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3 MIKULÁŠ MRVA

4 REFLECTION PRINCIPLES AND LARGE
5 CARDINALS
6 Bakalářská práce

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¹⁰ Prohlašuji, že jsem bakalářskou práci vypracoval samostatně a že jsem uvedl
¹¹ všechny použité prameny a literaturu.

¹² V Praze 22. května 2016

Abstract

Práce zkoumá vztah tzv. principů reflexe a velkých kardinálů. Lévy ukázal, že v ZFC platí tzv. věta o reflexi a dokonce, že věta o reflexi je ekvivalentní schématu nahrazení a axiomu nekonečna nad teorií ZFC bez axiomu nekonečna a schématu nahrazení. Tedy lze na větu o reflexi pohlížet jako na svého druhu axiom nekonečna. Práce zkoumá do jaké míry a jakým způsobem lze větu o reflexi zobecnit a jaký to má vliv na existenci tzv. velkých kardinálů. Práce definuje nedosažitelné, Mahlovy a nepopsatelné kardinály a ukáže, jak je lze zavést pomocí reflexe. Přirozenou limitou kardinálů získaných reflexí jsou kardinály nekonzistentní s L. Práce nabídne intuitivní zdůvodnění, proč tomu tak je.

Abstract

This thesis aims to examine relations between the so called Reflection Principles and Large cardinals. Lévy has shown that the Reflection Theorem is a sound theorem of ZF and it is equivalent to the Replacement Scheme and the Axiom of Infinity. From this point of view, Reflection theorem can be seen a specific version of an Axiom of Infinity. This paper aims to examine the Reflection Principle and its generalisations with respect to the existence of Large Cardinals. This thesis will establish the Inaccessible, Mahlo and Indescribable cardinals and show how can those be defined via reflection. A natural limit of Large Cardinals obtained via reflection are cardinals inconsistent with L. This thesis will offer an intuitive explanation of why this holds.

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1 Introduction

1.1 Motivation and Origin

“The Universe of sets cannot be uniquely characterised (i. e. distinguished from all its initial elements) by any internal structural property of the membership relation in it, which is expressible in any logic of finite or transfinite type, including infinitary logics of any cardinal order.”

— Kurt Gödel [Wang, 1997]

1.2 Notation and Terminology

1.2.1 The Language of Set Theory

This text assumes the knowledge of basic terminology and some results from first-order predicate logic.¹

We will now shortly review the basic notions that allow us to define the *Zermelo–Fraenkel* set theory.

When we talk about *class*, we have the notion of definable class in mind. If $\varphi(x, p_1, \dots, p_n)$ is a formula in the language of set theory, we call

$$A = \{x : \varphi(x)\} \tag{1.1}$$

a class of all sets satisfying $\varphi(x)$ in a sense that

$$x \in A \leftrightarrow \varphi(x) \tag{1.2}$$

Given classes A, B , one can easily define the elementary set operations such as $A \cap B$, $A \cup B$, $A \setminus B$, $\bigcup A$, see the first part of [Jech, 2006] for details. Axioms are the tools by which we can decide whether a particular class is “small enough” to be considered a set². A class that fails to be considered a set is called a *proper class*.

We will often write “ M is a limit ordinal”, it should always be clear that this can be rewritten as a formula that was introduced earlier.

77

¹todo odkaz na pripadny zdroj? svejdar? neco en?

²“Small enough” means that it doesn’t introduce a paradox similar to Russell’s.

78 **1.2.2 The Axioms**79 **Definition 1.1** (*The Existence of a Set*)

$$\exists x(x = x) \quad (1.3)$$

80 **Definition 1.2** (*Axiom of Extensionality*)

$$\forall x, y(x = y \leftrightarrow \forall z(z \in x \leftrightarrow z \in y)) \quad (1.4)$$

81 **Definition 1.3** (*Axiom Schema of Specification*)82 *The following yields an axiom for every first-order formula $\varphi(x, p_1, \dots, p_n)$*
83 *with no free variables other than x, p_1, \dots, p_n .*

$$\forall x, p_1, \dots, p_n \exists y \forall z(z \in y \leftrightarrow z \in x \ \& \ \varphi(z, p_1, \dots, p_n)) \quad (1.5)$$

84 We will now provide two definitions that are not axioms, but will be
85 helpful in establishing some axioms in a more comprehensible way.86 **Definition 1.4** ($x \subseteq y, x \subset y$)

$$x \subseteq y \leftrightarrow (\forall z \in x) z \in y \quad (1.6)$$

87

$$x \subset y \leftrightarrow x \subseteq y \ \& \ x \neq y \quad (1.7)$$

88 *We read $x \subseteq y$ as x is a subset of y and $x \subset y$ as x is a proper subset of y .*89 **Definition 1.5** (*Empty Set*) *For an arbitrary set x , the empty set, repre-*
90 *sented by the symbol " \emptyset ", is defined by the following formula:*

$$(\forall y \in x)(y \in \emptyset \leftrightarrow \neg(y = y)) \quad (1.8)$$

91 \emptyset is a set due to Specification. While the empty set could also be defined by
92 the formula $\forall y(y \in \emptyset \leftrightarrow \neg(y = y))$, the version we use is Δ_0 , which we will find
93 useful later. The two definitions yield the same set for every x given because
94 of Extensionality.95 **Definition 1.6** (*Axiom of Pairing*)

$$\forall x, y \exists z \forall q(q \in z \leftrightarrow q = x \vee q = y) \quad (1.9)$$

96 **Definition 1.7** (*Axiom of Union*)

$$\forall x \exists y \forall z(z \in y \leftrightarrow \exists q(z \in q \ \& \ q \in x)) \quad (1.10)$$

97 Now we can introduce more axioms.

98 **Definition 1.8** (*Axiom of Foundation*)

$$\forall x(x \neq \emptyset \rightarrow (\exists y \in x)(x \cap y = \emptyset)) \quad (1.11)$$

99 **Definition 1.9** (*Axiom of Powerset*)

$$\forall x \exists y \forall z (z \in y \leftrightarrow z \subseteq x) \quad (1.12)$$

100 **Definition 1.10** (*Axiom of Infinity*)

$$\exists x(\emptyset \in x \ \& \ (\forall y \in x)(y \cup \{y\} \in x)) \quad (1.13)$$

101 *The least set satisfying this is denoted “ ω ”.*

102 Let us introduce a few more definitions that will make the two remaining
103 axioms more comprehensible.

104 **Definition 1.11** (*Powerset Function*)

105 *Given a set x , the powerset of x , denoted $\mathcal{P}(x)$ and satisfying 1.9, is defined*
106 *as follows:*

$$\mathcal{P}(x) \stackrel{\text{def}}{=} \{y : y \subseteq x\} \quad (1.14)$$

107 **Definition 1.12** (*Function*)

108 *Given arbitrary first-order formula $\varphi(x, y, p_1, \dots, p_n)$, we say that φ is a func-*
109 *tion iff*

$$\forall x, y, z, p_1, \dots, p_n (\varphi(x, y, p_1, \dots, p_n) \ \& \ \varphi(x, z, p_1, \dots, p_n) \rightarrow y = z) \quad (1.15)$$

110 When a $\varphi(x, y)$ is a function, we also write the following:

$$f(x) = y \leftrightarrow \varphi(x, y) \quad (1.16)$$

111 Alternatively, $f = \{\langle x, y \rangle : \varphi(x, y)\}$ is a class.

112 **Definition 1.13** (*Domain of a Function*)

113 *Let f be a function. We call the domain of f the set of all sets for which f*
114 *yields a value. We use “ $\text{Dom}(f)$ ” to refer to this set.*

$$x \in \text{Dom}(f) \leftrightarrow \exists y(f(x) = y) \quad (1.17)$$

115 We say “ f is a function on A ”, A being a class, if $A = \text{dom}(f)$.

116 **Definition 1.14** (*Range of a Function*)

117 *Let f be a function. We call the range of f the set of all sets that are images*
118 *of other sets via f . We use “ $\text{Rng}(f)$ ” to refer to this set.*

$$x \in \text{Rng}(f) \leftrightarrow \exists y(f(y) = x) \quad (1.18)$$

119 We say that f is a *function into* A , A being a class, if $\text{rng}(f) \subseteq A$. We say
 120 that f is a *function onto* A if $\text{rng}(f) = A$. We say a function f is a *one to one*
 121 *function*, iff

$$(\forall x_1, x_2 \in \text{dom}(f))(f(x_1) = f(x_2) \rightarrow x_1 = x_2) \quad (1.19)$$

122 We say that f is a *bijection* iff it is a one to one function that is onto.

123 Note that $\text{Dom}(f)$ and $\text{Rng}(f)$ are not definitions in a strict sense, they
 124 are in fact definition schemas that yield definitions for every function f given.
 125 Also note that they can be easily modified for φ instead of f , with the only
 126 difference being the fact that it is then defined only for those φ s that are
 127 functions, which must be taken into account. This is worth noting as we will
 128 use the notions of *function* and *formula* interchangeably.

129 **Definition 1.15** (*Function Defined For All Ordinals*)

130 We say a function f is defined for all ordinals, this is sometimes written
 131 $f : \text{Ord} \rightarrow A$ for any class A , if $\text{Dom}(f) = \text{Ord}$. Alternatively,

$$(\forall \alpha \in \text{Ord})(\exists y \in A)(f(\alpha) = y) \quad (1.20)$$

132 And now for the axioms.

133 **Definition 1.16** (*Axiom Schema of Replacement*)

134 The following is an axiom for every first-order formula $\varphi(x, p_1, \dots, p_n)$ with
 135 no free variables other than x, p_1, \dots, p_n .

$$“\varphi \text{ is a function}” \rightarrow \forall x \exists y \forall z (z \in y \leftrightarrow (\exists q \in x)(\varphi(x, y, p_1, \dots, p_n))) \quad (1.21)$$

136 **Definition 1.17** (*Choice*)

137

$$\begin{aligned} &\forall x \exists f ((f \text{ is a choice function with } \text{dom}(f) = x \setminus \{\emptyset\}) \\ &\quad \& \forall y ((y \in x \& y \neq \emptyset) \rightarrow f(y) \in y)) \end{aligned} \quad (1.22)$$

138 We will refer to the axioms by their name, written in italic type, e.g.
 139 *Foundation* refers to the Axiom of Foundation. Now we need to define the
 140 set theories to be used in the article.

141 **Definition 1.18** (**S**)

142 We call **S** an axiomatic theory in the language $\mathcal{L} = \{=, \in\}$ with exactly the
 143 following axioms:

- 144 (i) Existence of a set (see 1.1)
- 145 (ii) Extensionality (see 1.2)
- 146 (iii) Specification (see 1.3)

- 147 (iv) Foundation (see 1.8)
- 148 (v) Pairing (see 1.6)
- 149 (vi) Union (see 1.7)
- 150 (vii) Powerset (see 1.9)

151 **Definition 1.19** (ZF)

152 We call ZF an axiomatic theory in the language $\mathcal{L} = \{=, \in\}$ that contains
 153 all the axioms of S in addition to the following:

- 154 (i) Replacement schema (see 1.16)
- 155 (ii) Infinity (see 1.10)
- 156 Existence of a set is usually left out because it is a consequence of infinity.

157 **Definition 1.20** (ZFC)

158 ZFC is an axiomatic theory in the language $\mathcal{L} = \{=, \in\}$ that contains all the
 159 axioms of ZF plus Choice (1.17).

160

161 **1.2.3 The Transitive Universe**

162 **Definition 1.21** (Transitive Class)

163 We say a class A is transitive iff

$$(\forall x \in A)(x \subseteq A) \quad (1.23)$$

164 **Definition 1.22** (Well Ordered Class) A class A is said to be well ordered
 165 by \in iff the following hold:

- 166 (i) $(\forall x \in A)(x \not\subseteq x)$ (Antireflexivity)
- 167 (ii) $(\forall x, y, z \in A)(x \in y \ \& \ y \in z \rightarrow x \in z)$ (Transitivity)
- 168 (iii) $(\forall x, y \in A)(x = y \vee x \in y \vee y \in x)$ (Linearity)
- 169 (iv) $(\forall x \subseteq A)(x \neq \emptyset \rightarrow (\exists y \in x)(\forall z \in x)(z = y \vee z \in y))$ (Existence of the
 170 least element)

171 **Definition 1.23** (Ordinal Number)

172 A set x is said to be an ordinal number if it is transitive and well-ordered
 173 by \in .

174 For the sake of brevity, we usually just say “ x is an ordinal”. Note that
 175 “ x is an ordinal” is a well-defined formula in the language of set theory, since
 176 1.21 is a first-order formula and 1.22 is in fact a conjunction of four first-
 177 order formulas. Ordinals will be usually denoted by lower case greek letters,
 178 starting from the beginning of the alphabet: $\alpha, \beta, \gamma, \dots$. Given two different
 179 ordinals α, β , we will write $\alpha < \beta$ for $\alpha \in \beta$, see Lemma 2.11 in [Jech, 2006]
 180 for technical details.

181 **Definition 1.24** (*Non-Zero Ordinal*) We say an ordinal α is non-zero iff
 182 $\alpha \neq \emptyset$.

183 **Definition 1.25** (*Successor Ordinal*)
 184 Consider the following function defined for all ordinals. Let β be an arbitrary
 185 ordinal. We call S the successor function.

$$S(\beta) = \beta \cup \{\beta\} \quad (1.24)$$

186 An ordinal α is called a successor ordinal iff there is an ordinal β , such that
 187 $\alpha = S(\beta)$. We also write $\alpha = \beta + 1$.

188 **Definition 1.26** (*Limit Ordinal*)
 189 A non-zero ordinal α is called a limit ordinal iff it is not a successor ordinal.

190 **Definition 1.27** (*Ord*)
 191 The class of all ordinal numbers, which we will denote “ Ord ”³ is the proper
 192 class defined as follows.

$$x \in \text{Ord} \leftrightarrow x \text{ is an ordinal} \quad (1.25)$$

193 **Definition 1.28** (*Von Neumann’s Hierarchy*)
 194 The Von Neumann’s Hierarchy is a collection of sets indexed by elements of
 195 Ord , defined recursively in the following way:

$$(i) \quad V_0 = \emptyset \quad (1.26)$$

$$(ii) \quad V_{\alpha+1} = \mathcal{P}(V_\alpha) \text{ for any ordinal } \alpha \quad (1.27)$$

$$(iii) \quad V_\lambda = \bigcup_{\beta < \lambda} V_\beta \text{ for a limit ordinal } \lambda \quad (1.28)$$

196 We will also refer to the Von Neumann’s Hierarchy as Von Neumann’s Uni-
 197 verse or the Cumulative Hierarchy.

198 **Definition 1.29** (*Rank*)
 199 Given a set x , we say that the rank of x (written as $\text{rank}(x)$) is the least
 200 ordinal α such that $x \in V_{\alpha+1}$

201 Due to *Regularity*, every set has a rank.⁴

202

³Other authors use “ On ”, we will stick to the notation used in [Jech, 2006]

⁴See chapter 6 of [Jech, 2006] for details.

1.2.4 Cardinal Numbers

Definition 1.30 (Cardinality)

Given a set x , let the cardinality of x , written $|x|$, be defined as the smallest ordinal number such that there is a one to one mapping from x to α .

Definition 1.31 (Aleph function)

Let ω be the set defined by ω . We will recursively define the function \aleph for all ordinals.

(i) $\aleph_0 = \omega$

(ii) $\aleph_{\alpha+1}$ is the least cardinal larger than \aleph_α ⁵

(iii) $\aleph_\lambda = \bigcup_{\beta < \lambda} \aleph_\beta$ for a limit ordinal λ

If $\kappa = \aleph_\alpha$ and α is a successor ordinal, we call κ a successor cardinal. If α is a limit ordinal, we call κ a limit cardinal.

Definition 1.32 (Cardinal number)

(i) A set x is called a finite cardinal iff $x \in \omega$.

(ii) A set is called an infinite cardinal iff there is an ordinal α such that $\aleph_\alpha = x$

(iii) A set is called a cardinal iff it is either a finite cardinal or an infinite cardinal.

We say κ is an uncountable cardinal iff it is an infinite ordinal and $\aleph_0 < \kappa$. Infinite cardinals will be notated by lowercase greek letters from the middle of the alphabet, e.g. κ, μ, ν, \dots ⁶

For formal details as well as why every set can be well-ordered assuming *Choice*, and therefore has a cardinality, see [Jech, 2006].

Definition 1.33 (Sequence)

We say that a function $\varphi(x, y)$ is a sequence iff there is an ordinal α such that $\text{dom}(\varphi) = \alpha$. In other words, a function is called a sequence if it is defined exactly for every ordinal from 0 to some α . We then say it is an α -sequence. We usually write $\langle \beta_i : i \in \alpha \rangle$ or $\langle \beta_0, \beta_1, \dots \rangle$ when referring to a sequence, ξ_i denote the elements of $\text{rng}(\varphi)$ for every $i \in \text{dom}(\varphi)$.

Definition 1.34 (Cofinal Subset)

Given a class A , we say that $B \subseteq A$ is cofinal in A iff

$$(\forall x \in A)(\exists y \in B)(x \in y) \quad (1.29)$$

⁵“The least cardinal larger than \aleph_α ” is sometimes notated as \aleph_α^+

⁶Except λ which is preferably used for limit ordinals.

235 **Definition 1.35** (*Cofinality of a Limit Ordinal*)

236 *Let λ be a limit ordinal. We say that the cofinality of λ is κ iff κ is the least*
 237 *cardinal, such that there is a cofinal κ -sequence $\langle \beta_\xi : \xi < \kappa \rangle$, such that*

$$\sup(\{\beta_\xi : \xi < \kappa\}) = \lambda \quad (1.30)$$

238 *We write $cf(\lambda) = \kappa$.*

239 **Definition 1.36** (*Regular Cardinal*)

240 *We say a cardinal κ is regular iff $cf(\kappa) = \kappa$*

241 **Definition 1.37** (*Strong Limit Cardinal*)

242 *We say that an ordinal κ is a strong limit cardinal if it is a limit cardinal*
 243 *and*

$$(\forall \alpha \in \kappa)(\mathcal{P}(\alpha) \in \kappa) \quad (1.31)$$

244 **Definition 1.38** (*Generalised Continuum Hypothesis*)

245

$$\aleph_{\alpha+1} = \mathcal{P}(\aleph_\alpha) \quad (1.32)$$

246 *If GCH holds (for example in Gödel's L , see chapter 3), the notions of limit*
 247 *cardinal and strong limit cardinal are equivalent.*

248

249 1.2.5 Relativisation and Absoluteness

250 **Definition 1.39** (*Relativization*)

251 *Let M be a class, $R \subseteq M \times M$ and let $\varphi(p_1, \dots, p_n)$ be a first-order formula*
 252 *with no free variables besides p_1, \dots, p_n . The relativization of φ to M and R*
 253 *is the formula, written as $\varphi^{M,R}(p_1, \dots, p_n)$, defined in the following inductive*
 254 *manner:*

- 255 (i) $(x \in y)^{M,R} \leftrightarrow R(x, y)$
- 256 (ii) $(x = y)^{M,R} \leftrightarrow x = y$
- 257 (iii) $(\neg \varphi)^{M,R} \leftrightarrow \neg \varphi^{M,R}$
- 258 (iv) $(\varphi \ \& \ \psi)^{M,R} \leftrightarrow \varphi^{M,R} \ \& \ \psi^{M,R}$
- 259 (v) $(\varphi \vee \psi)^{M,R} \leftrightarrow \varphi^{M,R} \vee \psi^{M,R}$
- 260 (vi) $(\varphi \rightarrow \psi)^{M,R} \leftrightarrow \varphi^{M,R} \rightarrow \psi^{M,R}$
- 261 (vii) $(\exists x \varphi(x))^{M,R} \leftrightarrow (\exists x \in M) \varphi^{M,R}(x)$
- 262 (viii) $(\forall x \varphi(x))^{M,R} \leftrightarrow (\forall x \in M) \varphi^{M,R}(x)$

263 *When $R = \in \cap (M \times M)$, we usually write φ^M instead of $\varphi^{M,R}$. When we talk*
 264 *about $\varphi^M(p_1, \dots, p_n)$, it is understood that $p_1, \dots, p_n \in M$. We will also use*
 265 *$M \models \varphi(p_1, \dots, p_n)$ and $\varphi^M(p_1, \dots, p_n)$ interchangeably.*

Definition 1.40 (*Absoluteness*) Given a transitive class M , we say a formula φ is absolute in M if for all $p_1, \dots, p_n \in M$

$$\varphi^M(p_1, \dots, p_n) \leftrightarrow \varphi(p_1, \dots, p_n) \quad (1.33)$$

Definition 1.41 (*Hierarchy of First-Order Formulas*)

- (I) A first-order formula φ is Δ_0 iff it is logically equivalent to a first-order formula φ' satisfying any of the following:
- (i) φ' contains no quantifiers
 - (ii) y is a set, ψ is a Δ_0 formula, and φ' is either $(\exists x \in y)\psi(y)$ or $(\forall x \in y)\psi(y)$.
 - (iii) ψ_1, ψ_2 are Δ_0 formulas and φ' is any of the following: $\psi_1 \vee \psi_2$, $\psi_1 \& \psi_2$, $\psi_1 \rightarrow \psi_2$, $\neg\psi_2$,
- (II) If a formula is Δ_0 it is also Σ_0 and Π_0
- (III) A formula φ is $\Pi_n + 1$ if it is logically equivalent to a formula φ' such that $\varphi' = \forall x\psi$ where ψ is a Σ_n -formula for any $n < \omega$.
- (IV) A formula φ is $\Sigma_n + 1$ if it is logically equivalent to a formula φ' such that $\varphi' = \forall x\psi$ where ψ is a Π_n -formula for any $n < \omega$.

Note that we can use the pairing function so that for $\forall p_1, \dots, p_n \psi(p_1, \dots, p_n)$, there is a logically equivalent formula of the form $\forall x\psi'(x)$.

Lemma 1.42 (Δ_0 absoluteness) Let φ be a Δ_0 formula, then φ is absolute in any transitive class M .

Proof. This will be proven by induction over the complexity of a given Δ_0 formula φ . Let M be an arbitrary transitive class.

Atomic formulas are always absolute by the definition of relativisation, see 1.39. Suppose that Δ_0 formulas ψ_1 and ψ_2 are absolute in M . Then from relativization, $(\psi_1 \& \psi_2)^M \leftrightarrow \psi_1^M \& \psi_2^M$, which is, from the induction hypothesis, equivalent to $\psi_1 \& \psi_2$. The same holds for \vee, \rightarrow, \neg .

Suppose that a Δ_0 formula ψ is absolute in M . Let y be a set and let $\varphi = (\exists x \in y)\psi(x)$. From relativization, $(\exists x\psi(x))^M \leftrightarrow (\exists x \in M)\psi^M(x)$. Since the hypotheses makes it clear that $\psi^M \leftrightarrow \psi$, we get $((\exists x \in y)\psi(x))^M \leftrightarrow (\exists x \in y \cap M)\psi(x)$, which is the equivalent of $\varphi^M \leftrightarrow \varphi$. The same applies to $\varphi = (\forall x \in y)\psi(x)$. \square

Lemma 1.43 (*Downward Absoluteness*)

Let φ be a Π_1 formula and M a transitive class. Then the following holds:

$$(\forall p_1, \dots, p_n \in M)(\varphi(p_1, \dots, p_n) \rightarrow \varphi(p_1, \dots, p_n)^M) \quad (1.34)$$

299 *Proof.* Since $\varphi(p_1, \dots, p_n)$ is Π_1 , there is a Δ_0 formula $\psi(p_1, \dots, p_n, x)$ such
 300 that $\varphi = \forall x \psi(p_1, \dots, p_n, x)$. From relativization and lemma 1.42, $\varphi^M(p_1, \dots, p_n) \leftrightarrow$
 301 $(\forall x \in M) \psi(p_1, \dots, p_n, x)$.

302 Assume that for $p_1, \dots, p_n \in M$ fixed, that $\forall x \psi(p_1, \dots, p_n, x)$ holds, but
 303 $(\forall x \in M) \psi(p_1, \dots, p_n, x)$ does not. Therefore $\exists x \neg \psi(p_1, \dots, p_n, x)$, which
 304 contradicts $\forall x \psi(p_1, \dots, p_n, x)$. \square

305 **Lemma 1.44** (*Upward Absoluteness*)

306 *Let φ be a Σ_1 formula and M a transitive class. Then the following holds:*

$$(\forall p_1, \dots, p_n \in M)(\varphi^M(p_1, \dots, p_n) \rightarrow \varphi(p_1, \dots, p_n)) \quad (1.35)$$

307 *Proof.* Since $\varphi(p_1, \dots, p_n)$ is Σ_1 , there is a Δ_0 formula $\psi(p_1, \dots, p_n, x)$ such
 308 that $\varphi = \exists x \psi(p_1, \dots, p_n, x)$. From relativization and lemma 1.42, $\varphi^M(p_1, \dots, p_n) \leftrightarrow$
 309 $(\exists x \in M) \psi(p_1, \dots, p_n, x)$.

310 Assume that for $p_1, \dots, p_n \in M$ fixed, that $(\exists x \in M) \psi(p_1, \dots, p_n, x)$
 311 holds, but $\exists x \psi(p_1, \dots, p_n, x)$ does not. This is an obvious contradiction. \square

312 1.2.6 More Functions

313 **Definition 1.45** (*Strictly Increasing Function*)

314 *A function $f : \text{Ord} \rightarrow \text{Ord}$ is said to be strictly increasing iff*

$$\forall \alpha, \beta \in \text{Ord} (\alpha < \beta \rightarrow f(\alpha) < f(\beta)). \quad (1.36)$$

315 **Definition 1.46** (*Continuous Function*)

316 *A function $f : \text{Ord} \rightarrow \text{Ord}$ is said to be continuous iff*

$$\lambda \text{ is limit} \rightarrow f(\lambda) = \bigcup_{\alpha < \lambda} f(\alpha). \quad (1.37)$$

317 **Definition 1.47** (*Normal Function*)

318 *A function $f : \text{Ord} \rightarrow \text{Ord}$ is said to be normal iff it is strictly increasing*
 319 *and continuous.*

320 **Definition 1.48** (*Fixed Point*)

321 *We say x is a fixed point of a function f iff $x = f(x)$.*

322 **Definition 1.49** (*Unbounded Class*)

323 *We say a class A is unbounded iff*

$$\forall x (\exists y \in A)(x < y) \quad (1.38)$$

324 **Definition 1.50** (*Limit Point*)

325 *Given a class $x \subseteq \text{Ord}$, we say that $\alpha \neq \emptyset$ is a limit point of x iff*

$$\alpha = \bigcup (x \cap \alpha) \quad (1.39)$$

326 **Definition 1.51** (*Closed Class*)

327 *We say a class $A \subseteq \text{Ord}$ is closed iff it contains all its limit points.*

328 **Definition 1.52** (*Club set*)

329 *For a regular uncountable cardinal κ , a set $x \subset \kappa$ is a closed unbounded*
 330 *subset, abbreviated as a club set, iff x is both closed and unbounded in κ .*

331 **Definition 1.53** (*Stationary set*)

332 *For a regular uncountable cardinal κ , we say a set $A \subset \kappa$ is stationary in κ*
 333 *iff it intersects every club subset of κ .*

334 1.2.7 Structure, Substructure and Embedding

335 Structures will be denoted $\langle M, \in, R \rangle$ where M is a domain, \in stands for the
 336 standard membership relation, it is assumed to be restricted to the domain⁷,
 337 $R \subseteq M$ is a relation on the domain. When R is not needed, we can as well
 338 only write M instead of $\langle M, \in \rangle$.

339 **Definition 1.54** (*Elementary Embedding*)

340 *Given the structures $\langle M_0, \in, R \rangle$, $\langle M_1, \in, R \rangle$ and a one-to-one function $j :$
 341 $M_0 \rightarrow M_1$, we say j is an elementary embedding of M_0 into M_1 , we write
 342 $j : M_0 \prec M_1$, when the following holds for every formula $\varphi(p_1, \dots, p_n)$ and
 343 every $p_1, \dots, p_n \in M_0$:*

$$\langle M_0, \in, R \rangle \models \varphi(p_1, \dots, p_n) \leftrightarrow \langle M_1, \in, R \rangle \models \varphi(j(p_1), \dots, j(p_n)) \quad (1.40)$$

344 **Definition 1.55** (*Elementary Substructure*)

345 *Given the structures $\langle M_0, \in, R \rangle$, $\langle M_1, \in, R \rangle$ and a one-to-one function $j :$
 346 $M_0 \rightarrow M_1$ such that $j : M_0 \prec M_1$, we say that M_0 is an elementary sub-
 347 structure of M_1 , denoted as $M_0 \prec M_1$, iff j is an identity on M_0 . In other
 348 words*

$$\langle M_0, \in, R \rangle \models \varphi(p_1, \dots, p_n) \leftrightarrow \langle M_1, \in, R \rangle \models \varphi(p_1, \dots, p_n) \quad (1.41)$$

349 *for $p_1, \dots, p_n \in M_0$*

⁷To be totally explicit, we should write $\langle M, \in \cap M \times M, R \rangle$

2 Levy's First-Order Reflection

2.1 Lévy's Original Paper

This section is based on Lévy's paper *Axiom Schemata of Strong Infinity in Axiomatic Set Theory*, [Lévy, 1960]. It presents Lévy's general reflection principle and its equivalence to *Replacement* and *Infinity* under S^8 .

First, we should point out that set theory has changed over the last 66 years and show a few notable, albeit only formal, differences. Firstly, when reading Lévy's article, one should bear in mind that while the author often speaks about a model of ZF, usually denoted u , it doesn't necessarily mean that there is a set u that is a model of ZF⁹, we are nowadays used to using the notion of universal class V in similar sense, even though independently from a particular axiomatic set theory. The theory ZF is practically identical to the theory we have established in (1.19), the differences are only formal. One might be confused by the fact that Lévy treats the *Subsets* axiom, which we call *Specification*, as a single axiom rather than a schema. He even takes the conjunction of all axioms of ZF and treats it like a formula. This is possible because the underlying logic calculus is different. Lévy works with set theories formulated in the *non-simple applied first order functional calculus*, see Chapter IV in [Church, 1996] for details. For now, we only need to know that the calculus contains a substitution rule for functional variables. This way, *Subsets* is de facto a schema even though it sometimes treated as a single formula¹⁰. It should also be noted that the logical connectives look different. The now usual symbol for an universal quantifier does not appear, $\forall x\varphi(x)$ would be written as $(x)\varphi(x)$. The symbol for negation is " \sim ", implication is written as " \supset " and equivalence is " \equiv ". We will use standard notation with " \neg ", " \rightarrow " and " \leftrightarrow " respectively when presenting Lévy's results.

This subsection uses ZF instead of the usual ZFC as the underlying theory.

Definition 2.1 (*Standard Complete Model of a Set Theory*)

Let \mathbf{Q} be an arbitrary axiomatic set theory. We say that u is a standard complete model of \mathbf{Q} iff

(i) $(\forall \sigma \in \mathbf{Q})(u \models \sigma)$

(ii) $\forall y(y \in u \rightarrow y \subset u)$

We write $Scm^{\mathbf{Q}}(u)$.

⁸See definition (1.18).

⁹This is indeed impossible to prove in ZF due to Gödel's Incompleteness.

¹⁰This way, the conjunction of all axioms is then in fact an axiom schema.

385 **Definition 2.2** (*Cardinals Inaccessible With Respect to Q*)

386 *Let Q be an arbitrary axiomatic set theory. We say that a cardinal κ is*
 387 *inaccessible with respect to theory Q iff*

$$Scm^Q(V_\kappa) \quad (2.42)$$

388 *We write $In^Q(\kappa)$*

389 **Definition 2.3** (*Inaccessible Cardinal With Respect to ZF*)

390 *When a cardinal κ is inaccessible with respect to ZF, we only say that it is*
 391 *inaccessible. We write $In(\kappa)$.*

$$In(\kappa) \leftrightarrow In^{ZF}(\kappa) \quad (2.43)$$

392 The above definition of inaccessibles is used because it doesn't require *Choice*.

393 For the definition of relativization, see (1.39). The notation used by Lévy
 394 is " $Rel(u, \varphi)$ ", we will stick to " φ^u ".

395 **Definition 2.4** (*N*)

396 *The following is an axiom schema of complete reflection over ZF, denoted as*
 397 *N. For every first-order formula φ in the language of set theory with no free*
 398 *variables except for p_1, \dots, p_n , the following is an instance of schema N.*

$$\exists u(Scm^{ZF}(u) \ \& \ (\forall p_1, \dots, p_n \in u)(\varphi \leftrightarrow \varphi^u)) \quad (2.44)$$

399 Let S be an axiomatic set theory defined in (1.18).

400 **Definition 2.5** (*N₀*)

401 *Axiom schema N₀ is similar to N defined above, but with S instead of ZF.*
 402 *For every φ , a first-order fomula in the language of set theory with no free*
 403 *variables except p_1, \dots, p_n , the following is an instance of N₀.*

$$\exists u(Scm^S(u) \ \& \ (\forall p_1, \dots, p_n \in u)(\varphi \leftrightarrow \varphi^u)) \quad (2.45)$$

404 We will now show that in S, N₀ implies both *Replacement* and *Infinity*.

405

406 Let N₀ be defined as in (2.5), for *Infinity* see (1.10).

407 **Theorem 2.6** *In S, the axiom schema N₀ implies Infinity.*

408 *Proof.* Let $\varphi = \forall x \exists y (y = x \cup \{x\})$. This clearly holds in S because given a
 409 set x , there is a set $y = x \cup \{x\}$ obtained via *Pairing* and *Union*. From N₀,
 410 there is a set u such that φ^u holds. This u satisfies the conditions required
 411 by *Infinity*. \square

412 Lévy proves this theorem in a different way. He argues that for an arbitrary
 413 formula φ , N_0 gives us $\exists u Scm^S(u)$ and this u already satisfies *Infinity*.
 414 To do this, we would need to prove lemma (2.12) now, which would make
 415 second half of this chapter quite confusing.

416

417 Let S be a set theory defined in (1.18), N_0 a schema defined in (2.5) and
 418 *Replacement* a schema defined in (1.16).

419 **Theorem 2.7** *In S , axiom the schema N_0 implies Replacement.*

420 *Proof.* Let $\varphi(x, y, p_1, \dots, p_n)$ be a formula with no free variables except
 421 x, y, p_1, \dots, p_n . Let χ be an instance of the *Replacement* schema for the
 422 φ given. We want to verify that χ holds in S with N_0 .

$$\begin{aligned} \chi = \forall x, y, z (\varphi(x, y, p_1, \dots, p_n) \ \& \ \varphi(x, z, p_1, \dots, p_n) \rightarrow y = z) \\ \rightarrow \forall x \exists y \forall z (z \in y \leftrightarrow (\exists q \in x) (\varphi(x, y, p_1, \dots, p_n))) \end{aligned} \quad (2.46)$$

423 Now consider the following formulas.

- 424 (i) $(\forall x, y, p_1, \dots, p_n \in u) (\varphi \leftrightarrow \varphi^u)$
- 425 (ii) $(\forall x, p_1, \dots, p_n \in u) (\exists y \varphi \leftrightarrow (\exists y \varphi)^u)$
- 426 (iii) $(\forall x, p_1, \dots, p_n \in u) (\chi \leftrightarrow \chi^u)$
- 427 (iv) $\forall x, p_1, \dots, p_n \chi \leftrightarrow (\forall x, p_1, \dots, p_n \chi)^u$

428 The above formulas are instances of the N_0 schema for φ , $\exists y \varphi$, χ and the
 429 universal closure of χ respectively. By N_0 , there exists a set u where all four
 430 formulas hold.¹¹ From relativization, $(\exists y \varphi)^u$ is equivalent to $(\exists y \in u) \varphi^u$,
 431 together with (i) and (ii), we get

$$(\forall x, p_1, \dots, p_n \in u) ((\exists y \in u) \varphi \leftrightarrow \exists y \varphi) \quad (2.47)$$

432 If φ is a function, then for every $x \in u$, which is also $x \subset u$ since $Scm^S(u)$
 433 and therefore u is transitive, it maps elements of x into u . From the *Speci-*
 434 *fication*, we can find y , a set of all images of the elements of x . That gives
 435 us $x, p_1, \dots, p_n \in u \rightarrow \chi$. By (iii) we get that $x, p_1, \dots, p_n \in u \rightarrow \chi^u$
 436 holds. The universal closure of this formula is $\forall x, p_1, \dots, p_n (x, p_1, \dots, p_n \in$
 437 $u \rightarrow \chi^u)$ which is equivalent to $(\forall x, p_1, \dots, p_n \in u) (\chi)^u$, which is exactly
 438 $(\forall x, p_1, \dots, p_n \chi)^u$. From (iv), $\forall x, p_1, \dots, p_n \chi$ holds. \square

439 What we have just proven is only a single theorem from Lévy's afore-
 440 mentioned article, we will introduce other interesting results, mostly related
 441 to Mahlo and inaccessible cardinals, later in their appropriate context in
 442 chapter 3.

¹¹Despite the fact that N_0 is defined for one formula, we have just used it for four at once. To make this formally possible, we can either prove that N_0 is equivalent to a more general version for any finite number of formulas or we can reflect their conjunction and argue that if $u \models \varphi_1 \ \& \ \dots \ \& \ \varphi_n$, then $(u \models \varphi_1), \dots, (u \models \varphi_n)$.

2.2 Contemporary Restatement

We will now introduce and prove a theorem that is called Lévy's Reflection in contemporary set theory. The only difference is that while Lévy originally reflects a formula φ from V to a set u which is a *standard complete model of* S , we say that there is a V_λ for a limit λ that reflects φ . Those two conditions are equivalent due to lemma (2.12).

Lemma 2.8 *Let $\varphi_1, \dots, \varphi_n$ be first-order formulas in the language of set theory, all with m free variables¹².*

(i) *For each set M_0 there is such set M that $M_0 \subset M$ and the following holds for every i , $1 \leq i \leq n$:*

$$\exists x \varphi_i(p_1, \dots, p_{m-1}, x) \rightarrow (\exists x \in M) \varphi_i(p_1, \dots, p_{m-1}, x) \quad (2.48)$$

for every $p_1, \dots, p_{m-1} \in M$.

(ii) *Furthermore, there is a limit ordinal λ such that $M_0 \subset V_\lambda$ and the following holds for each i , $1 \leq i \leq n$:*

$$\exists x \varphi_i(p_1, \dots, p_{m-1}, x) \rightarrow (\exists x \in V_\lambda) \varphi_i(p_1, \dots, p_{m-1}, x) \quad (2.49)$$

for every $p_1, \dots, p_{m-1} \in M$.

(iii) *Assuming Choice, there is M , $M_0 \subset M$ such that (2.48) holds for every M , $i \leq n$ and $|M| \leq |M_0| \cdot \aleph_0$.*

Proof. We will simultaneously prove statements (i) and (ii), denoting M^T the transitive set required by part (ii). Steps in the construction of M^T that are not explicitly included are equivalent to steps for M .

Let us first define an operation $H_i(p_1, \dots, p_{m-1})$ that yields the set of x 's with minimal rank¹³ satisfying $\varphi_i(p_1, \dots, p_{m-1}, x)$ for p_1, \dots, p_{m-1} and for every i , $1 \leq i \leq n$.

$$H_i(p_1, \dots, p_n) = \{x \in C_i : (\forall z \in C)(\text{rank}(x) \leq \text{rank}(z))\} \quad (2.50)$$

for each $1 \leq i \leq n$, where

$$C_i = \{x : \varphi_i(p_1, \dots, p_{m-1}, x)\} \text{ for } 1 \leq i \leq n \quad (2.51)$$

¹²For formulas with a different number of free variables, take for m the highest number of parameters among those formulas. Add spare parameters to every formula that has less than m parameters in a way that preserves the last parameter, which we will denote x . E.g. let φ'_i be the a formula with k parameters, $k < m$. Let us set $\varphi_i(p_1, \dots, p_{m-1}, x) = \varphi'_i(p_1, \dots, p_{k-1}, x)$, notice that the parameters p_k, \dots, p_{m-1} are not used.

¹³Rank is defined in (1.29)

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Next, let's construct M from given M_0 by induction.

$$M_{i+1} = M_i \cup \bigcup_{j=0}^n \{H_j(p_1, \dots, p_{m-1}) : p_1, \dots, p_{m-1} \in M_i\} \quad (2.52)$$

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In other words, in each step we include into the construction the elements satisfying $\varphi(p_1, \dots, p_{m-1}, x)$ for p_1, \dots, p_{m-1} from the previous step. For statement (ii), this is the only part that differs from (i). To end up with a transitive M , we need to extend every step to its transitive closure transitive closure of M_{i+1} from (i). In other words, let γ be the smallest ordinal such that

$$(M_i^T \cup \bigcup_{j=0}^n \{\bigcup \{H_j(p_1, \dots, p_{m-1}) : p_1, \dots, p_{m-1} \in M_i\}\}) \subset V_\gamma \quad (2.53)$$

474

Then the incremental step is

$$M_{i+1}^T = V_\gamma \quad (2.54)$$

475

and the final M is obtained by joining the previous steps.

$$M = \bigcup_{i=0}^{\infty} M_i, \quad M^T = \bigcup_{i=0}^{\infty} M_i^T = V_\lambda \text{ for some limit } \lambda. \quad (2.55)$$

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We have yet to finish part (iii). Let's try to construct a set M' that satisfies the same conditions like M but is kept as small as possible. Assuming the Axiom of Choice, we can modify the construction so that the cardinality of M' is at most $|M_0| \cdot \aleph_0$. Note that the size of M in the previous construction is determined by the size of M_0 and, most importantly, by the size of $H_i(p_1, \dots, p_{m-1})$ for every i , $1 \leq i \leq n$ in individual iterations of the construction. Since (i) only ensures the existence of an x that satisfies $\varphi_i(p_1, \dots, p_{m-1}, x)$ for any i , $1 \leq i \leq n$, we only need to add one x for every set of parameters but $H_i(u_1, \dots, u_{m-1})$ can be arbitrarily large. Let F be a choice function on $\mathcal{P}(M')$. Also let $h_i(p_1, \dots, p_{m-1}) = F(H_i(p_1, \dots, p_{m-1}))$ for i , where $1 \leq i \leq n$, which means that h is a function that outputs an x that satisfies $\varphi_i(p_1, \dots, p_{m-1}, x)$ for i such that $1 \leq i \leq n$ and has minimal rank among all such sets. The induction step needs to be redefined to

$$M'_{i+1} = M'_i \cup \bigcup_{j=0}^n \{h_j(p_1, \dots, p_{m-1}) : p_1, \dots, p_{m-1} \in M'_i\} \quad (2.56)$$

490 This way, the amount of elements added to M'_{i+1} in each step of the con-
 491 struction is the same as the amount of m -tuples of parameters that yielded
 492 elements not included in M'_i . It is easy to see that if M_0 is finite, M' is
 493 countable because it was constructed as a countable union of sets that are
 494 themselves at most countable. If M_0 is countable or larger, the cardinality
 495 of M' is equal to the cardinality of M_0 .¹⁴ Therefore $|M'| \leq |M_0| \cdot \aleph_0$ \square

496 **Theorem 2.9** (*Lévy's first-order reflection theorem*)

497 Let $\varphi(p_1, \dots, p_n)$ be a first-order formula.

498 (i) For every set M_0 there exists a set M such that $M_0 \subset M$ and the
 499 following holds:

$$\varphi^M(p_1, \dots, p_n) \leftrightarrow \varphi(p_1, \dots, p_n) \quad (2.57)$$

500 for every $p_1, \dots, p_n \in M$.

501 (ii) For every set M_0 there is a transitive set M , $M_0 \subset M$ such that the
 502 following holds:

$$\varphi^M(p_1, \dots, p_n) \leftrightarrow \varphi(p_1, \dots, p_n) \quad (2.58)$$

503 for every $p_1, \dots, p_n \in M$.

504 (iii) For every set M_0 there is a limit ordinal λ such that $M_0 \subset V_\lambda$ and the
 505 following holds:

$$\varphi^{V_\lambda}(p_1, \dots, p_n) \leftrightarrow \varphi(p_1, \dots, p_n) \quad (2.59)$$

506 for every $p_1, \dots, p_n \in M$.

507 (iv) Assuming Choice, for every set M_0 there is M such that $M_0 \subset M$ and
 508 $|M| \leq |M_0| \cdot \aleph_0$ and the following holds:

$$\varphi^M(p_1, \dots, p_n) \leftrightarrow \varphi(p_1, \dots, p_n) \quad (2.60)$$

509 for every $p_1, \dots, p_n \in M$.

510 *Proof.* Let's now prove (i) for given φ via induction by complexity. We
 511 can safely assume that φ contains no quantifiers besides " \exists " and no logical
 512 connectives other than " \neg " and " $\&$ ". Let $\varphi_1, \dots, \varphi_n$ be all subformulas of φ .
 513 Then there is a set M , obtained by the means of lemma (2.8), for all of the
 514 formulas $\varphi_1, \dots, \varphi_n$.

¹⁴It can not be smaller because $|M'_{i+1}| \geq |M'_i|$ for every i . It may not be significantly larger because the maximum of elements added is the number of n -tuples in M'_i , which is of the same cardinality as M'_i .

Let's first consider atomic formulas in the form of either $x_1 = x_2$ or $x_1 \in x_2$. It is clear from relativisation¹⁵ that (2.57) holds for both cases, $(x_1 = x_2)^M \leftrightarrow (x_1 = x_2)$ and $(x_1 \in x_2)^M \leftrightarrow (x_1 \in x_2)$.

We now want to verify the inductive step. First, take $\varphi = \neg\varphi'$. From relativization, we get $(\neg\varphi')^M \leftrightarrow \neg(\varphi'^M)$. Because the induction hypothesis tells us that $\varphi'^M \leftrightarrow \varphi'$, the following holds:

$$(\neg\varphi')^M \leftrightarrow \neg(\varphi'^M) \leftrightarrow \neg\varphi' \quad (2.61)$$

The same holds for $\varphi = \varphi_1 \& \varphi_2$. From the induction hypothesis, we know that $\varphi_1^M \leftrightarrow \varphi_1$ and $\varphi_2^M \leftrightarrow \varphi_2$, which together with relativization for formulas in the form of $\varphi_1 \& \varphi_2$ gives us

$$(\varphi_1 \& \varphi_2)^M \leftrightarrow \varphi_1^M \& \varphi_2^M \leftrightarrow \varphi_1 \& \varphi_2 \quad (2.62)$$

Let's now examine the case when $\varphi = \exists x\varphi'(p_1, \dots, p_n, x)$. The induction hypothesis tells us that $\varphi'^M(p_1, \dots, p_n, x) \leftrightarrow \varphi'(p_1, \dots, p_n, x)$, so, together with above lemma (2.8), the following holds:

$$\begin{aligned} & \varphi(p_1, \dots, p_n, x) \\ & \leftrightarrow \exists x\varphi'(p_1, \dots, p_n, x) \\ & \leftrightarrow (\exists x \in M)\varphi'(p_1, \dots, p_n, x) \\ & \leftrightarrow (\exists x \in M)\varphi'^M(p_1, \dots, p_n, x) \\ & \leftrightarrow (\exists x\varphi'(p_1, \dots, p_n, x))^M \\ & \leftrightarrow \varphi^M(p_1, \dots, p_n, x) \end{aligned} \quad (2.63)$$

Which is what we wanted to prove for part (i).

We now need to verify that the same holds for any finite number of formulas $\varphi_1, \dots, \varphi_n$. This has in fact been already done since lemma (2.8) gives us a set M for any finite amount of formulas and given M_0 . We can therefore find a set M for the union of all of their subformulas. When we obtain such M , it should be clear that it also reflects every formula in $\varphi_1, \dots, \varphi_n$.

Since V_λ is a transitive set, by proving (iii) we also satisfy (ii). To do so, we only need to look at part (ii) of lemma (2.8). All of the above proof also holds for $M = V_{\text{lambda}}$.

¹⁵See (1.39). This only holds for relativization to $M, \in \cap M \times M$, not M, R for an arbitrary R .

539 To finish part (iv), we take M of size $\leq |M_0| \cdot \aleph_0$, which exists due to
 540 part (iii) of lemma (2.8), the rest being identical. \square

541 Let \mathbf{S} be a set theory defined in (1.18), for ZFC see definition (1.20).

542 The two following lemmas are based on [Drake, 1974][Chapter 3, Theorem
 543 1.2].
 544

545 **Lemma 2.10** *If M is a transitive set, then $M \models \text{Extensionality}$.*

546 *Proof.* Given a transitive set M , we want to show that the following holds.

$$M \models \forall x, y (x = y \leftrightarrow \forall z (z \in x \leftrightarrow z \in y)) \quad (2.64)$$

547 Given arbitrary $x, y \in M$, we want to prove that $M \models (x = y \leftrightarrow \forall z (z \in$
 548 $x \leftrightarrow z \in y))$. This is equivalent to $M \models x = y$ iff $M \models \forall z (z \in x \leftrightarrow z \in y)$,
 549 which is the same as $x = y$ iff $M \models \forall z (z \in x \leftrightarrow z \in y)$.

550 So all elements of x are also elements of y in M , and vice versa. Because
 551 M is transitive, all elements of x and y are in M , so $M \models \forall z (z \in x \leftrightarrow z \in y)$
 552 holds iff x and y contain the same elements and are therefore equal. \square

553 **Lemma 2.11** *If M is a transitive set, then $M \models \text{Foundation}$.*

554 *Proof.* We want to prove the following:

$$M \models \forall x (x \neq \emptyset \rightarrow (\exists y \in x) (x \cap y = \emptyset)) \quad (2.65)$$

555 Given an arbitrary non-empty $x \in M$ let's show that $M \models (\exists y \in x) (x \cap$
 556 $y = \emptyset)$.

557 Because M is transitive, every element of x is an element of M . Take for
 558 y the element of x with the lowest rank¹⁶. It should be clear that there is no
 559 $z \in y$ such that $z \in x$, because then $\text{rank}(z) < \text{rank}(y)$, which would be a
 560 contradiction. \square

561 Let \mathbf{S} be a set theory as defined in (1.18).

562 **Lemma 2.12** *The following holds for every λ .*

$$“\lambda \text{ is a limit ordinal}” \rightarrow V_\lambda \models \mathbf{S} \quad (2.66)$$

563 *Proof.* Given an arbitrary limit ordinal λ , we will verify the axioms of \mathbf{S} one
 564 by one.

565 (i) *The existence of a set* comes from the fact that V_λ is a non-empty set
 566 because limit ordinal is non-zero by definition.

¹⁶Rank is defined in (1.29).

567 (ii) *Extensionality* holds from (2.10).

568 (iii) *Foundation* holds from (2.11).

569 (iv) *Union*:

570 Given any $x \in V_\lambda$, we want verify that $y = \bigcup x$ is also in V_λ . Note that
 571 $y = \bigcup x$ is a Δ_0 -formula.

$$y = \bigcup x \leftrightarrow (\forall z \in y)(\exists q \in x)z \in q \ \& \ (\forall z \in x)(\forall q \in z)q \in y \quad (2.67)$$

572 So by lemma (1.42)

$$y = \bigcup x \leftrightarrow V_\lambda \models y = \bigcup x \quad (2.68)$$

573 (v) *Pairing*:

574 Given two sets $x, y \in V_\lambda$, we want to show that $z = \{x, y\}$ is also an
 575 element of V_λ .

$$z = \{x, y\} \leftrightarrow x \in z \ \& \ y \in z \ \& \ (\forall q \in z)(q = x \vee q = y) \quad (2.69)$$

576 So $z = \{x, y\}$ is a Δ_0 -formula, and thus by lemma (1.42) it holds that

$$z = \{x, y\} \leftrightarrow V_\lambda \models z = \{x, y\} \quad (2.70)$$

577 (vi) *Powerset*:

578 Given any $x \in V_\lambda$, we want to make sure that $\mathcal{P}(x) \in V_\lambda$. Let $\varphi(y)$ denote
 579 the formula $y \in \mathcal{P}(x) \leftrightarrow y \subset x$. according to definition of subset (1.4),
 580 $y \subset x$ is Δ_0 , so for any given $x, y \in V_\lambda$, $y = \mathcal{P}(x) \leftrightarrow V_\lambda \models y = \mathcal{P}(x)$.
 581 Because λ is limit and $\text{rank}(\mathcal{P}(x)) = \text{rank}(x) + 1$, if $\mathcal{P}(x) \in V_\lambda$ for every
 582 $x \in V_\lambda$.

583 (vii) *Specification*:

584 Given a first-order formula φ , we want to show the following:

$$V_\lambda \models \forall x, p_1, \dots, p_n, \exists y \forall z (z \in y \leftrightarrow z \in x \ \& \ \varphi(z, p_1, \dots, p_n)) \quad (2.71)$$

585 Given any x along with parameters p_1, \dots, p_n in V_λ , we set

$$y = \{z \in x : \varphi^{V_\lambda}(z, p_1, \dots, p_n)\} \quad (2.72)$$

586 From transitivity of V_λ and the fact that $y \subset x$ and $x \in V_\lambda$, we know that
 587 $y \in V_\lambda$, so $V_\lambda \models \forall z (z \in y \leftrightarrow z \in x \ \& \ \varphi(z, p_1, \dots, p_n))$.
 588 □

589 **Definition 2.13** (*First-Order Reflection Schema*)

590 For every first-order formula φ , the following is an axiom:

$$\forall M_0 \exists M (M_0 \subseteq M \ \& \ (\varphi(p_1, \dots, p_n) \leftrightarrow \varphi(p_1, \dots, p_n)^M)) \quad (2.73)$$

591 We will refer to this axiom schema as First-order reflection.

Let *Infinity* and *Replacement* be as defined in (1.10) and (1.16) respectively.

Theorem 2.14 First-order reflection is equivalent to Infinity & Replacement under S.

Proof. Since (2.9) already gives us one side of the implication, we are only interested in showing the converse which we shall do in two parts:

First-order reflection \rightarrow Infinity This is done exactly like (2.6). We pick for φ the formula $(\forall y \in x)(y \cup \{y\} \in x)$, $M_0 = \{\emptyset\}$. From (2.13), there is a set M that satisfies φ , so there is an inductive set. We have picked M_0 so that $\emptyset \in M$ obviously holds and M is the witness for

$$\exists x(\emptyset \in x \ \& \ (\forall y \in x)(y \cup \{y\} \in x)) \quad (2.74)$$

which is exactly (1.10).

First-order reflection \rightarrow Replacement

Let's first point out that while *First-order reflection* gives us a set for one formula, we can generalize it to hold for any finite number of formulas. We will show how it is done for two formulas, which is what we will use in this proof. Given two first-order formulas φ, ψ , we can suppose that there are formulas φ' and ψ' that are equivalent to φ and ψ respectively, but their free variables are different¹⁷. Let $\xi = \varphi \ \& \ \psi$, given any M_0 , we can find a M such that $\xi \leftrightarrow \xi^M$. It is easy to see that from relativisation, the following holds:

$$\varphi \ \& \ \psi \leftrightarrow \varphi' \ \& \ \psi' \leftrightarrow \xi \leftrightarrow \xi^M \leftrightarrow (\varphi' \ \& \ \psi')^M \leftrightarrow \varphi'^M \ \& \ \psi'^M \leftrightarrow \varphi^M \ \& \ \psi^M \quad (2.75)$$

Now given a function $\varphi(x, y)$, we know from *First-order reflection* that for every M_0 , there is a set M such that $M_0 \subseteq M$ and both

$$(\forall x, y \in M)(\varphi(x, y) \leftrightarrow \varphi^M(x, y)) \quad (2.76)$$

and

$$(\forall x, y \in M)(\exists y \varphi(x, y) \leftrightarrow (\exists y \varphi(x, y))^M) \quad (2.77)$$

hold, the latter being equivalent to

$$(\forall x, y \in M)(\exists y \varphi(x, y) \leftrightarrow (\exists y \in M) \varphi^M(x, y)) \quad (2.78)$$

¹⁷This is plausible since we can for example substitute all free variables in φ' for x_0, x_2, x_4, \dots and use x_1, x_3, x_5, \dots for free variables in ψ' , the resulting formulas will be equivalent.

617 Therefore

$$(\forall x, y \in M)(\exists y \varphi(x, y) \leftrightarrow (\exists y \in M)\varphi(x, y)) \quad (2.79)$$

618 holds too. That means that we have a set M such that for every $x \in M$, if
619 φ is defined for x , $(\exists y \in M)\varphi(x, y)$.

620 To show that *Replacement* holds for this particular φ , we need to verify
621 that given a set M_0 , $M'_0 = \{y : (\exists x \in M_0)\varphi(x, y)\}$ is also a set. But since
622 $M_0 \subseteq M$ and because given any $x \in M$, there is $y \in M$ satisfying $\varphi(x, y)$,
623 the following is a set due to *Specification*:

$$M'_0 = \{y : (\exists x \in M_0)\varphi(x, y)\} = \{y \in M : (\exists x \in M_0)\varphi(x, y)\} \quad (2.80)$$

624

□

625

626 We have shown that *Reflection* for first-order formulas, *First-order reflec-*
627 *tion* is a theorem of ZFC. We have also shown that it can be used instead of
628 the *Infinity* and *Replacement* scheme, but ZFC + *First-order reflection* is
629 a conservative extension of ZF. Besides being a starting point for more gen-
630 eral and powerful statements, it can be used to show that ZF is not finitely
631 axiomatizable. This follows from the fact that *Reflection* gives a model to
632 any consistent finite set of formulas. So if $\varphi_1, \dots, \varphi_n$ would be the axioms
633 of ZFC, *Reflection* would prove that every model of ZFC contains a smaller
634 model of ZFC, which would in turn contradict the Second Gödel's Theorem¹⁸.

635 It is also worthwhile to note that, in a way, Reflection is dual to compact-
636 ness. Compactness says that given a set of sentences, if every finite subset
637 yields a model, so does the whole set. Reflection, on the other hand, says
638 that while the whole set has no model in the underlying theory, every finite
639 subset has a model.

640 Furthermore, *Reflection* can be used in ways similar to upward Löwenheim–Skolem
641 theorem. Since Reflection extends any set M_0 into a model of given formulas
642 $\varphi_1, \dots, \varphi_n$, we can choose the lower bound of the size of M by appropriately
643 choosing M_0 .

644 In the next section, we will try to generalize *Reflection* in a way that
645 transcends ZF and finally yields some large cardinals.

¹⁸See chapter ?? for further details.

⁶⁴⁶ 3 Conclusion

References

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