

Connections between the Minimalist Foundation and Bishop’s constructive mathematics

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Abstract

We describe what characteristics of the Minimalist Foundation, for short **MF**, agree with Bishop’s conception of constructive mathematics and what differ from it. In particular we explain why adopting the pointfree approach of formal topology to develop mathematics in **MF**. We then end by describing an extension of **MF** with choice principles closer to Bishop’s conception of constructive mathematics.

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1 Introduction

A central aspect of Bishop’s constructive mathematics in [Bis67, BB85] emphasized in [BR87] is that of being a generalization of classical mathematics. Indeed, contrary to other constructive approaches, such as Brouwer’s intuitionistic mathematics or Markov’s recursive mathematics, in his mathematical development Bishop did not use any principle incompatible with classical mathematics as that formalizable in Zermelo-Fraenkel set theory. In this way Bishop produced an analysis of mathematical concepts that is finer than in other approaches.

Bishop himself in [Bis67, Bis70] and in unpublished notes sketched a foundation for his mathematics. Many proposals of a formal system apt to founding his constructive mathematics followed afterwards in the style of axiomatic set theory [Myh75, Acz78, Acz82, Acz86, Fef79] and in that of type theory by Martin-Löf in [Mar75, NPS90].

Most notably the so called notion of “setoid” over Martin-Löf’s type theory appears to be close to the idea of “set” sketched in [Bis67] as well as the notion of “type-theoretic function” appears to be an adequate representation of Bishop’s notion of “operation” because it explicitly shows its computational contents or “numerical meaning”.

Then the model of setoids formalized over Martin-Löf’s type theory appears to be a suitable framework where to formalize Bishop’s constructive mathematics. A whole study of its categorical structure as a quotient completion had been started and it is still on (see for example [NPS90, PW14, MR13b, MR13a, MR15]) and many different kinds of setoid models had been considered (see for example [Hof95, BCP03]).

The main drawback of the formalization of mathematics in the setoid models is that it is very far from the language used in the informal mathematical practice of constructive proofs, including that in Bishop’s literature and even more that of classical mathematics. This is because the formalization in this model, and more general in Martin-Löf’s type theory, requires to handle lots of computational details useful for the extraction of programs from proofs but apparently useless to develop the constructive proofs themselves.

To overcome this problem in [SV98] it was proposed that Martin-Löf’s type theory should be extended with some abstract concepts, like that of “proof-irrelevant proposition” and that of “subset”, as soon as they satisfy the *forget-restore principle* introduced by the second author of the present paper. This principle states that one can abstract away from irrelevant computational information when these information can be restored in the process of extracting a program from a constructive proof.

Pushing forward the idea of the forget-restore principle, in [MS05] we introduced the notion of *two-level foundation* for constructive mathematics. Such a foundation should consist of:

- one theory acting as the *extensional level* written in a language close to the usual mathematical practice of proofs;
- another theory acting as the *intensional level* written in a type-theoretic language suitable for extraction of programs from proofs;
- an interpretation of the extensional level in (a model of) the intensional level showing that the extensional level has been obtained from the intensional one following the forget-restore principle.

The introduction of a two-level foundation was also motivated by the need of building a new foundation for constructive mathematics. Indeed since 2005 with [MS05] we embarked in the project of building a *Minimalist Foundation* where the mathematics developed in it turns out to be compatible with the different approaches to constructivism, and also with classical mathematics. To this purpose to formalize Bishop’s mathematics we intended to build an intuitionistic and predicative foundation finer than the formal systems available in the literature and characterized by the lack of whatsoever choice principle, including the so called *axiom of unique choice*.

In [Mai09] a full formal system, called “Minimalist Foundation”, here named **MF** for short, was proposed.

In parallel, also a new approach to constructivism, called “dynamic”, was put forward in [Sam02, Sam08, Sam11, Sam12, Sam17, Sam19]. This is inspired by the constructive approach originated explicitly with Brouwer in the beginning of last century and revived in the 60s and 70s by Bishop [Bis67], Martin-Löf [Mar70] and others.

In the following we are going to describe what aspects of our minimalist approach and **MF** are in common with Bishop’s one, called **BISH**, and what differ.

The main common aspects include the following ones:

- the compatibility with classical mathematics via a language close to that of usual mathematical practice;
- the need of compiling this language in a strictly algorithmic language to extract the computational contents of constructive proofs.

Both aspects are fulfilled in **MF** by crucially employing its two-level structure.

Indeed compatibility with the standard Zermelo-Fraenkel foundation for classical mathematics is fulfilled at the extensional level of **MF** while the extraction of programs from proofs at its intensional level. In particular the intensional level can be interpreted in a realizability semantics extending *Kleene realizability of intuitionistic arithmetic* as shown in [IMMS18]. This fact has two main consequences which emphasize the constructivity of the whole **MF**.

The first is that the intensional level of **MF** is consistent with *full axiom of choice* and *formal Church thesis* as advocated in [MS05]. This characteristic is generally not satisfied by the other constructive intensional foundations in the literature. In particular, it is an open problem whether Martin-Löf type theory in [NPS90] enjoys such a consistency property.

The second consequence is that the extensional level of **MF** turns out to be consistent with the formal Church thesis (see [MM16]) via its interpretation at the intensional level.

Furthermore, the intensional level of **MF** could serve as a base for a minimalist proof-assistant whose formalized proofs can, a priori, be reused in proof-assistants based on the many extensions. This would be a practical application of the fact that **MF** can well serve as a basic theory where to compare the different approaches to mathematics and their proofs.

Then, we underline some major peculiarities of **MF** not present in Bishop’s conception of mathematics **BISH**.

One main difference is about the concept of function. As in **BISH** in **MF** we both have the notion of *operation* with the meaning of representing a computable function, and that of functional relation. However contrary to **BISH** and other type-theoretic foundations for **BISH**, in **MF** these two notions are kept well distinct by the fact that, while operations between two sets do form a set, functions do not generally do. This distinction is guaranteed by the lack of the general validity of choice principles in both levels of **MF** (see [Mai17]). Indeed it is enough to add a rule of unique choice to both levels of **MF** to guarantee the validity of the axiom of unique choice which makes the two notions coincide.

There is a major consequence of the absence of choice principles from **MF** combined with its predicative nature (even à la Feferman see [MM14, MM16, IMMS18]) when adopting **MF** to develop topology. It is that the constructive pointfree approach to topology introduced by Martin-Löf and the second author in the 80s [Sam87] under the name of *formal topology* constitutes not only a valid alternative to pointwise approaches for constructive analysis by Brouwer (see [Tv88]) and Bishop (see [Bis67, BB85]), but it appears to be compulsory. The main reason, as sketched in [Mai12, Mai18], is that in **MF** real numbers, either as Dedekind cuts or as Cauchy sequences, cannot be proven to be sets. Also choice sequences of Baire and Cantor spaces do not form a set. All this is a consequence of the fact that in **MF** functional relations between two sets do not generally form a set. Instead a priori, using Martin-Löf’s type theory in [NPS90] as a foundation, both pointwise approaches and pointfree ones could seem legitimate. In fact, one can define a pointwise topology on Dedekind real numbers, because these are in bijective correspondence with Cauchy sequences and the latter can be represented in Martin-Löf’s type theory as a setoid. Also in the predicative foundation of Aczel’s Constructive set theory CZF [Acz78, Acz82, Acz86] both Dedekind reals and Cauchy reals form a set and a pointwise approach is also possible.

In the paper we recall the basic definitions of formal topology necessary to introduce the mentioned example of real numbers and Baire and Cantor spaces by underlying how they are formalized in **MF**.

The way constructive topology is formalized in **MF** well agrees with our minimalist attitude, especially if we want to work in a constructive foundation compatible with classical predicativity where we can distinguish the real (effective) structure of a topology from a corresponding ideal (infinite) structure of formal points.

A major benefit from developing pointfree topology in **MF** in the form of formal topology is that we gain in clarity and in an analysis of topological concepts finer than in other foundations.

Finally we conclude by describing an extension of **MF**, actually of its extensional level, which appears closer to **BISH**.

This extension of **MF** is characterized by the validity of choice principles including the axiom of unique choice and the axiom of countable choices. It should also be interpretable in Martin-Löf’s type theory to form a two-level foundation by extending the interpretation in [Mai09]. But a proof of this is left to future work.

2 Why adopting a Minimalist Foundation.

A plurality of philosophical reasons for a constructive approach to mathematics have been proposed, both before and after Brouwer and Bishop.

Presently, various logical systems to formalize constructive mathematics are available in the literature. They range from axiomatic set theories, as Aczel’s CZF [Acz78, Acz82, Acz86] or Friedman’s IZF [Bee85], to the internal theory of categorical universes as topoi or pretopoi [MM92, JM95, Mai05a], to type theories as Martin-Löf’s type theory [NPS90] or Coquand’s Calculus of Inductive Constructions [Coq90, CP90]. No existing constructive foundation has yet superseded the others as the standard one, as Zermelo-Fraenkel axiomatic set theory did for classical mathematics.

Also various machine-aided proof development systems are available to implement mathematics (see, for example, [Wie06]). Many of those for constructive mathematics are based on type systems which are also paradigm of (functional) programming languages with the possibility of extracting the computational contents of constructive mathematical proofs. Some of these, as for example Coq [Coq10] or Matita [ARCT11], are based on impredicative typed systems, while some others, as for example

Agda [BDN09] and Nuprl [ABC⁺06], are based on predicative ones.

Beginning with [MS05], we embarked in the project of developing a foundation with minimal assumptions. The main reason for this choice is to support our general attitude to preserve all effective notions and conceptual distinctions as much as possible, with no a priori exception. The result is a foundation which is minimalist also in the sense that it becomes a common core among the most relevant constructive foundations. Thus we expect that such a minimalist foundation should be useful not only to constructive mathematicians but also to logicians, for example as a base system to do constructive reverse mathematics, and also to computer scientists, as a base for a *minimalist* proof-assistant suitable for formalizing reusable proofs and for program extraction from proofs.

2.1 Why founding constructive mathematics on a two-level theory

In our opinion, a constructive foundation should make evident those key aspects which differentiate constructive mathematics from classical mathematics. For example, a typical characteristic of constructive proofs, contrary to classical ones, is the possibility of extracting programs computing witnesses of true existential statements occurring in them.

Even better, any proof in a constructive system should be seen as a program. Hence, a foundation for constructive mathematics should be at the same time a theory of sets, in which to formalize mathematical theorems, and a programming language, in which to extract the computational contents of mathematical proofs.

In [MS05] we argued that such a constructive foundation (validating Heyting arithmetics at least) should be a two-level theory consisting of:

- a level, called *extensional*, which should be an extensional set theory (with undecidable equality of sets and elements) formulated in a language close to that used in the common practice of developing mathematics;
- another level, called *intensional*, which should be an intensional theory (with decidable equality of sets and elements) enjoying extraction of programs from proofs; according to [MS05] this level should be possibly a proofs-as-programs theory, i.e. a theory consistent with the axiom of choice

$$(AC) \quad \forall x \in A \exists y \in B R(x, y) \longrightarrow \exists f \in A \rightarrow B \forall x \in A R(x, f(x))$$

for A, B sets and $R(x, y)$ a logical relation, and the formal Church thesis for functions between natural numbers denoted with the symbol $Fun(Nat, Nat)$

$$(CT) \quad (\forall f \in Fun(Nat, Nat) \quad (\exists e) \in Nat \quad (\forall x \in Nat \exists y \in Nat T(e, x, y) \& U(y) = f(x))$$

where Nat is the set of natural numbers and $T(e, x, y)$ is the Kleene predicate expressing that y is the computation executed by the program numbered e on the input x and $U(y)$ is output of the computation y .

- Then, in order to guarantee the extraction of programs even from proofs written at the extensional level, we required that the extensional level should be obtained as an abstraction of the intensional level according to the forget-restore principle proposed by the second author of the present paper in [SV98].

The link between the two-levels was then made more technical in [Mai09], by requiring that the extensional level should be interpreted in the intensional one by means of a quotient completion of the latter, i.e. the extensional level should be seen as (a fragment of) the internal language of a quotient completion built on the intensional one.

This kind of link captures what happens in the practice of computer-aided formalization of mathematics in an intensional type theory, which makes use of the so called model of “setoids” built on it (see [Hof97, BCP03]). Actually another motivation behind the notion of two-level foundation in [MS05, Mai09] is the desire of making explicit the extensional theory validated in the quotient model used to formalize mathematical proofs in intensional type theory.

Our two-level structure where the intensional level is consistent with axiom of choice and formal Church thesis fully agrees with Bishop's need of exhibiting the computational contents of constructive proofs, in particular of existential statements whose witness can be chosen computationally (see chapter 1 of [Bis67] and [Bis70]).

3 The Minimalist Foundation

In [Mai09] we presented a two-level formal system which satisfies the requirements in [MS05] of a two-level foundation for constructive mathematics. We call this system *the two-level minimalist foundation*, for short **MF**. We are aware, however, that a specific formal system, which is static by definition, cannot fully capture the dynamics of the minimalist approach to constructivism, started in [MS05, Sam08, Sam11, Sam12].

The two levels of **MF** are both given by a type theory à la Martin-Löf: the intensional level, called mTT, is an intensional type theory including aspects of Martin-Löf's one in [NPS90] (and extending the set-theoretic version in [MS05] with collections), and its extensional level, called emTT, is an extensional type theory including aspects of extensional Martin-Löf's one in [Mar84]. Then a quotient model of setoids à la Bishop [Bis67, Hof97, BCP03, Pal05a] over the intensional level is used in [Mai09] to interpret the extensional level in the intensional one. A categorical study of this quotient model has been carried on in [MR13b, MR13a, MR15] and related to the construction of Hyland's effective topos [Hyl82, HJP80].

In the following we explain the main characteristics of the extensional level emTT and of mTT viewed more as a many sorted logic than as a type theory. This is because both levels of **MF** are given by a type theory that includes a primitive notion of proposition, which allows us to control the validity of choice principles.

Need of two types of entities: sets and collections. A minimalist foundation for constructive mathematics should certainly be based on intuitionistic predicate logic and include at least the axioms of Heyting arithmetic. Hence we could expect to build it starting from a many-sorted logic, such as Heyting arithmetic of finite types [Tv88], where sorts, that we call *types*, include the basic sets we need to represent our mathematical entities.

However, in order to develop topology in an intuitionistic and predicative way, we need a foundation with two kinds of entities: sets and collections. The main reason is that the *power of a non-empty set*, namely the discrete topology over a non-empty set, fails to be a set in a predicative foundation, and it is only a *collection*.

Need of two types of propositions. In parallel with the presence of sets and collections, to keep the system predicative we also need to distinguish two types of propositions: those closed under quantifications on sets, called here *small propositions* as in [Mai09] (and *proper propositions* in [Sam]), from those closed under any kind of quantification, called here simply *propositions* as in [Mai09] (and *improper propositions* in [Sam]). Both kind of propositions include propositional equalities which are small propositions only if they refer to elements of a set.

Need of two types of functions. It is well known that *adding the principle of excluded middle* to some constructive foundations, as Aczel's CZF or Martin-Löf's type theory, one can derive that *power-collections become sets* and thus get an impredicative theory. In both such theories this is due to the fact that the collection of functions from a set A to the boolean set $\{0, 1\}$, called *exponentiation of the boolean set over A* , forms a set, too. Therefore, if we wish compatibility with classical theories where the power of a non-empty set is not a set as in Feferman's predicative theories [Fef79], we need to avoid exponentiation of functions.

A drastic solution is to drop all axioms yielding any form of exponentiation. What we propose is to allow exponentiation only of a certain kind, as it happens in [Fef79]. To this purpose, we introduce a primitive notion of *operation*, represented by certain functional terms

$$f(x) \in B \ [x \in A]$$

in a set B with a free variable in the set A . These operations can be defined as *type-theoretic functions* of a type theory, like in Martin-Löf's type theories [NPS90, Mar84]. Clearly any operation $f(x) \in B [x \in A]$ must give rise to a functional relation $f(x) =_B y [x \in A, y \in B]$, i.e. what is usually called function. What we do not wish to guarantee is the converse. Our idea is then that *only exponentiation of operations from a set A to a set B forms a set*.

3.1 The main types of the extensional level of the Minimalist Foundation

The formal system emTT of the extensional level of the Minimalist Foundation in [Mai09] is written in the style of Martin-Löf's type theory [NPS90] by means of the following four kinds of judgements:

$$A \text{ type } [\Gamma] \quad A = B \text{ type } [\Gamma] \quad a \in A [\Gamma] \quad a = b \in A [\Gamma]$$

that is the type judgement (expressing that something is a specific type), the type equality judgement (expressing that two types are equal), the term judgement (expressing that something is a term of a certain type) and the term equality judgement (expressing the *definitional equality* between terms of the same type), respectively, all under a context Γ .

The word *type* is used as a meta-variable to indicate four kinds of entities: collections, sets, propositions and small propositions, namely

$$\text{type} \in \{ \text{coll}, \text{set}, \text{prop}, \text{prop}_s \}$$

Therefore, in emTT types are actually formed by using the following judgements:

$$A \text{ set } [\Gamma] \quad B \text{ coll } [\Gamma] \quad \phi \text{ prop } [\Gamma] \quad \psi \text{ prop}_s [\Gamma]$$

saying that A is a set, that B is a collection, that ϕ is a proposition and that ψ is a small proposition.

Here, contrary to [Mai09] where we use only capital latin letters as meta-variables for all types, we use greek letters ψ, ϕ as meta-variables for propositions and capital latin letters A, B as meta-variables for sets or collections, and small latin letters a, b, c as meta-variables for terms, i.e. elements of the various types.

Observe that for a set A , when we say that

$$a \in A [\Gamma]$$

is derivable in emTT, we actually mean that the term a is an element of the set A under the context Γ and hence the symbol \in stands for a *set membership*. As usual in type theory, *equality of sets* is given *primitively* and is not defined by equating sets with the same elements. This is indeed a main difference between a set theory defined as a typed system in the style of Martin-Löf's type theory [NPS90] and an axiomatic set theory à la Zermelo-Fraenkel.

We now proceed by briefly describing the various kinds of types in emTT, starting from small propositions and propositions, then sets and finally collections.

Small propositions in emTT include all the logical constructors of intuitionistic predicate logic with equality and quantifications restricted to sets:

$$\phi \text{ prop}_s \equiv \perp \mid \phi \wedge \psi \mid \phi \vee \psi \mid \phi \rightarrow \psi \mid \forall x \in A \phi(x) \mid \exists x \in A \phi(x) \mid x =_A y$$

provided that A is a set. Here we use the more familiar $x =_A y$ for the *extensional equality type* $\text{Eq}(A, a, b)$ of Martin-Löf type theory in [Mar84].

Then, *propositions* of emTT include all the logical constructors of intuitionistic predicate logic with equality and quantifications on all kinds of types, i.e. sets and collections. Of course, small propositions are also propositions.

$$\phi \text{ prop} \equiv \phi \text{ prop}_s \mid \phi \wedge \psi \mid \phi \vee \psi \mid \phi \rightarrow \psi \mid \forall x \in B \phi(x) \mid \exists x \in B \phi(x) \mid x =_B y$$

In order to close sets under comprehension, for example to include the set of positive natural numbers $\{x \in \mathbb{N} \mid x \geq 1\}$, and to define operations on such sets, we need to think of propositions as types of their proofs: small propositions are seen as sets of their proofs while generic propositions are seen as collections of their proofs. That is, we add to emTT the following rules

$$\text{prop}_s\text{-into-set) } \frac{\phi \text{ prop}_s}{\phi \text{ set}} \qquad \text{prop-into-coll) } \frac{\phi \text{ prop}}{\phi \text{ coll}}$$

The difference between the notion of set and collection will be explained later.

A key feature of the extensional typed system emTT is proof irrelevance of propositions. This means that in emTT a proof of a proposition, if it exists, is *unique* and equal to a canonical proof term called *true* thanks to the following rules

$$\text{prop-mono) } \frac{\phi \text{ prop } [\Gamma] \quad p \in \phi [\Gamma] \quad q \in \phi [\Gamma]}{p = q \in \phi [\Gamma]} \qquad \text{prop-true) } \frac{\phi \text{ prop} \quad p \in \phi}{\text{true} \in \phi}$$

Proof-irrelevance of propositions justifies the introduction of a judgement asserting that *a proposition ϕ is true under a context Γ assuming propositions ψ_1, \dots, ψ_m true* as in [Mar84, Mar85]. This judgement can be directly interpreted in emTT as follows:

$$\phi \text{ true } [\Gamma; \psi_1 \text{ true}, \dots, \psi_m \text{ true}] \equiv \text{true} \in \phi [\Gamma, y_1 \in \psi_1, \dots, y_m \in \psi_m]$$

In emTT *sets* are characterized as inductively generated types and they include the following:

$$A \text{ set} \equiv \phi \text{ prop}_s \mid N_0 \mid N_1 \mid \text{List}(A) \mid \Sigma_{x \in A} B(x) \mid A + B \mid \Pi_{x \in A} B(x) \mid A/\rho$$

where the notation N_0 stands for the empty set, N_1 for the singleton set, $\text{List}(A)$ for the set of lists on the set A , $\Sigma_{x \in A} B(x)$ for the indexed sum of the family of sets $B(x)$ *set* $[x \in A]$ indexed on the set A , $A + B$ for the disjoint sum of the set A with the set B , $\Pi_{x \in A} B(x)$ for the product type of the family of sets $B(x)$ *set* $[x \in A]$ indexed on the set A , and A/ρ for the quotient set provided that ρ is a small equivalence relation $\rho \text{ prop}_s [x \in A, y \in A]$. Moreover, we call \mathbb{N} the set of natural numbers represented by $\text{List}(N_1)$.

The notion of set in emTT agrees with that in Bishop [Bis67] and Martin-Löf [Mar70]. According to them sets must have an effective nature which is mostly forgotten in any axiomatic approach where a universe of sets closed under certain properties is assumed as given?? as the underlying range of the set variables?? In fact, each set A must be specified by providing a finite number of rules to construct all its elements (see the rules of emTT forming elements of sets in [Mai09]). It is understood that the rules defining a set are inductive, that is, their application can be iterated any finite number of times. The infinite is only potential, and in a certain sense it is always reduced to a finite description, at a higher order: not a finite number of elements, but a finite number of rules to generate (the infinite number of) them. In particular the elements of the product type $\Pi_{x \in A} B(x)$ are only terms

$$b(x) \in B(x) [x \in A].$$

In the case the family $B(x)$ *set* $[x \in A]$ is just a constant set B indexed on the set A , we indicate the product type simply as

$$A \rightarrow B \equiv \Pi_{x \in A} B$$

and its elements are just *operations*

$$b(x) \in B [x \in A]$$

Hence, in emTT *operations between two sets form a set*, but generic functions between them do not.

Finally, *collections* in emTT include the following types:

$$B \text{ coll} \equiv A \text{ set} \mid \phi \text{ prop} \mid \mathcal{P}(1) \mid A \rightarrow \mathcal{P}(1) \mid \Sigma_{x \in B} C(x)$$

where $\mathcal{P}(1)$ and $A \rightarrow \mathcal{P}(1)$ stand for the power-collections of the singleton and of a set A respectively, and $\Sigma_{x \in B} C(x)$ stands for the indexed sum of the family of collections $C(x)$ *col* $[x \in B]$ indexed on the collection B . Actually, for a set A , we will use the common abbreviation of power-collection

$$\mathcal{P}(A) \equiv A \rightarrow \mathcal{P}(1)^1$$

Elements of the power-collections rely on the notion of subset, which in emTT is inspired by that in [SV98] put on top of Martin-Löf's type theory. A *subset of a set* A is defined as the equivalence class of a *small* propositional function $\phi(x)$ depending on one argument in A with respect to the equivalence relation of equiprovability. This is the minimum we must require in order to close subsets under comprehension. Indeed, for any small propositional function $\phi(x)$ *prop_s* $[x \in A]$ on a set A we can define its subset comprehension as

$$\{x \in A \mid \phi(x)\} \in \mathcal{P}(A)$$

Moreover, two equiprovable small propositional functions give rise to the same subset, that is in emTT we can derive

$$\frac{\phi_1(x) \leftrightarrow \phi_2(x) \text{ true } [x \in A]}{\{x \in A \mid \phi_1(x)\} =_{\mathcal{P}(A)} \{x \in A \mid \phi_2(x)\} \text{ true}}$$

In the following we indicate subsets of a set A with capital letters $U, V, W \dots$.

Associated with the notion of subset we have also a *subset membership* indicated with the symbol ϵ , which we distinguish from the primitive set membership \in used to say that an element belongs to a certain set. Given a subset $U \subseteq A$ of a set A , i.e. $U \in \mathcal{P}(A)$, for any $a \in A$ we define a new small proposition

$$a \in U \text{ prop}_s .$$

We can prove in emTT that

$$U = \{x \in A \mid x \in U\} \in \mathcal{P}(A)$$

and also that, for any small propositional function $\phi(x) \in \text{prop}_s [x \in A]$ on the set A and for any element $a \in A$,

$$a \in \{x \in A \mid \phi(x)\} \leftrightarrow \phi(a) \text{ true}$$

The subset equality is equivalent to usual extensional equality with respect to membership ϵ , namely we can derive in emTT that

$$\forall x \in A (x \in U \leftrightarrow x \in W) \leftrightarrow U =_{\mathcal{P}(A)} W \text{ true}$$

and, of course, that

$$\{x \in A \mid \phi(x)\} =_{\mathcal{P}(A)} \{x \in A \mid \psi(x)\} \leftrightarrow \forall_{x \in A} (\phi(x) \leftrightarrow \psi(x)) \text{ true}$$

In particular, $\mathcal{P}(1)$ denotes the power-collection of the singleton N_1 and its elements are equivalence classes of small propositions closed under the equivalence relation of equiprovability.

The fact that subset equality corresponds to usual extensional equality of sets suggests that we can view the subset theory in emTT as a *local set theory* where subsets of a set A can be considered *local sets* [Bel88] in the style of Zermelo-Fraenkel set theory. Then, membership and extensional equality via elements becomes a local property restricted to a given set A . To this purpose, observe that among subsets of A , there is A itself thought of as the subset

$$\{x \in A \mid \text{tt}\}$$

where tt is any tautology. Moreover, we can define quantifiers relativized to a subset; this means that, if $U \subseteq A$ and φ is a propositional function with an argument in A , we write $\exists x \in U \varphi$ as an abbreviation for $\exists x \in A (x \in U \ \& \ \varphi)$, and $\forall x \in U \varphi$ as an abbreviation for $\forall x \in A (x \in U \rightarrow \varphi)$. A consequence of these definitions is that all laws of many-sorted intuitionistic logic regarding quantifiers extend to quantifiers relativized to a subset.

¹The notation $A \rightarrow \mathcal{P}(1)$ for the power-collection $\mathcal{P}(A)$ is used to remember that its elements are operations from a set A to the power-collection on the singleton.

Note that the membership relation ϵ between terms and subsets is crucial in emTT to obtain an embedding of subsets into sets, which associates the set

$$\Sigma_{x \in A} x \in U \text{ set}$$

with a subset $U \subseteq A$. In this way an operation from $U \subseteq A$ to a set B can be represented as an operation in $\Sigma_{x \in A} x \in U \rightarrow B$.

The emTT-distinction between set and collection is analogous to the distinction between set and class in axiomatic set theory. But while in axiomatic set theory the distinction is mainly due to problems with consistency (or size), here it is motivated by quality of information and preservation of predicativity. Indeed, sets are kept distinct from collections to be able to keep a distinction between computable, effective domains (represented by sets) and non computable ones (represented by collections). This distinction is also extended to propositions in emTT by selecting small propositions as those propositions closed only under quantifications over sets and only under propositional equality only on sets. Then, to avoid an impredicative power-collection of a set, a subset must be defined as an equivalence class of small propositional functions and not of generic ones. ??

An important conceptual reason why even the power-collection $\mathcal{P}(1)$ of the singleton is only a collection and not a set is that in emTT we intend the notion of small proposition as *open*. The same we do for that of proposition, of set and of collection. Indeed, whilst we have fixed the system emTT, new sets or collections can be introduced at any time. This implies in particular that the collection of small propositions (quotiented under equiprovability) is not a set. Indeed, each time we fix our propositions or sets by fixing a formal system, both notions become inductively generated. However, we cannot support an induction principle inside the formal system, given that the number of inductive hypotheses should change any time we introduce a new set or proposition. This is different from the induction principle on the set of natural numbers, which has only two hypothesis: what we do on the number zero, and with any successor number.

3.2 The main types of the intensional level of the Minimalist Foundation

Here we briefly describe the main types of the formal system mTT of the intensional level of the Minimalist Foundation in [Mai09] by simply pointing out the differences with those of emTT.

In essence mTT is a dependent type theory which provides a *predicative version* of Coquand's Calculus of Constructions in [Coq90]. It is written in the style of *intensional* Martin-Löf's type theory [NPS90] by means of the following four kinds of judgements:

$$A \text{ type } [\Gamma] \quad A = B \text{ type } [\Gamma] \quad a \in A [\Gamma] \quad a = b \in A [\Gamma]$$

As emTT, mTT includes *small propositions* and *propositions* which are closed under the same type constructors as those in emTT except that the propositional equality type is written $\text{ld}(A, a, b)$ and has proper rules specifying its elements. There are also the rules stating that small propositions are propositions, that small propositions are sets and that propositions are collections. A main difference with respect to emTT is that in mTT the rules **prop-mono**) and **prop-true**) are omitted. As a consequence all propositions in mTT are seen as types of their proofs which are *not in general unique* as usual in intensional type theory. Moreover, as in the intensional version of Martin-Löf's type theory, in mTT the definitional equality of terms of the same type given by the judgement

$$a = b \in A [\Gamma]$$

which should be computable, is *no longer equivalent* to the propositional equality type

$$\text{ld}(A, a, b) \text{ prop } [\Gamma]$$

which is not necessarily computable and not necessarily equipped with only one proof.

Sets in mTT are closed under the same constructors as those in emTT with the exception of the quotient set constructor A/ρ . As in emTT, in mTT there is also the rule stating that sets are collections.

Finally, *collections* in mTT include the same constructors as those of emTT except that the power-collection of the singleton $\mathcal{P}(1)$ is replaced by the universe of small propositions prop_s as well as the

power-collection constructor $A \rightarrow \mathcal{P}(1)$ on a set A is replaced by the collection of propositional functions $A \rightarrow \text{prop}_s$ on the set A .

The dependent type theory mTT was designed in order to serve as a base for a proof-assistant.

3.3 On the extraction of programs from proofs in MF

Here we describe how Bishop's desire of compiling a foundation for constructive mathematics in a programming language is fulfilled for MF.

First of all MF was structured as a two-level theory so that to interpret constructive proofs done at its extensional level emTT to proofs done at its intensional level mTT from which to extract the computational contents in the form of programs. However the extraction of the computational contents of proofs in mTT can not be performed in mTT itself as shown in [Mai17] but in a stronger theory or in the realizability semantics in [IMMS18]. One could then think of enlarging the intensional level to become the stronger theory needed, but this would not satisfy the forget-restore principle according to which the entities at the extensional level should be obtained by abstraction from the intensional ones, or more concretely as quotients of intensional entities.

A priori the intensional level mTT itself could serve as a programming language where to compile proofs done at the extensional level. Indeed mTT is a dependent type theory where we can construct a correct and terminating program as a typed term meeting a certain specification defined as its type. But to extract programs from constructive proofs it is desirable that from a proof of an existential statement under hypothesis

$$p(x) \in \exists y \in B R(x, y) [x \in A]$$

for generic types A and B , one may extract a functional program $f \in A \rightarrow B$ whose graph is contained in the graph of $R(x, y)$, namely for which we can prove that there exists a proof-term $q(x)$ such that we can derive

$$q(x) \in R(x, f(x)) [x \in A]$$

This property is called *choice rule*.

In all the versions of Martin-Löf dependent type theory [NPS90, Mar84] the choice rule is valid thanks to the identification of the MLTT-existential quantifier with the *the strong indexed sum of a set family*, which characterizes the so called *propositions-as-sets isomorphism*. Then also the axiom of choice

$$(AC) \quad \forall x \in A \exists y \in B R(x, y) \longrightarrow \exists f \in A \rightarrow B \forall x \in A R(x, f(x))$$

is valid for generic types A and B .

However in mTT the existential quantifier is not identified with the strong indexed sum type whilst it is still a type of its proofs. The result is that the choice rule defined below is not valid.

Def. 3.1 The dependent type theory mTT satisfies the *choice rule* if for every small proposition $R(x, y) \text{ prop}_s [x \in A, y \in B]$ derivable in mTT, for any derivable judgement in mTT of the form

$$p(x) \in \exists_{y \in B} R(x, y) [x \in A]$$

there exists in mTT a typed term

$$f(x) \in B[x \in A]$$

for which we can find a proof-term $q(x)$ and derive in mTT

$$q(x) \in R(x, f(x)) [x \in A]$$

Proposition 3.2 In mTT the choice rule is not valid.

Proof. See [Mai17].

From the above result it follows that, when proving a statement of the form

$$\forall_{x \in A} \exists y \in B R(x, y)$$

in the dependent typed theory mTT, we can not always extract a functional term $f \in A \rightarrow B$ computing the witness of the existential quantification depending on a $x \in A$ within the theory itself but we need to find it in a more expressive proofs-as-programs theory.

For mTT we can use Martin-Löf's type theory, for short MLTT, in [NPS90] as the more expressive theory where to perform the mentioned witness extraction. Indeed, we can interpret mTT inside MLTT as shown in [Mai09] by preserving the meaning of its entities.

This extraction is done by first embedding the proof-term

$$p \in \forall_{x \in A} \exists y \in B R(x, y)$$

derived in mTT and then using MLTT-projections to extract f .

The other possibility is to perform this witness extraction in the realizability model of mTT in [IMMS18]. This realizability model guarantees that the intensional level mTT of **MF** is a “proofs-as-programs theory” in the sense of [MS05], namely that mTT is consistent with the axiom of choice (AC) and the formal Church Thesis (CT) by identifying $Fun(Nat, Nat)$ in mTT with the type of *functional relations between natural numbers*

$$\Sigma_{R \in \mathcal{P}(N, N)} \forall_{x \in A} \exists! y \in B \langle x, y \rangle \varepsilon R$$

where $\exists! y \in B \langle x, y \rangle \varepsilon R \equiv \forall_{y_1 \in B} \forall_{y_2 \in B} R(x, y_1) \ \& \ R(x, y_2) \rightarrow \text{Id}(B, y_1, y_2)$.

Actually in [IMMS18] mTT is shown to be consistent with (AC) and the *Formal Church thesis for operations between natural numbers*

$$(CT_{tt})^2 \quad \forall f \in N \rightarrow N \quad \exists e \in N \quad \forall x \in N \exists y \in N \ (T(e, x, y) \wedge U(y) =_N f(x))$$

stating that all operations between natural numbers are recursive.

The consistency of mTT with (AC) and (CT_{tt}) implies the consistency of mTT with (AC) and (CT) since we can easily show:

Lemma 3.3 *In mTT extended with (AC) the formal Church thesis for functional relations CT is equivalent to the formal Church thesis for operations CT_{tt} .*

Therefore we conclude:

Proposition 3.4 *The intensional level mTT of **MF** in [Mai09] is consistent with (CT) and the axiom of choice in this form*

$$(AC) \quad \forall x \in A \exists y \in B R(x, y) \quad \longrightarrow \quad \exists f \in A \rightarrow B \forall x \in A R(x, f(x))$$

for A, B sets and $R(x, y)$ any small proposition in mTT.

Proof. It follows from lemma 3.3 and [IMMS18].

As a consequence from the interpretation of the extensional level of **MF** into its intensional level in [Mai09], we can deduce that also the extensional level of **MF** is consistent with the formal Church thesis:

Proposition 3.5 *The extensional level emTT of **MF** in [Mai09] is consistent with (CT).*

Proof. A proof of this proposition can be obtained in various other ways. For example it follows also from the realizability interpretations of mTT in [MM14, MM16], or from the fact that emTT can be interpreted by preserving the meaning of its entities both in the internal theory of a topos and then in Hyland's Effective Topos [Hyl82] or in Aczel's set theory [Acz78].

It is worth noting that the consistency requirement of a proofs-as-programs theory with (AC) and (CT) just guarantees that from proofs of existential statements on natural numbers under hypothesis

$$\exists y \in N R(x, y) \text{ true } [x \in Nat]$$

²The subscript *tt* stands for “type-theoretic functions”, which we call operations in our foundation.

we can extract of a computable choice function

$$f \in \mathbb{N} \rightarrow \mathbb{N}$$

producing a witness under hypothesis such that we can find a proof of

$$R(x, f(x)) \text{ true } [x \in \mathbb{N}]$$

It is then clear that our proofs-as-programs requirement does not fully capture the idea of a foundational theory that is in the same time also a programming language satisfying the choice rule, as MLTT in [NPS90].

It is still an open problem whether MLTT enjoys our proofs-as-programs requirement, or equivalently, whether MLTT is consistent with the formal Church thesis (CT).

Our purpose in [MS05] with the proofs-as-programs requirement was to single out a property characterizing theories which are interpretable in extensions of Kleene realizability semantics for Heyting Arithmetics with finite types (see [Tv88]).

3.4 Benefits of distinguishing operations from functions

Inspired by Brouwer's difference between lawlike and choice sequences [Tv88], in **MF** contrary to **BISH** we can define *choice sequences* from the set of natural numbers \mathbb{N} to a set B as *functions* (in the sense of functional relations, that is, total and single-valued relations), and *lawlike sequences* as *operations*:

Def. 3.6 (choice and lawlike sequences) *Given a set A , a choice sequence from the set N of natural numbers to A is a function defined by a small functional relation $\alpha(x, y)$ $\text{prop}_s [x \in N, y \in A]$ in emTT .*

A lawlike sequence from the set N of natural numbers to A is an operation

$$f \in N \rightarrow A$$

in emTT , or equivalently, thanks to the rules in [Mai09] defining elements in $N \rightarrow A$, an emTT -term $f(x) \in A [x \in N]$.

It is possible to keep a distinction between choice sequences and lawlike sequences because in emTT the *axiom of unique choice*

$$(\text{AC!}_{N,N}) \quad \forall x \in \mathbb{N} \exists! y \in \mathbb{N} R(x, y) \longrightarrow \exists f \in \mathbb{N} \rightarrow \mathbb{N} \forall x \in \mathbb{N} R(x, f(x)),$$

which turns a function between natural numbers into an operation, is not valid, as shown in [Mai12, Mai17]. Our distinction allows us to clarify and compare results about choice sequences in the literature, since choice sequences are sometimes identified with our functions [Rat05], sometimes with our operations [Tv88].

Another consequence of the distinction between operations and functions is that we can refine the notion of decidable subset of the set of natural numbers \mathbb{N} . In constructive mathematics it is common to say that a subset $U \subseteq \mathbb{N}$ is decidable if $\forall x (x \in U \vee x \notin U)$ holds. In our theory we can distinguish three notions:

Def. 3.7 *A subset U of the set N is said to be:*

- complemented, if $\forall x (x \in U \vee x \notin U)$ holds. In this case U is classified by a function from N to the boolean set **Bool**

$$\chi_U(x, y) \equiv (x \in U \ \& \ y =_{\text{Bool}} 1) \vee (x \notin U \ \& \ y =_{\text{Bool}} 0)$$

- detachable, if the subset U is classified by an operation, namely we can derive

$$\exists_{f \in N \rightarrow \text{Bool}} \forall x \in N ((x \in U \ \& \ f(x) =_{\text{Bool}} 1) \vee (x \notin U \ \& \ f(x) =_{\text{Bool}} 0))$$

- decidable, if U is classified by a computable operation, namely we can derive

$$\begin{aligned} \exists_{f \in N \rightarrow \text{Bool}} \quad & (\forall x \in N ((x \in U \ \& \ f(x) =_{\text{Bool}} 1) \vee (x \notin U \ \& \ f(x) =_{\text{Bool}} 0)) \\ & \ \& \ \exists e \in N \quad \forall x \in N \exists y \in N (T(e, x, y) \wedge U(y) =_N f(x))) \end{aligned}$$

where $T(e, x, y)$ is the Kleene predicate expressing that y is the computation executed by the program numbered e on the input x and $U(y)$ is output of the computation y .

Observe that, classically, all subsets are complemented. Of course, in the presence of the axiom of unique choice, functions and operations coincide and hence complemented and detachable subsets coincide, too, as for example in Martin-Löf's type theory.

All the three kinds of subsets coincide in the Kleene realizability interpretation of Heyting arithmetic. This interpretation is in some sense the intended interpretation of the arithmetic fragment of a constructive foundation. Hence, the identification of the name “decidable” with our notion of complemented subsets, (that we do not follow here, though) has its own (plausible) justification.

In [Mai12, Mai18], we observed that if we extend emTT with the principle of excluded middle then we can prove the existence of a power-set of detachable subsets, which do not necessarily coincide with all subsets, i.e. with complemented ones. This option of restricting exponentiation as a set to lawlike sequences opens the way to build a theory compatible with classical predicativity as in Feferman's theories [Fef79].

4 Why adopting the pointfree approach to develop topology in MF

Bishop, like Brouwer, developed constructive analysis by adopting a pointwise approach which presented some difficulties solved by them in different ways (see [Pal05b, Tv88]). When developing topology in **MF** we need to adopt the pointfree approach. The most important reason is that, when working in **MF**, the pointwise approach is not suitable because relevant examples of classical topologies (real numbers both as Dedekind cuts or Cauchy sequences, Baire space, Cantor space,...) do not give rise to a pointwise topology since their points do not form a set.

A solution is to work with the pointfree topology associated to each of these spaces. The constructive approach to pointfree topology given by formal topology has provided evidence that most important results of constructive analysis (see for example [Mar70, Pal05b]) can be reached without assuming further principles, such as the Fan Theorem adopted by Brouwer in his pointwise approach [BR87, Tv88, Ish05, Bri08], and in a compatible way with classical mathematics as in Bishop's constructive approach.

Before entering into details, we briefly review a constructive notion of topological space and then the main concepts of formal topology.

4.1 A predicative constructive notion of topological space

Considering that in a predicative foundation the discrete topology on a given non-empty set is not a set but a collection, we need to review the concept of topological space by distinguishing what belongs to the realm of sets from what belongs to the realm of collections.

At first, one could think of simply keeping the traditional definition of topological space $(X, \mathcal{O}X)$ by just declaring the topology $\mathcal{O}X$ to be only a subcollection of the power of X which is a suplattice, i.e. a complete join-semilattice, with finite distributive meets. This approach is compulsory in order to include the discrete topology among topologies. Even more, as shown in [Cur10], there is no non-trivial suplattice, and hence no non-trivial topology, which is a set.

One should then define suplattices as collections closed under sups of *set-indexed* families. However, as in [Sam87] and [BS06], suplattices are easier to handle by restricting to the notion of *set-based* suplattice, namely a semilattice that is generated by taking sups from a set(-indexed family) of elements, called *generators*.

Topologically this means that we need to assume that the collection of opens of a space has a base that is a set. To make this assumption rigorous, we require that for a given set of points X we have a set S together with a family of subsets $\text{ext}(a) \subseteq X$ [$a \in S$] acting as a base for the topology on X . Elements a of S act as names of basic opens of X ; they are called *formal basic neighbourhoods* or simply *observables*.

Then, following [Sam03], we define a subset of X to be open if it is equal to $\text{ext} U \equiv \bigcup_{a \in U} \text{ext} a$ for some subset $U \subseteq S$. It is immediate to see that open subsets are closed under unions of set-indexed families.

Then we need to require closure of open subsets under intersection. To this purpose, it is convenient to start from *basic neighbourhoods*, that is subsets of X of the form $\text{ext} a$ for some $a \in S$. For all $a, b \in S$, the intersection $\text{ext} a \cap \text{ext} b$ is open, that is, it is equal to $\text{ext} W$ for some $W \subseteq S$, if and only if

$$\text{B0} \quad \text{ext} a \cap \text{ext} b = \text{ext}(a \downarrow b) \text{ for all } a, b \in S,$$

where

$$a \downarrow b \equiv \{c \in S : \text{ext} c \subseteq \text{ext} a \cap \text{ext} b\}.$$

In fact, $\text{ext}(a \downarrow b)$ is by its definition the greatest open subset contained in $\text{ext} a \cap \text{ext} b$. Then, from B0, by two applications of distributivity in $\mathcal{P}X$, we can easily obtain

$$\text{B1} \quad \text{ext} U \cap \text{ext} V = \text{ext}(U \downarrow V) \text{ for all } U, V \subseteq S,$$

where

$$U \downarrow V \equiv \bigcup_{a \in U} \bigcup_{b \in V} a \downarrow b.$$

Finally, to obtain that the whole space is open we need to add the requirement

$$\text{B2} \quad X = \text{ext} S.$$

It is clear that for any family of subsets of X indexed by the set S , i.e. for any $\text{ext} a \subseteq X$ for $a \in S$, satisfying B1 and B2 the collection of subsets $\text{ext} U \subseteq X$ for $U \in \mathcal{P}S$ is closed under set-indexed unions and finite intersections.

Therefore we can give the following constructive version of topological spaces (see [Sam03]):

Def. 4.1 *A concrete space is a structure $\mathcal{X} = (X, \text{ext}, S)$ where X, S are sets and $\text{ext}(a) \subseteq X$ [$a \in S$] is a set-indexed family of subsets satisfying:*

$$\text{B1} \quad \text{ext} U \cap \text{ext} V = \text{ext}(U \downarrow V) \text{ for all } U, V \subseteq S,$$

$$\text{B2} \quad X = \text{ext} S.$$

In an impredicative foundation with powersets, this is just a reformulation of the common notion of topological space.

The notion of concrete space is present in Bishop [Bis67], under the name of neighbourhood space. The discrete topology on a set X is obviously an example of concrete space with X itself as base and $\text{ext}(x) \equiv \{x\}$ for $x \in X$.

A useful example of concrete space is given by the set \mathbb{Q} of rational numbers with the topology produced by the base of open intervals. In more detail, the base is the set $\mathbb{Q} \times \mathbb{Q}$ of pairs $\langle p, q \rangle$ of rational numbers, and the basic neighbourhood with index $\langle p, q \rangle$ is the subset

$$\text{ext}(\{\langle p, q \rangle\}) \equiv \{r \in \mathbb{Q} \mid p < r < q\}$$

for all $p, q \in \mathbb{Q}$.

In other constructive and predicative foundations, as Aczel's CZF and Martin-Löf's type theory in [NPS90], another example of concrete space is that of real numbers. It is not so in our **MF**, as we shall see later. Even when the topology of real numbers provides an example of concrete space, it is well known from Brouwer that a constructive pointwise development of analysis fails to get important properties [Tv88], as compactness of the closed interval $[0, 1]$, unless further principles, as the Fan Theorem, are assumed or some basic topological notions are changed as in Bishop's approach (see [Bis67, BB85, BR87]). An alternative approach to constructive topology, and analysis, is offered by formal topology.

4.2 The predicative constructive pointfree approach of formal topology

The approach of formal topology to pointfree topology was introduced by Per Martin-Löf and the second author in the 80s; the first published account is [Sam87]. The intended foundation was then Martin-Löf's type theory MLTT in [NPS90]. However, as underlined in the introduction of [Sam87], to the second author it was already clear that it was necessary to work with an explicit notion of subset, and with a primitive notion of proposition using the judgement that a proposition is true without any reference to proof-terms in [Mar85]. Such a conception of subsets and propositions was later specified in [SV98] as a tool to be added on top of type theory. As noticed in [Mai98, Mai05a], working with existential quantifiers with no proof terms means that the axiom of choice no longer holds. This is different from MLTT where existential quantifications are identified with indexed sums, according to the proposition-as-set isomorphism, thus making the axiom of choice (AC) derivable. Moreover, this explains why in formal topology, as developed by the second author, every use of the axiom of choice was explicit. Given that the notion of subset in [SV98] and a primitive notion of proof-irrelevant propositions have been incorporated in our Minimalist Foundation, all the main definitions and results on formal topology (by the second author) can be carried in it. Actually the combination of the tool of *extensional* subsets with the *intensional* MLTT partly anticipated the notion of two-level theory in [MS05], because subsets are not formally included in MLTT.

The main idea of formal topology is to replace the notion of concrete space with an abstract axiomatization of the structure of open subsets, and then to recover its points in a *formal way* as suitable subsets of opens. The precise definition is reached by describing the structure of the set S of basic neighbourhoods in a concrete space (X, ext, S) with no mention of the set X of points.

While in the concept of concrete space (X, ext, S) points in X are given in the same time with the formal basic neighbourhoods in S and both form a set, in formal topology only the structure of opens is described starting from the set S of formal basic neighbourhoods and from a new primitive relation $a \triangleleft U$, called *formal cover*, between formal basic neighbourhoods $a \in S$ and subsets $U \subseteq S$. A formal cover relation is the abstract counterpart of

$$\text{ext } a \subseteq \text{ext } U$$

which expresses in a concrete space that the open $\text{ext } U$ is a covering of the basic neighbourhood $\text{ext } a$. Then, the notion of *formal topology* extends that of formal cover with the addition of a primitive predicate $\text{Pos}(a)$ for $a \in S$, which is the abstract counterpart of the assertion that the basic neighbourhood $\text{ext } a$ is inhabited. Details of the definitions are now presented.

Def. 4.2 (formal cover) A formal cover $\mathcal{A} = (S, \triangleleft)$ is given by a set S and a relation $\triangleleft \subseteq S \times \mathcal{P}(S)$ between elements and subsets of S that satisfies the following rules for every $a \in S$ and $U, V \subseteq S$:

$$\frac{a \in U}{a \triangleleft U} \text{ reflexivity} \qquad \frac{a \triangleleft U \quad U \triangleleft V}{a \triangleleft V} \text{ transitivity} \qquad \frac{a \triangleleft U \quad a \triangleleft V}{a \triangleleft U \downarrow_{\mathcal{A}} V} \text{ convergence}$$

where $U \triangleleft V \stackrel{\text{def}}{\iff} (\forall b \in U) (b \triangleleft V)$ and $U \downarrow_{\mathcal{A}} V = \{a \in S : (\exists u \in U)(a \triangleleft u) \ \& \ (\exists v \in V)(a \triangleleft v)\}$.

This definition provides a predicative counterpart of the impredicative notion of pointfree topology called *locale* [MM92, Joh82]. In fact, to any formal cover $\mathcal{A} = (S, \triangleleft)$ we can associate an operator \mathcal{A} on $\mathcal{P}(S)$, i.e. an operation $\mathcal{A} : \mathcal{P}(S) \rightarrow \mathcal{P}(S)$ (that by abuse of notation we call as the formal cover itself!), by putting

$$\mathcal{A}U \stackrel{\text{def}}{=} \{a \in S \mid a \triangleleft U\}. \tag{1}$$

for any $U \subseteq S$. Then, reflexivity and transitivity of the cover means that the operator \mathcal{A} is a *saturation* (or closure operator) and convergence means that \mathcal{A} satisfies

$$\mathcal{A}(U \downarrow_{\mathcal{A}} V) = \mathcal{A}U \cap \mathcal{A}V.$$

The collection $\text{Sat}(\mathcal{A})$ of all fixed points of the operator \mathcal{A} (i.e. all subsets U of S satisfying $\mathcal{A}(U) = U$) with the order given by inclusion form a locale. See [CMS13] for an account and discussion on the several variants of the definitions of formal cover.

Then a formal topology is defined as follows:

Def. 4.3 A formal topology $\mathcal{S} = (S, \triangleleft, \text{Pos})$ is a formal cover (S, \triangleleft) equipped with a positivity predicate, that is a predicate $\text{Pos}(a)$ for $a \in S$ which satisfies the conditions

$$\text{(monotonicity)} \frac{\text{Pos}(a) \quad a \triangleleft U}{(\exists u \in U) \text{Pos}(u)} \quad \text{(positivity)} \frac{\text{Pos}(a) \rightarrow a \triangleleft U}{a \triangleleft U}$$

Formal topologies provide a predicative counterpart of the impredicative notion of *open locale* [JT84].

Formal covers, as well as formal topologies, can be inductively generated from a set-indexed family of axioms of the form $a \triangleleft U$:

Def. 4.4 Given a set S , an axiom-set is a pair I, C , given by a family of sets $I(a)$ for each $a \in S$ and a family of subsets $C(a, i) \subseteq S$ for $a \in S$ and $i \in I(a)$ (with the intended meaning that $a \triangleleft C(a, i)$ holds).

The definition of inductively generated formal cover was introduced in [CSSV03] and for our purposes we just recall that:

Def. 4.5 Given a pre-ordered set (S, \leq) and an axiom-set I, C , the inductively generated formal cover (formal topology) $(S, \triangleleft_{I,C})$ is a formal cover (formal topology) satisfying:

- (i) $a \triangleleft_{I,C} C(a, i)$ for every $a \in S$ and $i \in I(a)$;
- (ii) if \triangleleft' is another formal cover (formal topology) such that $a \triangleleft' C(a, i)$ for all $a \in S$ and $i \in I(A)$, then $a \triangleleft_{I,C} U \rightarrow a \triangleleft' U$ holds for all $a \in S$ and $U \subseteq S$.

??Observe that in generating the formal topology the preorder on the set of basic neighbourhoods (S, \leq) is essential to produce a distributive lattice of open subsets (see [CMS13] for a detailed explanation). ??

In the Minimalist Foundation we assume the existence of an inductively generated cover when needed both at the extensional and at the intensional levels. See [Val07] for a proof on how to build inductively generated formal covers, and formal topologies, in an extension of Martin-Löf's type theory with ordinals.

We now recall the notion of formal point. Given any formal topology \mathcal{S} , a formal point over \mathcal{S} is a subset α of the set S such that it makes sense to think of $a \in \alpha$ as meaning that the observable a is an approximation of α . To obtain a precise definition, one considers the case in which \mathcal{S} is the topology of a concrete space X and takes some pointfree properties of the subset $\{a \in A \mid x \in \text{ext}(a)\}$, which is the trace on S of a concrete point $x \in X$, as the conditions to define a subset $\alpha \subseteq S$ to be a formal point.

Def. 4.6 (Formal point) Let $\mathcal{A} \equiv (A, \triangleleft)$ be a formal cover. Then an inhabited subset α of A is a formal point if, for any $a, b \in A$ and any $U \subseteq A$, it satisfies the following conditions:

$$\text{(\alpha is filtering)} \frac{a \in \alpha \quad b \in \alpha}{(\exists c \in \{a\} \downarrow_{\mathcal{A}} \{b\}) c \in \alpha} \quad \text{(\alpha splits the cover)} \frac{a \in \alpha \quad a \triangleleft U}{(\exists u \in U) u \in \alpha}$$

Then, one can take the collection of $Pt(\mathcal{A}) \equiv \{\alpha \in \mathcal{P}(S) \mid \alpha \text{ formal point}\}$ and make it a formal space as follows:

Def. 4.7 (formal space) For any formal cover $\mathcal{A} \equiv (S, \triangleleft)$, the collection $Pt(\mathcal{A})$ of formal points of \mathcal{A} with the topology generated by the basic neighbourhoods of the form $\text{Ext}(a) \equiv \{\alpha \in Pt(\mathcal{A}) \mid a \in \alpha\}$ for $a \in S$ defines the formal space of points of \mathcal{A} (that by abuse of notation we still call $Pt(\mathcal{A})$).

In an impredicative foundation, where power-collections are sets, it is clear that $Pt(\mathcal{A})$ defines a concrete space for any formal cover \mathcal{A} . Hence, as it is well known, impredicatively one can prove the existence of an adjunction between formal covers and concrete spaces [Joh82, MM92]. This impredicative adjunction associates to a formal cover its formal space, and conversely to a concrete space (X, ext, S) the formal cover (S, \triangleleft_X) defined by

$$a \triangleleft_X U \equiv \text{ext } a \subseteq \text{ext } U$$

But, not all formal covers arise from concrete spaces in this way. Moreover, the formal cover induced by a formal space is not necessarily equal to the starting formal cover \mathcal{A} , i.e. not all formal covers are

spatial. And even more the formal space of a formal cover arising from a concrete space is not necessarily equivalent to the starting concrete space, i.e. not all concrete spaces are *sober*.

In a constructive and predicative foundation as our minimalist one, such an adjunction is no longer available, because the collection $Pt(\mathcal{A})$ is *not necessarily* a set.

Here we will see at least three relevant examples of proper formal spaces, i.e. formal spaces whose formal points cannot form a set in our **MF**: the formal space of real numbers, Cantor and Baire spaces. In all these examples, we will see how our foundation allows to distinguish points which are given effectively, i.e. concrete points identified with lawlike sequences, from points which are only ideally so, i.e. formal points, which are identified with choice sequences. It is a predicative foundation which allows one, and, in the same time compels one, to take care of this distinction between an effective or real structure, as that of open basic neighbourhoods, from an ideal or non effective structure as that of formal points.

So in a constructive approach to topology as our minimalist one, formal topologies and formal points are not just an option to describe something which is there in any case. They are introduced as the only way to treat also those spaces which otherwise would be constructively unreachable.

4.3 Examples of pointfree topologies whose formal points do not form a set

The first example of topology whose formal points do not form a set in the Minimalist Foundation is the formal topology of real numbers as Dedekind cuts:

Def. 4.8 (Formal topology of real numbers) *The formal topology of real numbers $\mathcal{R} \equiv (\mathbb{Q} \times \mathbb{Q}, \triangleleft_{\mathcal{R}}, \text{Pos}_{\mathcal{R}})$ is an inductively generated formal topology defined as follows. The base is $\mathbb{Q} \times \mathbb{Q}$ and the basic neighbourhoods are pairs of rational numbers, $\langle p, q \rangle$ with $p, q \in \mathbb{Q}$. A preorder on $\mathbb{Q} \times \mathbb{Q}$ is defined as follows*

$$\langle p, q \rangle \leq \langle p', q' \rangle \equiv p' \leq p \leq q \leq q'$$

for p, q, p', q' in \mathbb{Q} . The cover is defined inductively by the following rules (which are a formulation in our context of Joyal axioms, cf. [Joh82], pp. 123-124):

$$\frac{q \leq p}{\langle p, q \rangle \triangleleft_{\mathcal{R}} U} \quad \frac{\langle p, q \rangle \in U}{\langle p, q \rangle \triangleleft_{\mathcal{R}} U} \quad \frac{p' \leq p < q \leq q' \quad \langle p', q' \rangle \triangleleft_{\mathcal{R}} U}{\langle p, q \rangle \triangleleft_{\mathcal{R}} U} \\ \frac{p \leq r < s \leq q \quad \langle p, s \rangle \triangleleft_{\mathcal{R}} U \quad \langle r, q \rangle \triangleleft_{\mathcal{R}} U}{\langle p, q \rangle \triangleleft_{\mathcal{R}} U} \quad \text{wc} \frac{\text{wc}(\langle p, q \rangle) \triangleleft_{\mathcal{R}} U}{\langle p, q \rangle \triangleleft_{\mathcal{R}} U}$$

where in the last axiom we have used the abbreviation

$$\text{wc}(\langle p, q \rangle) \equiv \{ \langle p', q' \rangle \in \mathbb{Q} \times \mathbb{Q} \mid p < p' < q' < q \}$$

(wc stands for ‘well-covered’).

The positivity predicate is $\text{Pos}_{\mathcal{R}}(\langle p, q \rangle) \equiv p < q$, expressing that the pair of rationals represents a non-empty interval.

Observe that the formal topology \mathcal{R} is definable in emTT as explained in [MMR21].

As shown in [NS99], formal points of the formal topology \mathcal{R} are in bijection with the collection of Dedekind cuts on the rationals. The proof carries over to our foundation after observing that \mathcal{R} can be defined in emTT as described in [MMR21].

Def. 4.9 *A Dedekind cut on the rationals is a pair (L, U) with inhabited $L, U \subseteq \mathbb{Q}$ satisfying the following properties:*

$$\begin{array}{ll} \text{(disjointness)} & \forall q \in \mathbb{Q} \quad \neg(q \in U \ \& \ q \in L) \\ \text{(L-openness)} & \forall p \in L \quad \exists q \in L \quad p < q \\ \text{(U-openness)} & \forall q \in U \quad \exists p \in U \quad p < q \\ \text{(L-monotonicity)} & \forall q \in L \quad \forall p \in \mathbb{Q} \quad (p < q \rightarrow p \in L) \\ \text{(U-monotonicity)} & \forall p \in U \quad \forall q \in \mathbb{Q} \quad (p < q \rightarrow q \in U) \\ \text{(locatedness)} & \forall q \in \mathbb{Q} \quad \forall p \in \mathbb{Q} \quad (p < q \rightarrow p \in L \vee q \in U) \end{array}$$

Proposition 4.10 *In emTT the formal points of the inductively generated formal topology \mathcal{R} are in bijection with the collection of Dedekind cuts on the rationals.*

Proof. Given a formal point $\alpha \in Pt(\mathcal{R})$ we can build the following Dedekind cut:

$$L_\alpha \equiv \{ p \in \mathbb{Q} \mid \exists q \in \mathbb{Q} \langle p, q \rangle \in \alpha \} \quad U_\alpha \equiv \{ q \in \mathbb{Q} \mid \exists p \in \mathbb{Q} \langle p, q \rangle \in \alpha \}^3$$

Conversely, given a Dedekind cut (L, U) we can define the following formal point

$$\alpha_{(L,U)} \equiv \{ \langle p, q \rangle \in \mathbb{Q} \times \mathbb{Q} \mid p \in L \ \& \ q \in U \}$$

In [NS99] it is proved that formal points of \mathcal{R} , or Dedekind cuts, are also in bijective correspondence with Cauchy sequences à la Bishop [Bis67]. This correspondence does not work in emTT: only Cauchy sequences à la Bishop can be shown to be formal points of \mathcal{R} . To make this point clear, we recall the notion of Cauchy sequence à la Bishop. In the following with \mathbb{N}^+ we mean the set of positive natural numbers.

Def. 4.11 (Cauchy sequence à la Bishop) *A function $R(n, x)$ prop_s $[n \in \mathbb{N}^+, x \in \mathbb{Q}]$, indicated with the usual notation $(x_n)_{n \in \mathbb{N}^+}$, is a Cauchy sequence in emTT if we can prove for any $n, m \in \mathbb{N}^+$*

$$\mid x_n - x_m \mid \leq 1/n + 1/m^4$$

As in [NS99], also in emTT we can prove that any Cauchy sequence $(x_n)_{n \in \mathbb{N}}$ determines a formal point α of the formal topology \mathcal{R} if we define it by:

$$\alpha \equiv \{ \langle p, q \rangle \in \mathbb{Q} \times \mathbb{Q} \mid \exists n \in \mathbb{N}^+ \ p < x_n - 2/n < x_n + 2/n < q \}$$

Conversely, given a formal point α , we can prove in emTT that within α there exists a countable number of strictly decreasing intervals as follows

$$\begin{aligned} \forall n \in \mathbb{N}^+ \ \exists \langle x_n, y_n \rangle \in \mathbb{Q} \times \mathbb{Q} \ (\ (\langle x_n, y_n \rangle \in \alpha \ \& \ \mid x_n - y_n \mid < (2/3)^n) \\ \& \ \exists \langle x_{n+1}, y_{n+1} \rangle \in \mathbb{Q} \times \mathbb{Q} \ (\ x_n \leq x_{n+1} < y_{n+1} \leq y_n \ \& \\ (\ \langle x_{n+1}, y_{n+1} \rangle \in \alpha \ \& \ \mid x_{n+1} - y_{n+1} \mid < (2/3)^{n+1})) \end{aligned}$$

This is proved by induction; in fact, for $n \in \mathbb{N}$ and $\langle x_n, y_n \rangle \in \alpha$ we can find a covering

$$\langle x_n, y_n \rangle \triangleleft_{\mathcal{R}} \{ l_{n1}, l_{n2} \}$$

such that $l_{n1} \equiv \langle x_n, z_{n1} \rangle$ and $l_{n2} \equiv \langle z_{n2}, y_n \rangle$ with $z_{n1} \equiv x_n + (2 \cdot (y_n - x_n))/3$ and $z_{n2} \equiv x_n + (y_n - x_n)/3$. Since the formal point α splits the cover, we can prove

$$\forall n \in \mathbb{N} \ \exists i \ (i \in \{1, 2\} \ \& \ l_{ni} \in \alpha).$$

However, such l_{ni} is *not necessarily unique*, because the formal point can be contained in both!

Classically, one can define a function $\mathcal{L}(n)$ for $n \in \mathbb{N}$ by cases by putting

$$\mathcal{L}(n) \equiv \begin{cases} l_{n1} & \text{if } l_{n1} \in \alpha \\ l_{n2} & \text{if } l_{n2} \in \alpha \ \& \ \neg l_{n1} \in \alpha \end{cases}$$

Constructively this does not work because α is not complemented. But, if we work in a foundation as Martin-Löf's type theory MLTT, actually in the setoid model over it, by using the axiom of dependent choice on $\mathbb{Q} \times \mathbb{Q}$ we can even extract an operation $l(n) \in \mathbb{Q} \times \mathbb{Q} \ [n \in \mathbb{N}^+]$ such that for any $n \in \mathbb{N}^+$

$$l(n) \in \alpha$$

³Note that the base of our topology \mathcal{R} does not contain $+\infty, -\infty$ as that in [NS99].

⁴This is formally written as $\forall p \in \mathbb{Q} \ \forall q \in \mathbb{Q} \ (\ R(n, p) \ \& \ R(m, q) \ \rightarrow \ \mid q - p \mid \leq 1/n + 1/m)$ where the definition of module is the usual one.

and, after naming $l(n) =_{Q \times Q} \langle x_n, y_n \rangle$ the values of the operation on each natural number, the conditions $x_n - y_n \leq (2/3)^n$ and $x_n \leq x_{n+1} < y_{n+1} \leq y_n$ hold for each natural number n . Then, a Cauchy sequence can be defined by taking the first components $(x_n)_{n \in \mathbb{N}}$ or the second components $(y_n)_{n \in \mathbb{N}}$. Hence, any Dedekind cut or formal point of \mathcal{R} corresponds to a lawlike Cauchy sequence à la Bishop in MLTT.

Since in our foundation no axiom of choice is available, this proof cannot be carried out. At a closer look, it does not appear constructively justified to be able to extract a choice of the interval where the formal point is, with no extra information.

What actually happens in MLTT is that the splitting of points is *already given* with an operation choosing an interval where the point is, and hence from this choice a definition by cases can be given similarly to that done classically. This example explains why in Martin-Löf's type theory real numbers as formal points are only the lawlike ones, namely those for which we can extract a lawlike Cauchy sequence.

This is not true in our foundation. In fact, the property that a formal point splits the cover is expressed through an existential quantifier $\exists_{x \in A} \phi(x) [w \in \Gamma]$ under a context Γ , which does not necessarily provide an operation $\text{wit}(d) \in A [w \in \Gamma]$ (depending on the context Γ) returning a witness for the existential statement when this holds. Such an operation is available only in a Kleene realizability interpretation of our foundation. As expected, in emTT real numbers as formal points of the formal topology \mathcal{R} *cannot coincide* with lawlike Cauchy sequences [Mai12, Mai18]. Even more, *real numbers as formal points of \mathcal{R} , and hence as Dedekind cuts, do not form a set*. Analogously, also *real numbers as Cauchy sequences à la Bishop do not form a set*. These results are obtained through a realizability interpretation of emTT which interprets emTT-sets as countable subsets of natural numbers and emTT-collections as entities which are not necessarily countable.

Now we describe two other examples of formal topologies whose formal points do not form a set in emTT. These are Cantor and Baire formal topologies, which are defined as instances of the more general notion of formal topology on the tree over a set. In order to define such formal topologies, we need to represent the tree over a set A , which we identify with the nodes labelled by lists of elements in a set A , using the abbreviation $A^* \equiv \text{List}(A)$. We write $[l, x]$ for the list obtained by appending $x \in A$ to the list $l \in A^*$ and $[l, t]$ for the list obtained by appending the list $t \in A^*$ to the list $l \in A^*$.

Def. 4.12 *The tree formal topology over a set A is the formal topology $A^N \equiv (A^*, \triangleleft_{A^N}, \text{Pos}_{A^N})$ where \triangleleft_{A^N} is inductively generated by the following rules*

$$\text{rfl} \frac{l \in V}{l \triangleleft_{A^N} V} \quad \leq \frac{s \sqsubseteq l \quad l \triangleleft_{A^N} V}{s \triangleleft_{A^N} V} \quad \text{tr} \frac{\forall x \in A \quad [l, x] \triangleleft_{A^N} V}{l \triangleleft_{A^N} V}$$

where $s \sqsubseteq l \equiv \exists_{t \in A^*} s =_{A^*} [l, t]$, i.e. l is an initial segment of s .

The positivity predicate is true on any element, i.e. $\text{Pos}_{A^N}(l) \equiv \text{tt}$ for any $l \in A^*$.

Among tree formal topologies, we distinguish Cantor and Baire formal topologies as follows:

Def. 4.13 (Cantor and Baire formal topologies) *The tree formal topology when $A \equiv \{0, 1\}$, namely*

$$\{0, 1\}^N \equiv (\{0, 1\}^*, \triangleleft_{\{0, 1\}^N}, \text{Pos}_{\{0, 1\}^N})$$

is called Cantor formal topology.

The tree formal topology when $A \equiv \mathbb{N}$, namely

$$\mathbb{N}^N \equiv (\mathbb{N}^*, \triangleleft_{\mathbb{N}^N}, \text{Pos}_{\mathbb{N}^N})$$

is called Baire formal topology.

Formal points of such topologies coincide with choice sequences of definition 3.6:

Proposition 4.14 *Formal points $\text{Pt}(A^N)$ of the tree formal topology over a set A are in bijective correspondence with choice sequences on the tree A^* .*

Proof. Given a formal point α , we define a function $R_\alpha(n, x) \text{ prop}_s [n \in \mathbb{N}, x \in A]$ as follows:

$$R_\alpha(n, a) \equiv \exists l \in \alpha \ l_{n+1} =_A a$$

where l_n is the n -th component of l .

Conversely, given a function $R(n, x) \text{ prop}_s [n \in \mathbb{N}, x \in A]$ the subset

$$\alpha_R \equiv \{ l \in A^* \mid \forall n \in \mathbb{N} (0 \leq n \leq \text{lh}(l) \rightarrow R(n, l_{n+1})) \}$$

where $\text{lh}(l)$ is the length of l , turns out to be a formal point.

An alternative proof follows after noting, as observed in [Sig95], that the tree formal topology over a set A is isomorphic to the exponential formal topology of the discrete formal topology of N over the discrete formal topology on the set A (see [Mai05b] for a predicative treatment of exponentiation). Therefore its formal points are in bijection with functions, because every function between discrete topologies is continuous. This explains why we denote the tree formal topology with the symbol A^N .

The realizability interpretation in [Mai12, Mai18], showing that real numbers (both as Dedekind cuts or Cauchy sequences) do not form a set, also shows that *choices sequences as formal points of Cantor or Baire formal topology do not form a set either* and hence they only form a proper collection. Therefore predicatively we can only work with the pointfree topologies of usual Cantor and Baire spaces.

The equivalence of each of our pointfree topologies with the corresponding pointwise topology of their formal spaces as in definition 4.7, i.e. spatiality, is not generally valid in emTT. Indeed, spatiality of our tree formal topologies amounts to the well known principle of Bar Induction, as first observed in [FG82].

Def. 4.15 (Bar Induction in topological form) In emTT extended with the inductive definitions necessary to define the formal topologies \triangleleft_{A^N} for any set A , the principle of Bar Induction is the following statement: for any given set A

$$(\text{BI}(A)) \quad \forall l \in A^* \forall V \in \mathcal{P}(A^*) \ (\forall \alpha \in \text{Pt}(\triangleleft_{A^N}) \ (l \in \alpha \rightarrow \alpha \not\Downarrow V) \rightarrow l \triangleleft_{A^N} V)$$

where

$$V \not\Downarrow W \equiv \exists a \in A \ (a \in V \wedge a \in W)$$

expresses that two subsets V, W of a set A overlap (see [Sam03]).

The above formulation of BI(A) means that the topology put on the formal points of the tree A^* , that are its choice sequences, coincides with the pointfree one. Hence, Bar Induction implies that we can reason topologically on choice sequences by induction on finite sequences, given that the pointfree topologies are inductively generated (see [Sam08, Sam]).

The usual Fan theorem in [Tv88] is then an instance of Bar Induction (see [FG82, GS07]):

Def. 4.16 (Fan theorem) We call *Fan theorem* the formulation BI($\{0, 1\}$) of BI(A) on Cantor formal topology, namely when $A \equiv \{0, 1\}$.

Spatiality of Cantor formal topology allows to derive compactness of Cantor space [FG82].

In [Mai12, Mai18] it is shown that emTT is compatible with the described principle of Bar Induction BI(A) for any set A , and the identification of lawlike sequences with recursive ones. Indeed, there exists a realizability interpretation showing that real numbers and choice sequences do not form a set validating the *Formal Church thesis for operations between natural numbers* (CT_{tt}).

Hence, the realizability interpretation in [Mai12, Mai18] shows that emTT is compatible with constructive foundations where Bar Induction or Fan theorem is used as in Brouwer's constructive pointwise approach of topology, by keeping a computable interpretation of operations between natural numbers with the validity of CT_{tt} . Actually a motivation to develop our **MF** was exactly to study a development of topology in the presence of these extra axioms.

Observe that compatibility with Bar Induction and CT_{tt} is not possible for Martin-Löf's type theory, because the axiom of choice, and hence also the axiom of unique choice, is valid in there. To

see this, first observe that in our **MF** we can prove the well known result by Kleene [Tv88] that formal Church thesis for choice sequences is contradictory with Fan Theorem, and hence also with Bar Induction. Observe then that this result can be formulated by saying that *there is no model of* $\text{emTT} + \triangleleft_{A^{\mathbb{N}}} + \text{FT} + \text{CT}_{\text{tt}} + \text{AC}^!_{\mathbb{N},\mathbb{N}}$. Therefore a theory validating the axiom of unique choice cannot keep together a computational interpretation of operations and Bar Induction. Hence, the consistency of emTT with Bar Induction and CT_{tt} explains why the axiom of unique choice, and a fortiori the axiom of choice, is not valid in emTT .

5 Extending MF with choice principles

The aim of this section is to show an extension of **MF** with choice principles in the spirit of BISH.

Ideally one would choose - as the most adequate basic foundation for Bishop's mathematics - a theory which fully axiomatizes the setoid model on Martin-Löf's type theory [NPS90]. But Martin-Löf's type theory is intended as a full-scale theory for formalizing constructive mathematics only if it is left opened to further extensions with all the needed inductive definitions. Currently only the first order fragment of the setoid model has been axiomatized categorically in [Pal12]. It would be desirable to have a type-theoretic presentation of the internal theory of the setoid model over MLTT as an extension of emTT , or better as an extension of the internal type theory of an arithmetic locally cartesian closed pretopos in [Mai05a].

Here we just consider an extension of emTT with the forms of axiom of choice which are acceptable constructively. Indeed it is well known since [GM78] that the full axiom of choice is not acceptable constructively in foundations with extensional principles.

The two-level structure of **MF** makes very evident the connection established in [ML06] between Zermelo's choice axiom and the type-theoretical axiom of choice in showing that the formula of the full axiom of choice

$$(AC) \quad \forall x \in A \exists y \in B R(x, y) \longrightarrow \exists f \in A \rightarrow B \forall x \in A R(x, f(x))$$

for A, B sets and $R(x, y)$ a small propositions, written at the extensional level of **MF** gets interpreted at the intensional level of **MF** as *Martin-Löf's extensional axiom of choice* [ML06] represented by the formula

$$(AC_{ext}) \quad \forall x \in A \exists y \in B R(x, y) \longrightarrow \exists f \in A \rightarrow B \left(\mathbf{Ext}(f) \stackrel{\simeq_B}{\simeq_A} \& \forall x \in A R(x, f(x)) \right)$$

where A, B are sets and

$$\mathbf{Ext}(f) \stackrel{\simeq_B}{\simeq_A} \equiv \forall x_1 \in A \forall x_2 \in A (x \simeq_A y \rightarrow f(x_1) \simeq_B f(x_2))$$

provided that $R(x, y)$ is a small proposition preserving given equivalence relations \simeq_A and \simeq_B in the sense that we can find in mTT a proof of

$$\forall x_1 \in A \forall x_2 \in A \forall y \in B (x_1 \simeq_A x_2 \rightarrow (R(x_1, y) \leftrightarrow R(x_2, y)))$$

and of

$$\forall x \in A \forall y_1 \in B \forall y_2 \in B (y_1 \simeq_B y_2 \rightarrow (R(x, y_1) \leftrightarrow R(x, y_2)))$$

As expected, the extensional axiom of choice (AC_{ext}) is not constructively acceptable since it implies the law of the excluded middle (see [Car04, ML06, Mai09]).

Therefore, to develop constructive mathematics we can not use the axiom of choice on all sets if we work in an extensional foundation as emTT . On the contrary as shown in section 3.3, the intensional level mTT is consistent with the full axiom of choice

$$(AC) \quad \forall x \in A \exists y \in B R(x, y) \longrightarrow \exists f \in A \rightarrow B \forall x \in A R(x, f(x))$$

which is called *intensional* by Martin-Löf in [ML06].

The different status of (AC) in the extensional and intensional levels of **MF** reflects the different status of the axiom of choice in axiomatic set theory and in type theory. This fact was another motivation for building a two-level theory where to distinguish the various kinds of choice principles. Indeed, as described above the two forms of (AC) can only be visible in an intensional theory, like mTT or MLTT, but the fact that they express the same formula in different contexts is only visible in the two-level structure of **MF**.

5.1 The extension emtt_{ac} of **MF**

We extend the extensional level of **MF** to form a theory that we call emtt_{ac} for short.

This theory emtt_{ac} is simply obtained from emTT by adding the axiom of unique choice for all types and the axiom of choice for what we call *intensional sets*.

Intensional sets are sets of emTT whose interpretations in mTT given in [Mai09] turn out to be “faithful copies” of sets of mTT with their terms and their propositional equality, and they include the following:

$$A \text{ set}_i \equiv N_0 \mid N_1 \mid \text{List}(A) \mid \Sigma_{x \in A} B(x) \mid A + B$$

provided that A and B are intensional sets, as well as $B(x) [x \in A]$ is a family of intensional sets on an intensional set A .

Then, formally the theory emtt_{ac} is obtained by extending emTT with:

- the *axiom of unique choice* written as follows

$$(\mathbf{AC!}_R) \quad \frac{R(a, b) \text{ prop } [a \in A, b \in B]}{\forall x \in A \exists! y \in B R(x, y) \longrightarrow \exists f \in A \rightarrow B \forall x \in A R(x, f(x)) \text{ true}}$$

for all A and B types in emTT where as usual

$$\exists! y \in A R(x, y) \equiv \exists y \in B R(x, y) \wedge \forall y_1, y_2 \in B (R(x, y_1) \wedge R(x, y_2) \rightarrow y_1 =_B y_2)$$

- the axiom of choice on intensional sets

$$(\mathbf{iAC}_R) \quad \frac{A \text{ set}_i \quad B \text{ set} \quad R(a, b) \text{ prop}_s [a \in A, b \in B]}{\forall x \in A \exists y \in B R(x, y) \longrightarrow \exists f \in A \rightarrow B \forall x \in A R(x, f(x)) \text{ true.}}$$

By adding the axiom of unique choice we guarantee that the graph of each functional relation is also a graph of an operation and hence has a computational meaning in accordance with BISH.

Following the interpretation in [Mai09] emtt_{ac} can be interpreted in mTT extended with a proof term \mathbf{p}_{ac}

$$(\mathbf{AC}_R) \quad \frac{A \text{ set} \quad B \text{ set} \quad R(a, b) \text{ prop}_s [a \in A, b \in B]}{\mathbf{p}_{ac} \in \forall x \in A \exists y \in B R(x, y) \longrightarrow \exists f \in A \rightarrow B \forall x \in A R(x, f(x))}$$

In turn this extension of mTT naturally interprets in Martin-Löf’s type theory MLTT where we can also extract programs from its proofs. Hence, MLTT could serve for the intensional level of a two-level foundation with emtt_{ac} for the extensional level. But a direct extension of the interpretation in [Mai09] for emtt_{ac} into MLTT is left to future work.

6 Concluding remarks

In our opinion the existence in **MF** of proper formal spaces, as the space of real numbers both as Dedekind cuts or Cauchy sequences, constitutes an advantage which could be useful for performing reverse Bishop constructive mathematics. In fact, a positive and practical motivation of the minimalist approach is to provide with a finer grid to look at reality, in particular topology, and thus preserve pieces of information, structures, conceptual distinctions (for example, all what is necessary to be able to instruct a computer) which would be lost, and actually are not even considered, in a classical or

impredicative foundation. For instance, our Minimalist Foundation allows us to distinguish infinitary or ideal topological concepts not enjoying induction principles, like Brouwer’s choice sequences, from inductive or real ones, as for example lawlike sequences. On the other hand, the minimalist attitude means that all results in the Minimalist Foundation about topology are valid also for the most relevant constructive and classical foundations.

Another important motivation supporting the pointfree approach to topology is given by a recent result showing that pointfree topology can be seen as a generalization of topology with points. To obtain this, one first has to introduce the notion of *positive topology*, that is an enrichment of formal topologies by the addition of a suitable primitive notion of closed subset. Then one can show that the category of concrete spaces can be embedded in the category of positive topologies. A full book [Sam] on positive topologies and their developments is going to appear.

For the future, we plan to investigate topologies of real numbers and of choice sequences using the more powerful tool provided by positive topologies.

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