Realizability algebras: a program to well order $\mathbb{R}$

Jean-Louis Krivine

To cite this version:

Jean-Louis Krivine. Realizability algebras: a program to well order $\mathbb{R}$. Logical Methods in Computer Science, 2011, 7 (3), pp.1-47. hal-00483232v2
Realizability algebras:
a program to well order $\mathbb{R}$

Jean-Louis Krivine
krivine@pps.jussieu.fr

May 12, 2010 (updated April 22, 2011)

Introduction

When we want to obtain programs from mathematical proofs, the main problem is, naturally, raised by the axioms: indeed, it has been a long time since we know how to transform a proof in pure (i.e. without axioms) intuitionistic logic, even at second order [1, 2, 3].

The very first of these axioms is the excluded middle, and it seemed completely hopeless for decades. The solution, given by T. Griffin [4] in 1990, was absolutely surprising. It was an essential discovery in logic because, at this moment, it became clear that all other axioms will follow, as soon as we will work in a suitable framework.

The theory of classical realizability is such a framework: it was developed in [12, 13], where we treat the axioms of Analysis (second order arithmetic with dependent choice).

In [15], we attack a more difficult case of the general axiom of choice, which is the existence of a non trivial ultrafilter on $\mathbb{N}$; the main tool is the notion of realizability structure, in which the programs are written in $\lambda$-calculus.

In the present paper, we replace it with the notion of realizability algebra, which has many advantages: it is simpler, first order and much more practical for implementation. It is a three-sorted variant of the usual notion of combinatory algebra. Thus, the programming language is no longer the $\lambda$-calculus, but a suitable set of combinators; remarkably enough, this is almost exactly the original set given by Curry. The $\lambda$-terms are now considered only as notations or abbreviations, very useful in fact: a $\lambda$-term is infinitely more readable than its translation into a sequence of combinators. The translation used here is new, as far as I know; its fundamental property is given in theorem 2.

The aim of this paper is to show how to transform into programs, the classical proofs which use dependent choice and:

i) the existence of a non trivial ultrafilter on $\mathbb{N}$;
ii) the existence of a well ordering on $\mathbb{R}$.

Of course, (ii) implies (i) but the method used for (i) is interesting, because it can give simpler programs. This is an important point, because a new problem is appearing now,
an important and very difficult problem: to understand the programs we obtain in this way, that is to explain their behavior. A fascinating, but probably long work.

The logical frame is given by classical second order logic, in other words the (first order) theory of the comprehension scheme. However, since we use a binary membership relation on individuals, we work, in reality, in at least third order logic. Moreover, this is indispensable since, although the axiom of dependent choice on \( \mathbb{R} \) can be expressed as a second order scheme, axioms (i) and (ii) cannot be expressed in this way.

By using the method expounded in [11], we can obtain the same results in ZF.

It seems clear to me that, by developing the technology of classical realizability, we shall be able to treat all “natural” axioms introduced in set theory. It is already done for the continuum hypothesis, which will be the topic of a forthcoming paper. In my opinion, the axiom of choice and the generalized continuum hypothesis in ZF do not pose serious issues, except this: it will be necessary to use the proper class forcing of Easton [6] inside the realizability model, and it will probably be very painful.

A very interesting open problem is posed by axioms such as the existence of measurable cardinals or the determination axiom.

But the most important open problem is to understand what all these programs do and, in this way, to be able to execute them. I believe that big surprises are waiting for us here. Indeed, when we realize usual axioms of mathematics, we need to introduce, one after the other, the very standard tools in system programming: for the law of Peirce, these are continuations (particularly useful for exceptions); for the axiom of dependent choice, these are the clock and the process numbering; for the ultrafilter axiom and the well ordering of \( \mathbb{R} \), these are no less than read and write instructions on a global memory, in other words assignment.

It seems reasonable to conjecture that such tools are introduced for some worthwhile purpose, and therefore that the very complex programs we obtain by means of this formalization work, perform interesting and useful tasks. The question is: which ones?

Remark.

The problem of obtaining a program from a proof which uses a given axiom, must be set correctly from the point of view of computer science. As an example, consider a proof of a theorem of arithmetic, which uses a well ordering of \( \mathcal{P}(\mathbb{N}) \): if you restrict this proof to the class of constructible sets, you easily get a new proof of the same theorem, which does not use this well ordering any more. Thus, it looks like you simply have to transform this new proof into a program.

But this program would be extracted from a proof which is deeply different from (and dramatically more complicated than) the original one. Moreover, with this method, it is impossible to associate a program with the well ordering axiom itself. From the point of view of computer science, this is an unacceptable lack of modularity: since we cannot put the well ordering axiom in a program library, we need to undertake again the programming work with each new proof.

With the method which is explained below, we only use the \( \lambda \)-term extracted from the original proof. Therefore, this term contains an unknown instruction for the well ordering axiom on \( \mathcal{P}(\mathbb{N}) \), which is not yet implemented. Then, by means of a suitable compilation, we transform this term into a true program which realizes the initial theorem.

As a corollary of this technology, we obtain a program which is associated with the well ordering
Realizability algebras

A realizability algebra is composed of three sets: \( \Lambda \) (the set of terms), \( \Pi \) (the set of stacks), \( \Lambda \ast \Pi \) (the set of processes) with the following operations:

- \((\xi, \eta) \mapsto \xi \eta\) from \(\Lambda^2\) into \(\Lambda\) (application);
- \((\xi, \pi) \mapsto \xi \cdot \pi\) from \(\Lambda \times \Pi\) into \(\Pi\) (push);
- \((\xi, \pi) \mapsto \xi \ast \pi\) from \(\Lambda \times \Pi\) into \(\Lambda \ast \Pi\) (process);
- \(\pi \mapsto k_\pi\) from \(\Pi\) into \(\Lambda\) (continuation).

We have, in \(\Lambda\), the distinguished elements \(B, C, E, I, K, W, cc\), called elementary combinators or instructions.

**Notation.** The term \((\ldots(\xi_1 \eta_1)\ldots)\eta_n\) will be also denoted by \((\xi_1 \eta_1 \ldots \eta_n)\) or \(\xi_1 \eta_2 \ldots \eta_n\).

For example:

- \(\xi \eta \zeta = ((\xi) \eta) \zeta = (\xi) \eta \zeta\).

We define on \(\Lambda \ast \Pi\) a preorder relation, denoted by \(\succ\). It is the least reflexive and transitive relation such that we have, for any \(\xi, \eta, \zeta \in \Lambda\) and \(\pi, \varpi \in \Pi\):

- \((\xi) \eta \ast \pi \succ \xi \ast \eta \ast \pi\).
- \(I \ast \xi \ast \pi \succ \xi \ast \pi\).
- \(K \ast \xi \ast \eta \ast \pi \succ \xi \ast \pi\).
- \(E \ast \xi \ast \eta \ast \pi \succ (\xi) \eta \ast \pi\).
- \(W \ast \xi \ast \eta \ast \pi \succ (\xi) \eta \ast \pi\).
- \(C \ast \xi \ast \eta \ast \pi \succ (\xi) \ast (\eta) \ast \pi\).
- \(B \ast \xi \ast \eta \ast \pi \succ (\xi) \ast (\eta) \ast \pi\).
- \(cc \ast \xi \ast \pi \succ \xi \ast k_\pi \ast \pi\).
- \(k_\pi \ast \xi \ast \varpi \succ \xi \ast \pi\).

Finally, we are given a subset \(\bot\) of \(\Lambda \ast \Pi\) which is a terminal segment for this preorder, which means that:

- \(p \in \bot\), \(p' \succ p \Rightarrow p' \in \bot\).

In other words, we ask that \(\bot\) be such that:

- \((\xi) \eta \ast \pi \notin \bot \Rightarrow \xi \ast \eta \ast \pi \notin \bot\).
- \(I \ast \xi \ast \pi \notin \bot \Rightarrow \xi \ast \pi \notin \bot\).
- \(K \ast \xi \ast \eta \ast \pi \notin \bot \Rightarrow \xi \ast \pi \notin \bot\).
- \(E \ast \xi \ast \eta \ast \pi \notin \bot \Rightarrow (\xi) \eta \ast \pi \notin \bot\).
- \(W \ast \xi \ast \eta \ast \pi \notin \bot \Rightarrow (\xi) \eta \ast \pi \notin \bot\).
- \(C \ast \xi \ast \eta \ast \pi \notin \bot \Rightarrow \xi \ast (\eta) \ast \pi \notin \bot\).
- \(B \ast \xi \ast \eta \ast \pi \notin \bot \Rightarrow (\xi) \ast (\eta) \ast \pi \notin \bot\).
- \(cc \ast \xi \ast \pi \notin \bot \Rightarrow \xi \ast k_\pi \ast \pi \notin \bot\).
- \(k_\pi \ast \xi \ast \varpi \notin \bot \Rightarrow \xi \ast \pi \notin \bot\).

**c-terms and \(\lambda\)-terms**

We call **c-term** a term which is built with variables, the elementary combinators \(B, C, E, I, K, W, cc\) and the application (binary function). A c-term is called **closed** if it
contains no variable; it will then also be called proof-like; a proof-like term has a value in $\Lambda$.

Given a c-term $t$ and a variable $x$, we define inductively on $t$, a new c-term denoted by $\lambda x t$. To this aim, we apply the first possible case in the following list:

1. $\lambda x t = (K)t$ if $t$ does not contain $x$.
2. $\lambda x x = I$.
3. $\lambda x tu = (C\lambda x (E)t)u$ if $u$ does not contain $x$.
4. $\lambda x tx = (E)t$ if $t$ does not contain $x$.
5. $\lambda x tx = (W)\lambda x (E)t$ (if $t$ contains $x$).
6. $\lambda x (t)(u)v = \lambda x (B)tuw$ (if $uv$ contains $x$).

We easily see that this rewriting is finite, for any given c-term $t$: indeed, during the rewriting, no combinator is introduced inside $t$, but only in front of it. Moreover, the only changes in $t$ are: moving parentheses and erasing occurrences of $x$. Now, rules 1 to 5 strictly decrease the part of $t$ which remains under $\lambda x$, and rule 6 can be applied consecutively only finitely many times.

The $\lambda$-terms are defined as usual. But, in this paper, we consider $\lambda$-terms only as a notation for particular c-terms, by means of the above translation. This notation is essential, because almost every c-term we shall use, will be given as a $\lambda$-term. Theorem 2 gives the fundamental property of this translation.

**Remark.** We cannot use the well known KS-translation of $\lambda$-calculus, because it does not satisfy Theorem 2.

**Lemma 1.** If $t$ is a c-term with the only variables $x, y_1, \ldots, y_n$, and if $\xi, \eta_1, \ldots, \eta_n \in \Lambda$, then:

\[ (\lambda x t)[\eta_1/y_1, \ldots, \eta_n/y_n] \star \xi \star \pi \rightarrow t[\xi/x, \eta_1/y_1, \ldots, \eta_n/y_n] \star \pi. \]

To lighten the notation, let us put $u^* = u[\eta_1/y_1, \ldots, \eta_n/y_n]$ for each c-term $u$; thus, we have:

$u^*[\xi/x] = u[\xi/x, \eta_1/y_1, \ldots, \eta_n/y_n]$.

The proof is done by induction on the number of rules 1 to 6 used to translate the term $\lambda x t$. Consider the rule used first.

If it is rule 1, then we have:

\[ (\lambda x t)^* \star \xi \star \pi \equiv (K)t^* \star \xi \star \pi \rightarrow t^* \star \pi \equiv t[\xi/x, \eta_1/y_1, \ldots, \eta_n/y_n] \star \pi. \]

If it is rule 2, we have $t = x$ and $\lambda x t)^* \star \xi \star \pi \equiv I \star \xi \star \pi \rightarrow \xi \star \pi \equiv t[\xi/x, \eta_1/y_1, \ldots, \eta_n/y_n] \star \pi.$

If it is rule 3, we have $t = uv$ and $\lambda x t)^* \star \xi \star \pi \equiv (C\lambda x (E)u)^* \star \xi \star \pi$.

\[ \rightarrow C \star (\lambda x (E)u)^* \star v^* \star \xi \star \pi \rightarrow (\lambda x (E)u)^* \star \xi \star v^* \star \pi \rightarrow (E)u^*[\xi/x] \star v^* \star \pi \text{ (by induction hypothesis)} \rightarrow E \star u^*[\xi/x] \star v^* \star \pi \rightarrow (u^*[\xi/x])v^* \star \pi \equiv t[\xi/x, \eta_1/y_1, \ldots, \eta_n/y_n] \star \pi \text{ since } x \text{ is not in } v. \]

If it is rule 4, we have $t = ux$ and $\lambda x t)^* \star \xi \star \pi \equiv (E)u^* \star \xi \star \pi \rightarrow E \star u^* \star \xi \star \pi \rightarrow u^* \star \xi \star \pi \equiv t[\xi/x, \eta_1/y_1, \ldots, \eta_n/y_n] \star \pi \text{ since } u \text{ does not contain } x.$

If it is rule 5, we have $t = uv$ and $\lambda x t)^* \star \xi \star \pi \equiv (W\lambda x (E)u)^* \star \xi \star \pi \rightarrow W \star (\lambda x (E)u)^* \star \xi \star \pi$

\[ \rightarrow (\lambda x (E)u)^* \star \xi \star \pi \rightarrow (E)u^*[\xi/x] \star \xi \star \pi \text{ (by induction hypothesis)} \rightarrow E \star u^*[\xi/x] \star \xi \star \pi \rightarrow (u^*[\xi/x])\xi \star \pi \equiv t[\xi/x, \eta_1/y_1, \ldots, \eta_n/y_n] \star \pi. \]

If it is rule 6, we have $t = (u)(v)w$ and $\lambda x t)^* \star \xi \star \pi \equiv (\lambda x (B)uvw)^* \star \xi \star \pi$.
\[ (B)u^*[\xi/x]v^*[\xi/x]w^*[\xi/x] \ast \pi \text{ (by induction hypothesis)} \]
\[ B \ast u^*[\xi/x] \ast v^*[\xi/x] \ast w^*[\xi/x] \ast \pi \succ (u^*[\xi/x])(v^*[\xi/x])w^*[\xi/x] \ast \pi \]
\[ \equiv t[\xi/x, \eta_1/y_1, \ldots, \eta_n/y_n] \ast \pi. \]

Q.E.D.

**Theorem 2.** If \( t \) is a c-term with the only variables \( x_1, \ldots, x_n \), and if \( \xi_1, \ldots, \xi_n \in \Lambda \), then \( \lambda x_1 \ldots \lambda x_n t \ast \xi_1 \ast \ldots \ast \xi_n \ast \pi \succ t[\xi_1/x_1, \ldots, \xi_n/x_n] \ast \pi. \)

Proof by induction on \( n \); the case \( n = 0 \) is trivial.

We have \( \lambda x_1 \ldots \lambda x_{n-1} t \ast \xi_1 \ast \ldots \ast \xi_{n-1} \ast \xi_n \ast \pi \succ (\lambda x_n t)[\xi_1/x_1, \ldots, \xi_{n-1}/x_{n-1}] \ast \xi_n \ast \pi \)
(by induction hypothesis) \[ \succ t[\xi_1/x_1, \ldots, \xi_{n-1}/x_{n-1}, \xi_n/x_n] \ast \pi \text{ by lemma }[]. \]

Q.E.D.

**Natural deduction**

Before giving the formal language that we shall use, it is perhaps useful to describe informally the structures (models) we have in mind. They are second order structures, with two types of objects: individuals also called conditions and predicates (of various arity). Since we remain at an intuitive level, we start with a full model which we call the ground model. Such a model consists of:

- an infinite set \( P \) (the set of individuals or conditions).
- the set of \( k \)-ary predicates is \( P(P^k) \) (full model).
- some functions from \( P^k \) into \( P \).

In particular, there is an individual 0 and a bijective function \( s : P \rightarrow (P \setminus \{0\}) \). This enables us to define the set of integers \( \mathbb{N} \) as the least set which contains 0 and which is closed for \( s \).

There is also a particular condition denoted by 1 and an application denoted by \( \wedge \) from \( P^2 \) into \( P \).

- some relations (fixed predicates) on \( P \). In particular, we have the equality relation on individuals and the subset \( C \) of non trivial conditions.

\( C[\ni p \land q] \) reads as: “\( p \) and \( q \) are two compatible conditions”.

We now come to the formal language, in order to write formulas and proofs about such structures. It consists of:

- **individual variables** or **variables of conditions** called \( x, y, \ldots \) or \( p, q, \ldots \).

- **predicate variables** or **second order variables** \( X, Y, \ldots \); each predicate variable has an arity which is in \( \mathbb{N} \).

- **function symbols on individuals** \( f, g, \ldots \); each one has an arity which is in \( \mathbb{N} \).

In particular, there is a function symbol of arity \( k \) for each recursive function \( f : \mathbb{N}^k \rightarrow \mathbb{N} \). This symbol will also be written as \( f \).

There is also a constant symbol 1 (which represents the greatest condition) and a binary function symbol \( \wedge \) (which represents the inf of two conditions).

The **terms** are built in the usual way with variables and function symbols.

The **atomic formulas** are the expressions \( X(t_1, \ldots, t_n) \), where \( X \) is an \( n \)-ary predicate variable, and \( t_1, \ldots, t_n \) are terms.
Formulas are built as usual, from atomic formulas, with the only logical symbols \( \rightarrow, \forall : \)

- each atomic formula is a formula;
- if \( A, B \) are formulas, then \( A \rightarrow B \) is a formula;
- if \( A \) is a formula, then \( \forall x \ A \) and \( \forall X \ A \) are formulas.

Notations.
The formula \( A_1 \rightarrow (A_2 \rightarrow (\ldots (A_n \rightarrow B) \ldots) \) will be written \( A_1, A_2, \ldots, A_n \rightarrow B. \)
The usual logical symbols are defined as follows:
\[ \top \equiv \forall \]

- We shall sometimes write \( \exists \)
- Then, we shall also write \( \top \)
- More generally, we shall write \( \exists \top \)
\[ s \]
is the interpretation of the symbol \( s \).

In particular, there is a distinguished element \( 0 \) in \( s \), also called \textit{propositional variable}.

Formulas are built as usual, from atomic formulas, with the only logical symbols \( \top, \land, \lor, \rightarrow, \forall \).

Each recursive function \( f \) can be extended to \( t, u \) are \( c \)-terms:

1. \( x_1 : A_1, \ldots, x_n : A_n \vdash x_i : A_i. \)
2. \( x_1 : A_1, \ldots, x_n : A_n \vdash t : A \rightarrow B, \ x_1 : A_1, \ldots, x_n : A_n \vdash u : A \ \Rightarrow \ x_1 : A_1, \ldots, x_n : A_n \vdash tu : B. \)
3. \( x_1 : A_1, \ldots, x_n : A_n, x : A \vdash t : B \ \Rightarrow \ x_1 : A_1, \ldots, x_n : A_n \vdash \lambda x \ t : A \rightarrow B. \)
4. \( x_1 : A_1, \ldots, x_n : A_n \vdash t : A \ \Rightarrow \ x_1 : A_1, \ldots, x_n : A_n \vdash t : \forall x \ A \) for every variable \( x \) (individual or predicate) which does not appear in \( A_1, \ldots, A_n. \)
5. \( x_1 : A_1, \ldots, x_n : A_n \vdash t : \forall X \ A \ \Rightarrow \ x_1 : A_1, \ldots, x_n : A_n \vdash t : A[\tau/x] \) where \( x \) is an individual variable and \( \tau \) is a term.
6. \( x_1 : A_1, \ldots, x_n : A_n \vdash t : \forall X \ A \ \Rightarrow \ x_1 : A_1, \ldots, x_n : A_n \vdash t : A[F/Xy_1 \ldots y_k] \) where \( X \) is a predicate variable of arity \( k \) and \( F \) an arbitrary formula.

Remark.
In the notation \( A[F/Xy_1 \ldots y_k] \), the variables \( y_1, \ldots, y_k \) are bound. A more usual notation is: \( A[\lambda y_1 \ldots \lambda y_k F/X]. \) I prefer this one, to avoid confusion with the \( \lambda \) defined for \( c \)-terms.

Realizability
Given a realizability algebra \( A = (\Lambda, \Pi, \Lambda \otimes \Pi, \perp) \), a \( A \)-model \( M \) consists of the following data:

- An infinite set \( P \) which is the domain of variation of individual variables.
- The domain of variation of \( k \)-ary predicate variables is \( P(\Pi)^{Pk}. \)
- We associate with each \( k \)-ary function symbol \( f \), a function from \( P^k \) into \( P \), denoted by \( \overline{f} \) or even \( f \) if there is no ambiguity.

In particular, there is a distinguished element \( 0 \) in \( P \) and a function \( s : P \rightarrow P \) (which is the interpretation of the symbol \( s \)). We suppose that \( s \) is a bijection from \( P \) onto \( P \setminus \{0\}. \) Then, we can identify \( s^n0 \in P \) with the integer \( n \), and therefore, we have \( \mathbb{N} \subset P. \) Each recursive function \( f : \mathbb{N}^k \rightarrow \mathbb{N} \) is, by hypothesis, a function symbol. Of course, we
assume that its interpretation $\mathcal{T} : P^k \to P$ takes the same values as $f$ on $\mathbb{N}^k$.

Finally, we have also a condition $1 \in P$ and a binary function $\wedge$ from $P^2$ into $P$.

A closed term (resp. a closed formula) with parameters in the model $\mathcal{M}$ is, by definition, a term (resp. a formula) in which all free occurrences of each variable have been replaced with a parameter, i.e., an object of the same type in the model $\mathcal{M}$: a condition for an individual variable, an application from $P^k$ into $\mathcal{P}(\Pi)$ for a $k$-ary predicate variable.

Each closed term $t$, with parameters in $\mathcal{M}$ has a value $\mathcal{T} \in P$.

An interpretation $\mathcal{I}$ is an application which associates an individual (condition) with each individual variable and a parameter of arity $k$ with each second order $k$-ary variable. $\mathcal{I}[x \leftarrow p]$ (resp. $\mathcal{I}[X \leftarrow \mathcal{X}]$) is, by definition, the interpretation obtained by changing, in $\mathcal{I}$, the value of the variable $x$ (resp. $X$) and giving to it the value $p \in P$ (resp. $\mathcal{X} \in \mathcal{P}(\Pi)^{P^k}$).

For each formula $F$ (resp. term $t$), we denote by $F^\mathcal{I}$ (resp. $t^\mathcal{I}$) the closed formula (resp. term) with parameters obtained by replacing each free variable with the value given by $\mathcal{I}$.

For each closed formula $F^\mathcal{I}$ with parameters in $\mathcal{M}$, we define two truth values:

$$ \|F^\mathcal{I}\| \subseteq \Pi \quad \text{and} \quad \|F^\mathcal{I}\| \subseteq \Lambda. $$

$\|F^\mathcal{I}\|$ is defined as follows:

$$ \xi \in \|F^\mathcal{I}\| \iff (\forall \pi \in \|F^\mathcal{I}||) \xi \star \pi \in \bot. $$

$\|F^\mathcal{I}\|$ is defined by recurrence on $F$:

- $F$ is atomic: then $F^\mathcal{I}$ has the form $\mathcal{X}(t_1, \ldots, t_k)$ where $\mathcal{X} : P^k \to \mathcal{P}(\Pi)$ and the $t_i$’s are closed terms with parameters in $\mathcal{M}$. We set $\|\mathcal{X}(t_1, \ldots, t_k)\| = \mathcal{X}(\bar{t}_1, \ldots, \bar{t}_k)$.
- $F \equiv A \to B$: we set $\|F^\mathcal{I}\| = \{\xi \star \pi : \xi \in \|A^\mathcal{I}\|, \pi \in \|B^\mathcal{I}\|\}$.
- $F \equiv \forall X A$: we set $\|F^\mathcal{I}\| = \{\|A^\mathcal{I}[X \leftarrow \mathcal{X}]\| : \mathcal{X} \in \mathcal{P}(\Pi)^{P^k}\}$ if $X$ is a $k$-ary predicate variable.

**Notation.** We shall write $\xi \models F$ for $\xi \in \|F\|$.

**Theorem 3 (Adequacy lemma).**

If $x_1 : A_1, \ldots, x_k : A_k \vdash t : A$ and if $\xi_1 \models A_1^\mathcal{I}, \ldots, \xi_k \models A_k^\mathcal{I}$, where $\mathcal{I}$ is an interpretation, then $t[\xi_1/x_1, \ldots, \xi_k/x_k] \models A^\mathcal{I}$.

In particular, if $A$ is closed and if $\vdash t : A$, then $t \models A$.

Proof by recurrence on the length of the derivation of $x_1 : A_1, \ldots, x_n : A_n \vdash t : A$.

We consider the last used rule.

1. We have $t = x_i, A \equiv A_i$. Now, we have assumed that $\xi_i \models A_i^\mathcal{I}$; and it is the desired result.

2. We have $t = uv$ and we already obtained:

$x_1 : A_1, \ldots, x_k : A_k \vdash u : B \to A$ and $x_1 : A_1, \ldots, x_k : A_k \vdash v : B$.

Given $\pi \in \|A^\mathcal{I}\|$, we must show $(uv)[\xi_1/x_1, \ldots, \xi_k/x_k] \star \pi \in \bot$.

By hypothesis on $\bot$, it suffices to show $u[\xi_1/x_1, \ldots, \xi_k/x_k] \star v[\xi_1/x_1, \ldots, \xi_k/x_k] \star \pi \in \bot$.

By the induction hypothesis, we have $v[\xi_1/x_1, \ldots, \xi_k/x_k] \models B^\mathcal{I}$ and therefore:

$$ v[\xi_1/x_1, \ldots, \xi_k/x_k] \star \pi \in \|B^\mathcal{I} \to A^\mathcal{I}\|. $$

But, by the induction hypothesis, we have also $u[\xi_1/x_1, \ldots, \xi_k/x_k] \models B^\mathcal{I} \to A^\mathcal{I}$, hence the result.

3. We have $A = B \to C$, $t = \lambda x u$. We must show $\lambda x u[\xi_1/x_1, \ldots, \xi_k/x_k] \models B^\mathcal{I} \to C^\mathcal{I}$; thus, we suppose $\xi \models B^\mathcal{I}, \pi \in \|C^\mathcal{I}\|$ and we have to show $\lambda x u[\xi_1/x_1, \ldots, \xi_k/x_k] \star \pi \in \bot$. 

7
By hypothesis on $\bot$ and lemma $[$, it suffices to show $ u[\xi/x, \xi_1/x_1, \ldots, \xi_k/x_k] \ast \pi \in \bot$. This follows from the induction hypothesis applied to $x : A_1, \ldots, x_n : A_n, x : B \vdash u : C$.

4. We have $A \equiv \forall X B$, and $X$ is not free in $A_1, \ldots, A_n$. We must show:

$t[\xi_1/x_1, \ldots, \xi_2/x_2] \vdash (\forall X B)^2$, i.e. $t[\xi_1/x_1, \ldots, \xi_k/x_k] \vdash B^2$ with $J = J[X \leftarrow X]$. But, by hypothesis, $\xi_i \vdash A_i^2$ therefore $\xi_i \vdash A_i^2$; indeed, since $X$ is not free in $A_i$, we have:

$||A_i^2|| = ||A_i^2||$. Then, the induction hypothesis gives the result.

6. We have $A = B[F/Xy_1 \ldots y_n]$ and we must show:

$t[\xi_1/x_1, \ldots, \xi_k/x_k] \vdash B[F/Xy_1 \ldots y_n]$ assuming that $t[\xi_1/x_1, \ldots, \xi_k/x_k] \vdash (\forall X B)^2$. This follows from lemma $[$ below.

Q.E.D.

Lemma 4. $\| B[F/Xy_1 \ldots y_n] \|^X = \| B[X \leftrightarrow Y] \|^X$ where $X : P^n \rightarrow P(\Pi)$ is defined by:

$I \vdash X(p_1, \ldots, p_n) = \| F[p_1, \ldots, p_n] \|^X$.

The proof is by induction on $B$. That is trivial if $X$ is not free in $B$. Indeed, the only non trivial case of the induction is $B = \forall Y C$; and then, we have $Y \neq X$ and:

$\| B[F/Xy_1 \ldots y_n] \|^X = \| Y \vdash C[F/Xy_1 \ldots y_n] \|$. By induction hypothesis, this gives $\| Y \vdash C[Z \leftrightarrow Y] \|^X$, that is $\| (\forall Y C)^2[\leftrightarrow Y] \|^X$. Q.E.D.

Lemma 5. Let $X, Y \subset \Pi$ be truth values. If $\pi \in X$, then $k_\pi \vdash X \rightarrow Y$.

Suppose $\xi \vdash X$ and $\rho \in Y$; we must show $k_\pi \ast \xi \ast \rho \in \bot$, that is $\xi \ast \rho \in \bot$, which is clear.

Q.E.D.

Proposition 6 (Law of Peirce). $cc \vdash (\forall X \forall Y)((X \rightarrow Y) \rightarrow X)$.

We want to show that $cc \vdash ((X \rightarrow Y) \rightarrow X)$; thus, we take $\xi \vdash (X \rightarrow Y) \rightarrow X$ and $\pi \in X$; we must show that $cc \ast \xi \ast \pi \in \bot$, that is $\xi \ast \pi \in \bot$. By hypothesis on $\xi$ and $\pi$, it is sufficient to show that $k_\pi \vdash X \rightarrow Y$, which results from lemma $[$.

Q.E.D.

Proposition 7.

i) If $\xi \vdash A \rightarrow B$, then $\forall \eta(\eta \vdash A \Rightarrow \xi \eta \vdash B)$.

ii) If $\forall \eta(\eta \vdash A \Rightarrow \xi \eta \vdash B)$, then $(E)\xi \vdash A \rightarrow B$.

i) From $\xi \eta \ast \pi \Rightarrow \xi \ast \pi$. 

ii) From $(E)\xi \ast \pi \Rightarrow \xi \eta \ast \pi$. 

Q.E.D.

Remark. Proposition $[$ shows that $\xi \vdash A \rightarrow B$ is “almost” equivalent (i.e. up to an $\eta$-expansion of $\xi$) to $\forall \eta(\eta \vdash A \Rightarrow \xi \eta \vdash B)$. 

8
Predicate symbols

In the following, we shall use extended formulas which contain predicate symbols (or predicate constants) $R, S, \ldots$ on individuals. Each one has an arity, which is an integer. In particular, we have a unary predicate symbol $C$ (which represents the set of non trivial conditions).

We have to add some rules of construction of formulas:

- If $F$ is a formula, $R$ is a $n$-ary predicate constant and $t_1, \ldots, t_n$ are terms, then $R(t_1, \ldots, t_n) \rightarrow F$ and $R(t_1, \ldots, t_n) \leftrightarrow F$ are formulas.
- $\top$ is an atomic formula.

In the definition of a $\mathcal{A}$-model $\mathcal{M}$, we add the following clause:

- With each relation symbol $R$ of arity $n$, we associate an application, denoted by $R_{\mathcal{M}}$ or $R$, from $P^n$ into $\mathcal{P}(\Lambda)$. We shall also write $|R(p_1, \ldots, p_n)|$, instead of $R(p_1, \ldots, p_n)$, for $p_1, \ldots, p_n \in P$.

In particular, we have an application $\overline{C}: P \rightarrow \mathcal{P}(\Lambda)$, which we denote as $|C[p]|$.

We define as follows the truth value in $\mathcal{M}$ of an extended formula:

\[
\begin{align*}
\|\top\| &= \emptyset, \\
\|R(t_1, \ldots, t_n) \rightarrow F\| &\equiv \{t \cdot \pi; t \in |R(t_1^0, \ldots, t_n^0)|, \pi \in \|F\|\}, \\
\|R(t_1, \ldots, t_n) \leftrightarrow F\| &\equiv \|F\| \text{ if } I \in |R(t_1^0, \ldots, t_n^0)|; \\
\|R(t_1, \ldots, t_n) \rightarrow F\| &\equiv \emptyset \text{ otherwise.}
\end{align*}
\]

**Proposition 8.**

i) $\lambda x(x) \parallel \forall \lambda y \forall \lambda z \exists \lambda w [(R(x, \ldots, y) \rightarrow X) \rightarrow (R(x, \ldots, y) \rightarrow X)]$.

ii) If we have $|R(p_1, \ldots, p_n)| \neq \emptyset \Rightarrow I \in |R(p_1, \ldots, p_n)|$ for every $p_1, \ldots, p_n \in P$, then:

$K \parallel \forall \lambda y \forall \lambda z \exists \lambda w [(R(x, \ldots, y) \rightarrow X) \rightarrow (R(x, \ldots, y) \rightarrow X)]$.

Trivial.

Q.E.D.

**Remark.** By means of proposition 8, we see that, if the application $R: P^n \rightarrow \mathcal{P}(\Lambda)$ takes only the values $\{I\}$ and $\emptyset$, we can replace $R(t_1, \ldots, t_n) \rightarrow F$ with $R(t_1, \ldots, t_n) \leftrightarrow F$.

We define the binary predicate $\simeq$ by putting $\|p \simeq q\| = \{I\}$ if $p = q$ and $\|p \simeq q\| = \emptyset$ if $p \neq q$.

By the above remark, we can replace $p \simeq q \rightarrow F$ with $p \simeq q \rightarrow F$. Proposition 8 shows that we can also replace $p = q \rightarrow F$ with $p \simeq q \rightarrow F$.

**Notations.** We shall write $p = q \rightarrow F$ instead of $p \simeq q \rightarrow F$. Thus, we have:

\[
\|p = q \rightarrow F\| = \|F\| \text{ if } p = q; \quad \|p = q \rightarrow F\| = \emptyset \text{ if } p \neq q.
\]

We shall write $p \neq q$ for $p = q \rightarrow \bot$. Thus, we have:

\[
\|p \neq q\| = \Pi \text{ if } p = q \text{ and } \|p \neq q\| = \emptyset \text{ if } p \neq q.
\]

Using $p = q \rightarrow F$ instead of $p = q \rightarrow F$, and $p \neq q$ instead of $p = q \rightarrow \bot$, greatly simplifies the computation of the truth value of a formula which contains the symbol $=.$

**Proposition 9.**

i) $\lambda x(x) \parallel \forall \lambda y \forall \lambda z \exists \lambda w [(x = y \rightarrow X) \rightarrow (x = y \rightarrow X)]$.

ii) $\lambda x \lambda y \lambda z \lambda w \parallel \forall \lambda y \lambda z \lambda w [(x = y \rightarrow X), x = y \rightarrow X].$
i) Let $a, b \in P$, $X \subset \Pi$, $\xi \models a = b \rightarrow X$ and $\pi \models ||a = b \rightarrow X||$. Then, we have $a = b$, thus $I \models a = b$, therefore $\xi \ast I \ast \pi \in \bot$, thus $\lambda x \, x I \ast \xi \ast \pi \in \bot$.

ii) Now let $\eta \models (a = b \rightarrow X)$, $\zeta \models a = b$ and $\rho \in ||X||$.

We show that $\lambda x \, \lambda y \, y \ast \eta \ast \zeta \ast \rho \in \bot$ in other words $\xi \ast \eta \ast \rho \in \bot$.

If $a = b$, then $\eta \models X$, $\zeta \models \forall Y (Y \rightarrow Y)$. We have $\eta \ast \rho \in ||X \rightarrow X||$, thus $\xi \ast \eta \ast \rho \in \bot$.

If $a \neq b$, then $\zeta \models \top \rightarrow \bot$, thus $\xi \ast \eta \ast \rho \in \bot$.

In both cases, we get the desired result.

Q.E.D.

Remark.

Let $R$ be a subset of $P^k$ and $1_R : P^k \rightarrow \{0, 1\}$ its characteristic function, defined as follows:

$1_R(p_1, \ldots, p_n) = 1$ (resp. $= 0$) if $(p_1, \ldots, p_n) \in R$ (resp. $(p_1, \ldots, p_n) \notin R$).

Let us define the predicate $R$ in the model $M$ by putting:

$|R(p_1, \ldots, p_n)| = \{I\}$ (resp. $= 0$) if $(p_1, \ldots, p_n) \in R$ (resp. $(p_1, \ldots, p_n) \notin R$).

By propositions 8 and 9, we see that $R(x_1, \ldots, x_n)$ and $1_R(x_1, \ldots, x_n) = 1$ are interchangeable.

More precisely, we have: $I \models \forall X \forall x_1 \ldots \forall x_n ((R(x_1, \ldots, x_n) \rightarrow X) \leftrightarrow (1_R(x_1, \ldots, x_n) = 1 \rightarrow X))$.

For each formula $A[x_1, \ldots, x_k]$, we can define the $k$-ary predicate symbol $N_A$, by putting $|N_A(p_1, \ldots, p_k)| = \{k_x; \pi \in ||A(p_1, \ldots, p_k)||\}$. Proposition 10 below shows that $N_A$ and $\neg A$ are interchangeable; this may simplify truth value computations.

**Proposition 10.**

i) $I \models \forall x_1 \ldots \forall x_k (N_A(x_1, \ldots, x_k) \rightarrow \neg A(x_1, \ldots, x_k))$;

ii) $\cc \models \forall x_1 \ldots \forall x_k ((N_A(x_1, \ldots, x_k) \rightarrow \bot) \rightarrow A(x_1, \ldots, x_k))$.

i) Let $p_1, \ldots, p_k \in P$, $\pi \in ||A(p_1, \ldots, p_k)||$, $\xi \models A(p_1, \ldots, p_k)$ and $\rho \in \Pi$. We must show: $I \ast k_x \ast \xi \ast \rho \in \bot$, that is $\xi \ast \pi \in \bot$, which is obvious.

ii) Let $\eta \models N_A(p_1, \ldots, p_k) \rightarrow \bot$ and $\pi \in ||A(p_1, \ldots, p_k)||$. We must show:

$\cc \ast \eta \ast \pi \in \bot$, i.e. $\eta \ast k_x \ast \pi \in \bot$, which is clear, since $k_x \in |N_A(p_1, \ldots, p_k)|$.

Q.E.D.

**Fixed point combinator**

**Theorem 11.** Let $Y = AA$ with $A = \lambda a \, \lambda f \, (f)(a) \, a \, f$. Then, we have $Y \ast \xi \ast \pi \models \xi \ast Y \ast \xi \ast \pi$.

Let $f : P^2 \rightarrow P$ such that $f(x, y) = 1$ is a well founded relation on $P$. Then:

i) $Y \models \forall X \{\forall x[\forall y (f(y, x) = 1 \rightarrow X y) \rightarrow X x] \rightarrow \forall x \, X x\}$.

ii) $Y \models \forall x_1 \ldots \forall x_k$

$\{\forall x [\forall y(X_1y, \ldots, X_ky \rightarrow f(y, x) \neq 1), X_1x, \ldots, X_kx \rightarrow \bot] \rightarrow \forall x(X_1x, \ldots, X_kx \rightarrow \bot)\}$.

The property $Y \ast \xi \ast \pi \models \xi \ast Y \ast \xi \ast \pi$ is immediate, from theorem 2.

i) We take $X : P \rightarrow P(\Pi)$, $\rho \in P$ and $\xi \models \forall x[\forall y (f(y, x) = 1 \rightarrow X y) \rightarrow X x]$. We show, by induction on the well founded relation $f(x, y) = 1$, that $Y \ast \xi \ast \pi \in \bot$ for every $\pi \in X \rho$.

Let $\pi \in X \rho$; from (i), we get $Y \ast \xi \ast \pi \models \xi \ast Y \ast \xi \ast \pi$ and thus, it is sufficient to prove that $\xi \ast Y \ast \xi \ast \pi \models \xi \ast \pi \in \bot$. By hypothesis, we have $\xi \models \forall y(f(y, p) = 1 \rightarrow X y) \rightarrow X \rho$; thus, it suffices to show that $Y \xi \models f(q, p) = 1 \rightarrow X q$ for every $q \in P$. This is clear if $f(q, p) \neq 1$, by definition of $\rightarrow$.
If $f(q,p) = 1$, we must show $Y\xi \vdash Xq$, i.e. $Y \star \xi \star \rho \in \bot$ for every $\rho \in Xq$. But this follows from the induction hypothesis.

ii) The proof is almost the same: take $X_1, \ldots, X_k : P \to \mathcal{P}(\Pi)$, $p \in P$ and $\xi \vdash \forall y(X_1y, \ldots, X_ky \to f(y,x) \neq 1), X_1x, \ldots, X_kx \to \bot]$. We show, by induction on the well founded relation $f(x,y) = 1$, that $Y \star \xi \star \pi \in \bot$ for every $\pi \in \|X_1p, \ldots, X_kp \to \bot\|$. As before, we have to show that: $Y \xi \vdash X_1q, \ldots, X_kq \to f(q,p) \neq 1$ for all $q \in P$; 
this is obvious if $f(q,p) \neq 1$. If $f(q,p) = 1$, we must show $Y \xi \vdash X_1q, \ldots, X_kq \to \bot$, or else:

$Y \star \xi \star \rho \in \bot$ for every $\rho \in \|X_1q, \ldots, X_kq \to \bot\|$. But this follows from the induction hypothesis.

Q.E.D.

Integers, storage and recursive functions

Recall that we have a constant symbol 0 and a unary function symbol $s$ which is interpreted, in the model $\mathcal{M}$ by a bijective function $s : P \to (P \setminus \{0\})$.

And also, that we have identified $s^n0$ with the integer $n$; thus, we suppose $N \subseteq P$.

We denote by $\text{int}(x)$ the formula $\forall X(\forall y(Xy \to Xsy), X0 \to Xx)$.

Let $u = (u_n)_{n \in N}$ be a sequence of elements of $\Lambda$. We define the unary predicate symbol $\nu \circ e_u$ by putting : $|\nu (s^n0)| = \{u_n\}$ ; $|\nu (p)| = \emptyset$ if $p \notin N$.

Theorem 12. Let $T_u, S_u \in \Lambda$ be such that $S_u \vdash (\top \to \bot), \top \to \bot$ and:

$T_u \star \phi \star \nu \star \pi \to \nu \star S_u \star \phi \star u_0 \star \pi ; \ S_u \star \psi \star u_n \star \pi \to \psi \star u_{n+1} \star \pi$

for every $\nu, \phi, \psi \in \Lambda$ and $\pi \in \Pi$. Then :

$T_u \vdash \forall X \forall x[\nu (\circ e_u(x) \to X), \text{int}(x) \to X]$.

$T_u$ is called a storage operator.

Let $p \in P, \phi \vdash \nu (p) \to X, \nu \vdash \text{int}(p)$ and $\pi \in \|X\|$. We must show $T_u \star \phi \star \nu \star \pi \in \bot$ i.e. $\nu \star S_u \star \phi \star u_0 \star \pi \in \bot$.

• If $p \notin N$, we define the unary predicate $Y$ by putting : $Y(q) \equiv \top$ if $q \in N ; \ Y(q) \equiv \top \to \bot$ if $q \notin N$.

Thus, we have obviously $\phi \vdash Y(0)$ and $u_0 \star \pi \in \|Y(p)\|$.

But, by hypothesis on $\nu$, we have $\nu \vdash \forall y(Yy \to Ysy), Y0 \to Yp$.

Thus, it is sufficient to show that :

$S_u \vdash \forall y(Yy \to Ysy)$, i.e. $S_u \vdash Y(q) \to Y(sq)$ for every $q \in P$.

This is clear if $q \in N$, since we have $\|Y(sq)\| = \emptyset$.

If $q \notin N$, we must show $S_u \vdash (\top \to \bot), \top \to \bot$, which follows from the hypothesis.

• If $p \in N$, we have $p = s^n0$; we define the unary predicate $Y$ by putting :

$\|Y(s^n0)\| = \{u_{i-p} \star \pi\}$ for $0 \leq i \leq p$ and $\|Yq\| = \emptyset$ if $q \notin \{s^n0; 0 \leq i \leq p\}$.

By hypothesis on $\nu, \phi, \pi$, we have :

$\nu \vdash \forall y(Yy \to Ysy), Y0 \to Ys^n0 ; \ \phi \vdash Y0 \ ; \ u_0 \star \pi \in \|Ys^n0\|$. Thus, it suffices to show that $S_u \vdash \forall y(Yy \to Ysy)$, i.e. $S_u \vdash Yq \to Ysq$ for every $q \in P$.

This is clear if $q \notin \{s^n0; 0 \leq i < p\}$, since then $\|Ysq\| = \emptyset$.

If $q = s^n0$ with $i < p$, let $\xi \vdash Yq$; we must show $S_u \star \xi \star u_{i-1} \star \pi \in \bot$.

But we have $S_u \star \xi \star u_{i-1} \star \pi \to \xi \star u_{i-1} \star \pi$ which is in $\bot$, by hypothesis on $\xi$.

Q.E.D.
Notation. We define the closed c-terms \( \varnothing = \lambda x y y \); \( \sigma = \lambda n f \lambda x (f(n)f x) \); and, for each \( n \in \mathbb{N} \), we put \( \Pi = (\sigma)^n \varnothing \). We define the unary predicate symbol \( \text{ent}(x) \) by putting:

\[
\text{ent}(n) = \{n\} \quad \text{if} \ n \in \mathbb{N} ; \\
\text{ent}(p) = \emptyset \quad \text{if} \ p \notin \mathbb{N} .
\]

In other words, \( \text{ent}(x) \) is the predicate \( e_u(x) \) when the sequence \( u \) is \( (n)_{n \in \mathbb{N}} \).

**Theorem 13.**

We put \( T = \lambda f \lambda n (n) S f \varnothing \) with \( S = \lambda g \lambda x (g)(\sigma)x \). Then, we have:

i) \( T \models \forall X \forall x ((\text{ent}(x) \rightarrow X), \text{int}(x) \rightarrow X) \).

ii) \( I \models \forall x ((\text{ent}(x) \rightarrow \text{int}(x)) \).

Therefore, \( T \) is a storage operator (theorem [2]).

i) We immediately have, by theorem [3]:

\[
T \triangleright \nu \cdot \pi \triangleright \nu \cdot \sigma \cdot \phi \cdot \varnothing \cdot \pi ; \quad S \triangleright \psi \cdot (\sigma)^n \varnothing \cdot \pi \triangleright \psi \cdot (\sigma)^{n+1} \varnothing \cdot \pi
\]

for every \( \nu, \phi, \psi, \pi \in \Pi \).

Now, we check that \( S \models (\rightarrow \rightarrow \downarrow), \rightarrow \rightarrow \downarrow ; \) indeed, if \( \xi \models T \rightarrow \downarrow \), then \( S \triangleright \xi \cdot \eta \cdot \pi \triangleright \xi \cdot \sigma \eta \cdot \pi \in \downarrow \) for every \( \eta \in \Lambda \) and \( \pi \in \Pi \) (by theorem [4]).

Then, the result follows immediately, from theorem [12].

ii) We must show \( I \models \text{ent}(p) \rightarrow \text{int}(p) \) for every \( p \in P \). We may suppose \( p \in \mathbb{N} \) (otherwise \( \text{ent}(p) = \emptyset \) and the result is trivial). Then, we must show:

\[
I \triangleright \sigma^n \varnothing \cdot p \in \downarrow \quad \text{knowing that} \quad p \in \| \text{int}(s^0) \| .
\]

Therefore, we can find a unary predicate \( X \models P(\Pi), \phi \models \forall y (Xy \rightarrow Xs y), \omega \models X0 \)
and \( \pi \in \| Xs^0 \| \) such that \( p = \phi \cdot \omega \cdot \pi \). We must show \( (\sigma)^n \varnothing \cdot \phi \cdot \omega \cdot \pi \in \downarrow \). In fact, we show by recurrence on \( p \), that \( (\sigma)^n \varnothing \cdot \phi \cdot \omega \cdot \pi \in \downarrow \) for all \( \pi \in \| Xs^0 \| \).

If \( p = 0 \), let \( \pi \in \| X0 \| \) ; we must show \( \varnothing \cdot \phi \cdot \omega \cdot \pi \in \downarrow \), i.e. \( \omega \cdot \pi \in \downarrow \), which is clear, since \( \omega \models X0 \).

To move up from \( p \) to \( p + 1 \), let \( \pi \in \| Xs^{p+1}0 \| \). We have:

\[
(\sigma)^{p+1} \varnothing \cdot \phi \cdot \omega \cdot \pi \equiv (\sigma)(\sigma)^p \varnothing \cdot \phi \cdot \omega \cdot \pi \triangleright \sigma \cdot (\sigma)^p \varnothing \cdot \phi \cdot \omega \cdot \pi \triangleright \phi \cdot (\sigma) \varnothing \phi \cdot \omega \cdot \pi .
\]

But, by induction hypothesis, we have \( (\sigma)^p \varnothing \cdot \phi \cdot \omega \cdot \rho \in \downarrow \) for every \( \rho \in \| Xs^0 \| \). It follows that \( (\sigma)^p \varnothing \phi \omega \models Xs^0 \). Since \( \phi \models Xs^0 \rightarrow Xs^{p+1}0 \), we obtain \( \phi \cdot (\sigma) \varnothing \phi \omega \cdot \pi \in \downarrow \).

Q.E.D.

Theorem [13] shows that we can use the predicate \( \text{ent}(x) \) instead of \( \text{int}(x) \), which greatly simplifies many computations. In particular, we define the universal quantifier restricted to integers \( \forall x \text{int} \) by putting \( \forall x \text{int} F \equiv \forall x (\text{int}(x) \rightarrow F) \).

Thus, we can replace it with the universal quantifier restricted to \( \text{ent}(x) \) defined as follows:

\( \forall x \text{ent} F \equiv \forall x (\text{ent}(x) \rightarrow F) \). Then, we have \( [\forall x \text{ent} F] = \{n \cdot \pi ; n \in \mathbb{N}, \pi \in \| F[s^0/x] \| \} \).

Therefore, the truth value of the formula \( \forall x \text{ent} F \) is much simpler than the one of the formula \( \forall x \text{int} F \).

**Theorem 14.** Let \( \phi : \mathbb{N} \rightarrow \mathbb{N} \) be a recursive function. There exists a closed \( \lambda \)-term \( \theta \) such that, if \( m \in \mathbb{N} \), \( n = \phi(m) \) and \( f \) is a \( \lambda \)-variable, then \( \theta m f \) reduces into \( f n \) by weak head reduction.

This is a variant of the theorem of representation of recursive functions by \( \lambda \)-terms. It is proved in [13].
Theorem 15. Let $\phi : \mathbb{N}^k \to \mathbb{N}$ be a recursive function. We define, in $\mathcal{M}$, a function symbol $f$, by putting $f(s^m0, \ldots, s^n0) = s^00$ with $n = \phi(m_1, \ldots, m_k)$; we extend $f$ on $P^k \setminus \mathbb{N}^k$ in an arbitrary way. Then, there exists a proof-like term $\theta$ such that:

$$\theta \vdash \forall x_1 \ldots \forall x_k [\text{int}(x_1), \ldots, \text{int}(x_k) \to \text{int}(f(x_1, \ldots, x_k))].$$

For simplicity, we assume $k = 1$. By theorem [13], it suffices to find a proof-like term $\theta$ such that $\theta \vdash \forall x [\text{ent}(x), (\text{ent}(f(x)) \to \bot) \to \bot]$. In other words:

$$\theta \vdash \text{ent}(p), (\text{ent}(f(p)) \to \bot) \to \bot$$

for every $p \in P$. We can suppose that $p = s^00$ (otherwise, $-\text{ent}(p) = \emptyset$ and the result is trivial). Thus, we have $\text{ent}(p) = \{m\}$; we must show:

$$\theta \ast m \ast \xi \ast \pi \in \bot \text{ for all } \pi \in \Pi \text{ and } \theta \vdash \text{ent}(s^n0) \to \bot, \text{ with } n = \phi(m).$$

Take the $\lambda$-term $\theta$ given by theorem [14]. From this theorem, we get:

$$\theta \ast m \ast \xi \ast \pi \succ \xi \ast n \ast \pi, \text{ which is in } \bot, \text{ by hypothesis on } \xi.$$

Q.E.D.

Remark. We have now found proof-like terms which realize all the axioms of second order arithmetic, with a function symbol for each recursive function.

Standard realizability algebras

A realizability algebra $\mathcal{A}$ is called standard if its set of terms $\Lambda$ and its set of stacks $\Pi$ are defined as follows:

We have a countable set $\Pi_0$ which is the set of stack constants.

The terms and the stacks of $\mathcal{A}$ are finite sequences of elements of the set:

$$\Pi_0 \cup \{B, C, E, I, K, W, cc, \varsigma, \chi, \chi', k, (,), [ ], \ast\}$$

which are obtained by the following rules:

- $B, C, E, I, K, W, cc, \varsigma, \chi, \chi'$ are terms;
- each element of $\Pi_0$ is a stack;
- if $\xi, \eta$ are terms, then $(\xi)\eta$ is a term;
- if $\xi$ is a term and $\pi$ a stack, then $\xi \ast \pi$ is a stack;
- if $\pi$ is a stack, then $k[\pi]$ is a term.

A term of the form $k[\pi]$ is called continuation. It will also be denoted as $k_{\pi}$.

The set of processes of the algebra $\mathcal{A}$ is $\Lambda \times \Pi$.

If $\xi \in \Lambda$ and $\pi \in \Pi$, the ordered pair $(\xi, \pi)$ is denoted as $\xi \ast \pi$.

Therefore, every stack has the form $\pi = \xi_1 \ast \ldots \ast \xi_n \ast \pi_0$, where $\xi_1, \ldots, \xi_n \in \Lambda$ and $\pi_0 \in \Pi_0$ ($\pi_0$ is a stack constant). Given a term $\tau$, we put:

$$\pi^\tau = \xi_1 \ast \ldots \ast \xi_n \ast \tau \ast \pi_0.$$

We choose a recursive bijection from $\Pi$ onto $\mathbb{N}$, which is written $\pi \mapsto n_{\pi}$.

We define a preorder relation $\succ$, on $\Lambda \ast \Pi$. It is the least reflexive and transitive relation such that, for all $\xi, \eta, \zeta \in \Lambda$ and $\pi, \varpi \in \Pi$, we have:

$$(\xi)\eta \ast \pi \succ \xi \ast \eta \ast \pi.$$

$$_I \ast \xi \ast \pi \succ \xi \ast \pi.$$

$$_K \ast \xi \ast \eta \ast \pi \succ \xi \ast \pi.$$

$$_E \ast \xi \ast \eta \ast \pi \succ (\xi)\eta \ast \pi.$$

$$_W \ast \xi \ast \eta \ast \pi \succ \xi \ast \eta \ast \eta \ast \pi.$$
We define the function $f$.

Finally, we have a subset $\bot$ of $\Lambda \cdot \Pi$ which is a final segment for this preorder, which means that: $p \in \bot$, $p' > p$ implies $p' \in \bot$.

In other words, we ask that $\bot$ means that:

$(\xi) \eta \ast \pi \not\in \bot \Rightarrow \xi \ast \eta \ast \pi \not\in \bot$.

$I \ast \xi \ast \pi \not\in \bot \Rightarrow \xi \ast \pi \not\in \bot$.

$K \ast \xi \ast \eta \ast \pi \not\in \bot \Rightarrow \xi \ast \pi \not\in \bot$.

$E \ast \xi \ast \pi \not\in \bot \Rightarrow (\xi)\eta \ast \pi \not\in \bot$.

$W \ast \xi \ast \eta \ast \pi \not\in \bot \Rightarrow \xi \ast \eta \ast \eta \ast \pi \not\in \bot$.

$C \ast \xi \ast \pi \not\in \bot \Rightarrow \xi \ast \eta \ast \pi \not\in \bot$.

$B \ast \xi \ast \eta \ast \pi \not\in \bot \Rightarrow (\xi)\eta \ast \pi \not\in \bot$.

$\eta \ast \xi \ast \pi \not\in \bot \Rightarrow \xi \ast \pi \not\in \bot$.

$\chi \ast \pi \not\in \bot \Rightarrow \xi \ast \pi \not\in \bot$.

$\chi' \ast \pi \not\in \bot \Rightarrow \xi \ast \pi \not\in \bot$.

**Remark.** Thus, the only arbitrary elements in a standard realizability algebra are the set $\Pi$ of stack constants and the set $\bot$ of processes.

### The axiom of choice for individuals (ACI)

Let $\mathcal{A}$ be a standard realizability algebra and $\mathcal{M}$ a $\mathcal{A}$-model, the set of individuals of which is denoted as $P$. Then, we have:

**Theorem 16 (ACI).** For each closed formula $\forall x_1 \ldots \forall x_m \forall y F$ with parameters, there exists a function $f : P^{m+1} \to P$ such that:

i) $\xi \parallel \forall x_1 \ldots \forall x_m (\forall x (\text{ent}(x) \to F[f(x_1, \ldots, x_m, x)/y]) \to \forall y F)$.

ii) $\xi \parallel \forall x_1 \ldots \forall x_m (\forall x (\text{int}(x) \to F[f(x_1, \ldots, x, x)/y]) \to \forall y F)$.

For $p_1, \ldots, p_m, k \in P$, we define $f(p_1, \ldots, p_m, k)$ in an arbitrary way if $k \not\in \mathbb{N}$.

If $k \in \mathbb{N}$, we have $k = n_{\pi_k}$ for one and only one stack $\pi_k \in \Pi$.

We define the function $f(p_1, \ldots, p_m, k)$ by means of the axiom of choice, in such a way that, if there exists $q \in P$ such that:

$p_{\pi_k} \in \|F[p_1, \ldots, p_m, q]\|$, then we have $\pi_k \in \|F[p_1, \ldots, p_m, f(p_1, \ldots, p_m, k)]\|$.

i) We must show $\xi \parallel \forall x (\text{ent}(x) \to F[p_1, \ldots, p_m, f(p_1, \ldots, p_m, x)]) \to \forall y F$, for every $p_1, \ldots, p_m, q \in P$.

Thus, let $\xi \parallel \forall x (\text{ent}(x) \to F[p_1, \ldots, p_m, f(p_1, \ldots, p_m, x)])$ and $\pi \in \|F[p_1, \ldots, p_m, q]\|$; we must show $\xi \ast \xi \ast \pi \not\in \bot$, that is $\xi \ast n_{\pi_k} \ast \pi \not\in \bot$. But we have:

$\xi \parallel \text{ent}(n_{\pi_k}) \to F[p_1, \ldots, p_m, f(p_1, \ldots, p_m, n_{\pi_k})]$ by hypothesis on $\xi$;
\( \gamma \in |\text{ent}(n)| \) by definition of \( \text{ent} \);
\( \pi \in |F[p_1, \ldots ,p_m, f(p_1, \ldots ,p_m, n)]| \) by hypothesis on \( \pi \) and by definition of \( f \).

ii) The proof is the same; in fact, (ii) is weaker than (i) since \( |\text{ent}(x)| < |\text{int}(x)| \).

Q.E.D.

**Remarks.**

1. A seemingly simpler formulation of this axiom of choice is the existence of a function \( \phi : P^m \to P \) such that \( \forall x_1 \ldots \forall x_m (F[\phi(x_1, \ldots ,x_m)/y] \to \forall y F) \). It clearly follows from theorem [17]: simply define \( \phi(x_1, \ldots ,x_m) = f(x_1, \ldots ,x_m) \) for the first integer \( x \) such that \( -F[f(x_1, \ldots ,x_m, x)/y] \) if there is such an integer; otherwise, \( \phi(x_1, \ldots ,x_m) \) is arbitrary.

But this function \( \phi \) is not a function symbol, i.e. it cannot be defined in the ground model. For this reason, we prefer to use this axiom in the form stated in theorem [10], which is, after all, much simpler.

2. The axiom of dependent choice DC is a trivial consequence of ACI; therefore theorem [16] shows that DC is realized by a proof-like term. Theorem [16] is also crucial to prove theorem [38] (see lemma [40]).

3. In the following, there will be individuals which represent sets of integers (proposition [50]), but extensionality is not realized. That is why ACI is much weaker than the usual axiom of choice. For instance, it does not imply well-ordering.

**Generic models**

Given a standard realizability algebra \( A \) and a \( A \)-model \( M \), we now build a new realizability algebra \( B \) and a \( B \)-model \( N \), which is called generic over \( M \). Then, we shall define the notion of forcing, which is a syntactic transformation on formulas; it is the essential tool in order to compute truth values in the generic model \( N \).

Thus, we consider a standard realizability algebra \( A \) and a \( A \)-model \( M \), the set of individuals of which is \( P \).

We have a unary predicate \( C : P \to \mathcal{P}(A) \), a binary function \( \land : P^2 \to P \) and a distinguished individual \( 1 \in P \). We suppose that the data \( \{ C, \land, 1 \} \) constitute what we call a forcing structure in \( M \), which means that we have the following property:

There exist six proof-like terms \( \alpha_0, \alpha_1, \alpha_2, \beta_0, \beta_1, \beta_2 \) such that:

\[
\begin{align*}
\tau \in |C[(p \land q) \land r]| & \Rightarrow \alpha_0 \tau \in |C[p \land (q \land r)]| ; \\
\tau \in |C[p]| & \Rightarrow \alpha_1 \tau \in |C[p \land 1]| ; \\
\tau \in |C[p \land q]| & \Rightarrow \alpha_2 \tau \in |C[q]| ; \\
\tau \in |C[p]| & \Rightarrow \beta_0 \tau \in |C[p \land p]| ; \\
\tau \in |C[p \land q]| & \Rightarrow \beta_1 \tau \in |C[q \land p]| ; \\
\tau \in |C[(p \land q) \land r]\land s| & \Rightarrow \beta_2 \tau \in |C[(p \land (q \land r)) \land s]|.
\end{align*}
\]

We shall call \( C \)-expression any finite sequence of symbols of the form \( \gamma = (\delta_0)(\delta_1) \ldots (\delta_k) \) where each \( \delta_i \) is one of the proof-like terms \( \alpha_0, \alpha_1, \alpha_2, \beta_0, \beta_1, \beta_2 \).

Such an expression is not a \( C \)-term, but \( \gamma \tau \) is, for every \( C \)-term \( \tau \); the term \( \gamma \tau = (\delta_0)(\delta_1) \ldots (\delta_k) \tau \) will also be written \( (\gamma) \tau \).

**Notation.** A \( \land \)-term is, by definition, a term which is written with the variables \( p_1, \ldots ,p_k \), the constant \( 1 \) and the binary function symbol \( \land \). Let \( t(p_1, \ldots ,p_k), u(p_1, \ldots ,p_k) \) be two \( \land \)-terms. The notation:
\[
\gamma :: t(p_1, \ldots, p_k) \Rightarrow u(p_1, \ldots, p_k)
\]
means that \(\gamma\) is a \(C\)-expression such that \(\tau \in |C[t(p_1, \ldots, p_k)]| \Rightarrow (\gamma)\tau \in |C[u(p_1, \ldots, p_k)]|\).

Thus, with this notation, the above hypothesis can be written as follows:

\[
\alpha_0 :: (p \land q) \Rightarrow p \land (q \land r) ; \quad \alpha_1 :: p \land q \Rightarrow q ; \quad \alpha_2 :: p \land q \Rightarrow q \land p ; \quad \beta_0 :: p \Rightarrow p \land q ; \quad \beta_1 :: p \land q \Rightarrow q \land p ; \quad \beta_2 :: ((p \land q) \land r) \land s \Rightarrow (p \land (q \land r)) \land s.
\]

**Lemma 18.** There exist \(C\)-expressions \(\beta_0', \beta_1', \beta_2', \beta_3, \beta_3'\) such that:

\[
\beta_0' :: p \land q \Rightarrow (p \land q) \land r ; \quad \beta_1' :: (p \land q) \land r \Rightarrow (q \land p) \land r ; \quad \beta_2' :: p \land (q \land r) \Rightarrow (p \land q) \land r ; \quad \beta_3' :: (p \land q) \land r \land s \Rightarrow (p \land (q \land r)) \land s.
\]

We write the sequence of transformations, with the \(C\)-expressions which perform them:

- \(\beta_0' = (\beta_1')(\alpha_0)(\beta_0)\).
- \(p \land q ; \beta_0' \land \alpha_0) \land (p \land q) ; \alpha_0, p \land (q \land (p \land q)) ; \alpha_2 ; q \land (p \land q) ; \beta_1 ; (p \land q) \land q\).
- \(\beta_2' = (\alpha_2)(\alpha_0)(\beta_2')(\beta_1)\).
- \(p \land (q \land r) ; \beta_1' ; (q \land r) \land p ; \alpha_0, p \land (q \land (p \land q)) ; \alpha_2 ; q \land (p \land q) ; \beta_1 ; (p \land q) \land r\).
- \(\beta_3' = (\alpha_2)(\alpha_0)(\alpha_0)(\beta_3')(\beta_1)\).
- \(p \land (q \land r) ; \beta_1' ; (q \land r) \land p ; \beta_1 ; (p \land q) \land r\).
- \(\beta_3' = (\beta_3')(\beta_1)\).
- \(p \land (q \land r) ; \beta_1 ; (q \land r) \land p ; \beta_1 ; (p \land q) \land r\).
- \(\beta_3' = (\alpha_2)(\alpha_0)(\beta_3')(\beta_1)\).
- \(p \land (q \land r) ; \beta_1' ; (q \land r) \land p ; \beta_1 ; (p \land q) \land r\).
- \(\beta_3' = (\beta_3')(\beta_1)\).
- \(p \land (q \land r) ; \beta_1 ; (q \land r) \land p ; \beta_1 ; (p \land q) \land r\).
- \(\beta_3' = (\alpha_2)(\alpha_0)(\beta_3')(\beta_1)\).
- \(p \land (q \land r) ; \beta_1 ; (q \land r) \land p ; \beta_1 ; (p \land q) \land r\).

Q.E.D.

**Lemma 19.** Let \(t, u\) be two \(\land\)-terms such that each variable of \(u\) appears in \(t\). Then, there exists a \(C\)-expression \(\gamma\) such that \(\gamma :: t \Rightarrow t \land u\).

Proof by induction on the number of symbols of \(t\) which stand after the last occurrence of \(p\). If this number is 0, then \(t = p\) or \(t = u \land p\). Then, we have \(\gamma = \beta_0\) or \(\beta_0'\) (lemma 17). Otherwise, we have \(t = u \land v\); if the last occurrence of \(p\) is in \(u\), the recurrence hypothesis gives \(\gamma' :: u \land v \Rightarrow (u \land v) \land p\). Then, we have \(\gamma = (\beta_1')(\gamma')(\beta_1)\).

If the last occurrence of \(p\) is in \(v\), we have \(v = v_0 \land v_1\). If this occurrence is in \(v_0\), the recurrence hypothesis gives \(\gamma' :: u \land (v_1 \land v_0) \Rightarrow (u \land (v_1 \land v_0)) \land p\). We put \(\gamma = (\beta_2')(\gamma')(\beta_3)\) (lemma 17). If this occurrence is in \(v_1\), the recurrence hypothesis gives \(\gamma' :: (u \land v_0) \land v_1 \Rightarrow ((u \land v_0) \land v_1) \land p\). Then, we put \(\gamma = (\beta_2')(\gamma')(\beta_2')\).

Q.E.D.
Theorem 20. Let \( t, u \) be two \( \land \)-terms such that each variable of \( u \) appears in \( t \). Then, there exists a \( C \)-expression \( \gamma \) such that \( \gamma :: t \Rightarrow u \).

By lemma 13, we have \( \gamma' :: t \Rightarrow t \wedge u \). Thus, we can put \( \gamma = (\alpha \gamma') \).

Q.E.D.

Corollary 21. There exist \( C \)-expressions \( \gamma_l, \gamma_k, \gamma_c, \gamma_B, \gamma_e, \gamma_c, \gamma_k \) such that:

\[
\begin{align*}
\gamma_l &:: p \wedge q \Rightarrow q ; \quad \gamma_k :: 1 \wedge (p \wedge (q \wedge r)) \Rightarrow p \wedge r ; \quad \gamma_c :: 1 \wedge (p \wedge q) \wedge r ; \\
\gamma_B &:: 1 \wedge (p \wedge (q \wedge r)) \Rightarrow (p \wedge (q \wedge r)) ; \\
\gamma_e &:: 1 \wedge (p \wedge (q \wedge r)) \Rightarrow (p \wedge (q \wedge r)) ; \\
\gamma_k &:: p \wedge q \Rightarrow q \wedge p.
\end{align*}
\]

The algebra \( B \)

We define now a new realizability algebra \( B = (\Lambda, \Pi, \Lambda \star \Pi, \bot \) : its set of terms is \( \Lambda = \Lambda \times P \), its set of stacks is \( \Pi = \Pi \times P \) and its set of processes is \( \Lambda \star \Pi = (\Lambda \star \Pi) \times P \). The distinguished subset \( \bot_B \) of \( \Lambda \star \Pi \) is denoted by \( \bot \). It is defined as follows:

\[
(\xi, \pi, p) \in \bot \iff (\forall \tau \in \mathbb{C}[p]) \xi \star \pi^\tau \in \bot.
\]

For \( (\xi, p) \in \Lambda \) and \( (\pi, q) \in \Pi \), we put:

\[
(\xi, p) \star (\pi, q) = (\xi \star \pi, p \wedge q);
\]

\[
(\xi, p) \cdot (\pi, q) = (\xi \star \pi, p \wedge q).
\]

For \( (\xi, p), (\eta, q) \in \Lambda \), we put:

\[
(\xi, p)(\eta, q) = (\overline{\alpha}_0 \xi \eta, p \wedge q) \quad \text{with} \quad \overline{\alpha}_0 = \lambda x(\chi) \lambda y(\chi' y)(\alpha_0) y.
\]

Lemma 22. For each \( C \)-expression \( \gamma \), we put \( \overline{\gamma} = \lambda x(\chi) \lambda y(\chi' y)(\gamma) x \).

This is immediate, by means of theorem 2. We could take also \( \overline{\gamma} = (\chi) \lambda x \lambda y(\chi' y)(\gamma) x \).

Q.E.D.

Proposition 23. If we have \( \gamma :: t(p_1, \ldots, p_k) \Rightarrow u(p_1, \ldots, p_k) \), then:

\[
(\overline{\gamma} \star \xi \cdot \pi, t(p_1, \ldots, p_k)) \Rightarrow (\xi \cdot \pi, u(p_1, \ldots, p_k)).
\]

Suppose that \( (\overline{\gamma} \star \xi \cdot \pi, t(p_1, \ldots, p_k)) \notin \bot \). Thus, there exists \( \tau \in \mathbb{C}[t(p_1, \ldots, p_k)] \) such that:

\[
\overline{\gamma} \star \xi \cdot \pi^\tau \notin \bot. \quad \therefore \quad \exists \tau \in \mathbb{C}[u(p_1, \ldots, p_k)].
\]

It follows that:

\[
(\xi \star \pi, u(p_1, \ldots, p_k)) \notin \bot.
\]

Q.E.D.

Lemma 24. We have \( (\xi, p)(\eta, q) \star (\pi, r) \notin \bot \Rightarrow (\xi, p) \star (\eta, q) \cdot (\pi, r) \notin \bot \).

By hypothesis, we have \( (\overline{\alpha}_0 \xi \eta \cdot \pi, p \wedge q) \wedge r \notin \bot \); thus, there exists \( \tau \in \mathbb{C}[p \wedge (q \wedge r)] \) such that \( \overline{\alpha}_0 \xi \eta \cdot \pi^\tau \notin \bot \). By lemma 22, we have \( \xi \cdot \eta \cdot \pi^{\alpha_0 \tau} \notin \bot \); since \( \alpha_0 \tau \in \mathbb{C}[p \wedge (q \wedge r)] \), we have \( (\xi \cdot \eta \cdot \pi, p \wedge (q \wedge r)) \notin \bot \) and thus \( (\xi, p) \star (\eta, q) \cdot (\pi, r) \notin \bot \).

Q.E.D.

We define the elementary combinators \( B, C, E, I, K, W, cc \) of the algebra \( B \) by putting:
Suppose we shall prove only the cases $k^* = (k_\pi^*, \tilde{\pi})$ with $k_\pi^* = (\chi_\lambda \lambda_\lambda \lambda^\gamma_{E}(\gamma^C_k) \lambda^y_k x) \cdot \pi^\gamma$.

Theorem 25. For every $\tilde{\xi}, \tilde{\eta}, \tilde{\zeta} \in A$ and $\tilde{\pi}, \tilde{\omega} \in \Pi$, we have:

$$B \ast \xi \ast \tilde{\pi} \not\in \Pi \Rightarrow \tilde{\xi} \ast \tilde{\pi} \not\in \Pi;$$

$$K \ast \xi \ast \tilde{\eta} \ast \tilde{\pi} \not\in \Pi \Rightarrow \tilde{\xi} \ast \tilde{\eta} \ast \tilde{\pi} \not\in \Pi;$$

$$E \ast \xi \ast \tilde{\eta} \ast \tilde{\pi} \not\in \Pi \Rightarrow (\tilde{\xi} \tilde{\eta} \ast \tilde{\pi} \not\in \Pi;$$

$$W \ast \xi \ast \tilde{\eta} \ast \tilde{\pi} \not\in \Pi \Rightarrow \tilde{\xi} \ast \tilde{\eta} \ast \tilde{\pi} \not\in \Pi;$$

$$B \ast \tilde{\xi} \ast \tilde{\eta} \ast \tilde{\zeta} \not\in \Pi \Rightarrow (\tilde{\xi} \tilde{\eta} \ast \tilde{\zeta} \not\in \Pi;$$

$$CC \ast \tilde{\xi} \ast \tilde{\pi} \not\in \Pi \Rightarrow \tilde{\xi} \ast \tilde{\pi} \not\in \Pi.$$
proof-like term and 1_t a condition written with 1, ∧ and parentheses, which are obtained as follows, by recurrence on t:

- If t is an elementary combinator B, C, E, I, K, W, cc, then t* is already defined; 1_t = 1.
- (tu)* = σ0tu*; 1tu = 1t∧1u.

The model $\mathcal{N}$

The $\mathcal{B}$-model $\mathcal{N}$ has the same set $P$ of individuals and the same functions as $\mathcal{M}$.

By definition, the $k$-ary predicates of $\mathcal{N}$ are the applications from $P^k$ into $\mathcal{P}(\Pi)$. But, since $\Pi = \Pi \times P$, they are the same as the applications from $P^{k+1}$ into $\mathcal{P}(\Pi)$, i.e. the $k+1$-ary predicates of the model $\mathcal{M}$.

Each predicate constant $R$, of arity $k$, is interpreted, in the model $\mathcal{M}$, by an application $R_M$ from $P^k$ into $\mathcal{P}(\Lambda)$. In the model $\mathcal{N}$, this predicate constant is interpreted by the application $R_N : P^k \rightarrow \mathcal{P}(\Lambda)$, where $R_N(p_1, \ldots, p_k) = R_M(p_1, \ldots, p_k) \times \{1\}$.

For each closed formula $F$, with parameters in $\mathcal{N}$, its truth value, which is a subset of $\Pi$, will be denoted by $\|F\|$. We shall write $\langle \xi, p \rangle \models F$ to mean that $\langle \xi, p \rangle \in \Lambda$ realizes $F$, in other words $\langle \forall \pi \in \Pi \rangle \langle \forall q \in P \rangle (\langle (\pi, q) \in \|F\| \rangle) \Rightarrow \langle \xi, p \rangle \ast \langle \pi, q \rangle \in \|\|).$

**Theorem 26.**
If we have $\vdash t : A$ in classical second order logic, where $A$ is a closed formula, then $t_B = (t^*, 1_t) \models A$.

Q.E.D.

**Proposition 27.**

i) If $\langle \xi, 1 \rangle \models F$, then $\langle \neg\xi, p \rangle \models F$ for each $p \in P$, with $\gamma : p \neq q \Rightarrow 1 \wedge q$.

ii) Let $\xi, \eta \in \Lambda$ be such that $\xi \ast \pi \succ \eta \ast \pi$ for each $\pi \in \Pi$. Then, we have:

$\langle \xi \ast \pi, p \rangle \notin \|\| \Rightarrow \langle \eta \ast \pi, p \rangle \notin \|\|$ for every $\pi \in \Pi$ and $p \in P$;

$\langle \eta, p \rangle \models F \Rightarrow \langle \xi, p \rangle \models F$ for every closed formula $F$.

i) We must show that, for each $\langle \pi, q \rangle \in \|\|$, we have $\langle \neg\xi, p \rangle \ast \langle \pi, q \rangle \in \|\|$, that is:

$\langle \neg\xi \ast \pi, p \neq q \rangle \in \|\|$. Thus, let $\tau \in C[p \neq q]$, so that $\gamma \tau \in C[1 \neq q]$. Since we have, by hypothesis, $\langle \xi \ast \pi, 1 \rangle \in \|\|$, it follows that $\xi \ast \pi \tau \in \|\|$ and therefore $\neg\xi \ast \pi \tau \in \|\|$

ii) By hypothesis, there exists $\tau \in C[p]$ such that $\xi \ast \pi \tau \notin \|\|$. Thus, we have $\eta \ast \pi \tau \notin \|\|$, so that $\langle \eta \ast \pi, p \rangle \notin \|\|$. Let $\langle \pi, q \rangle \in \|\| \mid ;$ we have $\langle \eta, p \rangle \ast \langle \pi, q \rangle \in \|\|$, that is $\langle \eta \ast \pi, p \neq q \rangle \in \|\|$. From what we have just shown, it follows that $\langle \xi \ast \pi, p \neq q \rangle \in \|\|$, and therefore $\langle \xi, p \rangle \ast \langle \pi, q \rangle \in \|\|$. Q.E.D.

The integers of the model $\mathcal{N}$

Recall that we have put:

$\sigma = \lambda n \lambda f \lambda x (f)(n)fx, \quad 0 = \lambda x \lambda y \; y$ and $n = (\sigma)^n \underline{0}$ for every integer $n$.

Thus, we have $\sigma_\sigma = (\sigma^*, 1_\sigma)$ and $n_B = ((\sigma)^n \underline{0})_B = (n^*, 1_n)$.

Therefore $0_B = (K I)_B = (K^*, 1)(I^*, 1)$ and $n + 1_B = \sigma_B n_B = (\sigma^*, 1_\sigma)(n^*, 1_n)$.
Thus, the recursive definitions of $n^*$, $1_n$ are the following:

$\bar{n}^* = \bar{a}_0 K^* I^* ; (n+1)^* = a_0 \sigma^* n^*$ ;

$1_n = 1 \cdot 1 ; 1_{n+1} = 1_n \wedge 1_\bar{n}$.

We can define the unary predicate $ent(x)$ in the model $\mathcal{N}$ in two distinct ways:

i) From the predicate $ent(x)$ of the model $\mathcal{M}$, by putting:

$\text{ent}(s^n 0) = \{ (\bar{n}, 1) \} ; \mid \text{ent}(p) \mid = \emptyset$ if $p \notin \mathbb{N}$.

ii) By using directly the definition of $ent(x)$ in the model $\mathcal{N}$; we denote this predicate by $ent_\mathcal{N}(x)$. Therefore, we have:

$\mid \text{ent}_\mathcal{N}(s^n 0) \mid = \{ (\bar{n}, 1) \} ; \mid \text{ent}_\mathcal{N}(p) \mid = \emptyset$ if $p \notin \mathbb{N}$.

From theorem 13, applied in the model $\mathcal{N}$, we know that the predicates $int(x)$ and $ent_\mathcal{N}(x)$ are interchangeable. Theorem 28 shows that the predicates $int(x)$ and $ent_\mathcal{N}(x)$ are also interchangeable. Thus, we have three predicates which define the integers in the model $\mathcal{N}$; it is the predicate $ent(x)$ that we shall mostly use in the sequel. In particular, we shall often replace the quantifier $\forall x^{int}$ with $\forall x^{ent}$.

**Theorem 28.**

There exist two proof-like terms $T, J$ such that:

i) $(T, 1) \mid\mid \forall X \forall x((\text{ent}(x) \rightarrow X), \text{int}(x) \rightarrow X)$.

ii) $(J, 1) \mid\mid \forall x(\text{ent}(x) \rightarrow \text{int}(x))$.

i) We apply theorem 13 to the sequence $u : \mathbb{N} \rightarrow \Lambda$ defined by $u_n = (\bar{n}, 1)$.

We are looking for two proof-like terms $T, S$ such that:

$(S, 1) \star (\psi, p) \star (u, 1) \star (\pi, r) \Rightarrow (\psi, p) \star (n + 1, 1) \star (\pi, r) ; (S, 1) \mid\mid T \rightarrow \bot, T \rightarrow \bot.$

$(T, 1) \star (\phi, p) \star (\nu, q) \star (\pi, r) \Rightarrow (\nu, q) \star (S, 1) \star (\phi, p) \star (0, 1) \star (\pi, r).$

Then theorem 13 will give the desired result:

$(T, 1) \mid\mid \forall X \forall x((\text{ent}(x) \rightarrow X), \text{int}(x) \rightarrow X)$.

We put $S = \lambda f \lambda x(\overline{\sigma} f)(\sigma)x$, with $\gamma : (1 \wedge (p \wedge (q \wedge r))) \Rightarrow p \wedge (q \wedge r)$.

Then, we have $(S, 1) \star (\psi, p) \star (\nu, q) \star (\pi, r) \equiv (S \star \psi \star \nu \star \pi, 1 \wedge (p \wedge (q \wedge r))) \Rightarrow$

$(\overline{\sigma} \psi \star \overline{\sigma} \nu \star \overline{\sigma} \pi, 1 \wedge (p \wedge (q \wedge r)))$ (theorem 2 and proposition 27(ii))

$\Rightarrow (\psi \star \nu \star \pi, 1 \wedge (p \wedge (q \wedge r)))$ (proposition 23).

Suppose first that $(p, q) \mid\mid \exists \tau \rightarrow \bot$; then, we have $(p, q) \star (\nu, q) \star (\pi, r) \in \bot$ and thus:

$(S, 1) \star (\psi, p) \star (\nu, q) \star (\pi, r) \in \bot$. This shows that $(S, 1) \mid\mid \forall T \rightarrow \bot, T \rightarrow \bot.$

Moreover, if we put $\nu = n$, so that $\sigma \nu = n + 1$, and $q = 1$, we have shown that:

$(S, 1) \star (\psi, p) \star (n, 1) \star (\pi, r) \Rightarrow (\psi, p) \star (n + 1, 1) \star (\pi, r).$

Now, we put $T = (\lambda f \lambda x(\overline{\sigma} f)(\sigma)x)$ with $\gamma : (1 \wedge (p \wedge (q \wedge r))) \Rightarrow q \wedge (1 \wedge (p \wedge (q \wedge r)))$.

Then, we have $(T, 1) \star (\phi, p) \star (\nu, q) \star (\pi, r) \equiv (T \star \phi \star \nu \star \pi, 1 \wedge (p \wedge (q \wedge r))) \Rightarrow$

$(\overline{\sigma} \nu \star S \star \phi \star 0 \star \pi, 1 \wedge (p \wedge (q \wedge r)))$ (theorem 2 and proposition 27(ii))

$\Rightarrow (\nu \star S \star \phi \star 0 \star \pi, 1 \wedge (p \wedge (q \wedge r)))$ (proposition 23).

Then, we have $(T, 1) \star (\phi, p) \star (\nu, q) \star (\pi, r) \equiv (T \star \phi \star \nu \star \pi, 1 \wedge (p \wedge (q \wedge r))) \Rightarrow$

$(\overline{\sigma} \nu \star S \star \phi \star 0 \star \pi, 1 \wedge (p \wedge (q \wedge r)))$ (theorem 2 and proposition 27(ii))

$\Rightarrow (\nu \star S \star \phi \star 0 \star \pi, 1 \wedge (p \wedge (q \wedge r)))$ (proposition 23).

$\Rightarrow (\nu \star \pi, 1 \wedge (q \wedge r))$ (which is the desired result).
Thus, let \( \tau \in C[1 \land (1 \land q)] \); we have then \((\gamma)^n(\gamma_0)\tau \in C[1_n \land q]\)
where \( \gamma_0 \) and \( \gamma \) are two \( C \)-expressions such that:
\[ \gamma_0 : 1(1 \land q) \Rightarrow (1 \land 1) \land q; \quad \gamma : p \land q \Rightarrow (1 \land p) \land q. \]
Indeed, we have seen that \( 1_\emptyset = 1 \land 1 \) and \( 1_{n+1} = 1_n \land 1_n \). It follows that, if \( \tau \in C[1 \land (1 \land q)] \),
then \((\gamma_0)\tau \in C[1_0 \land q] \), and therefore \((\gamma)^n(\gamma_0)\tau \in C[1_n \land q] \).
Thus, we have \( \bigvee_{\tau} \pi \equiv (\gamma)^n(\gamma_0)\tau \in \bot. \)
Now, we build below two proof-like terms \( g, j \) such that, for each \( n \in \mathbb{N} \), we have:
a) \( g \cdot n \cdot [ \pi \cdot \gamma \cdot x \cdot \pi \Rightarrow \xi \cdot \pi \equiv \bigvee_{\tau} (\pi^n(\gamma_0)\tau \in \bot) \).
b) \( j \cdot n \cdot [ \pi \cdot \gamma \cdot x \cdot \pi \Rightarrow \xi \cdot \pi \equiv \bigvee_{\tau} (\pi^n(\gamma_0)\tau \in \bot) \), which is the desired result.

- We put \( g = \lambda k \lambda x (\gamma_0)(k) \gamma x \); from theorem 2, we have:
\[ g \cdot n \cdot [ \pi \cdot \gamma \cdot x \cdot \pi \Rightarrow \xi \cdot \pi \equiv \bigvee_{\tau} (\pi^n(\gamma_0)\tau \in \bot) \).
Thus, it suffices to show that \((\pi^n(\gamma_0)\tau \in \bot) \) which we do by recurrence on \( n \).

If \( n = 0 \), we have immediately \( \emptyset \cdot [ \pi \cdot \gamma \cdot x \cdot \pi \Rightarrow \xi \cdot \pi \equiv \bigvee_{\tau} (\pi^n(\gamma_0)\tau \in \bot) \) since \( \emptyset = \lambda x \lambda y \).

- We put \( j = \pi \equiv \bigvee_{\tau} (\pi^n(\gamma_0)\tau \in \bot) \).
Therefore, we have \( j \cdot n \cdot [ \pi \cdot \gamma \cdot x \cdot \pi \Rightarrow \xi \cdot \pi \equiv \bigvee_{\tau} (\pi^n(\gamma_0)\tau \in \bot) \).

- We put \( \beta \equiv \pi \equiv \bigvee_{\tau} (\pi^n(\gamma_0)\tau \in \bot) \).

For each formula \( \pi \equiv \bigvee_{\tau} (\pi^n(\gamma_0)\tau \in \bot) \) and a free condition variable \( \gamma \), we use the variables \( n, k \), which gives the desired result with \( k = 0 \).

- We put \( \pi \equiv \bigvee_{\tau} (\pi^n(\gamma_0)\tau \in \bot) \).

Q.E.D.

Forcing

Forcing is a method to compute truth values of formulas in the generic \( B \)-model \( N \).
For each \( k \)-ary predicate variable \( X \), we add to the language a new predicate variable, denoted by \( X^+ \), which has arity \( k + 1 \). In the \( A \)-model \( M \), we use the variables \( X \) and \( X^+ \) in the \( B \)-model \( N \), only the variables \( X \).
With each \( k \)-ary second order parameter \( X : P^k \rightarrow P(\Pi) \) of the model \( N \), we associate a \((k + 1)\)-ary second order parameter \( X^+ : P^{k+1} \rightarrow P(\Pi) \) of the model \( M \). It is defined in an obvious way, since \( \Pi = \Pi \times P \); we put:
\[ X^+(p, p_1, \ldots, p_k) = \{ \pi \in \Pi : (\pi, p) \in X(p_1, \ldots, p_k) \}. \]
For each formula \( F \) written without the variables \( X^+ \), with parameters in the model \( N \), we define, by recurrence on \( F \), a formula denoted by \( p \models F \) (read “ \( p \) forces \( F \)”), with parameters in the model \( A \), written with the variables \( X^+ \) and a free condition variable \( p : \)
If \( F \) is atomic of the form \( X(t_1, \ldots, t_k) \), then \( p \models F \) is \( \forall q(C[p \land q] \rightarrow X^+(q, t_1, \ldots, t_k)) \).

If \( F \) is atomic of the form \( X(t_1, \ldots, t_k) \), then \( p \models F \) is \( \forall q(C[p \land q] \rightarrow X^+(q, t_1, \ldots, t_k)) \).

If \( F \equiv (A \rightarrow B) \) where \( A, B \) are formulas, then \( p \models F \) is \( \forall q(q \models A \rightarrow p \land q \models B) \).

If \( F \equiv (R(t_1, \ldots, t_k) \rightarrow B) \), where \( R \) is a predicate constant, then:
\[ p \models F \text{ is } (R(t_1, \ldots, t_k) \rightarrow p \models B). \]
If $F \equiv (t_1 = t_2 \mapsto B)$, then $p \vdash F$ is $(t_1 = t_2 \mapsto p \vdash B)$.
If $F \equiv \forall x \, A$, then $p \vdash F$ is $\forall x (p \vdash A)$.
If $F \equiv \forall X \, A$, then $p \vdash F$ is $\forall X^+ (p \vdash A)$.

Thus we have, in particular:
If $F \equiv \forall x_{\text{ent}} \, A$, then $p \vdash F$ is $\forall x_{\text{ent}} (p \vdash A)$.

**Lemma 29.** Let $F$ be a formula the free variables of which are amongst $X_1, \ldots, X_k$ and let $X_1, \ldots, X_k$ be second order parameters in the model $\mathcal{N}$, with corresponding arities.

Then, we have:

$$(p \vdash F)[X_1^+/X_1', \ldots, X_k^+/X_k'] \equiv (p \vdash F[X_1/X_1', \ldots, X_k/X_k'])$$

Immediate, by recurrence on $F$.

Q.E.D.

**Theorem 30.**

For each closed formula $F$ with parameters in the model $\mathcal{N}$, there exist two proof-like terms $\chi_F, \chi'_F$, which only depend on the propositional structure of $F$, such that we have:

$$\xi \vdash (p \vdash F) \Rightarrow (\chi_F \xi, p) \vdash F$$

$$(\xi, p) \vdash F \Rightarrow \chi'_F \xi \vdash (p \nvdash F)$$

for every $\xi \in \Lambda$ and $p \in P$.

The *propositional structure* of $F$ is the simple type built with only one atom $O$ and the connective $\rightarrow$, which is obtained from $F$ by deleting all quantifiers, all symbols $\mapsto$ with their hypothesis, and by identifying all atomic formulas with $O$.

For instance, the propositional structure of the formula:

$$\forall X (\forall y (f(x, y) = 0 \mapsto X y) \mapsto X x) \mapsto \forall x X x)$$

is $(O \rightarrow O) \rightarrow O$.

Proof by recurrence on the length of $F$.

- If $F$ is atomic, we have $F \equiv X(t_1, \ldots, t_k)$; we show that $\chi_F = \chi$ and $\chi'_F = \chi'$.

Indeed, we have:

$$||p \vdash F|| = ||\forall q (C[p \land q] \mapsto X^+ (q, t_1, \ldots, t_k))||$$

$$= \bigcup_{(\pi, q) \in \mathbb{C}[p \land q]} (\pi, q) \in ||X(t_1, \ldots, t_k)||$$

because, by definition of $X^+$, we have $\pi \in ||X^+ (q, t_1, \ldots, t_k)|| \iff (\pi, q) \in ||X(t_1, \ldots, t_k)||$.

Therefore, we have:

$$(\xi, p) \vdash F \iff (\forall q \in P)(\forall \tau \in C[p \land q])(\forall \pi \in \Pi)((\pi, q) \in ||X(t_1, \ldots, t_k)|| \Rightarrow \xi \star \tau \star \pi \in \bot)$$

Moreover, we have:

$$(\xi, p) \nvdash F \iff (\forall \tau \in C[p \land q])(\forall \pi \in \Pi)((\pi, q) \in ||F|| \Rightarrow (\xi, p) \star (\pi, q) \in \bot)$$

$$(\forall q \in P)(\forall \pi \in \Pi)((\pi, q) \in ||F|| \Rightarrow (\xi \star \tau \star \pi \in \bot)$$

and finally, by definition of $\bot$:

$$(\xi, p) \vdash F \iff (\forall \tau \in C[p \land q])(\forall \pi \in \Pi)((\pi, q) \in ||F|| \Rightarrow \xi \star \tau \star \pi \in \bot)$$

Suppose that $\xi \vdash (p \vdash F)$. Since $\chi \xi \star \tau \star \pi \Rightarrow \xi \star \tau \star \pi$, we have from $(\ast)$:

$$(\forall \tau \in C[p \land q])(\forall \pi \in \Pi)((\pi, q) \in ||X^+ (q, t_1, \ldots, t_k)|| \Rightarrow \chi \xi \star \tau \star \pi \in \bot)$$

and therefore $(\chi \xi, p) \nvdash F$ from $(\ast)$.

Conversely, suppose that $(\xi, p) \nvdash F$. By applying $(\ast)$ and $\chi' \xi \star \tau \star \pi \Rightarrow \xi \star \tau \star \pi$, we obtain:

$$(\forall \tau \in C[p \land q])(\forall \pi \in \Pi)((\pi, q) \in ||F|| \Rightarrow \chi' \xi \star \tau \star \pi \in \bot)$$

and therefore $\chi' \xi \vdash (p \vdash F)$ from $(\ast)$.

- If $F \equiv \forall X \, A$, then $p \vdash F \equiv \forall X^+ (p \vdash A)$.

Therefore, we have:

$$\xi \vdash (p \vdash F) \equiv \forall X^+ (\xi \vdash (p \vdash A))$$

Moreover, we have:

$$(\xi, p) \vdash F \equiv \forall X ((\xi, p) \vdash A).$$
Let \( \mathcal{X} : P^k \rightarrow \mathcal{P}(\Pi) \) be a second order parameter in the model \( \mathcal{N} \), with the same arity as \( X \), and let \( \mathcal{X}^+ \) be the corresponding parameter of the model \( \mathcal{M} \).

If \( \xi \models (p \models F) \), then we have \( (\xi \models (p \models A))[\mathcal{X}^+/\mathcal{X}^+] \), thus \( \xi \models (p \models A[\mathcal{X}/\mathcal{X}]) \), from lemma 23.

By the recurrence hypothesis, we have \( (\chi_A \xi, p) \models A[\mathcal{X}/\mathcal{X}] \). Since \( \mathcal{X} \) is arbitrary, it follows that \( (\chi_A \xi, p) \models p \models A[\mathcal{X}/\mathcal{X}] \).

Conversely, if we have \( (\xi, p) \models F \), then \( (\xi, p) \models A[\mathcal{X}/\mathcal{X}] \) for every \( \mathcal{X} \).

By the recurrence hypothesis, we have \( \chi_A' \xi \models (p \models A[\mathcal{X}/\mathcal{X}]) \), and therefore : \( \chi_A' \xi \models (p \models A[\mathcal{X}/\mathcal{X}]) \), from lemma 23. Since \( \mathcal{X}^+ \) is arbitrary, it follows that : \( \chi_A^+ \xi \models A^+[\mathcal{X}^+/\mathcal{X}^+] \), that is \( \chi_A^+ \xi \models (p \models \forall X A) \).

- If \( F \equiv \forall x A \), then \( p \models F \equiv \forall x(p \models A) \). Therefore \( \xi \models p \models F \equiv \forall x(\xi \models (p \models A)) \).

Moreover, \( (\xi, p) \models F \equiv \forall x((\xi, p) \models A) \).

The result is immediate, from the recurrence hypothesis.

- If \( F \equiv (t_1 = t_2 \rightarrow A) \), then \( p \models F \equiv T \models t_1 = t_2 \rightarrow p \models A \). Therefore : \( \xi \models (p \models F) \equiv (t_1 = t_2 \rightarrow \xi \models (p \models A)) \).

Moreover, \( (\xi, p) \models F \equiv \forall x((\xi, p) \models A) \).

The result is immediate, from the recurrence hypothesis.

- If \( F \equiv A \rightarrow B \), we have \( p \models F \equiv \forall q(q \models A \rightarrow p \models q \models B) \) and therefore : \( (\chi_F \xi, p) \models (\forall q(q \models A \rightarrow p \models q \models B)) \).

Suppose that \( \xi \models (p \models F) \) and put \( \chi_F = \lambda x \lambda y (\gamma_0 ) (\chi_B)(x)(\chi_A^+)y \).

We must show \( (\chi_F \xi, p) \models A \rightarrow B \) ; thus, let \( (\eta, q) \models A \) and \( (\pi, r) \in B \).

We must show \( (\chi_F \xi, p) \ast (\eta, q) \ast (\pi, r) \ast [\mathcal{B}] \) that is \( (\chi_F \xi \ast \eta \ast \pi \ast (p \models q \models r)) \ast [\mathcal{B}] \).

Thus, let \( r \in c[p \models (q \models r)] \) ; we must show \( \chi_F \xi \ast r \ast \pi \ast \eta \ast [\mathcal{B}] \) or else \( \chi_F \xi \ast r \ast \pi \ast \eta \ast [\mathcal{B}] \).

From the recurrence hypothesis applied to \( (\eta, q) \models A \), we have \( \chi_A \eta \models (q \models A) \).

From \((\ast)\), we have therefore : \( (\xi, \chi_A) \eta \models (p \models q \models B) \).

Applying again the recurrence hypothesis, we get : \( ((\chi_B)(\xi)(\chi_A^+)\eta, p \models q) \models B \). But since \( (\pi, r) \in B \), we have : \( ((\chi_B)(\xi)(\chi_A^+)\eta, p \models q) \ast (\pi, r) \ast [\mathcal{B}] \), that is \( ((\chi_B)(\xi)(\chi_A^+)\eta \ast \pi \ast (p \models q \models r)) \ast [\mathcal{B}] \).

Since \( r \in c[p \models (q \models r)] \), we have \( \gamma_0 r \in c[(p \models q \models r)] \) and therefore \( (\chi_B)(\xi)(\chi_A^+)\eta \ast \pi \ast \gamma_0 r \ast [\mathcal{B}] \).

But, by definition of \( \chi_F \), we have, from theorem 2 : \( (\chi_F \xi \ast \eta \ast \pi \ast [\mathcal{B}] \), which gives the desired result : \( \chi_F \xi \ast \eta \ast \pi \ast [\mathcal{B}] \).

Suppose now that \( (\xi, p) \models A \rightarrow B \) ; we put \( \chi_F = \lambda x \lambda y (\gamma_0 ) (\chi_B)(x)(\chi_A) y \).

We must show \( \chi_F \xi \models (p \models \forall A \rightarrow B) \), that is \( \forall q(\chi_F \xi \models (q \models A \rightarrow p \models q \models B)) \).

Thus, let \( q \models A \) and \( q \in [\mathcal{B}] \) ; we must show \( \chi_F \xi \ast q \ast \pi \ast [\mathcal{B}] \).

By the recurrence hypothesis, we have \( (\chi_A \eta, q) \models A \rightarrow B \), therefore \( (\xi, p, \chi_A \eta, q) \models B \) or else, by definition of the algebra \( \mathcal{B} : ((\gamma_0 \chi_A)(\chi_A) \eta, p \models q) \models B \).

Applying again the recurrence hypothesis, we have \( (\chi_B)(\gamma_0 \chi_A)(\chi_A) \eta \models (p \models q \models B) \) and therefore : \( (\chi_B)(\gamma_0 \chi_A)(\chi_A) \eta \ast p \models q \ast [\mathcal{B}] \), from theorem 2 ; the desired result follows.

Q.E.D.

A formula \( F \) is said to be first order if it is obtained by the following rules :

- \( \perp \) is first order.
• If $A, B$ are first order, then $A \rightarrow B$ is first order.
• If $B$ is first order, $R$ is a predicate symbol and $t_1, \ldots, t_k$ are terms with parameters, then $R(t_1, \ldots, t_k) \rightarrow B$, $t_1 = t_2 \rightarrow B$ are first order.
• If $A$ is first order, then $\forall x A$ is first order ($x$ is an individual variable).

Remarks.
i) If $A$ is a first order formula, it is the same for $\forall x^\text{ent} A$.
ii) This notion will be extended below (see proposition 37).

Theorem 31. Let $F$ be a closed first order formula. There exist two proof-like terms $\delta_\text{F}, \delta'_\text{F}$, which depend only on the propositional structure of $F$, such that we have:

\begin{align*}
\xi \vdash (\text{C}[p] \rightarrow F) & \Rightarrow (\delta_\text{F}, \xi, p) \models F; \\
(\xi, p) \models F & \Rightarrow \delta'_\text{F}, \xi \models (\text{C}[p] \rightarrow F)
\end{align*}

for every $\xi \in \Lambda$ and $p \in P$.

The proof is by recursion on the construction of $F$ following the above rules.

• If $F$ is $\perp$, we put :
  $$\delta_\perp = \lambda x (\xi) (\chi) (\alpha y)(\alpha y)\text{ with } \alpha :: p q \Rightarrow p.$$
  $$\delta'_\perp = \lambda x (\xi) (\chi) (\alpha y)(\alpha y)\text{ with } \alpha :: p \Rightarrow p \land 1.$$

Indeed, suppose that $\xi \models \text{C}[p] \rightarrow \perp$ and let us show that $(\delta_\perp, \xi, p)(\pi, q) \models \perp$, that is :

$$(\delta_\perp, \xi) \star \pi, p q \models \perp.$$ 

Thus, let $\tau \in \text{C}[p \land q]$, so that $\alpha \tau \in \text{C}[p]$, so that $\xi \star \alpha \tau \cdot \pi \models \perp$, by hypothesis on $\xi$, which gives $\delta_\perp, \xi \star \pi \cdot \tau \models \perp$.

Conversely, if $(\xi, p) \models \perp$, we have $(\xi, p) \star (\pi, 1) \equiv (\xi \star \pi, p \land 1) \models \perp$ for every $\pi \in \Pi$.

But, if $\tau \in \text{C}[p]$, we have $\alpha \tau \in \text{C}[p \land 1]$, therefore $\xi \star \pi \cdot \tau \cdot \pi \models \perp$. Therefore $\delta'_\perp, \xi \models \text{C}[p] \rightarrow \perp$.

• If $F$ is $A \rightarrow B$, we put :
  $$\delta_{A \rightarrow B} = \lambda x (\chi) (\alpha y)(\alpha y)\text{ with } \alpha :: p \land q \Rightarrow p \text{, } \beta :: p \land (q \land r) \Rightarrow q \text{, } \gamma :: p \land (q \land r) \Rightarrow 1 \land r.$$

Indeed, suppose that $\xi \models \text{C}[p], A \rightarrow B, (\eta, q) \models A$ and $(\pi, r) \in \|B\|$. We must show $(\delta_{A \rightarrow B}, \xi, p, q, \eta, \pi, r) \models \|A\|$, that is $(\delta_{A \rightarrow B}, \xi \star \eta \cdot \pi \cdot \tau \models \|C[1] \rightarrow B\|$. We have $\alpha \tau \in \text{C}[p], \beta \tau \in \text{C}[q]$; but, by the recurrence hypothesis, we have :

$$(\delta'_{A, \eta} \models \text{C}[q] \rightarrow A), \text{ therefore } (\delta'_{A, \eta}(\beta) \tau \models A \text{ and } (\xi)(\alpha)\tau(\delta'_{A, \eta})(\beta) \tau \models B; \text{ thus } \lambda d(\xi)(\alpha)\tau(\delta'_{A, \eta})(\beta) \tau \models C[1] \rightarrow B).$$

From the recurrence hypothesis, we have $((\delta_{B})\lambda d(\xi)(\alpha)\tau(\delta'_{A, \eta})(\beta) \tau, 1) \models B$, thus :

$$((\delta_{B})\lambda d(\xi)(\alpha)\tau(\delta'_{A, \eta})(\beta) \tau, 1) \star (\pi, r) \models \|A\|, \text{ that is :}$$

$$((\delta_{B})\alpha \lambda d((\xi)(\alpha)\tau)(\delta'_{A, \eta})(\beta) \tau \star \pi \star 1 \land r) \models \|A\|.$$ 

But, we have $\gamma \tau \in \text{C}[1 \land r]$, therefore $(\delta_{B})\lambda d((\xi)(\alpha)\tau)(\delta'_{A, \eta})(\beta) \tau \star \pi \land \tau \models \|A\|, \text{ and thus :}$

$$(\chi)\lambda z((\delta_{B})\lambda d((\xi)(\alpha)\tau)(\delta'_{A, \eta})(\beta) \tau \star \pi \land \tau \models \|A\|, \text{ it follows that :}$$

$$(\chi)\lambda z((\delta_{B})\lambda d((\xi)(\alpha)\tau)(\delta'_{A, \eta})(\beta) \tau \star \pi \land \tau \models \|A\|, \text{ so that } \delta_{A \rightarrow B}, \xi \star \gamma \cdot \pi \cdot \tau \models \|A\|.$$ 

We now put :

$$\delta'_{A \rightarrow p} = \lambda x \lambda y \lambda z((\delta_{B})(\overline{p} q x)(\delta_{A})\lambda d z)(\alpha y) \text{ with } \alpha :: p \Rightarrow p \land 1.$$ 

Suppose that $(\xi, p) \models A \rightarrow B$; let $\tau \in \text{C}[p], \eta \models A$ and $\pi \in \|B\|$. We must show :

$$(\delta'_{A \rightarrow p}, \xi) \star \gamma \cdot \eta \cdot \pi \models \|A\| \text{. We have } \lambda d \eta \models C[1] \rightarrow A ; \text{ applying the recurrence hypothesis, we have } ((\delta_{A})\lambda d \eta, 1) \models A, \text{ thus } (\xi, p)(\delta_{A})\lambda d \eta, 1) \models B \text{ that is } ((\overline{p} q x)(\delta_{A})\lambda d \eta, p \land 1) \models B.$$
Applying again the recurrence hypothesis, we find:

\[(\delta_B')(\lambda z)(\alpha') \lambda d \eta \models C[p \land 1] \rightarrow B.\]

\[(\delta_B')(\lambda d)(\delta_A) \lambda d \eta \land \alpha \land \tau \land \pi \in \perp\] and finally \[\delta'_A \rightarrow B \models \alpha' \land \tau \land \eta \land \pi \in \perp\]

- If \(F \equiv R(q) \rightarrow B\), where \(R\) is a \(k\)-ary predicate symbol and \(p \in P^k\), we put:

\[\delta_{R \rightarrow B} = \lambda x \lambda y (\widetilde{\delta}_B(\lambda d)x \land y)\] with \(\alpha \equiv p \land (1 \land r) \rightarrow p \land r\).

\[\delta'_{R \rightarrow B} = \lambda x \lambda y \lambda z ((\lambda d)(\lambda x)(\lambda y)(\lambda z)(\alpha')y)\] with \(\alpha' \equiv p \equiv p \land 1\).

Suppose that \(\xi \models C[p], R[q] \rightarrow B\) and let \(\eta \equiv |R[q]|, (\tau, r) \in |B|\). We must show:

\[(\delta_{R \rightarrow B}(\xi, p)) \bullet (\eta, 1) \bullet (\tau, r) \in \perp,\] that is \((\delta_{R \rightarrow B}(\xi) \land \eta \land \tau \land r) \in \perp\).

Thus, let \(\tau \in C[p \land (1 \land r)\] ; we must show \(\delta_{R \rightarrow B}(\xi) \land \eta \land \tau \land r \in \perp\). But, we have:

\[\lambda z(\xi) \land \eta \models C[p] \rightarrow B\] and thus \((\delta_{R}(\xi) \land \eta, p) \models |B|\), by the recurrence hypothesis.

It follows that \((\delta_{R}(\xi) \land \eta, p) \land (\tau, r) \in \perp,\) that is:

\[(\delta_{R}(\xi) \land \eta, p, r) \land (\tau, r) \in \perp\].

- If \(F \equiv (p_1 = p_2 \rightarrow B)\), we put \(\delta_{F} = \delta_{B}\) and \(\delta'_{F} = \delta'_{B}\).

- Suppose that \(\xi \models C[p] \rightarrow (p_1 = p_2 \rightarrow B)\) and \((\tau, q) \in |B|\). We must show that \((\delta_{B}(\xi, p)) \land (\tau, q) \in \perp\). Since \(|p_1 = p_2 \rightarrow B| \models \perp\), we have \(p_1 = p_2 \land (\delta_{B}(\xi, p)) \land (\tau, q) \in \perp\). Hence the result, by the recurrence hypothesis.

Suppose now that \((\xi, p) \models p_1 = p_2 \rightarrow B, \tau \models C[p]\) et \(\pi \models C[p] \rightarrow B\). We must show \(\delta'_{B} \land \alpha' \land \pi \in \perp\). Since \(|p_1 = p_2 \rightarrow B| \models \perp\), we have \(p_1 = p_2 \land (\delta'_{B}(\xi, p) \land (\alpha' \land \pi \in \perp)\). Hence the result, by the recurrence hypothesis.

- If \(F \equiv \forall x A\), we put \(\delta_{F} = \delta_{A}\) and \(\delta'_{F} = \delta'_{A}\).

Indeed, if \(\xi \models C[p] \rightarrow \forall x A\), we have \(\xi \models C[p] \rightarrow A[a/x] \models \perp\).

By the recurrence hypothesis, we have \((\delta_{A}(\xi, p) \land (\alpha' \land \pi \in \perp)\). Thus \((\delta_{A}(\xi, p) \land (\alpha' \land \pi \in \perp)\). If \((\xi, p) \models \forall x A\), we have \((\xi, p) \models A[a/x] \models \perp\).

Q.E.D.

The generic ideal

We define a unary predicate \(J : P \rightarrow \mathcal{P}(\Pi)\) in the model \(\mathcal{N}\) (second order parameter of
arity 1), by putting \(J(p) = \Pi \times \{p\}\); we call it the generic ideal.

Thus, the binary predicate \(J^+ : P^2 \rightarrow \mathcal{P}(\Pi)\) which corresponds to it in the model \(\mathcal{M}\), is
such that \(J^+(p, q) = \emptyset\) (resp. \(\Pi\)) if \(p \neq q\) (resp. \(p = q\)). In other words:

\[J^+(p, q)\] is the predicate \(p \neq q\).

The formula \(p \models J(q)\) is \(\forall r(C[p \land r] \rightarrow J^+(r, q))\). Therefore, we have:

\[|p \models J(q)| = |\neg C[p \land q]|\] in other words:

\(p \models J(q)\) is exactly \(\neg C[p \land q]\).

Notations.

- We denote by \(p \subseteq q\) the formula \(\forall r(C[q \land r] \rightarrow \neg C[p \land r])\) and by \(p \sim q\) the formula
\[ p \subseteq q \land q \subseteq p, \text{ that is } \forall r(\neg C[p \land r] \leftrightarrow \neg C[p \land \neg r]) \]

In the sequel, we shall often write \( F \rightarrow C[p] \) instead of \( \neg C[p] \rightarrow \neg F \); then \( p \subseteq q \) is written \( \forall r(C[p \land r] \rightarrow C[q \land r]) \) and \( p \sim q \) is written \( \forall r(C[p \land \neg r] \leftrightarrow C[q \land \neg r]) \).

**Remark.** We recall that \( C[p] \) is not a formula, but a subset of \( \Lambda \); in fact, in some realizability models which will be considered below, there will exist a formula \( C[p] \) such that :

\[ |C[p]| = \{ \tau \in \Lambda : \tau \vdash C[p] \}. \]

In such cases, we can identify \( C[p] \) with the formula \( C[p] \).

- If \( F \) is a closed formula, we shall write \( \models F \) to mean that there exists a proof-like term \( \theta \) such that \( (\theta, 1) \models F \). From proposition [27](i), this is equivalent to say that there exists a proof-like term \( \theta \) such that \( (\theta, p) \models F \) for every \( p \in P \).

**Proposition 32.**

i) \( \xi \models \neg C[p \land q] \Rightarrow (\chi \xi, p) \models \mathcal{J}(q) \);

\( (\xi, p) \models \mathcal{J}(q) \Rightarrow \chi \xi \models \neg C[p \land q]. \)

ii) \( \xi \models \forall r(C[p \land (1 \land r)], C[q] \rightarrow \bot) \Rightarrow (\chi \xi, p) \models \neg \neg C[q] ;

\( (\xi, p) \models \neg \neg C[q] \Rightarrow \chi \xi \models \forall r(C[p \land (1 \land r)], C[q] \rightarrow \bot). \)

iii) If \( \xi \models \neg \neg R(a_1, \ldots, a_k) \) then \( (\xi, p) \models \neg \neg R(a_1, \ldots, a_k) \) for all \( p \) (\( R \) is a predicate symbol of arity \( k \)).

i) If \( \xi \models \neg \neg C[p \land q] \), then \( \chi \xi \star \tau, \pi \in \mathbb{I} \) and therefore \( \chi \xi \star \tau, \pi \in \mathbb{I} \) for all \( \tau \in C[p \land q] \). Thus, we have : \( (\chi \xi \star \tau, p \land q) \in \mathbb{I} \), that is \( (\chi \xi, p) \star (\pi, q) \in \mathbb{I} \) for every \( \pi \in P \), i.e. \( (\chi \xi, p) \models \mathcal{J}(q) \).

If \( (\xi, p) \models \mathcal{J}(q) \), we have \( (\xi, p) \star (\pi, q) \in \mathbb{I} \), thus \( (\chi \xi, p) \star (\pi, q) \in \mathbb{I} \) for all \( \pi \in P \). Therefore, we have \( \chi \xi \star \tau, \pi \in \mathbb{I} \) for each \( \tau \in C[p \land q] \). Therefore \( \chi \xi \models \neg \neg C[p \land q] \).

ii) If \( \xi \models \forall r(C[p \land (1 \land r)], C[q] \rightarrow \bot) \), we have \( \chi \xi \star \tau, \pi \in \mathbb{I} \) if \( v \in C[p \land (1 \land r)] \) and \( \tau \in C[q] \). Therefore \( \chi \xi \star \tau, \pi \in \mathbb{I} \) if \( \chi \xi \star \tau, \pi \in \mathbb{I} \) and \( \tau \in C[q] \). Thus, we have \( \chi \xi \models \forall r(C[p \land (1 \land r)], C[q] \rightarrow \bot) \).

iii) Let \( \tau \in \{R(a_1, \ldots, a_k)\} \); we have \( \chi \xi \star \tau, \pi \in \mathbb{I} \) for all \( \pi \in P \), thus \( (\chi \xi \star \tau, \pi, a) \in \mathbb{I} \) for all \( a \in P \), and therefore \( (\xi, p) \star (\tau, 1) \star (\pi, q) \in \mathbb{I} \).

Q.E.D.

**Theorem 33 (Elementary properties of the generic ideal).**

i) \((\tau, 1) \models \neg \mathcal{J}(1) \) with \( \alpha :: 1 \land (p \land q) \Rightarrow p \land 1 \).

ii) \((\tau, 1) \models \forall x(\neg C[x] \rightarrow \mathcal{J}(x)) \) where \( \theta = \lambda x(\chi x) \lambda y((\chi x)(\beta y)\alpha) y \) with \( \alpha :: 1 \land (p \land q) \Rightarrow q \) and \( \beta :: 1 \land (p \land q) \Rightarrow p \land (1 \land 1) \).

iii) \((\tau, 1) \models \forall x \forall y(\mathcal{J}(x \land y), \neg \mathcal{J}(x) \rightarrow \mathcal{J}(y)) \) where \( \theta = \lambda x \lambda y(\chi(y)(\beta x) \alpha) \) with \( \alpha :: 1 \land (p \land q) \rightarrow q \land (q \land p) \land 1 \) and \( \beta :: (q \land p) \land p \Rightarrow q \land p \).

iv) \((\tau, 1) \models \forall x \forall y(\neg C[x \land y] \rightarrow \mathcal{J}(y)) \) where \( \theta = \lambda x \lambda y(\gamma x)(\beta z) \alpha \) with \( \alpha :: 1 \land (r \land (q \land p)) \Rightarrow r \land (1 \land p) \).

v) \((\tau, 1) \models \forall x \forall y(\mathcal{J}(x, y \subseteq x \rightarrow \mathcal{J}(y)) \) where \( \theta = \lambda x \lambda y(\chi x)(\lambda z((\gamma z)(\beta z) \alpha)(\gamma)(\gamma)) \) with \( \alpha :: 1 \land (p \land q) \Rightarrow (r \land 1)(1 \land 1) \) and \( \beta :: 1 \land (p \land q) \Rightarrow q \land p \).
Theorem 34 (Density).

For each function \( \phi : P \to P \), we have:

\[
(\theta, 1) \mid | | \forall x (\neg (x \land \phi x) \to J(x)) \mid | | \forall x J(x \land \phi x) \to \bot
\]

where \( \theta = (\beta \lambda x y (\phi x) \theta) y \), \( \phi = (\chi \lambda \alpha x y (x \land \phi x) \alpha) y \) ;
with \( \alpha : q \to q \phi \Rightarrow q \phi (q \to r) \); \( \beta : 1 \to (p \land (q \land r)) \Rightarrow p \land (1 \land q) \).

Q.E.D.
Let \((\xi, p) \models \forall x (\neg C[x \wedge \phi(x)] \rightarrow J(x)), (\eta, q) \models \forall x J(x \wedge \phi(x))\) and \((\pi, r) \in \Pi\). We must show that \((\theta \ast \xi \ast \eta \ast \pi, 1 \wedge \lambda(q \wedge r)) \in \perp\); thus, let \(\tau_0 \in C[1 \wedge \lambda(p \wedge q)]\). We must show \(\theta \ast \xi \ast \eta \ast \pi \tau_0 \in \perp\).

We first show that \((\theta \ast \xi, 1) \models \neg C[q \wedge \phi(q)]\).

Thus, let \((\varpi, r') \in \Pi\) and \(\tau \in C[q \wedge \phi(q)]\); we must show \((\theta \ast \eta, 1) \ast (\tau, 1) \ast (\varpi, r') \in \perp\). i.e. \((\theta \ast \tau \ast \varpi, 1 \wedge (1 \wedge r')) \in \perp\) or else \(\theta \ast \tau \ast \varpi \wedge r' \in \perp\) for each \(r' \in C[1 \wedge (1 \wedge r')]\).

Now, \(\theta \ast \tau \ast \varpi \rightarrow \theta \ast \varpi \ast r\) and \(\theta \ast \tau \ast \varpi \rightarrow \ast \varpi \ast r\) for each \(r \in C[q \wedge \phi(q)]\). Thus, it suffices to show:

\[(\eta \ast \varpi, q \wedge (q \wedge \phi(q))) \in \perp\] or else \((\eta, q) \ast (\varpi, q \wedge \phi(q)) \in \perp\).

But this follows from the hypothesis on \((\eta, q)\), which implies \((\eta, q) \models J(q \wedge \phi(q))\).

By hypothesis on \(\xi\), we have \((\xi, p) \models \neg C[q \wedge \phi(q)] \rightarrow J(q)\). It follows that:

\[(\xi, p) \ast (\theta \ast \eta, 1) \ast (\pi, q) \in \perp,\] that is \((\theta \ast \xi \ast \eta \ast \pi, p \wedge (1 \wedge q)) \in \perp\).

But we have \(\tau_0 \in C[1 \wedge (p \wedge q)]\), thus \(\beta \tau_0 \in C[p \wedge (1 \wedge q)]\). It follows that \(\xi \ast \beta \tau_0 \ast \pi \tau_0 \in \perp\).

This gives the desired result, since \(\theta \ast \xi \ast \eta \ast \pi \tau_0 \rightarrow \xi \ast \beta \tau_0 \ast \pi \tau_0\).

Q.E.D.

**Countable downward chain condition**

In this section, we consider a standard realizability algebra \(A\) and a \(A\)-model \(M\). We suppose that the set \(P\) (domain of variation of individual variables) has a power \(\geq 2^{80}\).

We choose a surjection \(\varepsilon : P \rightarrow \mathcal{P}(\Pi)^{3}\) and we define a binary predicate in the model \(M\), which we denote also by \(\varepsilon\), by putting:

\[ ||n \varepsilon p|| = \varepsilon(p)(n) \text{ if } n \in \mathbb{N}; \quad ||n \varepsilon p|| = \emptyset \text{ if } n \notin \mathbb{N} \]

(we use, for the predicate \(\varepsilon\), the notation \(n \varepsilon p\) instead of \(\varepsilon(n, p)\)).

Therefore, the predicate \(\varepsilon\) enables us to associate, with each individual set of \(\Pi\), a set of its *elements*. Proposition 35 shows that the following axiom is realized:

For every set, there exists an individual which has the same elements.

This axiom will be called *axiom of representation of predicates on \(\mathbb{N}\).* and denoted by RPN.

**Proposition 35 (RPN).**

\[ \lambda x(x) \uplus \xi \ast \pi \ast n \varepsilon x \forall n \varepsilon \text{ent}(x) \]  

This formula is \(\forall X(\forall x[\forall n(\text{ent}(n), Xn \rightarrow n \varepsilon x), \forall n(\text{ent}(n), n \varepsilon x \rightarrow Xn) \rightarrow \perp] \rightarrow \perp)\).

Thus, we consider a unary parameter \(X : P \rightarrow \mathcal{P}(\Pi)\) and a term \(\xi \in \Lambda\) such that:

\[ \xi \models \forall x[\forall n(\text{ent}(n), Xn \rightarrow n \varepsilon x), \forall n(\text{ent}(n), n \varepsilon x \rightarrow Xn) \rightarrow \perp]\.

We must show that \(\lambda x(x) \uplus \xi \ast \pi \in \perp\), or else \(\xi \ast \uplus \ast \pi \in \perp\) for every stack \(\pi \in \Pi\).

By definition of \(\varepsilon\), there exists \(p_0 \in P\) such that \(Xn = ||n \varepsilon p_0||\) for every integer \(n\).

But, we have:

\[ \xi \models \forall n(\text{ent}(n), Xn \rightarrow n \varepsilon p_0), \forall n(\text{ent}(n), n \varepsilon p_0 \rightarrow Xn) \rightarrow \perp\]

Thus, it suffices to show that \(\uplus \models \forall n(\text{ent}(n), Xn \rightarrow n \varepsilon p_0)\) and \(\uplus \models \forall n(\text{ent}(n), n \varepsilon p_0 \rightarrow Xn)\).

Recall that the predicate \(\text{ent}(x)\) is defined as follows:

\[|\text{ent}(n)| = \{n\} \text{ if } n \in \mathbb{N} \text{ and } |\text{ent}(n)| = \emptyset \text{ if } n \notin \mathbb{N}.\]

Therefore, we have to show:

\[\uplus \ast n \ast \eta \ast \rho \in \perp \]  

for all \(n \in \mathbb{N}, \eta \ast X(n)\) and \(\rho \in ||n \varepsilon p_0||\).
If $\text{c.d.c.}$ is verified, then there exists a proof-like term $\eta'$ \, $\rho' \in X(n)$.

But this follows from $\eta \star \rho \in \bot$ and $\eta' \star \rho' \in \bot$, which is trivially true, since $Xn = ||n \in p_0||$. Q.E.D.

We suppose now that $\{C, \land, 1\}$ is a forcing structure in $M$. Then we define also the symbol $\varepsilon$ in the $\mathcal{B}$-model $\mathcal{N}$ by putting:

$$||n \in p|| = ||n \in p|| \times \{1\} \text{ for } n, p \in P.$$ In other words

$$||n \in p|| = \{(n, 1); \pi \in \varepsilon(p)(n)\} \text{ if } n \in N; ||n \in p|| = \emptyset \text{ if } n \notin N.$$

**Proposition 36.** The predicate $\varepsilon^+(q, n, p)$ is $q = 1 \rightarrow n \in p$.

The formula $q \models n \in p$ is $C[q \land 1] \rightarrow n \in p$.

Immediate, by definition of $||n \in p||$. Q.E.D.

**Proposition 37.**

i) $\xi \models (C[p] \rightarrow n \in q) \Rightarrow (\delta \xi, p) \models n \in q$ where $\delta = \lambda x(\chi)\lambda y(x)(\alpha)y$ and $\alpha : p \land 1 \Rightarrow p$.

ii) $(\xi, p) \models n \in q \Rightarrow \delta' \xi \models (C[p] \rightarrow n \in q)$ where $\delta' = \lambda x(\chi')\lambda y(x')(\alpha')y$ and $\alpha' : p \Rightarrow p \land 1$.

We have $(\xi, p) \models n \in q \equiv (\xi, \pi) \star (\pi, 1) \in \bot$ for all $\pi \in ||n \in p||$, or else :

$(\xi, p) \models n \in p \iff \xi \star \tau \in \bot$ for each $\tau \in C[p \land 1]$ and $\pi \in ||n \in p||$.

i) Suppose that $\xi \models (C[p] \rightarrow n \in q)$, $\tau \in C[p \land 1]$ and $\pi \in ||n \in p||$. Then, we have :

$$\delta \xi \star \tau \Rightarrow \xi \star \alpha \tau \cdot \pi \in \bot,$$

since $\alpha \tau \in C[p]$.

ii) Suppose that $(\xi, p) \models n \in q$, $\tau \in C[p]$ and $\pi \in ||n \in p||$. Then, we have :

$$\delta' \xi \star \tau \Rightarrow \xi \star \alpha' \tau \in \bot,$$

since $\alpha' \tau \in C[p \land 1]$. Q.E.D.

The notion of first order formula has been defined previously (see theorem 31). We extend this definition with the following clause :

• $t \in u$ is first order, for all terms $t, u$.

Proposition 37 shows that theorem 31 remains true for this extended notion.

We say that the forcing structure $\{C, \land, 1\}$ satisfies the countable downward chain condition (in abridged form c.d.c.) if there exists a proof-like term $\text{cdc}$ such that :

$$\text{cdc} \models \forall X\forall n\exists p(X(n, p), \forall n\forall q(X(n, p), X(n, q) \rightarrow q = p), \forall n\forall q(X(n, p), X(sn, q) \rightarrow q \subseteq p) \rightarrow$$

$$\exists p'(\forall n\forall q(X(n, p), X'(n, p) \rightarrow p' \subseteq p), (\forall n\forall q(X(n, p) \rightarrow C[p]) \rightarrow C[p'])\}.$$

The intuitive meaning of this formula is :

If $X(n, p)$ is a decreasing sequence of conditions, then there exists a condition $p'$ which is less than all of them ; moreover, if all these conditions are non trivial, then $p'$ is non trivial.

We intend, in this section to prove the :

**Theorem 38** (Conservation of reals).

If the c.d.c. is verified, then there exists a proof-like term $\text{cr}$ such that :

$$\text{cr} \models \forall X\exists x\forall n\forall x(X(n, p) \leftrightarrow n \in x).$$

This means that the axiom RPN, which is realized in the $\mathcal{A}$-model $\mathcal{M}$ (see proposition 35) is also realized in the generic $\mathcal{B}$-model $\mathcal{N}$. 

29
Notation.
The formula \( \forall q(C[p \land q], q \vdash X_n \rightarrow p \vdash X_n) \) reads as “\( p \) decides \( X_n \)”, and is denoted by \( p \models \pm X_n \).

It can also be written as \( \forall q \forall r(C[p \land q], q \vdash X_n, C[p \land r] \rightarrow X^+(r, n)) \).

If \( X : P \to P(\Pi \times P) \) is a unary predicate in the B-model \( \mathcal{N} \), and \( X^+ : P^2 \to P(\Pi) \) is the corresponding binary predicate in the standard \( \mathcal{A} \)-model \( \mathcal{M} \), the formula \( \forall q(C[p \land q], q \vdash X_n \rightarrow p \vdash X_n) \) is thus also denoted by \( p \vdash \pm X_n \).

**Theorem 39.** If the c.d.c. is verified, there exists a proof-like term \( \text{dec} \) such that :
\[
\text{dec} \vdash \forall X \forall p_0 \exists p'((C[p_0] \to C[p']), p' \subseteq p_0, \forall n \forall q (p' \vdash X_n)\).
\]

**Remark.** This formula means that, for any predicate \( X \), the set of conditions which decide \( X_n \) for all integers \( n \) is dense.

We first show how theorem 38 can be deduced from this theorem 39.

From theorem 38, it is sufficient to find a proof-like term \( \text{crl0} \) such that :
\[
\text{crl0} \vdash 1 \vdash \forall X \exists x \forall \nu \nu \nu \nu X_n \leftrightarrow n \in x
\]
or else, since \( 1 \vdash \neg A \equiv \forall p_0((p_0 \equiv A), C[1 \land p_0] \rightarrow \bot) \):
\[
\text{crl0} \vdash \forall X \forall p_0[(p_0 \equiv q(C[n \in q]) \rightarrow \bot)], C[1 \land p_0] \rightarrow \bot
\]

From theorem 33, it is sufficient to find a proof-like term \( \text{cr1} \) such that :
\[
\text{cr1} \vdash \forall X \forall p_0 \forall p'\{(C[p_0] \to C[p']), p' \subseteq p_0, \forall n \forall q (p' \vdash X_n), (p_0 \equiv q(C[n \in q] \rightarrow \bot))\}, C[1 \land p_0] \rightarrow \bot
\]

It is sufficient to find a proof-like term \( \text{crl2} \) such that :
\[
\text{crl2} \vdash \forall X \forall p_0 \forall p'\{(p_0 \equiv q(C[n \in q] \rightarrow \bot))\}, p' \subseteq p_0, \\
\forall n \forall q (p' \vdash X_n) \rightarrow \bot
\]

Indeed, we take then \( \text{crl1}=\lambda x \lambda y \lambda z \lambda u \lambda v((x)(c)(p)u)(\delta)v \) with \( \delta : 1 \rightarrow p \).

We fix \( X^+ : P^2 \rightarrow P(\Pi) \), \( p_0, p' \in P \), \( \xi \vdash (p_0 \equiv q(C[n \in q] \rightarrow \bot)) \), \( \eta \equiv \forall p' \vdash p_0, \zeta \equiv \forall n \forall q (p' \vdash X_n) \) and \( \tau \in C[p'] \). We must have \( \text{crl2}\xi \eta \zeta \tau \rightarrow \bot \).

We choose \( q_0 \in P \) such that we have \( n \in q_0 \equiv \|p' \equiv X_n\| \) for all \( n \in N \), which is possible, by definition of \( \varepsilon \).

We trivially have \( \xi \vdash (p_0 \equiv q(C[n \in q_0 \rightarrow X_n], \forall n \forall q (X_n \rightarrow n \in q_0) \rightarrow \bot)) \).

But, the formula \( p_0 \equiv q(C[n \in q_0 \rightarrow X_n], \forall n \forall q (X_n \rightarrow n \in q_0) \rightarrow \bot) \) is written as :
\[
\forall r \forall r'(r' \equiv q(C[n \in q_0 \rightarrow X_n], r' \equiv q(C[n \in q_0 \rightarrow X_n \rightarrow n \in q_0], C[p_0 \land r] \rightarrow \bot)) \rightarrow \bot)
\]

Replacing \( r \) and \( r' \) with \( p' \), we obtain :
\[
\xi \vdash (p' \equiv q(C[n \in q_0 \rightarrow X_n], p' \equiv q(C[n \in q_0 \rightarrow X_n \rightarrow n \in q_0], C[p_0 \land p'] \rightarrow \bot)) \rightarrow \bot)
\]

From \( \tau \in C[p'] \) and \( \eta \equiv \forall r(\neg C[p_0 \land r] \rightarrow \neg C[p_0 \land r]) \), we deduce that :
\[
\lambda h((\eta)\lambda x(h)(\beta)x)(\alpha)\tau \rightarrow \neg C[p_0 \land p'] \equiv \bot
\]

where \( \alpha, \beta \) are C-expressions such that \( \alpha : p \rightarrow p \land p \); \( \beta : p \lor q \rightarrow (p \lor q) \land q \).

Thus, we have :

1. \( \lambda y \lambda z((\eta)\lambda x(\xi y z)(\beta)x)(\alpha)\tau \rightarrow \)
\[
(p' \equiv q(C[n \in q_0 \rightarrow X_n], p' \equiv q(C[n \in q_0 \rightarrow X_n \rightarrow n \in q_0])) \rightarrow \bot.
\]

• The formula \( p' \equiv q(C[n \in q_0 \rightarrow X_n] \rightarrow \neg \forall r(r \equiv n \in q_0 \rightarrow p' \land r \rightarrow X_n)) \)

But \( r \vdash n \in q_0 \equiv C[r \land 1] \equiv n \in q_0 \) (proposition 39) \( \equiv \forall r(r \equiv n \in q_0 \rightarrow p' \land r \rightarrow X_n) \) by definition of \( q_0 \). Therefore \( p' \equiv q(C[n \in q_0 \rightarrow X_n] \rightarrow \neg \forall r((C[r \land 1] \rightarrow p' \equiv X(n)) \rightarrow p' \land r \equiv X_n) \equiv \forall n \forall q \forall q'[q(C[r \land 1], [p' \land q] \rightarrow X^+(q, n)), C[(p' \land r) \rightarrow \rightarrow X^+(q', n)] \rightarrow \bot).

30
Thus, we have:

\[ \lambda \alpha \lambda y \lambda ((x)(\alpha')(y)(\beta'))y \models (p' \models \forall n^{\text{ent}}(n \in q_0 \rightarrow Xn)) \]
with \( \alpha' :: (p \models \lambda) \lor q \Rightarrow r \lambda \frac{\mathbf{A}}{p' \models q} \) and \( \beta' :: (p \models \lambda) \Rightarrow p \land q \).

- The formula \( p' \models \forall n^{\text{ent}}(Xn \rightarrow n \in q_0) \) is written as \( \forall n^{\text{ent}} \forall r (r \models Xn \rightarrow p' \land r \models n \in q_0) \), or else \( \forall n^{\text{ent}} \forall r (r \models Xn, C[(p' \land r) \frac{\mathbf{A}}{1}] \rightarrow n \in q_0) \), that is, by definition of \( q_0 \):

\[ \forall n^{\text{ent}} \forall r (r \models Xn, C[(p' \land r) \frac{\mathbf{A}}{1}] \rightarrow p' \models Xn) \].

But, we have:

\[ \zeta \models \forall n^{\text{ent}}(p' \models \pm Xn) \], in other words \( \zeta \models \forall n^{\text{ent}} \forall r (r \models Xn, C[p' \land r] \rightarrow p' \models Xn) \). Therefore:

\[ (3) \lambda n \lambda x \lambda y((\zeta x)(\alpha')(n)y) \models p' \models \forall n^{\text{ent}}(Xn \rightarrow n \in q_0) \] with \( \alpha'' :: (p \models \lambda) \lor q \Rightarrow p \land r \).

It follows from (1,2,3) that:

\[ ((\lambda y \lambda z((\eta)\lambda x((\xi)y)(\beta)(x)(\alpha)\tau)) \lambda d \lambda x \lambda y((x)(\alpha')(y)(\beta')y) \lambda n \lambda x \lambda y((\zeta x)(\alpha'')(n)z)y \models \bot. \]

Therefore, we can put \( \text{cr2} = \lambda x_0 \lambda y_0 \lambda x \lambda y((\lambda y \lambda z((y_0)\lambda x(x_0y))(\beta)(x)(\alpha)\tau)) \lambda d \lambda x \lambda y((x)(\alpha')(y)(\beta')y) \lambda n \lambda x \lambda y(z_0nx)(\alpha'')y \).

Q.E.D.

The remaining of this section is devoted to the proof of theorem 39.

**Definition of a sequence by dependent choices**

In this section, we are given a fixed element \( p_0 \in P \) and a finite sequence of formulas with parameters \( F(n,p,p') \). We are also given a proof-like term \( \text{dse} \) such that:

\[ \text{dse} \models \forall n^{\text{ent}}p \models p' \models F(n,p,p'). \]

**Remark.** The aim of this section is to write down a formula \( \Phi(x,y) \) which represents the graph of a function \( \phi : \mathbb{N} \rightarrow P \) such that the formulas \( \phi(0) = p_0 \) and \( \forall n^{\text{ent}} F(n, \phi(n), \phi(n + 1)) \) are realized by proof-like terms. We shall only apply the results of this section to a particular sequence \( F \) of length 3.

From theorem 17(i) (axiom of choice for individuals), there exists a function \( f : P^2 \rightarrow P \) such that:

\[ \zeta \models \forall n^{\text{ent}}(\forall k)(\exists l \models (F(n,p,f(n,p,k)) \rightarrow \bot) \rightarrow (\forall l' \models (F(n,p,p') \rightarrow \bot))). \]

It follows that:

\[ \lambda x(\text{dse})(\zeta) x \models (\exists l \models (F(n,p,f(n,p,k)) \rightarrow \bot) \rightarrow (\forall l' \models (F(n,p,p') \rightarrow \bot))). \]

We define a function denoted by \((m,n)\), from \( P^2 \) into \( P \), by putting, for \( m,n \in P : (m,n) = 1 \) if \( m,n \in \mathbb{N} \) and \( m < n \); \((m,n) = 0 \) otherwise.

Obviously, the relation \((m,n) = 1 \) is well founded on \( P \).

Thus, from theorem 17(ii), we have:

\[ \forall k(\forall l(\forall (n,p,f(n,p,l)) \rightarrow (l_1k \neq 1), (F(n,p,f(n,p,k)) \rightarrow \bot) \rightarrow (\forall k(\forall (n,p,f(n,p,k)) \rightarrow \bot))) \rightarrow (\forall k(\forall (n,p,f(n,p,k)) \rightarrow \bot)). \]

Therefore, if we set \( \forall (\Phi') : \lambda x(\text{dse}) \models (\forall (\Phi') \models (\forall)$
Remark. The meaning of $\vec{H}(n,p,k)$ is "$k$ is the least integer such that $\vec{F}(n,p,f(n,p,k))$".

**Lemma 41.** Let $\text{cp}$ be a proof-like term such that, for every $m,n \in \mathbb{N}$, we have:
\[ \text{cp}^m \cdot n \cdot \xi \cdot \eta \cdot \zeta \cdot \pi \succ \xi \ast \pi \text{ (resp. } \eta \ast \pi, \zeta \ast \pi \text{) if } m < n \text{ (resp. } n < m, m = n). \]

Then:

i) $\text{cp} \models \forall m \cdot \text{ent}(\forall \cdot m \cdot \text{ent}((m,n) \neq 1, (n,m) \neq 1, m \neq n \rightarrow \bot))$.

ii) $\text{dsl} = \forall n \cdot \text{ent}(\forall \cdot n \cdot \text{ent}(\vec{H}(n,p,k), \vec{H}(n,p,k'), k \neq k' \rightarrow \bot))$ with $\text{dsl} = \lambda k \cdot \lambda k' \cdot \lambda x \cdot \lambda y \cdot \lambda x' \cdot \lambda y'((\text{cp} k' k)(x) k' y')(x') k' y'$, where $y', y''$ are two sequences of distinct variables of the same length as the sequence $\vec{F}$.

i) Trivial.

ii) Let $\xi \models G(n,p,k), \vec{y} \models \vec{F}(n,p,f(n,p,k))$, $\xi' \models G(n,p,k'), \vec{y}' \models \vec{F}(n,p,f(n,p,k'))$ and $\zeta \models k \neq k'$. We must show $\text{cp} \ast \vec{k}' \cdot \vec{k} \cdot (\xi) \kappa' \vec{y}' \cdot (\xi') \kappa \vec{y} \cdot \zeta \ast \pi \models \bot$.

If $k = k'$, it remains to prove $\zeta \ast \pi \models \bot$; but this is true because we then have $\zeta \models \bot$.

If $k' < k$, it remains to prove $\xi \ast \vec{k} \cdot \vec{y} \cdot \xi' \ast \vec{k}' \cdot \vec{y}' \cdot \pi \models \bot$. This results immediately from:

$\xi \models \forall \cdot k \cdot \text{ent}(\vec{F}(n,p,f(n,p,k')) \rightarrow (k' \cdot k) \neq 1)$ and thus:

$\xi \models \text{ent}(k'), \vec{F}(n,p,f(n,p,k')) \rightarrow \bot$, since $k' < k$.

Q.E.D.

We now define the binary predicate:

$\Phi(x,y) \equiv \forall X(\forall n \cdot \forall p \cdot \forall k \cdot \text{ent}(\vec{H}(n,p,k), X(n,p) \rightarrow X(sn,f(n,p,k))), X(0,p_0) \rightarrow X(x,y))$

and we show that $\Phi(x,y)$ is a sequence of functions (conditional relation on $\mathbb{N}$) and also some other properties of $\Phi$.

Remark. Intuitively, the predicate $\Phi$ is the graph of the function $\phi$ of domain $\mathbb{N}$, recursively defined by the conditions: $\phi(0) = p_0$; $\phi(n+1) = f'(n,\phi(n))$

where $f'(n,p)$ is $f(n,p,k)$ for the least $k$ such that $F(n,p,f(n,p,k))$. Unfortunately, we cannot introduce $f'$ as a function symbol because, unlike $f$, it is not defined in the ground model.

**Lemma 42.**

i) $\lambda x \lambda y \cdot y \models \Phi(0,p_0)$.

ii) $\lambda x \cdot x \text{II} \models \forall y(\Phi(0,y) \rightarrow y = p_0)$.

iii) $\text{rec} \models \forall x \cdot \forall y \cdot \forall k \cdot \text{ent}(\vec{H}(x,y,k), \Phi(x,y) \rightarrow \Phi(sx,f(x,y,k)))$

where $\text{rec} = \lambda k \cdot \lambda x \cdot \lambda y \cdot \lambda x' \cdot \lambda u(\lambda z \cdot \lambda x\vec{y}(\lambda z \cdot k' x \vec{y})(x') z u)$

and $\vec{y}$ is a sequence of distinct variables of the same length as $\vec{F}$.

i) Trivial.

ii) We define the binary predicate $X : P^2 \rightarrow \mathcal{P}(\Pi)$ by putting:

$X(0,q) = \|q = p_0\|$ and $X(p,q) = \emptyset$ for $p \neq 0$.

We replace $X$ with $X$ in the definition of $\Phi(0,y)$. Since we have $sn \neq 0$ for all $n \in \mathbb{N}$, we obtain $\|\Phi(0,y)\| \subseteq \|T, p_0 = p_0 \rightarrow y = p_0\|$; hence the result.

iii) Let $\xi \models G(x,y,k), \vec{y} \models \vec{F}(x,y,f(x,y,k)), \xi' \models \Phi(x,y), \zeta \models \forall n \cdot \forall p \cdot \forall k \cdot \text{ent}(\vec{H}(n,p,k), X(n,p) \rightarrow X(sn,f(n,p,k))), \nu \models X(0,p_0)$ and $\pi \in \|X(sx,f(x,y,k))\|$. Then $\xi' \nu \models X(x,y)$, therefore $\zeta \ast \vec{k} \cdot \xi \cdot \vec{y} \cdot \xi' \ast \nu \cdot \pi \models \bot$ i.e. $(\text{rec})(\vec{k} \ast \vec{y} \ast \nu \ast \pi \models \bot)$.

Q.E.D.
Lemma 43. $\text{cdc}1 \vdash \forall n \cdot \text{ent} \exists p \Phi(n, p)$ where :
$\text{cdc}1 = \lambda n \cdot (\lambda x \cdot \lambda y (y) \cdot \lambda z (\text{cdc}1) \cdot z \cdot y) \cdot \lambda x \cdot \lambda y \cdot y$
with $\text{cdc}1 = \lambda n \cdot \lambda y (\text{dse}0) \cdot \lambda \lambda z (y) (\text{rec}) \cdot \lambda \vec{z}$ ;
$\vec{z}$ is a sequence of distinct variables of the same length as $\vec{H}$.

Proof by recurrence on $n$ ; we have $\lambda x \cdot \lambda y \cdot y \vdash \Phi(0, p_0)$, therefore $\lambda x (x) \cdot \lambda x \cdot \lambda y \cdot y \vdash \exists y \Phi(0, y)$.

We now show that $\text{cdc}1 \vdash \Phi(x, y) \rightarrow \exists y \Phi(sx, y)$.

Thus, we consider $x \vdash \Phi(x, y)$, $\eta \vdash \forall y (\Phi(sx, y) \rightarrow \bot)$.

We have $\text{rec} \vdash \forall l \cdot (\vec{H} (x, y, l), \Phi(x, y) \rightarrow \Phi(sx, f(x, y, l)))$ (lemma 43(ii)), $\eta \vdash (\Phi(sx, f(x, y, l)) \rightarrow \bot)$, and therefore :
$\lambda \lambda z (y) (\text{rec}) \cdot \lambda \vec{z} \vdash \forall l \cdot (\vec{H} (x, y, l), \Phi(x, y, l) \rightarrow \bot)$, where $\vec{z}$ has the same length as $\vec{H}$.

Now, we have $\text{dse}0 \vdash \exists k \cdot (\vec{H} (x, y, k))$ (lemma [14]) ; therefore :
$\text{dse}0 \vdash \lambda \lambda z (y) (\text{rec}) \cdot \lambda \vec{z} \vdash \exists l \cdot (\vec{H} (x, y, k) \rightarrow \bot)$, that is $(\text{cdc}1) \xi \eta \vdash \bot$.

Thus, we have shown that $\text{cdc}1 \vdash \forall y (\Phi(x, y) \rightarrow \exists y \Phi(sx, y))$, and it follows that :
$
\lambda x \cdot \lambda y (\lambda z (\text{cdc}1) \cdot z \cdot y) \vdash \exists y \Phi(x, y) \rightarrow \exists y \Phi(sx, y)$.

Q.E.D.

Lemma 44. There exists a proof-like term $\text{cdc}2$ such that :
$\text{cdc}2 \vdash \forall n \cdot \text{ent} \forall p \cdot \forall q (\Phi(n, p), \Phi(n, q) \rightarrow p = q)$.

We give a detailed proof, by recurrence on $n$ . It enables us to write explicitly the proof-like term $\text{cdc}2$.

For $n = 0$, the lemma 42(ii) gives the result : $\Phi(0, p), \Phi(0, q) \rightarrow p = q$.

Let us fix $m$ and suppose that $\forall p \cdot \forall q (\Phi(m, p), \Phi(m, q) \rightarrow p = q)$.

We define the binary predicate :
$\Psi(n, q) \equiv \forall p \cdot \forall q (\Phi(m, p), \Phi(m, q) \rightarrow q = f(m, p, k))$.

We show that $\vdash \forall p \cdot \forall q (\vec{H} (n, p, k), \Phi(n, p) \rightarrow \Psi(sm, f(n, p, k)))$, that is to say :
$\vdash \forall p \cdot \forall q (\vec{H} (n, p, k), \Phi(n, p), sm = sm, \vec{H} (m, q, l), \Phi(m, q) \rightarrow f(n, p, k) = f(m, q, l))$.

But we have $\| sm = sm \| = \| n = m \|$, $\Phi(m, p), \Phi(m, q) \rightarrow p = q$ by hypothesis of recurrence ; $\vec{H} (m, p, k), \vec{H} (m, p, l) \rightarrow k = l$ (lemma [14](ii)), and it follows that $f(n, p, k) = f(m, q, l)$.

If we put $\Psi'(x, y) \equiv \Phi(x, y) \land \Psi(x, y)$, we have :
$\vdash (\Phi(x, y) \rightarrow \Psi'(sn, f(n, p, k)))$ ; we have also $\vdash (0, p_0)$. This shows that $\vdash (\Phi(x, y))$ by making $X \equiv \Psi'$ in the definition of $\Phi$.

Thus, we have $\vdash (\Phi(sm, q) \rightarrow \forall p \cdot \forall q (\vec{H} (m, p, k), \Phi(m, p) \rightarrow q = f(m, p, k)))$.

It follows that :
$\vdash (\Phi(sm, q), \Phi(sm, q') \rightarrow (\forall p \cdot \forall q (\vec{H} (m, p, k), \Phi(m, p) \rightarrow (q = f(m, p, k)) \land (q' = f(m, p, k)))$ and therefore $\vdash (\Phi(sm, q), \Phi(sm, q') \rightarrow (\forall p \cdot \forall q (\vec{H} (m, p, k), \Phi(m, p) \rightarrow q = q'))$.

Thus, we obtain $\vdash (\Phi(sm, q), \Phi(sm, q') \rightarrow q = q'$, since we have $\text{cdc}1 \vdash \exists p (\Phi(m, p))$ by lemma [13] and $\text{dse}0 \vdash \forall p \cdot \exists k (\vec{H} (m, p, k))$ by lemma [10].

Q.E.D.
Thus, let \( \xi_{II} \). We apply the above results, taking for \( \vec{F}(n, p, p') \) the sequence of three formulas:

\( \{ (C[p] \rightarrow C[p']), (p' \subseteq p), (p' \models \pm \lambda Xn) \} \).

**Lemma 45.** \( \text{dse} \models \forall p \exists p' \{ \vec{F}(n, p, p') \} \)

where \( \text{dse} = \lambda a(\lambda h(aII)\lambda x \lambda y h)\lambda z (cc) \lambda k((a \lambda x xz)\beta')(\lambda x \lambda y(k)(y)(\alpha)x) \)

with \( \beta' = \lambda x \lambda y(x)(\beta)y, \quad \alpha :: (p \lambda q) \lambda r \Rightarrow r \lambda q \) and \( \beta :: (p \lambda q) \lambda r \Rightarrow p \lambda r \).

The formula we consider is written as \( \forall p'[(C[p] \rightarrow C[p']), p' \subseteq p, (p' \models \pm Xn) \rightarrow \bot] \rightarrow \bot \).

Thus, let \( \xi \models \forall p'[(C[p] \rightarrow C[p']), p' \subseteq p, (p' \models \pm Xn) \rightarrow \bot] \). We must show \( (\text{dse})\xi \models \bot \).

- We now show \( \lambda(xcc)\lambda k((\xi_{II})\lambda x \lambda y(h)\lambda z (cc) \lambda k((\xi_{II})\lambda x \lambda y(k)(y)(\alpha)x \models (p \models \pm Xn)) \).

Thus, let \( \tau \in C[p \lambda q] \) and \( \pi \in X^+(q, n) \). We must show :

\( (\xi_{II})\lambda x \lambda y(k_{\pi})(y)(\alpha)x \models (p \models \pm Xn) \).

- We now show \( \lambda(xcc)\lambda k((\xi_{II})\lambda x \lambda y(k)(y)(\alpha)x \models (p \models \pm Xn)) \).

Thus, let \( \tau \in C[p \lambda q] \) and \( \pi \in X^+(q, n) \). We must show :

\( (\xi_{II})\lambda x \lambda y(k_{\pi})(y)(\alpha)x \models (p \models \pm Xn) \).

**Lemma 46.** Let \( \beta :: (p \lambda q) \lambda r \Rightarrow p \lambda r \). Then \( \lambda x \lambda y(x)(\beta)y \models \forall p \forall q[(p \lambda q) \subseteq p] \).

This formula is written \( \forall p \forall q \forall r (-C[p \lambda r], C[(p \lambda q) \lambda r] \rightarrow \bot) \).

Therefore, let \( \xi \models -C[p \lambda r] \), \( \tau \in C[(p \lambda q) \lambda r] \), thus \( \beta \tau \in C[p \lambda r] \) and \( (\xi)(\beta)\tau \models \bot \).

Thus, we obtain \( \lambda x \lambda y(x)(\beta)y \models \forall p \forall q[(p \lambda q) \subseteq p] \)

**Q.E.D.**

We propose now to apply the countable downward chain condition to the binary predicate \( \Phi(x, y) \). Lemmas [13] and [14] show that the first two hypothesis of the c.d.c. are realized by \( \text{cdc1} \) and \( \text{cdc2} \). The third one is given by lemma [17] below.
**Lemma 47.** There exist two proof-like terms $cdc3$ and for such that:

i) $cdc3 \vdash \forall n \forall q \forall q \Phi(n,p), \Phi(sn,q) \rightarrow q \sqsubseteq p$.

ii) for $\vdash \forall n \forall q \forall q \Phi(sn,q) \rightarrow q \rightarrow \pm Xn$.

By lemma $[13](i)$, we have:

$\text{rec} \vdash \forall k \Phi(\vec{H}(n,p,k), \Phi(n,p), \Phi(sn,q) \rightarrow q = f(n,p,k))$.

Using $cdc2$ (lemma $[14]$), we get:

$\vdash \forall k \Phi(\vec{H}(n,p,k), \Phi(n,p), \Phi(sn,q) \rightarrow q = f(n,p,k))$.

By lemma $42(iii)$, we have:

$\vec{H}(n,p,k)$ is a sequence of four formulas, the last two of which are:

$f(n,p,k) \sqsubseteq p$ and $f(n,p,k) \vdash \pm Xn$.

i) It follows first that $\vdash \forall k \Phi(\vec{H}(n,p,k), \Phi(n,p), \Phi(sn,q) \rightarrow q \sqsubseteq p)$.

Hence the result, since we have $\vdash \exists k \Phi(\vec{H}(n,p,k))$ (lemma $[10]$).

ii) It follows also that $\vdash \forall k \Phi(n,p,k), \Phi(n,p), \Phi(sn,q) \rightarrow q \vdash \pm Xn)$.

Thus, we obtain $\vdash \forall n \forall q \Phi(sn,q) \rightarrow q \rightarrow \pm Xn)$ since we have $cdc1 \vdash \forall n \exists p \Phi(n,p)$ (lemma $[13]$) and $\vdash \forall n \forall q \Phi(\vec{H}(n,p,k))$ (lemma $[14]$).

Q.E.D.

We can now apply the c.d.c. to the predicate $\Phi(x,y)$, which gives a proof-like term $cdc0$ such that $\vdash \exists p' \Omega(n,p,p')$ with:

$\Omega(n,p,p') \equiv \{ \forall n \forall q \forall p (\Phi(n,p) \rightarrow p' \sqsubseteq p), \forall n \forall q \forall p (\Phi(n,p), C[p] \rightarrow \bot), C[p'] \rightarrow \bot \}$.

Therefore, in order to complete the proof of theorem $[33]$, it is sufficient to find proof-like terms $dec0, dec1, dec2$ such that:

$\vdash \forall p' (\Omega(n,p,p'), C[p], C[p'] \rightarrow \bot)$

$\vdash \forall p' (\Omega(n,p,p'), C[p], C[p'] \rightarrow \bot)$

$\vdash \forall n \forall q \forall p' (\Phi(n,p), C[p] \rightarrow \bot, C[p'] \rightarrow \bot)$

Applying lemma $[12](i)$ with $n = 0, p = p_0$, we obtain $(\omega_0) \lambda x \lambda y \rightarrow p' \sqsubseteq p_0$.

Therefore, we can take $\lambda \alpha \lambda b(a) \lambda x \lambda y$.

**Lemma 48.** $\vdash (C[p_0] \rightarrow \forall n \forall q \forall p (\Phi(n,p), C[p] \rightarrow \bot))$ where $\lambda \alpha \lambda b \lambda c = (b \lambda x \alpha \lambda x_1 \lambda x_2 \lambda x_3 \lambda x \lambda y(x)(x_1)y)\lambda x x a c c$.

Let $\tau \in C[p_0]$, $\xi \vdash \Phi(n,p)$ and $\eta \vdash \neg C[p]$.

Making $X(x,y), y \equiv \neg C[y]$ in the definition of $\Phi$, we get:

$\xi \vdash \forall n \forall p \forall k \Phi(G[n',p',k], F[n',p',f(n',p',k)], \neg C[p'] \rightarrow \neg C[f(n',p',k)], \neg C[p] \rightarrow \bot, \neg C[p] \rightarrow \bot)$.

We have $\lambda (x) \tau \rightarrow \neg C[p_0]$.

Moreover, since $\neg C[p] \rightarrow \neg C[p']$, we easily get:

$\neg C[p] \rightarrow \neg C[p']$.

It follows that $((\lambda \alpha \lambda b(a) \lambda x \lambda x_1 \lambda x_2 \lambda x_3 \lambda x \lambda y(x)(x_1)y)\lambda x x a c c)\tau \xi \eta \rightarrow \bot$.

Q.E.D.

From lemma $[18]$, we immediately deduce $\lambda x (\omega_1)(cdc4)x \vdash C[p_0], C[p'] \rightarrow \bot$.

Therefore, we can put $\lambda \alpha \lambda b(a)(cdc4)x$.

35
Lemma 49.

i) \( \text{lef0} \models \forall \forall \forall q (p \models X_n, q \subseteq p \rightarrow q \models X'_n) \) with \( \text{lef0} = \lambda x \lambda y \lambda z ((cc) \lambda k ((y) \lambda u (k) (x) u) z) \).

ii) \( \text{lef1} \models \forall \forall \forall q (p \models X_n, q \subseteq p \rightarrow q \models X'_n) \) with \( \text{lef1} = \lambda x \lambda y \lambda z \lambda w ((\text{lef0}) (cc) \lambda h ((y) \lambda u (h) (x) v) u) z \).

i) This is immediate, if we write explicitly the formulas:

\[
p \models X_n \equiv \forall r (C[p r] \rightarrow X^+(r, n)) ;
q \subseteq p \models \forall r (C[p r] \rightarrow \neg C[q r]) ;
q \models X_n \equiv \forall r (C[q r] \rightarrow X^+(r, n)).
\]

We declare \( x : p \models X_n, \ y : q \subseteq p, \ z : C[q r], \ k : \neg X^+ n. \)

ii) We write down the formulas:

\[
p \models X_n \equiv \forall r (C[p r] \rightarrow X_n) ;
q \subseteq p \models \forall r (\neg C[p r] \rightarrow \neg C[q r]) ;
q \models X_n \equiv \forall r (C[q r] \rightarrow X_n).
\]

We declare \( x : p \models X_n, \ y : q \subseteq p, \ z : C[q r], \ u : r \models X_n, \ u : C[p r], \ h : \neg (p \models X_n) \).

Q.E.D.

By means of lemmas 17(ii) and 13 and also \( \omega_0 \models \forall n \text{ent} \forall p (\Phi(n, p) \rightarrow p' \subseteq p) \), we obtain:

\( \lambda x \lambda y \lambda z ((\text{lef1}) (\text{for} n x) (\omega_0) n x \models \forall n \text{ent} \forall q (\Phi(s n, q) \rightarrow p' \models X_n) \).

But, we have \( \text{cdc1} \models \forall n \text{ent} \exists p \Phi(n, p) \) (lemma 13) ; it follows that:

\( \lambda n (cc) \lambda k ((\text{cdc1}) (s n) \lambda x (k) ((\text{lef1}) (\text{for} n x) (\omega_0) n x \models \forall n \text{ent} (p x \models X_n) \).

Thus, we can put \( \text{dec2} = \lambda a \lambda b \lambda n (cc) \lambda k ((\text{cdc1}) (s n) \lambda x (k) ((\text{lef1}) (\text{for} n x) (a) n x) \).

This completes the proof of theorem 13.

Q.E.D.

The ultrafilter axiom on \( \mathbb{N} \)

Let us consider a standard realizability algebra \( \mathcal{A} \) and a \( \mathcal{A} \)-model \( \mathcal{M} \) in which the individual set (which is also the set of conditions) is \( P = \mathcal{P}(\mathbb{N}) \).

The binary relation \( \varepsilon \) is defined by \( \| n \varepsilon p \| = p(n) \) if \( n \in \mathbb{N} \) ; otherwise \( \| n \varepsilon p \| = \emptyset \).

1 is defined by \( 1(n) = \emptyset \) for every \( n \in \mathbb{N} \);
\( \Phi \) is defined by \( \| n \varepsilon (p \circ q) \| = \| n \varepsilon p \land n \varepsilon q \| \) for every \( n \in \mathbb{N} \).

The axiom of representation of predicates on \( \mathbb{N} \) (RPN)

We define the following recursive function of arity \( k \), denoted by \( (n_1, \ldots, n_k) \) (coding of \( k \)-uples) : \( (n_1, n_2) = n_1 + (n_1 + n_2)(n_1 + n_2 + 1)/2 ; (n_1, \ldots, n_{k+1}) = ((n_1, \ldots, n_k), n_{k+1}). \)

Proposition 50. \( \models \forall X \exists x \forall y_1^{int} \ldots \forall y_k^{int} (y_1, \ldots, y_k) \varepsilon x \leftrightarrow X(y_1, \ldots, y_k) \) where \( X \) is a predicate variable of arity \( k \).

Let \( X : P^k \to \mathcal{P}(\mathbb{N}) \) be a predicate of arity \( k \). We define \( a \in P \) by putting:

\( a(n) = X(n_1, \ldots, n_k) \) for \( n \in \mathbb{N} \), \( n = (n_1, \ldots, n_k) \). Then, we have immediately:

\( I \models \forall y_1^{ent} \cdots \forall y_k^{ent} ((y_1, \ldots, y_k) \varepsilon a \to X(y_1, \ldots, y_k)) \) and
\( I \models \forall y_1^{ent} \cdots \forall y_k^{ent} (X(y_1, \ldots, y_k) \to (y_1, \ldots, y_k) \varepsilon a). \)

It follows that :
Then, it suffices to apply theorem 13.

Q.E.D.

The comprehension scheme for \( \mathbb{N} \) (CSN)

Let \( F[y, x_1, \ldots, x_k] \) be a formula the free variables of which are taken among \( y, x_1, \ldots, x_k \).

We define a \( k \)-ary function \( g_F : P^k \to P \), in other words \( g_F : P^k \times \mathbb{N} \to \mathcal{P}(\Pi) \) by putting \( g_F(p_1, \ldots, p_k)(n) = \| F[n, p_1, \ldots, p_k] \| \) for every \( n \in \mathbb{N} \).

**Proposition 51.** We have \( \| \forall x_1 \ldots \forall x_k \forall y \, (y \in g_F(x_1, \ldots, x_k) \leftrightarrow F[y, x_1, \ldots, x_k]) \) for every formula \( F[y, x_1, \ldots, x_k] \).

Indeed, we have trivially:

**I** \( \vdash \forall x_1 \ldots \forall x_k \forall y \, \| (y \in g_F(x_1, \ldots, x_k) \rightarrow F[y, x_1, \ldots, x_k]) \) and 

**I** \( \vdash \forall x_1 \ldots \forall x_k \forall y \, \| (y \in g_F(x_1, \ldots, x_k) \rightarrow y \in g_F(x_1, \ldots, x_k)) \).

Then, it suffices to apply theorem 13.

Q.E.D.

**Remark.**
The binary function symbol \( \wedge \) is obtained by applying CSN to the formula \( y \in x_1 \land y \in x_2 \).

The generic model

We denote by \( C[x] \) the formula \( \forall m \exists n \forall (m + n) \, \varepsilon x \), which says that the set \( x \) of integers is infinite. The predicate \( C \) is defined by this formula: for every \( p \in P \), \( |C[p]| \) is, by definition, the set \( \{ \tau \in \Lambda ; \, \tau \vdash C[p] \} \).

It follows that the condition \( \gamma :: t(p_1, \ldots, p_n) \Rightarrow u(p_1, \ldots, p_n) \) is written as:

\[
\lambda x \gamma \vdash \forall p_1 \ldots \forall p_n (C[t(p_1, \ldots, p_n)] \rightarrow C[u(p_1, \ldots, p_n)]).
\]

Therefore, in order to complete the definition of the algebra \( B \) (and of the \( B \)-model \( N \)), it remains to find proof-like terms \( \alpha_0, \alpha_1, \alpha_2, \beta_0, \beta_1, \beta_2 \) such that:

\[
\begin{align*}
\alpha_0 & \vdash \forall p \forall q \forall r (C[(p \wedge q) \rightarrow r] \rightarrow C[(p \wedge q) \rightarrow r]) ; \\
\alpha_1 & \vdash \forall p (C[p] \rightarrow C[p \wedge 1]) ; \\
\alpha_2 & \vdash \forall p \forall q (C[p \wedge q] \rightarrow C[q]) ; \\
\beta_0 & \vdash \forall p \forall q (C[p \wedge q] \rightarrow C[p \wedge q]) ; \\
\beta_1 & \vdash \forall p \forall q (C[p \wedge q] \rightarrow C[q \wedge p]) ; \\
\beta_2 & \vdash \forall p \forall q \forall r \forall s (C[(p \wedge q) \wedge r] \rightarrow s) \rightarrow C[(p \wedge q) \wedge s] \rightarrow s).
\end{align*}
\]

Now, we easily have, in natural deduction:

\[
\vdash \theta : \forall n (n \in x \rightarrow n \in x') \rightarrow (C[x] \rightarrow C[x']) \text{ with } \theta = \lambda f \lambda u \lambda m \lambda h (u m \lambda x (hn)(f) x).
\]

Therefore, by theorem 3 (adequacy lemma), we can put \( \alpha_i = \theta \alpha_i^* \) and \( \beta_i = \theta \beta_i^* \), with proof-like terms \( \alpha_i^*, \beta_i^* (0 \leq i \leq 2) \) such that:

\[
\vdash \alpha_0^* : \forall x \forall Y \forall Z \{((X \wedge Y) \wedge Z) \rightarrow X \wedge (Y \wedge Z)\} ; \\
\vdash \alpha_1^* : \forall X \{X \rightarrow X \wedge T\} ; \\
\vdash \alpha_2^* : \forall X \forall Y \{X \wedge Y \rightarrow Y\} ; \\
\vdash \beta_0^* : \forall X \{X \rightarrow X \wedge X\} ; \\
\vdash \beta_1^* : \forall X \forall Y \{X \wedge Y \rightarrow Y \wedge X\} ; \\
\vdash \beta_2^* : \forall X \forall Y \forall Z \forall U \{((X \wedge Y) \wedge Z) \wedge U ightarrow (X \wedge (Y \wedge Z)) \wedge U\}.
\]

The countable downward chain condition

In this section, we show the:
Theorem 52.
The forcing structure \( \{ C, \wedge, 1 \} \) satisfies the countable downward chain condition in \( M \).

**Remark.** The proof of this theorem is a formalization of the following simple result:
The set of infinite subsets of \( N \) with the preorder “\( p \sqsubseteq q \Leftrightarrow p \setminus q \) is finite”, satisfies the countable downward chain condition.
The proof is as follows: let \( p_n \) be a decreasing sequence for this preorder; put \( h_n = \bigcap_{i \leq n} p_i \), \( k_n = \) the first element of \( h_n \) which is \( \geq n \), and consider \( \{ k_n ; n \in N \} \) which is an infinite subset of \( N \).

We have to find a proof-like term \( cdc \) such that:
\[
cdc \models \forall \mathcal{X} \exists x \forall n^{ent} \exists p X(n, p), \forall n^{ent} \exists p \forall q(X(n, p), X(n, q) \rightarrow p \equiv q),
\quad \forall n^{ent} \exists p \forall q(X(n, p), X(sn, q) \rightarrow q \sqsubseteq p) \rightarrow \forall n^{ent} \exists p X(n, p) \rightarrow x \sqsubseteq p) \wedge (\forall n^{ent} \exists p (X(n, p) \rightarrow C[p]) \rightarrow C[x])
\]
where \( p \sqsubseteq q \) is the formula \( r(C[p_n]) \rightarrow C[q_n] \).

By theorem [3], this amounts to find a proof-like term \( cdc' \) such that:
\[
cdc' \models \forall \mathcal{X} \exists x \forall n^{ent} \exists p X(n, p), \forall n^{ent} \exists p \forall q(X(n, p), X(n, q) \rightarrow p = q),
\quad \forall n^{ent} \exists p \forall q(X(n, p), X(sn, q) \rightarrow q \sqsubseteq p) \rightarrow \forall n^{ent} \exists p X(n, p) \rightarrow x \sqsubseteq p) \wedge (\forall n^{ent} \exists p (X(n, p) \rightarrow C[p]) \rightarrow C[x])
\]

By theorem [3](adequacy lemma), given a formula \( F \), we can use the following method to show \( \models F \):
First, show \( \models A_1, \ldots, A_k \), then show \( A_1, \ldots, A_k \vdash F \) by means of the rules of classical second order natural deduction (which contains the comprehension scheme), and of the following axioms which are realized by proof-like terms in the \( A \)-model \( M \):

- \( t \neq u \) for all closed terms \( t, u \) which take distinct values in \( M \).
- \( \forall x^{int} \ldots \forall x^{int} (t(x_1, \ldots, x_k) = u(x_1, \ldots, x_k)) \) for all the equations between terms which are true in \( N \).
- The foundation scheme (SCF, see theorem [3]) which consists of the formulas:
  \[
  \forall X_1 \ldots \forall X_k \{ \forall x^{int} [\forall y^{int} (X_1 y, \ldots, X_k y \rightarrow f(y, x) \neq 1), X_1 x, \ldots, X_k x \rightarrow \bot]
  \rightarrow \forall x^{int} (X_1 x, \ldots, X_k x \rightarrow \bot)
  \]
  where \( f : P^2 \rightarrow P \) is such that the relation \( f(y, x) = 1 \) is well founded on \( N \).
- The axiom of choice for individuals (ACI, see theorem [3]) which consists of the formulas:
  \[
  \forall \bar{x} (\forall y^{int} F(\bar{x}, f_F(\bar{x}, y)) \rightarrow \forall y F(\bar{x}, y)) ;
  \bar{x} = (x_1, \ldots, x_k) \] is a finite sequence of variables, \( \forall \bar{x} \forall y^{int} F \) is an arbitrary closed formula, and \( f_F \) is a function symbol of arity \( k + 1 \).
- The axiom of representation of predicates on \( N \) (RPN, see proposition [3]) which consists of the formulas:
  \[
  \forall X \exists y^{int} \forall x^{int} ((y_1, \ldots, y_k) \epsilon x \leftrightarrow X \bar{y}) ;
  \bar{y} = (y_1, \ldots, y_k) \] is a sequence of \( k \) variables and \( X \) is a predicate variable of arity \( k \).
- The comprehension scheme for integers (CSN, see proposition [3]), which consists of the formulas:
  \[
  \forall \bar{x} \forall y^{int} (y \epsilon g_F(\bar{x}) \leftrightarrow F[y, \bar{x}]) ;
  \bar{x} = (x_1, \ldots, x_k) \] is a sequence of \( k \) variables, \( \forall \bar{x} \forall y^{int} F \) is an arbitrary closed formula, and \( g_F \) is a function symbol of arity \( k \).

Lemma 53. \( \vdash \forall p \forall q (p \sqsubseteq q \Leftrightarrow \exists m^{int} \forall n^{int} (n + m \epsilon p \rightarrow n + m \epsilon q)) \).
We apply the CSN to the formula \( F[y, x] \equiv y \neq x \); thus, we obtain:
\[ \vdash \forall x \forall y \neg (y \in x \leftrightarrow y \notin x) \]

using the notation \( \neg x \) for \( g_F(x) \).

We have \( p \subseteq q \equiv \forall r (C[p \land r] \rightarrow C[q \land r]) \) and therefore \( p \subseteq q \vdash C[p \land \neg q] \rightarrow C[q \land \neg q] \).

But, we have \( C[q \land \neg q] \vdash \forall m \int \exists n \int (m + n \in q \land m + n \notin q) \vdash \bot \), and thus:
\[ p \subseteq q \vdash \neg C[p \land \neg q], \] that is \( p \subseteq q \rightarrow \exists m \int \forall n \int (m + n \notin p \land \neg (m + n \in q)) \).

Conversely, from the hypothesis:
\[ \forall n \int (m' + n' \in p \rightarrow m' + n' \in q), \forall m \int \exists n \int (m + n \in p \land m + n \in r) \), we deduce:
\[ \forall m \int \exists n \int ((m' + m) + n \in p \land (m' + m) + n \in r), \] then:
\[ \forall m \int \exists n \int (m + (m' + n) \in q \land m + (m' + n) \in r) \] then:
\[ \forall m \int \exists n \int (m + n \in q \land m + n \in r) \]. Therefore:
\[ \forall n' \int (m' + n' \in p \rightarrow m' + n' \in q) \vdash C[p \lor r] \rightarrow C[q \lor r] \] and thus:
\[ \exists m \int \forall n' \int (m' + n' \in p \rightarrow m' + n' \in q) \vdash C[p \lor r] \rightarrow C[q \lor r]. \]

Q.E.D.

Applying RPN and the comprehension scheme, we obtain \( \vdash \forall X \exists h \ D(h, X) \) with:
\[ D(h, X) \equiv \forall k \int \forall n \int ((k, n) \in h \leftrightarrow \forall q \forall i \int (i \leq n, X(i, q) \rightarrow k \in q)) \).

**Remark.** The intuitive meaning of \( D(h, X) \) is : \( h \) is the individual associated with the decreasing sequence of conditions \( X' \), the \( n \)-th term of which is the intersection of the \( n \) first terms of the sequence \( X \).

We apply CSN to the formula \( F(k, n, h) \equiv (k, n) \in h \). Thus, we obtain:
\[ \vdash \forall n \forall h \forall k \int \forall n (k \in g_F(n, h) \leftrightarrow (k, n) \in h) \).

We shall use the notation \( h_n \) for \( g_F(n, h) \). Therefore, we have:
\[ \vdash \forall n \forall h \forall k \int (k \in h_n \leftrightarrow (k, n) \in h) \).

and it follows that:
\[ D(h, X) \vdash \forall k \int \forall n \int (k \in h_n \leftrightarrow \forall q \forall i \int (i \leq n, X(i, q) \rightarrow k \in q)) \)

We put \( \Phi(k, h, n) \equiv \exists i \int \forall j \int (j + n \in h_n \rightarrow (j < i) \neq 1), i + n \in h_n, k = i + n \).

**Remark.** The intuitive meaning of \( \Phi(k, h, n) \) is : “ \( k \) is the first element of \( h_n \) which is \( \geq n \)”.

We apply CSN to the formula \( F(k, h, n) \equiv \exists n \int \Phi(k, h, n) \). Thus, we obtain:
\[ \vdash \forall h \forall k \int (k \in g_F(h) \leftrightarrow \exists n \int \Phi(k, h, n)) \).

We shall use the notation \( \inf(h) \) for \( g_F(h) \). Therefore, we have:
\[ \vdash \forall h \forall k \int (k \in \inf(h) \leftrightarrow \exists n \int \Phi(k, h, n)) \).

The hypothesis of the c.d.c. are:
\[ H_0[X] \equiv \forall n \int \exists p \ X(n, p) ; \]
\[ H_1[X] \equiv \forall n \int \forall q \ X(n, p), X(n, q) \rightarrow p = q ; \]
\[ H_2[X] \equiv \forall n \int \forall q \ X(n, p), X(sn, q) \rightarrow q \subseteq p ; \]
\[ H_3[X] \equiv \forall n \int \forall q \ X(n, p) \rightarrow C[p] . \]

We put \( \bar{H}[X] = \{H_0[X], H_1[X], H_2[X], H_3[X]\} \) and \( \bar{H}_4[X] = \{H_0[X], H_1[X], H_2[X] \} \).

Thus, it is sufficient to show:
\[ D(h, X), \bar{H}_4[X] \vdash \forall n \int \forall p \ X(n, p) \rightarrow \inf(h) \subseteq p \) and
\[ D(h, X), \bar{H}[X] \vdash C[\inf(h)]. \]

**Notation.** The formula \( \forall n \int (n \in p \rightarrow n \in q) \) is denoted by \( p \subseteq q \).

**Lemma 54.** \( D(h, X) \vdash \forall m \int \forall n \int (h_{n+m} \subseteq h_n) \).
This formula is written $\forall m^\text{int} \forall n^\text{int} \forall k^\text{int} (k \in h_{n+m} \to k \in h_n)$. Now, we have:

$D(h, X) \vdash \forall m^\text{int} \forall n^\text{int} \forall k^\text{int} (k \in h_{n+m} \to \forall q^\text{int} (i \leq n + m, X(i, q) \to k \in q))$;

$\vdash \forall m^\text{int} \forall n^\text{int} \forall k^\text{int} (i \leq n + m, X(i, q) \to k \in q) \to \forall q^\text{int} (i \leq n, X(i, q) \to k \in q) :$

$D(h, X) \vdash \forall m^\text{int} \forall n^\text{int} \forall k^\text{int} (\forall q^\text{int} (i \leq n, X(i, q) \to k \in q) \to k \in h_n)$.

Q.E.D.

**Lemma 55.** $D(h, X), H_0[X], H_1[X] \vdash \forall n^\text{int} \forall k^\text{int} \forall p(X(sn, p), k \in p, k \in h_n \to k \in h_{sn})$.

We have $D(h, X), \text{int}(k), \text{int}(n) \vdash \forall p^\text{int} (i \leq sn, X(i, p) \to k \in p) \to k \in h_{sn}$.

But, we have $\text{int}(n), \text{int}(i), i \leq sn \vdash i \leq n \lor i = sn$, and therefore:

$\text{int}(n), \forall p^\text{int} (i \leq n, X(i, p) \to k \in p), \forall p(X(sn, p) \to k \in p) \vdash \forall p^\text{int} (i \leq sn, X(i, p) \to k \in p)$.

It follows that:

$D(h, X), \text{int}(k), \text{int}(n) \vdash \forall p^\text{int} (i \leq n, X(i, p) \to k \in p), \forall p(X(sn, p) \to k \in p) \to k \in h_{sn}$, i.e.:

$D(h, X), \text{int}(k), \text{int}(n) \vdash k \in h_n, \forall p(X(sn, p) \to k \in p) \to k \in h_{sn}$. Therefore:

$D(h, X), \text{int}(k), \text{int}(n), H_0[X], H_1[X] \vdash \forall p(k \in h_n, X(sn, p), k \in p \to k \in h_{sn})$.

Q.E.D.

**Lemma 56.** $D(h, X), \tilde{H}[X] \vdash \forall n^\text{int} \forall p(X(n, p) \to p \subseteq h_n)$.

Proof by recurrence on $n$. We must show:

$D(h, X), \tilde{H}[X], \text{int}(n) \vdash \forall p^\text{int} \forall l^\text{int} (X(n, p), l + m \in p \to l + m \in h_n)$.

For $n = 0$, we have $D(h, X) \vdash \forall k^\text{int} (\forall q^\text{int} (X(0, q) \to k \in q) \to k \in h_0)$. Thus, it suffices to show:

$D(h, X), \tilde{H}[X], \text{int}(n) \vdash \forall p^\text{int} \forall l^\text{int} \forall q^\text{int} (X(0, p), l + m \in p, X(0, q) \to l + m \in q)$, which follows, in fact, from $H_1[X]$, that is $X(0, p), X(0, q) \to p = q$.

The recurrence hypothesis is $\forall p(X(n, p) \to p \subseteq h_n)$;

$H_2[X]$ is $\forall p^\text{int} q^\text{int} (X(n, p), X(sn, q) \to q \subseteq p)$; $H_0[X]$ is $\exists p X(n, p)$.

Moreover, we have easily $q \subseteq p, p \subseteq r \vdash q \subseteq r$. Thus, it follows that:

$\forall p(X(sn, p) \to p \subseteq h_n)$, i.e. $\forall p^\text{int} \forall l^\text{int} \forall q^\text{int} (X(sn, p), l + m \in p \to l + m \in h_n)$.

Now, we have, by lemma 54:

$D(h, X), H_0[X], H_1[X] \vdash X(sn, p), l + m \in p, l + m \in h_n \to l + m \in h_{sn}$.

Therefore, we have $\forall p^\text{int} \forall l^\text{int} \forall q^\text{int} (X(sn, p), l + m \in p \to l + m \in h_{sn})$ that is:

$\forall p(X(sn, p) \to p \subseteq h_{sn})$, which is the desired result.

Q.E.D.

**Lemma 57.** $D(h, X), \tilde{H}(X) \vdash \forall n^\text{int} C[h_n]$.

We have $\forall n^\text{int} \forall p(X(n, p) \to C[p])$ from $H_3$. Moreover, we have easily:

$\vdash \forall p^\text{int} q^\text{int} (C[p], p \subseteq q \to C[q])$. Thus, applying lemma 54, we obtain:

$D(h, X), \tilde{H}(X) \vdash \forall n^\text{int} \forall p(X(n, p) \to C[h_n])$. Hence the result, from $H_0[X]$.

Q.E.D.

**Lemma 58.** $D(h, X), \tilde{H}[X] \vdash \forall n^\text{int} \exists k^\text{int} \Phi(k, h, n)$.
By the foundation scheme (SCF), we have:
\[ \vdash \forall \int\{ j + n \in h_n \implies (ji) \neq 1 \}, i + n \in h_n \implies \bot \} \implies \forall \int(i + n \in h_n \implies \bot). \]
But, we have \( D(h, X), \vec{H}[X] \vdash \forall \int C[h_n] \) (lemma [7]), therefore:
\[ D(h, X), \vec{H}[X] \vdash \forall \int \exists \int i + n \in h_n. \]
It follows that:
\[ D(h, X), \vec{H}[X] \vdash \forall \int \exists \int \{ j + n \in h_n \implies (ji) \neq 1 \}, i + n \in h_n \}. \]
Q.E.D.

**Lemma 59.** \( D(h, X), \vec{H}[X] \vdash C[\inf(h)] \).

We have \( C[\inf(h)] \equiv \forall m \inf(i + \varepsilon \inf(h)). \)
Now, by definition of the function symbol \( \inf \), we have:
\[ \vdash \forall h \forall k \inf(k \in \inf(h) \iff \exists \inf(\Phi(k, h, n)). \]
Therefore \( \vdash C[\inf(h)] \iff \forall m \inf(\exists \inf \inf(k + m, h, n)). \)
By definition of \( \Phi \), we have trivially \( \vdash \forall \inf \forall k \inf(\Phi(k, h, n) \implies \exists \inf(\Phi = i + n)). \)
Moreover, we have \( D(h, X), \vec{H}[X] \vdash \forall \inf \exists \inf \Phi(k, h, n) \) (lemma [58]).
Therefore \( D(h, X), \vec{H}[X] \vdash \forall \inf \exists \inf \Phi(i + n, h, n) \), thus \( D(h, X), \vec{H}[X] \vdash C[\inf(h)]. \)
Q.E.D.

**Lemma 60.**
\[ D(h, X), \vec{H}[X] \vdash \forall h \forall k \inf \forall \int \inf \forall \int \inf(\Phi(k, h, n), \Phi(k', h, n'), k' > k \implies n' > n). \]

We have \( \Phi(k, h, n) \equiv \exists i \int \Phi(k, h, n, i) \), with:
\[ \Psi(k, h, n, i) \equiv \{ \forall \int(j + n \in h_n \implies (ji) \neq 1), i + n \in h_n, k = i + n \}. \]
Thus, we have to show:
\[ D(h, X), \vec{H}[X], \int(k), \int(k'), \int(n), \int(n'), \int(i), \int(i') \vdash \Xi(h, k, n, i, k', n', i', \bot) \implies \Xi(h, k, n, i, k', n', i', \bot). \]
That is:
\[ \Xi(h, k, n, i, k', n', i', \bot) \equiv \{ \forall \int(j + n \in h_n \implies (ji) \neq 1), i + n \in h_n, k = i + n, \forall \int(j' + n' \in h_{n'} \implies (j'i') \neq 1), i' + n' \in h_{n'}, k' = i' + n', k' > k, n' \leq n \}. \]

From \( n' \leq n \) and \( k = i + n \), we deduce \( n' \leq k \), thus \( k = j' + n' \).
From \( k' > k \), we deduce \( i' + n' > k' \), and thus \( j' < i' \).
Therefore, we have \( j' + n' \notin h_n \), i.e. \( k \notin h_n \). But, from \( n' \leq n \), we deduce \( h_n \subseteq h_{n'} \) (lemma [24]), thus \( k \notin h_n \), which contradicts \( i + n \in h_n, k = i + n \).
Q.E.D.

By definition of \( \Phi \), we have trivially \( \vdash \forall \int \forall k \inf(\Phi(k, h, n) \implies k \in h_n). \)

By lemmas [3] and [4], we get:
\[ D(h, X), \vec{H}[X] \vdash \forall h \forall k \inf \forall \int \inf \forall \int \inf \Phi(k, h, n), \Phi(k', h, n'), k' > k \implies k' \in h_n). \]
Lemma [58] gives \( \forall \int \exists \inf \Phi(k, h, n) \). It follows that:
\[ D(h, X), \vec{H}[X] \vdash \forall h \exists \inf \forall \int \forall k \inf(\Phi(k', h, n'), k' > k \implies k' \in h_n), \]
and therefore \( D(h, X), \vec{H}[X] \vdash \forall \inf(\inf(h) \subseteq h_n). \)
But, we have trivially \( D(h, X) \vdash \forall \int \forall k \inf \forall p(k \in h_n, X(n, p) \implies k \in p). \) Therefore, finally:
\[ D(h, X), \vec{H}[X] \vdash \forall \int \forall p(X(n, p) \implies \inf(h) \subseteq p). \]
We have eventually obtained the desired proof-like term \( \text{cdc}' \), which completes the proof of theorem \( 52 \).  
Q.E.D.

The ultrafilter

In the model \( \mathcal{N} \), we have defined the generic ideal \( \mathcal{J} \), which is a unary predicate, by putting: \( \mathcal{J}(p) = \Pi \times \{ p \} \) for every \( p \in P \).

By theorem \( 33 \), we have:

i) \( \models \neg \mathcal{J}(1) \)

ii) \( \models \forall x(\neg \mathcal{C}[x] \rightarrow \mathcal{J}(x)) \)

iii) \( \models \forall x\forall y(\mathcal{J}(x \land y) \rightarrow \mathcal{J}(x) \lor \mathcal{J}(y)) \)

iv) \( \models \forall x(\forall y(\neg \mathcal{C}[x \land y] \rightarrow \mathcal{J}(y)) \rightarrow \neg \mathcal{J}(x)) \)

v) \( \models \forall x\forall y(\mathcal{J}(x), y \subseteq x \rightarrow \mathcal{J}(y)) \)

By theorem \( 31 \), we have \( ||| \models \mathcal{F} \iff \models \mathcal{F} \) for every closed first order formula \( \mathcal{F} \).

Remark. A “first order” formula contains quantifiers on the individuals which, by means of the symbol \( \varepsilon \), represent the subsets of \( \mathbb{N} \). Therefore, it is a second order formula from the point of view of Arithmetic. But it contains no quantifier on sets of individuals.

By theorems \( 13 \) and \( 28 \), we can use, in \( \mathcal{F} \), the quantifier \( \forall \) \( \text{int} \), since the quantifier \( \forall \) \( \text{ent} \) is first order.

Therefore, we have:

vi) \( \models \mathcal{C}[x] \leftrightarrow \forall m \text{int} \exists n \text{int} (m + n \varepsilon x) \)

vii) \( \models y \subseteq x \leftrightarrow \exists m \text{int} \forall n \text{int} (m + n \varepsilon y \rightarrow m + n \varepsilon x) \)

viii) \( \models \forall n \text{int} n \varepsilon 1 ; \models \forall x\forall y\forall n \text{int} (n \varepsilon x \land y \varepsilon n) \)

since all these formulas are first order. Properties (i) to (viii) show that, in the \( \mathcal{B} \)-model \( \mathcal{N} \), the following formula is realized:

\( \mathcal{J} \) is a maximal non trivial ideal on the Boolean algebra of the subsets of \( \mathbb{N} \) which are represented by individuals.

Now, by theorems \( 38 \) and \( 52 \), the following formula is realized in \( \mathcal{N} \):

\( \text{Every subset of } \mathbb{N} \text{ is represented by an individual.} \)

Thus the following formula is realized in \( \mathcal{N} \):

\( \mathcal{J} \) is a maximal non trivial ideal on the Boolean algebra of the subsets of \( \mathbb{N} \).

Programs obtained from proofs

Let \( \mathcal{F} \) be a formula of second order arithmetic, that is to say a second order formula every individual quantifier of which is restricted to \( \mathbb{N} \) and every second order quantifier of which is restricted to \( \mathcal{P}(\mathbb{N}) \).

We associate with \( \mathcal{F} \), a first order formula \( \mathcal{F}^\uparrow \), defined by recurrence on \( \mathcal{F} \):

- If \( \mathcal{F} \) is \( t = u \), \( \mathcal{F}^\uparrow \equiv \mathcal{F} \).
- If \( \mathcal{F} \) is \( X t \), \( \mathcal{F}^\uparrow \) is \( t \in X^- \), where \( X^- \) is an individual variable associated with the unary predicate variable \( X \).
- If \( \mathcal{F} \) is \( A \rightarrow B \), \( \mathcal{F}^\uparrow \) is \( A^\uparrow \rightarrow B^\uparrow \).
• If \( F \) is \( \forall x \ A \), \( F^\dagger \) is \( \forall x^{\text{int}} A^\dagger \).
• If \( F \) is \( \forall X \ A \), \( F^\dagger \) is \( \forall X^\sim A^\dagger \).

We note that, if \( F \) is a formula of \textit{first order arithmetic}, then \( F^\dagger \) is simply the restriction \( F^{\text{int}} \) of \( F \) to the predicate \( \text{int}(x) \).

Let \( F \) be a closed formula of second order arithmetic and let us consider a proof of \( F \), which uses the axiom of dependent choice DC and the axiom UA of ultrafilter on \( \mathbb{N} \), written in the following form, with a constant \( J \) of predicate: “\( J \) is a maximal non trivial ideal on \( \mathcal{P}(\mathbb{N}) \)”.

We can transform it immediately into a proof of \( F^\dagger \) if we add the axiom RPN of representation of predicates on \( \mathbb{N} \): \( \forall X \exists x \forall y(y \in x \leftrightarrow Xy) \). Thus, we obtain:

\[
x : \text{UA}, \ y : \text{RPN}, \ z : \text{DC}^\dagger \vdash t[x, y, z] : F^\dagger.
\]

Therefore, we have \( \vdash u : \text{UA}, \ RPN \rightarrow G \) with \( u = \lambda x \lambda y \lambda z \ t[x, y, z] \) and \( G \equiv \text{DC}^\dagger \rightarrow F^\dagger \). Thus, \( G \) is a \textit{first order formula}.

In the previous section, we obtained proof-like terms \( \theta, \theta' \) such that \( (\theta, 1) \models \text{UA} \) and \( (\theta', 1) \models \text{RPN} \) (theorems [38] and [22]).

Therefore, theorem [22] (adequacy lemma) gives \( (u^*, 1_u)(\theta)(1') \models G \), that is to say:

\[
(v, (1_u \land 1) \land 1) \models G \quad \text{with} \quad v = ((\pi_1)(\pi_0)u^*)\theta'.
\]

By theorem [22], we thus have \( \delta_G^v \models C[(1_u \land 1) \land 1] \rightarrow G \), that is:

\[
\delta_G^v \models C[(1_u \land 1) \land 1], \text{DC}^\dagger \rightarrow F.
\]

The axiom DC^\dagger is consequence of ACI (axiom of choice for individuals). Therefore, by theorem [10], we have a proof-like term \( \eta_0 \models \text{DC}^\dagger \).

Moreover, we have obviously a proof-like term \( \xi_0 \models C[(1_u \land 1) \land 1] \).

Thus, finally, we have \( \delta_G^v \xi_0 \eta_0 \models F \).

Then, we can apply to the program \( \zeta = \delta_G^v \xi_0 \eta_0 \) all the results obtained in the framework of usual classical realizability. The case when \( F \) is an arithmetical (resp. \( \Pi_1 \)) formula is considered in [13] (resp. [14]).

Let us take two very simple examples:

If \( F \equiv \forall X(X_1, X_0 \rightarrow X_1) \), we have \( \zeta \equiv \kappa \cdot \kappa' \cdot \pi \models \kappa \cdot \pi \) for all terms \( \kappa, \kappa' \in \Lambda \) and every stack \( \pi \in \Pi \).

If \( F \equiv \forall m \in \mathbb{N} \exists n \in \mathbb{N} (\phi(m, n) = 0) \), where \( \phi \) is a function symbol, then for every \( m \in \mathbb{N} \), there exists \( n \in \mathbb{N} \) such that \( \phi(m, n) = 0 \) and \( \zeta \equiv \overline{m} \cdot T \kappa \cdot \pi \models \kappa \cdot \overline{n} \cdot \pi' \).

\( T \) is the proof-like term for integer storage, given in theorem [13](i).

\( \pi, \kappa \) are arbitrary; therefore, by taking a constant for \( \kappa \), we obtain a program which computes \( n \) from \( m \).

**Well ordering on \( \mathbb{R} \)**

The \( \mathcal{A} \)-model \( \mathcal{M} \) is the same as in the previous section: the set of individuals is \( P = \mathcal{P}(\Pi)^{\mathcal{M}} \). Recall that an element of \( P \) is called sometimes an \textit{individual}, sometimes a \textit{condition}, depending on the context.

We put \( (m, n) = m + (m + n)(m + n + 1)/2 \) (bijection of \( \mathbb{N}^2 \) onto \( \mathbb{N} \)). We define a binary function \( \gamma : \mathbb{P}^2 \rightarrow P \) by putting:

\[
\gamma(n, p)(i) = p(i, n) \quad \text{if} \quad n \in \mathbb{N} \quad \text{and} \quad \gamma(n, p) \text{is arbitrary (for instance 0) if} \quad n \notin \mathbb{N}.
\]

43
Notation. In the sequel, we shall write $p_n$ instead of $\gamma(n, p)$. Thus, it is the same to give an individual $p$ or a sequence of individuals $p_n (n \in \mathbb{N})$. If $i, n \in \mathbb{N}$, we have $\| (i, n) \in p \| = \| i \in p_n \|$.

We fix a well ordering $\prec$ on $P = \mathcal{P}(\mathbb{N})$, which is strict (i.e. $\forall x \prec (x \prec x)$) and isomorphic to the cardinal $2^{\aleph_0}$: every proper initial segment of $\prec$ is therefore of power $< 2^{\aleph_0}$. We define a binary function, denoted by $(p \triangleright q)$ by putting $(p \triangleright q) = 1$ if $p \prec q$; $(p \triangleright q) = 0$ otherwise.

Since the relation $(p \triangleright q) = 1$ is well founded on $P$, we have (theorem [11]):

$\forall Y(y < x) = 1 \mapsto Xy \mapsto Xx \mapsto \forall x Xx$ in the $\mathcal{A}$-model $\mathcal{M}$, but also in every $\mathcal{B}$-model $\mathcal{N}$.

We shall write, in abridged form, $y < x$ for $(y < x) = 1$.

Thus, in $\mathcal{M}$ and $\mathcal{N}$, the relation $\prec$ is well founded but, in general, not total.

It is a strict order relation, in both models; indeed we have immediately, in the model $\mathcal{M}$:

$I \models \forall x((x < x) \neq 1); I \models \forall x \forall y \forall z((x < y) = 1 \mapsto ((y < z) = 1 \mapsto (x < z) = 1))$.

Since all these formulas are first order, by theorem [11], we have also, in the model $\mathcal{N}$:

$I \models \forall x((x < x) \neq 1); I \models \forall x \forall y \forall z((x < y) = 1 \mapsto ((y < z) = 1 \mapsto (x < z) = 1))$.

We shall write, in abridged form, $y < x$ for $(y < x) = 1$.

Thus, in $\mathcal{M}$ and $\mathcal{N}$, the relation $\prec$ is well founded but, in general, not total.

It is a strict order relation, in both models; indeed we have immediately, in the model $\mathcal{M}$:

$I \models \forall x((x < x) \neq 1); I \models \forall x \forall y \forall z((x < y) = 1 \mapsto ((y < z) = 1 \mapsto (x < z) = 1))$.

Since all these formulas are first order, by theorem [11], we have also, in the model $\mathcal{N}$:

$I \models \forall x((x < x) \neq 1); I \models \forall x \forall y \forall z((x < y) = 1 \mapsto ((y < z) = 1 \mapsto (x < z) = 1))$.

A condition $p \in P$ is also a sequence of individuals $p_k$. Intuitively, we shall consider it, as “ the set of individuals $p_{k+1}$ for $k \in p_0$ ”; we define accordingly the condition 1, the formula $C[p]$ which says that $p$ is a non trivial condition, and the binary operation $\land$.

1 is the empty set, in other words $i \in 1$ (i.e. $(i, 0) \in 1$) must be false. Therefore, we put : $1(n) = \Pi$ for every $n \in \mathbb{N}$.

A condition is non trivial if the set of individuals, which is associated with it, is totally ordered by $\prec$. Therefore, we put :

$C[p] \equiv \forall i \in \text{ent} \forall j \in \text{ent} (i \in p_0, j \in p_0 \mapsto E[p_{i+1}, p_{j+1}])$ with :

$E[x, y] \equiv (x = y \lor x \prec y \lor y \prec x)$ that is $E[x, y] \equiv (x \neq y, (x \prec y) \neq 1, (y \prec x) \neq 1 \mapsto \bot)$.

The set associated with $p \triangleright q$ is the union of the sets associated with $p$ and with $q$; therefore, we put :

$p \triangleright q = r$ where $r_0$ is defined by : $\| 2i \in r_0 \| = \| i \in p_0 \| ; \| 2i + 1 \in r_0 \| = \| i \in q_0 \|$;

$r_{j+1}$ is defined by : $r_{2i+1} = p_{i+1} ; r_{2i+2} = q_{i+1}$.

The notation $p \triangleright q$ means that the set associated with $q$ contains the one associated with $p$.

Therefore, we put :

$p \triangleright q \equiv \forall i \in \text{ent} (i \in p_0 \mapsto \exists j \in \text{ent} (j \in q_0, p_{i+1} = q_{j+1})).$

Lemma 61.

i) $\theta \models \forall p \forall q \forall r(p \subset q, q \subset r \mapsto p \subset r)$ with $\theta = \lambda f \lambda g \lambda i \lambda x \lambda h (f i x) \lambda j \lambda y (g j y) j h$.

ii) $\theta' \models \forall p \forall q \forall r(p \subset q \mapsto p \triangleright q \subset q \triangleright r)$ with :

$\theta' = \lambda f \lambda g \lambda u (\lambda (e i) (u i y))(f (d i) j y) \lambda j (u (d_0) j)$

where $d_0, d_1, d_2, e$ are proof-like terms representing respectively the recursive functions :

$n \mapsto 2n, n \mapsto 2n + 1, n \mapsto \lceil n/2 \rceil, n \mapsto \text{parity of } n \text{ (e returns boolean values).}$

We suppose :

$f \models \forall i (\text{ent}(i), i \in p_0, \forall j (\text{ent}(j), j \in q_0 \mapsto p_{i+1} \neq q_{j+1} \mapsto \bot)$ ;

$g \models \forall j (\text{ent}(j), j \in q_0, \forall k (\text{ent}(k), k \in r_0 \mapsto q_{j+1} \neq r_{k+1} \mapsto \bot)$ ;

$x \models i \in p_0 ; h \models \forall k (\text{ent}(k), k \in r_0 \mapsto p_{i+1} \neq r_{k+1})$ ; and we have $i \in |\text{ent}(i)|$. 

44
It follows that \( f'x \vdash \forall j(\text{ent}(j), j \in q_0 \rightarrow p_{i+1} \neq q_{j+1}) \rightarrow \bot \).
Suppose that \( y \vdash j \in \text{ent}(j) \) and let \( j \in \text{ent}(j) \).
If \( p_{i+1} = q_{j+1} \), then \( g_{jy}h \vdash \bot \); therefore \( g_{jy}h \vdash p_{i+1} \neq q_{j+1} \). We have shown:
\( \lambda j \lambda y (g) jy_h \vdash \forall j(\text{ent}(j), j \in q_0 \rightarrow p_{i+1} \neq q_{j+1}) \). Therefore \( (f'x) \lambda j \lambda y (g) jy_h \vdash \bot \).

ii) We suppose:
\( f \vdash \forall i(\text{ent}(i), i \in p_0, \forall j(\text{ent}(j), j \in q_0 \rightarrow p_{i+1} \neq q_{j+1}) \rightarrow \bot) \);
\( y \vdash i' \in (p \land r)_0 \); \( u \vdash j'(\text{ent}(j'), j' \in (q \land r)_0 \rightarrow (p \land r)'_{i+1} \neq (q \land r)_{j'+1} \).
If we replace \( j' \) with \( 2j'' \), and then with \( 2j'' + 1 \), we obtain, by definition of \( \land \):
1) \( (u)(d_0)j''_\vdash j'' \in q_0 \rightarrow (p \land r)'_{i+1} \neq q_{j''+1} \);
2) \( (u)(d_1)j''_\vdash j'' \in r_0 \rightarrow (p \land r)'_{i+1} \neq r_{j''+1} \).
Then, there are two cases:

- If \( i' = 2i'' + 1 \), we have \( y \vdash i'' \in p_0 \) and, by (1), \( (u)(d_0)j''_\vdash j'' \in q_0 \rightarrow p_{i''+1} \neq q_{j''+1} \).
Therefore:
\( \lambda j(u)(d_0)j \vdash \forall j(\text{ent}(j), j \in q_0 \rightarrow p_{i''+1} \neq q_{j+1}) \) and it follows that:
\( (((f')(d)_0)j)gjy(h)(u)(d_0)j \vdash \bot \).

- If \( i' = 2i'' + 1 \), we have \( y \vdash i'' \in r_0 \) and, by (2), \( (u)(d_1)j''_\vdash j'' \in r_0 \rightarrow r_{i''+1} \neq r_{j''+1} \).
By making \( j'' = i'' \), we obtain \( (u)(d_1)j''_\vdash i'' \in r_0 \vdash \bot \) and therefore:
\( (u)j''y \vdash \bot \).
Thus, in both cases, we get:
\( (((f')(d)_0)j)gjy(h)(u)(d_0)j \vdash \bot \).
Q.E.D.

**Lemma 62.**

i) \( \theta \vdash \forall p \forall q (p \subset q, C[q] \rightarrow C[p]) \) with
\( \theta = jf'(x) \lambda y (\lambda x \lambda x' \lambda u \lambda vwx'y'yy'uwv)(f'x') \lambda y' \lambda y' (f'x) \lambda y (g) jy'y'uwv \).

ii) \( \vdash \forall p \forall q \forall r (p \subset q, C[q \land r] \rightarrow C[p \land r]) \) in other words \( \vdash \forall p \forall q (p \subset q \rightarrow q \subset p) \).

i) Let \( f \vdash p \subset q, g \vdash C[q] \), that is:
\( f \vdash \forall i(\text{ent}(i), i \in p_0, \forall j(\text{ent}(j), j \in q_0 \rightarrow p_{i+1} \neq q_{j+1}) \rightarrow \bot) \);
\( g \vdash \forall j' \forall j(\text{ent}(j), j \in q_0 \rightarrow \exists j' \in (q \land r)_0, j' \in q_0 \rightarrow E[q_{j+1}, q_{j'+1}] \) with :
\( E[x, y] \equiv (x \neq y, \forall x < y \neq 1 \rightarrow \bot) \).
Let \( x \vdash i \in p_0, x' \vdash i' \in p_0, u \vdash p_{i+1} \neq p_{i'+1}, v \vdash (p_{i+1} \land p_{i'+1}) \neq 1, w \vdash (p_{i'+1} \land p_{i+1}) \neq 1 \).
Let \( y \vdash j \in q_0, y' \vdash j' \in q_0 \).
We have \( gj_{j'y'yy'uwv} \vdash E[q_{j+1}, q_{j'+1}] \) if \( p_{i+1} = q_{j+1} \) and \( p_{i'+1} = q_{j'+1} \), then:
\( gj_{j'y'yy'uwv} \vdash E[p_{i+1}, p_{i'+1}] \), and therefore \( gj_{j'y'yy'uwv} \vdash \bot \).
Thus, we have \( \lambda j \lambda y (g) jy'y'uwv \vdash \text{ent}(j), j \in q_0 \rightarrow \bot \) if \( p_{i+1} = q_{j+1} \) and \( p_{i'+1} = q_{j'+1} \).
Therefore, \( \lambda j \lambda y (g) jy'y'uwv \vdash \forall j(\text{ent}(j), j \in q_0 \rightarrow p_{i+1} \neq q_{j+1}) \) if \( p_{i+1} = q_{j+1} \), thus:
\( (f'x) \lambda y (g) jy'y'uwv \vdash \bot \) if \( p_{i'+1} = q_{j'+1} \), thus:
\( \lambda j' \lambda y (f'x) \lambda y (g) jy'y'uwv \vdash \forall j'(\text{ent}(j'), j' \in q_0 \rightarrow p_{i'+1} \neq q_{j'+1}) \).
Therefore:
\( (f'x') \lambda j' \lambda y (f'x) \lambda y (g) jy'y'uwv \vdash \bot \).

ii) Follows immediately from (i) and \( \vdash \forall p \forall q \forall r (p \subset q \rightarrow p \subset q \land r) \) (lemma [1]).
Q.E.D.

The following lemma shows that we can build the algebra \( \mathcal{B} \) and the \( \mathcal{B} \)-model \( \mathcal{N} \).

**Lemma 63.** There exist six proof-like terms \( \alpha_0, \alpha_1, \alpha_2, \beta_0, \beta_1, \beta_2 \) such that:
\( \alpha_0 \vdash \forall p \forall q \forall r (C[p \land q \land r] \rightarrow C[p \land q \land r]) \); \( \alpha_1 \vdash \forall p (C[p] \rightarrow C[p \land 1]) \);
\[\alpha_2 \models \forall p \forall q (C[p \land q] \rightarrow C[q]) ; \ \beta_0 \models \forall p (C[p] \rightarrow C[p \land p]) ; \ \beta_1 \models \forall p \forall q (C[p \land q] \rightarrow C[q \land p]) ; \ \beta_2 \models \forall p \forall q \forall r \forall s (C[(p \land q) \land r] \land s) \rightarrow C[(p \land (q \land r)) \land s]).\]

We only show the first case. By lemma \([\text{II}2](i)\), it suffices to find a proof-like term:
\[\theta \models \forall p \forall q \forall r (p \land (q \land r) \subset (p \land q) \land r).\]
Thus, we suppose:
\[y \models i \in (p \land (q \land r))_0 ; u \models \forall j (\text{ent}(j), j \in ((p \land q) \land r)_0 \rightarrow (p \land (q \land r))_{j+1} \neq ((p \land q) \land r)_{j+1}).\]

There are three cases:

1. \(i = 2i'\); then, we have \(y \models i' \in p_0\). We make \(j = 2i = 4i'\), therefore:
   \[u \models \text{ent}(2i), i' \in p_0 \rightarrow p_{i'+1} \neq p_{i'+1}\]. Thus, we have:
   \[(u)(d_0)\overline{i}y \models \bot.\]

2. \(i = 4i' + 1\); then, we have \(y \models i' \in q_0\). We make \(j = i + 2 = 4i' + 3\), thus:
   \[u \models \text{ent}(i + 2), i' \in q_0 \rightarrow q_{i'+1} \neq q_{i'+1}\]. Thus, we have:
   \[(u)(\sigma)^2\lambda y \models \bot.\]

3. \(i = 4i' + 3\); then, we have \(y \models i' \in r_0\). We make \(j = i - 3 = 4i'\), thus:
   \[u \models \text{ent}(i - 3), i' \in r_0 \rightarrow r_{i'+1} \neq r_{i'+1}\]. Therefore, we have:
   \[(u)(p)^3\lambda y \models \bot (p \text{ is the program for the predecessor}).\]

Thus, we put \(\theta = \exists ! \lambda \exists ! \lambda (((e_4 \lambda \lambda \lambda \lambda \lambda (u)(d_0)\delta y) ((u)(\sigma)^2 i) y)((u)(p)^3 i) y)\), where \(e_4\) is defined by its execution rule:
\[e_4 * \hat{z} * \xi * \eta * \zeta * \pi \rightarrow \xi * \pi \text{ (resp. } \eta * \pi, \zeta * \pi) \text{ if } i = 4i' \text{ (resp. } 4i' + 1, 4i' + 3)\.\]

Q.E.D.

We now show the:

**Theorem 64.**
The forcing structure \(\{C, \land, 1\}\) satisfies the countable downward chain condition in \(\mathcal{M}\).

The hypothesis of the c.d.c. are:
\[H_0 \equiv \forall n \exists p \mathcal{X}(n, p) ; \]
\[H_1 \equiv \forall n \exists \exists int \exists \forall \exists q \{\mathcal{X}(n, p), \mathcal{X}(n, q) \rightarrow p = q\} ; \]
\[H_2 \equiv \forall n \exists \exists int \exists \forall \exists q \forall \mathcal{X}(n, p), \mathcal{X}(sn, q) \rightarrow q \subseteq p\] ;
\[H_3 \equiv \forall n \exists \exists int \exists \forall \exists \mathcal{X}(n, p) \rightarrow C[p]).\]
Moreover, by theorem \([\text{II}1]\), we have a binary function \(f : P^2 \rightarrow P\) such that:
\[\forall \exists \exists int \exists \exists \exists int (\exists p \mathcal{X}(n, p) \rightarrow \exists k \exists \mathcal{X}(n, f(n, k))\).

Therefore, by \(H_0\), we can also use the hypothesis:
\[H'_0 \equiv \forall n \exists \exists int \exists \exists \mathcal{X}(n, f(n, k))\].
Let us put \(\overline{H} = \{H_0, H'_0, H_1, H_2, H_3\}\) and \(\overline{H}_* = \{H_0, H'_0, H_1, H_2\}.

**Lemma 65.**
\[\overline{H} \models \forall n \exists \exists \exists int (\forall \exists \exists \exists int (\mathcal{X}(m, p), \mathcal{X}(n, q) \rightarrow C[p \land q])).\]

We show \(\forall n \exists \exists \exists int (\mathcal{X}(m, p), \mathcal{X}(m + n, q) \rightarrow q \subseteq p)\) by recurrence on \(n\). For \(n = 0\), this follows from \(H_1, H_3\). For the recurrence step, we use \(H_2\).

Thus, we have \(\forall p \forall q \forall e \forall m \exists \exists \exists int (\mathcal{X}(m, p), \mathcal{X}(n, q) \rightarrow p \subseteq q \lor q \subseteq p)\).

From \(p \subseteq q\), we deduce \(C[p \land p] \rightarrow C[q \land p]\), and the result follows, by \(H_3\) and \(C[p] \rightarrow C[p \land p]\).

Q.E.D.

We define the wanted limit \(h\) by defining \(h_0\) and \(h_{m+1}\) for each \(m \in \mathbb{N}\).

For \(m = (i, n, k)\) (that is \((i, (n, k))\)), we put:
\[\|m \in e_0\| = \|\mathcal{X}(n, f(n, k)) \land i \in (f(n, k))_0\|;\]
then \(h_{m+1} = (f(n, k))_{i+1}\).

Intuitively, \(\mathcal{X}\) defines a sequence of countable sets, and \(h\) is the union of these sets.
We define now two functions on $P$.

By lemma 52(ii), it suffices to show $X(n, p) \rightarrow p \subseteq h$, that is:

$X(n, p), i \in p_0 \forall m^\text{ent}(m \in h_0 \rightarrow h_{m+1} \neq p_{i+1}) \rightarrow \bot$, for $n, i \in \mathbb{N}$.

We fix $k \in \mathbb{N}$ and we put $m = (i, n, k)$. By definition of $h$, it suffices to show:

$X(n, p), i \in p_0 \forall k^\text{ent}(X(n, f(n, k)), i \in (f(n, k), i+1 \neq p_{i+1}) \rightarrow \bot$.

Now, from $H_1, X(n, p), X(n, f(n, k))$, we deduce $f(n, k) = p$ and therefore:

$(f(n, k))_0 = p_0$ and $(f(n, k))_{i+1} = p_{i+1}$. Thus, it remains to show:

$X(n, p), i \in p_0 \forall k^\text{ent}(X(n, f(n, k)), i \in p_0 \rightarrow p_{i+1} \neq p_{i+1}) \rightarrow \bot$.

But this formula follows immediately from $H_0$.

Proof of $\mathcal{H} \vdash C[h]$.

We must show $C[u]$, that is $m \in h_0, m' \in h_0 \rightarrow E[h_{m+1}, h_{m'+1}]$. Now, we have:

$m = (i, n, k) ; \|m \epsilon h_0\| = \|X(n, f(n, k)) \wedge i \epsilon (f(n, k))_0\| ; h_{m+1} = (f(n, k))_{i+1} ;$

$m' = (i', n', k') ; \|m' \epsilon h_0\| = \|X(n', f(n', k')) \wedge i' \epsilon (f(n', k'))_0\| ; h_{m'+1} = (f(n', k'))_{i'+1}$.

From $X(n, f(n, k)), X(n', f(n', k'))$, it follows that:

$C[u] \equiv u = f(n, k) \wedge f(n', k')$ (lemma 53). Therefore, we have:

$\|i \epsilon (f(n, k))_0\| = \|2i \epsilon u\| ; \|i' \epsilon (f(n', k'))_0\| = \|2i' + 1 \epsilon u\| ;$

$h_{m+1} = u_{2i+1} ; h_{m'+1} = u_{2i'+2}$.

From $C[u]$, we deduce $E(u_{2i+1}, u_{2i'+2})$, that is $E[h_{m+1}, h_{m'+1}]$.

This completes the proof of theorem 34.

Q.E.D.

The well ordering on $P(\mathbb{N})$

In the model $\mathcal{N}$, we define the unary predicate $G(x) \equiv \exists p \exists i^\text{ent}\{\neg \mathcal{J}(p), i \epsilon p_0, x = p_{i+1}\}$.

Lemma 66. $\mathcal{H} \vdash G(x), G(y) \rightarrow \mathcal{H}[x, y]$.

We must show $\mathcal{H} \vdash \neg \mathcal{J}(p), \neg \mathcal{J}(q), i \epsilon p_0, x = p_{i+1}, j \epsilon q_0, y = q_{j+1} \rightarrow E[x, y]$, that is:

$\mathcal{H} \vdash \neg \mathcal{J}(p), \neg \mathcal{J}(q), i \epsilon p_0, j \epsilon q_0 \rightarrow E[p_{i+1}, q_{j+1}]$.

By theorem 33(ii) and (iii), we have $\mathcal{H} \vdash \neg \mathcal{J}(p), \neg \mathcal{J}(q) \rightarrow C[p \wedge q]$.

Therefore, it is sufficient to show that $\mathcal{H} \vdash C[p \wedge q], i \epsilon p_0, j \epsilon q_0 \rightarrow E[p_{i+1}, q_{j+1}]$.

We show below that we have $I \vdash C[p \wedge q], i \epsilon p_0, j \epsilon q_0 \rightarrow E[p_{i+1}, q_{j+1}]$. Since this is a first order formula, this gives the desired result, by theorem 31.

Indeed, we have:

$p_{i+1} = (p \wedge q)_{2i+1} ; q_{j+1} = (p \wedge q)_{2j+2} ;$

$\|i \epsilon p_0\| = \|2i \epsilon (p \wedge q)_0\| ; \|j \epsilon q_0\| = \|2j + 1 \epsilon (p \wedge q)_0\|.$

Therefore, it remains to show:

$I \vdash C[p \wedge q], 2i \epsilon (p \wedge q)_0, 2j + 1 \epsilon (p \wedge q)_0 \rightarrow E[(p \wedge q)_{2i+1}, (p \wedge q)_{2j+2}]$

which is obvious, by definition of $C[p \wedge q]$.

Q.E.D.

Lemma 66 shows that $\prec$ is a total relation on $G$. But, moreover, $\prec$ is a well founded relation in $\mathcal{N}$. Therefore, we have:

$\mathcal{H} \vdash G$ is well ordered by $\prec$.

We define now two functions on $P$:

- a unary function $\delta : P \rightarrow P$ by putting $\|i \epsilon \delta(p)_0\| = \|i + 1 \epsilon p_0\| ; \delta(p)_0 = p_{i+2}$.
- a binary function $\phi : P^2 \rightarrow P$ by putting:
∥0 ∈ φ(p, q)0∥ = ∅ ; ∥i + 1 ∈ φ(p, q)0∥ = ∥i ∈ p0∥; 
φ(p, q)0 = q ; φ(p, q)i+2 = p(i+1) for every i ∈ N.
Therefore, we have δ(φ(p, q)) = p and φ(p, q)1 = q for all p, q ∈ P and thus:
I ∥→ ∀pφq(δ(φ(p, q)) = p) ; I ∥→ ∀pφq(δ(φ(p, q)) = p) ;
I ∥→ ∀pφq(φ(p, q)1 = q) ; I ∥→ ∀pφq(φ(p, q)1 = q).

Intuitively, δ(p) defines the set we obtain by removing p1 from the set associated with p ;
φ(p, q) defines the set we obtain by adding q to the set associated with p.

Lemma 67. If p, q ∈ P, there exists q′ ∈ P such that δ(q′) = q and p1 < q′ for every i ∈ N.

For each a ∈ P, we have δ(φ(q, a)) = q. But the application a → φ(q, a) is obviously injective, since φ(q, a)1 = a. Thus, the set {φ(q, a); a ∈ P} is of cardinal 2^{ℵ0}. Now, by hypothesis on <, every proper initial segment of P, for the well ordering <, is of cardinal < 2^{ℵ0}. Thus, there exists some a0 ∈ P such that p1 < φ(q, a0) for every i ∈ N. Then, it suffices to put q′ = φ(q, a0).
Q.E.D.

Therefore, we can define a binary function ψ : P^2 → P such that we have:
δ(ψ(p, q)) = q and (p1 < ψ(p, q)) = 1 for all p, q ∈ P and i ∈ N. Thus, we have:
I ∥→ ∀pφq(δ(ψ(p, q)) = q) ; I ∥→ ∀pφq(δ(ψ(p, q)) = q).
KI ∥→ ∀pφq|ιent(p, ψ(p, q)) ; KI ∥→ ∀pφq|ιent(p, ψ(p, q)).

Lemma 68. We have ∥→ ∀q∃x{G(x), δ(x) = q}.

This is written as ∥→ ∀q[∀x∀pφq|ιent(δ(x) = q, i ∈ p0, x = p1 → J(p)) → ⊥] or else:
|→ ∀q[∀pφq|ιent(i ∈ p0, δ(p1) = q → J(p)) → ⊥].

By making i = 0, it is sufficient to show:
(1) ∥→ ∀q[∀p(0 ∈ p0, δ(p1) = q → J(p)) → ⊥].

By replacing p with φ(p, ψ(p, q)) in (1), we see that it remains to show:
∥→ ∀q¬∀p J(φ(p, ψ(p, q))).

Lemma 69. ∥→ ∀pφq[C[p] → C[φ(p, ψ(p, q))]].

We have C[p] ≡ ∀i|ιent j|ιent(i ∈ r0, j ∈ r0 → E[r1+i, r1+j+1]). Therefore, to show that
∥→ C[p] → C[r] it suffices to show:
(1) ∥→ C[p] → ∀i|ιent j|ιent(i + 1 ∈ r0, j + 1 ∈ r0 → E[r1+i+1, r1+j+2]) and
(2) ∥→ C[p] → ∀j|ιent(0 ∈ r0, j + 1 ∈ r0 → E[r1+i, r1+j+2]).

We apply this remark by putting r = φ(p, ψ(p, q)). Then (1) is written as ∥→ C[p] → C[p]
since ∥i + 1 ∈ r0∥ = ∥i ∈ p0∥ and r1+i+1 = p1+i and the same for j.

Thus, it suffices to show (2), that is:
∥→ C[p] → ∀j|ιent(0 ∈ φ(p, ψ(p, q)), j + 1 ∈ φ(p, ψ(p, q)) → E[φ(p, ψ(p, q)), j+1]).

But, we have I ∥→ ∀pφq(0 ∈ φ(p, q)) ; I ∥→ ∀pφq(j ∈ p0 → j + 1 ∈ φ(p, ψ(p, q))) ;
I ∥→ ∀pφq(φ(p, ψ(p, q)), j = ψ(p, q)) ; I ∥→ ∀pφq(φ(p, ψ(p, q))j+2 = p1+j).

Therefore, it remains to show:
∥→ C[p] → ∀j|ιent(j ∈ p0 → E[ψ(p, q), p1+j])
which is trivial, since we have KI ∥→ ∀pφq|ιent(p1+j < ψ(p, q)).
Q.E.D.

48
Lemma 70. $\lambda i \lambda x \lambda y ((y)(\sigma)i)x \models \forall p \forall q (p \subseteq \phi(p,q))$.

This is written as:

$\lambda i \lambda x \lambda y ((y)(\sigma)i)x \models \forall i (\text{ent}(i), i \in p_0, \forall j (\text{ent}(j), j \in \phi(p,q)_0 \rightarrow \phi(p,q)_{j+1} \neq p_{i+1}) \rightarrow \bot)$

which is immediate, by making $j = i + 1$.

Q.E.D.

We have $\models p \subseteq \phi(p, \psi(p,q))$ (lemma 70), and it follows that:

$\models \phi(p, \psi(p,q)) \subseteq p$ (lemma 62ii), and thus $\models C[p, \psi(p,q)] \rightarrow C[p \land \phi(p, \psi(p,q))]$.

Therefore, by lemma 68, we have:

$\models \forall p \forall q (C[p] \rightarrow C[p \land \phi(p, \psi(p,q))])$. Since this is a first order formula, we have, by theorem 31:

$\models \forall p \forall q (C[p] \rightarrow C[p \land \phi(p, \psi(p,q))])$

and therefore, by theorem 33(ii):

$\models \forall p \forall q (\neg C[p \land \phi(p, \psi(p,q))] \rightarrow J(p))$.

Then, we apply theorem 34 which gives:

$\models \forall q \forall \neg \forall p J(\phi(p, \psi(p,q)))$

which is the desired result.

Q.E.D.

Theorem 71. The following formulas are realized in $\mathcal{N}$:

i) There exists a well ordering on the set of individuals.

ii) There exists a well ordering on the power set of $\mathbb{N}$.

i) Lemma 68 shows that, in $\mathcal{N}$, the function $\delta$ is a surjection from $\mathcal{G}$ onto the set $P$ of individuals. But, we have seen that the formula: “$\mathcal{G}$ is well ordered by $\triangleleft$” is realized in $\mathcal{N}$.

ii) By theorems 38 and 64, the following formula is realized in $\mathcal{N}$: “Every subset of $\mathbb{N}$ is represented by an individual”. Hence the result, by (i).

Q.E.D.

Theorem 71(ii) enables us to transform into a program any proof of a formula of second order arithmetic, which uses the existence of a well ordering on $\mathbb{R}$. The method is the same as the one explained above for the ultrafilter axiom.

References


http://www.pps.jussieu.fr/krivine/articles/zf_epi.pdf

http://hal.archives-ouvertes.fr/hal-00154478
http://www.pps.jussieu.fr/krivine/articles/quote.pdf

In *Interactive models of computation and program behaviour.*
http://hal.archives-ouvertes.fr/hal-00154500
Version mise à jour à :
http://www.pps.jussieu.fr/krivine/articles/Luminy04.pdf

Geocal’06 (fevrier 2006 - Marseille); Mathlogaps’07 (juin 2007 - Aussois).
http://cel.archives-ouvertes.fr/cel-00154509
Version mise à jour à :
http://www.pps.jussieu.fr/krivine/articles/Mathlog07.pdf

http://hal.archives-ouvertes.fr/hal-00321410

***********