) Although nothing we say here hinges on this choice, let us say a couple of things about why it is a natural choice to make (other than our faith in (ME)). Firstly, there is a very precise sense in which — from a logical point of view — the pretopos completion of a coherent category adds only those concepts that are already *definable* from the coherent structure of the original category. Secondly, the pretopos completion is the *maximal* such extension, i.e. it contains *everything* that is definable from the coherent structure of a coherent category (for a precisification of this statement see (Harnik, 2011)). As such, if one agrees with us that the initial syntactic presentation of a theory does not constitute its essential content then moving from \mathbf{Coh} to \mathbf{Pretop} should seem a very reasonable move to make.

Now what are the arrows in \mathbf{Pretop} ? Since the objects of \mathbf{Pretop} are categories, the arrows should be functors. Perhaps surprisingly, the arrows we care about in this particular case are obtained by considering a pretopos as a coherent category (recall that every pretopos is coherent). But do coherent categories have additional structure that ought to be preserved by our arrows? The answer, in short, is yes: a coherent category has limits and colimits that encode various syntactic structures — in particular, conjunction, disjunction, and existential quantification. Thus, we define an arrow between pretoposes P and P' to be a *coherent functor* in the sense of (Johnstone, 2002, p. 34), also called a *logical functor* in (Makkai and Reyes, 1977, p. 121). In other words, we consider \mathbf{Pretop} as a full subcategory of

Coh.¹²

Choosing coherent functors as arrows has the nice consequence that arrows from P_T to P_S correspond to translations of the theory T into S (so do, incidentally, arrows from C_T to C_S). A way to see this is the following: each P_T contains the so-called *generic model* M_T of T (Johnstone, 2002, Proposition D1.4.12.(ii)). This is a model of T taken in the pretopos completion P_T (recall that P_T is coherent and therefore has the capacity to model any coherent theory T). It is *generic* in the sense that it satisfies exactly those sentences that are provable in T , i.e.

$$M_T \models \phi \iff T \vdash \phi.$$

Now, since coherent functors preserve the coherent structure and since models of coherent theories in coherent categories are built using (only) that coherent structure, we have that any coherent functor $F: P_T \rightarrow D$ into a coherent category D will give us a model $F(M_T)$ of T in D . In particular, when $D = P_{T'}$ for some other theory T' then $F(M_T)$ is a model of T in $P_{T'}$. But a (\mathcal{S} -)model of T' is simply a coherent functor from $P_{T'}$ into \mathcal{S} . Therefore, any model $G: P_{T'} \rightarrow \mathcal{S}$ of T' will also give rise to a model of T , viz. $GF: P_T \rightarrow \mathcal{S}$. In plain terms: any model of T' contains a model of T ; this is just another way of saying that there is a translation of T into T' .¹³ Finally, it is important to note that everything we've said in this paragraph can be said pretty much verbatim for syntactic categories themselves (rather than their pretopos completions). More on translations and definability at the level of syntactic categories can be found in (Caramello, 2012).

It should immediately be pointed out that **Pretop** is most naturally thought of as a 2-category, rather than just a category. A 2-category \mathbf{C} is (roughly speaking) a category such that for any two objects a, b of \mathbf{C} ,

¹²The fact that it is reasonable to do so essentially boils down to the above-mentioned fact that the pretopos completion of a coherent category is “definable” (in a precise sense) from the coherent structure of the category in question. In particular, even though coherent morphisms will not, in general, preserve arbitrary coproducts or coequalizers, they will preserve binary coproducts and coequalizers arising from equivalence relations. This means that “disjoint unions” and “quotients by equivalence relations” are concepts within the grasp of coherent logic and taking the pretopos completion of a coherent category amounts to a (maximal) “definitional extension” of the original coherent category by these definable concepts. Indeed, removing the scare quotes from the previous sentences and making this way of talking about pretopos completions fully precise was one of the motivations behind (Barrett and Halvorson, 2015b) and (Tsementzis, 2015).

¹³Indeed, in (Pitts, 1989) translations of a theory T into another theory T' are *defined* to be models of T in $P_{T'}$. This is the same thing as saying that translations are functors $C_T \rightarrow P_{T'}$ which in turn is the same thing as saying that translations are functors $P_T \rightarrow P_{T'}$.

instead of $\mathbf{C}(a, b)$ being a *set* of arrows from a to b , it is a *category*; and the composition operation on arrows is functorial (see Borceux, 1994; Lack, 2010). The arrows in the category $\mathbf{C}(a, b)$ are called *2-cells*. The paradigm example of a 2-category is \mathbf{Cat} , the category of (small) categories, with functors as arrows, and natural transformations as 2-cells. That is, if C and D are categories, then $\mathbf{Cat}(C, D)$ is the category whose objects are functors $F : C \rightarrow D$, and whose arrows are natural transformations between such functors. Similarly, we define $\mathbf{Pretop}(P, P')$ to be the category whose objects are coherent functors from P to P' , and whose arrows (2-cells) are natural transformations.¹⁴

Basking in the full 2-categorical glory of \mathbf{Pretop} is no mere pretension, nor is it a pointless exercise to prepare us for the altitude sickness that comes with the steep ascent towards higher category theory. It is, rather, a perspective that brings, among other things, new purely logical insights.¹⁵ Whether these logical insights translate into insights about analogous concepts in the philosophy of science remains to be seen – we devote Section 4 to plausible lines of investigation in this direction. For now, we turn to an application of our point of view to a more concrete question in the philosophy of science: the debate between the semantic and the syntactic views of theories.

3 On the duality of syntax and semantics

Recall that the logical positivists hoped to provide an explication for the notion of a *scientific theory*.¹⁶ That is, they hoped to be able to say that a scientific theory is a certain sort of (rigorously defined) mathematical object. But what kind of object? According to the earliest proposals (by Carnap and others), a theory is a set of sentences in a formal language. This proposal and its later elaborations have come to be known as the *syntactic view of theories*.

As is well known, the syntactic view of theories was subjected to severe criticism in the later 20th century. The consensus in the 1970s was the syntactic view couldn't be salvaged, and required a wholesale replacement. The proposed replacement was the so-called *semantic view of theories*, which claims that a scientific theory is a collection of models — perhaps the models

¹⁴A 2-category is a “strict” version of a bicategory in the sense of (Bénabou, 1967).

¹⁵To convince oneself of this one need look no further than Pitts’ proof of conceptual completeness for coherent logic (resp. intuitionistic logic) using the 2-categorical structure of \mathbf{Pretop} (resp. $\mathbf{HPretop}$, the category of Heyting pretoposes) – see (Pitts, 1987, 1989).

¹⁶For further elaboration of this story, see (Halvorson, 2015).

of some first-order logical theory, or perhaps a collection of models of some more general sort.¹⁷

It has long been thought that the semantic view of theories has many advantages over the syntactic views – see e.g. the works of Suppe, van Fraassen, and Lloyd, et al.. Of course, that claim presupposes that there is a genuine dilemma of choice between the two points of view. Only a couple of isolated philosophers have suggested that this might be a false dilemma (see e.g. Friedman, 1982). In this section, we survey mathematical results that argue for a formal duality between the syntactic and semantic points of view. We also propose that this duality could be exploited in order to better understand the structure of scientific theories.

Recall the previous discussion of Stone duality for theories in propositional logic. While it’s not true that a propositional theory can be reconstructed from its category of models alone (i.e. the set of ultrafilters on the Lindenbaum algebra), it can be reconstructed from the category of models *plus* relevant topological information.

In recent years, logicians have attempted to generalize Stone duality to the case of full first-order logic. And while the results to date are only partial, they all point in a similar direction.¹⁸

First, Makkai (1991) makes use of an insight from Łos’ theorem: if $\{m_i\}_{i \in I}$ are models of a theory T , then so is an ultraproduct $\prod_{i \in I} m_i / \mathcal{U}$, where \mathcal{U} is an ultrafilter on I . What’s more, in the case where T is a propositional theory, the ultraproduct $\prod_{i \in I} m_i / \mathcal{U}$ is simply the Stone topology limit of the sequence $\{m_i\}_{i \in I}$ along the ultrafilter \mathcal{U} . In other words, in the propositional case the Stone topology on $\text{Mod}(T)$ can be alternatively described as “ultraproduct structure” on $\text{Mod}(T)$; and the relevant functors $F : \text{Mod}(T) \rightarrow \text{Mod}(T')$ are those that preserve this ultraproduct structure (i.e. that are continuous in the Stone topology).

Now Makkai defines an *ultracategory* to be a category with a sort of ultraproduct structure (see Makkai, 1991). Of course, the motivating example of an ultracategory is the category $\underline{\text{Mod}}(T)$ of models of a first-order theory. Then the question arises:

Can a theory T be reconstructed from the corresponding ultracategory $\underline{\text{Mod}}(T)$?

¹⁷To be clear, Van Fraassen (2014) has recently pointed out that for him, a theory is a class of models together with representational content. However, for this discussion, we are concerned only with the mathematically representable part of a theory.

¹⁸Such dualities as the ones we will outline below sometimes go under the name of “Isbell Duality” and many examples have been studied at a very high level of generality – see Porst and Tholen (1991) and Barr et al. (2008) for a sampling.

Makkai shows that the answer is Yes. For any pretopos P , let $\Theta(P) = \mathbf{Coh}(P, \mathcal{S})$ denote the category of coherent functors from P into the category \mathcal{S} of sets (i.e. models of the theory corresponding to P). Makkai shows that there is another functor $\Gamma : \mathbf{UCat} \rightarrow \mathbf{Pretop}^{op}$, such that $(\Gamma \circ \Theta)(P)$ is equivalent to P . Stated more generally: there is a pair of adjoint functors as follows:

$$\begin{array}{ccc} & \Theta & \\ & \curvearrowright & \\ \mathbf{Pretop}^{op} & & \mathbf{UCat} \\ & \curvearrowleft & \\ & \Gamma & \end{array}$$

Unfortunately, this adjunction is *not* an equivalence of categories, as in the case of propositional theories (i.e. Stone duality for Boolean algebras). In particular, not every ultracategory is of the form $\text{Mod}(T) \simeq \mathbf{Coh}(P_T, \mathcal{S})$, for some first-order theory T . In slogan form: there are more ultracategories than there are coherent theories.

A more recent attempt to generalize Stone duality has been undertaken by Awodey and Forssell (2013). Here the insight comes not from model theory (as in the case of Makkai’s ultraproducts), but from topos theory. Joyal and Tierney (1984) proved that for every Grothendieck topos \mathcal{E} , there is a localic groupoid G such that $\mathcal{E} \simeq \mathbf{B}(G)$, where $\mathbf{B}(G)$ is the topos of continuous actions of G . It was also shown by Butz and Moerdijk (1998) that when \mathcal{E} has enough points — as is the case when $\mathcal{E} \simeq \mathcal{E}_T$ is the classifying topos of a coherent theory — then G may be taken to be a topological groupoid.¹⁹

The models of a (coherent) theory T naturally form a category $\text{Mod}(T)$. Now, if we eliminate all non-isomorphism arrows from $\text{Mod}(T)$ then the resulting category $\text{Mod}_i(T)$ is a groupoid, i.e. a category in which every arrow has a two-sided inverse. Intuitively speaking, $\text{Mod}_i(T)$ is the category of models of T and their symmetries (i.e. automorphisms).

¹⁹Roughly, locales are topological spaces without a notion of a point, axiomatized instead with a primitive notion of a neighborhood and lattice operations on such neighborhoods (corresponding to unions and intersections). The advantage of locales is that they are amenable to a first-order axiomatization (albeit with a caveat: the category of locales is defined as the *dual* of the category of models of that axiomatization). The disadvantage is that they are strictly more general than topological spaces: every topological space is a locale but not every locale is a topological space. More precisely, it can be shown that the category of topological spaces is a coreflective subcategory of the category of locales. For this and more motivation on “pointless” topology see the introductory survey by Johnstone (1983).

Since $\text{Mod}(T)$ doesn't contain enough information to reconstruct T , a fortiori $\text{Mod}_i(T)$ doesn't contain enough information to reconstruct T . To reiterate, a theory's models and their automorphisms do not tell us everything about that theory! But now the insight of Awodey and Forssell was that if $\text{Mod}_i(T)$ is equipped with an appropriate topology, then the resulting topological groupoid G , could be the very G that appears in the representation theorem of Butz and Moerdijk. To be more precise, if C_T is the syntactic category of T , and if $Sh(C_T)$ is the topos of sheaves on C_T , then

$$Sh(C_T) \simeq B(G_T),$$

where G_T is the topological groupoid of models of T , and $B(G_T)$ is the Grothendieck topos of continuous actions of G_T . Furthermore, since the pretopos completion of C_T can be recovered as the coherent objects in $Sh(C_T)$, it follows that the pretopos completion of C_T can be recovered from the topological groupoid G_T . In other words, T itself can be recovered from G_T up to Morita equivalence.

This result suggests that the syntactic and semantic categories of theories are dual to each other. On the one hand, we have **Pretop**, the category of theories (understood as (conceptually complete) syntactic categories). On the other hand, we have **TopGrpd**, the category of semantic categories, viz. topological groupoids. The “semantic functor” $\Theta : \mathbf{Pretop} \rightarrow \mathbf{TopGrpd}$ is defined by first taking $\mathbf{Pretop}(P, \mathcal{S})$, the category of set-valued models of P , then restricting to the isomorphisms between models, and finally equipping the resulting groupoid with the “logical” topology. The “syntactic functor” $\Gamma : \mathbf{TopGrpd} \rightarrow \mathbf{Pretop}$ is defined by taking a topological groupoid G to the topos $B(G)$ of continuous G -sets, and then extracting the pretopos of coherent objects in $B(G)$.²⁰

The two functors Θ and Γ are indeed adjoint to each other.

$$\begin{array}{ccc} & \Theta & \\ \text{Pretop}^{op} & \xrightarrow{\quad} & \text{TopGrpd} \\ & \Gamma & \end{array}$$

However, once again, this adjunction is *not* an equivalence of categories; i.e.

TopGrpd is not exactly dual to **Pretop**. Thus, a natural question: can the

²⁰Technically, Awodey and Forssell work with the category **dCoh** rather than **Pretop**, and the results must be adjusted accordingly.

semantic category \mathbf{Pretop}^{op} be characterized independently of the functor Θ ? i.e. can we provide an independent characterization of the category of (semantically presented) theories? Doing so would lead to a so-called “perfect duality” but such an independent characterization has so far proved elusive.²¹

Why do mathematicians value duality results? One reason is that it enables them to transfer results and concepts from one category to its dual category. Thus, if we had a duality result for syntactic and semantic categories, then we could use information about theories as presented semantically in order to understanding theories as presented syntactically, and vice versa.

For example, suppose that the theory T' results from adding a new predicate symbol (but no new axioms) to the theory T . There is then an obvious translation of T into T' , namely the translation that takes each piece of non-logical vocabulary to itself. This translation corresponds to a functor $F : P_T \rightarrow P_{T'}$ that is faithful, full (since no new functional relations are created), but not essentially surjective (since no formula from the smaller language maps to the new predicate symbol). Recalling that F is an arrow in \mathbf{Pretop} , there is a dual arrow $F^* : G_{T'} \rightarrow G_T$ in the semantic category \mathbf{TopGrp} . It is natural to ask then: given that F has such and such features, what features does its dual arrow F^* have? In this case, the failure of essential surjectivity of F corresponds to the fact that F^* is not full, i.e. it forgets structure in the sense of (Weatherall, 2016).²²

Of course, the question can also be asked the other way around: given a functor $K : \mathbf{M} \rightarrow \mathbf{N}$ between categories of models, how do features of K correspond to features of its dual arrow K_* in the syntactic category? But here we pause, because in our opinion, the semantic category — whose objects are categories of models — has not yet been adequately characterized.

²¹One reason for this – mysterious as it may sound – is certainly the fact that there seems to be nothing inherently “category-theoretic” about ultraproducts. As Makkai’s work proves and Los’ theorem has long made obvious, taking ultraproducts is a fundamental operation when it comes to elementary classes: elementary classes are exactly those classes closed under elementary equivalence and the taking of ultraproducts. Since every pretopos corresponds to an elementary class (more precisely: to the category of models of a coherent theory) one would imagine that any such characterization of \mathbf{Pretop} would amount to a characterization of “closure under ultraproducts”. Absent any useful purely categorical description of ultraproducts (or even ultrafilters) this seems like a significant obstruction. Nevertheless the work of Leinster (2013) on ultrafilter monads as codensity monads might provide a way out, though this is still very far from being made precise.

²²It ought to be remarked that the “functorial” explication of the idea of forgetting structure (or properties or stuff) is originally due to John Baez.

First, not every topological groupoid is the groupoid of models of a coherent theory, i.e. \mathbf{Pretop}^{op} has fewer objects than $\mathbf{TopGrpd}$. Second, \mathbf{Pretop}^{op} is a 2-category; hence, if \mathbf{Pretop}^{op} is to be seen as living inside $\mathbf{TopGrpd}$, then we must understand the latter as itself a 2-category. But what is the appropriate 2-categorical structure and how should we understand it?²³

So, for anyone who wishes to develop the semantic view of theories, the following is a pressing question:

Given two categories of models \mathbf{M} and \mathbf{N} , what is a fruitful definition of an arrow $K : \mathbf{M} \rightarrow \mathbf{N}$? Furthermore, which arrows should be thought of as “reductions” of one theory to another, which as “equivalences” of theories, and which as other theoretical relations with which philosophers of science have been concerned?

Recalling what we said earlier: to choose the arrows of a category is to choose a notion of equivalence, and hence to choose a notion of identity of the category’s objects. (Here the objects of the semantic category are themselves categories, viz. *categories of models*.) Thus, until one proposes a notion of arrows between semantic categories, then one lacks a clear notion of equivalence of theories, and hence of how a theory can be identified semantically. For philosophers of science, this issue demands immediate attention.

But why do we care about these results and how do they relate to the framework we have been advocating? Essentially, because the above-described duality between the category of syntactic and (suitably structured) semantic categories offers a large-scale dissolution of the syntax-semantics dichotomy. What this guarantees – and the reason why it is important – is that intertheoretic relations get preserved regardless of whether we replace a theory with its syntactic category or its category of models. In other words, the way in which a syntactic category of a theory T “sits” within other syntactic categories is equivalent (in an appropriate sense) to the way in which $\text{Mod}(T)$ “sits” within other categories of models. That this is the case is in no way trivial, or automatic. One could very well imagine it being true that moving back and forth between syntactic categories and categories of models changed the way in which these different presentations of a theory related to other theories. But it does not – this is what makes the duality results presented in this section essential, and what paves the way for several of the technical projects we will now go on to outline.

²³Moerdijk (1988, 1990) defines a bicategory $\mathbf{LocGrpd}$ of localic groupoids, with bimodules as arrows, and shows that $G \mapsto B(G)$ is an equivalence of categories between $\mathbf{LocGrpd}$ and the bicategory of Grothendieck toposes.

4 Future Directions

Given this elegant formal framework, numerous technical questions — of philosophical interest — suggest themselves. We will now list and discuss a few such questions.

1. We saw that if the syntactic categories C_T and C_S are equivalent, then the theories T and S are Morita equivalent, i.e. that (SE) implies (ME). We also saw that the converse fails: two theories can be Morita equivalent even though their syntactic categories are inequivalent.

An interesting question we can now raise is this: What kind of conditions can we place on theories such that (SE) coincides with (ME)? (One well-known case in which they do coincide is that of algebraic theories.) Furthermore, what can we say about Morita equivalences over particular categories? For example, for any two first-order theories T and T' whose semantic categories are equivalent (over \mathcal{S} , and not necessarily naturally) how can we characterize their relation from a purely syntactic standpoint? And what about their thin categories? Namely, if

$$\mathcal{S}\text{-Mod}_e(T) \simeq \mathcal{S}\text{-Mod}_e(T')$$

then – purely syntactically – how are T and T' related?

2. Let's consider some natural relations between theories. First, let T be a theory in signature Σ , and let T' be an extension of T by some additional axioms, also in the language Σ (such “extensions” are also called “quotients”). Then there will be a canonical functor $F : C_T \rightarrow C_{T'}$. What can we say about this functor? What features does it have? In the case of geometric theories a lot of work in this area has been done by O. Caramello starting with the “Duality Theorem” in her Phd thesis – for a big picture view see (Caramello, 2009, 2010). See also (Forssell, 2013).

Similarly, let T be a theory in signature Σ , and let T' be the same theory, but considered in a larger signature Σ' . Again there will be a canonical functor $F : C_T \rightarrow C_{T'}$. What features does this functor have?

Furthermore, philosophers of science have been interested in questions about when one theory T' is *reducible* to another theory T . Can reduction be thought of as a functor $F : C_{T'} \rightarrow C_T$ (see Van Benthem and Pearce, 1984)? How does this functorial account compare to the

classical Nagelian account (see Nagel, 1979, Ch 11)? How does this functorial account compare to semantic accounts (see Bickle, 1998)?

3. If we were to think of **Coh** or **Pretop** as merely a category, then a natural technical question might be: does this category have limits? Or, does this category have colimits? And, if it does have limits or colimits, then do these have any sort of natural interpretation as operations on theories? For example, is there any sense in which a coproduct of two coherent categories represents a sort of amalgamation of the two theories? And if so, does the notion of an “amalgamation of theories” have a clear interpretation?

However, it’s more natural to think of either **Coh** or **Pretop** as a 2-category, in which case the better questions have to do with the existence of limits and colimits in the bicategorical sense. Does **Pretop** have 2-limits and 2-colimits? And if it does, do these limits and colimits have a natural interpretation as operations on theories?²⁴

Philosophers of science should be particularly interested in whether the categorical structure of **Pretop** can be used to explicate various relations between theories, such as limiting relations.

4. The relation between “thick” and “thin” semantic categories provides very fertile ground for investigation, as noted above. One obstruction here is that the thin semantic categories of first-order theories are almost invariably “too thin” in the sense that they rarely contain interesting categorical structure (e.g. limits, colimits etc.)

On the other hand, it is perhaps worth investigating relations between pairs of theories (T_1, T_2) such that there are interesting functors

$$F: \text{Mod}_e(T_1) \rightarrow \text{Mod}(T_2)$$

where T_1 would be thought of as the “background spacetime” theory and T_2 would be thought of as the “physical system theory”. To be a little more specific, this formal situation seems to us an interesting generalization of the nowadays very common situation (e.g. with (Q)FTs) where we have a category of “state spaces” represented by algebraic objects (e.g. Hilbert spaces, C^* -algebras) and a category of “spacetimes” understood as categories of “physical spacetimes with

²⁴Makkai (1995) proves a version of the Craig interpolation theorem using the 2-categorical version of a pushout of syntactic categories.

embeddings as arrows” and where a theory of physics is defined as a functor relating those two.

For example, Fewster (2015) defines a locally covariant theory to be a functor

$$F: \mathbf{Bkgnd} \rightarrow \mathbf{Phys}.$$

In Fewster’s set-up, \mathbf{Bkgnd} seems to us to be best understood as essentially the thin category of models of some theory, since the morphisms are basically elementary embeddings (see Fewster, 2015, p. 4). On the other hand, the categories which he calls \mathbf{Phys} seem to us to be best understood as the thick categories of models of some theory, since they are usually categories of algebraic structures. This suggests that it is worth looking at what kind of interesting things can be said about such functors, when T_1 and T_2 are first-order theories: what can we say about them, modulo some constraints on T_1 , T_2 and F ? Is this a fruitful general set-up with which to study properties of (Q)FTs?

It might not be immediately clear how this is related to the category of theories perspective that we have been advocating. It very much does. Assuming for the time being that both $\text{Mod}_e(T_1)$ and $\text{Mod}(T_2)$ live in the same category \mathbf{Th} , then what we are suggesting is to study certain objects in the category of arrows of \mathbf{Th} , i.e. the category whose objects are the arrows of \mathbf{Th} and morphisms are commutative squares connecting these arrows. (Once again, since \mathbf{Th} is a 2-category, its arrow category will also have a natural 2-categorical structure.) It appears to us to be a fruitful way to understand field theories in general: as functors relating a “spacetime” category (e.g. Minkowski spacetimes) to a “state-space” category (e.g. C^* -algebras).²⁵

5. The (2-)category \mathbf{Pretop} might be used to explicate the notion of a *symmetry* of a theory.

In recent literature in philosophy of science, discussion of symmetries has proceeded in absence of an agreed upon background framework. These discussions sometimes think of symmetries in terms of equations, and sometimes in terms of models. What’s more, we find ambiguity

²⁵A complication arises here, however, with respect to how to actually view $\text{Mod}_e(T_1)$ and $\text{Mod}(T_2)$ as living in the same category. It is not immediately clear how this can be done in an interesting way when we’ve identified \mathbf{Th} as either \mathbf{Coh} or \mathbf{Pretop} . This is an important question in itself to which we have no satisfying answer at present. As a result, we have decided to present the above question in terms of functors between “free-floating” categories of models. We thank an anonymous referee for pressing us on this point.

about whether symmetries operate at the level of individual models of a theory, or at the level of the collection of all models of a theory.

A category-theoretic point of view makes it clear, however, that there are both syntactic and semantic notions of symmetries — as can be made precise with the category \mathbf{Th} of theories (understood here as **Pretop**). Let T be a theory and let P_T be its syntactic category, which is an object of \mathbf{Th} .²⁶ Then we propose:

A syntactic symmetry of T is an auto-equivalence of the syntactic category P_T .

Recall that a coherent functor $F : P_T \rightarrow P_S$ corresponds to a translation from T into S . Thus, an auto-equivalence $F : P_T \rightarrow P_T$ corresponds to a translation of T into itself (i.e. a sort of permutation of the vocabulary of T).

But more is true. A coherent functor $F : P_T \rightarrow P_S$ induces a functor $F^* : \text{Mod}(S) \rightarrow \text{Mod}(T)$ from models of S to models of T (see Gajda et al., 1987; Makkai and Reyes, 1977). In particular, an automorphism $F : P_T \rightarrow P_T$ induces a functor $F^* : \text{Mod}(T) \rightarrow \text{Mod}(T)$ on the category of models of T , which raises another technical question:

Is it true that any essentially invertible functor $G : \text{Mod}(T) \rightarrow \text{Mod}(T)$ has the feature that $G = F^$ for some coherent functor $F : P_T \rightarrow P_T$?*

The answer to this question is No, as can be seen by again looking at the example of the two propositional theories. Thus, philosophers of science should *not* necessarily suppose that any auto-equivalence $G : \text{Mod}(T) \rightarrow \text{Mod}(T)$ should count as a symmetry of T . But can we say something about further conditions on G so that it is indeed dual to some functor F on the syntactic category P_T ?

6. Since the demise of the syntactic view of theories, philosophers of science have been fond of pointing out that interesting scientific theories — even those in rigorous mathematical physics — typically fail to admit a first-order axiomatization. Thus, we might conclude that a typical scientific theory cannot be described by an object in **Coh** or

²⁶A note of clarification on terminology: we are now using the term “syntactic category” to refer to an arbitrary object of the category of theories \mathbf{Th} rather than the explicit construction as carried out in Section 1.1.

Pretop. We already dealt with this point at the end of Section 1 but let us now add a few more words.

Firstly, is this dismissal too fast? Note that some logics stronger than first-order logic — e.g. geometric logic, or even higher-order logics — will also give rise to syntactic categories that are coherent. In fact, if a logic is stronger than first-order logic, then the corresponding categories can be expected to have more structure than coherent categories.²⁷

Relatedly, recent work in “cohesive” homotopy type theory (CoHoTT) uses syntactic methods (based on a logic much more “exotic” than first-order logic) to study higher gauge theories (see (Schreiber, 2013) as well as (Corfield, 2016) in this volume). Among other things, Schreiber envisions a certain class of ∞ -toposes (the so-called “cohesive” ones) as the correct setting at which to study the foundations of higher gauge theories, *exactly because* these cohesive ∞ -toposes are (conjectured to be) the syntactic categories of CoHoTT. Of course, Schreiber’s use of syntactic methods is not motivated by considerations on theoretical equivalence and the structure of scientific theories – his mathematical work is carried out with the explicit goal of articulating a general foundation for higher gauge theories. Nevertheless, the way in which he blends syntactic and semantic methods is a great illustration, in our opinion, of how representing scientific theories as categories (in his case *higher* categories) is an illuminating perspective to take.

So, is being a coherent category a *minimal* necessary condition for representing a bona fide scientific theory? In any case, it would be natural to ask:

Given a formalized theory T of the empirical sciences, is there some category C_T that can be thought of as the “syntactic category” of T ?

Consider a couple of examples. First, let T be Einstein’s general theory of relativity. We do have some sense of what the *semantic* category — i.e. the category of models of T — ought to be, viz. the category of differentiable manifolds with Lorentzian metric and stress-energy tensor satisfying Einstein’s field equations. But is there a category C_T

²⁷For example, in the case of intuitionistic type theory (ITT), there is a syntactic category C_{ITT} (produced by a similar but different process than the one we outlined for first-order theories T) which bears the structure of an elementary topos – see Lambek and Scott (1986) for the classical account.

that could be considered the syntactic category of GTR?²⁸ And could the failure to distinguish between semantic and syntactic points of view be partially responsible for some of the difficulties that philosophers have had understanding the nature of symmetries in GTR?

As a second example, let T be quantum mechanics. In this case we also have a sense of what the semantic category of T ought to be — namely, the category of (finite-dimensional) Hilbert spaces and linear operators. (This example was one of the main motivators for the semantic view, at least in the mind of van Fraassen.) Now, what might the syntactic category C_T of T look like? Is there a way to present quantum mechanics syntactically? If so, what are its axioms, and what sorts of objects does it quantify over?

5 Conclusion

In this paper, we have assumed that it can be useful, for a philosophical understanding of science, to represent theories as mathematical objects. But what is a good, fruitful mathematical framework for understanding theories? We have surveyed a number of concepts and results from category theory, which we believe provide strong evidence that it should be the locus of attention for formal philosophers of science.

Firstly, we have shown that category theory provides the resources to get past philosophy of science's false dichotomy, viz. the dichotomy between syntactic versus semantic presentations of theories. On the one hand, a semantic presentation of a theory is nonetheless a presentation — written in a mathematical language. On the other hand, the syntactic category of a theory is a hybrid object, neither purely syntactic, nor purely semantic. Enough of the original syntax of theory can be reconstructed from its associated syntactic category. Moreover, having equivalent syntactic categories guarantees having equivalent categories of models. As such, the syntactic category of a theory unites the semantic and the syntactic approach to (first-order) theories, via the notion of Morita equivalence: as long as we care about theories up to (a suitable notion of) definitional equivalence and as long as we care about the classes of models of a theory up to its categorical structure, then the tension between syntactic and semantic presentations disappears. With this formal groundwork in place our most urgent task now is to carry as much of this lesson as possible over to the philosophy of science.

²⁸One might hope for some help here from investigations in synthetic differential geometry. See, for example, (Reyes, 2009).

Secondly, with this false dichotomy set aside, philosophers of science are now set free from the illusion of a direct access to the “theory in itself” (sometimes erroneously identified with a class of models), and to study how different representations of the world can be related one to another. The category **Th** is the first formal approximation to how this kind of project might be carried out. The kind of notions about theoretical relations that will emerge will no doubt be interesting and we hope the philosophy of science lends a keen ear. Aside from this however, the very notion of studying scientific theories in their totality (i.e. as a structured whole) should lead to a philosophy of science more directly attuned to the way theoretical physics is carried out today – where the interaction and interplay of (sometimes incompatible) theories is not seen merely as a temporary state of confusion as we approach some ultimate truth, but rather the necessary interactions that have to take place within any ecosystem before more advanced life can evolve out of it.

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