PMATH433/733 — Model Theory and Set Theory

CLASSNOTES FOR FALL 2018

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Foreword

This course has a ratio of about 1:3 for naive set theory to model theory.

Part I

Set Theory

1 Lecture 1 Sep 06th

1.1 Introduction to Set Theory

IN THIS COURSE, we shall focus only on practical set theory, which is more commonly knowned as naive set theory. In practical set theory, we look at set theory as a language of mathematics. Some of the examples of which we look into in this flavour of set theory are (transfinite) induction and recursion, and the measuring of the sizes of sets.

Another approach to set theory, one that is deemed required in order to learn set theory is a more formal way, is to look at set theory as the foundations of mathematics. Such an approach is more axiomatic, rigorous, and grounding as compared to practical set theory. This course will try to work around going into these topics, as they can take a life of their own, and within the context of this course, the topics that will be explored using this approach are not required.

1.2 Ordinals

1.2.1 Zermelo-Fraenkel Axioms

We use the natural numbers, i.e.

to **count** finite sets. There are two related meanings attached to the word "count" here:

- enumeration; and
- measuring (of sizes)

In order to facilitate the introduction to certain axioms that we shall need, let our current goal be to develop an infinitary generalization of the natural numbers, so as to be able to enumerate and measure arbitrary sets.

To CONSTRUCT the natural numbers, we require 3 basic notions that shall remain undefined but understood:

- a set;
- membership, denoted by \in ; and
- equality.

One such construction is

 $0 := \emptyset$, the empty set

 $1 := \{0\} = \{\emptyset\}$, the set whose only member is 0

 $2 := \{0,1\} = \{\emptyset, \{\emptyset\}\}\$, the set whose only members are 0 and 1.

Definition 1 (Successor)

Given a natural number n, the **successor** of n is the natural number next to n, which can be obtained by

$$S(n) := n \cup \{n\}.$$

We can use the definition of a successor to construct the rest of the natural numbers.

Example 1.2.1

Just to verify to ourselves that the definition indeed works, observe that

$$S(1) = 2 = \{\emptyset, \{\emptyset\}\} = \{\emptyset\} \cup \{\{\emptyset\}\}.$$

So to construct the natural number 3, we see that

$$S(2) = 3 = \{0, 1, 2\} = 2 \cup \{2\} = \{\emptyset, \{\emptyset\}\} \cup \{\{\emptyset, \{\emptyset\}\}\}\}$$
$$= \{\emptyset, \{\emptyset\}, \{\emptyset, \{\emptyset\}\}\}\}$$

We have that

enumeration \rightarrow ordinals measuring \rightarrow cardinals

where \rightarrow represents "leads to" here.

Looking at these, we start wondering to ourselves: how do we know that \emptyset exists in the first place? How do we know that we can use ∪ and what does it even mean? Now it is meaningless if we cannot take that \emptyset always exists, nor is it meaningful if we cannot take the \cup of sets. And so, to allow us to continue, or even start with these notions, we require axioms.

■ Axiom 1 (Empty Set Axiom)

There exists a set, denoted by \emptyset *, with no members.*

With this axiom, we can indeed construct 0. To get 1 from 0, we have that 1 is a set whose only member is zero, and so if we take a member from 1, that member must be 0.

■ Axiom 2 (Pairset Axiom)

Given set x, y, there exists a set, denoted by $\{x, y\}$, whose only members are x and y. In other words,

$$t \in \{x, y\} \leftrightarrow (t = x \lor t = y)$$

Now note that in \mathbf{U} Axiom 2, if x = y, then the set $\{x, y\}$ has only x as its member. For example, we realize that $1 = \{0,0\} = \{0\}$. But why exactly does this equality make sense? What exactly does "realize" mean?

▼ Axiom 3 (Axiom of Extension)

Given sets x, y, x = y if and only if x and y have the same members.

Now, using the above 3 axioms, we are guaranteed that

 $0 = \emptyset$ exists by the Empty Set Axiom

 $1 = \{\emptyset\}$ exists by the Pairset Axiom

 $2 = \{\emptyset, \{\emptyset\}\}$ exists by the Pairset Axiom

Now we've constructed 3 to be the set whose only members are 0,1, and 2. So far, within our axioms, there is no such thing as $\{0,1,2\}$, which is what our 3 is supposed to be. We now require the following axiom:

▼ Axiom 4 (Union Set Axiom)

Given a set x, there exists a set denoted by $\cup x$, whose members are precisely the members of the members of x, i.e.

$$t \in \bigcup x \leftrightarrow (t \in y \text{ for some } y \in x)$$

So, by this axiom, we have that given any n, $S(n) = \bigcup \{n, \{n\}\}$, or in other words,

$$t \in S(n) \leftrightarrow t \in n \lor t = n$$
.

With all of the above axioms, we can iteratively construct each and every natural number in a rigorous manner. However, our goal is to construct infinitely many of them.

It is tempting to simply take the infinitude of natural numbers simply as an axiom, i.e.

There exists a set whose members are precisely the natural numbers.

There is a certain rule to which we set down axioms, and that is, axioms must be expressable in a "finitary" manner, i.e. they must be expressible using first-order logic.

Definition 2 (Definite Condition)

We define a definite condition as follows:

- $x \in y$ and x = y are definite conditions, where x and y are both indeterminants, standing for sets, or are sets themselves;
- if P and Q are definite conditions, then so are
 - not P, denoted as $\neg P$;
 - P and Q, denoted as $P \wedge Q$;

- P or Q, denoted as $P \vee Q$;
- for all x, P, denoted as $\forall xP$; and
- there exists x, P, denoted as $\exists x P$.

Example 1.2.2

$$x \in 1, 0 \in 2, 2 \in 0$$

are all definite conditions. Note, however, that $2 \in 0$ is false.

66 Note

"If P then Q", which is also written as $P \rightarrow Q$, is also a definite condition since it is "equivalent" to the statement $\neg P \lor Q$.

Consequently, Pifandonlyif Q, which is also expressed as $P \leftrightarrow Q$, can be written as

$$(\neg P \lor Q) \land (\neg Q \lor P)$$

Now, with this definition, and first-order logic notations in mind, we can write:

- Empty Set Axiom: $\exists x \ \forall t \ \neg (t \in x)$
- Pairset Axiom: $\forall x \ \forall y \ \exists p \ \forall t \ (t \in p \leftrightarrow ((t = x) \lor (t = y)))$
- Union Set Axiom: $\forall x \; \exists z \; \forall t \; ((t \in z) \leftrightarrow (\exists y \; ((y \in x) \land (t \in y))))$

Note that the statement that we proposed as an axiom for the set of natural numbers in page 16 is not definite, although that itself is not obvious.

For example, we may try to write

$$\exists x \ (\forall t \ ((t \in x) \leftrightarrow ((t = 0) \lor (t = 1) \lor (t = 2) \lor ...)))$$

and then notice that we do not have the notion of "..." within the "tools" that we are allowed to use.

¹ We have yet to define what equivalent statements are but we shall take this for granted for now.

Exercise 1.2.1

Write **Ū** Axiom 3 in first-order logic notation.

Solution

$$\forall x \, \forall y$$
$$(x = y) \leftrightarrow (\forall t \, ((t \in x) \leftrightarrow (t \in y)))$$

2 Lecture 2 Sep 11th

2.1 *Ordinals* (Continued)

2.1.1 Zermelo-Fraenkel Axioms (Continued)

We stopped at the discussion about allowing for an infinite set, so that we can construct our set of infinite natural numbers. The idea here is to take *the smallest set that contains* 0 *and is preserved by the successor function*¹

¹ Q: Why the smallest set?

■ Axiom 5 (Infinity Axiom)

There exists a set I that contains 0 and is preserved by the successor function. We may express this as

$$\exists I((0 \in I) \land \forall x (x \in I \to S(x) \in I))$$

where we have defined that $S(x) \in I$ means

$$\exists y (\forall t (t \in y \leftrightarrow (t \in x) \lor (t = x)) \land (y \in I))$$

We call I the successor set.

Since we want the smallest of such successor sets, we can try taking the intersection of all successor sets. But before we can do that, we require more axiomatic statements.

Definition 3 (Subsets)

 $x \subseteq y$ means that every element of x is an element of y, i.e.

$$\forall t ((t \in x) \to (t \in y))$$

With a definition of a subset, we can define the Powerset Axiom.

■ Axiom 6 (Powerset Axiom)

Given a set x, there exists a set P(x) that contains all subsets of x, i.e.

$$\forall t((t \subseteq \mathcal{P}(x)) \leftrightarrow (t \subseteq x))$$

We also require the following axiom.

■ Axiom 7 ((Bounded) Separation Axiom)

Given a set x and a definition condition P, there exists a set whose elements are precisely the members of x that satisfies P, i.e.

$$\forall x \; \exists y \; \forall t \; ((t \in y) \leftrightarrow \forall y \; ((t \in x) \land P(t)))$$

where

$$y = \{z \in x \mid P(z)\}.$$

Exercise 2.1.1 (Set Intersection)

Prove that given a non-empty set x, there exists a set $\cap x$ satisfying

$$\forall t \ ((t \in \cap x) \leftrightarrow \forall y \ ((y \in x) \to (t \in y)))$$

Proof

to be solved

Definition 4 (Natural Numbers)

There are two important aspects to the Bounded Separation Axiom:

- it is bounded by the set *x*; and
- *P* is a definite condition.

Let I be a successor set. The set of natural numbers is²

$$\omega := \cap \{J \subseteq I : J \text{ is a successor set } \}$$

² We can also write $J \subseteq I$ as $J \in \mathcal{P}(I)$ and invoke the Bounded Separation

66 Note

J being a successor set can be expressed by the definite condition

$$(0 \in J) \land \forall x \ (x \in J \rightarrow S(x) \in J),$$

so we can write the definite condition in the above definition by

$$\omega := \cap \{ J \subseteq I : (0 \in J) \lor \forall x \ (x \in J \to S(x) \in J) \}$$

Exercise 2.1.2

Show that the definition of ω does not actually depend on I, i.e. if given I₁ and I2 such that we have

$$\omega_1 = \bigcap \{ J \subseteq I_1 : J \text{ is a successor set } \}$$

 $\omega_2 = \bigcap \{ J \subseteq I_2 : J \text{ is a successor set } \}$

we have

$$\omega_1 = \omega_2$$

Proof

to be solved

Another useful axiom that we will use later is the following:

▼ Axiom 8 (Replacement Axiom)

Suppose P is a binary definite condition³ such that for every set x, there is a unique y satisfying P(x,y). Given a set A, there is a set B such that $t \in B$ if and only if there is an $a \in A$ with P(a, t).

³ A binary definite condition has only two variables.

66 Note

The slogan for the Replacement Axiom is:

The image of a set under a definite operation exists.

These eight axioms, along with another ninth axiom called the Regularity Axiom⁴, constitutes the **Zermelo-Fraenkel Set Theory**.

Note that all axioms, save the Extensionality, assert the existence of sets.

⁴ We shall not discuss too much about this. According to the lecture and the lecture notes, the Regularity Axiom states that every set has a minimal element. On Wikipedia, the axiom states that every set has an element that does not intersect with the set itself.

2.1.2 Classes

There are times where we are interested in a collection of sets that do not form a set themselves.

Example 2.1.1 (Russell's Paradox)

There is no set containing all sets.

Proof

Suppose such a set exists, and call it *U*. Now consider the set

$$R := \{x \in U : x \notin x\},\$$

which exists by Bounded Separation. Observe that

$$R \in R \implies R \notin R$$
 $\implies R \notin R \implies R \in R$

Thus such a set *U* cannot exist.

To talk about such collections, that may or may not be sets, we define *classes*.

Definition 5 (Class)

A class is any collection of sets defined by definite property, i.e. given any difinite condition P,

$$\llbracket z \mid P(z) \rrbracket$$

is the class of all sets satisfying P.

Here, instead of Bounded Separation, we have what is called unbounded separation.

66 Note

We shall use $[\![\]\!]$ rather than $\{\ \}$ to emphasize that we are talking about classes, i.e. we may be talking about non-sets.

Example 2.1.2

$$Set := [\![z \mid z = z]\!]$$

is the universal class of all sets.

66 Note

• Every set is a class.

Proof

Suppose x is a set. We may write

$$x = \parallel z \mid z \in x \parallel$$
.

• Some classes are not sets; these are called proper classes. E.g. the universal class of all sets, and

$$Russell := [\![z \mid z \notin z]\!].$$

3 Lecture 3 Sep 13th

3.1 Ordinals (Continued 2)

3.1.1 Cartesian Products and Function

Definition 6 (Ordered Pairs)

Given sets x, y, an **ordered pair** of x and y is defined as¹

$$(x,y) = \{\{x\}, \{x,y\}\}$$

¹ This invokes the Pairset Axiom thrice. Why did we not define an ordered pair as

$$(x, y) = \{\{x\}, \{y\}\}$$

instead?

66 Note

Note that we must have

$$((x,y) = (x',y')) \iff (x = x' \land y = y').$$

Proof

The (\iff) direction is clear by Extensionality. For the other direction, we shall break it into 2 cases:

Case 1: x = y. Then $\{x, y\} = \{x\}$ by Extensionality, and so

$$(x,y) = \{\{x\}\}$$

Therefore, we have that

$$\{\{x\}\} = (x,y) = (x',y') = \{\{x'\}, \{x',y'\}\}$$

So we have

$$\{x\} = \{x'\} \implies x = x'$$

and

$$\{x\} = \{x', y'\} \implies y' = x = y.$$

Thus we have

$$x = x' \wedge y = y'$$

Case 2: Suppose $x \neq y$ and $x' \neq y'$ ² We have

$$\{\{x\},\{x,y\}\} = \{\{x'\},\{x',y'\}\}$$

Then

$$\{x\} = \{x'\} \lor \{x\} = \{x', y'\}$$

The latter leads to a contradiction, since it would imply

$$x' = x = y'$$
.

Thus x = x'. Also, we have

$$\{x,y\} = \{x'\} \lor \{x,y\} = \{x',y'\}$$

Now the former leads to a contradiction since it would imply that

$$x = x' = y$$
.

Now since x = x', it must be that y = y', otherwise y = x' = x would contradict our assumption. Therefore, we have that

$$x = x' \wedge y = y'$$

With ordered pairs, we can build Cartesian products:

Definition 7 (Cartesian Product)

Given classes X and Y, the Cartesian Product of X and Y is defined as

$$X \times Y := [[z : z = (x, y), x \in X, y \in Y]]$$

² If any of them are equal, Case 1 would apply.

66 Note

We can express this definition using definite conditions;

$$\forall x, y \bigg((x \in X) \land (y \in Y) \land \Big(\exists a, b (\forall t (t \in a \leftrightarrow t = x)) \land \forall t (t \in b \leftrightarrow (t = x) \lor (t = y)) \Big) \land$$
$$\forall t \Big(t \in z \leftrightarrow \big((t = a) \lor (t = b) \big) \Big) \bigg)$$

66 Note

- *A Cartesian product is a class.*
- If A is a set and B is a class, and $B \subseteq A$, then B is also a set. This is easy to show: observe that by Extentionality,

$$B = \{a \in A \mid a \in B\}.$$

By Bounded Separation Axiom, B is a set³.

³ This statement can be rephrased as: subclasses of a set are subsets.

Consequently, Cartesian products of sets are sets themselves; if X and Y are sets, we want to show that $X \times Y$ is a set so it is sufficient to show that it is contained in one. Recall that

$$(x,y) = \{\{x\}, \{x,y\}\}$$

and $\{x,y\} \subset X \cup Y$ which means $\{x,y\} \in \mathcal{P}(X)$, and we observe that $\{x\} \in \mathcal{P}(X \cup Y)$. So $(x,y) \in \mathcal{P}(X \cup Y)$. Therefore, $X \times Y \subset$ $\mathcal{P}(\mathcal{P}(X \cup Y))$, and we show to ourselves that $X \times Y$ is indeed a set.

Definition 8 (Definite Operation)

Given classes X and Y, a **definite operation** $f: X \rightarrow Y$ is a subclass $\Gamma(f) \subseteq X \times Y$ such that

$$\forall x \in X \exists ! y \in Y (x, y) \in \Gamma(f).$$

66 Note

We write f(x) = y to mean $(x,y) \in \Gamma(f)$. We also refer to $\Gamma(f)$ as the graph of f.

Example 3.1.1

The successor function $S : Set \rightarrow Set$ is a definite operation such that

$$S(x) = x \cup \{x\}$$

This is true since is can be expressed as

$$\forall t (t \in y \leftrightarrow (t \in x \lor t = x)).$$

To show that S is a definite operation, we need to show that S is a definite condition.

66 Note

If X and Y are sets and f is a definite operation, then $\Gamma(f) \subseteq X \times Y$ is a set. In such a case, we call f a function.

Definition 9 (Functions)

A function is a definite operation $f: X \to Y$ where X and Y are both sets.

We can now restate the Replacement Axiom.

■ Axiom 9 (Replacement Axiom (Restated))

If $f: X \to Y$ is a definite operation, and $A \subseteq X$ is a set, then $\exists B \subseteq Y$ that is a set such that $t \in B$ if and only if t = f(a) for some $a \in A$.

3.1.2 The Natural Numbers

Theorem 10 (Induction Principle)

Suppose $I \subseteq \omega$, $0 \in I$ and whenever $n \in I$, $S(n) \in I$. Then $I = \omega$.

Proof

By assumption, *J* is a successor set, therefore $\omega \subseteq J$ by definition. Thus, sinec $J \subseteq \omega$, we have $J = \omega$.

Lemma 11 (Properties of the Natural Numbers)

Suppose $n \in \omega$. We have

- 1. $n \subseteq \omega$;
- 2. $\forall m \in n \quad m \subseteq n$;
- 3. $n \notin n$;
- 5. $y \in n \implies S(y) \in n \vee S(y) = n$.

Proof

1. Let⁴

$$J:=\{n\in\omega:n\subseteq\omega\}\subseteq\omega.$$

Note that $\emptyset \subseteq \omega$ and so $0 \subseteq \omega$. By membership, $0 \in J$.

Suppose $m \in J$. Consider $S(m) = m \cup \{m\}$. Since $J \subseteq \omega$, $m \in \omega$. Since $m \in \omega$, $\{m\} \subseteq \omega$. Therefore $S(m) = m \cup \{m\} \subseteq \omega$, and so $S(m) \in J$. So J is a successor set. And thus by Induction Principle, $I = \omega$.

2. Let

$$J := \{ n \in \omega : \forall m \in n, m \subseteq n \}.$$

It is vacuously true that $0 \in J$ since \emptyset is a subset of every $n \in J$. Suppose $n \in J$. Then $\forall m \in n$, we have $m \subseteq n$. Consider $S(n) = n \cup \{n\}$. Note that $n \in S(n)$ and $n \subseteq S(n)$. For $x \in S(n)$ such that $x \neq n$, we must have that $x \in n$. By assumption, $x \subseteq n \subseteq S(n)$. Therefore, $S(n) \in I$, and so I is a successor set. By the Induction Principle, $I = \omega$.

⁴ We construct this *J* and show that it is a successor set. Note that if $J = \omega$, our proof is complete.

3. Let

$$J := \{ n \in \omega : n \notin n \}.$$

We have $0 = \emptyset \notin \emptyset$. So $0 \in J$.

Let $n \in J$. Consider $S(n) = n \cup \{n\}$. In particular, note that $n \in S(n)$. Suppose, for contradiction, that $S(n) \in S(n)$. Then S(n) = n or $S(n) \in n$.

$$S(n) = n \implies n \in S(n) = n \notin n$$
.

$$S(n) \in n \implies S(n) \subseteq n \text{ by part 2} \implies n \in n \not = n.$$

Thus $S(n) \notin S(n)$ and so $S(n) \in J$. So J is a successor set, and so by the Induction Principle, $J = \omega$.

4. It suffices to show that

$$\omega = \{0\} \cup \{n \in \omega : 0 \in n\}.$$

Let J = RHS. We have that $0 \in J$. Suppose $n \in J$ such that $n \neq 0$. Then $0 \in n$. Since $n \subseteq S(n) = n \cup \{n\}$, we have that $0 \in S(n)$. Therefore, $S(n) \in J$. So J is a successor set, and so by the Induction Principle, $J = \omega$ as required.

5. Let

$$J := \{ n \in \omega : y \in n \implies S(y) \in n \veebar S(y) = n \}.$$

 $0 \in J$ is vacuously true, since there are no $y \in 0$. Suppose $n \in J$. Let $y \in S(n) = n \cup \{n\}$. We have two choices: either $y \in n$ or y = n. If $y \in n$, then $S(y) \in n \veebar S(y) = n$, since $n \in J$. We have that

 $S(y) \in n \subseteq S(n)$ in which case we are done; and

$$(sy) \subseteq n \in S(n)$$
.

Otherwise, if $y \notin n$, then y = n. Then we simply have S(y) = S(n). Thus J is a succesor set and so by the Induction Principle, $J = \omega$.

Definition 10 (Strict Partially Ordered Set)

A strict partially ordered set (or strict poset⁵) is a set E together with $R \subseteq E^2 = E \times E$ such that

⁵ This is my unofficial terminology

- 1. (anti-reflexive) $\forall a \in E \quad (a,a) \notin R$;
- 2. (anti-symmetric) $\forall a,b \in E \quad (a,b) \in R \wedge (b,a) \in R \implies a = b$; and
- 3. (transitivity) $\forall a, b, c \in E \quad (a, b), (b, c) \in R \implies (a, c) \in R$.

Definition 11 (Strict Totally Ordered Set)

A strict poset is **total** (or **linear**) if

$$\forall a, b \in E \quad (a, b) \in R \vee (b, a) \in R$$

Definition 12 (Well-Order)

A strict linear order is well-ordered if

$$\forall X \subseteq E(X \neq \emptyset) \quad \exists a \in X \quad \forall b \in X(b \neq a) \quad (a,b) \in R$$

i.e. every nonempty subset of E has a *least element*.

We shall prove the following next lecture.⁶

⁶ Anti-reflexivity and Anti-symmetry were proven in this lecture, but I am moving it to the next for ease of reading.

 (ω, \in) is a strict well-ordering.

[•] Proposition (ω is Strictly Well-ordered)

4 Lecture 4 Sep 18th

4.1 Ordinals (Continued 3)

4.1.1 Well-Orderings (Continued)

• Proposition 12 (ω is Strictly Well-Ordered)

 (ω, \in) is a strict well-ordering.

Proof

By Lemma 11, we have that $\forall n \in \omega, n \notin n$. (anti-reflexivity \checkmark).

 $\forall n, m \in \omega$, suppose, for contradiction, that $n \in m$ and $m \in n$. Again, by Lemma 11, we have $n \subseteq m$ and $m \subseteq n$, which implies that n = m. Thus, we have $n \in m = n$ and $m \in n = m$, a contradiction to the fact that $n \notin n$ and $m \notin m$ (anti-symmetry \checkmark).

 $\forall x, y, z \in \omega$ such that $x \in y$ and $y \in z$, by Lemma 11, $y \in z \implies y \subseteq z \implies x \in z$ (transitivity \checkmark).

To show totality of the relation, let $n \in \omega$. WTS for any $m \in \omega$, either

$$m \in n$$
, $m = n$, or $n \in m$.

Let1

$$J = \underset{\in n}{n} \cup \{n\} \cup \{m \in \omega : n \in m\}.$$

Case 1: n = 0. In this case, we have²

$$J = \emptyset \cup \{\emptyset\} \cup \{m \in \omega : 0 \in m\}$$

As a consequence of Lemma 11 (4), we have that $J = \omega$.

♣ Lemma (Lemma 11)

Suppose $n \in \omega$. We have

- 1. $n \subseteq \omega$;
- 2. $\forall m \in n \quad m \subseteq n$;
- 3. n ∉ n:
- 5. $y \in n \implies S(y) \in n \vee S(y) = n$.

¹ We construct J such that J will contain all the possible cases, and use this fact to prove that $J=\omega$ so these 3 cases are the only scenarios that can happen.

² Note that $0 = \emptyset$.

Case 2: $n \neq 0$. Again, by Lemma 11 (4), since $n \neq 0$, we must have $0 \in n \subseteq J$ and so $0 \in J$. Now suppose that $m \in J$.

Case 2(a): $m \in n$. Then by Lemma 11 (5), $S(m) \in n$ or S(m) = n. $S(m) \in n \implies S(m) \in J$ $S(m) \in n \implies S(m) \in J$

Case 2(b): m = n. Then $S(m) = S(n) = n \cup \{n\}$. And so $n \in S(m)$, which implies $S(m) \in J$.

Case 2(c): $n \in m$ Then since $S(m) = m \cup \{m\}$, we have that $m \in m \subseteq S(m)$. Therefore $S(m) \in J$.

Therefore, J is a successor subset of ω . Thus by the Induction Principle, $J = \omega$. (totality \checkmark)

To prove that \in is a well-ordering, suppose $X \subseteq \omega$ is non-empty. Suppose, for contradiction, that X has no \in -least element. Now consider

$$J = \{ n \in \omega : S(n) \cap X = \emptyset \}$$

Claim: *J* is a successor set.³

By Lemma 11 (4), 0 is the \in -least element of ω . If $0 \in X$, then 0 would be \in -least in X, contradicting our supposition. Thus $0 \notin X$, And so

$$S(0) \cap X = (0 \cup \{0\}) \cap X = \{0\} \cap X = \emptyset$$

since $0 \notin X$. Thus $0 \in I$.

Suppose $n \in J$. By construction of J, we have $S(n) \cap X = \emptyset$. Observe that

$$S(S(n)) \cap X = (S(n) \cup \{S(n)\}) \cap X.$$

Now if RHS of the above is non-empty (aiming for contradiction), then we may have $S(n) \in X$. Then S(n) would be the \in -least element in X, a contradiction. If $m \in S(n)$, we have that $m \notin X$ since $S(n) \cap X = \emptyset$. Thus $SS(n) \cap X = \emptyset$ and so $S(n) \in J$. Therefore, by the Induction Principle, $J = \omega$.

We observe that $\forall n \in \omega$,

$$\emptyset = S(n) \cap X) = (n \cup \{n\}) \cap X$$

 $\implies n \notin X$, and so we must have $X = \emptyset$ (well-ordered \checkmark).

³ Since we want to prove that ∈ is a well-ordering, we can suppose that there is a non-empty subset of ω that is not empty, and has no ∈-least element. The core idea here is that, by the construction of J, if $J = \omega$, then all elements of ω would be disjoint from X, forcing X to be the empty set.

66 Note

Given $n, m \in \omega$, we often write n < m to mean $n \in m$.

Definition 13 (Ordinals)

An **ordinal** is a set α satisfying:

- 1. $x \in \alpha \implies x \subseteq \alpha$;
- 2. (α, \in) is a strict well-ordering.

Example 4.1.1

 ω is an ordinal: $\forall n \in \omega$, by Lemma 11, $n \subseteq \omega$, and ω is proven to have a strict well-ordering under \in .

Example 4.1.2

Every natural number is an ordinal (finite ordinals): by Lemma 11 (2), the first property is satisfied; well-ordering follows from the property of ω .

Let Ord denote the class of all ordinals. We shall show later that Ord is a proper class.

Exercise 4.1.1

Verify that for a set to be an ordinal is a definite condition.

Observe that

$$\forall t (t \in \text{Ord} \leftrightarrow ((x \in t \implies x \subseteq t) \land ((t, \in) \text{ is a strict well-ordering })))$$

where $(x \in t \implies x \subset t)$ is the definite condition

$$\forall x (x \in t \to \forall a (a \in x \to a \in t))$$

and (t, \in) is a strict well-ordering is the definite condition

$$\forall s (s \subseteq t \land s \neq \emptyset \rightarrow \exists a (a \in s \rightarrow \forall b (b \in s \land b \neq a \rightarrow (a,b) \in (\in))))$$

♣ Lemma 13 (Proper Subsets of an Ordinal Are Its Elements)

If α , $\beta \in$ Ord and $\alpha \subseteq \beta$, then $\alpha \in \beta$.

Proof

We shall prove that α is the least element in β that is not in α itself.⁴

Let $D := \beta \setminus \alpha = \{x \in \beta : x \notin \alpha\} \subset \beta^5$. Since $\alpha \subseteq \beta$, $D \neq \emptyset$. Since $\beta \in \text{Ord}$, (β, \in) has a strict well-ordering, and so D has a least element, d. Note that $d \in \beta$, and since $\beta \in \text{Ord}$, $d \subseteq \beta$.

<u>Claim</u>: $\alpha = d$. WTS $\alpha \subseteq d$. $\forall x \in \alpha$, we have $x, d \in \beta$. Then since (β, \in) is a strict well-ordering, we have either

$$x < d$$
, $x = d$, or $d < x$

Note that $x \neq d$, otherwise $x = d \in D = \beta \setminus \alpha$.

⁷ If *d* < *x*, then *d* ∈ *x* (by our notation). Now since *α* ∈ Ord, $x < \alpha \implies x \in \subseteq$, and so $d \in \alpha$, which is yet another contradiction $(d \in D = \beta \setminus \alpha)$.

Thus we must have x < d, i.e. $x \in d$. So $\alpha \subseteq d$.

WTS $d \subseteq \alpha$. Suppose not. Then let $x \in d \setminus \alpha$. Then since $d \in D = \beta \setminus \alpha$, we have $x \in \beta \setminus \alpha$, which then contradicts the minimality of d. Therefore, $d = \alpha$ as required.

- 4 We shall construct a subset of $\beta \setminus \alpha$ and show that α is its element.
- ⁵ Exists by Bounded Separation Axiom.
- ⁶ If $\alpha = d$, then α is the said least element

⁷ This is an errorneous proof.

*Warning

$$d < x \land x < \alpha$$

$$\underset{transitivity}{\Longrightarrow} d < \alpha \implies d \in \alpha$$

This argument is errorneous because we do not yet know if $\alpha \in \beta$.

Proposition 14 (Properties of Ordinals)

- 1. Every member of an ordinal is an ordinal.
- $2. \ \alpha \in Ord \implies \alpha \notin \alpha.$
- 3. $\alpha \in \text{Ord} \implies S(\alpha) \in \text{Ord}$.
- 4. $\alpha, \beta \in \text{Ord} \implies \alpha \cap \beta \in \text{Ord}$.
- 5. $\alpha, \beta \in \text{Ord} \implies \alpha \in \beta \vee \alpha = \beta \vee \beta \in \alpha$.
- 6. $E \subseteq \text{Ord } a \text{ subset } \Longrightarrow (E, \in) \text{ is a strict well-ordering.}^8$

Some of proofs of these properties are available in the course notes.

Exercise 4.1.2

Prove Item 3, Item 4, and Item 5 of

• Proposition 14.

⁸ **I think** that such an E need not be an ordinal itself. For example, $E = \{1, 5, 10\} \subset \text{Ord}$, but $4 \in 5$ and $4 \notin E$, and so $5 \in E$ but $5 \nsubseteq E$.

7. Ord is a proper class.

Proof

1. Suppose $x \in \beta \in \text{Ord}$. WTS $x \in \text{Ord}$, and we shall show that $x \in \beta$ satisfies **D**efinition 13.

Since $\beta \in \text{Ord}$, $x \in \beta \implies x \subseteq \beta$. Thus (x, \in) is a strict wellordering (through inheriting the property). So it suffices to show that $y \in x \implies y \subseteq x$. So let $y \in x$, and let $t \in x^9$. Observe that

$$t \in y \implies t < y$$

$$y \in x \implies y < x$$

and $t, y, x \in \beta \in \text{Ord}$. Therefore, by transitivity, we have $t < y < \beta$ $x \implies t \in x$.

- 2. Suppose not, i.e. $\alpha \in \alpha$. Then $\alpha \subseteq \alpha \in Ord$, and so (α, \in) is a strict well-ordering, i.e. $\alpha \notin \alpha$, a contradiction.
- 6. Suppose $A \subseteq E$ and $A \neq \emptyset$. Let $\alpha \in A$.

Case 1: $\alpha \cap A = \emptyset$. Then $\forall \beta \in \alpha \implies \beta \notin A$. Therefore α is \in -least in A.

Case 2: $a \cap A \neq \emptyset$. Let $A' = \alpha \cap A \subseteq \alpha$. Since $\alpha \in A \subseteq E \subseteq Ord$, we have (α, \in) is a strict well-ordering, and so A' has a strict well-ordering as well, and thus it must have a \in -least element, x. Then x is the \in -least element in A.

7. If Ord is a set, then by Item 6, (Ord, \in) is a strict well-ordering. Also, by Item 1, every element of Ord is a subset of Ord. Therefore, Ord satisfies **■** Definition 13, and so Ord ∈ Ord, which contradicts Item 2. Therefore Ord ∉ Set.

⁹ To show that $y \subseteq x$, we need to show that $\forall t \in y, t \in x$.

5 Lecture 5 Sep 20th

5.1 Ordinals (Continued 4)

66 Note

If $A, B \in \text{Ord}$, we will write A < B to mean $A \in B$.

• Proposition 15 (Properties of Ordinals 2)

- 1. If $\alpha \in \text{Ord}$, then $\alpha < S(\alpha)$, and there is nothing in between.
- 2. Let $E \subseteq \text{Ord}$, where $E \neq \emptyset$ is a set, and $\sup E := \bigcup E$. Then $\sup E \in \text{Ord}$, and it is a least upper bound for E.¹
- 3. If $E \subseteq \text{Ord}$ is a subset, then there is a least ordinal that is not in E.

Proof

1. Since $S(\alpha) = \alpha \cup \{\alpha\}$, $\alpha \in S(\alpha)$ and so $\alpha < S(\alpha)$.

It suffices to show that $\forall x < S(\alpha)$, we have $x \le \alpha$. Let $x < S(\alpha)$, i.e. $x \in S(\alpha)$. So $x \in \alpha$ or $x = \alpha$, i.e. $x < \alpha$ or $x = \alpha$.

- 2. By definition, $\forall x \in E \subseteq \text{Ord}$, we have that $x \subseteq \text{Ord}$. Since $\cup E \subseteq E$, we have that $\cup E \subseteq \text{Ord}$ is a subset. Thus by \bullet Proposition 14 Item 6, $(\cup E, \in)$ is a strict well-ordering.
 - ² Suppose $\alpha \in \cup E$, then $\exists e \in E$ such that $\alpha \in e \subseteq E \subseteq \text{Ord}$. So e is an ordinal and so $\alpha \subseteq e$. ³ $\forall x \in \alpha$, we have $x \in e \in E$, and so $x \in \cup E$ by definition. Therefore $\alpha \subseteq \cup E$.

And so, we have shown that $\cup E = \sup E \in \text{Ord}$.

¹ I noted down from the lectures that this is "not necessarily strict", but I do not remember what it means now. (Clarification required.)

Perhaps this related to my question; can $E = \sup E$?

This is not necessarily true. If $E \notin \text{Ord}$, then $E \neq \sup E$.

Exercise 5.1.1

Prove ♠ Proposition 15 Item 3.

RECOMMENDED STRATEGY: $\alpha \in \text{Ord}$ such that $E \subsetneq \alpha$ and take the least element of $\alpha \setminus E$ (which is non-empty). Prove that this least element is the least ordinal that is not in E.

You can take $\alpha = SS(\sup E)$. Verify that this works.

- 2 This part shows that ∪*E* is also an ordinal.
- ³ Now we show that $\alpha \subseteq \cup E$.

Claim 1: sup *E* is an upper bound for *E*.

Suppose, for contradiction, that $\exists e \in E$ such that $\sup E < e$. Then since $\sup E$ and e are both ordinals, we have $\sup E \in e \in E$. Then by definition of \cup , we have that $\sup E \in \cup E = \sup E$, but by \bullet Proposition 14 Item 2, $\sup E \notin \sup E$, a contradiction.

Thus sup *E* is an upper bound as claimed.

Claim 2: sup *E* is the supremum (least upper bound).

 $\forall \alpha < \sup E$, we have that $\alpha \in \sup E = \bigcup E$, and so $\exists e \in E$ such that $\alpha \in e$. Then $\alpha < e \in E$, i.e. α is not an upper bound of E.

Definition 14 (Successor Ordinal)

The successor ordinal is an ordinal of the form $S(\alpha)$ for some $\alpha \in Ord$.

Definition 15 (Limit Ordinal)

A *limit ordinal* is an ordinal that is not a successor.

Example 5.1.1

0 and ω are both limit ordinals; 0 is vacuosly a limit ordinal, and ω is not a successor of any $\alpha \in Ord^4$.

On the other hand, for $n \in \omega$ such that $n \neq 0$, $\exists \cup n \in \omega$ such that $S(\cup n) = n^{5}$.

Exercise 5.1.2

Prove that $S(\omega)$ *is a successor ordinal.*

Solution

5.1.1

We have that $\omega \in \text{Ord}$, and so $S(\omega)$ is a successor ordinal.

Transfinite Induction & Recursion

■ Theorem 16 (Transfinite Induction Theorem v1)

⁺ Need a more careful proof, which I cannot do. The idea is to show that any such ordinal α will be an element of ω , and so will its successor $S(\alpha)$, and $\omega \notin \omega$.

⁵ See A1.

Suppose P is a definite condition, with the property

$$\forall \alpha \in \operatorname{Ord} \wedge (\forall \beta < \alpha \ P(\beta)) \implies P(\alpha). \tag{5.1}$$

Then P is true of all ordinals.

Proof

P(0) is vacuously true, since there are no elements that are less than 0. Suppose $P(\alpha)$ is false for some $\alpha \in \text{Ord}$ such that $\alpha > 0$. By the Bounded Separation Axiom,

$$D := \{ \beta \le \alpha : \neg P(\beta) \}$$

is a set ⁶. Note that $D \neq \emptyset$, since $\alpha \in D$. Since $\alpha \in Ord$, we have $D \subseteq \alpha \subseteq \text{Ord}$, and so (D, \in) has a strict well-ordering. Let $\alpha_0 \in D$ be \in -least. Then $\forall \beta < \alpha_0$, we have that $\neg P(\beta)$, which contradicts the assumption Equation (5.1). Thus $P(\alpha)$ is true for all ordinals. \square ⁶ Note that $\beta \le \alpha \iff \beta < \alpha \lor \beta =$ $\alpha \iff \beta \in S(\alpha)$

Theorem 17 (Transfinite Induction Theorem v2)

Suppose P is a definite condition satisfying

- 1. P(0);
- 2. $\forall \beta \in \text{Ord } P(\beta) \implies P(S(\beta))$; and
- 3. If $\alpha \in \text{Ord}$ is a limit ordinal and $\forall \beta < \alpha$, $P(\beta)$, then $P(\alpha)$.

Then P is true of all ordinals.

This statement strongly resembles the Induction Princple that we have learnt in the earlier years of university. In contrast, v1 resembles Strong Induction Principle. It can be shown that $v_1 \iff$ v2. v1 \implies v2 is proven in this lecture.

Exercise 5.1.3

Prove that \blacksquare *Theorem 17* \Longrightarrow Theorem 16.

Proof

It suffices to show that *P* satisfies Equation (5.1), i.e. $\forall \alpha \in \text{Ord}$, we want to prove that $\forall \beta < \alpha$, if $P(\beta)$, then $P(\alpha)$.

When $\alpha = 0$, we have P(0) and so Equation (5.1) is satisfies. When $\alpha > 0$ is a limit ordinal, our assumption immediately satisfies Equation (5.1). Now suppose $\alpha > 0$ is a successor ordinal, and suppose that $\alpha = S(\gamma)$ for some $\gamma \in Ord$. By the assumption in

Equation (5.1), we have that

$$\forall \beta < \gamma \ P(\beta) \implies P(\gamma)$$

and so by condition (2), we have $P(S(\gamma))$ since $\gamma \in \text{Ord}$. Thus we have $P(\alpha) = P(S(\gamma))$.

We shall prove the following in the next lecture:

Theorem (Transfinite Recursion)

Let X be a class of all definite operations whose domain is an ordinal. Given a definite operation

$$G: X \to \mathbf{Set}$$

 $\exists ! F : Ord \rightarrow Set$, a definite operation, such that $F(\alpha = F(F \upharpoonright_{\alpha}))$, for all $\alpha \in Ord$.

We want to use Transfinite Recursion to construct definite operations on ordinals such that they have properties that we are familiar with (and hence desire).

66 Note (Notation - Restriction)

Let $H: U \to Y$ be a definite operation on classes U, Y, and $Z \subseteq U$ a subclass. $H \upharpoonright_Z$ is the definite operation

$$H \upharpoonright_Z : Z \to Y$$

obtained by restricting H onto Z.

66 Note

In the theorem, we stated that F has its domain on Ord. We know that for $\alpha \in \text{Ord}$, $\alpha \subseteq \text{Ord}$, and so $F \upharpoonright_{\alpha}$ makes sense; in particular,

$$F \upharpoonright_{\alpha} : \alpha \to \operatorname{Set}$$
.

Note that $F \upharpoonright_{\alpha} \in X$ *, and so* $G(F \upharpoonright_{\alpha})$ *is valid and makes sense.*

6 Lecture 6 Sep 25th

6.1 Ordinals (Continued 5)

6.1.1 Transfinite Induction & Recursion (Continued)

■ Theorem 18 (Transfinite Recursion v1)

Let X be a class of all definite operations whose domain is an ordinal. Given a definite operation

$$G: X \to \mathbf{Set}$$

 $\exists ! F : \mathrm{Ord} \to \mathrm{Set}$, a definite operation, such that $F(\alpha) = G(F \upharpoonright_{\alpha})$), for all $\alpha \in \mathrm{Ord}$.

Before proving the theorem, we shall note the following definition.

Definition 16 (α -function)

Using definitions in \blacksquare Theorem 18, a function t with domain in the ordinals is called an α -function defined by G if

$$\forall \beta < \alpha \quad t(\beta) = G(t \upharpoonright_{\beta}).$$

Proof

We shall first prove for **uniqueness**. Suppose F and F' are two

definition operations such that

$$F: \operatorname{Ord} \to \operatorname{Set} \quad F': \operatorname{Ord} \to \operatorname{Set}$$

$$F(\alpha) = G(F \upharpoonright_{\alpha}) \quad F'(\alpha) = G(F' \upharpoonright_{\alpha})$$

¹Suppose $\forall \beta < \alpha \in \text{Ord}$, we have $F(\beta) = F'(\beta)$. Note that

$$F(\beta) = F'(\beta) \iff F \upharpoonright_{\alpha} = F' \upharpoonright_{\alpha}$$
$$\implies F(\alpha) = G(F \upharpoonright_{\alpha}) = G(F' \upharpoonright_{\alpha}) = F'(\alpha)$$

Thus, uniqueness of *F* is guaranteed.

To prove existence, firstly, we note that the α -functions defined in \square Definition 16 are approximations to the F that we want. However, before going further, we need to show that they are also unique and that we can form a chain of extensions on these functions over Ord.

Uniqueness of t_{α} Let t, t' be a α -functions defined by G. WTS $\forall \beta < \alpha, t(\beta) = t'(\beta)$. If an α -function defined by G exists, we shall denote it as t_{α} .

Consider the definite condition

$$P(x) := (x \ge \alpha) \lor (t(x) = t'(x)).$$

Suppose that $\forall \gamma < \beta$, $P(\gamma)$ holds, i.e. $\gamma \ge \alpha$ or $t(\gamma) = t'(\gamma)$, which implies that $t \upharpoonright_{\beta} = t' \upharpoonright_{\beta}$. Therefore $t(\beta) = t'(\beta)$, i.e. $P(\beta)$ holds. Thus t_{α} is unique if it exists by Transfinite Induction.

 t_{α} as a chain of extensions Now $\forall \beta < \alpha \in \text{Ord}$, we have that $\beta \subseteq \alpha$. If t_{α} and t_{β} exist, then

$$\Gamma(t_{\beta})\subseteq\Gamma(t_{\alpha}),$$

or in other words

$$t_{\alpha} \upharpoonright_{\beta} = t_{\beta}$$
.

We shall denote this relation as $t_{\beta} \subseteq t_{\alpha}$.

Existence of t_{α} The existence of t_{α} is a definite condition: by the Replacement Axiom, a function that maps $\alpha \mapsto t_{\alpha}$ is definite, and by Bounded Separation Axiom, the set

$$\Gamma(t_{\alpha}) = \{ (\beta, G(t_{\alpha} \upharpoonright_{\beta}) \mid \beta < \alpha, t_{\alpha}(\beta) = G(t_{\alpha} \upharpoonright_{\beta}) \} \subseteq \text{Ord} \times \text{Set}$$

¹ Here, we want to use Transfinite Induction v1 to show that they are unique.

exists. ²Now $t_0 = t_{\emptyset}$ is vacuously true. Suppose for any successor ordinal α , t_{α} exists. Since $\alpha \in Ord$, we have that there is nothing between α and its successor $S(\alpha)$, and $\alpha < S(\alpha)$. Thus

² We use Transfinite Induction v2 to CTP.

$$t_{S(\alpha)} = t_{\alpha} \cup \{(\alpha, G(t_{\alpha}))\},$$

which exists by Union Set Axiom. We see that $t_{S(\alpha)}$ extends t_{α} onto α itself.

Suppose $\alpha > 0$ is a limit ordinal. Since t_{α} is a definite condition by Replacement, by Bounded Separation, we have that³

$$t_{\alpha} = \bigcup_{\beta < \alpha} t_{\beta} = \cup \{t_{\beta} : \beta < \alpha\}.$$

Note that t_{α} is, indeed, an α -function defined by G:

- t_{α} is a function on α : we have that $\forall \beta < \alpha$, the t_{β} 's form a chain of extensions;
- t_{α} is an α -function defined by G: $\forall \beta < \alpha$, since α is a limit ordinal, $S(\beta) < \alpha$, and so

$$t_{\alpha}(\beta) = t_{S(\beta)}(\beta) = G(t_{S(\beta)} \upharpoonright_{\alpha}) = G(t_{\beta} \upharpoonright_{\alpha}).$$

And so by Transfinite Induction, $\forall \alpha \in Ord$, t_{α} exists as required.

Construction of F Now for any $\beta < \alpha$, we have a chain of extensions

$$t_0 \subseteq t_1 \subseteq t_2 \subseteq \ldots \subseteq t_\beta \subseteq t_\alpha \subseteq \ldots$$

Let4

$$F := \bigcup_{\alpha \in \operatorname{Ord}} t_{\alpha} = \bigcup \llbracket t_{\alpha} \mid \alpha \in \operatorname{Ord} \rrbracket$$

³ Verify the motivation in using or the reason behind getting this.

⁴ I will leave the proof unfinished here. Need to verify my understanding

► Corollary 19 (Transfinite Recursion v2)

Given $G_1 \in \text{Set}$, $G_2 : \text{Set} \to \text{Set}$ a definite operation, $G_3 : X \to \text{Set}$ a definite operation, where X is the class of all definite opeartion whose domain is an ordinal. Then

$$\exists ! F : \mathsf{Ord} \to \mathsf{Set}$$

such that

1.
$$F(0) = G_1$$
;

2.
$$\forall \alpha \in \text{Ord } F(S(\alpha)) = G_2(F(\alpha))$$
; and

3.
$$\forall \beta > 0$$
 a limit ordinal, $F(\beta) = G_3(F \upharpoonright_{\beta})$.

Proof

The result is clear by \blacksquare Theorem 16 with $G: X \rightarrow Set$ defined by

$$G(f) = egin{cases} G_1 & f = \varnothing \ G_2(f(lpha)) & \mathrm{Dom}(f) = S(lpha) \ G_3(f) & \mathrm{Dom}(f) > 0 \text{ a limit ordinal} \end{cases}$$

6.1.2 Ordinal Arithmetric

6.1.2.1 Ordinal Addition

Definition 17 (Ordinal Addition)

Let $\beta \in \text{Ord}$. For any $\alpha \in \text{Ord}$, we define

$$\beta + \alpha$$

using Transfinite Recursion⁵ on α as follows:

- $\beta + 0 := \beta$;
- if α is a successor ordinal, then $\beta + S(\alpha) := S(\beta + \alpha)$; and
- *if* $\alpha > 0$ *is a limit ordinal, then* $\beta + \alpha := \sup\{\beta + \gamma : \gamma < \alpha\}$.

⁵ Note that we are using ► Corollary 19 with

$$G_1 = \beta$$

$$G_2 = S : \mathsf{Set} \to \mathsf{Set}$$

$$G_3 : X \to \mathsf{Set} \ \ \mathsf{by} \ G_3(f) = \sup \mathsf{Im}(f)$$

Exercise 6.1.1

Using both the Induction Principle and Transfinite Induction, prove that $\beta + \alpha \in \text{Ord}$.

Example 6.1.1

We have that

$$0, 1, 2, ..., \omega, \omega + 1, \omega + 2, ..., \omega + \omega$$

Observe that

$$\omega + 1 = \omega + S(0) = S(\omega + 0) = S(\omega)$$

and so $\omega + 1$ is a successor to ω . In general, we have that $\forall \alpha \in \text{Ord}$, $\alpha + 1 = S(\alpha)$. For example,

$$\omega + 2 = \omega + S(1) = S(\omega + 1).$$

On the other hand, note that

$$\omega + \omega = \sup \{ \omega + n : n \in \omega \}.$$

Unlike regular addition, ordinal addition is not commutative. For instance, while $\omega + 1 = S(\omega)$,

$$1 + \omega = \sup\{1 + n : n \in \omega\} = \omega.$$

Exercise 6.1.2

Prove that ordinal addition is only commutative for "finite" ordinals.

Ordinal Multiplication 6.1.2.2

Definition 18 (Ordinal Multiplication)

Let $\beta \in \text{Ord}$. For any $\alpha \in \text{Ord}$, we define

$$\beta \cdot \alpha$$

using Transfinite Recusion⁶ as follows:

- $\beta \cdot 0 := 0$;
- *if* α *is a successor ordinal,* $\beta \cdot S(\alpha) := \beta \alpha + \beta$
- *if* $\alpha > 0$ *is a limit ordinal,* $\beta \cdot \alpha := \sup\{\beta \cdot \gamma : \gamma < \alpha\}$.

$$G_1 = 0$$

 $G_2 : \text{Set} \to \text{Set by } G_2(x) = x + \beta$
 $G_3(f) = \sup \text{Im}(f)$

Example 6.1.2

We have

$$\omega \cdot 1 = \omega \cdot S(0) = \omega \cdot 0 + \omega = 0 + \omega = \omega.$$

Exercise 6.1.3

Prove that in general, $\forall \beta \in \text{Ord}$ *, we have* $\beta \cdot 1 = \beta$ *.*

Exercise 6.1.4

Prove that $\forall \alpha, \beta \in \text{Ord}$, $\alpha \cdot \beta \in \text{Ord}$.

Example 6.1.3

We have

$$\omega \cdot 2 = \omega \cdot S(1) = \omega \cdot 1 + \omega = \omega + \omega$$
.

Exercise 6.1.5

Prove that in general, $\forall \beta \in \text{Ord}$ *, we have* $\beta \cdot 2 = \beta + \beta$ *.*

Note that ordinal multiplication, like its addition counterpart, is not necessarily commutative.

Example 6.1.4

While we have

$$1 \cdot \omega = \sup\{1 \cdot n \mid n \in \omega\} = \omega = \omega \cdot 1,$$

observe that

$$2 \cdot \omega = \sup\{2 \cdot n \mid n \in \omega\} = \omega \neq \omega + \omega = \omega \cdot 2.$$

• Proposition 20 (Properties of Ordinal Addition and Ordinal Multiplication)

Let α , β , $\delta \in \text{Ord}$.

•
$$\alpha < \beta \iff \delta + \alpha < \delta + \beta$$
;

• $\alpha = \beta \iff \delta + \alpha = \delta + \beta$;

- ((associativity)) $(\alpha + \beta) + \delta = \alpha + (\beta + \delta)$;
- if $\delta \neq 0$, then $\alpha < \beta \iff \delta\alpha < \delta\beta$;
- if $\delta \neq 0$, then $\alpha = \beta \iff \delta\alpha = \delta\beta$;
- $(\alpha\beta)\delta = \alpha(\beta\delta)$.

Exercise 6.1.6

Prove 6 Proposition 20.

Ordinal Exponentiation 6.1.2.3

Definition 19 (Ordinal Exponentiation)

Let $\beta \in \text{Ord}$. *For any* $\alpha \in \text{Ord}$, *define*

using Transfinite Recursion by

- $\beta^0 := 1$;
- if α is a successor ordinal, then $\beta^{S(\alpha)} := \beta^{\alpha} \cdot \beta$;
- if $\alpha > 0$ is a limit ordinal, then $\beta^{\alpha} := \sup \{ \beta^{\gamma} \mid \gamma < \alpha \}$.

In the next lecture, we shall study the following theorem:

Theorem (Strict Well-Ordered Sets are Isomorphic to a Unique Ordinal)

Every strict well-ordering is isomorphic to an ordinal. Both the ordinal and the isomorphism are unique.

The definition of isomorphism is:

Definition 20 (Isomorphism)

Let E, F be sets and R, S be relations defined on each set respectively so. We say that (E, R) and (F, S) are **isomorphic**, which we denote by

$$(E,R) \simeq (F,S),$$

if $\exists f : E \rightarrow F$, a bijection, such that

$$e_1Re_2 \iff f_1Sf_2$$
.

Such an f is called an isomorphism.

<mark>7</mark> Lecture 7 Sep 27th

7.1 Ordinals (Continued 6)

7.1.1 Well-Orderings and Ordinals

Before proving the theorem stated at the end of last lecture, we require the following 2 lemmas:

Lemma 21 (Rigidity of Well-Orderings)

Well-orderings are rigid, i.e. the only automorphism¹ is the identity.

¹ An **automorphism** is an isomorphism from a set to itself.

Proof

Suppose (E,<) is a well-ordering, and $f:E\to E$ an automorphism. Let²

$$D = \{ x \in E \mid f(x) \neq x \}.$$

Suppose for contradiction that f is not the identity map, i.e. $D \neq \emptyset$. Then, since $D \subseteq E$, D has a well-ordering, and so we can pick $\alpha \in D$ to be the least element.

Case 1: f(a) < a. Then $f(a) \notin D$ since a is least. But then that would mean

$$f(f(a)) = f(a) \implies f(a) = a$$

since f is a bijection. This contradicts the choice that $a \in D$.

<u>Case 2: a < f(a).</u> Since f is a bijection, its inverse exists, and so

$$f^{-1}(a) < a \implies f^{-1}(a) \notin D$$

 $\iff ff^{-1}(a) = f^{-1}(a) \iff a = f^{-1}(a)$

² We look at the fellas that were

'moved'.

which contradicts the choice that $a \in D$, yet again. Thus there is no such element $a \in D$, forcing $D = \emptyset$, and so f must be the identity map.

♣ Lemma 22 (Strict Well-Ordering ≄ Any of Its Proper Initial Segment)

A strict well-ordering is not isomorphic to any proper initial segment³ of itself.

Proof

Let (E, <) be a strict well-ordering. $\forall b \in E$,

$$I_b := \{ x \in E : x < b \}$$

has an induced well-order, in particular $(I_b, <)$.

Suppose for contradiction that there exists an isomorphism $f: E \rightarrow I_b$. Let

$$D = \{ x \in E \mid f(x) \neq x \}$$

 $b \notin I_b$ and so $b \notin D$. Proof is left incomplete until I verify the proof with the prof.

■ Theorem 23 (Strict Well-Ordered Sets are Isomorphic to a Unique Ordinal)

Every strict well-ordering is isomorphic to an ordinal. Both the ordinal and the isomorphism are unique.

Proof

Uniqueness

Let (E, R) be a strict well-ordering. Suppose that

$$(E,R) \simeq (\alpha, \in) \text{ and } (E,R) \simeq (\beta, \in)$$
 (7.1)

Definition 21 (Initial Segment)For a strict well-order (E, <), an **initial**segment is a subset of the form

$$\{x \in E : x < b\}$$

for some $b \in E$.

where $\alpha, \beta \in \text{Ord}$. Then, either

$$\alpha < \beta$$
, $\alpha = \beta$ or $\beta < \alpha$.

Suppose $\alpha < \beta$ (this argument also works for $\beta < \alpha$, by simply swapping the inequality on α and β). Then α is a proper initial segment of β . From Equation (7.1), we have that $(\alpha, \in) \simeq (\beta, \in)$ via (E, R), but this contradicts Lemma 22. Thus we must have $\alpha = \beta$.

If $E = \emptyset$, then we can choose $0 \in Ord$ to be the ordinal of which *E* is isomorphic to. Suppose $E \neq \emptyset$. Denote an initial segment of *E* by

$$I_x := \{ y \in E \mid y < x \}.$$

Let

$$A = \{x \in E \mid \exists \beta \in \text{Ord } (I_x, R) \simeq (\beta, \in)\}.$$

Notice that $(I_x, R) \simeq (\beta, \in)$ is a definite condition: the both I_x and β are sets, and so by Replacement, there is a graph, $\Gamma(f)$, from I_x to β ; injectivity of an element in $\Gamma(f)$ is expressible as

$$\forall y_1 \forall y_2 \forall \beta_1 \forall \beta_2 (y_1, y_2 \in I_x \land \beta_1, \beta_2 \in \text{Ord}((y_1, \beta_1) = (y_2, \beta_2) \leftrightarrow y_1 = y_2));$$

surjectivity is expressible as

$$\forall \beta (\beta \in \alpha \rightarrow \exists y (y \in I_x \rightarrow (y, \beta) \in \Gamma(f))).$$

Thus by Bounded Separation, A is a set. Also, A is nonempty, since the least element of *E* will be isomorphic to 0.

By our uniqueness proof above, let f be a function on A, where f(x) is the unique ordinal that is isomorphic to (I_x, R) . By Replacement,

$$\operatorname{Im}(f) = \{ f(x) \in \operatorname{Ord} \mid x \in A \} \subset \operatorname{Ord}$$

is a set. By \bullet Proposition 15 Item 3, $\exists \alpha \in \text{Ord} \setminus \text{Im}(f)$ that is \in least. We want to show that $f: A \to \text{Im}(f)$ is an isomorphism between (E, R) and (α, \in) .⁴

f is order-preserving: We shall also show here that A is downward closed. $\forall x, y \in E$, we want to show that $xRy \land y \in A \implies$ $x \in A$. By the assumption, we have that

$$f(x) \stackrel{h}{\simeq} I_X \subsetneq I_y \stackrel{h}{\simeq} f(y)$$

- ⁴ This is why we need to show that
- 1. f is order-preserving, which is one of the requirements of an isomorphism (by our definition in Definition 20);
- 2. *f* is injective;

where the last 2 items will force f to be surjective.

Since f(x), $f(y) \in Ord$, we have either

$$f(x) < f(y)$$
, $f(x) = f(y)$, or $f(y) < f(x)$.

If f(x) = f(y), then $I_x \simeq I_y$ which contradicts Lemma 22. If f(y) < f(x), then

$$h(I_x) \subseteq h(I_y) = f(y) < f(x) = h(I_x),$$

which is a contradiction. Thus we must have f(x) < f(y), i.e. f preserves order as claimed, and f(x) is an initial segment of f(y), i.e. $f(x) \in \text{Ord}$, which implies that $x \in A$.

 $\underline{\alpha = \operatorname{Im}(f)}$: Suppose $\beta \in \alpha \implies \beta < \alpha \implies \beta \in \operatorname{Im}(f)$ by choice of α being the least. Therefore, $\alpha \in \operatorname{Im}(f)$.

Now suppose that $\beta \in \text{Im}(f)$. Then $\exists x \in A$ such that $(I_x, R) \simeq (\beta, \in)$. Again, we have 3 possibilities; either

$$\alpha < \beta$$
, $\alpha = \beta$ or $\beta < \alpha$.

Now $\alpha < \beta \implies \alpha \in \beta \implies \alpha = h(I_y)$ where yRx and $I_y \subset I_X$. Since A is downward closed, $\alpha \in \operatorname{Im}(f)$, a contradiction. We also have that $\alpha \neq \beta$ since $\beta \in \operatorname{Im}(f)$ and $\alpha \in \operatorname{Ord} \backslash \operatorname{Im}(f)$, i.e. $\alpha \notin \operatorname{Im}(f)$. Thus $\beta < \alpha$, and so $\beta \in \alpha$. Therefore $\alpha = \operatorname{Im}(f)$.

<u>f</u> is injective: Suppose that f(x) = f(y). $xRy \implies I_x$ is an initial segment of I_y , which contradicts Lemma 22. The argument is similar for if yRx. Thus we must have x = y.

 $\underline{A} = \underline{E}$: It suffices to show that $E \setminus A = \emptyset$. Suppose for contradiction that $E \setminus A \neq \emptyset$, i.e. E = A. Then $\exists x \in E \setminus A$, since $E \setminus A \subset E$ which has a strict well-ordering. Since f preserves order, for any $y \in E$, $xRy \implies y \notin A$. On the other hand, $yRx \implies y \in A$. Thus $I_x = A$. However, since f is an isomorphism between (A, R) and (α, \in) (since we assume that A = E), we have that $I_x = A \simeq \alpha$, i.e. $x \in A$, which is a contradiction to the choice that $x \in E \setminus A$.

This completes the proof.

7.2 Cardinals

While ordinals allow us to enumerate, we cannot use it to "measure". For example, $\omega \neq \omega + 1$, but they have the same size.

Definition 22 (Equinumerous)

Two sets A and B have the same size, or equinumerous, if there is a bijection from A to B. We denote this relation by |A| = |B|.5

⁵ Note that we have yet to define $|\cdot|$.

The following is a well-known theorem that makes proving equinumerosity a lot easier.

♣ Lemma 24 (Schröder-Bernstein Theorem)

Given two sets A and B, |A| = |B| if and only if there exists injections in both directions, i.e. an injection from A to B, and an injection from B to

Proof

The (\Longrightarrow) direction is easy, since a bijection exists. So it suffices to show the (\iff) direction. We shall use $A \hookrightarrow B$ to say that there is an injection from *A* to *B*.

Suppose

$$A \hookrightarrow B \stackrel{g}{\hookrightarrow} A$$

Then $\exists f: A \rightarrow A$ an injective map, and we would have

$$f(A) \subseteq g(B) \subseteq A.$$
 (7.2)

From here, it suffices to show that for an injective ap $f: X \to X$, if we have

$$f(X) \subset Y \subset X$$

then |Y| = |X|. From our observation in Equation (7.2), we have

$$X \supseteq Y \supseteq f(X) \supseteq f(Y) \supseteq f^2(X) \supseteq f^2(Y) \supseteq f^3(X) \supseteq \dots$$

Let

$$Z = X \setminus Y \stackrel{.}{\cup} f(X) \setminus f(Y) \stackrel{.}{\cup} f^{2}(X) \setminus f^{2}(Y) \stackrel{.}{\cup} \dots$$

and

$$W = X \setminus Z$$

Then

$$X = Z \stackrel{\cdot}{\cup} W$$

<u>Claim:</u> For sets *A* and *B* such that $B \subseteq A$, we have that

$$f(A \setminus B) = f(A) \setminus f(B).$$

Note that since f is injective, $f: B \to f(B)$ is a bijective map. Suppose $\exists x \in A \setminus B$ such that $f(x) \in f(B)$. Since $f: B \to f(B)$ is bijective, $\exists b \in B$ such that f(b) = f(x), but f is injective. Thus the claim is true.

Using a similar argument, it can be shown that $f(A \cup B) = f(A) \cup f(B)$.

Observe that

$$f(Z) = f(X \setminus Y) \stackrel{\cdot}{\cup} f(f(X) \setminus f(Y)) \stackrel{\cdot}{\cup} f(f^2(X) \setminus f^2(Y)) \stackrel{\cdot}{\cup} \dots$$

= $f(X) \setminus f(Y) \stackrel{\cdot}{\cup} f^2(X) \setminus f^2(Y) \stackrel{\cdot}{\cup} f^3(X) \setminus f^3(Y) \stackrel{\cdot}{\cup} \dots$

and note that

$$f(Z) = Z \setminus (X \setminus Y).$$

Since $W = X \setminus Z$, we have $W \subseteq Y$. Since $Z \cap W = \emptyset$, we still have $f(Z) \cap W = \emptyset$. Also, note that $(X \setminus Y) \cap W = \emptyset$. Thus, we have

$$Y = X \setminus (X \setminus Y) = (Z \stackrel{\cdot}{\cup} W) \setminus (X \setminus Y) = f(Z) \stackrel{\cdot}{\cup} W$$

Let $g: X \to Y$ such that

$$g(A) = \begin{cases} A & A \subseteq W \\ f(A) & A \subseteq Z \end{cases}$$

Clearly so, *g* is bijective.

Example 7.2.1

We claimed that $|\omega| = |\omega + 1|$.

⁶ Forgive me if the proof of this claim is a little sloppy.

We can simply use the identity map from $\omega \to \omega + 1$. For $\omega + 1 \to$ ω , consider the mapping

$$f(\alpha) = \begin{cases} S(\alpha) & \alpha \in \omega \\ 0 & \alpha = \omega \end{cases}$$

This map is clearly injective by properties of elements of ω .

Definition 23 (Cardinal)

A cardinal is an ordinal α with the property that $\forall \beta < \alpha, |\alpha| \neq |\beta|$

In the next lecture, we shall see that the collection of cardinals is a proper class, and is a subclass of the ordinals.

Definition 24 (Finite & Countable)

A set A is finite if |A| = |n| for some $n \in \omega$. A is countable if A is *finite or* $|A| = |\omega|$.

8 Lecture 8 Oct 02nd

8.1 Cardinals (Continued)

66 Note

If $\kappa \in C$ and κ is infinite, then κ is a limit ordinal. In other words, successor ordinals are either finite or are not Cardinals. This is true since $\forall \alpha \in C$ ord such that $\alpha \geq \omega$, clearly we have $\alpha \hookrightarrow S(\alpha)$, and we can define a function $f: S(\alpha) \to \alpha$ such that

$$f(\beta) = \begin{cases} S(\beta) & \beta < \omega \\ \beta & \omega \le \beta < \alpha \\ 0 & \beta = \alpha \end{cases}$$

which is injective, and so by Schröder-Bernstein, $|S(\alpha)| = |\alpha|$.

♦ Proposition 25 (The Least Cardinality Not Equinumerous to Subsets of a Set)

 $\forall E \in \text{Set } \exists \alpha \in \text{Ord } \forall e \subseteq E$

$$|e| \neq |\alpha|$$

and there exists a least such $h(E) \in Ord$.

66 Note

Note that $h(E) \in Card$.

Proof

Suppose not, i.e. $\exists \alpha \in Ord$ such that $|h(E)| = |\alpha|$ and $\alpha < h(E)$. Since h(E) is the least, we must have $|\alpha| = |A|$ or some $A \subseteq E$. Then |h(E)| = |A|, which is a contradiction to the definition of h(E).

In particular, we have that $h(\omega)$ is an uncountable cardinal.

Now to prove • Proposition 25.

Proof

It suffices to prove the existence of h(E). Consider the class

$$H = \llbracket \alpha \in \text{Ord} \mid \exists e \subseteq E \mid |e| = |\alpha| \rrbracket.$$

If we can show that H is a set, then the least element not in H shall be our h(E). Consider

$$W := \{(A, R) \mid A \subseteq E, (A, R) \text{ is a strict well-ordering } \}$$

which is a set by Replacement, i.e.

$$W \subseteq \mathcal{P}(E) \times \mathcal{P}(E \times E)$$
.

Note that $W \neq \emptyset$, since $\emptyset \subseteq E$ and the empty relation would be a well-ordering of \emptyset . By \blacksquare Theorem 23, $\exists f : W \to \text{Ord such that } f(A, R)$ is a unique ordinal. By Replacement, $\text{Im}(f) \subseteq \text{Ord}$ is a set.

Claim: $\operatorname{Im}(f) = H$: It is clear that $\operatorname{Im}(f) \subseteq H$, since all elements of $\operatorname{Im}(f)$ are isomorphic to some subset of E by definition. Now let $\alpha \in H$. Then $\exists g : \alpha \to A$ a bijection, for some $A \subseteq E$. Then define \prec on A by

$$a \prec b \iff g^{-1}(a) < g^{-1}(b).$$

Then $(\alpha, <) \stackrel{g}{\underset{\sim}{\longrightarrow}} (A, \prec)$. Therefore, $(A, \prec) \in W$ and $f(A, \prec) = (\alpha, <)$, i.e. $H \subseteq \text{Im}(f)$. Thus H = Im(f) and so H is a set as required. \square

Remark

This revelation tells us that Card is a proper class.

To use Card to measure all sets, we need every set to be equinumerous with a cardinal. In particular, every set would then have to be equinumerous to an ordinal. This would then require evrey set to have a strict well-ordering, which is something that we cannot prove with our axioms thus far.

Axiom of Choice 8.1.1

Definition 25 (Choice Function)

Suppose \mathcal{F} is a set. A **choice function** on \mathcal{F} is a function

$$c: \mathcal{F} \to \cup \mathcal{F}$$
 such that $\forall F \in \mathcal{F} \ c(F) \in F$.

66 Note

If $\emptyset \in \mathcal{F}$, then \mathcal{F} has no choice function, since nothing belongs in \emptyset .

V Axiom 26 (Axiom of Choice)

Every $\mathcal{F} \in \text{Set}$ such that $\emptyset \notin \mathcal{F}$ admits a choice function.¹

¹ This is, again, an existential axiom.

66 Note

Unlike the other axioms, while the Axiom of Choice asserts the existence of choice functions on sets, the choice function need not be unique. Recall that in other axioms, the sets of which we assert their existence are

■ Theorem 27 (Axiom of Choice and Its Equivalents)

TFAE

- 1. Axiom of Choice
- 2. Well-ordering Principle: Every set admits a well-ordering.

3. Zorn's Lemma: If (E, R) is a strict poset with the property that every totally ordered subset of E has an upper bound, i.e.

$$\forall A \subset E(\forall a, b \in A \ aRb \lor bRa \lor a = b) \ \forall a \in A \exists e \in E(aRe \lor a = e).$$

Then (E,R) has a maximal elements, i.e. $\exists z \in E$ such that $\forall x \in E$, $\neg zRx$.

Proof

(1) \implies (2): Let $A \in \text{Set.}$ If $A = \emptyset$, then there is nothing to do and the statement is vacuously true. So suppose $A \neq \emptyset$. By the assumption, fix a choice function c on $\mathcal{F} := \mathcal{P}(A) \setminus \{\emptyset\}$. Let $\theta \in \text{Ord } \setminus A$. Define a definite operation $F : \text{Ord} \to \text{Set}$ such that

$$F(\alpha) = \begin{cases} c(A \setminus \operatorname{Im}(F \upharpoonright_{\alpha})) & A \setminus \operatorname{Im}(F \upharpoonright_{\alpha}) \neq \emptyset \\ \theta & \text{otherwise} \end{cases}$$

Note that F exists by Transfinite Recursion².

<u>Claim 1</u>: *F* halts, i.e. $\exists \alpha \in \text{Ord such that } F(\alpha) = \theta \text{ and } \forall \beta \in \text{Ord such that } \alpha < \beta, F(\beta) = \theta.$

Suppose not. Then F must be injective and has codomain $\cup \mathcal{F} = \cup (\mathcal{P}(A) \setminus \{\emptyset\}) = A$, i.e. we have that $F : \operatorname{Ord} \to A$ injective. Then by \bullet Proposition 25, there exists h(A) that is the least ordinal that is not equinumerous with any subset of A. We may consider $F \upharpoonright_{h(A)} : h(A) \to A$ since $h(A) \subset \operatorname{Ord}$. Now $\forall \alpha < \beta \in h(A)$, by our supposition, $F(\beta) \neq \theta$, and so $F(\beta) = c(A \setminus \operatorname{Im}(F \upharpoonright_{\beta})) \in (A \setminus \operatorname{Im}(F \upharpoonright_{\beta}))$. Thus $F(\beta) \notin \operatorname{Im}(F \upharpoonright_{\beta})$. But since $\alpha < \beta$, it must be that $F(\alpha) \in \operatorname{Im}(F \upharpoonright_{\beta})$. Then $F(\alpha) \neq F(\beta)$. Consequently, since $\forall \beta \in h(A)$, we have that $F(\beta) \neq \theta$, and so we created an injection from h(A) to A. This is impossible by the definition of h(A). Thus it must be the case that $\exists \beta \in h(A)$ such that $F(\beta) = \theta$.

Let α be the least such β . The previous paragraph showed that $F \upharpoonright_{\alpha}$ is an injection from α to A. It remains to show that the map is surjective. Suppose $\text{Im}(F \upharpoonright_{\alpha}) \neq A$. Then $A \setminus \text{Im}(F \upharpoonright_{\alpha}) \neq \emptyset$. Then

$$F(\alpha) = c(A \setminus \operatorname{Im}(F \upharpoonright_{\alpha})) \in A$$

which is a contradiction since $F(\alpha) = \theta$. So $A = \text{Im}(F \upharpoonright_{\alpha})$ and so

² I am not sure how.

 $F \upharpoonright \alpha$ is surjective.

Therefore $F \upharpoonright_{\alpha}$ is a bijection from α to A, and so A has an induced strict well-ordering from α .

(3) \implies (1): Let \mathcal{F} be a set such that $\emptyset \notin \mathcal{F}$. Let Λ be the set of all partial choice functions on \mathcal{F} , identified with their graphs, i.e. $\forall f \in \Lambda$, $f : \mathcal{G} \to \cup \mathcal{G}$ such that $f(G) \in G$ for all $G \in \mathcal{G}$, and $\mathcal{G} \subseteq \mathcal{F}$. Note that Λ is indeed a set since the graphs exist by Replacement, and Λ is therefore a set from Bounded Separation. $\Lambda \neq \emptyset$, since the function f(F) = x exists for $F \in \mathcal{F} \neq \emptyset$, and $F \neq \emptyset$.

Now (Λ, \subseteq) is a poset, where we order the functions by extensions. For every Θ that is a totally ordered subset of Λ , we have that the union, $\cup \Theta$ is the upper bound of Θ . Thus the assumptions for Zorn's Lemma are satisfied, and so there exists a maximal function

$$f: \mathcal{G} \to \cup \mathcal{G}$$
 in Λ .

To prove that this f is a choice function on \mathcal{F} , we want to prove that $f: \mathcal{F} \to \cup \mathcal{F}$, i.e. we need to show that $Dom(f) = \mathcal{F}$. Suppose not, i.e. $\exists F \in \mathcal{F}$ such that $F \notin Dom(f)$. Then since $F \neq \emptyset$, $\exists x \in F$, and so $f \cup \{(F, x)\}$ is a larger partial choice function on \mathcal{F} , contradicting the maximality of f in Λ . Thus $Dom(f) = \mathcal{F}$ as claimed, and so f is a choice function on \mathcal{F} , proving the Axiom of Choice.

(2) \implies (3): Suppose (E, R) is a strict poset. By (2), let < be a strict well-ordering on *E*. Now by \blacksquare Theorem 23, $\exists ! \alpha \in \text{Ord such}$ that $(E,R) \simeq (\alpha, \in)$ through a unique isomorphism. Therefore, we may assume that $E \in \text{Ord.}$ Suppose that (E, R) satisfies the assumptions of Zorn's Lemma.

Assume, to the contrary, that (E, R) does not have an R-maximal element. From \bullet Proposition 25, $\exists h(E) \in Ord$ such that $\forall \beta < h(E)$, $\forall A \subseteq E, |\beta| \neq |A|^3$. Recursively so, define $F: h(E) \to E$ by

$$F(0) = e$$
 for some $e \in E$

 $F(S(\beta)) = \langle \text{-least element } \gamma \text{ of } E \text{ such that } F(\beta)R\gamma$

³ The strategy here is to use, once again, 6 Proposition 25 to arrive at a contradiction that is similar to when we were proving $(1) \implies (2)$.

and for $\beta > 0$ a limit ordinal,

$$F(\beta) = \begin{cases} < -\text{least } \gamma \text{ such that } F(\zeta)R\gamma \text{ for all } \zeta < \beta \text{ if such } \gamma \text{ exists} \\ e & \text{otherwise} \end{cases}$$

Note that this function is well-defined, since $F(\beta)R\gamma$ properly distinguishes the ordinals, for there are no R-maximal element in E, and < is a strict well-ordering on E.

Now since $h(E) \in Card$, it is a limit ordinal, to show that F is injective, it suffices to show that $\forall \beta < h(E)$, $F \upharpoonright_{\beta}$ is strictly order-preserving, i.e. $\forall x < y < \beta$, F(x)RF(y). We shall prove this by Transfinite Induction.

 $\beta=0$ is vacuously true. If $\beta>0$ is a limit ordinal, then $\beta=\bigcup_{\gamma<\beta}\gamma$, and so the strict ordering is preserved as given by the induction hypothesis. For β a successor ordinal, consider $F\upharpoonright_{S(\beta)}$. $\forall x< y< S(\beta)$, if $y\neq \beta$, then we are done by the induction hypothesis. Suppose $y=\beta$. Since β is a successor ordinal, $\exists \gamma\in$ Ord such that $S(\gamma)=\beta$. Since $\gamma< S(\gamma)$ (by \bullet Proposition 15 Item 1), either $x=\gamma$ or $x<\gamma$. If $x<\gamma$, then our proof is complete by the induction hypothesis. If $x=\gamma$, then since $x=\gamma< S(\gamma)=\beta$, regardless if γ is a limit ordinal or successor ordinal, we have that $F(\gamma)RF(\beta)$.

Thus, by Transfinite Induction, we have that $F \upharpoonright_{\beta}$ is strictly order-preserving for any $\beta < h(E)$, implying that $F : h(E) \hookrightarrow E$, hence contradicting the definition of h(E). Thus, an R-maximal must exist.

9 Lecture 9 Oct 04th

9.1 Cardinals (Continued 2)

9.1.1 Axiom of Choice (Continued)

From hereon, unless stated otherwise, we shall assume AC.

• Proposition 28 (Using Cardinals to Measure Sets)

Assume AC. Every set is equinumerous with a cardinal.

Proof

Let $A \in \text{Set}$. By the Well-Ordering Principle, A is well-orderable, i.e. there is a strict well-ordering on A. By \blacksquare Theorem 23, $\exists ! \alpha \in \text{Ord such that } (A, <) \simeq (\alpha, \in)$. Let

$$S = \{ \beta \le \alpha \mid |\beta| = |\alpha| \},\$$

which is a set by Bounded Separation. Note that $S \neq \emptyset$ since $\alpha \in S$. Let β be the least such ordinal in S. By this minimal choice, $\beta \in \text{Card}$, $|\beta| = |\alpha| = |A|$.

And now our notation of |A|=|B| makes sense provided the following definition.

Definition 26 (Cardinality)

Let $A \in Set$. |A|, in which we shall call the **cardinality** of A, is the (unique) cardinal which is equinumerous with A.

• Proposition 29 (Lesser Cardinality)

 $\forall A, B \in \text{Set} \quad |A| \leq |B| \iff \exists f : A \hookrightarrow B.$

Proof

Let $\kappa = |A|$ and $\lambda = |B|$. If $\kappa \leq \lambda$, then

$$A \stackrel{\text{bijection}}{\rightarrow} \kappa \stackrel{id}{\hookrightarrow} \lambda \stackrel{\text{bijection}}{\rightarrow} B$$

By composition of the 3 functions, $A \hookrightarrow B$.

Conversely, suppose $\exists h: A \hookrightarrow B$. Suppose to the contrary that $\lambda < \kappa$. Then $\lambda \subseteq \kappa$. Then

$$\kappa \stackrel{\text{bijection}}{\rightarrow} A \stackrel{h}{\hookrightarrow} B \stackrel{\text{bijection}}{\rightarrow} \lambda$$

and so there exists an injection from $\kappa \to \lambda$. By Schröder-Bernstein, we have $|\kappa| = |\lambda|$, which contradicts the fact that $\kappa \in \text{Card}$. Thus $\kappa \le \lambda$.

► Corollary 30 (Cardinalities are Always Comparable)

 $\forall A, B \in \text{Set} \quad A \hookrightarrow B \lor B \hookrightarrow A.$

Proof

WLOG, suppose $\neg (B \hookrightarrow A)$. Then $\neg (|B| \leq |A|)$, i.e. |A| < |B|, i.e. (not by \triangleleft Proposition 29), $\exists f : A \hookrightarrow B$.

• Proposition 31 (Functions are "Lossy Compressions")

Suppose $f: A \to B$. Then $|\text{Im}(f)| \le |A|$.

Proof

Let

$$\mathcal{F} = \{ f^{-1}(y) \mid y \in \operatorname{Im}(f) \}$$

be the set of fibres¹ of f. Note that $\emptyset \notin \mathcal{F}$, as otherwise we would be saying that $\exists y \in \text{Im}(f)$ that has no pre-image. Let $h : \text{Im}(f) \rightarrow$ A by

$$h(y) := c(f^{-1}(y)) \in A$$

where $c: \mathcal{F} \to \cup \mathcal{F}$ is a choice function that exists by AC. Clearly so, *h* is injective, and so by \bullet Proposition 29, $|\text{Im}(f)| \leq |A|$.

• Proposition 32 (Countable Union of Countable Sets is Countable)

Let $A \in Set$ be countable, and every $a \in A$ is also countable. Then $\cup A$ is countable.

Proof

to be added

Hierarchy of Infinite Cardinals 9.1.2

66 Note (Notation)

Let $\kappa \in \text{Card}$. Let $\kappa^+ := h(\kappa)$, which is the least ordinal not equinu*merous with any subset of* κ *. We proved that* $\forall E \in \text{Set}$ *,* $h(E) \in \text{Card}$ *. Therefore,* $\kappa^+ \in Card$.

Remark

 κ^+ is the least cardinal that contains κ . This follows immediately from the *definition of* $h(\kappa)$ *.*

And so we observe that $\kappa \mapsto \kappa^+$ is a "successor" operation on cardinals.2

Definition 27 (Fibres)

Let $f: A \to B$. For $y \in \text{Im}(f)$, the **fibre** of y is defined as

$$f^{-1}(y) = \{ x \in A \mid f(x) = y \}$$

The fibres are also commonly called the

² Note that $\kappa + 1$ is not necessarily κ^+ .

Definition 28 (Cardinal Numbers)

Using Transfinite Recursion, define the following ordinal-enumerated collection of cardinals

- $\aleph_0 = \omega$;
- $\forall \alpha \in \text{Ord that is a successor ordinal, } \aleph_{S(\alpha)} = \aleph_{\alpha+1} = \aleph_{\alpha}^+$; and
- $\forall \alpha > 0$ that is a limit ordinal, $\aleph_{\alpha} := \sup \{\aleph_{\beta} \mid \beta < \alpha\}.$

The \aleph_{α} 's are called cardinal numbers.

♣ Lemma 33 (Cardinal Numbers are Cardinals)

If $\alpha \in \text{Ord}$, then $\aleph_{\alpha} \in \text{Card}$.

Proof

We shall use Transfinite Induction. The result is clear for $\alpha=0$, since $\aleph_0=\omega$ and $\forall n\in\omega$, $|n|\neq |\omega|$. For successor ordinals α , since $h(\alpha)$ is an ordinal, we have that $\aleph_\alpha^+=h(\aleph_\alpha)$ is also a cardinal. Now for $\alpha>0$ a limit ordinal, suppose that $\beta<\aleph_\alpha$. Since $\aleph_\alpha=\sup\{\aleph_\gamma\mid\gamma<\alpha\}$, $\exists\gamma<\alpha$ such that $\beta<\aleph_\gamma$. Since \aleph_γ is a cardinal by the Inductive Hypothesis, and $\beta<\aleph_\gamma<\aleph_\alpha$, we have that

$$|\beta| < |\aleph_{\gamma}| \le |\aleph_{\alpha}|$$
.

Thus \aleph_{α} is not equinumerous with any lesser ordinal, i.e. it is a cardinal.

♣ Lemma 34 (Ordinals Index the Cardinal Numbers)

 $\forall \alpha < \beta \in \text{Ord}$, we have $\aleph_{\alpha} < \aleph_{\beta}$.

Proof

We shall use Transfinite Induction on β . $\beta = 0$ is true vacuously

so. For β a successor ordinal, suppose $\forall \alpha < \beta, \aleph_{\alpha} < \aleph_{\beta}$. Now $\aleph_{\beta+1} = \aleph_{\beta}^+ = h(\aleph_{\beta})$, which we have that $\aleph_{\beta} < h(\aleph_{\beta})$ as proven before.

Now suppose that $\beta > 0$ is a limit ordinal. Then $\aleph_{\beta} = \sup{\{\aleph_{\alpha} \mid$ $\alpha < \beta$ and $\forall \gamma < \alpha < \beta$, $\aleph_{\gamma} < \aleph_{\alpha}$. Since β is a limit ordinal, $\exists \zeta < \beta$ such that $\alpha < \zeta$. By the Induction Hypothesis, we have that $\aleph_{\alpha} < \aleph_{\zeta}$, and $\aleph_{\zeta} \leq \aleph_{\beta}$. Thus $\aleph_{\zeta} \subseteq \aleph_{\beta}$, and so $\aleph_{\alpha} < \aleph_{\beta}$.

Lemma 35 (Infinite Cardinals are Distant)

 $\forall \alpha \in \text{Ord}$, $\alpha \leq \aleph_{\alpha}$. The inequality is strict if α is a successor ordinal.

Proof

Again, we shall use Transfinite Induction on α . For $\alpha = 0$, we have $0 < \aleph_0 = \omega$, and so $\alpha = 0$ holds. For α a successor ordinal, suppose $\alpha \leq \aleph_{\alpha}$. Thus $\alpha + 1 \leq \aleph_{\alpha} + 1$. By definition of $h(\aleph_{\alpha})$ and definition of cardinal numbers

$$\alpha + 1 \leq \aleph_{\alpha} + 1 < \aleph_{\alpha}^{+} = \aleph_{\alpha+1}.$$

Thus the statement holds for $\alpha + 1$, and indeed, the inequality is strict for successor ordinals. For $\alpha > 0$ a limit ordinal, suppose that $\forall \beta < \alpha$, we have $\beta \leq \aleph_{\beta}$. By Lemma 34, we have

$$\beta \leq \aleph_{\beta} < \aleph_{\alpha}$$
.

Thus

$$\alpha = \sup\{\beta \mid \beta < \alpha\} < \aleph_{\alpha}$$

as required.

• Proposition 36 (All Infinite Cardinals are Indexed by the Ordinals)

Every infinite cardinal is of the form \aleph_{α} for some $\alpha \in \operatorname{Ord}$.

Proof

Let $\kappa \in$ Card. By Lemma 35, we have $\kappa \leq \aleph_{\kappa} < \aleph_{\kappa+1}$. And so we can show that $\forall \beta \in$ Ord, $\forall \kappa < \aleph_{\beta}$, $\exists \alpha < \beta$ such that $\kappa = \aleph_{\alpha}$. We shall use Transfinite Induction on β .

Since there are no infinite cardinals strictly below ω , $\beta=0$ is trivially true. Suppose $\beta=\gamma+1$ is a successor ordinal, where $\gamma\in$ Ord, and suppose $\kappa<\aleph_{\beta}$. Since $\gamma<\beta$, Lemma 34 implies that $\aleph_{\gamma}<\aleph_{\beta}=\aleph_{\gamma+1}=\aleph_{\gamma}^+$, and by definition, there are no cardinals between \aleph_{γ} and \aleph_{β} . Thus $\kappa\leq\aleph_{\gamma}$. We thus have that either $\kappa=\aleph_{\gamma}$ or, by the Induction Hypothesis, $\exists \alpha<\gamma$ such that $\kappa=\aleph_{\alpha}$. Thus the statement holds for successor ordinals.

Let $\beta > 0$ be a limit ordinal and $\kappa < \aleph_{\beta} = \sup{\aleph_{\gamma} \mid \gamma < \beta}$. Then $\exists \gamma < \beta$ such that $\kappa < \aleph_{\gamma}$, and so by the Induction Hypothesis, $\exists \alpha < \gamma$ such that $\kappa = \aleph_{\alpha}$.

Consequently, we have ourselves an *ordinal-valued*, *order-preserving complete indexing* of the infinite cardinals.

Exercise 9.1.1

For the inequality in Lemma 35, show that the equality can occur. In particular, consider the sequence of ordinals defined recursively by $\alpha_0 = 0$, and $\alpha_{n+1} = \aleph_{\alpha_n}$, and verify that $\alpha = \aleph_{\alpha}$. In fact, this works if we start with any ordinal α_0 , not just 0.

10 Lecture 10 Oct 11th

10.1 Cardinals (Continued 3)

10.1.1 Cardinal Arithmetic

10.1.1.1 Cardinal Summation

Definition 29 (Cardinal Sum)

 $\forall \kappa_1, \kappa_2 \in Card$. Let the cardinal sum

$$\kappa_1 + \kappa_2 := |X_1 \cup X_2|$$

where $X_1, X_2 \in Set$ such that

$$|X_1| = \kappa_1 \ and \ |X_2| = \kappa_2$$

and $X_1 \cap X_2 = \emptyset$.

Remark

This definition does not depend on the choice of X_1 and X_2 , i.e. if we have another X_1' and X_2' such that

$$|X_i'| = |X_i| = \kappa_i \quad i = 1, 2$$

and $X_1' \cap X_2' = \emptyset$, then

$$|X_1' \cup X_2'| = |X_1 \cup X_2|.$$

This shows that the cardinal summation is well-defined.

Contents in this lecture should be extended upon. A lot of the contents need to be explored for it was presented tersely so without all the details of which we need.

Exercise 10.1.1

Prove this remark.

66 Note

If $X, Y \in Set$ *are arbitarily chosen, then*

$$|X \cup Y| \le |X| + |Y|$$

₩ Warning

The cardinal summation is different from ordinal summation. For example, $\aleph_0 + \aleph_0$, where the + represents the ordinal summation, is not a cardinal, as we have shown that $|\omega + \omega| = |\omega|$.

Therefore, there is a need to explicitly mention the context of which + is used.

10.1.1.2 Cardinal Product

Definition 30 (Cardinal Product)

 $\forall \kappa_1, \kappa_2 \in Card$, the cardinal product

$$\kappa_1 \kappa_2 := |X_1 \times X_2|$$

where $X_1, X_2 \in \text{Set } with |X_i| = \kappa_i$, for i = 1, 2.

Exercise 10.1.2

Prove that Definition 30 is well-defined.

Remark

We may as well choose

$$X_1 = \kappa_1$$
 and $X_2 = \kappa_2$,

and so $\kappa_1 \kappa_2 = |\kappa_1 \times \kappa_2|$.

Exercise 10.1.3

Prove that the cardinal sum and product agrees with ordinal sum and products on the finite ordinals. This is the usual arithmetic on natural numbers.

¹ We cannot do so for cardinal sums, for $\kappa_1 \cap \kappa_2 \neq \emptyset$.

■ Theorem 37 (Dominance of the Larger Cardinal)

Let $\kappa_1, \kappa_2 \in Card$ not both finite. Then

- 1. $\kappa_1 + \kappa_2 = \max{\{\kappa_1, \kappa_2\}}$; and
- 2. *if neither* κ_1 *or* κ_2 *is* 0, then $\kappa_1 \kappa_2 = \max{\{\kappa_1, \kappa_2\}}$.

Exercise 10.1.4 Prove/read 里 Theorem 37.

We can generalize the notions of cardinal sum and cardinal product. But first, a definition.

Definition 31 (*I*-sequence)

Let $I \in Set$. By an I-sequence of sets, we mean a definite operation²

$$f: I \to \operatorname{Set}$$
.

We write such sequences as

$$(x_i:i\in I)$$

where $x_i := f(i)$.

² Note that $f: I \to \operatorname{Im}(f)$ is a function by the Replacement Axiom.

Definition 32 (Generalized Cardinal Sum)

Suppose $(\kappa_i : i \in I)$ is a sequence of cardinals. We define the (generalized) cardinal sum to be

$$\Sigma_{i\in I}\kappa_i := \left|igcup_{i\in I} X_i
ight|$$

where $(X_i : i \in I)$ is a sequence of pairwise disjoint sets with $|X_i| =$

Exercise 10.1.5

Check that Definition 32 is well-defined.

66 Note

Observe that

$$\bigcup_{i\in I} X_i = \cup \{X_i \mid i\in I\} = \cup \operatorname{Im}(f)$$

where $(X_i : i \in I)$ is a sequence of functions and $f : I \to Set$ is given by $f(i) = X_i$.

■ Theorem 38 (Properties of Cardinal Sum)

Let $I \in Set$ be infinite, and $(\kappa_i : i \in I)$ a sequence of cardinals not all zero. Then

- 1. $\sup_{i \in I} \kappa_i \in Card$; and
- 2. $\sum_{i \in I} \kappa_i = \max\{|I|, \sup_{i \in I} \kappa_i\}.$

Exercise 10.1.6

Prove/read 🖳 Theorem 38

Example 10.1.1

We have that

$$\sum_{0 < n \in \omega} n = \max\{|\omega \setminus \{0\}|, \sup_{0 < n \in \omega} n\} = \max\{\aleph_0, \omega\} = \aleph_0.$$

Definition 33 (Generalized Cardinal Product)

Suppose $(\kappa_i : i \in I)$ is a sequence of cardinals. Then the **cardinal product** is defined as

$$\prod_{i \in I} \kappa_i := |X_1 \times X_2 \times \ldots| = \left| \underset{i \in I}{\times} X_i \right|$$

where $(X_i : i \in I)$ is a sequence of sets with $|X_i| = \kappa_i$.

Exercise 10.1.7

Check that Definition 33 is well-defined.

66 Note

Note that $\underset{i \in I}{\times} X_i$ *is properly defined, as*

$$i \in I \times X_i := \{(a_i : i \in I) \mid \forall i \in I, a_i \in X_i\}$$
$$= \left\{ f : I \to \bigcup_{i \in I} X_i, f(i) = X_i \right\}.$$

Remark

Once again, we might as well take $X_i = \kappa_i$, just as we did when we defined pair products.

Example 10.1.2

Suppose $\kappa_i = 2$ for all $i \in I$. Define a function such that

$$\underset{i \in I}{\times} 2 \to \mathcal{P}(I)$$

given by

$$(a_i:i\in I)\mapsto \{i\in I:a_i=1\}.$$

Note that $2 = \{0, 1\}$, and so each $a_i = 0$ or 1. Clearly so, this is a bijection³. Consequently, we have

$$\prod_{i \in I} 2 = \left| \underset{i \in I}{\times} 2 \right| = |\mathcal{P}(I)|$$

We claim that

$$|I| < |\mathcal{P}(I)|$$
.

An Interlude on the Continuum Hypothesis 10.1.2

Theorem 39 (Cantor's Diagonalization)

 $\forall I \in \text{Set}$, we have $|I| < |\mathcal{P}(I)|$.

Clearly we have that $I \hookrightarrow \mathcal{P}(I)$ through the map $i \mapsto \{i\}$. Thus $|I| \leq |\mathcal{P}(I)|$.

Suppose to the contrary that there exists a bijection $f: I \to \mathcal{P}(I)$.

³ This is the usual correspondence between subsets and characteristic functions.

Let⁴

$$\Delta = \{i \in I : i \notin f(i)\} \subseteq I.$$

which is a set by Bounded Separation. Thus $\Delta \in \mathcal{P}(I)$. Then $\exists i_0 \in I$ such that $f(i_0) = \Delta$. Now if $i_0 \in \Delta$, then $i_0 \in f(i_0) = \Delta$, but this contradicts the membership condition which states that $i_0 \notin f(i_0)$. If $i_0 \notin \Delta$, then $i_0 \notin f(i_0) = \Delta$, but by the membership condition, it must be that $i_0 \in \Delta$, yet another contradiction. Thus such a bijection does not exist.

⁴ This definition looks awfully familiar to Russell's Paradox.

This proves our earlier claim. In fact, so long as |I| > 2,

$$\prod_{i \in I} 2 \neq \max\{|I|, \sup_{i \in I} 2\} = \max\{|I|, 2\},\$$

since RHS = |I| while $LHS = |\mathcal{P}(I)|$.

Definition 34 (Cardinal Exponentiation)

 $\forall \kappa, \lambda \in Card$, the cardinal exponentiation is defined as

$$\kappa^{\lambda} := |\operatorname{Fun}(\lambda, \kappa)|,$$

where $\operatorname{Fun}(\lambda, \kappa)$ is the set of all functions from λ to κ .

Exercise 10.1.8

Prove that

$$\prod_{i<\lambda}\kappa=\kappa^{\lambda}.$$

As a consequence, we have that $2^{\lambda}=|\mathcal{P}(\lambda)|.$ Then what is $|\mathcal{P}(\aleph_0)|$?

■ Axiom 40 (Continuum Hypothesis)

We have that

$$\aleph_0 < 2^{\aleph_0} = |\mathcal{P}(\aleph_0)|$$
,

i.e. $2^{\aleph_0} = \aleph_1$.

More generally,

■ Axiom 41 (Generalized Continuum Hypothesis)

 $\forall \kappa \in Card$, we have

$$2^{\kappa} = \kappa^+$$
.

In this course, we will not assume the Continuum Hypothesis (nor for the general case).

It has been proven by Paul Cohen (1963)⁵ that the Continuum Hypothesis is independent from ZFC.

⁵ Cohen, P. J. (1963). The independence of the continuum hypothesis.

Part II

Model Theory

11 Lecture 11 Oct 16th

The course will not cover for cofinality and coregularity, but it may be helpful to read through the material.

WE SHALL now venture into Model Theory.

11.1 First-order Logic

11.1.1 Structure

■ Definition 35 (Structure)

A structure \mathcal{M} consists of the following data:

- 1. A non-empty set M, called the universe of M;
- 2. A sequence $(c_i : i \in I_{con})$, where I_{con} is an I-sequence of constants, of distinguished elements of M, called the **constants** of M;
- 3. A sequence of M-valued functions on powers of M,

$$(f_i:M^{n_i}\to M:i\in I_{\operatorname{fun}}),$$

called the basic functions of M, and for each $i \in I_{fun}$, $n_i < \omega$ is called the arity of f_i ;

4. A sequence of subsets of powers of M,

$$(R_i \subset M^{m_i}: i \in I_{\mathrm{rel}})$$

called the basic relations of M, and for each $i \in I_{rel}$, $m_i < \omega$ is called the arity of R_i .

66 Note

- 1. Note that we defined $M \neq \emptyset$, as there is nothing too interesting to study from an empty universe.
- 2. Also, note that we shall always use the corresponding capital alphabet as the universe of the structure (e.g. the universe of the structure $\mathcal M$ is $\mathcal M$).
- 3. While $M \neq \emptyset$, we allow I_{con} , I_{fun} and I_{rel} to be \emptyset . In such a case, the structure that we have is about a pure set.
- 4. If f is a 0-ary basic function, then we have

$$f:M^0\to M$$
.

By convention, we have that $M^0 = 1 = \{0\}$, and so we have $f(0) \in M$. Thus, such an f is "essentially" a basic constant. Therefore, we shall usually assume that the arity of f is strictly positive.

Example 11.1.1

Consider \mathbb{R} , the set of real numbers¹. The following are some of the structures that we can study on \mathbb{R} :

- 1. as a pure set: $\mathcal{R} = \mathbb{R}$, with $I_{con} = I_{fun} = I_{rel} = \emptyset$.
- 2. as an ordered set: $\mathcal{R} = (\mathbb{R}, <)$, with the basic **binary** relation <, and no basic functions or constants.
- 3. as an additive group: $\mathcal{R} = (\mathbb{R}, 0, +, -)$, with
 - 0 as a constant;
 - + as a basic **binary** function; and
 - — as a basic **unary** function.
- 4. as a ring: $\mathcal{R} = (\mathbb{R}, 0, 1, +, -, \cdot)$.
- 5. as a Q-vector space: $\mathcal{R} = (\mathbb{R}, 0, +, -, (\lambda_q)_{q \in \mathbb{Q}})$, where $\lambda_q : \mathbb{R} \to \mathbb{R}$ is scalar multiplication by q.
- 6. as an ordered ring: $\mathcal{R} = (\mathbb{R}, 0, 1, +, -, \cdot, <)$.

¹ We did not construct $\mathbb R$ in our section on Set Theory. I may write up a full construction from $\mathbb N$ to $\mathbb R$ on my site.

Definition 36 (Expansion & Reduct)

Suppose $\mathcal M$ and $\mathcal N$ are structures with the same universe. We say that $\mathcal M$ is an **expansion** of $\mathcal N$ or that $\mathcal N$ is a **reduct** of $\mathcal M$ if the basic constants, basic functions, and basic relations of N are contained in those of \mathcal{M} .

Example 11.1.2

- $(\mathbb{R}, 0, +, -)$ is a reduct of $(\mathbb{R}, 0, 1, +, -, \cdot)$;
- $(\mathbb{R}, 0, 1, +, -, \cdot, <)$ is an expansion of $(\mathbb{R}, 0, 1, +, -, \cdot)$.

Language 11.1.2

Example 11.1.3

Consider the following 2 structures

$$\mathcal{R} = (\mathbb{R}, 0, +, -)$$
 $\mathcal{Z} = \left(\mathbb{Z}/_{2\mathbb{Z}}, 0, +, -\right)$

Notice that the 0, + and - do not not actually share the same meaning, since, e.g., + in \mathcal{R} is addition on the reals, while + in \mathcal{Z} is addition on the integers modulo 2.

Definition 37 (Language)

A *language* \mathcal{L} *consists of* 3 *sets of symbols:*

- 1. a set \mathcal{L}^{con} of constant symbols;
- 2. a set \mathcal{L}^{fun} of function symbols, where each function symbol comes with an arity, which is a natural number;
- 3. a set \mathcal{L}^{rel} of relation symbols, where each relation symbol comes with an arity, which is a natural number.

■ Definition 38 (*L*-structure)

An \mathcal{L} -structure is a structure \mathcal{M} with bijections between

$$\mathcal{L}^{\mathrm{con}} \to I_{\mathrm{con}} \qquad c \mapsto c^{\mathcal{M}}$$
 $\mathcal{L}^{\mathrm{fun}} \to I_{\mathrm{fun}} \qquad f \mapsto f^{\mathcal{M}}$
 $\mathcal{L}^{\mathrm{rel}} \to I_{\mathrm{rel}} \qquad R \mapsto R^{\mathcal{M}}$

that preserves arity. We call

$$c^{\mathcal{M}}$$
, $f^{\mathcal{M}}$, and $R^{\mathcal{M}}$

the **Interpretation** of c, f, R in \mathcal{M} .

So in our previous example, we have that \mathcal{R} and \mathcal{Z} are both \mathcal{L} -structures, where $\mathcal{L} = \{0, +, -\}$ is the language with

- one constant symbol, 0;
- one binary function symbol, +;
- one unary function symbol, –.

This particular language is often referred to as the language of additive groups, for obvious² reasons.

² Obvious, if you have studied Group Theory.

Remark

• To be precise, we should really write

$$\mathcal{R} = (\mathbb{R}, 0^{\mathcal{R}}, +^{\mathcal{R}}, -^{\mathcal{R}}),$$

so as to not obfuscate the symbols themselves and their interpretations in \mathcal{R} , but we shall forgive ourselves for this abuse of notation, for we shall leave this for the context to resolve this confusion.

• Every group is naturally an \mathcal{L} -structure, where $\mathcal{L} = \{0, +, -\}$. The converse is definitely false. E.g. the following \mathcal{L} -structure

$$\mathcal{M} = (\mathbb{Z}, 0^{\mathcal{M}}, +^{\mathcal{M}}, -^{\mathcal{M}})$$

given by

$$0^{\mathcal{M}} = 12$$

 $+^{\mathcal{M}} : \mathbb{Z}^2 \to \mathbb{Z} \quad (a, b) \mapsto -2$
 $-^{\mathcal{M}} : \mathbb{Z} \to \mathbb{Z} \quad a \mapsto 2^2$

Example 11.1.4

Let F be a field, and let \mathcal{L} be the language of F-vector spaces, i.e.

$$\mathcal{L}^{ ext{con}} = \{0\}$$

$$\mathcal{L}^{ ext{fun}} = \{+, -, (\lambda_f)_{f \in F}\}$$
 $\mathcal{L}^{ ext{rel}} = \emptyset$

where + is a binary function, - a unary function, and λ_f a unary function for each $f \in F$. Then any F-vector spaces V is an \mathcal{L} -structure:

- 0 is interpreted as the zero vector
- + is interpreted as vector addition
- is interpreted as the additive inverse of a vector
- λ_f is interpreted as scalar multiplication by f

The converse is, however, **not true**, and we shall study the reasons behind why this is not true later on.

Definition 39 (*L*-Embedding)

Suppose \mathcal{L} is a language, and \mathcal{M} and \mathcal{N} are \mathcal{L} -structures. An \mathcal{L} -embedding, $j:\mathcal{M}\to\mathcal{N}$, is an injective function $j:M\to N$ such that

- 1. $\forall c \in \mathcal{L}^{con} \quad j(c^{\mathcal{M}}) = c^{\mathcal{N}};$
- 2. $\forall f \in \mathcal{L}^{\text{fun}}$ each with arity n_f , and $\forall a_1, \ldots, a_{n_f} \in M$, we have

$$j(f^{\mathcal{M}}(a_1,\ldots,a_{n_f}))=f^{\mathcal{N}}(j(a_1),\ldots,j(a_{n_f}))$$

3. $\forall R \in \mathcal{L}^{\mathrm{rel}}$ each with arity m_R , and $\forall (a_1, \ldots, a_{m_R}) \in M^{m_R}$, we have

$$(a_1,\ldots,a_{m_R})\in R^{\mathcal{M}}\iff (j(a_1),\ldots,j(a_{m_R}))\in R^{\mathcal{N}}.$$

Definition 40 (Substructure)

Continuing with the above assumptions and notation, if $M \subseteq N$, then we say that \mathcal{M} is a **substructure** on \mathcal{N} if the identity map $id: M \to N$ is an \mathcal{L} -embedding. We denote this notion, without confusion, by $\mathcal{M} \subset \mathcal{N}$.

We may also say that N is an extension of M.

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12.1 First-order Logic (Continued)

12.1.1 Language (Continued)

66 Note

Notice that \mathcal{L} -structures $\mathcal{M} \subseteq \mathcal{N}$ *iff*

- $M \subseteq N$;
- $\forall c \in \mathcal{L}^{\text{con}}$ $c^{\mathcal{M}} = c^{\mathcal{N}}$;
- $\forall f \in \mathcal{L}^{\text{fun}}$, each with arity n_f , $f^{\mathcal{M}} = f^{\mathcal{M}} \upharpoonright_{M^{n_f}}$;
- $\forall R \in \mathcal{L}^{\mathrm{rel}}$, each with arity m_R , $R^{\mathcal{M}} \subseteq R^{\mathcal{N}} \cap M^{m_R}$.

Exercise 12.1.1

Suppose $\mathcal N$ is an $\mathcal L$ -structure with $A\subset \mathcal N$, where $A\neq \emptyset$. Show that A is the universe of some (unique) substructure of $\mathcal N$ iff

- $\forall c \in \mathcal{L}^{\text{con}} \quad c^{\mathcal{N}} \in A;$
- $\forall f \in \mathcal{L}^{\text{fun}}$ that is n-ary, $f^{\mathcal{N}}(A^n) \subset A$.

The choice of the language determine what the substructures are.

Example 12.1.1

The following is table showing an example of a substructure in the given structures:

Structure	Substructures
\mathbb{R}	all non-empty subsets
$(\mathbb{R},0,+)$	all submonoids of \mathbb{R}^{1}
$(\mathbb{R},0,+,-)$	all subgroups
$(\mathbb{R},0,1,+,-,\cdot)$	all subrings
$(\mathbb{R},<)$	all non-empty subsets with induced order
$(\mathbb{R},0,+,-,(\lambda_q)_{q\in\mathbb{Q}})$	all Q-subspaces

Definition 41 (*L*-isomorphism)

An L-isomorphism is a surjective L-embedding.

Exercise 12.1.2

Let $j: \mathcal{M} \to \mathcal{N}$ be an \mathcal{L} -embedding. Then j induces an \mathcal{L} -isomorphism between \mathcal{M} and a unique substructure $\mathcal{M}' \subseteq \mathcal{N}$.

12.1.2 Terms & Formulas

From hereon, we shall have the following countable infinite set,

$$Var = \{x_0, x_1, \ldots\},\$$

which we shall call as our set of variables2.

² This is not to be confused with the variance in probability theory.

 1 Not that substructures of $(\mathbb{R},0,+)$ is not necessarily a group, and this is why we have always specified for - for the language of additive groups. However, this is not necessary for the unique inverse in the language of fields, of

which we shall clarify in a later section.

■ Definition 42 (*L*-terms)

Let \mathcal{L} be a language. The set of \mathcal{L} -terms is the smallest set of strings of symbols from

$$\mathcal{L} \cup \text{Var} \cup \{(,)\} \cup \{,\}$$
 3

satisfying

- every variable is an L-term;
- every constant of \mathcal{L}^{con} is also an \mathcal{L} -term;
- 4if $t_1, t_2, ..., t_n$ are \mathcal{L} -terms and $f \in \mathcal{L}^{\text{fun}}$ is n-ary, then $f(t_1, ..., t_n)$ is also an \mathcal{L} -term.
- 3 By $\{(,)\}$ and $\{,\}$, we mean the punctuation symbols "(", ",", ")".
- ⁴ This is a recursive formula.

We often write a term t as

$$t = t(x_1, \ldots, x_n)$$

to mean that the variables in t come from $\{x_1, \ldots, x_n\}$.

Remark

All x_1, \ldots, x_n need not always appear in t.

We shall use the following example to show another abuse of notation that we shall gladly do in this course:

Example 12.1.2

Let $\mathcal{L} = \{0, 1, +, -, \times\}$. The following is an \mathcal{L} -term:

$$\times (+(x_0, -(x_1)), \times (1, x_2)).$$

It is fairly straightforward to verify that the above is indeed an \mathcal{L} term: using items (1), (2) and (3) in our definition above, by the given order,

- 1. all $x_0, x_1, 1, x_2$ are \mathcal{L} -terms by (1) and (2);
- 2. is a unary function, and so by (3), we have that $-(x_1)$ is an \mathcal{L} -term;
- 3. + is a binary function, and by (3), we have that $+(x_0, -(x_1))$ is an \mathcal{L} -term;
- 4. \times is a binary function, and so by (3), we have that \times (1, x_2) is an \mathcal{L} -term;
- 5. finally, by (3), $\times (+(x_0, -(x_1)), \times (1, x_2))$ is an \mathcal{L} -term.

We shall "informally" write this as

$$(x_0 + (-x_1))(1x_2).$$

Note that we do not simply write $x_2 = 1x_2$, since we may not have that 1 acts as a "multiplicative identity" of sorts, as we would have in a ring.

Definition 43 (Interpretation)

Suppose \mathcal{M} is an \mathcal{L} -structure, and $t = t(x_1, ..., x_n)$ is an \mathcal{L} -term. We define the **itnerpretation** of t in \mathcal{M} to be the function

$$t^{\mathcal{M}}:M^n\to M$$
.

defined recursively by

• If t is x_i for some $1 \le i \le n$, then

$$t^{\mathcal{M}}: M^n \to M \quad (a_1, \ldots, a_n) \mapsto a_i.$$

• If t is c for some $c \in \mathcal{L}^{con}$, then

$$t^{\mathcal{M}}: M^n \to M \quad (a_1, \ldots, a_n) \mapsto c^{\mathcal{M}}.$$

• If t is $f(t_1,...,t_l)$, where $t_1,...,t_l$ are \mathcal{L} -terms and f is an l-ary function symbol, then $t^{\mathcal{M}}: M^n \to M$

$$(a_1,\ldots,a_n)\mapsto f(t_1^{\mathcal{M}}(a_1,\ldots,a_n),t_2^{\mathcal{M}}(a_1,\ldots,a_n),\ldots,t_1^{\mathcal{M}}(a_1,\ldots,a_n))$$

66 Note

Note that the function $t^{\mathcal{M}}$ depends not just on t but on its presentation $t = t(x_1, \dots, x_n)$.

Example 12.1.3

Let $\mathcal{L} = \{0, +, -\}$ and $\mathcal{R} = (\mathbb{R}, 0, +, -)$ an \mathcal{L} -structure. Let t be the term $x \in \text{Var}$. Then for $y \in \text{Var}$, the following are some interpretations of t in \mathcal{R} :

- 1. if t = t(x), then we may interpret $t^{\mathcal{R}} : \mathbb{R} \to \mathbb{R}$ as the identity map, i.e. $r \mapsto r$;
- 2. if t = t(x, y), then we may interpret $t^{\mathcal{R}} : \mathbb{R}^2 \to \mathbb{R}$ as taking the first component of the tuple, i.e. $(a, b) \mapsto a$;
- 3. if t = t(x,y), then we may interpret $t^{\mathcal{R}} : \mathbb{R}^2 \to \mathbb{R}$ as taking the second component of the tuple, i.e. $(a,b) \mapsto b$.

Exercise 12.1.3

Prove the following: suppose M *is an* L-structure, and $A \subseteq M$ such that $A \neq \emptyset$, then A is the universe of the substructure iff $\forall t = t(x_1, \dots, x_n)$ that are \mathcal{L} -terms, we have $t^{\mathcal{M}}(A^n) \subseteq A$.

Example 12.1.4

Let $\mathcal{L} = \{0, 1, +, -, \times\}$ and $\mathcal{Z} = (\mathbb{Z}, =, 1, +, -, \times)$. Let $P \in \mathbb{Z}[x]$ where *P* is $x^2 + 2y - 1$. Then let $t_P = t_P(x, y)$ be the \mathcal{L} -term

$$x^2 + (y + y) + (-1)$$
.

Then the interpretation of t_P is

$$t_P^Z: \mathbb{Z}^2 \to \mathbb{Z} \quad (a,b) \mapsto a^2 + 2b + 1.$$

Definition 44 (Atomic \mathcal{L} -Formulas)

An atomic *L*-formula is a (finite) string of symbols from

$$\mathcal{L} \cup \text{Var} \cup \{(,)\} \cup \{,\} \cup \{=\}$$

of the form:

- 1. (t = s) where t, s are \mathcal{L} -terms;
- 2. $R(t_1,...,t_l)$ where $t_1,...,t_l$ are \mathcal{L} -terms, and $R \in \mathcal{L}^{\mathrm{rel}}$ with arity $l \in \omega$.

Definition 45 (*L*-formulas)

The set of \mathcal{L} -formulas is the smallest set of (finite) strings of symbols from

$$\mathcal{L} \cup \text{Var} \cup \{(,)\} \cup \{,\} \cup \{=\} \cup \{\land,\lor,\neg,\exists,\forall\}$$

satisfying:

- 1. every atomic *L*-formula is an *L*-formula;
- 2. *if* ϕ , ψ *are* \mathcal{L} -formulae, then so is $(\phi \land \psi)$, $\neg \phi$, and $(\phi \lor \psi)$;
- *3. if* ϕ *is an* \mathcal{L} -formula and $x \in \text{Var}$, then $\exists x \phi$ and $\forall x \phi$ are \mathcal{L} -formulae.

Remark

- 1. We shall use the following abbreviations:
 - $\phi \rightarrow \psi$ for $(\neg \phi \lor \psi)$;
 - $\phi \leftrightarrow \psi$ for $(\phi \rightarrow \psi) \land (\psi \rightarrow \phi)$.
- 2. We shall gleefully make the following abuse of notation: for the language $\mathcal{L} = \{\times, <\}$, we write $x < y^2$ instead of $< (x, \times (y, y))$.

Definition 46 (Bound and Free Variables)

Suppose ϕ is an \mathcal{L} -formula. An occurrence of a variable x in ϕ is called **bound** if it appears inside the scope of a quantifer (i.e. in the existence of \exists and \forall). Otherwise, they are called **free**.

Example 12.1.5

Let $\mathcal{L} = \{ \in \}$, and $x, y, z \in \text{Var}$. The following is an \mathcal{L} -formula:

$$(x \in y) \land \forall z \Big((z \in y) \to \big((z \in x) \lor (z = x) \big) \Big)$$

We have that x, y are the free variables while z is bound.

We write $\phi = \phi(x_1, ..., x_n)$ to mean that the free variables of ϕ come from $\{x_1, ..., x_n\}$, but it is not necessary that all of the variables appear in the \mathcal{L} -formula.

For the sake of convenience, we hall assume that no variable can be simultaneously bound and free in an \mathcal{L} -formula.

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