

# Chapter udf

## Theories and Their Models

### mat.1 Introduction

fol:mat:int:sec The development of the axiomatic method is a significant achievement in the explanation history of science, and is of special importance in the history of mathematics. An axiomatic development of a field involves the clarification of many questions: What is the field about? What are the most fundamental concepts? How are they related? Can all the concepts of the field be defined in terms of these fundamental concepts? What laws do, and must, these concepts obey?

The axiomatic method and logic were made for each other. Formal logic provides the tools for formulating axiomatic theories, for proving theorems from the axioms of the theory in a precisely specified way, for studying the properties of all systems satisfying the axioms in a systematic way.

**Definition mat.1.** A set of **sentences**  $\Gamma$  is *closed* iff, whenever  $\Gamma \vDash \varphi$  then  $\varphi \in \Gamma$ . The *closure* of a set of **sentences**  $\Gamma$  is  $\{\varphi : \Gamma \vDash \varphi\}$ .

We say that  $\Gamma$  is *axiomatized by* a set of sentences  $\Delta$  if  $\Gamma$  is the closure of  $\Delta$

We can think of an axiomatic theory as the set of sentences that is explanation axiomatized by its set of axioms  $\Delta$ . In other words, when we have a first-order language which contains non-logical symbols for the primitives of the axiomatically developed science we wish to study, together with a set of **sentences** that express the fundamental laws of the science, we can think of the theory as represented by all the **sentences** in this language that are entailed by the axioms. This ranges from simple examples with only a single primitive and simple axioms, such as the theory of partial orders, to complex theories such as Newtonian mechanics.

The important logical facts that make this formal approach to the axiomatic method so important are the following. Suppose  $\Gamma$  is an axiom system for a theory, i.e., a set of sentences.

1. We can state precisely when an axiom system captures an intended class of **structures**. That is, if we are interested in a certain class of **struc-**

tures, we will successfully capture that class by an axiom system  $\Gamma$  iff the structures are exactly those  $\mathfrak{M}$  such that  $\mathfrak{M} \models \Gamma$ .

2. We may fail in this respect because there are  $\mathfrak{M}$  such that  $\mathfrak{M} \models \Gamma$ , but  $\mathfrak{M}$  is not one of the structures we intend. This may lead us to add axioms which are not true in  $\mathfrak{M}$ .
3. If we are successful at least in the respect that  $\Gamma$  is true in all the intended structures, then a sentence  $\varphi$  is true in all intended structures whenever  $\Gamma \models \varphi$ . Thus we can use logical tools (such as proof methods) to show that sentences are true in all intended structures simply by showing that they are entailed by the axioms.
4. Sometimes we don't have intended structures in mind, but instead start from the axioms themselves: we begin with some primitives that we want to satisfy certain laws which we codify in an axiom system. One thing that we would like to verify right away is that the axioms do not contradict each other: if they do, there can be no concepts that obey these laws, and we have tried to set up an incoherent theory. We can verify that this doesn't happen by finding a model of  $\Gamma$ . And if there are models of our theory, we can use logical methods to investigate them, and we can also use logical methods to construct models.
5. The independence of the axioms is likewise an important question. It may happen that one of the axioms is actually a consequence of the others, and so is redundant. We can prove that an axiom  $\varphi$  in  $\Gamma$  is redundant by proving  $\Gamma \setminus \{\varphi\} \models \varphi$ . We can also prove that an axiom is not redundant by showing that  $(\Gamma \setminus \{\varphi\}) \cup \{\neg\varphi\}$  is satisfiable. For instance, this is how it was shown that the parallel postulate is independent of the other axioms of geometry.
6. Another important question is that of definability of concepts in a theory: The choice of the language determines what the models of a theory consists of. But not every aspect of a theory must be represented separately in its models. For instance, every ordering  $\leq$  determines a corresponding strict ordering  $<$ —given one, we can define the other. So it is not necessary that a model of a theory involving such an order must *also* contain the corresponding strict ordering. When is it the case, in general, that one relation can be defined in terms of others? When is it impossible to define a relation in terms of other (and hence must add it to the primitives of the language)?

## mat.2 Expressing Properties of Structures

explanation It is often useful and important to express conditions on functions and relations, or more generally, that the functions and relations in a structure satisfy these conditions. For instance, we would like to have ways of distinguishing those fol:mat:exs:  
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structures for a language which “capture” what we want the predicate symbols to “mean” from those that do not. Of course we’re completely free to specify which structures we “intend,” e.g., we can specify that the interpretation of the predicate symbol  $\leq$  must be an ordering, or that we are only interested in interpretations of  $\mathcal{L}$  in which the domain consists of sets and  $\in$  is interpreted by the “is an element of” relation. But can we do this with sentences of the language? In other words, which conditions on a structure  $\mathfrak{M}$  can we express by a sentence (or perhaps a set of sentences) in the language of  $\mathfrak{M}$ ? There are some conditions that we will not be able to express. For instance, there is no sentence of  $\mathcal{L}_A$  which is only true in a structure  $\mathfrak{M}$  if  $|\mathfrak{M}| = \mathbb{N}$ . We cannot express “the domain contains only natural numbers.” But there are “structural properties” of structures that we perhaps can express. Which properties of structures can we express by sentences? Or, to put it another way, which collections of structures can we describe as those making a sentence (or set of sentences) true?

**Definition mat.2** (Model of a set). Let  $\Gamma$  be a set of sentences in a language  $\mathcal{L}$ . We say that a structure  $\mathfrak{M}$  is a model of  $\Gamma$  if  $\mathfrak{M} \models \varphi$  for all  $\varphi \in \Gamma$ .

**Example mat.3.** The sentence  $\forall x x \leq x$  is true in  $\mathfrak{M}$  iff  $\leq^{\mathfrak{M}}$  is a reflexive relation. The sentence  $\forall x \forall y ((x \leq y \wedge y \leq x) \rightarrow x = y)$  is true in  $\mathfrak{M}$  iff  $\leq^{\mathfrak{M}}$  is anti-symmetric. The sentence  $\forall x \forall y \forall z ((x \leq y \wedge y \leq z) \rightarrow x \leq z)$  is true in  $\mathfrak{M}$  iff  $\leq^{\mathfrak{M}}$  is transitive. Thus, the models of

$$\left\{ \begin{array}{l} \forall x x \leq x, \\ \forall x \forall y ((x \leq y \wedge y \leq x) \rightarrow x = y), \\ \forall x \forall y \forall z ((x \leq y \wedge y \leq z) \rightarrow x \leq z) \end{array} \right\}$$

are exactly those structures in which  $\leq^{\mathfrak{M}}$  is reflexive, anti-symmetric, and transitive, i.e., a partial order. Hence, we can take them as axioms for the *first-order theory of partial orders*.

### mat.3 Examples of First-Order Theories

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**Example mat.4.** The theory of strict linear orders in the language  $\mathcal{L}_{<}$  is axiomatized by the set

$$\left\{ \begin{array}{l} \forall x \neg x < x, \\ \forall x \forall y ((x < y \vee y < x) \vee x = y), \\ \forall x \forall y \forall z ((x < y \wedge y < z) \rightarrow x < z) \end{array} \right\}$$

It completely captures the intended structures: every strict linear order is a model of this axiom system, and vice versa, if  $R$  is a linear order on a set  $X$ , then the structure  $\mathfrak{M}$  with  $|\mathfrak{M}| = X$  and  $<^{\mathfrak{M}} = R$  is a model of this theory.

**Example mat.5.** The theory of groups in the language  $\mathbf{1}$  (constant symbol),  $\cdot$  (two-place function symbol) is axiomatized by

$$\begin{aligned}\forall x (x \cdot \mathbf{1}) &= x \\ \forall x \forall y \forall z (x \cdot (y \cdot z)) &= ((x \cdot y) \cdot z) \\ \forall x \exists y (x \cdot y) &= \mathbf{1}\end{aligned}$$

**Example mat.6.** The theory of Peano arithmetic is axiomatized by the following sentences in the language of arithmetic  $\mathcal{L}_A$ .

$$\begin{aligned}\neg \exists x x' &= \mathbf{0} \\ \forall x \forall y (x' = y' \rightarrow x = y) \\ \forall x \forall y (x < y \leftrightarrow \exists z (x + z' = y)) \\ \forall x (x + \mathbf{0}) &= x \\ \forall x \forall y (x + y') &= (x + y)' \\ \forall x (x \times \mathbf{0}) &= \mathbf{0} \\ \forall x \forall y (x \times y') &= ((x \times y) + x)\end{aligned}$$

plus all sentences of the form

$$(\varphi(\mathbf{0}) \wedge \forall x (\varphi(x) \rightarrow \varphi(x'))) \rightarrow \forall x \varphi(x)$$

Since there are infinitely many sentences of the latter form, this axiom system is infinite. The latter form is called the *induction schema*. (Actually, the induction schema is a bit more complicated than we let on here.)

The third axiom is an *explicit definition* of  $<$ .

**Example mat.7.** The theory of pure sets plays an important role in the foundations (and in the philosophy) of mathematics. A set is pure if all its elements are also pure sets. The empty set counts therefore as pure, but a set that has something as an element that is not a set would not be pure. So the pure sets are those that are formed just from the empty set and no “urelements,” i.e., objects that are not themselves sets.

The following might be considered as an axiom system for a theory of pure sets:

$$\begin{aligned}\exists x \neg \exists y y \in x \\ \forall x \forall y (\forall z (z \in x \leftrightarrow z \in y) \rightarrow x = y) \\ \forall x \forall y \exists z \forall u (u \in z \leftrightarrow (u = x \vee u = y)) \\ \forall x \exists y \forall z (z \in y \leftrightarrow \exists u (z \in u \wedge u \in x))\end{aligned}$$

plus all sentences of the form

$$\exists x \forall y (y \in x \leftrightarrow \varphi(y))$$

The first axiom says that there is a set with no **elements** (i.e.,  $\emptyset$  exists); the second says that sets are extensional; the third that for any sets  $X$  and  $Y$ , the set  $\{X, Y\}$  exists; the fourth that for any sets  $X$  and  $Y$ , the set  $X \cup Y$  exists.

The **sentences** mentioned last are collectively called the *naive comprehension scheme*. It essentially says that for every  $\varphi(x)$ , the set  $\{x : \varphi(x)\}$  exists—so at first glance a true, useful, and perhaps even necessary axiom. It is called “naive” because, as it turns out, it makes this theory unsatisfiable: if you take  $\varphi(y)$  to be  $\neg y \in y$ , you get the **sentence**

$$\exists x \forall y (y \in x \leftrightarrow \neg y \in y)$$

and this **sentence** is not satisfied in any **structure**.

**Example mat.8.** In the area of *mereology*, the relation of *parthood* is a fundamental relation. Just like theories of sets, there are theories of parthood that axiomatize various conceptions (sometimes conflicting) of this relation.

The language of mereology contains a single two-place predicate symbol  $P$ , and  $P(x, y)$  “means” that  $x$  is a part of  $y$ . When we have this interpretation in mind, a **structure** for this language is called a *parthood structure*. Of course, not every structure for a single two-place predicate will really deserve this name. To have a chance of capturing “parthood,”  $P^M$  must satisfy some conditions, which we can lay down as axioms for a theory of parthood. For instance, parthood is a partial order on objects: every object is a part (albeit an *improper* part) of itself; no two different objects can be parts of each other; a part of a part of an object is itself part of that object. Note that in this sense “is a part of” resembles “is a subset of,” but does not resemble “is an element of” which is neither reflexive nor transitive.

$$\begin{aligned} &\forall x P(x, x), \\ &\forall x \forall y ((P(x, y) \wedge P(y, x)) \rightarrow x = y), \\ &\forall x \forall y \forall z ((P(x, y) \wedge P(y, z)) \rightarrow P(x, z)), \end{aligned}$$

Moreover, any two objects have a mereological sum (an object that has these two objects as parts, and is minimal in this respect).

$$\forall x \forall y \exists z \forall u (P(z, u) \leftrightarrow (P(x, u) \wedge P(y, u)))$$

These are only some of the basic principles of parthood considered by metaphysicians. Further principles, however, quickly become hard to formulate or write down without first introducing some defined relations. For instance, most metaphysicians interested in mereology also view the following as a valid principle: whenever an object  $x$  has a proper part  $y$ , it also has a part  $z$  that has no parts in common with  $y$ , and so that the fusion of  $y$  and  $z$  is  $x$ .

## mat.4 Expressing Relations in a Structure

One main use **formulas** can be put to is to express properties and relations in a **structure**  $\mathfrak{M}$  in terms of the primitives of the language  $\mathcal{L}$  of  $\mathfrak{M}$ . By this we mean the following: the **domain** of  $\mathfrak{M}$  is a set of objects. The **constant symbols**, **function symbols**, and **predicate symbols** are interpreted in  $\mathfrak{M}$  by some objects in  $|\mathfrak{M}|$ , functions on  $|\mathfrak{M}|$ , and relations on  $|\mathfrak{M}|$ . For instance, if  $A_0^2$  is in  $\mathcal{L}$ , then  $\mathfrak{M}$  assigns to it a relation  $R = A_0^{2\mathfrak{M}}$ . Then the formula  $A_0^2(v_1, v_2)$  *expresses* that very relation, in the following sense: if a variable assignment  $s$  maps  $v_1$  to  $a \in |\mathfrak{M}|$  and  $v_2$  to  $b \in |\mathfrak{M}|$ , then

$$Rab \quad \text{iff} \quad \mathfrak{M}, s \models A_0^2(v_1, v_2).$$

Note that we have to involve variable assignments here: we can't just say " $Rab$  iff  $\mathfrak{M} \models A_0^2(a, b)$ " because  $a$  and  $b$  are not symbols of our language: they are **elements** of  $|\mathfrak{M}|$ .

Since we don't just have atomic **formulas**, but can combine them using the logical connectives and the quantifiers, more complex **formulas** can define other relations which aren't directly built into  $\mathfrak{M}$ . We're interested in how to do that, and specifically, which relations we can define in a **structure**.

**Definition mat.9.** Let  $\varphi(v_1, \dots, v_n)$  be a **formula** of  $\mathcal{L}$  in which only  $v_1, \dots, v_n$  occur free, and let  $\mathfrak{M}$  be a **structure** for  $\mathcal{L}$ .  $\varphi(v_1, \dots, v_n)$  *expresses the relation*  $R \subseteq |\mathfrak{M}|^n$  iff

$$Ra_1 \dots a_n \quad \text{iff} \quad \mathfrak{M}, s \models \varphi(v_1, \dots, v_n)$$

for any variable assignment  $s$  with  $s(v_i) = a_i$  ( $i = 1, \dots, n$ ).

**Example mat.10.** In the standard model of arithmetic  $\mathfrak{N}$ , the **formula**  $v_1 < v_2 \vee v_1 = v_2$  expresses the  $\leq$  relation on  $\mathbb{N}$ . The **formula**  $v_2 = v_1'$  expresses the successor relation, i.e., the relation  $R \subseteq \mathbb{N}^2$  where  $Rnm$  holds if  $m$  is the successor of  $n$ . The formula  $v_1 = v_2'$  expresses the predecessor relation. The **formulas**  $\exists v_3 (v_3 \neq 0 \wedge v_2 = (v_1 + v_3))$  and  $\exists v_3 (v_1 + v_3' = v_2)$  both express the  $<$  relation. This means that the predicate symbol  $<$  is actually superfluous in the language of arithmetic; it can be defined.

explanation

This idea is not just interesting in specific **structures**, but generally whenever we use a language to describe an intended model or models, i.e., when we consider theories. These theories often only contain a few **predicate symbols** as basic symbols, but in the domain they are used to describe often many other relations play an important role. If these other relations can be systematically expressed by the relations that interpret the basic **predicate symbols** of the language, we say we can *define* them in the language.

**Problem mat.1.** Find **formulas** in  $\mathcal{L}_A$  which define the following relations:

1.  $n$  is between  $i$  and  $j$ ;
2.  $n$  evenly divides  $m$  (i.e.,  $m$  is a multiple of  $n$ );

3.  $n$  is a prime number (i.e., no number other than 1 and  $n$  evenly divides  $n$ ).

**Problem mat.2.** Suppose the formula  $\varphi(v_1, v_2)$  expresses the relation  $R \subseteq |\mathfrak{M}|^2$  in a structure  $\mathfrak{M}$ . Find formulas that express the following relations:

1. the inverse  $R^{-1}$  of  $R$ ;
2. the relative product  $R \mid R$ ;

Can you find a way to express  $R^+$ , the transitive closure of  $R$ ?

**Problem mat.3.** Let  $\mathcal{L}$  be the language containing a 2-place predicate symbol  $<$  only (no other constant symbols, function symbols or predicate symbols—except of course  $=$ ). Let  $\mathfrak{N}$  be the structure such that  $|\mathfrak{N}| = \mathbb{N}$ , and  $<^{\mathfrak{N}} = \{\langle n, m \rangle : n < m\}$ . Prove the following:

1.  $\{0\}$  is definable in  $\mathfrak{N}$ ;
2.  $\{1\}$  is definable in  $\mathfrak{N}$ ;
3.  $\{2\}$  is definable in  $\mathfrak{N}$ ;
4. for each  $n \in \mathbb{N}$ , the set  $\{n\}$  is definable in  $\mathfrak{N}$ ;
5. every finite subset of  $|\mathfrak{N}|$  is definable in  $\mathfrak{N}$ ;
6. every co-finite subset of  $|\mathfrak{N}|$  is definable in  $\mathfrak{N}$  (where  $X \subseteq \mathbb{N}$  is co-finite iff  $\mathbb{N} \setminus X$  is finite).

## mat.5 The Theory of Sets

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Almost all of mathematics can be developed in the theory of sets. Developing mathematics in this theory involves a number of things. First, it requires a set of axioms for the relation  $\in$ . A number of different axiom systems have been developed, sometimes with conflicting properties of  $\in$ . The axiom system known as **ZFC**, Zermelo-Fraenkel set theory with the axiom of choice stands out: it is by far the most widely used and studied, because it turns out that its axioms suffice to prove almost all the things mathematicians expect to be able to prove. But before that can be established, it first is necessary to make clear how we can even *express* all the things mathematicians would like to express. For starters, the language contains no constant symbols or function symbols, so it seems at first glance unclear that we can talk about particular sets (such as  $\emptyset$  or  $\mathbb{N}$ ), can talk about operations on sets (such as  $X \cup Y$  and  $\wp(X)$ ), let alone other constructions which involve things other than sets, such as relations and functions.

To begin with, “is an element of” is not the only relation we are interested in: “is a subset of” seems almost as important. But we can *define* “is a subset of” in terms of “is an element of.” To do this, we have to find a formula  $\varphi(x, y)$  in the language of set theory which is satisfied by a pair of sets  $\langle X, Y \rangle$  iff

$X \subseteq Y$ . But  $X$  is a subset of  $Y$  just in case all **elements** of  $X$  are also **elements** of  $Y$ . So we can define  $\subseteq$  by the formula

$$\forall z (z \in x \rightarrow z \in y)$$

Now, whenever we want to use the relation  $\subseteq$  in a formula, we could instead use that formula (with  $x$  and  $y$  suitably replaced, and the bound variable  $z$  renamed if necessary). For instance, extensionality of sets means that if any sets  $x$  and  $y$  are contained in each other, then  $x$  and  $y$  must be the same set. This can be expressed by  $\forall x \forall y ((x \subseteq y \wedge y \subseteq x) \rightarrow x = y)$ , or, if we replace  $\subseteq$  by the above definition, by

$$\forall x \forall y ((\forall z (z \in x \rightarrow z \in y) \wedge \forall z (z \in y \rightarrow z \in x)) \rightarrow x = y).$$

This is in fact one of the axioms of **ZFC**, the “axiom of extensionality.”

There is no **constant symbol** for  $\emptyset$ , but we can express “ $x$  is empty” by  $\neg \exists y y \in x$ . Then “ $\emptyset$  exists” becomes the **sentence**  $\exists x \neg \exists y y \in x$ . This is another axiom of **ZFC**. (Note that the axiom of extensionality implies that there is only one empty set.) Whenever we want to talk about  $\emptyset$  in the language of set theory, we would write this as “there is a set that’s empty and ...” As an example, to express the fact that  $\emptyset$  is a subset of every set, we could write

$$\exists x (\neg \exists y y \in x \wedge \forall z x \subseteq z)$$

where, of course,  $x \subseteq z$  would in turn have to be replaced by its definition.

To talk about operations on sets, such as  $X \cup Y$  and  $\wp(X)$ , we have to use a similar trick. There are no function symbols in the language of set theory, but we can express the functional relations  $X \cup Y = Z$  and  $\wp(X) = Y$  by

$$\begin{aligned} \forall u ((u \in x \vee u \in y) \leftrightarrow u \in z) \\ \forall u (u \subseteq x \leftrightarrow u \in y) \end{aligned}$$

since the **elements** of  $X \cup Y$  are exactly the sets that are either **elements** of  $X$  or **elements** of  $Y$ , and the **elements** of  $\wp(X)$  are exactly the subsets of  $X$ . However, this doesn’t allow us to use  $x \cup y$  or  $\wp(x)$  as if they were terms: we can only use the entire **formulas** that define the relations  $X \cup Y = Z$  and  $\wp(X) = Y$ . In fact, we do not know that these relations are ever satisfied, i.e., we do not know that unions and power sets always exist. For instance, the **sentence**  $\forall x \exists y \wp(x) = y$  is another axiom of **ZFC** (the power set axiom).

Now what about talk of ordered pairs or functions? Here we have to explain how we can think of ordered pairs and functions as special kinds of sets. One way to define the ordered pair  $\langle x, y \rangle$  is as the set  $\{\{x\}, \{x, y\}\}$ . But like before, we cannot introduce a **function symbol** that names this set; we can only define the relation  $\langle x, y \rangle = z$ , i.e.,  $\{\{x\}, \{x, y\}\} = z$ :

$$\forall u (u \in z \leftrightarrow (\forall v (v \in u \leftrightarrow v = x) \vee \forall v (v \in u \leftrightarrow (v = x \vee v = y))))$$

This says that the **elements**  $u$  of  $z$  are exactly those sets which either have  $x$  as its only **element** or have  $x$  and  $y$  as its only **elements** (in other words, those



sets that are either identical to  $\{x\}$  or identical to  $\{x, y\}$ ). Once we have this, we can say further things, e.g., that  $X \times Y = Z$ :

$$\forall z (z \in Z \leftrightarrow \exists x \exists y (x \in X \wedge y \in Y \wedge \langle x, y \rangle = z))$$

A function  $f: X \rightarrow Y$  can be thought of as the relation  $f(x) = y$ , i.e., as the set of pairs  $\{\langle x, y \rangle : f(x) = y\}$ . We can then say that a set  $f$  is a function from  $X$  to  $Y$  if (a) it is a relation  $\subseteq X \times Y$ , (b) it is total, i.e., for all  $x \in X$  there is some  $y \in Y$  such that  $\langle x, y \rangle \in f$  and (c) it is functional, i.e., whenever  $\langle x, y \rangle, \langle x, y' \rangle \in f$ ,  $y = y'$  (because values of functions must be unique). So “ $f$  is a function from  $X$  to  $Y$ ” can be written as:

$$\begin{aligned} & \forall u (u \in f \rightarrow \exists x \exists y (x \in X \wedge y \in Y \wedge \langle x, y \rangle = u)) \wedge \\ & \forall x (x \in X \rightarrow (\exists y (y \in Y \wedge \text{maps}(f, x, y)) \wedge \\ & \quad (\forall y \forall y' ((\text{maps}(f, x, y) \wedge \text{maps}(f, x, y')) \rightarrow y = y')))) \end{aligned}$$

where  $\text{maps}(f, x, y)$  abbreviates  $\exists v (v \in f \wedge \langle x, y \rangle = v)$  (this formula expresses “ $f(x) = y$ ”).

It is now also not hard to express that  $f: X \rightarrow Y$  is **injective**, for instance:

$$\begin{aligned} f: X \rightarrow Y \wedge \forall x \forall x' ((x \in X \wedge x' \in X \wedge \\ \exists y (\text{maps}(f, x, y) \wedge \text{maps}(f, x', y))) \rightarrow x = x') \end{aligned}$$

A function  $f: X \rightarrow Y$  is **injective** iff, whenever  $f$  maps  $x, x' \in X$  to a single  $y$ ,  $x = x'$ . If we abbreviate this formula as  $\text{inj}(f, X, Y)$ , we’re already in a position to state in the language of set theory something as non-trivial as Cantor’s theorem: there is no **injective** function from  $\wp(X)$  to  $X$ :

$$\forall X \forall Y (\wp(X) = Y \rightarrow \neg \exists f \text{inj}(f, Y, X))$$

One might think that set theory requires another axiom that guarantees the existence of a set for every defining property. If  $\varphi(x)$  is a formula of set theory with the variable  $x$  free, we can consider the **sentence**

$$\exists y \forall x (x \in y \leftrightarrow \varphi(x)).$$

This **sentence** states that there is a set  $y$  whose **elements** are all and only those  $x$  that satisfy  $\varphi(x)$ . This schema is called the “comprehension principle.” It looks very useful; unfortunately it is inconsistent. Take  $\varphi(x) \equiv \neg x \in x$ , then the comprehension principle states

$$\exists y \forall x (x \in y \leftrightarrow x \notin x),$$

i.e., it states the existence of a set of all sets that are not **elements** of themselves. No such set can exist—this is Russell’s Paradox. **ZFC**, in fact, contains a restricted—and consistent—version of this principle, the separation principle:

$$\forall z \exists y \forall x (x \in y \leftrightarrow (x \in z \wedge \varphi(x))).$$

**Problem mat.4.** Show that the comprehension principle is inconsistent by giving a **derivation** that shows

$$\exists y \forall x (x \in y \leftrightarrow x \notin x) \vdash \perp.$$

It may help to first show  $(A \rightarrow \neg A) \wedge (\neg A \rightarrow A) \vdash \perp$ .

## mat.6 Expressing the Size of Structures

**explanation** There are some properties of structures we can express even without using the non-logical symbols of a language. For instance, there are **sentences** which are true in a **structure** iff the **domain** of the **structure** has at least, at most, or exactly a certain number  $n$  of **elements**. **fol:mat:siz:sec**

**Proposition mat.11.** *The sentence*

$$\begin{aligned} \varphi_{\geq n} \equiv \exists x_1 \exists x_2 \dots \exists x_n \quad & (x_1 \neq x_2 \wedge x_1 \neq x_3 \wedge x_1 \neq x_4 \wedge \dots \wedge x_1 \neq x_n \wedge \\ & x_2 \neq x_3 \wedge x_2 \neq x_4 \wedge \dots \wedge x_2 \neq x_n \wedge \\ & \vdots \\ & x_{n-1} \neq x_n) \end{aligned}$$

*is true in a structure  $\mathfrak{M}$  iff  $|\mathfrak{M}|$  contains at least  $n$  elements. Consequently,  $\mathfrak{M} \models \neg \varphi_{\geq n+1}$  iff  $|\mathfrak{M}|$  contains at most  $n$  elements.*

**Proposition mat.12.** *The sentence*

$$\begin{aligned} \varphi_{=n} \equiv \exists x_1 \exists x_2 \dots \exists x_n \quad & (x_1 \neq x_2 \wedge x_1 \neq x_3 \wedge x_1 \neq x_4 \wedge \dots \wedge x_1 \neq x_n \wedge \\ & x_2 \neq x_3 \wedge x_2 \neq x_4 \wedge \dots \wedge x_2 \neq x_n \wedge \\ & \vdots \\ & x_{n-1} \neq x_n \wedge \\ & \forall y (y = x_1 \vee \dots \vee y = x_n) \dots) \end{aligned}$$

*is true in a structure  $\mathfrak{M}$  iff  $|\mathfrak{M}|$  contains exactly  $n$  elements.*

**Proposition mat.13.** *A structure is infinite iff it is a model of*

$$\{\varphi_{\geq 1}, \varphi_{\geq 2}, \varphi_{\geq 3}, \dots\}$$

There is no single purely logical sentence which is true in  $\mathfrak{M}$  iff  $|\mathfrak{M}|$  is infinite. However, one can give **sentences** with non-logical **predicate symbols** which only have infinite models (although not every infinite **structure** is a model of them). The property of being a finite structure, and the property of being a **non-enumerable** structure cannot even be expressed with an infinite set of

**sentences.** These facts follow from the compactness and Löwenheim-Skolem theorems.

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# Bibliography