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REFLECTION PRINCIPLES AND LARGE CARDINALS

Bakalářská práce

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Prohlašuj, že jsem bakalářkou práci vypracoval samostatně a že jsem uvedl všechny použité prameny a literaturu.

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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 zdůvodněn, proč tomu tak je.

Abstract

This thesis aims to examine relations between so called "Reflection Principles" and Large cardinals. Lévy has shown that Reflection Theorem is a sound theorem of ZFC and it is equivalent to 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 it's generalisations with respect to existence of Large Cardinals. This thesis will establish Inaccessible, Mahlo and Indescribable cardinals and their definition via reflection. A natural limit of Large Cardinals obtained via reflection are cardinals inconsistent with L. The thesis will offer an intuitive explanation of why this is the case.

Contents

1 Introduction

1.1 Motivation and Origin

> The Universe of sets cannot be uniquely characterized (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 of transfinite type, including infinitary logics of any cardinal order.

— Kurt Gödel [5]

To understand why do need reflection in the first place, let's think about infinity for a moment. In the intuitive sense, infinity is an upper limit of all numbers. But for centuries, this was merely a philosophical concept, closely bound to religious and metaphysical way of thinking, considered separate from numbers used for calculations or geometry. It was a rather vague concept. In ancient Greece, Aristotle's response to famous Zeno's paradoxes introduced the distinction between actual and potential infinity. He argued, that potential infinity is (in today's words) well defined, as opposed to actual infinity, which remained a vague incoherent concept. He didn't think it's possible for infinity to inhabit a bounded place in space or time, rejecting Zeno's thought experiments as a whole. Aristotle's thoughts shaped western thinking partly due to Aquinas, who himself believed actual infinity to be more of a metaphysical concept for describing God than a mathematical property attributed to any other entity. In his Summa Theologica [1] he argues:

> A geometrician does not need to assume a line actually infinite, but takes some actually finite line, from which he subtracts whatever he finds necessary; which line he calls infinite.

Less than hundred years later, Gregory of Rimini wrote

> If God can endlessly add a cubic foot to a stone–which He can–then He can create an infinitely big stone. For He need only add one cubic foot at some time, another half an hour later, another a quarter of an hour later than that, and so on ad infinitum. He would then have before Him an infinite stone at the end of the hour.

Which is basically a Zeno's Paradox made plausible with God being the actor. In contrast to Aquinas' position, Gregory of Rimini theoretically constructs an object with actual infinite magnitude that is essentially different from God.

[1] Part I, Question 7, Article 3, Reply to Objection 1

Even later, in the 17th century, pushing the property of infinitness from the Creator to his creation, Nature, Leibniz wrote to Foucher in 1962:

> I am so in favor of the actual infinite that instead of admitting that Nature abhors it, as is commonly said, I hold that Nature makes frequent use of it everywhere, in order to show more effectively the perfections of its Author. Thus I believe that there is no part of matter which is not, I do not say divisible, but actually divided; and consequently the least particle ought to be considered as a world full of an infinity of different creatures.

But even though he used potential infinity in what would become foundations of modern Calculus and argued for actual infinity in Nature, Leibniz refused the existence of an infinite, thinking that Galileo's Paradoxon[2] is in fact a contradiction. The so called Galileo's Paradoxon is an observation Galileo Galilei made in his final book "Discourses and Mathematical Demonstrations Relating to Two New Sciences". He states that if all numbers are either squares and non–squares, there seem to be less squares than there is all numbers. On the other hand, every number can be squared and every square has it's square root. Therefore, there seem to be as many squares as there are all numbers. Galileo concludes, that the idea of comparing sizes makes sense only in the finite realm.

> Salviati: So far as I see we can only infer that the totality of all numbers is infinite, that the number of squares is infinite, and that the number of their roots is infinite; neither is the number of squares less than the totality of all the numbers, nor the latter greater than the former; and finally the attributes "equal," "greater," and "less," are not applicable to infinite, but only to finite, quantities. When therefore Simplicio introduces several lines of different lengths and asks me how it is possible that the longer ones do not contain more points than the shorter, I answer him that one line does not contain more or less or just as many points as another, but that each line contains an infinite number.

Leibniz insists in part being smaller than the whole saying

> Among numbers there are infinite roots, infinite squares, infinite cubes. Moreover, there are as many roots as numbers. And there are as many squares as roots. Therefore there are as many squares

[2] zneni galileova paradoxu

> as numbers, that is to say, there are as many square numbers as there are numbers in the universe. Which is impossible. Hence it follows either that in the infinite the whole is not greater than the part, which is the opinion of Galileo and Gregory of St. Vincent, and which I cannot accept; or that infinity itself is nothing, i.e. that it is not one and not a whole.

TODO nejakej Hegel–strucne?

TODO Cantor

TODO mene teologie, vice matematiky

TODO definovat pojmy (trida etc)

In his work, he defined transfinite numbers to extend existing natural number structure so it contains more objects that behave like natural numbers and are based on an object (rather a meta-object) that doesn't explicitly exist in the structure, but is closely related to it. This is the first instance of reflection. This paper will focus on taking this principle a step further, extending Cantor's (or Zermelo–Fraenkel's, to be more precise) universe so it includes objects so big, they could be considered the universe itself, in a certain sense.

TODO dal asi smazat

The original idea behind reflection principles probably comes from what could be informally called "universality of the universe". The effort to precisely describe the universe of sets was natural and could be regarded as one of the impulses for formalization of naive set theory. If we try to express the universe as a set $\{x|x = x\}$, a paradox appears, because either our set is contained in itself and therefore is contained in a set (itself again), which contradicts the intuitive notion of a universe that contains everything but is not contained itself.

TODO ???

If there is an object containing all sets, it must not be a set itself. The notion of class seems inevitable. Either directly the ways for example the Bernays–Gödel set theory, we will also discuss later in this paper, does in, or on a meta–level like the Zermelo–Fraenkel set theory, that doesn't refer to them in the axioms but often works with the notion of a universal class. duet Another obstacle of constructing a set of all sets comes from Georg Cantor, who proved that the set of all subsets of a set (let A be the set and $\mathscr{P}(()A)$ its powerset) is strictly larger that A. That would turn every aspiration to finally establish an universal set into a contradictory infinite regression.[3]. We

[3] An intuitive analogy of this *reductio ad infinitum* is the status of ω, which was originally thought to be an unreachable absolute, only to become starting point of Cantor's hierarchy of sets growing beyond all boundaries around the end of the 19^{th} century

will use V to denote the class of all sets. From previous thoughts we can easily argue, that it is impossible to construct a property that holds for V and no set and is neither paradoxical like $\{x|x = x\}$ nor trivial. Previous observation can be transposed to a rather naive formulation of the reflection principle:

Reflection Any property which holds in V already holds in some initial segment of V.

To avoid vagueness of the term "property", we could informally reformulate the above statement into a schema:

For every first-order formula[4] φ holds in $V \leftrightarrow \varphi$ holds in some initial segment of V.

Interested reader should note that this is a theorem scheme rather than a single theorem. [5]

1.2 A few historical remarks on reflection

Reflection made it's first in set-theoretical appearance in Gödel's proof of GCH in L (citace Kanamori ? Lévy and set theory), but it was around even earlier as a concept. Gödel himself regarded it as very close to Russel's reducibility axiom (an earlier equivalent of the axiom schema of Zermelo's separation). Richard Montague then studied reflection properties as a tool for verifying that Replacement is not finitely axiomatizable (citace?). a few years later Lévy proved in [2] the equivalence of reflection with Axiom of infinity together with Replacement in proof we shall examine closely in chaper 2.

TODO co dal? recent results?

1.3 Notation (??) TODO

1. *Reflection* je obecne reflexe (jaka presne)

[4] this also works for finite sets of formulas [3, p. 168]

[5] If there were a single theorem stating "for any formula φ that holds in V there is an initial segment of V where φ also holds", we would obtain the following contradiction with the second Gödel's theorem: In ZFC, any finite group of axioms of ZFC holds in some initial segment of the universe. If we take the largest of those initial segments it is still strictly smaller than the universe and thus we have, via compactness, constructed a model of ZFC within ZFC. That is, of course a harsh contradiction. This also leads to an elegant way to prove that ZFC is not finitely axiomatizable.

2. *Reflection*$_1$ je reflexe prvoradovych formuli
3. *Reflection*$_2$ je reflexe druhoradovych formuli
4. etc...

2 Levy's first-order reflection

2.1 Introduction

This section will try to present Lévy's proof of a general reflection principle being equivalent to Replacement and Infinity under ZF minus Replacement and Infinity. We will first introduce a few axioms and definitions that were a different in Lévy's paper[2], but are equivalent to today's terms. We will write them in contemporary notation, our aim is the result, not history of set theory notation.

Please note that Lévy's paper was written in a period when Set theory was oriented towards semantics, which means that everything was done in a model. All proofs were theodel that of ZFC was V_α (notated as $R(\alpha)$ at the time) for some cardinal α, which means that α is a inaccessible cadinal. Please bear in mind that this is vastly different from saying that there is an inaccessible α inside the model. This V_α is also referred to as $Scm^{\mathsf{Q}}(u)$, which means that u ($u = V_\alpha$ in our case) is a standard complete model of an undisclosed axiomatic set theory Q formulated in the "non-simple applied first order functional calculus", which is second-order theory is today's terminology, we are allowed to quantify over functions and thus get rid of axiom schemes. (Note that Lévy always speaks of "the axiom of replacement"). Besides placeholder set theory Q and ZF, which the reader should be familiar with, theories Z, S, and SF are used in the text. Z is ZF minus replacement, S is ZF minus replacement and infinity, and finally SF is ZF minus infinity. "The axiom of subsets" is an older name for the axiom scheme of specification (and it's not a scheme since we are now working in second order logic). Also note that universal quantifier does not appear, $\forall x \varphi(x)$ would be written as $(x)\varphi(x)$, the symbol for negation is "$\sim$".

2.2 Lévy's Original Paper

The following are a few definitions that are used in Lévy's original article. [6]

Definition 2.1 *Relativization*
TODO (jech:161)

Next two definitions are not used in contemporary set theory, but they illustrate 1960's set theory mind-set and they are used heavily in Lévy's text,

[6] While some of them won't be of much use in this paper, they will provide extremely helpful when reading the original article as set theory notation and terminology has evolved in the last 50 years considerably.

so we will include and explain them for clarity. Generally in this chapter, Q stands for an undisclosed axiomatic set theory, u is usually a model, counterpart of today's V[7], e is a relation that serves as $\in$ in the given model.

TODO je to relativizovany, jak rika shepherdson?

Definition 2.2 *Standard model of a set theory*
We say the u is a standard model of Q with a membership relation e, written as $Sm^{\mathsf{Q}}(u)$, if both of the following hold
(i) $(x, y) \in e \leftrightarrow y \in u \;\&\; x \in y$
(ii) $y \in u \;\&\; x \in y \rightarrow x \in u$

Definition 2.3 *Standard complete model of a set theory*
We say that that u is a standard complete model of a set theory Q with a membership relation e if:
(i) u is a transitive set with respect to $\in$
(ii) $\forall e((x, y) \in e \leftrightarrow (y \in u \;\&\; x \in y) \;\&\; Sm^{\mathsf{Q}}(u, e))$
this is written as $Scm^{\mathsf{Q}}(u)$.

TODO what is "simple first-order functional calculus" a "non-simple first-order functional calculus"? Levyho ucebnice?

Definition 2.4 *Cardinal inaccessible with respect to* Q

$$In^{\mathsf{Q}}(\alpha) \;=\; Scm^{\mathsf{Q}}(V_\alpha) \tag{2.1}$$

TODO tohle je lepsi protoze nepotrebujes AC

Definition 2.5 *Strictly increasing function*
A function $F(\alpha)$ defined on the ordinal number into the ordinal numbers is said to be strictly increasing *if* $\forall \alpha, \beta \in On(\alpha < \beta \rightarrow F(\alpha) < F(\beta))$.

Definition 2.6 *Continuous function*
A function $F(\alpha)$ defined on the ordinal number into the ordinal numbers is said to be continuous *if for any limit α, $F(\alpha) = lim_{\beta < \alpha} F(\beta)$.*

Definition 2.7 *Normal function*
A function $F(\alpha)$ defined on the ordinal number into the ordinal numbers is said to be normal *if it is* strictly increasing *and* continuous

[7] Which is of course not referred to as a model, but it is used in a similar fashion, in this case the term "model" was a metamathematical notion because it was not based on any underlying structure of theory. It can be easily formalized in any set theory, but it's not helpful for our case.

TODO jak znacim usporadane dvojice?

TODO porovnani Mahlovy a Lévyho konstrukce, viz ref{mahlovy kardinaly}

TODO asi doplnit jak to souvisi se soucasnou definici slabe Mahlovych kardinalu pres stacionarni mnoziny?

Lévy's article mentions various schemata that are not instances of reflection themselves. We will mention them because they are equivalent to N_0 and because they are fixed-point theorems, which we will find useful later in this thesis.

Definition 2.8 *M Every normal function defined for all ordinals has at least one inaccessible number in its range.*

Definition 2.9 *M' Every normal function defined for all ordinals has at least one fixed point which is inaccessible.*

Definition 2.10 *M'' Every normal function defined for all ordinals has arbitrarily great fixed points which are inaccessible.*

Theorem 2.11

$$M \leftrightarrow M' \leftrightarrow M'' \tag{2.2}$$

We will omit this proof because it is not essential for our goal. An interested reader will find it in [2,].

TODO z M se pak odvodi Mahlovska hierarchie?

The following is a principle of complete reflection over ZF.

Definition 2.12 $N(\varphi)$

$$\exists u(Scm^{\mathsf{ZF}}(u) \;\&\; \forall x_1, \ldots, x_n(x_1, \ldots, x_n \in u \to \varphi \leftrightarrow \varphi^u)) \tag{2.3}$$

where φ is a formula which does not contain free variables except $x_1, \ldots, x_n$.

Note that this by (2.4) equivalent to $\exists u(In^{\mathsf{ZF}}(u) \;\&\; \forall x_1, \ldots, x_n(x_1, \ldots, x_n \in u \to \varphi \leftrightarrow \varphi^u))$, where $In(\alpha)$ is equivalent to the standard notion of inaccessibility.

Theorem 2.13

$$M \leftrightarrow N \tag{2.4}$$

Proof. TODO (Theorem 3)? neudelam ho spis v dalsi sekci v modernejsi variante? $\square$

2.3 $\mathsf{S} \models$ ***Reflection*** $\leftrightarrow$ (***Replacement*** & ***Infinity***)

Definition 2.14 $N_0(\varphi)$

$$\exists u(Scm^{\mathsf{S}}(u) \ \& \ \forall x_1, \ldots, x_n(x_1, \ldots, x_n \in u \rightarrow \varphi \leftrightarrow \varphi^u)) \tag{2.5}$$

where φ is a formula which does not contain free variables except $x_1, \ldots, x_n$.

Note that the only difference between N and N_0 is the set theory used.

Theorem 2.15 *In S, the schema N_0 implies the Axiom of Infinity.*

Proof. For any φ, N_0 gives us $\exists u Scm^{\mathsf{S}}(u)$, which means that there is a set u that is identical to V_α for some alpha, so $\exists \alpha Scm^{\mathsf{S}}(V_\alpha)$. We don't know the exact size of this α, but we know that $\alpha \geq \omega$, otherwise α would be finite, therefore not closed under the powerset operation, which would contradict the axiom of powersets. In order to prove that it is a model of S, we would need to verify all axioms of S . We have already shown that ω is closed under the powerset operation. Foundation, extensionality and comprehension are clear from the fact that we work in ZF[8], pairing is clear from the fact, that given two sets A, B, they have ranks a, b, without loss of generality we can assume that $a \leq b$, which means that $A \in V_a \in V_b$, therefore V_b is a set that satisfies the paring axiom: it contains both A and B.

TODO vyhodit axiomy, staci vyrobit ω

We now want to prove that V_α leads to existence of an inductive set, which is a set that satisfies $\exists A(\emptyset \in A \ \& \forall x \in A \ ((x \cup \{x\}) \in A))$. If we can find a way to construct V_ω from any V_α satisfying $\alpha \geq \omega$, we are done. Since ω is the least limit ordinal, all we need is the following

$$\bigcap \{V_\kappa \mid \forall \lambda(\lambda < \kappa \rightarrow \exists \mu(\lambda < \mu < \kappa))\} \tag{2.6}$$

because V_κ is a transitive set for every κ, thus the intersection is non-empty unless empty set satisfies the property or the set of V_κs is itself empty. □

Theorem 2.16 *In S, the schema N_0 implies Replacement schema.*

Proof. TODO vysvetlit! (podle contemporary verze)

[8]We only need to verify axioms that provide means of constructing larger sets from smaller to make sure they don't exceed ω. Since ω is an initial segment of ZF, the axiom scheme of specification can't be broken, the same holds for foundation and extensionality.

Let $\varphi(v,w)$ be a formula wth no free variables except $v, w, x_1, \ldots, x_n$ where n is any natural number. Let χ be an instance of replacement schema for this φ:

$$\chi = \forall r,s,t(\varphi(r,s)\&\varphi(r,t) \to s = t) \to \forall x\exists y\forall w(w \in y \leftrightarrow \exists v(v \in x\&\varphi(v,w))) \tag{2.7}$$

We can deduce the following from N_0:

(i) $x_1, \ldots, x_n, v, w \in u \to (\varphi \leftrightarrow \varphi^u)$

(ii) $x_1, \ldots, x_n, v \in u \to (\exists w\varphi \leftrightarrow (\exists w\varphi)^u)$

(iii) $x_1, \ldots, x_n, x \in u \to (\chi \leftrightarrow \chi^u)$

(iv) $\forall x_1, \ldots, x_n\forall x(\chi \leftrightarrow (\forall x_1, \ldots, x_n\forall x\chi)^u)$

Note that (i), (ii), (iii) are obtained from instances of N_0 for φ, $\exists w\varphi$ and χ respectively. From relativization we also know that $(\exists w\varphi)^u$ is equivalent to $\exists w(w \in u\&\varphi^u)$. Therefore (ii) is equivalent to $x_1, \ldots, x_n, v \in u \to (\exists w(w \in u\&\varphi^u)$.

If φ is a function $(\forall r,s,t(\varphi(r,s)\&\varphi(r,t) \to r = t))$, then for every $x \in u$, which is also $x \subset u$ by $Scm^{\mathsf{S}}(u)$, it maps elements of x onto u. From the axiom scheme of comprehension[9], we can find a set of all images of elements of x. Let's call it y. That gives us $x_1, \ldots, x_n, x \in u \to \chi$. By (iii) we get $x_1, \ldots, x_n, x \in u \to \chi^u$, closure of this formula is $(\forall x_1, \ldots, x_n\forall x\chi)^u$, which together with (iv) yields $\forall x_1, \ldots, x_n\forall x\chi$. By the means of specification we end up with χ, which is all we need for now.

TODO btw co je x? nemela by tam tam byt nejaka volna promenna?

TODO shrnout zbytek clanku, fixed-point vety a spol

TODO S-¿ZM-¿ZM'-¿ZM", neco jako mahlovy kardinaly

$\square$

2.4 Contemporary restatement

TODO nejaky uvod.

TODO Levy rika ze existuje $Scm^S(u)$ reflektujici varphi, coz uz nepotrebujeme. atd.

TODO Ze prvoradova reflexe je theorem ZFC, vys uz max jako axiom/schema.

TODO ?

The following lemma is usually done in more parts, the first being with one formula and the other with n. We will only state and prove the generalised version for n formulas, knowing that $n = 1$ is just a specific case and the proof is exactly the same.

[9] axiom of subsets in Levy's version

Lemma 2.17 *Lemma Let $\varphi_1, \ldots, \varphi_n$ be any formulas with m parameters*[10]*.*

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

$$\exists x \varphi_i(u_1, \ldots, u_{m-1}, x) \rightarrow (\exists x \in M)\varphi_i(u_1, \ldots, u_{m-1}, x) \tag{2.8}$$

for every $u_1, \ldots, u_{m-1} \in M$.

(ii) Furthermore there is an ordinal α such that $M_0 \subset V_\alpha$ and the following holds for each $i \leq n$:

$$\exists x \varphi_i(u_1, \ldots, u_{m-1}, x) \rightarrow (\exists x \in V_\alpha)\varphi_i(u_1, \ldots, u_{m-1}, x) \tag{2.9}$$

for every $u_1, \ldots, u_{m-1} \in M$.

Proof. We will simultaneously prove statements (i) and (ii), denoting M^T the transitive set required by part (ii). Unless explicitly stated otherwise for specific steps, it is thought to be equivalent to M.

Let us first define operation $H(u_1, \ldots, u_{m-1})$ that gives us the set of x's with minimal rank satisfying $\varphi_i(u_1, \ldots, u_{m-1}, x)$ for given parameters $u_1, \ldots, u_{m-1}$ for every $i \leq n$.

$$H_i(u_1, \ldots, u_n) = \{x \in C_i : (\forall z \in C)(rank(x) \leq rank(z))\} \tag{2.10}$$

for each $i \leq n$, where

$$C_i = \{x : \varphi_i(u_1, \ldots, u_{m-1}, x)\} \text{ for } i \leq n \tag{2.11}$$

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

$$M_{i+1} = M_i \cup \bigcup_{j=0}^{n} \bigcup \{H_j(u_1, \ldots, u_{m-1}) : u_1, \ldots, u_{m-1} \in M_i\} \tag{2.12}$$

In other words, in each step we add the elements satisfying $\varphi(u_1, \ldots, u_{m-1}, x)$ for all parameters that were either available earlier or were added in the previous step. For statement (ii), this is the only part that differs from (i).

[10] For formulas with different number of parameters take for m the highest number of parameters among given formulas. Add spare parameters to the other formulas so that x remains the last parameter. That can be done in a following manner: Let φ_i' be the a formula with k parameters, $k < m$. Let us set $\varphi_i(u_1, \ldots, u_{m-1}, x) = \varphi_i'(u_1, \ldots, u_{k-1}, u_k, \ldots, u_{m-1}, x)$, notice that $u_k, \ldots, u_{m-1}$ are spare variables added just for formal simplicity.

Let us take for each step transitive closure of M_{i+1} from (i). In other words, let γ be the smallest ordinal such that

$$(M_i^T \cup \bigcup_{j=0}^{n}\{\bigcup\{H_j(u_1,\ldots,u_{m-1}) : u_1,\ldots,u_{m-1} \in M_i\}\}) \subset V_\gamma \tag{2.13}$$

Then the incremetal step is like so:

$$M_{i+1}^T = V_\gamma \tag{2.14}$$

The final M is obtained by joining all incremental steps together.

$$M = \bigcup_{i=0}^{\infty} M_i,\ \ M^T = \bigcup_{i=0}^{\infty} M_i^T \tag{2.15}$$

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 process so that cardinality of M' is at most $|M_0|{\cdot}\aleph_0$. Note that the size of M' is determined by the size of M_0 an, most importantly, by the size of $H_i(u_1,\ldots,u_{m-1})$ for any $i \leq n$ in individual levels of the construction. Since the lemma only states existence of some x that satisfies $\varphi_i(u_1,\ldots,u_{m-1},x)$ for any $i \leq n$, we only need to add one x for every set of parameters but $H_i(u_1,\ldots,u_{m-1})$ can be arbitrarily large. Since Axiom of Choice ensures that there is a choice function, let F be a choice function on $\mathscr{P}(()M')$. Also let $h_i(u_1,\ldots,u_{m-1}) = F(H_i(u_1,\ldots,u_{m-1}))$ for $i \leq n$, which means that h is a function that outputs an x that satisfies $\varphi_i(u_1,\ldots,u_{m-1},x)$ for $i \leq n$ and has minimal rank among all such witnesses. The induction step needs to be redefined to

$$M'_{i+1} = M'_i \cup \bigcup_j = 0^n\{h_j(u_1,\ldots,u_{m-1}) : u_1,\ldots,u_{m-1} \in M'_i\} \tag{2.16}$$

In every step, the amount of elements added in M'_{i+1} is equivalent to the amount of sets of parameters the yielded elements not included in M'_i. So the cardinality of M'_{i+1} exceeds the cardinality of M'_i only for finite M'_i. It is easy to see that if M_0 is finite, M' is countable because it was built from countable union of finite sets. If M_0 is countable or larger, cardinaly of M' is equal to the cardinality of M_0.[11] Therefore $|M'| \leq |M_0| \cdot \aleph_0$

□

TODO proc $\leq$ a ne =?

[11] It 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 is M'_i. ((proc? Ramsey?))

Theorem 2.18 *First-order Reflection*
Let $\varphi(x_1, \ldots, x_n)$ be a first-order formula.

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

$$\varphi^M(x_1, \ldots, x_n) \leftrightarrow \varphi(x_1, \ldots, x_n) \tag{2.17}$$

for every $x_1, \ldots, x_n$.

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

$$\varphi^M(x_1, \ldots, x_n) \leftrightarrow \varphi(x_1, \ldots, x_n) \tag{2.18}$$

for every $x_1, \ldots, x_n$.

(iii) For every set M_0 there is α such that $M_0 \subset V_\alpha$ and the following holds:

$$\varphi^{V_\alpha}(x_1, \ldots, x_n) \leftrightarrow \varphi(x_1, \ldots, x_n) \tag{2.19}$$

for every $x_1, \ldots, x_n$.

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

$$\varphi^M(x_1, \ldots, x_n) \leftrightarrow \varphi(x_1, \ldots, x_n) \tag{2.20}$$

for every $x_1, \ldots, x_n$.)

Proof. Let's prove (i) for one formula φ via induction by complexity first. We can safely assume that φ contains no quantifiers besides $\exists$ and no logical connectives other than $\neg$ and &. Assume that this M is obtained from lemma 2.17. The fact, that atomic formulas are reflected in every M comes directly from definition of relativization and the fact that they contain no quantifiers.[12] The same holds for formulas in the form of $\varphi = \neg\varphi'$. Let us recall the definition of relativization for those formulas in 2.1.

$$(\neg\varphi_1)^M \leftrightarrow \neg(\varphi_1^M) \tag{2.21}$$

Because we can assume from induction that $\varphi'^M \leftrightarrow \varphi'$, the following holds:

$$(\neg\varphi')^M \leftrightarrow \neg(\varphi'^M) \leftrightarrow \neg\varphi' \tag{2.22}$$

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

$$(\varphi_1 \;\&\; \varphi_2)^M \leftrightarrow \varphi_1^M \;\&\; \varphi_2^M \leftrightarrow \varphi_1 \;\&\; \varphi_2 \tag{2.23}$$

[12]Note that this does not hold generally for relativizations to M, E, but only for relativization to $M, \in$, which is our case.

Let's now examine the case when from the induction hypothesis, M reflects $\varphi'(u_1, \ldots, u_n, x)$ and we are interested in $\varphi = \exists x \varphi'(u_1, \ldots, u_n, x)$. The induction hypothesis tells us that

$$\varphi'^M(u_1, \ldots, u_n, x) \leftrightarrow \varphi'(u_1, \ldots, u_n, x) \tag{2.24}$$

so, together with above lemma 2.17, the following holds:

$$\begin{aligned} &\varphi(u_1, \ldots, u_n, x) \\ &\leftrightarrow \exists x \varphi'(u_1, \ldots, u_n, x) \\ &\leftrightarrow (\exists x \in M)\varphi'(u_1, \ldots, u_n, x) \\ &\leftrightarrow (\exists x \in M)\varphi'^M(u_1, \ldots, u_n, x) \\ &\leftrightarrow (\exists x \varphi'(u_1, \ldots, u_n, x))^M \\ &\leftrightarrow \varphi^M(u_1, \ldots, u_n, x) \end{aligned} \tag{2.25}$$

Which is what we have needed to prove:

So far we have proven part (i) of this theorem for one formula φ, we only need to verify that the same holds for any finite number of formulas. This has in fact been already done since lemma 2.17 gives us M for any (finite) amount of formulas. We can than use the induction above to verify that it reflects each of the formulas individually.

Now we want to verify other parts of our theorem. Since V_α is a transitive set, by proving (iii) we also satisfy (ii). To do so, we only need to look at part (ii) of lemma 2.17. All of the above proof also holds for $M = V_\alpha$. To finish part (iv)

TODO spocetna varianta!! □

Theorem 2.19 Reflection *is equivalent to* Infinity & Replacement *under ZFC minus* Infinity & Replacement

Proof. Since 2.18 already gives one side of the implication, we are only interested in showing the converse which we shall do in two parts:

Reflection → Infinity

Let us first find a formula to be reflected that requires a set M at least as large as V_ω. Let us consider the following formula:

$$\varphi'(x) = \forall\lambda(\lambda < x \to \exists\mu(\lambda < \mu < x)) \tag{2.26}$$

Because φ says "there is a limit ordinal", if it holds for some x, the Infinity axiom is very easy to satisfy. But we know that there are limit ordinals in ZF, therefore $\varphi = \exists x \varphi'(x)$ is a valid statement. *Reflection* then gives us a set M in which φ^M holds, that is, a set that contains a limit ordinal. So the set of off limit ordinals is non-empty and because ordinals are well-founded, it has a minimal element. Let's call it μ.

$$\mu = \bigcap \{V_\kappa \ : \ \forall \lambda (\lambda < \kappa \rightarrow \exists \mu (\lambda < \mu < \kappa))\} \tag{2.27}$$

We can see that μ is the least limit ordinal and therefore it satisfies *Infinity.*

Reflection $\rightarrow$ *Replacement*

Given a formula $\varphi(x, y, u_1, \ldots, u_n)$, we can suppose that it is reflected in any M [13] What we want to obtain is the following:

$$\forall x, y, z(\varphi(x, y, u_1, \ldots, u_n) \& \varphi(x, z, u_1, \ldots, u_n) \rightarrow y = z) \rightarrow \tag{2.28}$$

$$\rightarrow \forall X \exists Y \forall y \ (y \in Y \leftrightarrow \exists x (\varphi(x, y, u_1, \ldots, u_n) \ \& \ x \in X)) \tag{2.29}$$

We do also know that $x, y \in M$, in other words for every X, $Y = \{y \mid \varphi(x, y, u_1, \ldots, u_n)\}$ we know that $X \subset M$ and $Y \subset M$, which, together with the comprehension schema[14] implies that Y, the image of X over φ, is a set. Which is exactly the Replacement Schema we hoped to obtain. $\square$

We have shown that *Reflection* for first-order formulas, *Reflection*$_1$ is a theorem of ZF, which means that it won't yield us any large cardinals. We have also shown that it can be used instead of the Axiom of Infinity and Replacement Scheme, but ZF + *Reflection*$_1$ is a conservative extension of ZF. Besides being a starting point for more general and powerful statements, it can be used to show that ZF is not finitely axiomatizable. That is because *Reflection* gives a model to any finite number of (consistent) formulas. So if $\varphi_1, \ldots, \varphi_n$ for any finite n would be the axioms of ZF, *Reflection* would always contain a model of itself, which would in turn contradict the Second Gödel's Theorem[15]. Notice that, in a way, reflection is complementary to compactness. Compactness argues that given an infinite[16] set of sentences, if every finite subset yields a model, so does the whole set. Reflection, on the other hand, says that while the whole set has no model in the underlying theory, every finite subset does have one.

[13]Which means that for $x, y, u_1, \ldots, u_n \in M$, $\varphi^M(x, y, u_1, \ldots, u_n) \leftrightarrow \varphi(x, y, u_1, \ldots, u_n)$.
[14]Called the axiom of subsets in Levy's proof.
[15]See chapter 3.3 for further details.
[16]Countable?

Also, notice how reflection can be used in ways similar to upward Löwenheim–Skolem theorem. Since Reflection extends any set M_0 into a model of given formulas $\varphi_1, \ldots, \varphi_n$, we can choose M_0 such that the final M is at least as big as we need it to be.[17]

TODO znacit *Reflection* asi jako *Reflection*$_1$ pokud mluvime o prvoradovych formulich (definice je nahore v posledni subsection section 1)

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

[17] Too vague?

3 Reflecting Large Cardinals

In this chapter we aim to explore the possible generalisations of *Reflection* for second- and higher-order formulas and use those to establish the existence of various large cardinals. We will also argue whether there is a limit to the size of large cardinals obtainable via generalised form of *Reflection*.

3.1 Reflecting Second-order Formulas

To see that there is a way to transcend ZF, let us briefly show how a model of ZF can be obtained in ZF^2+"second-order reflection"[18]. This will be more closely examined in section 3.3.

We know that ZF can not be finitely axiomatized in first-order formulas, however if Replacement and Comprehension schemes can be substituted by second-order formulas, ZF becomes ZF^2, which is finitely axiomatizable in second-order logic. Therefore if we take second-order reflection into consideration, we can obtain a set M that is a model of ZF^2. For now, we have left out the details of how exactly is first-order reflection generalised into stronger statements and how second-order axiomatization of ZF looks like as we will examine those problems closely in the following pages.

We will now define reflection for second-order formulas.

Definition 3.1 *Second-order reflection TODO*

3.2 Preliminaries

But first, let's establish some elementary terms that will allow us to define the relevant large cardinals.

Definition 3.2 *(limit cardinal) kappa is a* limit cardinal *if it is $\aleph_\alpha$ for some limit ordinal α.*

Definition 3.3 *(strong limit cardinal) kappa is a* strong limit cardinal *if for every $\lambda < \kappa$, $2^\lambda < \kappa$*

We also need to rigorously define ZF^2, the second-order axiomatization of ZF we have already used in the previous section. Let's take advantage of second-order variables and replace Replacement and Specification schemes

[18] ZF^2 is an axiomatization of ZF in second-order formulas, to be more rigorously established later.

with a single Replacement and a Specification axiom respectively. Lower-case letters represent first-order variables and upper-case P represents a second-order variable.

Definition 3.4 Replacement^2

$$\begin{aligned}\forall P(\forall x, y, z(P(x,y)\&P(x,z) \to y \ = \ z) \to \\ \to (\forall x \exists y \forall z(z \in y \leftrightarrow \exists w \in x(P(w,z)))))\end{aligned} \tag{3.30}$$

We will denote this axiom Replacement$_2$.

Definition 3.5 Specification$_2$

$$\forall P \forall x \exists y \forall z \, (z \in y \leftrightarrow [z \in x \& P(z,x)]) \tag{3.31}$$

Definition 3.6 ZF^2
Let ZF^2 *be a theory with all axioms identical with the axioms of* ZF *with the exception of* Replacement *and* Specification *schemes, which are replaced with* Replacement$_2$ *and* Specification$_2$ *respectively.*

TODO vsechny jmena axiomu emph?
TODO sjednotit *Replacement*$_2$ s *Replacement*^{2}

TODO budeme potrebovat club sety, stacionarni mnoziny? treba abychom dokazali ekvivalence?

3.3 Inaccessibility

The inaccessible cardinal is the smallest of large cardinals[19]

Definition 3.7 *(weak inaccessibility) An uncountable cardinal* κ *is* weakly inaccessible $\leftrightarrow$ *it is* regular *and* limit.

Definition 3.8 *(inaccessibility) An uncountable cardinal* κ *is* inaccessible $\leftrightarrow$ *it is* regular *and* strongly limit.

Note that the above requirements could in fact be satisfied by V_ω, except for the need for uncountability, which is being added exactly to leave out V_ω for practical purposes.[20]

We will now show that the above notion is equivalent to the definition Levy uses in [2], which is, in more contemporary notation, the following:

[19] citation needed.

[20] Informally, this clearly illustrates the fact stressed in section 1, that large cardinals are obtained by similar way of thining that lead mathematicians to establish ω as an actual object.

Theorem 3.9 *The following are equivalent:*[21]

1. *κ in inaccessible*
2. $\langle V_\kappa, \in \rangle \models \mathsf{ZFC}$

Proof. Let's first prove that if κ is inaccessible, it is a model of ZFC. We will do that by verifying the axioms of ZFC just like Kanamori does it in **1.2** in [1]. Because κ is a limit ordinal, there's no need for us to verify the Powerset, Foundation, Extensionality, Subset, Pairing and Union axioms and the Specification scheme. Thus we only have the Replacement Scheme to verify.

Given an arbitrary set $x \in V_\kappa$ and a function $F : x \to V_\kappa$, we need to verify that $y = F[x]$ is indeed a set and that it is an element of V_κ. The fact that F is a function imples that $|y| \leq |x|$. It follows from Specification that $y \subset V_\kappa$, which is still not exactly what we want. Let $\alpha < \kappa$ be the least ordinal such that $y \in V_\alpha$[22], since $V_{\alpha+1} = \mathscr{P}(()V_\alpha)$, $y \in V_{\alpha+1}$, together with $\alpha + 1 < \kappa$ this means that $y \in V_\kappa$.

We will now show that if a set is a model of ZFC, it is in fact an inaccessible cardinal. So let V_κ be a model of ZFC which means that it is closed under the powerset operation, in other words:

$$\forall \lambda (\lambda < \kappa \to 2^\lambda < \kappa) \tag{3.32}$$

which is exactly the definition of strong limitness. κ is regular from the following argument by contradiction:
Let us suppose for a moment that κ is singular. Therefore there is an ordinal $\alpha < \kappa$ and a function $F : \alpha \to \kappa$ such that the range of F in unbounded in κ, in other words, $F[\alpha] \subseteq V_\kappa$ and $sup(F[\alpha]) = \kappa$. In order to achieve the desired contradiction, we need to see that it is the case that $F[\alpha] \in V_\kappa$. Let $\varphi(x, y)$ be the following first-order formula:

$$F(x) = y \tag{3.33}$$

Then there is an instance of Axiom Schema of Replacement that states the following:

$$\begin{aligned}(\forall x, y, z(\varphi(x, y) \& \varphi(x, z) \to y = z)) \to \\ \to (\forall x \exists y \forall z (z \in y \leftrightarrow \exists w(\varphi(w, z)))\end{aligned} \tag{3.34}$$

[21] TODO skutecne plati na obe strany? viz http://math.stackexchange.com/questions/1060005/h-kappa-a-model-of-all-the-axioms-of-zfc-for-kappa-not-inaccessible

[22] TODO pozor – jak vime ze takove alpha existuje?

Which in turn means that there is a set $y = F[\alpha]$ and $y \in V_\kappa$, which is the contradiction with $sup(y) = \kappa$ we are looking for. $\square$

The same holds for ZF^2, the proof is very similar.

Theorem 3.10

$$V_\kappa \models \mathsf{ZF}^2 \leftrightarrow \kappa \textit{ is inaccessible} \tag{3.35}$$

Proof. κ is a strong limit cardinal because from ZF^2 and the Powerset Axiom we know that for every $\lambda < \kappa$, we know that $2^\lambda < \kappa$.

κ is also regular, because otherwise there would be an ordinal α and a function $F : \alpha \to \kappa$ with a range unbounded in κ. *Replacement*^{2} gives us a set $y = F[\alpha]$, so $y \in V_\kappa$, which contradicts the fact that $sup(y) = \kappa$. It can not be the case that $\kappa \in V_\kappa$.

The other direction is exactly like the first part of above theorem 3.9. $\square$

We have transcended ZF, but that is just a start. Naturally, we could go on and consider the next inaccessible cardinal, which is inaccessible with respect to the theory $\mathsf{ZF} + \exists\kappa(\kappa \models \mathsf{ZF})$. But

TODO α-inaccessibles etc?

TODO mention fixed-point phenomena

TODO typografie – mezery kolem vsech = a asi i vyrokovych ostatnich spojek

TODO krok smerem k Mahlovym kardinalum

3.4 Mahlo Cardinals

TODO viz [4] Rucker – 253 - 265 !!

TODO reflektuji nedosazitelnost?

TODO zminit Mahlovu konstrukci v Levym?

TODO zavest pomoci reflexe

ocisluj nedosazitelne kardinaly, Mahlovy kardinaly jsou pevne body (ale pevne body nejsou Mahlovy kardinaly)

Definition 3.11 *Weakly Mahlo Cardinals κ is* weakly Mahlo $\leftrightarrow$ *it is a limit ordinal and the set of all regular ordinals less then κ is stationary in κ*

TODO napsat co to znamena

Thus a Mahlo cardinal κ is not only inaccessible, but also has κ inaccessibles below it.

Definition 3.12 *Mahlo cardinals*
The folllowing definitions are equivalent:

(i) κ *is Mahlo*
(ii) κ *is weakly Mahlo and strong limit*
(iii) κ *is inaccessible and the regular cardinals below* κ *form a stationary subset of* κ*.*
(iv) κ *is regular and the stationary sets below* κ *form a stationary subset of* κ*.*
(v) $\{\lambda < \kappa : \lambda isinaccessible\}$ *is stationary in* κ*.*

TODO κ is hyper-Mahlo iff κ is inaccessible and the set $\{\lambda < \kappa : \lambda isMahlo\}$ is stationary in κ.

Note that Mahlo cardinals were first described in 1911, almost 50 years before Lévy's reflection, which was heavily inspired by them.

" We also state the appropriate generalization for greatly Mahlo cardinals."

3.5 Weakly Compact Cardinals

TODO souvislost s reflexi!

TODO co je "partition property"?

Definition 3.13 *A cardinal* κ *is* weakly compact *if it is uncountable and satisfies the partition property* $\kappa \to (\kappa)^2$

opsano z jecha!

3.6 Indescribable Cardinals

TODO uvod / intuice

TODO souvislost s reflexi

3.7 Bernays–Gödel Set Theory

TODO Plagiat – prepsat a vysvetlit

TODO

3.8 Reflection and the constructible universe

TODO reflektovat muzeme jenom kardinaly konzistentni s V=L, proc?

TODO Plagiat – prepsat a vysvetlit

L was introduced by Kurt Gödel in 1938 in his paper *The Consistency of the Axiom of Choice and of the Generalised Continuum Hypothesis* and denotes a class of sets built recursively in terms of simpler sets, somewhat similar to Von Neumann universe V. Assertion of their equality, $V = L$, is called the *axiom of constructibility.* The axiom implies GCH and therefore also AC and contradicts the existence of some of the large cardinals, our goal is to decide whether those introduced earlier are among them.

On order to formally establish this class, we need to formalize the notion of definability first:

TODO zduvodneni

TODO kratka diskuse jestli refl implikuje transcendenci na L - polemika, nazor - V=L a slaba kompaktnost a dalsi

TODO asi nekde bude meritelny kardinal

4 Higher-order reflection

TODO rict ze to je zobecneni a nejaky dalsi uvodni veci

4.1 Sharp

TODO je tohle higher-order vec?

4.2 Welek: Global Reflection Principles

TODO ma to vubec cenu?

5 Conclusion

TODO na konec

References

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