

# Set Theory Notes

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*These notes are not necessarily correct, consistent, representative of the course as it stands today, or rigorous. Any result of the above is not the author's fault.*

**These notes are in progress.**

## 0 Notation

We commonly deal with the following concepts in Set Theory which I will abbreviate as follows for brevity:

Term	Notation
$\{0, 1, 2, \dots\}$	$\mathbb{N}$

# Contents

<b>0</b>	<b>Notation</b>	<b>1</b>
<b>1</b>	<b>The Fundamentals</b>	<b>5</b>
1.1	Axiom of Extensionality . . . . .	5
1.2	Axiom of Pair Sets . . . . .	5
1.3	Axiom of the Powerset . . . . .	5
1.4	Axiom of the Empty Set . . . . .	5
1.5	Axiom of Subsets . . . . .	5
1.6	Axiom of Unions . . . . .	6
1.7	Classes . . . . .	6
1.8	The Set $\omega$ . . . . .	6
1.9	Russell's Theorem . . . . .	6
1.10	The Universe of Sets . . . . .	7
<b>2</b>	<b>Relations</b>	<b>8</b>
2.1	Partial Orderings . . . . .	8
2.2	Bounding . . . . .	9
2.3	Order Preserving Maps . . . . .	9
2.4	Representation Theorem for Partially Ordered Sets . . . . .	9
2.5	Total Orderings . . . . .	10
2.6	Well-orderings . . . . .	10
2.7	Ordered Pairs . . . . .	10
2.7.1	Uniqueness of Ordered Pairs . . . . .	10
2.7.2	The Ordered $k$ -tuple . . . . .	10
2.7.3	The Product of Sets . . . . .	11
2.8	Binary Relations . . . . .	11
2.8.1	Domain and Range . . . . .	11
2.9	Functions . . . . .	11
2.9.1	Ranges and Restrictions . . . . .	11
2.9.2	The Set of Functions . . . . .	12
2.9.3	Indexed Cartesian Products . . . . .	12
<b>3</b>	<b>Transitive Sets</b>	<b>13</b>
3.1	The Successor Function . . . . .	13
3.2	Transitive Closure . . . . .	13
3.2.1	Properties of Transitive Closure . . . . .	13

<b>4</b>	<b>Number Systems</b>	<b>14</b>
4.1	Von Neumann Numerals . . . . .	14
4.2	Inductive Sets . . . . .	14
4.3	Axiom of Infinity . . . . .	14
4.4	Natural Numbers . . . . .	14
4.5	Principle of Mathematical Induction . . . . .	15
4.6	Representation of Natural Numbers . . . . .	15
4.7	Transitivity of $\omega$ . . . . .	15
4.8	Ordering on the Naturals . . . . .	15
4.9	Total Ordering on the Naturals . . . . .	16
4.10	Well-ordering Theorem for $\omega$ . . . . .	16
4.11	Recursion Theorem on $\omega$ . . . . .	17
<b>5</b>	<b>Well-orderings and Ordinals</b>	<b>19</b>
5.1	The Principle of Transfinite Induction . . . . .	19
5.2	Initial Segments . . . . .	19
5.3	Order Preserving Maps on Well-orderings . . . . .	19
5.3.1	Uniqueness of Order Isomorphisms . . . . .	19
5.3.2	Non-existence of Order Isomorphisms to Segments . . . . .	20
5.3.3	Order Isomorphism to Set of Segments . . . . .	20
5.4	Ordinal Numbers . . . . .	20
5.4.1	Elements and Segments . . . . .	20
5.4.2	Subsets and Segments . . . . .	20
5.4.3	Segments . . . . .	21
5.4.4	The Intersection of Ordinals . . . . .	21
5.5	Classification Theorem for Ordinals . . . . .	21
5.6	Equality under Isomorphisms . . . . .	21
5.7	Bound on Isomorphisms . . . . .	22
5.8	Criterion for Ordinals . . . . .	22
5.9	Representation Theorem for Well-orderings . . . . .	23
5.10	Order Type of Well-orderings . . . . .	23
5.11	Classification Theorem for Well-orderings . . . . .	23
<b>6</b>	<b>Properties of Ordinals</b>	<b>24</b>
6.1	Principle of Transfinite Induction . . . . .	24
6.2	The Class of Ordinals . . . . .	25
6.3	Sum of Orderings . . . . .	25
6.4	Product of Orderings . . . . .	25
6.5	Supremum of Ordinals . . . . .	26
6.6	Types of Ordinals . . . . .	26
6.7	Transfinite Recursion Theorem on Ordinals . . . . .	26

6.8	Alternative Transfinite Recursion on Ordinals . . . . .	28
6.9	Ordinal Addition . . . . .	28
6.10	Ordinal Multiplication . . . . .	28
6.11	Ordinal Exponentiation . . . . .	29
6.12	Monotonicity of $A_\alpha$ . . . . .	29

# 1 The Fundamentals

## 1.1 Axiom of Extensionality

For two sets  $a$  and  $b$ , we have that  $a = b$  if and only if for all  $x$  we have that:

$$x \in a \iff x \in b.$$

For two classes  $A$  and  $B$ , we have that  $A = B$  if and only if for all  $x$  we have that:

$$x \in a \iff x \in b.$$

## 1.2 Axiom of Pair Sets

For any sets  $x$  and  $y$ , there is a set  $z = \{x, y\}$ . This is the (unordered) pair set of  $x$  and  $y$ .

## 1.3 Axiom of the Powerset

For each set  $x$ , there exists a set which is the collection of the subsets of  $x$ , the powerset  $\mathcal{P}(x)$ .

For some set  $x$ , we have the powerset defined as follows  $\mathcal{P}(x) = \{z : z \subseteq x\}$ .

## 1.4 Axiom of the Empty Set

There exists a set with no members, the empty set  $\emptyset$ .

We have the empty set defined as follows  $\emptyset = \{x : x \neq x\}$ .

## 1.5 Axiom of Subsets

For some set  $x$ , we have that  $\{y \in x : \Phi(y)\}$  is a set for some well-defined property of sets  $\Phi$ .

## 1.6 Axiom of Unions

We have the basic union of two sets  $x_1$  and  $x_2$ :

$$x_1 \cup x_2 = \{y : y \in x_1 \text{ or } y \in x_2\},$$

but for cases where we want to unify the members of the sets in a set  $X$ , we define:

$$\bigcup X = \{y : \exists x \in X, y \in x\}.$$

This axiom states that for a set  $X$ ,  $\bigcup X$  is a set.

## 1.7 Classes

We have that classes are collection of objects, these could also be sets. Classes that are not sets are called proper classes.

## 1.8 The Set $\omega$

We have the set of natural numbers,  $\mathbb{N} = \{0, 1, 2, \dots\}$ , and from this, we define  $\omega$ :

$$\omega = \{0, 1, 2, \dots\},$$

where for some  $n$  in  $\omega$ ,

$$n = \{0, 1, 2, \dots, n-1\},$$

with  $0_\omega$  being the empty set. We can go beyond this definition, defining:

$$\begin{aligned}\omega + 1 &= \{0, 1, 2, \dots, \omega\}, \\ \omega + 2 &= \{0, 1, 2, \dots, \omega, \omega + 1\}, \\ &\dots \\ \omega + n &= \{0, 1, 2, \dots, \omega, \omega + 1, \dots, \omega + n - 1\}.\end{aligned}$$

## 1.9 Russell's Theorem

We have that  $R = \{x : x \notin x\}$  is not a set.

*Proof.* Suppose we have a set  $z$  such that  $z = R$ , is  $z$  in  $R$ ? If we suppose  $z$  is in  $R$ , we have that  $z$  is not in  $z$  by the definition of  $R$  (as  $z = R$ ) but  $z$  is  $R$  so  $z$  is not in  $R$ , a contradiction. Thus, we have that there is no set  $z$  equal to  $R$ , so  $R$  is not a set but a proper class.  $\square$

## 1.10 The Universe of Sets

We define the universe of sets as  $V = \{x : x = x\}$ . We have that  $V$  is a proper class.

*Proof.* If we suppose  $V$  is a set, we apply the axiom of subsets with  $\Phi(x) = x \notin x$  and reach a contradiction via Russell's theorem.  $\square$

## 2 Relations

We will first state the significant properties relations can have. Taking a relation  $R$  on  $X$  with  $x, y, z$  arbitrary in  $X$ :

Name	Property
Reflexive	$xRx$
Irreflexive	$\neg(xRx)$
Symmetric	$xRy \Rightarrow yRx$
Antisymmetric	$[xRy \text{ and } yRx] \Rightarrow [x = y]$
Connected	$[x = y] \text{ or } [xRy] \text{ or } [yRx]$
Transitive	$[xRy \text{ and } yRz] \Rightarrow [xRz]$

For example, equivalence relations must satisfy reflexivity, symmetry, and transitivity.

### 2.1 Partial Orderings

We say that a relation  $\prec$  on a set  $X$  is a (strict) partial ordering if it is irreflexive and transitive.

Similarly, we say that a relation  $\preceq$  on a set  $X$  is a non-strict partial ordering if it is reflexive, antisymmetric, and transitive.

A partial ordering  $(X, \prec)$  is wellfounded if for any non-empty subset  $Y$  of  $X$ ,  $Y$  has a least element under  $\prec$ .



## 2.2 Bounding

For a partially ordered set  $(X, \prec)$ :

- $x_0$  in  $X$  is the minimum of  $X$  if for all  $x$  in  $X$ ,  $x_0 \preceq x$ ,
- $x'$  in  $X$  is minimal in  $X$  if for all  $x$  in  $X$ ,  $\neg(x \prec x')$ ,
- $x_1$  in  $X$  is the maximum of  $X$  if for all  $x$  in  $X$ ,  $x \preceq x_1$ ,
- $x'$  in  $X$  is maximal in  $X$  if for all  $x$  in  $X$ ,  $\neg(x' \prec x)$ .

Taking a non-empty subset  $Y$  of  $X$ , we consider the subordering  $(Y, \prec)$  and for some  $\alpha$  in  $X$  we say:

- $\alpha$  is a lower bound for  $Y$  if for all  $y$  in  $Y$ ,  $\alpha \prec y$ ,
- $\alpha$  is the infimum of  $Y$  if it's a lower bound and for all lower bounds  $\lambda$  of  $Y$ ,  $\alpha \preceq \lambda$ ,
- $\alpha$  is an upper bound for  $Y$  if for all  $y$  in  $Y$ ,  $y \prec \alpha$ ,
- $\alpha$  is the supremum of  $Y$  if it's an upper bound and for all upper bounds  $\tau$  of  $Y$ ,  $\tau \preceq \alpha$ .

## 2.3 Order Preserving Maps

We say that  $f : (X, \prec_1) \rightarrow (Y, \prec_2)$  is an order preserving map if for each  $x_1, x_2$  in  $X$ :

$$x_1 \prec_1 x_2 \implies f(x_1) \prec_2 f(x_2).$$

Two orderings are (order) isomorphic if there is a bijective order preserving map between them.

## 2.4 Representation Theorem for Partially Ordered Sets

For a partially ordered set  $(X, \prec)$ , there is a set  $Y \subseteq \mathcal{P}(X)$  which is such that  $(X, \preceq)$  is order isomorphic to  $(Y, \subseteq)$ .

*Proof.* For some  $x$  in  $X$ , we set  $X^x = \{x' \in X : x' \preceq x\}$ , the set of elements preceding or equal to  $x$ . For  $x, y$  in  $X$ ,  $x \neq y$  implies that  $X^x \neq X^y$  as these sets contain  $x$  and  $y$  (resp.) so  $x \mapsto X^x$  is injective. This map is surjective trivially (mapping from  $X$  to  $\{X^x : x \in X\}$ ). We have that:

$$x \preceq y \iff X^x \subseteq X^y,$$

by our definition. Thus,  $x \mapsto X^x$  is an order isomorphism.  $\square$

## 2.5 Total Orderings

A relation  $\prec$  on a set  $X$  is a (strict) total ordering if it is a connected strict partial ordering.

Similarly, we say that a relation  $\preceq$  on a set  $X$  is a non-strict total ordering if it is a connected non-strict partial ordering.

## 2.6 Well-orderings

A relation  $\prec$  on a set  $X$  is a well-ordering if it is a strict total ordering and for any non-empty subset  $Y$  of  $X$ ,  $Y$  has a least element under  $\prec$ . We denote this with  $(X, \prec) \in WO$ .

## 2.7 Ordered Pairs

For  $x, y$  sets, the ordered pair of  $x$  and  $y$  is the set:

$$\langle x, y \rangle = \{\{x\}, \{x, y\}\}.$$

### 2.7.1 Uniqueness of Ordered Pairs

For  $x, y, u, v$  sets, we have that:

$$\langle x, y \rangle = \langle u, v \rangle \iff (x = u) \text{ and } (y = v).$$

*Proof.* Suppose the former, if  $x = y$  then  $\langle x, y \rangle = \{\{x\}, \{x, x\}\} = \{\{x\}\}$ . Thus,  $\langle u, v \rangle = \{\{u\}\}$  as it is equal to  $\langle x, y \rangle$  which has one element, hence  $u = v$ . By the Axiom of Extensionality, we have that  $x = u$  and so  $y = x = u = v$ .

If  $x \neq y$ , then  $\langle x, y \rangle$  and  $\langle u, v \rangle$  both have the same two elements by our assumption (so  $u \neq v$ ). We cannot have  $\{x\} = \{u, v\}$  so  $\{x\} = \{u\}$  which means  $x = u$  by the Axiom of Extensionality. Thus,  $\{u, v\} = \{x, y\} = \{u, y\}$  so  $y = v$ .

Suppose the latter, then the former holds trivially.  $\square$

### 2.7.2 The Ordered $k$ -tuple

We define the  $k$ -tuple inductively. The 2-tuple is already defined. We define the 3-tuple:

$$\langle x_1, x_2, x_3 \rangle = \langle \langle x_1, x_2 \rangle, x_3 \rangle,$$

and for  $k$  in  $\{3, 4, \dots\}$ :

$$\langle x_1, x_2, \dots, x_k \rangle = \langle \langle x_1, x_2, \dots, x_{k-1} \rangle, x_k \rangle.$$

### 2.7.3 The Product of Sets

For  $A, B$  sets, we define:

$$A \times B = \{\langle a, b \rangle : a \in A, b \in B\}.$$

Similarly to  $k$ -tuples, for  $A_1, A_2, \dots, A_k$  sets, we have  $A_1 \times A_2$  defined, so we define:

$$A_1 \times A_2 \times \dots \times A_k = (A_1 \times A_2 \times \dots \times A_{k-1}) \times A_k,$$

defining the  $k$ -product for  $k$  in  $\{2, 3, \dots\}$ . This is not associative.

## 2.8 Binary Relations

A binary relation  $R$  is a class of ordered pairs. We write  $R^{-1} = \{\langle y, x \rangle : \langle x, y \rangle \in R\}$ .

### 2.8.1 Domain and Range

For a relation  $R$ , we define:

$$\begin{aligned}\text{dom}(R) &= \{x : \exists y \text{ where } \langle x, y \rangle \in R\}, \\ \text{ran}(R) &= \{y : \exists x \text{ where } \langle x, y \rangle \in R\}, \\ \text{Field}(R) &= \text{dom}(R) \cup \text{ran}(R).\end{aligned}$$

## 2.9 Functions

A relation  $F$  is a function if for all  $x$  in  $\text{dom}(F)$ , there is a unique  $y$  in  $\text{ran}(F)$  with  $\langle x, y \rangle$  in  $F$ .

If  $F$  is a function, it is injective if and only if for all  $x, x'$ :

$$(\langle x, y \rangle \in F \text{ and } \langle x', y \rangle \in F) \Rightarrow (x = x').$$

### 2.9.1 Ranges and Restrictions

For  $F : X \rightarrow Y$ :

- $F''A = \{y \in Y : \exists x \in A \text{ such that } F(x) = y\}$  the range of  $F$  on  $A$ ,
- $F \upharpoonright A = \{\langle x, y \rangle \in F : x \in A\}$  the restriction of  $F$  to  $A$ .

We can see that  $F''A = \text{ran}(F \upharpoonright A)$ .

### 2.9.2 The Set of Functions

For  $X, Y$  sets, we have that  ${}^XY = \{F : F : X \rightarrow Y\}$ .

### 2.9.3 Indexed Cartesian Products

For a set  $I$  with each  $i$  in  $I$  corresponding to a non-empty set  $A_i$ :

$$\prod_{i \in I} A_i = \{\text{functions } f : \text{dom}(f) = I \text{ and } f(i) \in A_i \text{ for all } i \in I\}.$$

### 3 Transitive Sets

A set  $x$  is transitive if and only if for all  $y$  in  $x$ ,  $y \subseteq x$ . This can be abbreviated to  $\cup x \subseteq x$ .

#### 3.1 The Successor Function

For a set  $x$ ,  $S(x) = x \cup \{x\}$  is the successor of  $x$ .  $S(x) = x$  is equivalent to saying  $x$  is transitive.

#### 3.2 Transitive Closure

For a set  $x$ , to find a superset of  $x$  which is transitive, the transitive closure  $TC$  of  $x$ , we recurse:

$$\begin{aligned}\bigcup^0 x &= x, \\ \bigcup^{n+1} x &= \bigcup \left( \bigcup^n x \right),\end{aligned}$$

which we can write as:

$$TC(x) = \bigcup \left\{ \bigcup^n x : n \in \mathbb{N} \right\}.$$

The transitive closure is always transitive.

##### 3.2.1 Properties of Transitive Closure

For a set  $x$ :

1.  $x \subseteq TC(x)$ ,
2. If  $t$  is transitive and  $x \subseteq t$  then  $TC(x) \subseteq t$ .  $TC(x)$  is the smallest transitive set containing  $x$ ,
3. By the above,  $TC(x) = x$  if and only if  $x$  is transitive.

*Proof.* (1) This is true as  $\bigcup^0 = x$ .

(2) If  $x \subseteq t$  then clearly  $\bigcup^0 x \subseteq t$ . We assume  $\bigcup^k x \subseteq t$  and use the fact that:

$$\left[ A \subseteq B \text{ with } B \text{ transitive} \right] \Rightarrow \bigcup A \subseteq B,$$

to deduce that  $\bigcup^{k+1} x \subseteq t$ . By induction we have that  $TC(x) \subseteq t$  as required.

(3) By (1),  $x \subseteq TC(x)$ . If  $x$  is transitive, we substitute it for  $t$  in (2) and get that  $TC(x) \subseteq x$  as required.  $\square$

## 4 Number Systems

### 4.1 Von Neumann Numerals

We have the von Neumann numerals defined as:

$$\begin{aligned}0 &= \emptyset, \\1 &= \{\emptyset\} = \{0\}, \\2 &= \{\emptyset, \{\emptyset\}\} = \{1, 2\}, \\&\dots \\n+1 &= \{0, 1, \dots, n\}.\end{aligned}$$

### 4.2 Inductive Sets

A set  $X$  is called inductive if  $\emptyset$  is in  $X$  and for all  $x$  in  $X$ ,  $S(x)$  is in  $X$ .

### 4.3 Axiom of Infinity

There exists an inductive set.

### 4.4 Natural Numbers

We say that  $x$  is a natural number if for all  $X$ :

$$X \text{ is an inductive set} \Rightarrow x \in X.$$

We define  $\omega$  as the class of natural numbers,  $\omega = \cap\{X : X \text{ is an inductive set}\}$ . We have that  $\omega$  is the smallest inductive set.

*Proof.* Let  $z$  be an inductive set (by the Axiom of Infinity it exists). By the Axiom of Subsets, we define a set  $N$ :

$$N = \{x \in z : \forall Y, Y \text{ is inductive} \Rightarrow x \in Y\},$$

the elements of  $z$  in every inductive set. But  $N = \omega$ , so  $\omega$  is a set.

We know that  $\emptyset$  is in every inductive set by definition, so  $\emptyset$  is in  $\omega$  as it is the intersection of all inductive sets. For any  $x$  in  $\omega$ , we know that for any inductive set  $Y$  that  $x$  is in  $Y$  (by the definition of  $\omega$ ) and thus  $S(x)$  is also in  $Y$  (by the definition of an inductive set). Thus,  $S(x)$  is also in  $\omega$  as  $Y$  was chosen arbitrarily. Hence,  $\omega$  is an inductive set and the smallest such set by its definition.  $\square$

## 4.5 Principle of Mathematical Induction

We suppose  $\Phi$  is a well-defined property of sets, then we have that:

$$\left[ \Phi(0) \text{ and } \forall x \in \omega \text{ we have that } \Phi(x) \Rightarrow \Phi(S(x)) \right] \Rightarrow \left[ \forall x \in \omega \text{ we have that } \Phi(x) \right].$$

*Proof.* We assume the antecedent, it suffices to show that the collection of  $x$  in  $\omega$  where  $\Phi(x)$  holds is inductive (as we assume  $\Phi(0)$  holds).

Let  $Y = \{x \in \omega : \Phi(x)\}$ . As we assumed  $\Phi(0)$ , we know that 0 is in  $Y$ . Then, by the second half of our assumption, we can see that  $Y$  is closed under the successor function. Thus,  $Y$  is inductive and as  $\omega$  is the smallest inductive set,  $\omega \subseteq Y$  as required.  $\square$

## 4.6 Representation of Natural Numbers

We have that every natural number is either 0 or  $S(x)$  for some natural number  $x$ .

*Proof.* Let  $Z = \{y \in \omega : y = 0 \text{ or } \exists x \in \omega \text{ such that } S(x) = y\}$ . It suffices to show that  $Z$  is inductive. Clearly, 0 is in  $Z$ . Suppose we have some  $u$  in  $Z$ , then  $u$  is in  $\omega$ . As  $\omega$  is inductive,  $S(u)$  is also in  $\omega$  so  $S(u)$  is in  $Z$ . Thus,  $Z$  is inductive as required.  $\square$

## 4.7 Transitivity of $\omega$

We have that  $\omega$  is transitive.

*Proof.* Let  $X = \{n \in \omega : n \subseteq \omega\}$ . If  $X = \omega$  then by definition  $\omega$  is transitive. It suffices to show that  $X$  is inductive. We know that  $\emptyset$  is in  $X$  as 0 is in  $\omega$ . Taking  $n$  in  $X$ , then clearly  $\{n\} \subseteq \omega$  as  $n$  is in  $\omega$ . Furthermore,  $n \subseteq \omega$  as  $n$  is in  $X$ . Thus,  $n \cup \{n\} \subseteq \omega$  so  $S(n) \in X$  which means  $X$  is inductive as required.  $\square$

## 4.8 Ordering on the Naturals

For  $m, n$  in  $\omega$ , we define:

$$\begin{aligned} m < n &\iff m \in n, \\ m \leq n &\iff m = n \text{ or } m \in n. \end{aligned}$$

By definition,  $n < S(n)$ .

We have that:

1. This ordering is transitive,
2. For all  $n$  in  $\omega$  and for all  $m$  we have that  $m < n$  if and only if  $S(m) < S(n)$ ,
3. For all  $n$  in  $\omega$ ,  $n \not< n$ .

*Proof.* (1) This follows from the transitivity of set inclusion.

(2) We take  $\Phi(k) = [(m < k) \Rightarrow (S(m) < S(k))]$ . We see  $\Phi(0)$  holds. Supposing  $\Phi(k)$  holds for some  $k$ , let  $m < S(k)$  then  $m$  is in  $k \cup \{k\}$ . If  $m$  is in  $k$  then by  $\Phi(k)$  we have that  $S(m) < S(k) < S(S(k))$ . If  $m = k$  then  $S(m) = S(k) < S(S(k))$ . Thus, by induction, we have our result.

Assume  $S(m) < S(n)$ ,  $m$  is in  $S(m) = m \cup \{m\}$  which is in  $S(n) = n \cup \{n\}$ . If  $S(m) = n$ , then  $m$  is in  $n$  so  $m < n$ . If  $S(m)$  is in  $n$  then  $m$  is in  $n$  as  $n$  is transitive.

(3) We know that  $0 \not< 0$  as  $0 \notin 0$ . If  $k \notin k$  then  $S(k) \notin S(k)$  by Part (ii). Thus,  $X = \{k \in \omega : k \notin k\}$  is inductive which makes it equal to  $\omega$  as required.  $\square$

## 4.9 Total Ordering on the Naturals

We have that  $<$  is a (strict) total ordering on the naturals.

## 4.10 Well-ordering Theorem for $\omega$

Let  $X \subseteq \omega$ , then either  $X = \emptyset$  or there is some  $n_0$  in  $X$  such that for any  $m$  in  $X$  either  $n_0 = m$  or  $n_0 < m$ .

*Proof.* Suppose  $X \subseteq \omega$  but has no least element. Let  $Z = \{k \in \omega : \forall n < k, n \notin X\}$ . We want to show  $Z$  is inductive, meaning  $Z = \omega$  and so  $X = \emptyset$ .

Vacuously,  $0$  is in  $Z$ . Suppose we have  $k$  in  $Z$ , we let  $n < S(k) = k \cup \{k\}$  and consider:

- If  $n \in k$  then  $n \notin X$  as  $n < k \in Z$ ,
- If  $n = k$  then  $n \notin X$  because if  $n$  was in  $X$  then it would be the least element of  $X$ , a contradiction.

Thus,  $S(k)$  is in  $Z$  so  $Z$  is inductive.  $\square$



### 4.11 Recursion Theorem on $\omega$

Let  $A$  be any set with  $a$  in  $A$  and  $f : A \rightarrow A$  any function. There exists a unique function  $h : \omega \rightarrow A$  such that for any  $n$  in  $\omega$ :

$$\begin{aligned} h(0) &= a, \\ h(S(n)) &= f(h(n)). \end{aligned}$$

*Proof.* We will find  $h$  as a union of  $k$ -approximations where  $u$  is a  $k$ -approximation if it is a function with  $\text{dom}(u) = k$  and for:

- If  $k > 0$  then  $u(0) = a$ ,
- If  $k > S(n)$  then  $u(S(n)) = f(u(n))$ .

From this, we see that  $\{\langle 0, a \rangle\}$  is a 1-approximation in particular. Furthermore, if  $u$  is a  $k$ -approximation and  $l \leq k$  then  $u \upharpoonright l$  is an  $l$ -approximation, finally if  $u(k-1) = c$  for some  $c$ , then  $u' = u \cup \{\langle k, f(c) \rangle\}$  is a  $(k+1)$ -approximation.

#### Agreement on Domain

If  $u$  is a  $k$ -approximation and  $v$  is a  $k'$ -approximation for some  $k \leq k'$  then  $v \upharpoonright k = u$  (hence  $u \subseteq v$ ).

*Proof.* We appeal to the contrary with  $0 \leq m < k$  being the least natural such that  $u(m) \neq v(m)$ . We know that  $m \neq 0$  as  $u(0) = a = v(0)$ . So,  $m = S(m')$  for some  $m'$ . As  $m$  is chosen minimally,  $u(m') = v(m')$ . We can then see that  $u(m) = f(u(m')) = f(v(m')) = v(m)$ , a contradiction.  $\square$

#### Uniqueness

If  $h$  exists, it is unique.

*Proof.* Suppose  $h$  and  $h'$  are two different functions with domain  $\omega$  satisfying the theorem. We take  $0 \leq m < \omega$  to be the least natural such that  $h(m) \neq h'(m)$  and apply the same reasoning to the above.  $\square$

#### Existence

Let  $u$  be in  $B$  if and only if there exists  $k$  in  $\omega$  such that  $u$  is a  $k$ -approximation. For any  $u, v$  in  $B$  either  $u \subset v$  or vice-versa by our previous results. We take  $h = \bigcup B$ .

We have that  $h$  is a function:

*Proof.* We appeal to the contrary. If  $\langle n, c \rangle$  and  $\langle n, d \rangle$  are in  $h$  with  $c \neq d$ , then we have  $u, v$  in  $B$  with  $u(n) = c$  and  $v(n) = d$  but this is impossible by **Agreement on Domain**.  $\square$

We have that  $\text{dom}(h) = \omega$ :

*Proof.* We appeal to the contrary and suppose  $\emptyset \neq X = \{n \in \omega : n \notin \text{dom}(h)\}$ . By the definition of  $h$  this means that:

$$X = \{n \in \omega : \text{There's no } u\text{-approximation with } n \in \text{dom}(u)\}.$$

We saw that there is a 1-approximation, so 0 is not the least element of  $X$ . We suppose  $n_0 = S(m)$  is the least element of  $X$ . As  $m$  is not in  $X$ , there must be an  $n_0$ -approximation  $n$  with  $n(m) = c$  for some  $c$ . But, we saw that we can extend  $k$ -approximations, so we can generate a  $(n_0 + 1)$ -approximation which is a contradiction. Thus,  $X = \emptyset$ .  $\square$

Thus, we have that  $h$  exists and is a unique function as required.  $\square$

## 5 Well-orderings and Ordinals

### 5.1 The Principle of Transfinite Induction

Let  $\langle X, \prec \rangle$  be a well-ordering. We have that:

$$[\forall x \in X, (\forall y \prec x, \Phi(y)) \Rightarrow \Phi(x)] \Rightarrow \forall x \in X, \Phi(x).$$

*Proof.* We appeal to the contrary and assume the antecedent but suppose that  $\emptyset \neq Z = \{x \in X : \neg \Phi(x)\}$ . As  $\langle Z, \prec \rangle$ , there is  $\prec$ -least element  $z_0$ . But then for all  $x \prec z_0$ ,  $\Phi(x)$  holds. But, by the antecedent, this means  $\Phi(z_0)$  holds, a contradiction.  $\square$

### 5.2 Initial Segments

For a well-ordering  $\langle X, \prec \rangle$ , the  $\prec$ -initial segment of some element  $z$  in  $X$  is the set of predecessors of  $z$ , denoted by  $X_z$ . Note that  $X_z$  does not contain  $z$ .

### 5.3 Order Preserving Maps on Well-orderings

For a well-ordering  $\langle X, \prec \rangle$  with  $f : \langle X, \prec \rangle \rightarrow \langle X, \prec \rangle$  an order preserving map, we have that for all  $x$  in  $X$ ,  $x \prec f(x)$ .

*Proof.* We appeal to the contrary, that for some  $x$  in  $X$ , we have  $f(x) \prec x$ . As  $\langle X, \prec \rangle$  is a well-ordering, there's a  $\prec$ -least  $x_0$  in  $X$  with the property that  $f(x_0) \prec x_0$ . But  $f(f(x_0)) \prec f(x_0)$  as  $f$  is order preserving. Thus, a contradiction to the minimality of  $x_0$ .  $\square$

#### 5.3.1 Uniqueness of Order Isomorphisms

For well-orderings  $\langle X, \prec_x \rangle$ ,  $\langle Y, \prec_y \rangle$  with  $f : \langle X, \prec_x \rangle \rightarrow \langle Y, \prec_y \rangle$  an order isomorphism. We have that  $f$  is unique.

*Proof.* Suppose we have two such isomorphisms  $f$  and  $g$ . We have that  $(f^{-1} \circ g)$  is also an order isomorphism. Taking  $x$  arbitrary in  $X$ :

$$\begin{aligned} & x \preceq_x (f^{-1} \circ g)(x) \\ \implies & f(x) \preceq_y f(f^{-1} \circ g)(x) \\ \implies & f(x) \preceq_y g(x). \end{aligned}$$

By applying this argument again with the roles of  $f$  and  $g$  swapped, we can also see that  $g(x) \preceq_y f(x)$ . Thus,  $f(x) = g(x)$ .

In particular, if  $\langle X, \prec_x \rangle = \langle Y, \prec_y \rangle$  then this isomorphism is the identity map.  $\square$

### 5.3.2 Non-existence of Order Isomorphisms to Segments

A well-ordered set is not order isomorphic to any segment of itself.

*Proof.* We appeal to the contrary and suppose there is such an order isomorphism on a well-ordering  $\langle X, \prec \rangle$  to  $\langle X_z, \prec \rangle$  for some  $z$  in  $X$ . But, we have that  $x \preceq f(x)$  for any  $x$  in  $X$  and  $f(z) \prec z$  as  $f(z)$  is in  $X_z$ . Thus, we have that  $z \preceq f(z)$  and  $z \succ f(z)$ , a contradiction.  $\square$

### 5.3.3 Order Isomorphism to Set of Segments

A well-ordered set  $\langle X, \prec \rangle$  is order isomorphic to the set of its initial segments ordered by  $\subset$ .

*Proof.* We let  $Y = \{X_a : a \in X\}$ , we have that  $\varphi$  characterised by  $a \mapsto X_a$  is an injective map as segments do not contain the element which determines it. As  $a \prec b \Leftrightarrow X_a \subset X_b$ , the mapping is order preserving.  $\square$

## 5.4 Ordinal Numbers

We say that  $\langle X, \in \rangle$  is an ordinal if and only if  $X$  is transitive, and where  $\prec = \in$ ,  $\langle X, \prec \rangle$  is a well-ordering. We have that  $\langle \omega, \in \rangle$  is an ordinal.

### 5.4.1 Elements and Segments

For an ordinal  $\langle X, \in \rangle$ , then every element  $z$  in  $X$  is identical to  $X_z$ .

*Proof.* Suppose  $X$  is transitive and  $\in$  well-orders  $X$ . Taking  $z$  in  $X$ :

$$\begin{aligned} w \in X_z &\iff w \in X \text{ and } w \in z \\ &\iff w \in z, \end{aligned} \quad (\text{as } z \subseteq X)$$

thus,  $X_z = z$  as required.  $\square$

So, for any elements  $a, b$  of an ordinal:

$$a \in b \iff a \subset b \iff X_a \subset X_b.$$

### 5.4.2 Subsets and Segments

For an ordinal  $\langle X, \in \rangle$  with  $Y \subset X$ , if  $\langle Y, \in \rangle$  is also an ordinal, then  $Y$  is an  $\in$ -initial segment of  $X$ .

*Proof.* Taking  $a$  in  $Y$  as supposed, as  $Y$  is an ordinal so  $Y_a = a$ . As  $Y \subset X$ ,  $a$  is in  $X$  so  $X_a = a$ . Thus,  $X_a = Y_a$ . Furthermore, as  $Y \neq X$ , we consider  $c = \inf\{z \in X : z \notin Y\}$  which exists as the set is non-empty and  $\langle X, \in \rangle$  is a well-ordering. Hence,  $Y = X_c$ .  $\square$

### 5.4.3 Segments

For an ordinal  $\langle X, \in \rangle$  any  $\in$ -initial segment of  $\langle X, \in \rangle$  is an ordinal.

*Proof.* We take some  $u$  in  $X$  and  $w$  in  $X_u$ . As  $\in$  well-orders  $X$ , it well-orders any subset of  $X$  so  $\langle X_u, \in \rangle$  is a well-ordering. We have that:

$$t \in w \in u \implies t \in u = X_u,$$

thus  $X_u$  is transitive as required.  $\square$

### 5.4.4 The Intersection of Ordinals

For ordinals  $X, Y$ ,  $X \cap Y$  is also an ordinal.

*Proof.* We take  $\in$  to be the ordering on  $X$ . We know that  $X \cap Y$  is transitive as  $X$  and  $Y$  are transitive. Any subset of  $X$  is a well-ordering under  $\in$ , in particular  $X \cap Y$  is well-ordered by  $\in$ .  $\square$

## 5.5 Classification Theorem for Ordinals

For two ordinals  $X, Y$ , either  $X = Y$  or one is an initial segment of the other (or equivalently a member).

*Proof.* Suppose that  $X \neq Y$ . We know that  $X \cap Y$  is an ordinal also. We have two cases.

If  $X = X \cap Y$  or  $Y = X \cap Y$ , one must be an initial segment of the other as it must be a proper subset under our assumption  $X \neq Y$ .

If  $X \cap Y$  is a proper subset of  $X$  and  $Y$ , it is an initial segment of  $X$  and  $Y$  simultaneously we set  $X \cap Y = X_a = Y_b$  for some  $a$  in  $X$  and  $b$  in  $Y$ . But, we know that as  $X$  and  $Y$  are ordinals,  $a = X_a = Y_b = b$ . However, this means:

$$a = b \in X \cap Y = X_a,$$

but  $a \notin X_a$ , a contradiction.  $\square$

## 5.6 Equality under Isomorphisms

For two ordinals  $X$  and  $Y$ , if  $X$  is order isomorphic to  $Y$  then  $X = Y$ .

*Proof.* Suppose  $X \neq Y$ , then without loss of generality we take  $X$  to be an initial segment of  $Y$ . But, this would mean  $Y$  is order isomorphic to a segment of itself which is a contradiction.  $\square$

## 5.7 Bound on Isomorphisms

A well-ordering is order isomorphic to at most one ordinal.

*Proof.* If a well-ordering is isomorphic to more than one ordinals, then these ordinals are isomorphic to each other and thus, equal.  $\square$

## 5.8 Criterion for Ordinals

If every segment of a well-ordered set  $\langle A, \prec \rangle$  is order isomorphic to some ordinal,  $\langle A, \prec \rangle$  itself is order isomorphic to an ordinal.

*Proof.* Each segment must be order isomorphic to at most one ordinal (thus exactly one). We define a function  $F$  from the segments of  $A$  to the ordinal  $F(A_b)$  such that  $\langle A_b, \prec \rangle \cong \langle F(b), \in \rangle$ . We know that this ordinal is unique as non-identical segments have differing sizes. We let  $Z = \text{ran}(F)$ :

$$Z = \{F(b) : \exists b \in A, \exists \text{ an isomorphism } g_b \text{ from } \langle A_b, \prec \rangle \text{ to } \langle F(b), \in \rangle\},$$

noting that the isomorphism between  $A_b$  and  $F(b)$  is unique. If  $c, b$  are in  $A$  with  $c \prec b$  then  $A_c = (A_b)_c$  implying that  $F(c) \neq F(b)$  so  $F$  is injective and thus bijective between  $A$  and  $Z$ . Continuing with  $c \prec b$ :

$$g_b \upharpoonright A_c : \langle A_c, \prec \rangle \cong \langle (F(b))_{g_b(c)}, \in \rangle,$$

by the uniqueness of order isomorphisms  $(g_b \upharpoonright A_c) = g_c$  and  $F(c) = (F(b))_{g_b(c)}$ . Thus,  $F(c) \in F(b)$ .

We know that  $Z$  is well-ordered by  $\in$  as  $A$  is well-ordered by  $\prec$  and  $F$  is an order isomorphism. For  $u \in F(b) \in Z$ , as  $g_b$  is surjective,  $u = g_b(c)$  for some  $c \prec b$ . Then,  $u = F(b)_u = F(b)_{g_b(c)} = F(c)$ . Hence,  $u$  is in  $Z$ , so  $Z$  is transitive. Thus,  $Z$  is an ordinal.  $\square$

## 5.9 Representation Theorem for Well-orderings

Every well-ordering is order isomorphic to exactly one ordinal.

*Proof.* For a well-ordering  $\langle X, \prec \rangle$ , we know that if it is isomorphic to an ordinal, this is the only such ordinal. We take:

$$Z = \{v \in X : X_v \text{ is not isomorphic to an ordinal}\},$$

and want to show it's empty as this will suffice combined with our criterion. Supposing the contrary, we take  $v_0$  to be the  $\prec$ -least element of  $Z$ . We have that  $\langle X_{v_0}, \prec \rangle$  is a well-ordering with each element preceding  $v_0$ , as such  $(X_{v_0})_w = X_w$  for each  $w$  in  $X_{v_0}$  is order isomorphic to an ordinal. Which means  $X_{v_0}$  must also be order isomorphic to an ordinal via our criterion, a contradiction. Thus,  $Z$  is empty, as required.  $\square$

## 5.10 Order Type of Well-orderings

For a well-ordering  $\langle X, \prec \rangle$ , the order type of  $\langle X, \prec \rangle$  is the unique ordinal isomorphic to  $\langle X, \prec \rangle$ , written as  $\text{ot}(\langle X, \prec \rangle)$ .

## 5.11 Classification Theorem for Well-orderings

For two well-orderings  $\langle A, \prec_A \rangle$  and  $\langle B, \prec_B \rangle$  we have that exactly one of the following holds:

- $\langle A, \prec_A \rangle \cong \langle B, \prec_B \rangle$ ,
- There exists  $b$  in  $B$  such that  $\langle A, \prec_A \rangle \cong \langle B_b, \prec_B \rangle$ ,
- There exists  $a$  in  $A$  such that  $\langle A_a, \prec_A \rangle \cong \langle B, \prec_B \rangle$ .

*Proof.* We take  $\langle X, \in \rangle$  and  $\langle Y, \in \rangle$  to be the unique ordinals isomorphic to  $\langle A, \prec_A \rangle$  and  $\langle B, \prec_B \rangle$  (resp.) via maps:

$$\begin{aligned} f : \langle X, \in \rangle &\rightarrow \langle A, \prec_A \rangle, \\ g : \langle Y, \in \rangle &\rightarrow \langle B, \prec_B \rangle. \end{aligned}$$

We know that either these ordinals are order isomorphic or order isomorphic to an initial segment of the other. If the former is true, then we have that our well-orderings are isomorphic via  $f$  and  $g$  and their inverses. If the latter is true, we know that (without loss of generality)  $\langle X, \in \rangle \cong \langle Y_y, \in \rangle$  for some  $y$  in  $Y$ . Thus:

$$f(\langle X, \in \rangle) \cong g(\langle Y_y, \in \rangle) \implies \langle A, \prec_A \rangle \cong \langle B_{g(y)}, \prec_B \rangle,$$

as required.  $\square$

## 6 Properties of Ordinals

We collate the properties of ordinals covered so far for some ordinals  $\alpha$ ,  $\beta$ , and  $\gamma$ :

- Ordinals are transitive,
- Ordinals are well-ordered by  $\in$ ,
- $\alpha \in \beta \in \gamma$  implies that  $\alpha \in \gamma$ ,
- If  $X \in \alpha$  then  $X$  is an ordinal with  $X = \alpha_X$ ,
- If  $\alpha \cong \beta$  then  $\alpha = \beta$ ,
- Exactly one of the following holds:
  - $\alpha = \beta$ ,
  - $\alpha \in \beta$ ,
  - $\beta \in \alpha$ .

### 6.1 Principle of Transfinite Induction

For  $\Phi$  a well-defined and definite property of ordinals, we have that for all ordinals  $\alpha$ :

$$[\forall \beta < \alpha, \Phi(\beta) \Rightarrow \Phi(\alpha)] \Rightarrow [\Phi(\alpha)].$$

Hence, the class of ordinals is well-ordered.

*Proof.* We consider  $C = \{\alpha \text{ an ordinal} : \neg\Phi(\alpha)\}$  and suppose it's non-empty. We take  $\alpha_0$  in  $C$ , if it is not the least element we have that  $\alpha_0 \cap C$  is non-empty as there is some  $\beta$  in  $C$  with  $\beta < \alpha_0$  which is equivalent to saying that  $\beta \in \alpha_0$ . As  $\alpha_0$  is an ordinal, we have that  $\alpha_0$  is well-ordered by  $\in$ , hence  $C \cap \alpha_0 \subseteq \alpha_0$  has an  $\in$ -least element  $\alpha_1$  which is the least element of  $C$ .

Thus, we have that  $\neg\Phi(\alpha_1)$  holds, but as this is the least element of  $C$ , for all ordinals  $\beta$  less than  $\alpha_1$  we have that  $\Phi(\beta)$  holds. However, by our antecedent, this means  $\Phi(\alpha_1)$  holds, a contradiction. Thus,  $C$  is empty as required.

Note that our argument showed that any non-empty class on the ordinals has a least element. Thus, the class of ordinals is well-ordered by  $\in$ .  $\square$



## 6.2 The Class of Ordinals

The class of ordinals is a proper class.

*Proof.* Suppose the class of ordinals is a set  $z$ . We have that  $\langle z, \in \rangle$  is transitive and well-ordered by  $\in$ . Thus,  $z$  is an ordinal, as such  $z$  is in  $z$ . But, this contradicts the strict ordering of  $\in$ .  $\square$

## 6.3 Sum of Orderings

For  $\langle A, R \rangle$  and  $\langle B, S \rangle$  strict total orderings with  $A \cap B$  empty, we define the sum ordering  $\langle C, T \rangle$  as:

$$C = A \cup B,$$

$$xTy \Leftrightarrow \begin{cases} xRy & \text{for } x, y \in A \\ xSy & \text{for } x, y \in B \\ x \in A \text{ and } y \in B & \text{otherwise.} \end{cases}$$

We can avoid the disjoint constraint by taking the sum of  $\langle A \times \{0\}, R \rangle$  and  $\langle B \times \{1\}, S \rangle$ . We can built this functionality into our operation. We name this operation  $+$ ' and for  $\alpha, \beta$  ordinals:

$$\alpha +' \beta = \text{ot}(\langle \alpha \times \{0\} \cup \beta \times \{1\} \rangle, T),$$

$$\langle \gamma, i \rangle T \langle \delta, j \rangle \Leftrightarrow (i = j \text{ and } \gamma < \delta) \text{ or } (i < j).$$

## 6.4 Product of Orderings

For  $\langle A, R \rangle$  and  $\langle B, S \rangle$  strict total orderings. We define the product of these orderings  $\langle A, R \rangle \times \langle B, S \rangle$  to be the ordering  $\langle C, U \rangle$ :

$$C = A \times B$$

$$\langle x, y \rangle U \langle x', y' \rangle \Leftrightarrow (ySy') \text{ or } (y = y' \text{ and } xRx'),$$

taking the latter and replacing each member by the former. We can again construct an operation for ordinals  $\alpha$  and  $\beta$ :

$$\alpha \cdot' \beta = \text{ot}(\langle A \times B, U \rangle),$$

with  $U$  defined as above.

## 6.5 Supremum of Ordinals

For a set of ordinals  $A$ ,  $\sup(A)$  is the least ordinal  $\gamma$  such that for all  $\delta$  in  $A$ ,  $\delta \leq \gamma$ . Furthermore, we have the strict supremum  $\sup^+(A)$  as the least ordinal  $\gamma^+$  such that for all  $\delta$  in  $A$ ,  $\delta < \gamma^+$ .

We can also write  $\sup(A) = \bigcup A$ .

*Proof.* If we suppose there isn't an ordinal which is an upper bound for  $A$ , there's some  $\delta$  in  $A$  such that  $\delta > \gamma$  for each ordinal  $\gamma$ . But,  $\bigcup A$  must be a set and equal to the set of ordinals, a contradiction.

Take  $S = \sup(A)$  and take  $u$  in  $\bigcup A$ . For some  $a$  in  $A$ ,  $u < a < A$ , so  $u < S$  and so  $u$  is in  $S$ ,  $\bigcup A \subseteq S$ . Conversely, we consider  $s$  in  $S$ , then  $s < S = \sup(A)$  so there is some  $a$  in  $A$  with  $s < a \leq S$ . Thus,  $s$  is in  $A$  so  $s$  is in  $\bigcup A$ ,  $S \subseteq \bigcup A$ . Thus  $S = \bigcup A$ .  $\square$

## 6.6 Types of Ordinals

We can consider three types of ordinals:

- The zero ordinal, 0,
- Successor ordinals, ordinals with immediate predecessors,
- Limit ordinals, ordinals that are not of the other types.

## 6.7 Transfinite Recursion Theorem on Ordinals

For  $F : V \rightarrow V$  a function, there exists a unique function  $H$  from the ordinals to  $V$  such that for all  $\alpha$ :

$$H(\alpha) = F(H \upharpoonright \alpha).$$

*Proof.* We define a function  $u$  to be a  $\delta$ -approximation if  $\text{dom}(u) = \delta$  and for all  $\alpha < \delta$ ,  $u(\alpha) = F(u \upharpoonright \alpha)$ .

### Observations

We consider  $u$  to be a  $\delta$ -approximation. For  $\delta > 0$ , we see that  $u(0) = F(u \upharpoonright 0) = F(\emptyset)$  so a 1-approximation is equal to  $\{\langle 0, F(\emptyset) \rangle\}$  with domain  $\{0\} = 1$ . Additionally, for some  $\gamma < \delta$ ,  $u \upharpoonright \gamma$  is a  $\gamma$ -approximation. Furthermore,  $u \cup \{\langle \delta, F(u) \rangle\}$  is a  $(\delta + 1)$ -approximation. We take  $B = \{u : \exists \delta \text{ such that } u \text{ is a } \delta\text{-approximation}\}$ .

### Agreement on Domain

For  $u$  a  $\delta$ -approximation and  $v$  any  $\gamma$ -approximation with  $\delta < \gamma$ ,  $u = v \restriction \delta$ .

*Proof.* We appeal to the contrary and take  $\tau$  be the least value such that  $u(\tau) \neq v(\tau)$ . Thus,  $(u \restriction \tau = v \restriction \tau)$  but then:

$$u(\tau) = F(u \restriction \tau) = F(v \restriction \tau) = v(\tau),$$

which is a contradiction.  $\square$

### Uniqueness

If such  $H$  exists, it is unique.

*Proof.* We appeal to the contrary, taking  $H'$  to be some differing derivation of  $H$ . We consider the least  $\tau$  such that  $H(\tau) \neq H'(\tau)$  and apply the same reasoning to the above.  $\square$

### Limits

For some limit ordinal  $\lambda$ , if for all  $\alpha < \lambda$  we have that  $u_\alpha$  is an  $\alpha$ -approximation,  $\bigcup_{\alpha < \lambda} u_\alpha$  is a  $\lambda$ -approximation.

*Proof.* This union is a union of an increasing sequence of sets (so  $\alpha < \beta < \lambda \Rightarrow u_\alpha \subseteq u_\beta$ ). As each element is a function, the union is also a function with domain  $\lambda$ . Thus, this union is a  $\lambda$ -approximation.  $\square$

### Existence

We define  $H = \bigcup B$  which is a function with  $\text{dom}(H)$  being the set of ordinals.

*Proof.* We know that  $H$  is a function by **Agreement on Domain**. We take  $C = \{\delta : \text{There's no } \delta\text{-approximation}\}$  and suppose  $C$  is non-empty. By the principle of transfinite induction on the ordinals,  $C$  has a least element  $\psi$ . We know that  $\psi > 1$  as we defined a 1-approximation and by **Limits** it cannot be a limit ordinal. If  $\psi = \mu + 1$  then there's a  $\mu$ -approximation  $v$  by the minimality of  $\psi$ . However, we can extend  $v$  to a  $\psi$ -approximation  $u$  by setting  $u(\mu) = F(v)$ . This is a contradiction.  $\square$

Thus, we have that  $H$  exists and is a unique function as required.  $\square$

## 6.8 Alternative Transfinite Recursion on Ordinals

For  $a$  in  $V$  and  $F_0, F_1 : V \rightarrow V$  functions, there's a unique function  $H$  from the set of ordinals to  $V$  such that:

$$\begin{aligned} H(0) &= a, \\ \text{succ}(\alpha) &\implies H(\alpha) = F_0(H(\beta)) \text{ where } \alpha = \beta + 1, \\ \text{lim}(\alpha) &\implies H(\alpha) = F_1(H \upharpoonright \alpha). \end{aligned}$$

*Proof.* We define  $F : V \rightarrow V$  by:

$$F(u) = \begin{cases} a & \text{for } u = \emptyset \\ F_0(u) & \text{if } u \text{ is a function with a successor domain} \\ F_1(u) & \text{if } u \text{ is a function with a limit domain} \\ \emptyset & \text{otherwise,} \end{cases}$$

and apply the previous recursion theorem. □

## 6.9 Ordinal Addition

We define ordinal addition  $A_\alpha$  for some successor ordinal  $\beta + 1$  and limit ordinal  $\lambda$  as:

$$\begin{aligned} A_\alpha(0) &= \alpha + 0 = \alpha, \\ A_\alpha(\beta + 1) &= S(A_\alpha(\beta)) = A_\alpha(\beta) + 1, \\ A_\alpha(\lambda) &= \sup(\{A_\alpha(x) : x < \lambda\}). \end{aligned}$$

## 6.10 Ordinal Multiplication

We define ordinal multiplication  $M_\alpha$  for some successor ordinal  $\beta + 1$  and limit ordinal  $\lambda$  as:

$$\begin{aligned} M_\alpha(0) &= 0, \\ M_\alpha(\beta + 1) &= M_\alpha(\beta) + \alpha, \\ M_\alpha(\lambda) &= \sup(\{M_\alpha(x) : x < \lambda\}). \end{aligned}$$

## 6.11 Ordinal Exponentiation

We define ordinal exponentiation  $A_\alpha$  for some successor ordinal  $\beta + 1$  and limit ordinal  $\lambda$  as:

$$\begin{aligned} E_\alpha(0) &= 1, \\ E_\alpha(\beta + 1) &= E_\alpha(\beta) \cdot \alpha, \\ E_\alpha(\lambda) &= \sup(\{E_\alpha(x) : x < \lambda\}). \end{aligned}$$

## 6.12 Monotonicity of $A_\alpha$

The functions  $A_\alpha$  are strictly increasing and thus injective.

*Proof.* We consider  $\beta, \gamma, \delta$  ordinals with:

$$[\beta < \gamma] \implies [A_\alpha(\beta) < A_\alpha(\gamma)], \quad (1)$$

for all  $\gamma \leq \delta$ . The base case is trivial, we consider  $\delta + 1$ . For  $\beta < \delta + 1$ , if  $\beta = \delta$ , then:

$$\begin{aligned} A_\alpha(\delta) &= A_\alpha(\beta) \\ &< A_\alpha(\beta + 1) \\ &= S(A_\alpha(\beta)) \\ &= S(A_\alpha(\delta)). \end{aligned}$$

Otherwise,  $\beta < \delta$  so by our hypothesis:

$$\begin{aligned} A_\alpha(\beta) &< A_\alpha(\delta) \\ &< S(A_\alpha(\delta)) \\ &= A_\alpha(\delta + 1). \end{aligned}$$

Now, we suppose (1) holds for all  $\gamma < \lambda$  for some limit ordinal  $\lambda$ . For  $\beta < \lambda$ , clearly  $\beta < \beta + 1 < \lambda$  as  $\lambda$  has no immediate predecessor. By the hypothesis:

$$\begin{aligned} A_\alpha(\beta) &< A_\alpha(\beta + 1) \\ &\leq \sup(\{A_\alpha(\gamma) : \gamma < \lambda\}) \\ &= A_\alpha(\lambda), \end{aligned}$$

as required. □

Similarly, both  $M_\alpha$  and  $E_\alpha$  are strictly increasing, for ordinals  $\alpha, \beta, \gamma$  with  $\beta > \gamma$ :

- If  $\alpha > 0$  then  $M_\alpha(\beta) < M_\alpha(\gamma)$ ,
- If  $\alpha > 1$  then  $E_\alpha(\beta) < E_\alpha(\gamma)$ .