THE SET OF FORMULAS OF PrAL^{+} VALID IN A FINITE STRUCTURE IS UNDECIDABLE

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Abstract: We consider a probabilistic logic of programs. In [6] it is proved that the set of formulas of the logic PrAL, valid in a finite structure, is decidable with respect to the diagram of the structure. We add to the language L_P of PrAL a sign $\bigcup$ and a functor lg. Next we justify that the set of formulas of extended logic, valid in a finite at least 2-element structure (for L_P^+) is undecidable.

Keywords: Probabilistic Algorithmic Logic, existential iteration quantifier

1. Introduction

In [6] the Probabilistic Algorithmic Logic PrAL is considered, constructed for expressing properties of probabilistic algorithms understood as iterative programs with two probabilistic constructions $x :=$ **random** and **either**$_p$ ... **or** ... **ro**. In order to describe probabilities of behaviours of programs a sort of variables (interpreted as real numbers) and symbols $+, -, *, 0, 1, <$ (interpreted in the standard way in the ordered field of real numbers) was added to the language L_P of PrAL.

In the paper [5] the changes of information which depend on realizations of probabilistic program was considered. That's why the language L_P was extended by adding the sign $\bigcup$ (called the existential iteration quantifier) and the functor lg (for the one-argument operation of a logarithm with a base 2 interpreted in the real ordered field). The new language was denoted by L_P^+.

The paper [6] contains an effective method of determining probabilities for probabilistic programs interpreted in a finite structure. The effectiveness of the method leads to the decidability of the set of formulas of L_P, valid in a fixed finite structure (provided that we have at our disposal a suitable finite part of the diagram of the structure). Here we shall justify that the set of probabilistic algorithmic formulas of L_P^+,

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valid in an arbitrary, finite at least 2-element structure, is undecidable with respect to its diagram.

We shall start from a presentation of the syntax and the semantics of the language L_P^+. We use the syntax and the semantics of L_P proposed by W. Danko in [6].

2. Syntax and Semantics of L_P^+

A language L_P is an extension of a first-order language L and includes three kinds of well-formed expressions: terms, formulas and programs. As mentioned above, the alphabet of L_P^+ contains two additional elements: the arithmetic one-argument functor lg and the sign $\bigcup$ (the existential iteration quantifier). An interpretation of L_P^+ relies on an interpretation of the first-order language L in a structure $\mathfrak{I}$ (We take into consideration only finite structures. By finite structure we mean a structure with a finite, at least 2-element set A.) and on the standard interpretation of the language $L_{\mathfrak{R}}$ in the ordered field of real numbers (cf. [6]).

The alphabet of the language L_P^+ contains

- a set of constants C_P, which consists of a finite subset $C = \{c_1, \ldots, c_u\}$ of symbols for each element of the set $A = \{a_1, \ldots, a_u\}$, a subset $C_{\mathfrak{R}}$ of real constant symbols and a subset C_L of logical constant symbols,
- an enumerable set $V_P = \{V \cup V_{\mathfrak{R}} \bigcup V_0\}$ of variables, where a subset $V = \{v_0, v_1, \ldots\}$ consists of non-arithmetic individual variables, a subset $V_{\mathfrak{R}} = \{x_0, x_1, \ldots\}$ contains real variables and a subset $V_0 = \{q_0, q_1, \ldots\}$ contains propositional variables,
- a set of signs of relations $\Psi_P = \{\Psi \cup \Psi_{\mathfrak{R}}\}$, where the subset Ψ consists of non-arithmetic predicates and the subset $\Psi_{\mathfrak{R}} = \{<_{\mathfrak{R}}, =_{\mathfrak{R}}\}$ contains arithmetic predicates,
- an enumerable set of functors $\Phi_P = \{\Phi \cup \Phi_{\mathfrak{R}}\}$, which consists of the subset $\Phi_{\mathfrak{R}} = \{+, -, *, \lg\}$ of symbols for arithmetic operations and the subset Φ of symbols for non-arithmetic operations,
- the set $\{\neg, \wedge, \vee, \Rightarrow, \Leftrightarrow\}$ of logical connectives,
- the set {**if**, **then**, **else**, **fi**, **while**, **do**, **od**, **either**, **or**, **ro**, **random**$_l$[1]} of symbols for program constructions,
- the set $\{\exists, \forall\}$ of symbols for classical quantifiers (for real variables only),
- the existential iteration quantifier $\bigcup$,

[1] For each probability distribution defined on a set A we generate a different random assignment. We use a number l to distinguish them.

– the set $\{(,)\}$ of auxiliary symbols.

In the language L_P^+ we distinguish two kinds of terms (arithmetic and non-arithmetic), formulas (classical and algorithmic) and programs.

The set of terms $T_P = \{T \cup T_{\Re}\}$ of L_P^+ consists of a subset of non-arithmetic terms T and a subset $T_{\Re}$ of arithmetic terms.

Definition 2.1 The set T of *non-arithmetic terms* is defined as the smallest set of expressions satisfying the following conditions:
– each constant of C and each variable of V belongs to T,
– if $\phi_i \in \Phi$ (ϕ_i – an n_i-argument functor $(n_i \geq 0)$) and $\tau_1, \ldots, \tau_{n_i} \in T$ then an expression $\phi_i(\tau_1, \ldots, \tau_{n_i})$ belongs to T.

Definition 2.2 The set $T_{\Re}$ of *arithmetic terms* is the smallest set such that:
– each constant of $C_{\Re}$ and each real variable of $V_{\Re}$ belongs to $T_{\Re}$,
– if $t_1, t_2 \in T_{\Re}$ then expressions $t_1 + t_2$, $t_1 - t_2$, $t_1 * t_2$, $\lg t_1$ belong to $T_{\Re}$,
– if α is a formula of L then $P(\alpha)$ belongs to $T_{\Re}$. (We read the symbol P as follows "probability that".)

Definition 2.3 The set F_O of *open formulas* is the smallest set such that:
– if $\tau_1, \ldots, \tau_{m_j} \in T$ and $\psi_j \in \Psi$ (ψ_j – an m_j-argument predicate) then $\psi_j(\tau_1, \ldots, \tau_{m_j}) \in F_O$,
– if $\alpha, \beta \in F_O$ then expressions $\neg\alpha$, $\alpha \vee \beta$, $\alpha \wedge \beta$, $\alpha \Rightarrow \beta$, $\alpha \Leftrightarrow \beta$ belong to F_O.

Definition 2.4 The set Π of all *programs* is defined as the smallest set of expressions satisfying the following conditions:
– each expression of the form $v := \tau$ or $v :=$**random**$_l$, where $v \in V$, $\tau \in T$ is a program,
– if $\gamma \in F_O$ and $M_1, M_2 \in \Pi$ then expressions $M_1; M_2$, **if** γ **then** M_1 **else** M_2 **fi**, **while** γ **do** M_1 **od**, **either**$_p$ M_1 **or** M_2 **ro** (p is a real number) are programs.

We establish that in an expression $\bigcup K\alpha$ (where K is a program) the letter α denotes a formula which does not contain any iteration quantifiers.

Definition 2.5 The set F_P of all *formulas* of the language L_P^+ is the smallest extension of the set F_O such that:
– if $t_1, t_2 \in T_{\Re}$ then $t_1 =_{\Re} t_2$, $t_1 <_{\Re} t_2$ belong to F_P,
– if $\alpha, \beta \in F_P$ then the expressions $\neg\alpha$, $\alpha \vee \beta$, $\alpha \wedge \beta$, $\alpha \Rightarrow \beta$, $\alpha \Leftrightarrow \beta$ belong to F_P,

– if $\alpha \in F_P$ and $x \in V_{\mathfrak{R}}$ is a free variable in α then $\exists x\alpha$, $\forall x\alpha$ belong to F_P,
– if $K \in \Pi$ and $\alpha \in F_P$ then $K\alpha$ is a formula of F_P,
– if $K \in \Pi$ and $\alpha \in F_P$ then $\bigcup K\alpha$ belongs to F_P.

A variable x is *free* in a formula α if x is not bounded by any quantifier.

Let L_P^+ be a fixed algorithmic language of the type $< \{n_k\}_{\phi_k \in \Phi_P}, \{m_l\}_{\psi_l \in \Psi_P} >$ and let a relational system $\Im =< A \cup R; \{\phi_{k\Im}\}_{\phi_k \in \Phi_P}, \{\psi_{l\Im}\}_{\psi_l \in \Psi_P} >$ (which consists of the fixed, finite, at least 2-element set A, the set R of real numbers, operations and relations) be a fixed data structure for L_P^+.

We interpret non-arithmetic individual variables of L_P^+ as elements of A. Real variables are interpreted as elements of the set R of real numbers.

Let's denote the set of possible valuations w of non-arithmetic variables by W.

Definition 2.6 By *the interpretation of a non-aritmetic term* τ of L_P in the structure $\Im$ we mean a function $\tau_\Im : W \mapsto A$ which is defined recursively.
– If τ is a variable $v \in V$ then $v_\Im(w) \stackrel{df}{=} w(v)$.
– If τ is of the form $\phi(\tau_1, \ldots, \tau_n)$, where $\tau_1, \ldots, \tau_n \in T$ and $\phi \in \Phi$ is an n-argument functor then $\phi(\tau_1, \ldots, \tau_n)_\Im(w) \stackrel{df}{=} \phi_\Im(\tau_{1\Im}(w), \ldots, \tau_{n\Im}(w))$, where $\tau_{1\Im}(w), \ldots, \tau_{n\Im}(w)$ are defined earlier.

To interpret random assignments (i.e. constructions of the form $v :=$ **random**$_l$) in a probabilistic way we assume that there exists a fixed probability distribution defined on A

$$\rho_l : A \mapsto [0,1], \qquad \sum_{i=1}^{u} \rho_l(a_i) = 1.$$

Definition 2.7 (cf. [6]) A pair $< \Im, \rho >$, where ρ is a set of fixed probability distributions ρ_l defined on A and $\Im$ is a structure for L_P^+, is called *a probabilistic structure*. In this structure we interpret probabilistic programs.

By $\mathcal{M}$ we denote the set of all probability distributions defined on the set W of valuations of non-arithmetic variables such that

$$\mu : W \mapsto [0,1], \qquad \sum_{w_i \in W} \mu(w_i) \leq 1.$$

By S we mean the set of all *states*, i.e. all pairs $s =< \mu, w_{\mathfrak{R}} >$, where μ is a probability distribution of valuations of non-arithmetic variables and $w_{\mathfrak{R}}$ is a valuation of real variables of $V_{\mathfrak{R}}$.

Definition 2.8 (cf. [6]) A probabilistic program K is interpreted in the structure $< \Im, \rho >$ as a partial function transforming the set of states into the set of states

$$K_{<\Im,\rho>} : S \mapsto S.$$

Let $K(v_1,\ldots,v_h)$ represent a fixed program in L_P^+. An arbitrary program K contains only a finite number of non-arithmetic variables. We denote this set of variables by $V = \{v_1,\ldots,v_h\}$. Since $A = \{a_1,\ldots,a_u\}$ is also a finite set, then a set of all possible valuations of program variables will be also finite. We denote it by $\{w_1,\ldots,w_n\}$, where $n = u^h$.

Let's notice that programs do not operate on variables of $V_{\Re}$. Thus we can interpret an arbitrary program K as partial functions transforming probability distributions defined on the set of valuations of program variables (cf. [6])

$$K_{<\Im,\rho>} : \mathcal{M} \mapsto \mathcal{M}.$$

If μ is the input probability distribution of valuations of program variables (input probability distribution for short) then a realization of a program K leads to a new output probability distribution μ' of valuations of program variables (output probability distribution for short). A distribution μ (μ') associates with each valuation w of program variables a corresponding probability of its appearance.

The interpretation of program constructions (used in this paper) can be found in the Appendix.

An arithmetic term of the form $P(\alpha)$ denotes the probability, that the formula α of L is satisfied at a distribution μ (cf. [6])

$[P(\alpha)]_{\Im}(s) = \sum_{w \in W^{\alpha}} \mu(w)$, where $W^{\alpha} = \{w \in W : \Im, w \models \alpha\}$.

Let $s = < \mu, w_{\Re} >$ be a state and let $s' = < \mu', w_{\Re} >$ represent the state $s' = K_{<\Im,\rho>}(s)$.

Given below is the interpretation of a formula $K\alpha$ ($\alpha \in F_P$ and $K \in \Pi$).

$$(K\alpha)_{<\Im,\rho>}(s) = \begin{cases} \alpha_{<\Im,\rho>}(s') & \text{if } K_{<\Im,\rho>}(s) \text{ is defined and } s' = K_{<\Im,\rho>}(s) \\ \text{is not defined otherwise} \end{cases}$$

The satisfiability of a formula $K\alpha$, where $\alpha \in F_P$ and $K \in \Pi$, is defined in the following way (cf. [6])

$< \Im, \rho >, s \models K\alpha$ iff $< \Im, \rho >, s' \models \alpha$, where $s' = K_{<\Im,\rho>}(s)$.

The next definition establishes the meaning of the existential iteration quantifier ($K \in \Pi$, $\alpha \in F_P$).

$$(\bigcup K\alpha)_{<\Im,\rho>}(s) \overset{df}{=} \underset{i\in N}{\text{l.u.b.}}\,(K^i\alpha)_{<\Im,\rho>}(s).$$

We can informally express the formula $\bigcup K\alpha$ in the following way $\alpha \vee K\alpha \vee K^2\alpha \vee \ldots$

The satisfiability of a formula $\bigcup K\alpha$ ($K \in \Pi$, $\alpha \in F_P$) is defined as an infinite alternative of formulas $(K^i\alpha)$ for $i \in N$.

Example 2.10 Now we shall present a formula which contains the iteration quantifier. Let's consider the formula $\beta:\ K_0\bigcup K\alpha$ such that

K_0: $v_1 := 0;$
K : **if** $(v_1 = 0)$ **then** v_1 :=**random**$_1$; $v_2 := 0$; **else** $v_2 := 1$; **fi**
α: $x = \mathrm{P}(v_1 = 1\ \vee\ v_2 = 0)$

where K_0 and K are programs interpreted in the structure $<\Im,\rho>$ with a 2-element set $A = \{0,1\}$. For a random assignment v_1 :=**random**$_1$ we define the probability distribution $\rho_1 = [0.5, 0.5]$. The set of possible valuations of program variables contains 4 elements: $w_1 = (0,0)$, $w_2 = (0,1)$, $w_3 = (1,0)$, $w_4 = (1,1)$. We carry out computations for the input probability distribution $\mu = [0.25, 0.25, 0.25, 0.25]$. $\mathrm{P}(\gamma)$ denotes the probability that γ is satisfied (at a distribution μ). Let's notice, that formula β describes the following fact

$$(x = 0) \vee (x = 0.5) \vee (x = 0.5*0.5) \vee (x = 0.5*0.5*0.5) \vee \ldots.$$

3. The proof of the main lemma

As we have mentioned (it is proved in [6]), the set of probabilistic algorithmic formulas of PrAL valid in a finite structure for L_P is decidable with respect to the diagram of the structure. By the diagram $D(\Im)$ of the structure $\Im$ we understand the set of all atomic or negated atomic formulas $\phi(c_{i_1},\ldots,c_{i_m}) = c_{i_0}$ (ϕ is a functor of L) and $\psi(c_{i_1},\ldots,c_{i_m})$ (ψ is a predicate symbol of L), which are valid in $\Im$.

The proof of decidability of PrAL essentially uses the Lemma which reduces the problem of validity of sentences of L_P to the (decidable) problem of the validity of sentences of the first-order arithmetic of real numbers. Finally, it appears that the set of formulas of PrAL, valid in all at most u-element structures for L_P, is decidable.

We shall show that if the language L_P^+ contains additionally the sign $\bigcup$ and the functor lg (for the operation of a logarithm) we can define natural numbers and operations of addition and multiplication for natural numbers.

Let's assume that 0.5^i abbreviates the expression $\underbrace{0.5*0.5*\ldots*0.5}_{i\ times}$.

Lemma 3.1 Let $< \Im, \rho >$ be an arbitrary fixed probabilistic structure (for L_P^+) with a finite set $A = \{a_1, a_2, \ldots, a_u\}$, where $u > 1$. Let K_0 and K be as follows

K_0: $v_1 := a_u$;
K : **if** $(v_1 = a_u)$ **then**
  either$_{0.5}$ $v_1 := a_u$; $v_2 := a_u$; **or** $v_1 := a_{u-1}$; $v_2 := a_u$; **ro**
  else $v_1 := a_1$; $v_2 := a_u$; **fi**

For an arbitrary natural number $i > 0$, if $\mu = [\mu_1, \mu_2, \ldots, \mu_{u^2}]$ is an input probability distribution then as a result of realization of program $K_0; K^i$ we obtain the following output probability distribution

$$\mu' = K_0 K^i_{<\Im,\rho>}(\mu) = [\underbrace{0,\ldots,0}_{u-1\ times}, 1 - 0.5^{(i-1)}, \underbrace{0,\ldots,0}_{u^2-2u-1\ times}, 0.5^i, \underbrace{0,\ldots,0}_{u-1\ times}, 0.5^i].$$

Proof. Let us assume that $< \Im, \rho >$ is a fixed probabilistic structure (for L_P^+) with a finite at least 2-element set $A = \{a_1, a_2, \ldots, a_u\}$. Let's consider an arbitrary program $K_0; K^i$ ($i \in N_+$). The set of possible valuations of program variables contains u^2 elements: $w_1 = (a_1, a_1)$, $w_2 = (a_1, a_2)$, …, $w_u = (a_1, a_u)$, $w_{u+1} = (a_2, a_1)$, $w_{u+2} = (a_2, a_2)$, …, $w_{2u} = (a_2, a_u)$, …,$w_{u^2-u+1} = (a_u, a_1)$, $w_{u^2-u+2} = (a_u, a_2)$, …, $w_{u^2} = (a_u, a_u)$. We carry out computations for the input probability distribution $\mu = [\mu_1, \mu_2, \ldots, \mu_{u^2}]$. The proof of the Lemma 3.1 will proceed by induction on the length of programs.

(A) The base of induction.

First we shall justify that the realization of the program $K_0; K$ leads to the probability distribution

$$\mu' = K_0 K_{<\Im,\rho>}(\mu) = [\underbrace{0,\ldots,0}_{u^2-u-1\ times}, 0.5, \underbrace{0,\ldots,0}_{u-1\ times}, 0.5].$$

We shall determine the necessary probability distributions (cf. the Appendix).

$$[v_1 := a_1]_{<\Im,\rho>}(\mu) = [\mu_1 + \mu_{u+1} + \ldots + \mu_{u^2-u+1}, \mu_2 + \mu_{u+2} + \ldots + \mu_{u^2-u+2}, \ldots, \mu_u + \mu_{2u} + \ldots + \mu_{u^2}, \underbrace{0,\ldots,0}_{u^2-u\ times}]$$

$$[v_1 := a_{u-1}]_{<\Im,\rho>}(\mu) = [\underbrace{0,\ldots,0}_{u^2-2u\ times}, \mu_1 + \mu_{u+1} + \ldots + \mu_{u^2-u+1}, \mu_2 + \mu_{u+2} + \ldots + \mu_{u^2-u+2}, \ldots, \mu_u + \mu_{2u} + \ldots + \mu_{u^2}, \underbrace{0,\ldots,0}_{u\ times}]$$

$[v_1 := a_u]_{<\Im,\rho>}(\mu) = [\underbrace{0,\ldots,0}_{u^2-u\ times},\mu_1 + \mu_{u+1} + \ldots + \mu_{u^2-u+1},\mu_2 + \mu_{u+2} + \ldots + \mu_{u^2-u+2},\ldots,\mu_u + \mu_{2u} + \ldots + \mu_{u^2}]$

$[v_2 := a_u]_{<\Im,\rho>}(\mu) = [\underbrace{0,\ldots,0}_{u-1\ times},\mu_1 + \mu_2 + \ldots + \mu_u,\underbrace{0,\ldots,0}_{u-1\ times},\mu_{u+1} + \mu_{u+2} + \ldots + \mu_{2u},\underbrace{0,\ldots,0}_{u-1\ times},\ldots,\underbrace{0,\ldots,0}_{u-1\ times},\mu_{u^2-u+1} + \mu_{u^2-u+2} + \ldots + \mu_{u^2}]$

Let's denote the subprogram $v_1 := a_u$; $v_2 := a_u$; by N_1.

$N_{1<\Im,\rho>}(\mu) = [v_2 := a_u]_{<\Im,\rho>}([v_1 := a_u]_{<\Im,\rho>}(\mu)) =$
$= [\underbrace{0,\ldots,0}_{u^2-1\ times},(\mu_1 + \mu_{u+1} + \ldots + \mu_{u^2-u+1}) + (\mu_2 + \mu_{u+2} + \ldots + \mu_{u^2-u+2}) + \ldots + (\mu_u + \mu_{2u} + \ldots + \mu_{u^2})] =$
$= [\underbrace{0,\ldots,0}_{u^2-1\ times},\mu_1 + \mu_2 + \ldots + \mu_{u^2}] = [\underbrace{0,\ldots,0}_{u^2-1\ times},1]$

By N_2 we denote the subprogram $v_1 := a_{u-1}$; $v_2 := a_u$;.

$N_{2<\Im,\rho>}(\mu) = [v_2 := a_u]_{<\Im,\rho>}([v_1 := a_{u-1}]_{<\Im,\rho>}(\mu)) =$
$= [\underbrace{0,\ldots,0}_{u^2-u-1\ times},(\mu_1 + \mu_{u+1} + \ldots + \mu_{u^2-u+1}) + (\mu_2 + \mu_{u+2} + \ldots + \mu_{u^2-u+2}) + \ldots + (\mu_u + \mu_{2u} + \ldots + \mu_{u^2}),\underbrace{0,\ldots,0}_{u\ times}] =$
$= [\underbrace{0,\ldots,0}_{u^2-u-1\ times},\mu_1 + \mu_2 + \ldots + \mu_{u^2},\underbrace{0,\ldots,0}_{u\ times}] = [\underbrace{0,\ldots,0}_{u^2-u-1\ times},1,\underbrace{0,\ldots,0}_{u\ times}]$

The subprogram $v_1 := a_1$; $v_2 := a_u$; we denote by N_3.

$N_{3<\Im,\rho>}(\mu) = [v_2 := a_u]_{<\Im,\rho>}([v_1 := a_1]_{<\Im,\rho>}(\mu)) =$
$= [\underbrace{0,\ldots,0}_{u-1\ times},(\mu_1 + \mu_{u+1} + \ldots + \mu_{u^2-u+1}) + (\mu_2 + \mu_{u+2} + \ldots + \mu_{u^2-u+2}) + \ldots + (\mu_u + \mu_{2u} + \ldots + \mu_{u^2}),\underbrace{0,\ldots,0}_{u^2-u\ times}] =$
$= [\underbrace{0,\ldots,0}_{u-1\ times},\mu_1 + \mu_2 + \ldots + \mu_{u^2},\underbrace{0,\ldots,0}_{u^2-u\ times}] = [\underbrace{0,\ldots,0}_{u-1\ times},1,\underbrace{0,\ldots,0}_{u^2-u\ times}]$

Let's denote the subprogram **either**$_{0.5}$ N_1 **or** N_2 **ro** by E.

$E_{<\Im,\rho>}(\mu) = 0.5*(N_{1<\Im,\rho>}(\mu)) + 0.5*(N_{2<\Im,\rho>}(\mu)) =$
$= 0.5*[\underbrace{0,\ldots,0}_{u^2-1\ times},\mu_1 + \mu_2 + \ldots + \mu_{u^2}] + 0.5*[\underbrace{0,\ldots,0}_{u^2-u-1\ times},\mu_1 + \mu_2 + \ldots + \mu_{u^2},\underbrace{0,\ldots,0}_{u\ times}] =$

$= [\underbrace{0,\ldots,0}_{u^2-u-1\ times}, 0.5*(\mu_1+\ldots+\mu_{u^2}), \underbrace{0,\ldots,0}_{u-1\ times}, 0.5*(\mu_1+\ldots+\mu_{u^2})] =$
$= [\underbrace{0,\ldots,0}_{u^2-u-1\ times}, 0.5, \underbrace{0,\ldots,0}_{u-1\ times}, 0.5]$

$[(v_1 = a_u)?]_{<\mathfrak{I},\rho>}(\mu) = [\underbrace{0,\ldots,0}_{u^2-u\ times}, \mu_{u^2-u+1}, \mu_{u^2-u+2}, \ldots, \mu_{u^2}]$
$[\neg(v_1 = a_u)?]_{<\mathfrak{I},\rho>}(\mu) = [\mu_1, \mu_2, \ldots, \mu_{u^2-u}, \underbrace{0,\ldots,0}_{u\ times}]$

$K_{<\mathfrak{I},\rho>}(\mu) = E_{<\mathfrak{I},\rho>}([(v_1 = a_u)?]_{<\mathfrak{I},\rho>}(\mu)) + N_{3<\mathfrak{I},\rho>}([\neg(v_1 = a_u)?]_{<\mathfrak{I},\rho>}(\mu)) =$
$= [\underbrace{0,\ldots,0}_{u^2-u-1\ times}, 0.5*(\mu_{u^2-u+1}+\mu_{u^2-u+2}+\ldots+\mu_{u^2}), \underbrace{0,\ldots,0}_{u-1\ times}, 0.5*(\mu_{u^2-u+1}+$
$\mu_{u^2-u+2}+\ldots+\mu_{u^2})] + [\underbrace{0,\ldots,0}_{u-1\ times}, (\mu_1+\mu_2+\ldots+\mu_{u^2-u}), \underbrace{0,\ldots,0}_{u^2-u\ times}] =$
$= [\underbrace{0,\ldots,0}_{u-1\ times}, (\mu_1+\mu_2+\ldots+\mu_{u^2-u}), \underbrace{0,\ldots,0}_{u^2-2u-1\ times}, 0.5*(\mu_{u^2-u+1}+\mu_{u^2-u+2}+\ldots+$
$\mu_{u^2}), \underbrace{0,\ldots,0}_{u-1\ times}, 0.5*(\mu_{u^2-u+1}+\mu_{u^2-u+2}+\ldots+\mu_{u^2})]$

Finally

$K_{<\mathfrak{I},\rho>}(K_{0<\mathfrak{I},\rho>}(\mu)) = K_{<\mathfrak{I},\rho>}([v_1 := a_u]_{<\mathfrak{I},\rho>}(\mu)) =$
$= [\underbrace{0,\ldots,0}_{u^2-u-1\ times}, 0.5*((\mu_1+\mu_{u+1}+\ldots+\mu_{u^2-u+1})+(\mu_2+\mu_{u+2}+\ldots+\mu_{u^2-u+2})+\ldots+$
$(\mu_u+\mu_{2u}+\ldots+\mu_{u^2})), \underbrace{0,\ldots,0}_{u-1\ times}, 0.5*((\mu_1+\mu_{u+1}+\ldots+\mu_{u^2-u+1})+(\mu_2+\mu_{u+2}+$
$\ldots+\mu_{u^2-u+2})+\ldots+(\mu_u+\mu_{2u}+\ldots+\mu_{u^2}))] =$
$= [\underbrace{0,\ldots,0}_{u^2-u-1\ times}, 0.5*(\mu_1+\mu_2+\ldots+\mu_{u^2}), \underbrace{0,\ldots,0}_{u-1\ times}, 0.5*(\mu_1+\mu_2+\ldots+\mu_{u^2})] =$
$= [\underbrace{0,\ldots,0}_{u^2-u-1\ times}, 0.5, \underbrace{0,\ldots,0}_{u-1\ times}, 0.5].$

(B) The inductive step.

The inductive assumption. For a certain natural number k, if $\mu = [\mu_1, \mu_2, \ldots, \mu_{u^2}]$ is an input probability distribution then as a result of realization of the program $K_0; K^k$ we obtain the following output probability distribution

$K_0K^k{<}\Im,\rho{>}(\mu) =$
$= [\underbrace{0,\ldots,0}_{u-1\ times},(1-0.5^{(k-1)})*(\mu_1+\mu_2+\ldots+\mu_{u^2}), \underbrace{0,\ldots,0}_{u^2-2u-1\ times}, 0.5^k*(\mu_1+\mu_2+\ldots+$
$\mu_{u^2}), \underbrace{0,\ldots,0}_{u-1\ times}, 0.5^k*(\mu_1+\mu_2+\ldots+\mu_{u^2})] =$
$= [\underbrace{0,\ldots,0}_{u-1\ times},(1-0.5^{(k-1)}), \underbrace{0,\ldots,0}_{u^2-2u-1\ times}, 0.5^k, \underbrace{0,\ldots,0}_{u-1\ times}, 0.5^k]$

We shall apply the inductive assumption to show that if we take $\mu = [\mu_1,\mu_2,\ldots,\mu_{u^2}]$ as the input probability distribution then after the execution of the program $K_0;K^{k+1}$ we obtain the following output probability distribution
$K_0K^{k+1}_{<\Im,\rho>}(\mu) = [\underbrace{0,\ldots,0}_{u-1\ times},(1-0.5^k)*(\mu_1+\mu_2+\ldots+\mu_{u^2}), \underbrace{0,\ldots,0}_{u^2-2u-1\ times},$
$0.5^{(k+1)}*(\mu_1+\mu_2+\ldots+\mu_{u^2}), \underbrace{0,\ldots,0}_{u-1\ times}, 0.5^{(k+1)}*(\mu_1+\mu_2+\ldots+\mu_{u^2})] =$
$= [\underbrace{0,\ldots,0}_{u-1\ times},(1-0.5^k), \underbrace{0,\ldots,0}_{u^2-2u-1\ times}, 0.5^{(k+1)}, \underbrace{0,\ldots,0}_{u-1\ times}, 0.5^{(k+1)}]$

We can express a composition of programs in the following way (cf. the Appendix)
$K_0K^{k+1}_{<\Im,\rho>}(\mu) = K_{<\Im,\rho>}(K_0K^k_{<\Im,\rho>}(\mu))$

Hence by the inductive assumption
$K_{<\Im,\rho>}(K_0K^k_{<\Im,\rho>}(\mu)) = K_{<\Im,\rho>}([\underbrace{0,\ldots,0}_{u-1\ times},(1-0.5^{(k-1)})*(\mu_1+\mu_2+\ldots+\mu_{u^2}),$
$\underbrace{0,\ldots,0}_{u^2-2u-1\ times}, 0.5^k*(\mu_1+\mu_2+\ldots+\mu_{u^2}), \underbrace{0,\ldots,0}_{u-1\ times}, 0.5^k*(\mu_1+\mu_2+\ldots+\mu_{u^2})]) =$
$= [\underbrace{0,\ldots,0}_{u-1\ times},(1-0.5^{(k-1)}+0.5^k), \underbrace{0,\ldots,0}_{u^2-2u-1\ times}, 0.5*0.5^k, \underbrace{0,\ldots,0}_{u-1\ times}, 0.5*0.5^k] =$
$= [\underbrace{0,\ldots,0}_{u-1\ times},(1-0.5^k), \underbrace{0,\ldots,0}_{u^2-2u-1\ times}, 0.5^{(k+1)}, \underbrace{0,\ldots,0}_{u-1\ times}, 0.5^{(k+1)}]$

which accomplishes the inductive proof.

□

Lemma 3.2 Let $<\Im,\rho>$ be an arbitrary fixed structure (for L_P^+) with a finite set $A = \{a_1,a_2,\ldots,a_u\}$, where $u > 1$. The set of formulas of PrAL$^+$ valid in $<\Im,\rho>$ is undecidable.

Proof. Let $< \Im, \rho >$ be an arbitrary fixed structure (for L_P^+) with a finite at least 2-element set $A = \{a_1, \ldots, a_u\}$. Let's consider the formula β of the form $K_0 \bigcup K\alpha$, where K_0, K are the programs considered in the Lemma 3.1 and α is as follows

α: $x = P(v_1 = a_{u-1} \wedge v_2 = a_u)$.

The computations are carried out for the input probability distribution $\mu = [\mu_1, \mu_2, \ldots, \mu_{u^2}]$ and for programs K_0 and $K_0;K^i$, where $i \in N_+$. Let's denote $K_{0<\Im,\rho>}(\mu)$ by η. We know that

$$\eta = K_{0<\Im,\rho>}(\mu) = [v_1 := a_u]_{<\Im,\rho>}(\mu) = [\underbrace{0,\ldots,0}_{u^2-u \text{ times}}, \mu_1 + \mu_{u+1} + \ldots + \mu_{u^2-u+1}, \mu_2 + \mu_{u+2} + \ldots + \mu_{u^2-u+2}, \ldots, \mu_u + \mu_{2u} + \ldots + \mu_{u^2}].$$

By the Lemma 3.1 we obtain that for an arbitrary number $i > 0$

$$\mu' = K_0K^i_{<\Im,\rho>}(\mu) = [\underbrace{0,\ldots,0}_{u-1 \text{ times}}, (1 - 0.5^{(i-1)}), \underbrace{0,\ldots,0}_{u^2-2u-1 \text{ times}}, \underline{0.5^i}, \underbrace{0,\ldots,0}_{u-1 \text{ times}}, 0.5^i].$$

We recall, that $P(v_1 = a_{u-1} \wedge v_2 = a_u) = \mu'(w_{u^2-u})$, where $w_{u^2-u} = (a_{u-1}, a_u)$. We can notice that for $i \in N_+$ we have $\mu'(w_{u^2-u}) = \underline{0.5^i}$ and additionally $\eta(w_{u^2-u}) = \underline{0}$. Therefore the formula β: $K_0 \bigcup K\alpha$ describes the following fact

$$(x = 0) \vee (x = 0.5) \vee (x = 0.25) \vee (x = 0.125) \vee \ldots \vee (x = 0.5^i) \vee \ldots$$

Let's notice, that we can define an arbitrary natural number k in the following way. Let k be a real number

$$N(k) \text{ iff } < \Im, \rho > \models (k = 0 \vee \exists x((k = -\lg x) \wedge K_0 \bigcup K\alpha)).$$

Since the natural numbers were generated among real numbers and operations of addition and multiplication exist in the structure $\Re =< R; +, -, *, 0, 1, <>$, we can define these operations for constructed natural numbers. For arbitrary x_0, x_1, x_2

$x_0 \underline{+} x_1 = x_2$ iff $< \Im, \rho > \models N(x_0) \wedge N(x_1) \wedge x_2 = x_0 + x_1$,
$x_0 \underline{*} x_1 = x_2$ iff $< \Im, \rho > \models N(x_0) \wedge N(x_1) \wedge x_2 = x_0 * x_1$.

Since $Th(< N; \underline{+}, \underline{*}, 0, 1 >)$ is undecidable (cf. [2,11,7]), the set of formulas of considered algorithmic logic, valid in a fixed, finite at least 2-element structure (for L_P^+) is also undecidable.

□

4. Appendix (cf. [6])

By the interpretation of a program K of L_P^+ in the structure $< \mathfrak{I}, \rho >$ we mean a function $K_{<\mathfrak{I},\rho>} : \mathcal{M} \mapsto \mathcal{M}$ which is defined recursively.

- If K is *an assignment instruction* of the form $v_r := \tau$ (for $v_r \in V$, $r = 1,\dots,h$ and $\tau \in T$) then
  $[v_r := \tau]_{<\mathfrak{I},\rho>}(\mu) = \mu'$,where
  $\mu'(w_j) = \sum_{w \in W^{r,\tau}} \mu(w)$ for $j = 1,\dots,n$ and
  $W^{r,\tau} = \{w \in W : w(v_r) = \tau_{\mathfrak{I}}(w_{in}) \wedge \forall_{v \in V \setminus \{v_r\}} w(v) = w_{in}(v)\}$.
  w_{in} denotes an input valuation of program variables.

- If K is *a random assignment* of the form $v_r :=$**random**$_l$ (for $v_r \in V$, $r = 1,\dots,h$ and ρ_l being a probability distribution defined on A) then
  $[v_r :=$**random**$_l]_{<\mathfrak{I},\rho>}(\mu) = \mu'$, where
  $\mu'(w_j) = \rho_l(w_j(v_r)) * \sum_{w \in W^r} \mu(w)$ and
  $W^r = \{w \in W : \forall_{v \in V \setminus \{v_r\}} w(v) = w_{in}(v)\}$.

- We interpret the program **while** $\neg\gamma$ **do** $v := v$ **od** (for $v \in V$ and $\gamma \in F_O$) in the following way
  $[\gamma?]_{<\mathfrak{I},\rho>}(\mu) = [$**while** $\neg\gamma$ **do** $v := v$ **od**$]_{<\mathfrak{I},\rho>}(\mu) = \mu'$, where
  $\mu'(w_j) = \begin{cases} \mu(w_i) & \text{for } w_i = w_j \ \wedge \ \mathfrak{I}, w_i \models \gamma \\ 0 & \text{otherwise} \end{cases}$
  We denote this program construction by $[\gamma?]$.

- If K is *a composition of programs* M_1, M_2 and $M_{1<\mathfrak{I},\rho>}(\mu)$, $M_{2<\mathfrak{I},\rho>}(\mu)$ are defined then
  $[M_1;\ M_2]_{<\mathfrak{I},\rho>}(\mu) = M_{2<\mathfrak{I},\rho>}(M_{1<\mathfrak{I},\rho>}(\mu))$.

- If K is *a branching between the two programs* M_1, M_2 and $M_{1<\mathfrak{I},\rho>}(\mu)$, $M_{2<\mathfrak{I},\rho>}(\mu)$ are defined then
  $[$**if** γ **then** M_1 **else** M_2 **fi**$]_{<\mathfrak{I},\rho>}(\mu) =$
  $= M_{1<\mathfrak{I},\rho>}([\gamma?]_{<\mathfrak{I},\rho>}(\mu)) + M_{2<\mathfrak{I},\rho>}([\neg\gamma?]_{<\mathfrak{I},\rho>}(\mu))$.

- If K is *a probabilistic branching*, $p \in R$, $0 < p < 1$ and $M_{1<\mathfrak{I},\rho>}(\mu)$, $M_{2<\mathfrak{I},\rho>}(\mu)$ are defined then
  $[$**either**$_p$ M_1 **or** M_2 **ro**$]_{<\mathfrak{I},\rho>}(\mu) = p * M_{1<\mathfrak{I},\rho>}(\mu) + (1-p) * M_{2<\mathfrak{I},\rho>}(\mu)$.

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ZBIÓR FORMUŁ LOGIKI PrAL^{+} PRAWDZIWYCH W SKOŃCZONEJ STRUKTURZE JEST NIEROZSTRZYGALNY

Streszczenie Rozważamy probabilistyczną logikę algorytmiczną. W pracy [6] znajduje się uzasadnienie, że zbiór formuł logiki PrAL, prawdziwych w skończonej strukturze, jest rozstrzygalny ze względu na diagram struktury. Dodajemy do języka L_P logiki PrAL znak $\bigcup$ i funktor lg. Następnie uzasadniamy, że zbiór formuł rozszerzonej logiki, prawdziwych w skończonej co najmniej 2-elementowej strukturze (dla L_P^{+}), nie jest już rozstrzygalny.

Słowa kluczowe: probabilistyczna logika algorytmiczna, egzystencjalny kwantyfikator iteracji