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A Mathematical Model of CPU

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Summary. This paper is based on a previous work of the first author [15] in which a mathematical model of the computer has been presented. The model deals with random access memory, such as RASP of C. C. Elgot and A. Robinson [13], however, it allows for a more realistic modeling of real computers. This new model of computers has been named by the author (Y. Nakamura, [15]) Architecture Model for Instructions (AMI). It is more developed than previous models, both in the description of hardware (e.g., the concept of the program counter, the structure of memory) as well as in the description of instructions (instruction codes, addresses). The structure of AMI over an arbitrary collection of mathematical domains N consists of:

- a non-empty set of objects,
- the instruction counter,
- a non-empty set of objects called instruction locations,
- a non-empty set of instruction codes,
- an instruction code for halting,
- a set of instructions that are ordered pairs with the first element being an instruction code and the second a finite sequence in which members are either objects of the AMI or elements of one of the domains included in N,
- a function that assigns to every object of AMI its kind that is either *an instruction* or *an instruction location* or an element of N,
- a function that assigns to every instruction its execution that is again a function mapping states of AMI into the set of states.

By a state of AMI we mean a function that assigns to every object of AMI an element of the same kind. In this paper we develop the theory of AMI. Some properties of AMI are introduced ensuring it to have some properties of real computers:

- a von Neumann AMI, in which only addresses to instruction locations are stored in the program counter,
- data oriented, those in which instructions cannot be stored in data locations,
- halting, in which the execution of the halt instruction is the identity mapping of the states of an AMI,
- steady programmed, the condition in which the contents of the instruction locations do not change during execution,
- definite, a property in which only instructions may be stored in instruction locations.

We present an example of AMI called a Small Concrete Model which has been constructed in [15]. The Small Concrete Model has only one kind of data: integers and a set of instructions, small but sufficient to cope with integers.

MML Identifier: `AMI_1`.

WWW: http://mizar.org/JFM/Vol4/ami_1.html

The articles [18], [22], [8], [14], [2], [23], [5], [21], [6], [17], [12], [20], [1], [9], [19], [16], [10], [3], [11], [4], and [7] provide the notation and terminology for this paper.

1. Preliminaries

The following three propositions are true:

(1) $\mathbb{N} \neq \mathbb{Z}$.

(2) For all sets a, b holds $1 \neq \langle a, b \rangle$.

(3) For all sets a, b holds $2 \neq \langle a, b \rangle$.

Let X be a set. One can verify that X^X is non empty.

We now state two propositions:

(4) For all sets a, b, c, d and for every function g such that $\operatorname{dom} g = \{a, b\}$ and $g(a) = c$ and $g(b) = d$ holds $g = [a \longmapsto c, b \longmapsto d]$.

(5) For all sets a, b, c, d such that $a \neq b$ holds $\prod [a \longmapsto \{c\}, b \longmapsto \{d\}] = \{[a \longmapsto c, b \longmapsto d]\}$.

Let I_1 be a set. We say that I_1 has non empty elements if and only if:

(Def. 1) $\emptyset \notin I_1$.

Let us mention that there exists a set which is non empty and has non empty elements.

Let A be a non empty set. One can check that $\{A\}$ has non empty elements. Let B be a non empty set. Note that $\{A, B\}$ has non empty elements.

Let A, B be sets with non empty elements. Note that $A \cup B$ has non empty elements.

2. General concepts

In the sequel N denotes a set with non empty elements.

Let N be a set. We introduce AMI's over N which are systems

$\langle$ objects, an instruction counter, instruction locations, instruction codes, instructions, a object kind, a execution $\rangle$,

where the objects constitute a non empty set, the instruction counter is an element of the objects, the instruction locations constitute a non empty subset of the objects, the instruction codes constitute a non empty set, the instructions constitute a non empty subset of $\vdots$the instruction codes, $(\bigcup N \cup$ the objects$)^* \vdots$, the object kind is a function from the objects into $N \cup \{$the instructions, the instruction locations $\}$, and the execution is a function from the instructions into $(\prod$ the object kind$)^{\prod \text{ the object kind}}$.

Let N be a set and let S be an AMI over N. An object of S is an element of the objects of S. An instruction-location of S is an element of the instruction locations of S.

Let N be a set and let S be an AMI over N.

(Def. 2) An element of the instructions of S is said to be an instruction of S.

The functor $\mathbf{IC}_S$ yields an object of S and is defined by:

(Def. 3) $\mathbf{IC}_S =$ the instruction counter of S.

Let N be a set, let S be an AMI over N, and let o be an object of S. The functor ObjectKind(o) yielding an element of $N \cup \{$the instructions of S, the instruction locations of S $\}$ is defined by:

(Def. 4) ObjectKind(o) = (the object kind of S)(o).

Let A, B be sets and let f be a function from A into B. Note that $\prod f$ is functional.

Let A be a set, let B be a set with non empty elements, and let f be a function from A into B. Observe that $\prod f$ is non empty.

Let P be a functional set. Note that every element of P is function-like and relation-like.

Let N be a set and let S be an AMI over N. A state of S is an element of $\prod$ (the object kind of S).

Let N be a set with non empty elements, let S be an AMI over N, let I be an instruction of S, and let s be a state of S. The functor Exec(I, s) yields a state of S and is defined as follows:

(Def. 5) Exec(I, s) = (the execution of S)$(I)(s)$.

Let N be a set. The functor $\mathbf{AMI}_{\mathrm{t}}$ yielding a strict AMI over N is defined by the conditions (Def. 6).

(Def. 6) The objects of $(\mathbf{AMI}_{\mathrm{t}}) = \{0, 1\}$ and the instruction counter of $(\mathbf{AMI}_{\mathrm{t}}) = 0$ and the instruction locations of $(\mathbf{AMI}_{\mathrm{t}}) = \{1\}$ and the instruction codes of $(\mathbf{AMI}_{\mathrm{t}}) = \{0\}$ and the instructions of $(\mathbf{AMI}_{\mathrm{t}}) = \{\langle\langle 0, \varepsilon\rangle\rangle\}$ and the object kind of $(\mathbf{AMI}_{\mathrm{t}}) = [0 \longmapsto \{1\}, 1 \longmapsto \{\langle\langle 0, \varepsilon\rangle\rangle\}]$ and the execution of $(\mathbf{AMI}_{\mathrm{t}}) = \{\langle\langle 0, \varepsilon\rangle\rangle\} \longmapsto \mathrm{id}_{\prod[0 \longmapsto \{1\}, 1 \longmapsto \{\langle\langle 0, \varepsilon\rangle\rangle\}]}$.

Let us consider N, let S be an AMI over N, and let I be an instruction of S. We say that I is halting if and only if:

(Def. 7) For every state s of S holds Exec$(I, s) = s$.

Let us consider N and let S be an AMI over N. We say that S is halting if and only if:

(Def. 8) There exists an instruction I of S such that I is halting and for every instruction J of S such that J is halting holds $I = J$.

One can prove the following proposition

(6) $\mathbf{AMI}_{\mathrm{t}}$ is halting.

Let us consider N. Note that $\mathbf{AMI}_{\mathrm{t}}$ is halting.

Let us consider N. Note that there exists an AMI over N which is halting.

Let us consider N and let S be a halting AMI over N. The functor $\mathbf{halt}_S$ yields an instruction of S and is defined by:

(Def. 9) There exists an instruction I of S such that I is halting and $\mathbf{halt}_S = I$.

Let us consider N and let S be a halting AMI over N. Note that $\mathbf{halt}_S$ is halting.

Let N be a set and let I_1 be an AMI over N. We say that I_1 is von Neumann if and only if:

(Def. 10) ObjectKind$(\mathbf{IC}_{(I_1)})$ = the instruction locations of I_1.

Let N be a set and let I_1 be an AMI over N. We say that I_1 is data-oriented if and only if:

(Def. 11) (The object kind of $I_1)^{-1}(\{$the instructions of $I_1\ \}) \subseteq$ the instruction locations of I_1.

Let N be a set with non empty elements and let I_1 be an AMI over N. We say that I_1 is steady-programmed if and only if:

(Def. 12) For every state s of I_1 and for every instruction i of I_1 and for every instruction-location l of I_1 holds $(\mathrm{Exec}(i, s))(l) = s(l)$.

Let N be a set and let I_1 be an AMI over N. We say that I_1 is definite if and only if:

(Def. 13) For every instruction-location l of I_1 holds ObjectKind(l) = the instructions of I_1.

In the sequel E is a set.

The following propositions are true:

(7) $\mathbf{AMI}_{\mathrm{t}}$ is von Neumann.

(8) $\mathbf{AMI}_{\mathrm{t}}$ is data-oriented.

(9) For all states s_1, s_2 of $\mathbf{AMI}_{\mathrm{t}}$ holds $s_1 = s_2$.

(10) $\mathbf{AMI}_{\mathrm{t}}$ is steady-programmed.

(11) $\mathbf{AMI}_{\mathrm{t}}$ is definite.

Let E be a set. Observe that $\mathbf{AMI}_{\mathrm{t}}$ is data-oriented.

Let E be a set. One can check that $\mathbf{AMI}_{\mathrm{t}}$ is von Neumann and definite.

Let N be a set with non empty elements. Note that $\mathbf{AMI}_{\mathrm{t}}$ is steady-programmed.

Let E be a set. One can check that there exists an AMI over E which is data-oriented and strict.

Let M be a set. Note that there exists an AMI over M which is von Neumann, data-oriented, definite, and strict.

Let us consider N. Observe that there exists an AMI over N which is von Neumann, data-oriented, halting, steady-programmed, definite, and strict.

Let N be a set with non empty elements, let S be a von Neumann AMI over N, and let s be a state of S. The functor $\mathbf{IC}_s$ yielding an instruction-location of S is defined by:

(Def. 14) $\mathbf{IC}_s = s(\mathbf{IC}_S)$.

3. Preliminaries

We adopt the following convention: x, y, z, A, B, C denote sets, f, g, h denote functions, and i, j, k denote natural numbers.

One can prove the following propositions:

(12) A misses $B \setminus C$ iff B misses $A \setminus C$.

(13) For every function f holds $\pi_1(\operatorname{dom} f \times \operatorname{rng} f)^{\circ} f = \operatorname{dom} f$.

(14) If $f \approx g$ and $\langle x, y\rangle \in f$ and $\langle x, z\rangle \in g$, then $y = z$.

(15) Suppose for every x such that $x \in A$ holds x is a function and for all functions f, g such that $f \in A$ and $g \in A$ holds $f \approx g$. Then $\bigcup A$ is a function.

(16) If $\operatorname{dom} f \subseteq A \cup B$, then $f{\restriction}A +\cdot f{\restriction}B = f$.

(17) $\operatorname{dom} f \subseteq \operatorname{dom}(f +\cdot g)$ and $\operatorname{dom} g \subseteq \operatorname{dom}(f +\cdot g)$.

(18) For all sets x_1, x_2, y_1, y_2 holds $[x_1 \longmapsto y_1, x_2 \longmapsto y_2] = (x_1 \mathrel{\dot{\longmapsto}} y_1) +\cdot (x_2 \mathrel{\dot{\longmapsto}} y_2)$.

(19) For all x, y holds $x \mathrel{\dot{\longmapsto}} y = \{\langle x, y\rangle\}$.

(20) For all sets a, b, c holds $[a \longmapsto b, a \longmapsto c] = a \mathrel{\dot{\longmapsto}} c$.

(21) For every function f holds $\operatorname{dom} f$ is finite iff f is finite.

(22) If $x \in \prod f$, then x is a function.

4. Superproducts

Let f be a function. The functor $\prod^{\cdot} f$ yields a set and is defined by:

(Def. 15) $x \in \prod^{\cdot} f$ iff there exists g such that $x = g$ and $\operatorname{dom} g \subseteq \operatorname{dom} f$ and for every x such that $x \in \operatorname{dom} g$ holds $g(x) \in f(x)$.

Let f be a function. One can check that $\prod^{\cdot} f$ is functional and non empty.

One can prove the following propositions:

(23) $x \in \prod^{\cdot} f$ iff there exists g such that $x = g$ and $\operatorname{dom} g \subseteq \operatorname{dom} f$ and for every x such that $x \in \operatorname{dom} g$ holds $g(x) \in f(x)$.

(24) If $\operatorname{dom} g \subseteq \operatorname{dom} f$ and for every x such that $x \in \operatorname{dom} g$ holds $g(x) \in f(x)$, then $g \in \prod^{\cdot} f$.

(25) If $g \in \prod^{\cdot} f$, then $\operatorname{dom} g \subseteq \operatorname{dom} f$ and for every x such that $x \in \operatorname{dom} g$ holds $g(x) \in f(x)$.

(26) $\square \in \prod^{\cdot} f$.

(27) $\prod f \subseteq \prod^{\cdot} f$.

(28) If $x \in \prod^{\cdot} f$, then x is a partial function from $\operatorname{dom} f$ to $\bigcup \operatorname{rng} f$.

(29) If $g \in \prod f$ and $h \in \prod^{\cdot} f$, then $g +\cdot h \in \prod f$.

(30) If $\prod f \neq \emptyset$, then $g \in \prod^{\cdot} f$ iff there exists h such that $h \in \prod f$ and $g \leq h$.

(31) $\prod^{\cdot} f \subseteq \operatorname{dom} f \mathrel{\dot{\to}} \bigcup \operatorname{rng} f$.

(32) If $f \subseteq g$, then $\prod^{\cdot} f \subseteq \prod^{\cdot} g$.

(33) $\prod^{\cdot} \square = \{\square\}$.

(34) $A \mathrel{\dot{\to}} B = \prod^{\cdot} (A \longmapsto B)$.

(35) For all non empty sets A, B and for every function f from A into B holds $\prod^{\cdot} f = \prod^{\cdot} (f \restriction \{x; x \text{ ranges over elements of } A\colon f(x) \neq \emptyset\})$.

(36) If $x \in \operatorname{dom} f$ and $y \in f(x)$, then $x \mathrel{\dot{\longmapsto}} y \in \prod^{\cdot} f$.

(37) $\prod^{\cdot} f = \{\square\}$ iff for every x such that $x \in \operatorname{dom} f$ holds $f(x) = \emptyset$.

(38) If $A \subseteq \prod^{\cdot} f$ and for all functions h_1, h_2 such that $h_1 \in A$ and $h_2 \in A$ holds $h_1 \approx h_2$, then $\bigcup A \in \prod^{\cdot} f$.

(39) If $g \approx h$ and $g \in \prod^{\cdot} f$ and $h \in \prod^{\cdot} f$, then $g \cup h \in \prod^{\cdot} f$.

(40) If $g \subseteq h$ and $h \in \prod^{\cdot} f$, then $g \in \prod^{\cdot} f$.

(41) If $g \in \prod^{\cdot} f$, then $g \restriction A \in \prod^{\cdot} f$.

(42) If $g \in \prod^{\cdot} f$, then $g \restriction A \in \prod^{\cdot} (f \restriction A)$.

(43) If $h \in \prod^{\cdot} (f +\cdot g)$, then there exist functions f', g' such that $f' \in \prod^{\cdot} f$ and $g' \in \prod^{\cdot} g$ and $h = f' +\cdot g'$.

(44) For all functions f', g' such that $\operatorname{dom} g$ misses $\operatorname{dom} f' \setminus \operatorname{dom} g'$ and $f' \in \prod^{\cdot} f$ and $g' \in \prod^{\cdot} g$ holds $f' +\cdot g' \in \prod^{\cdot} (f +\cdot g)$.

(45) For all functions f', g' such that $\operatorname{dom} f'$ misses $\operatorname{dom} g \setminus \operatorname{dom} g'$ and $f' \in \prod^{\cdot} f$ and $g' \in \prod^{\cdot} g$ holds $f' +\cdot g' \in \prod^{\cdot} (f +\cdot g)$.

(46) If $g \in \prod^{\cdot} f$ and $h \in \prod^{\cdot} f$, then $g +\cdot h \in \prod^{\cdot} f$.

(47) For all sets x_1, x_2, y_1, y_2 such that $x_1 \in \operatorname{dom} f$ and $y_1 \in f(x_1)$ and $x_2 \in \operatorname{dom} f$ and $y_2 \in f(x_2)$ holds $[x_1 \longmapsto y_1, x_2 \longmapsto y_2] \in \prod^{\cdot} f$.

5. General theory

Let us consider N, let S be a von Neumann definite AMI over N, and let s be a state of S. The functor CurInstr(s) yields an instruction of S and is defined by:

(Def. 16) CurInstr(s) = $s(\mathbf{IC}_s)$.

Let us consider N, let S be a von Neumann definite AMI over N, and let s be a state of S. The functor Following(s) yields a state of S and is defined as follows:

(Def. 17) Following(s) = Exec(CurInstr(s), s).

Let us consider N, let S be a von Neumann definite AMI over N, and let s be a state of S. The functor Computation(s) yielding a function from $\mathbb{N}$ into $\prod$ (the object kind of S) is defined by:

(Def. 18) (Computation(s))(0) = s and for every i holds (Computation(s))(i + 1) = Following((Computation(s))(i)).

Let us consider N, let S be an AMI over N, let f be a function from $\mathbb{N}$ into $\prod$ (the object kind of S), and let us consider k. Then $f(k)$ is a state of S.

Let us consider N, let S be a halting von Neumann definite AMI over N, and let I_1 be a state of S. We say that I_1 is halting if and only if:

(Def. 19) There exists k such that CurInstr((Computation(I_1))(k)) = $\mathbf{halt}_S$.

Let N be a set and let I_1 be an AMI over N. We say that I_1 is realistic if and only if:

(Def. 20) The instructions of $I_1 \neq$ the instruction locations of I_1.

Next we state the proposition

(48) Let S be a von Neumann definite AMI over E. Suppose S is realistic. Then it is not true that there exists an instruction-location l of S such that $\mathbf{IC}_S = l$.

In the sequel S is a von Neumann definite AMI over N and s is a state of S.

Next we state four propositions:

(49) (Computation(s))(0) = s.

(50) (Computation(s))(k + 1) = Following((Computation(s))(k)).

(51) For every k holds (Computation(s))(i+k) = (Computation((Computation(s))(i)))(k).

(52) Suppose $i \leq j$. Let given N, S be a halting von Neumann definite AMI over N, and s be a state of S. If CurInstr((Computation(s))(i)) = $\mathbf{halt}_S$, then (Computation(s))(j) = (Computation(s))(i).

Let us consider N, let S be a halting von Neumann definite AMI over N, and let s be a state of S. Let us assume that s is halting. The functor Result(s) yields a state of S and is defined by:

(Def. 21) There exists k such that Result(s) = (Computation(s))(k) and CurInstr(Result(s)) = $\mathbf{halt}_S$.

One can prove the following proposition

(53) Let S be a steady-programmed von Neumann definite AMI over N, s be a state of S, and i be an instruction-location of S. Then $s(i)$ = (Following(s))(i).

Let us consider N, let S be a definite AMI over N, let s be a state of S, and let l be an instruction-location of S. Then $s(l)$ is an instruction of S.

The following propositions are true:

(54) Let S be a steady-programmed von Neumann definite AMI over N, s be a state of S, i be an instruction-location of S, and given k. Then $s(i) = (\mathrm{Computation}(s))(k)(i)$.

(55) Let S be a steady-programmed von Neumann definite AMI over N and s be a state of S. Then $(\mathrm{Computation}(s))(k+1) = \mathrm{Exec}(s(\mathbf{IC}_{(\mathrm{Computation}(s))(k)}), (\mathrm{Computation}(s))(k))$.

(56) Let S be a steady-programmed von Neumann halting definite AMI over N, s be a state of S, and given k. If $s(\mathbf{IC}_{(\mathrm{Computation}(s))(k)}) = \mathbf{halt}_S$, then $\mathrm{Result}(s) = (\mathrm{Computation}(s))(k)$.

(57) Let S be a steady-programmed von Neumann halting definite AMI over N and s be a state of S. If there exists k such that $s(\mathbf{IC}_{(\mathrm{Computation}(s))(k)}) = \mathbf{halt}_S$, then for every i holds $\mathrm{Result}(s) = \mathrm{Result}((\mathrm{Computation}(s))(i))$.

Let us consider N, let S be an AMI over N, and let o be an object of S. Note that $\mathrm{ObjectKind}(o)$ is non empty.

6. Finite substates

Let N be a set and let S be an AMI over N. The functor $\mathrm{FinPartSt}(S)$ yields a subset of $\prod^{\cdot}$ (the object kind of S) and is defined by:

(Def. 22) $\mathrm{FinPartSt}(S) = \{p; p \text{ ranges over elements of } \prod^{\cdot} \text{ (the object kind of } S\text{)}: p \text{ is finite}\}$.

Let N be a set and let S be an AMI over N. An element of $\prod^{\cdot}$ (the object kind of S) is said to be a finite partial state of S if:

(Def. 23) It is finite.

Let us consider N, let S be a von Neumann definite AMI over N, and let I_1 be a finite partial state of S. We say that I_1 is autonomic if and only if:

(Def. 24) For all states s_1, s_2 of S such that $I_1 \subseteq s_1$ and $I_1 \subseteq s_2$ and for every i holds $(\mathrm{Computation}(s_1))(i) \restriction \mathrm{dom}\, I_1 = (\mathrm{Computation}(s_2))(i) \restriction \mathrm{dom}\, I_1$.

Let us consider N, let S be a halting von Neumann definite AMI over N, and let I_1 be a finite partial state of S. We say that I_1 is halting if and only if:

(Def. 25) For every state s of S such that $I_1 \subseteq s$ holds s is halting.

Let us consider N and let I_1 be a von Neumann definite AMI over N. We say that I_1 is programmable if and only if:

(Def. 26) There exists a finite partial state of I_1 which is non empty and autonomic.

We now state two propositions:

(58) Let S be a von Neumann definite AMI over N, A, B be sets, and l_1, l_2 be objects of S. Suppose $\mathrm{ObjectKind}(l_1) = A$ and $\mathrm{ObjectKind}(l_2) = B$. Let a be an element of A and b be an element of B. Then $[l_1 \longmapsto a, l_2 \longmapsto b]$ is a finite partial state of S.

(59) Let S be a von Neumann definite AMI over N, A be a set, and l_1 be an object of S. Suppose $\mathrm{ObjectKind}(l_1) = A$. Let a be an element of A. Then $l_1 \longmapsto a$ is a finite partial state of S.

Let us consider N, let S be a von Neumann definite AMI over N, let l_1 be an object of S, and let a be an element of $\mathrm{ObjectKind}(l_1)$. Then $l_1 \dot{\longmapsto} a$ is a finite partial state of S.

Let us consider N, let S be a von Neumann definite AMI over N, let l_1, l_2 be objects of S, let a be an element of $\mathrm{ObjectKind}(l_1)$, and let b be an element of $\mathrm{ObjectKind}(l_2)$. Then $[l_1 \longmapsto a, l_2 \longmapsto b]$ is a finite partial state of S.

Next we state two propositions:

(60) $\mathbf{AMI}_{\mathrm{t}}$ is realistic.

(61) $\mathbf{AMI}_{\mathrm{t}}$ is programmable.

Let us consider E. One can check that $\mathbf{AMI}_{\mathrm{t}}$ is realistic.

Let us consider N. Note that $\mathbf{AMI}_{\mathrm{t}}$ is programmable.

Let us consider E. Note that there exists an AMI over E which is data-oriented, realistic, and strict.

Let M be a set. Note that there exists an AMI over M which is data-oriented, realistic, strict, von Neumann, and definite.

Let us consider N. Note that there exists a von Neumann definite AMI over N which is data-oriented, halting, steady-programmed, realistic, programmable, and strict.

Next we state two propositions:

(62) Let S be an AMI over N, s be a state of S, and p be a finite partial state of S. Then $s \restriction \operatorname{dom} p$ is a finite partial state of S.

(63) For every set N and for every AMI S over N holds $\emptyset$ is a finite partial state of S.

Let us consider N and let S be a programmable von Neumann definite AMI over N. One can check that there exists a finite partial state of S which is non empty and autonomic.

Let N be a set, let S be an AMI over N, and let f, g be finite partial states of S. Then $f +\cdot g$ is a finite partial state of S.

7. Preprograms

The following four propositions are true:

(64) Let S be a halting realistic von Neumann definite AMI over N, l_3 be an instruction-location of S, and l be an element of ObjectKind($\mathbf{IC}_S$). Suppose $l = l_3$. Let h be an element of ObjectKind(l_3). If $h = \mathbf{halt}_S$, then for every state s of S such that $[\mathbf{IC}_S \longmapsto l, l_3 \longmapsto h] \subseteq s$ holds CurInstr(s) $= \mathbf{halt}_S$.

(65) Let S be a halting realistic von Neumann definite AMI over N, l_3 be an instruction-location of S, and l be an element of ObjectKind($\mathbf{IC}_S$). Suppose $l = l_3$. Let h be an element of ObjectKind(l_3). If $h = \mathbf{halt}_S$, then $[\mathbf{IC}_S \longmapsto l, l_3 \longmapsto h]$ is halting.

(66) Let S be a realistic halting von Neumann definite AMI over N, l_3 be an instruction-location of S, and l be an element of ObjectKind($\mathbf{IC}_S$). Suppose $l = l_3$. Let h be an element of ObjectKind(l_3). Suppose $h = \mathbf{halt}_S$. Let s be a state of S. If $[\mathbf{IC}_S \longmapsto l, l_3 \longmapsto h] \subseteq s$, then for every i holds (Computation(s))(i) $= s$.

(67) Let S be a realistic halting von Neumann definite AMI over N, l_3 be an instruction-location of S, and l be an element of ObjectKind($\mathbf{IC}_S$). Suppose $l = l_3$. Let h be an element of ObjectKind(l_3). If $h = \mathbf{halt}_S$, then $[\mathbf{IC}_S \longmapsto l, l_3 \longmapsto h]$ is autonomic.

Let us consider N and let S be a realistic halting von Neumann definite AMI over N. Observe that there exists a finite partial state of S which is autonomic and halting.

Let us consider N and let S be a realistic halting von Neumann definite AMI over N. A pre-program of S is an autonomic halting finite partial state of S.

Let us consider N, let S be a realistic halting von Neumann definite AMI over N, and let s be a finite partial state of S. Let us assume that s is a pre-program of S. The functor Result(s) yielding a finite partial state of S is defined by:

(Def. 27) For every state s' of S such that $s \subseteq s'$ holds Result(s) $=$ Result(s') $\restriction \operatorname{dom} s$.

8. Computability

Let us consider N, let S be a realistic halting von Neumann definite AMI over N, let p be a finite partial state of S, and let F be a function. We say that p computes F if and only if the condition (Def. 28) is satisfied.

(Def. 28) Let x be a set. Suppose $x \in \operatorname{dom} F$. Then there exists a finite partial state s of S such that $x = s$ and $p{+}{\cdot}s$ is a pre-program of S and $F(s) \subseteq \operatorname{Result}(p{+}{\cdot}s)$.

Next we state three propositions:

(68) Let S be a realistic halting von Neumann definite AMI over N and p be a finite partial state of S. Then p computes $\square$.

(69) Let S be a realistic halting von Neumann definite AMI over N and p be a finite partial state of S. Then p is a pre-program of S if and only if p computes $\emptyset \mapsto\!\!\!\!\rightarrow \operatorname{Result}(p)$.

(70) Let S be a realistic halting von Neumann definite AMI over N and p be a finite partial state of S. Then p is a pre-program of S if and only if p computes $\emptyset \mapsto\!\!\!\!\rightarrow \emptyset$.

Let us consider N, let S be a realistic halting von Neumann definite AMI over N, and let I_1 be a partial function from $\operatorname{FinPartSt}(S)$ to $\operatorname{FinPartSt}(S)$. We say that I_1 is computable if and only if:

(Def. 29) There exists a finite partial state p of S such that p computes I_1.

We now state three propositions:

(71) Let S be a realistic halting von Neumann definite AMI over N and F be a partial function from $\operatorname{FinPartSt}(S)$ to $\operatorname{FinPartSt}(S)$. If $F = \square$, then F is computable.

(72) Let S be a realistic halting von Neumann definite AMI over N and F be a partial function from $\operatorname{FinPartSt}(S)$ to $\operatorname{FinPartSt}(S)$. If $F = \emptyset \mapsto\!\!\!\!\rightarrow \emptyset$, then F is computable.

(73) Let S be a realistic halting von Neumann definite AMI over N, p be a pre-program of S, and F be a partial function from $\operatorname{FinPartSt}(S)$ to $\operatorname{FinPartSt}(S)$. If $F = \emptyset \mapsto\!\!\!\!\rightarrow \operatorname{Result}(p)$, then F is computable.

Let us consider N, let S be a realistic halting von Neumann definite AMI over N, and let F be a partial function from $\operatorname{FinPartSt}(S)$ to $\operatorname{FinPartSt}(S)$. Let us assume that F is computable. A finite partial state of S is said to be a program of F if:

(Def. 30) It computes F.

Next we state four propositions:

(74) Let S be a realistic halting von Neumann definite AMI over N and F be a partial function from $\operatorname{FinPartSt}(S)$ to $\operatorname{FinPartSt}(S)$. If $F = \square$, then every finite partial state of S is a program of F.

(75) Let S be a realistic halting von Neumann definite AMI over N and F be a partial function from $\operatorname{FinPartSt}(S)$ to $\operatorname{FinPartSt}(S)$. If $F = \emptyset \mapsto\!\!\!\!\rightarrow \emptyset$, then every pre-program of S is a program of F.

(76) Let S be a realistic halting von Neumann definite AMI over N, p be a pre-program of S, and F be a partial function from $\operatorname{FinPartSt}(S)$ to $\operatorname{FinPartSt}(S)$. If $F = \emptyset \mapsto\!\!\!\!\rightarrow \operatorname{Result}(p)$, then p is a program of F.

(77) For every halting AMI S over N holds $\mathbf{halt}_S$ is halting.

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