Behavior Planning of Intelligent Agent with Sign World Model

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Abstract

Behavior planning is an important function of any complex technical facility intelligent control system. Presently, a symbol paradigm of artificial intelligence offers a variety of planning algorithms, including those that use precedent information, i.e. algorithms based on acquired knowledge. Symbol grounding problem within the exiting approaches of knowledge representation does not allow to effectively use the developed algorithms together with learning mechanisms for the purpose of solving a wide variety of applied problems by actual intelligent agents (robotics systems). This article presents the original planning algorithm (MAP Planner), which uses sign world model as the basis for acquisition and maintenance of knowledge for future use in behavior planning. Sign problem approach describes planning as a cognitive function actualized by the world model of a subject of activity. Apart from solving symbol grounding problem and ensuring psychological and biological plausibility, sign planning process model allows interaction of an intelligent agent with other participants in solving a cooperative task. The article presents the description of the knowledge representation method used, MAP planning algorithm, and model experiment in a "block world".

Keywords: behavior planning, sign world model, sign image, sign significance, sign personal meaning, causal matrix, semiotic network, MAP algorithm,

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1. Introduction

The issue of behavior planning of a complex technical or virtual subject has a long history and is mainly associated with the successes in the specific area of Artificial Intelligence discipline — automatic planning. In this sphere, considerable success has been achieved and a number of sign-based planning methods was proposed — both for classical problem definition, where actions are deterministic (these are such planning algorithms as FF [1], FD [2], LAMA [3]), and in non-deterministic definition, which takes into consideration the nonzero probabilities of non-appliance of actions and probabilistic environment reaction (algorithms based on Markov processes and dynamic programming [4, 5]). However, the development of effective and fast planning algorithms is based on the preset heuristic graph search principles and on the assumption that a set of actions is known in advance, which makes impossible automatic adaptation of planning system to new problems with a new list of actions.This implies that classical approaches do not offer a carry-over of planning experience or abstract actions, which may have varying realization in different situations. Substantial challenges arise when the existing algorithms are adapted for multi-agent applications, which suggest that agents possess both different action sets and different knowledge of the environment [6]. In case of cooperative interaction, it is also necessary to ensure non-discretionary incorporation of learning elements to augment database of an agent with information supplied by other participants of the group.

In more recent times, researchers in the fields of control and planning theory have focused on psychologically and biologically inspired models and architectures of agent control [7, 8]. The use of different types of memory (episodic, procedural, etc.) in cognitive architectures is aimed exactly at solving the task of reproducing biologic and psychological methods of information interchange and organization to solve such problems as behavior control and planning. This is primarily driven by the fact that the increasing complexity of tasks performed by robotics systems (agents) requires their higher self-sufficiency, versatility, and flexibility, which the existing methods and algorithms are unable to provide. Researchers in the field of Artificial Intelligence once again turn to the natural examples of such problem solving — to the research of human and animal behavior [9, 10]. Psychologically inspired models of cognitive functions (including planning) are focused both on reproducing human behavior in complex, specifically cooperative conditions, and at complying, as fully as possible, with the existing psychological concepts of human mind functioning. On the one hand, this may result in the increased resource intensity of the proposed algorithms, but, on the other hand, it will allow to realize new possibilities, which previously have been left out of the scope of problems tackled by planning specialists, for example goal-setting or role designation capacity. In the past, cognitive psychology concepts have been also used in classical planning, however, mainly in behavioristic agenda. For instance, the concept of dividing the entire multiplicity of actions into automatic, fast actions, specific, voluntary actions and generalized actions predicted by psychological theory [11] was implemented by hierarchical planning and the concept of planning experience maintenance — in precedent planning [12, 13, 14].

Cognitive psychology has a number of branches that study the phenomenon of planning, within which three main areas should be mentioned: planning as part of cognitive scheme [15], planning as a meta-process [16, 17] and planning as part of activity [18]. The first branch uses cognitive schemes to describe behavior of humans. For an example, a perceptive scheme is a program of gathering information about objects and events, as well as acquisition of new information to provide its consistent interpretation. The scheme simultaneously incorporates a plan and its implementation; it is both an actionable structure and a structure of actions. The second approach provides for the existence of metacognitive processes allowing a person to control his/her cognitive processes and knowledge. From Sternberg's point of view, one may talk about global (strategic) and local (tactical) planning. Global planning requires more time, however, this is compensated by the reduction of time dedicated to local, tactical planning. Finally, the third approach, which is one of the most general concepts, considers hierarchical activity theory. This theory is used in this article and is described in the following section.

It is also worth mentioning that psychologically and biologically inspired control and planning models provide a new perspective of symbol grounding problem [19, 20, 21, 22]. Neurophysiological models of brain cortex sensor region functioning together with psychological categorization and perception theory form the basis for the development of new consistent models of association of symbols and sensor data. Success in this field has made it possible to implement certain models in robotic systems [23].

This article will present a new psychologically and biologically inspired method of behavior planning based on sign theory of activity and structural models of cortical-thalamic regions of brain. Apart from its value in terms of modeling of human cognitive functions, sign approach may be used to solve a number of cooperative robotics problems (e.g., for intelligent movement problems [10, 24]), which cannot be solved by classical and other psychology-oriented methods (such as BDI [25]).

This article is further organized as follows: Section 2 introduces the main concepts used in the article: world model, as well as sign and its components are defined and substantiated from psychological and biological standpoint. Subsection 2.1 introduces the concept of causal matrix as a mathematical structure for the description of sign components and considers its main characteristics. Subsection **??** discusses the networks, which are formed on the basis of sets of causal matrices and which represent relations of sign components. Section **??** introduces the concept of semiotic network as a model of world model and discusses the main types of processes of activity propagation within a semiotic network. Section **??** presents the description of a MAP algorithm of behavior planning in a sign world model (in a semiotic network). Section 5 concludes with a model example of operation of the presented MAP Planner.

2. Sign World Model

In this article, the method of knowledge representation is based on sign world model [26, 27, 28], which both stores knowledge about objects, processes and relations of external environment and represents the internal parameters of the intelligent agent that determine its motivational constituent and activity experience. World model also includes the procedures of operation with knowledge: its acquisition and use in various processes, such as perception, reasoning, goal-setting and behavior planning [27]. The representation of world model is based on psychological concepts of human brain functioning, in particular, on the concepts of cultural and historical approach [29], activity theory [18, 30, 31] and dual systems [32, 33]. According to psychological views, world model component is a four-element structure, a sign, which represents all entities of external environment and inner space for the subject (in our case, an intelligent agent): objects, their properties, processes and relations between objects and processes. It should be noted that sign is a product of interaction of several subjects of activity forming a certain group (a cultural environment), thus, the concept of a sign inherently assumes that an individual's world model interacts with the world models of other individuals.

An image element of a sign holds specific attributes of the represented entity and, at the same time, is a function of representation of the entity on the basis of the stream of data drawn from both external and internal sensors, in which key attributes are distinguished. A image element is individual for each world model bearer and is formed as the result of observation and generalization [27, 34].

An element of significance of a sign represents the generalized conceptual knowledge of a subject about the entities of the external environment, as well as about the internal space, both its own and that of other participants of the group. This knowledge is coherent, that is, similar for all representatives of the group. Communication processes occurring in a group of subjects (intelligent agents) are based on the messages built with signs having common significance, which in such way determine the syntax of communication protocol.

A personal meaning element of a sign contains individual personal experience of interaction of the subject with the external environment with regard to the attitude to this experience — whether it served to achieve a certain goal (satisfy a certain need) or, conversely, was unsuccessful. Personal meaning of a sign is its dynamic characteristic, which is being constantly shaped and updated as the result of certain cognitive processes (planning or goal-setting). It is a personal meaning element, which is determined by the inner characteristics of a subject and its needs and motivations sphere.

Finally, the fourth component — a name — serves to identify a sign both for communication processes and in voluntary processes of planning and reasoning. A sign's name, as well as its significance, is an established element, which, within a group of subjects, is altered in the slowest manner out of all sign's elements.

Within a subject's world model, signs represent the static objects and the properties of external environment, as well as its dynamic components: processes, situations and internal characteristics of the agent: actions, objects and properties "of the internal environment". Let us assume that we have an object of external environment — *lemon*. Within the world model of a subject, it may be represented by a sign having the name "lemon" whose image also includes such attributes as *yellow color*, *oval form* and *acid flavor*. These attributes may also be represented in the world model by signs or may be the information received directly from sensors. Generalized actions and processes, in which (according to a common shared opinion of a group to which the subject belongs) *lemon* participates are the significance of "lemon" sign. Lemon *is usually eaten*, *is used as a souse for a fish course* or *is used for the prevention of diseases*. The personal meaning of a lemon for a subject includes specific personal actions and processes, in which the subject had the experience of using lemon for solving a certain problem. I *threw lemon at my classmate* or *ate a whole lemon without making a wry face*. All actions and processes may also be represented by certain signs or may not be brought to a sign voluntary level and may be some undesignated operations.

Apart from psychological basis of the four-element sign structure, there are neurophysiologic evidences proving the existence of such a structure for the storage and activation of components of individual experience [35, 36]. Besides, neurophysiologic data serve as the basis for developing sign element models and certain functions, such as perception and recognition [37, 27]. Neurophysiologic evidences proving high uniformity of structures of various regions of cerebral cortex, as well as participation of thalamus in formation and remembering of chronological sequences [38, 39], lead to the mathematic structure of causal matrix [27] employed to describe the structure of sign elements used in this article.

Symbolic approach to representation of knowledge and description of processes occurring in sign world model makes it possible to solve a number of important problems in the area of situational control [40, 41] and control of complex technical facilities [42]. The use of sign world model to implement strategic functions of robotics systems [42] demonstrates the applicability of the used approach not only to represent knowledge, but also to solve cooperative planning and role distribution problems.

2.1. Sign elements

Let us discuss the structure of sign elements on the example of an image element, which participates in the recognition (actualization) of the sign, or, in other words, in the formation of the concept of mediated object or process based on perceptual information coming from external environment and registered by internal motor-information sensors. Before giving it a name, let us call the sign proto-sign or feature.

Let us assume that within the incoming data flow a sequence $(x_1, x_2, \ldots, x_h)$ is isolated having the length of h and consisting of real number vectors from 0 to 1, which we will call *events*. Each event x_t with the length of q represents a record of output of q sensors and each component of the event means a certainty of triggering of the sensor. As an example, event $(0.1, 0.9, 0.9)$ arrives from three sensors — red, blue and green light transducers, and signifies that the certainty of red light transducer's triggering is 10%, and of blue and green light transducers — 90% each.

An image element of the sign shall determine, based on the input sequence, whether the mediated object or process is present (coded) in this sequence. To do this we will code characteristic attributes of the object or process in a special structure — causal matrix $z = (e_1, e_2, \dots, e_h)$ having the scale of q by h where q is dimension of input events and h is the length of sequence of the input events. Here every column e_t of the causal matrix is a bit vector having the length of q coding characteristics (to which 1 corresponds) that are necessary to be present in the input event at the moment of t so that the mediated object or process may be recognized within input data flow, that is, that determine a collection of simultaneous characteristics. As an example, image of sign s representing "square" may be represented by the causal matrix

$$z = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix},$$

where the first line represents the characteristic vector of information received by a sensor of angles of the image, the second one — by the position transducer of the visual sensor (upper position), the third — the lowest position of the sensor, the fourth — left position of the sensor and the fifth — right position (see Figure 2.1).

Several causal matrices determining various manifestations of the represented object or process may correspond to the image of each sign. We will designate the complete sequence of causal matrices of sign s image as $Z^p(s)$.

The case, in which a sign's characteristics are data received by sensors, is a special one. In more general statement, a sign's image attributes are other signs representing these specific characteristics. Thus, we are capable of associating the image of sign s with set $S_p(s)$ having the potency of q. Each element of the set corresponds to the number of line of causal matrix z having the dimensions

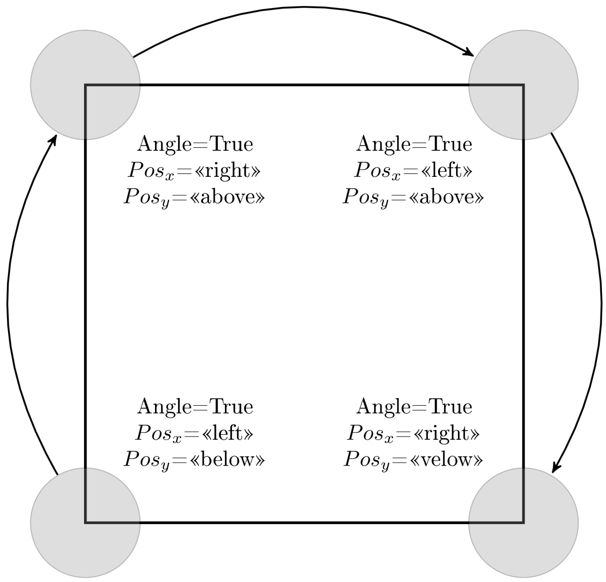

Figure 1: Visual interpretation of the causal matrix

of q by h, that is, each feature $s_i \in S_p(s)$ corresponds to an attribute bit vector setting at position 1 moments in time, when this attribute should be present in input data to actualize the sign s (recognize the image of the sign).

To refine the definition of the set $S_p(s)$ let us introduce a class of binary relations $\{\sqsubset_p, \sqsubset_p^1, \sqsubset_p^2, \dots\}$ determined by Cartesian product $S \times S$. Let us suppose that the sign s_i is *a component of image* of sign s, $(s_i, s) \in \sqsubset_p$ or $s_i \sqsubset_p s$ if $s_i \in S_p(s)$. If it is known that the sign s_i corresponds to 1 in tth column of a certain causal matrix $z \in Z^p(s)$ of sign s, we shall use nested relation $\sqsubset_p^t \subset \sqsubset_p$.

2.2. Causal Network

Let us introduce a special procedure $\Lambda_p : 2^Z \to 2^{\mathbb{N}} \times 2^{\mathbb{N}}$, which associates to every list of causal matrices $Z^p(s) \subset Z$ of image of sign s two non-overlapping subsets of indexes of its own columns $I^c \subset \mathbb{N}, \forall i \in I^c\ i \leq h$ (indexes of condition columns) and $I^e \subset \mathbb{N}, \forall i \in I^e\ i \leq h$ (indexes of effect columns). $\Lambda_p(Z^p(s)) = (I^c, I^e), I^c \cap I^e = \emptyset$. For example, if for a set of matrices $Z = \{((1,0),(0,1))\}$ procedure Λ_p returns two sets $\{1\}$ and $\{2\}$ this means that the occurrence of the feature corresponding to the first line of the matrix causes occurrence of the feature corresponding to the second line. In essence, the procedure Λ_p is a function of establishing cause-and-effect relationship at the set of input events and may be implemented by various means, including Norris algorithm, FcbO, or AddIntent ([43, 44, 45]).

In the case when for matrices $Z^p(s)$ of image of sign s the set of effect columns is empty, $I^e = \emptyset$, that is, when it is impossible to unambiguously determine what events always precede others we will assume that cause-and-effect relationship was not established and the sign mediates a certain object or situation. Otherwise, we will assume that the sign mediates a certain action or process, the result of which is coded in effect columns and condition — in condition columns.

The following statements in respect to properties of procedure Λ_p are valid:

- $I^c \cap I^e = \emptyset$ — a column of prediction matrix may not be simultaneously condition and effect;
- $|I^c \cup I^e| = h$ — a column of prediction matrix is either a condition or an effect;
- $I^c \neq \emptyset$ — among causal matrix columns there must be at least one condition column, whereas there may be no effects (in the case of object features);
- $\forall i \in I^e, j \in I^c \ i > j$ — all conditions precede effects.

Taking the above into consideration, a causal matrix diagram is shown at Figure 2.

Let us now introduce the concept of a causal network, which will determine the heterarchy of a set of images. Causal network $W_p = \langle V_p, E_p \rangle$ is a marked orgraph in which

- every node $v \in V_p$ is associated with a sequence if causal matrices $Z^p(s)$ of image of a certain sign s, which we will designate as $v \to Z^p(s)$;

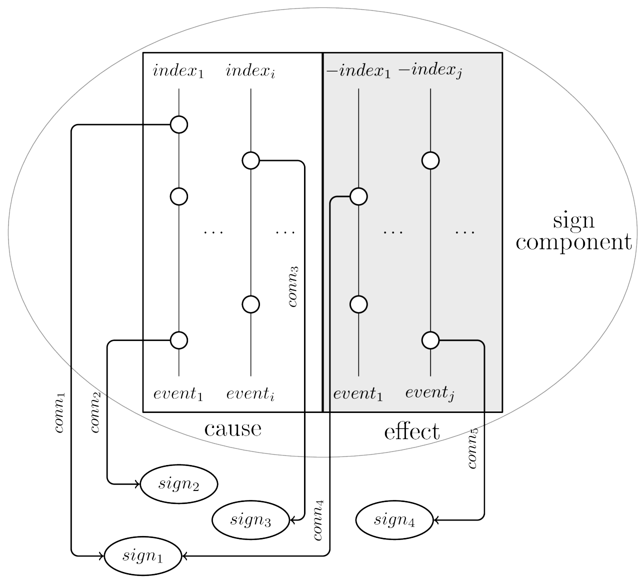

Figure 2: Schema of the causal matrix

- edge $e = (v_1, v_2)$ belongs to a set of graph edges E if $v_1 \rightarrow Z^p(s_1), v_2 \rightarrow Z^p(s_2)$ and $s_1 \in S_p(s_2)$, i.e. if the sign s_1 is an element of sign image s_2;

- each graph edge $e = (v_1, v_2), v_1 \rightarrow Z^p(s_1), v_2 \rightarrow Z^p(s_2)$ is associated with label $\epsilon = (\epsilon_1, \epsilon_2, \epsilon_3)$, a tuple of three natural numbers:

  – ϵ_1 — index of the initial matrix of the sequence $Z^p(s_1)$ may possess a special value of 0 if any matrices of the sequence may serve as source matrices;

  – $\epsilon_2$is the target matrix in the sequence $Z^p(s_2)$ the line of which is associated with feature s_1;

  – ϵ_2 is the index of a column in the target matrix in which the value of the line corresponding to feature s_1 is 1, and the index may possess positive values (condition columns) or negative values (effect column)s.

A causal network represents a certain set of overlapping hierarchies of signs. Every sign is represented by a set of causal matrices determining the image of

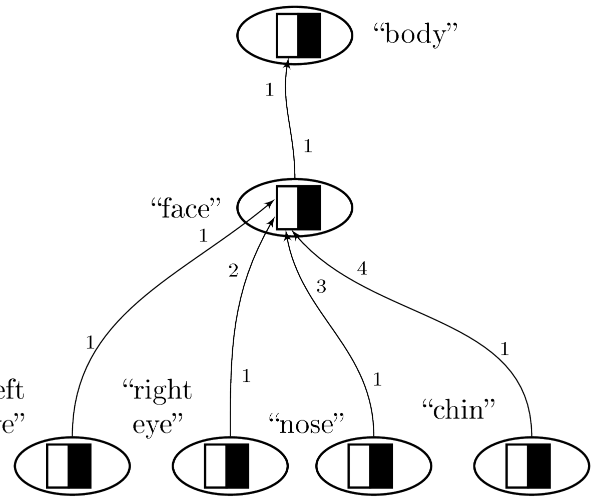

Figure 3: Schema of the causal network. Causal matrices are displayed as squares, condition columns are the left white part of the square, effect columns - the right black part of the square. Label ϵ_1 is placed at the beginning of each arrow, label ϵ_2 is defined as square number in the oval node, label ϵ_3 is placed at the end of each arrow.

the sign, and hierarchy represents hierarchical relations between images. This relation may be read as follows: “sign x participates in the formation of image of sign y”. Here we specify for what specific matrix of sign y and for what specific column of this matrix sign x is required (labels ϵ_2 and ϵ_3 accordingly). In some cases, we may also state sign matrix x (label ϵ_1) participating in the process. The example of such a network is shown on Figure 3.

Similarly, causal networks are determined for the remaining elements of the sign — for significance and personal meaning. For each sign s, sets $S_m(s)$ and $S_a(s)$ are determined, that is, classes of relations $\{\sqsubset_m, \sqsubset_m^1, \sqsubset_m^2, \dots\}$ and $\{\sqsubset_a, \sqsubset_a^1, \sqsubset_a^2, \dots\}$ are determined. Set $S_m(s)$ is interpreted as the role composition of sign s, for example, subset element or action role. Set $S_a(s)$ is interpreted as the immediate element composition of a certain situation observed and experienced presently by a subject, which is a bearer of a world model. Similarly, sets $Z^m(s)$ and $Z^a(s)$, as well as procedures Λ_m and Λ_a are determined.

3. Semiotic network

Let us define sign s as a quadruple $\langle n, p, m, a\rangle$ where n is the name of the sign, p is the image of the sign, a sequence of causal matrices $\langle z_1^p(s), z_2^p(s), \dots\rangle$ corresponding to node $w_p(s)$ of causal matrix for images; m is the significance of the sign, a sequence of causal matrices $\langle z_1^m(s), z_2^m(s), \dots\rangle$ corresponding to node $w_m(s)$ of causal matrix for significances and a is the personal meaning of the sign, a sequence of causal matrices $\langle z_1^a(s), z_2^a(s), \dots\rangle$ corresponding to node $w_a(s)$ of causal matrix for meanings.

Let us define *semiotic network* as the quintuple $\Omega = \langle W_p, W_m, W_a, R_n, \Theta\rangle$ where

- W_p, W_m, W_a are causal networks within the set of images, significances and personal meanings, respectively;
- R_n is a class of relations within the set of signs generated based on the three causal networks, that is $R_n = \{R_p, R_m, R_a\}$;
- Θ is the class of operations of set of signs, which are generated based on three types of causal networks to which respective sign elements belong (see [26] for more detail).

We must emphasize one more time that a sign represents not only the objects of external world, but also the processes occurring in it, realizable actions, as well as the situations observed in external environment. The three types of causal networks composing semiotic network are not independent from each other. The following unambiguous correspondence is established among the nodes of each network: for each node w_x of network W_x, such unique nodes w_y and w_z may be found within networks W_y, W_z $(x, y, z \in \{p, m, a\})$ that all three nodes correspond to the same sign $s = \langle w_p, w_m, w_a\rangle$. A sign's name is the label of nodes in each of the networks: in the causal network, there may be only one node with this label and nodes of all networks with the same labels compose elements of the sign. To associate causal matrices having different types of nodes within one sign, special binding functions are used: $\Psi_p^m, \Psi_m^a, \Psi_a^p$, and functions opposite to them $\Psi_m^p, \Psi_a^m, \Psi_p^a$ [26]. Every binding function associates causal matrix of one type with causal matrix of another type or generates this matrix in case it is absent in the respective node of the network.

Let us introduce the concepts of activity in semiotic network and of its propagation process. Let us introduce a label of activity for causal matrices of network W_x ($x \in \{p, m, a\}$) and call matrix set Z_x^* having this label "active". Activity propagation process is alteration of composition of set Z_x^* over time (at each discrete moment of time) and is described for each type of causal network with the following intrinsic function: $\varphi_a, \varphi_m, \varphi_p$. Activity propagation process is iterative, i.e., at each step a new composition of active matrices is initiated based on the previous composition and it depends on the matrices included into it. In the simplest case, we will discuss the process in which each matrix does not influence the course of activity propagation from another matrix, and consequently, we will assume that functions φ_x accept one active matrix as an input and generate a new subset of active matrices.

Due to the fact that edges of causal networks have directions, we will distinguish the propagation of activity upward within a network, if edges outbound from a node ($\varphi_x^{\uparrow}$ functions) are used, and the propagation of activity downward a network, if edges inbound to a node ($\varphi_x^{\downarrow}$ functions) are used. Further, describing planning algorithm we will need only the functions of significances and personal meaning networks. We will parametrize each function $\varphi_x^{\uparrow}, \varphi_x^{\downarrow}$ by the depth of activity propagation d_x, which shows, on which depth edges can be viewed in a given direction (upward or downward).

Further, when describing planning algorithm we will use the concept of causal network fragment. We will define a fragment F as a certain set of nodes V of network $W_x = \langle V_x, E_x \rangle$ together will all the edges E connecting them: $F = \langle V, E \rangle : V \subseteq V_x$ and $\forall e = (v_1, v_2) \in E v_1 \in V, v_2 \in V$.

4. Planning in Sign World Model

The process of planning in a sign world model is implemented with the use of MAP algorithm and is implemented inversely - from the final to the initial situation. Let us briefly describe the main stages of the algorithm's operation. A problem definition is at the input,

$$T = \langle N_T, S, Sit_{start}, Sit_{goal} \rangle,$$

where N_T is the problem identifier, S is the set of signs of semiotic network, $Sit_{start} = \langle \emptyset, \emptyset, a_{start} \rangle$ is the initial state having the meaning of $a_{start} = \{z^a_{start}\}$ and $Sit_{goal} = \langle \emptyset, \emptyset, a_{goal} \rangle$ is the target situation $a_{goal} = \{z^a_{goal}\}$. In general, problem T is the result of "designation" procedure, that is, the result of forming of a world model using the initial descriptions of planning domain D, which sets the lists of possible actions and object types, as well as planning problems P. The world model includes the definitions of starting conditions and that of final goal (step 1).

The result of MAP planning is a plan. $Plan = \{\langle z^a_{s1}, z^a_{p1} \rangle, \langle z^a_{s2}, z^a_{p2} \rangle, \ldots, \langle z^a_{sn}, z^a_{pn} \rangle\}$, a sequence with the length of n pairs $\langle z^a_{si}, z^a_{pi} \rangle$, where z^a_{si} is the causal matrix of certain network node for personal meanings representing ith planning situation and z^a_{pi} is the causal matrix of certain personal meaning representing the action used in situation z^a_{si}. Here, the situation z^a_{si+1} is the result of the performance of action z^a_{pi} in the meaning that will be elaborated further during the discussion of the algorithm, $z^a_{s1} := z^a_{start}$ is the causal matrix corresponding to the meaning of the initial situation, and $z^a_{sn} = z^a_{goal}$) is the causal matrix corresponding to the meaning of the target situation.

Input: planning domain D, planning task P, maximal iteration deep i_{max}
Output: plan $Plan$

1: $\mathrm{T} = \langle N_T, S, Sit_{start}, Sit_{goal} \rangle := \textsc{ground}(P)$

// N_T - task id, S - set of signs, $Sit_{start} = \langle id_{start}\emptyset, \emptyset, \{z^a_{start}\} \rangle$ - start situation with meaning a_{start}, $Sit_{goal} = \langle id_{goal}\emptyset, \emptyset, \{z^a_{goal}\} \rangle$ - goal situation with meaning a_{goal}

2: $Plan := \textsc{map\_search}(T)$

3: **function** $\textsc{map\_search}(T)$

4: $\quad z_{cur} := z^a_{goal}$

5: $\quad z_{start} := z^a_{start}$

6: $\quad Plans := \textsc{map\_iteration}(z_{cur}, z_{start}, \emptyset, 0)$

7: $\quad \{Plan_0, Plan_1, \dots\} = \textsc{sort}(Plans)$

8: $\quad$ **return** $Plan_0$

Planning process is hierarchical and consists in the repetition of MAP iterations, including four stages (see Figure 4):

- *S-stage* is search for a precedent for performing actions in current situation;
- *M-stage* is search of applicable actions in the network of significances;
- *A-stage* is generation of personal meanings, which correspond to the significances found;
- *P-stage* is building of a new situation using the set of features of conditions of the actions found.

In brief, MAP algorithm performs iterative generation of causal matrices z_{next} of personal meanings based on current active matrix z_{cur} until the maximum number of steps i_{max} is reached (step 10), or the initial matrix z_{start} (step 41) corresponding to the personal meaning a_{start} of the initial situation is completely activated. A matrix corresponding to the personal meaning of target situation z^a_{goal} (step 6) serves as active causal matrix for the first iteration. Upon completion of all iterations, the plans found are sorted by length (step 7)

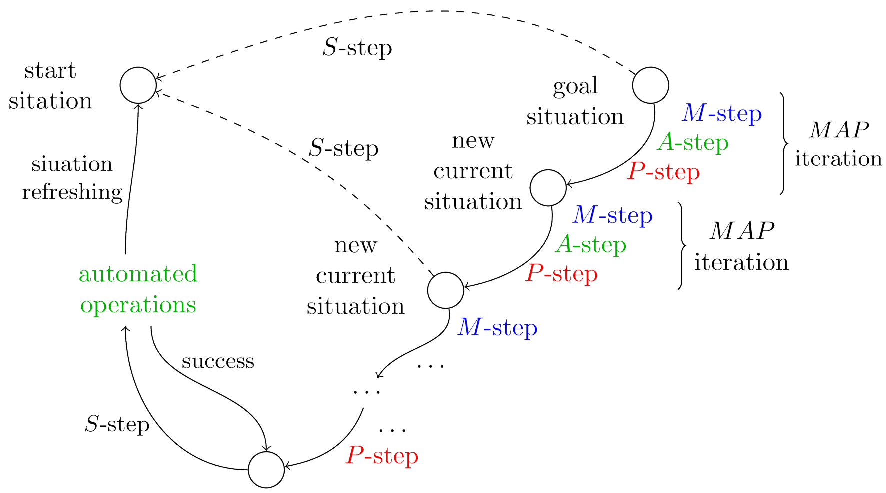

Figure 4: Schema of the behavior planning process

and the shortest of them represent the solution of the planning problem in sign world model (step 8).

The first stage of MAP iteration is S-stage. Its essence is that search for precedents is performed within the world model of an intelligent agent, i.e., search for actions that were performed in current conditions z_{cur}. To achieve that, all signs in world model S are reviewed, as well as their personal meanings $a(s)$ (steps13 – 14). If current conditions z_{cur} are satisfied with matrix z_a, the list of precedents $\hat{A}_{case}$ is supplemented by the activity in personal meaning networks of sign s for the distance of d_a (step 16).

After that, MAP algorithm switches to M-stage, at which the propagation of activity through personal meaning is performed over the distance of d_a for the purpose of activating all signs related to the current situation (step 17). The components of the obtained set of causal matrices A^* serve as the starting points for activity propagation over the network of significances: using binding function z_a, for each matrix Ψ_a^m the required node is determined in the causal network of significances, from which activity propagates over the distance of

9: **function** MAP_ITERATION(z_{cur},z_{start}, $Plan_{cur}$, i)

10:   **if** $i \geq i_{max}$ **then**

11:     **return** $\emptyset$

12:   $\hat{A}_{case} := \emptyset$ // List of precedents

// S-stage

// Search of action cases for current conditions

13:   **for all** $s \in S$ **do**

14:     **for all** $z_a \in a(s)$ **do**

15:       **if** $z_a \geq z_{cur}$ **then**

16:         $\hat{A}_{case} = \hat{A}_{case} \cup \varphi_a^{\uparrow}(s, d_a)$

d_m (step 20). If the activated matrices are causal, they are added to the set of active significances M^* (step 22).

// M-stage

// Spreading of activity downward in the personal meaning network

17:   $A^* = \varphi_a^{\downarrow}(z_{cur}, d_a)$

18:   $M^* = \emptyset$

19:   **for all** $z_a \in A^*$ **do**

// Spreading of activity upward in the significance network

20:     **for all** $z_m \in \varphi_m^{\uparrow}(s(z_a), d_m)$ **do**

21:       **if** $I^e(z_m) \neq \emptyset$ **then**

22:         $M^* := M^* \cup \{z_m\}$

After that, we switch to A-stage, at which causal matrix generation is performed in personal meaning network, the former represent actions z_{cur} specified in relation to current conditions determined by the active significances of the set M^*. For this purpose, steps 25 –27 are performed, during which the propagation of activity in causal network of significances over the distance of d_m leads to the activation of set of significances M^* of signs related to role structure of procedure matrix z_m. After that, using binding function Ψ_m^a a new causal matrix is generated in personal meaning network copying values z_m^* and it replaces abstract signs-roles with object signs associated with roles by a set-subset relation. Further, at A-stage, selection of causal matrices is performed that represent the actions in current conditions z_{cur} (steps 30 – 32). For this purpose, all causal matrices, the effects of which are not included in the current situation are deleted (it should be borne in mind that planning is performed inversely). Finally, at A-stage, one of the operations within world model θ_a is performed, which provides in this case meta-adjustment — checking for a certain heuristic rule, which may mean, for example, that no action may be repeated, or that it is better to perform the action that advances to the initial conditions z_{start} the fastest (step 33). Any heuristic rule can also be represented by a causal matrix of personal meaning of the sign representing the internal strategy of it behavior planning.

// *A*-stage

23: $\hat{A}_{gen} = \emptyset$

24: **for all** $z_m \in M^*$ **do**

// Spreading activity downward in the significance network

25: $M^* = \varphi_m^{\downarrow}(z_m, d_m)$

26: **for all** $z_m^* \in M^*$ **do**

27: $\hat{A}_{gen} := \hat{A}_{gen} \cup \{\Psi_m^a(z_m^*)\}$

// Merging of activity of formed meanings and meaning of the current situation

28: $\hat{A} = \hat{A}_{gen} \cup \hat{A}_{case}$

29: **for all** $z_a \in \hat{A}$ **do**

30: $z_{shift} = (e_i | i \in I^e)$

31: **if** $z_{cur} \not\supseteq z_{shift}$ **then**

32: $\hat{A} = \hat{A} \setminus \{z_a\}$

// Checking of metacognitive heuristic

33: $\hat{A} = \{\theta_a(z_a) | z_a \in \hat{A}\}$

34: **if** $\hat{A} = \emptyset$ **then**

35: **return** $\emptyset$

MAP algorithm concludes with P-stage. Here, for every generated causal matrix z_a, which represents a certain action, new situation Sit_{next} is generated, which is the result of reverse application of action in the current conditions z_{cur}. Reverse application (step 39) includes generation of a causal matrix z_{next} consisting of events, which are condition columns of action $e_i \in \{e_k | e_k \in z_a, k \in I^c(z_a)$ or belong to the current active causal matrix and are not condition columns of action $e_i \in z_{cur} \wedge e_i \notin \{e_j | e_j \in z_a, j \in I^e(z_a)\}$. In the current plan $Plan_{cur}$, current conditions are applicable action pair $\langle z_{cur}, z_a \rangle$. If the new situation does not overlap the starting situation (step 41), iterations continue with the new current situation thus supplementing all set of generated plans $Plans_{fin}$.

Constants d_a, d_m, which determine the depth of activity propagation within causal networks are parameters of the algorithm and determine internal characteristic of the world model bearer, varying from agent to agent. Usually, in model experiments these parameters do not exceed 5.

// P-stage

36: $Plans_{fin} := \emptyset$

37: **for all** $z_a \in \hat{A}$ **do**

38: $Plan_{cur} = Plan_{cur} \cup \{\langle z_{cur}, z_a \rangle\}$

// Generation of new situation - action application

39: $z_{next} := (e_i | (e_i \in z_{cur} \wedge e_i \notin \{e_j | e_j \in z_a, j \in I^e(z_a)\}) \vee e_i \in \{e_k | e_k \in z_a, k \in I^c(z_a)\})$

40: $Sit_{next} = \langle id_{next}, \emptyset, \emptyset, \{z_{next}\} \rangle$

41: **if** $z_{next} \geq z_{start}$ **then**

42: $Plans_{fin} = Plans_{fin} \cup \{Plan_{cur}\}$

43: **else**

44: $Plans_{rec} :=$ MAP_ITERATION(z_{next},z_{start}, $Plan_{cur}$, $i+1$)

45: $Plans_{fin} = Plans_{fin} \cup Plans_{rec}$

46: **return** $Plans_{fin}$

(define (**domain BLOCKS**) (:requirements :strips :typing) (:types block) (:predicates (on ?x - block ?y - block) (ontable ?x - block) (clear ?x - block) (handempty) (holding ?x - block))	(:**action pick-up** :parameters (?x - block) :precondition (and (clear ?x) (ontable ?x) (handempty)) :effect (and (not (ontable ?x)) (not (clear ?x)) (not (handempty)) (holding ?x)))	(:**action put-down** :parameters (?x - block) :precondition (holding ?x) :effect (and (not (holding ?x)) (clear ?x) (handempty) (ontable ?x)))
(:**action stack** :parameters (?x - block ?y - block) :precondition (and (holding ?x) (clear ?y)) :effect (and (not (holding ?x)) (not (clear ?y)) (clear ?x) (handempty) (on ?x ?y)))	(:**action unstack** :parameters (?x - block ?y - block) :precondition (and (on ?x ?y) (clear ?x) (handempty)) :effect (and (holding ?x) (clear ?y) (not (clear ?x)) (not (handempty)) (not (on ?x ?y)))))	(define (**problem BLOCKS-4-0**) (:domain BLOCKS) (:objects D B A C - block) (:INIT (CLEAR C) (CLEAR A) (CLEAR B) (CLEAR D) (ONTABLE C) (ONTABLE A) (ONTABLE B) (ONTABLE D) (HANDEMPTY)) (:goal (AND (ON D C) (ON C B) (ON B A))))

Table 1: Description of the planning domain “block world” and a task of tower building (“BLOCKS-4-0”).

5. A Model Experiment: Cube World

Let us demonstrate work of the presented behavior planning algorithm by a model experiment in which planning domain is the example of “block world” well known in the field of automation planning [46]. Description of the domain in PDDL language [47] consists of type definition of (*blocks*), four predicates (*ontable*, *clear*, *handempty*, *holding*) and four actions (*pick-up*, *put-down*, *stack*, *unstack*) (see Table 1).

Using MAP algorithm, let us make an example of a solution of a planning

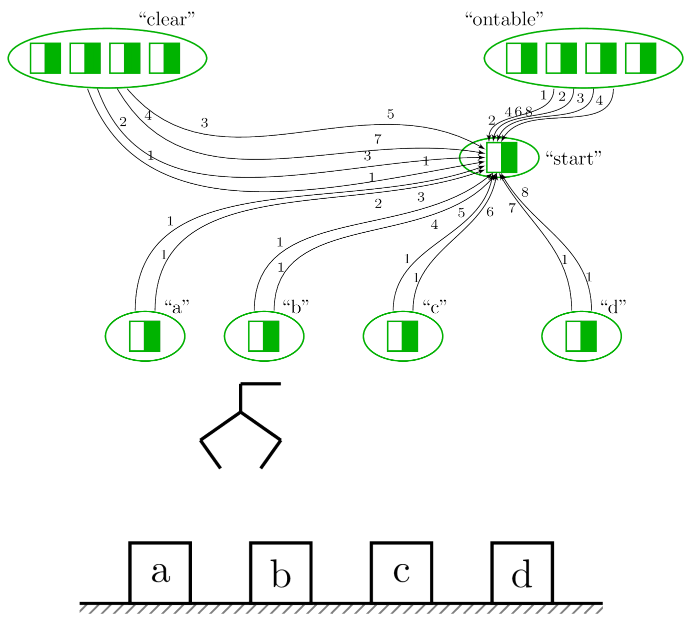

Figure 5: Start situation: all blocks are on the table.

problem — building a tower of four blocks, which lay on the table (Table 1). A fragment of causal network of personal meanings, which determines causal matrix of meaning named *start* is shown at Figure 5. Each separate block (a, b, c, d) has one causal matrix situated in a network node, whereas each of the predicates *clear* and *ontable* have four matrices in a node, since they participate in events with different blocks. For example, matrices of sign *clear* are preset in 1st, 3rd, 5th and 7th columns of sign matrix *start* simultaneously with blocks a, b, c and d respectively, which means that no blocks are located on any of the blocks.

Figure 6 shows the target situation in which all four blocks are stacked in a tower: block d is located at the table, block c — on d, b — on c, and finally block a is at the top. Predicate *on*, which defines the relation “located on” may be represented in the form of a procedural causal matrix, so as to demonstrate nonsymmetry of this relation distinctly, notwithstanding the fact that use of object matrix has no influence on the result. Here, one causal matrix of each

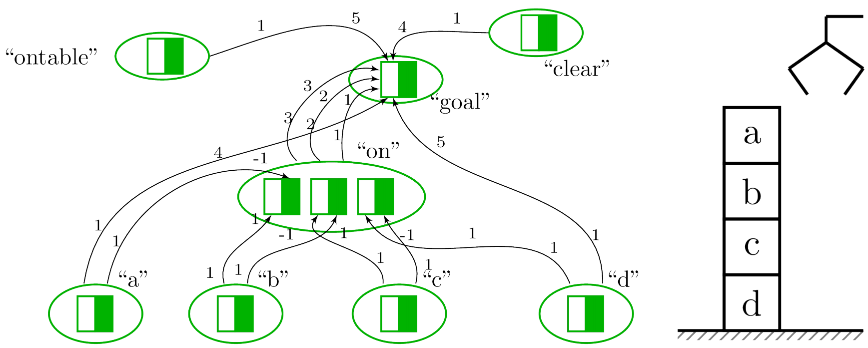

Figure 6: Goal situation: a tower built from four blocks.

block also participates in the situation, and the predicate *on* is represented as a node with three causal matrices, since it participates in causal matrix of the target situation *goal* in different columns with three different blocks.

Figure 7 shows a fragment of causal network for significances representing components of procedural causal matrix of sign *stack* and relations“set-subset” of objects (blocks), of class *block* and roles in action *stack*: *block?x* (analog of semantic role “object”) *block?y* (analog of semantic role“directive”). It should be noted here that in the case of “set-subset” relation ($a \rightarrow block$, $block \rightarrow block?x$) ϵ_1 edge label v (index of the original matrix of the node, from which the edge is outbound v) possesses special zero value indicating that any causal matrix of this node may be original. In other words, any of the blocks a, b, c or d may play the role of *block?x*.

Let us discuss the stages of MAP algorithm, S, M, A and P-stages, at the first iteration of the algorithm. Let us discuss the simplest case when our intelligent agent has not accumulated any experience of acting in the context of the presented problem. Due to this, at S-stage set of precedents $\hat{A}_{case}$ will be empty. Taking into consideration the fact that planning is performed inversely, at the first M-stage we view target situation as the current active prediction matrix z_{cur} and propagation of activity from it downward the personal meaning network will activate set A^*, which coincides with the fragment shown at

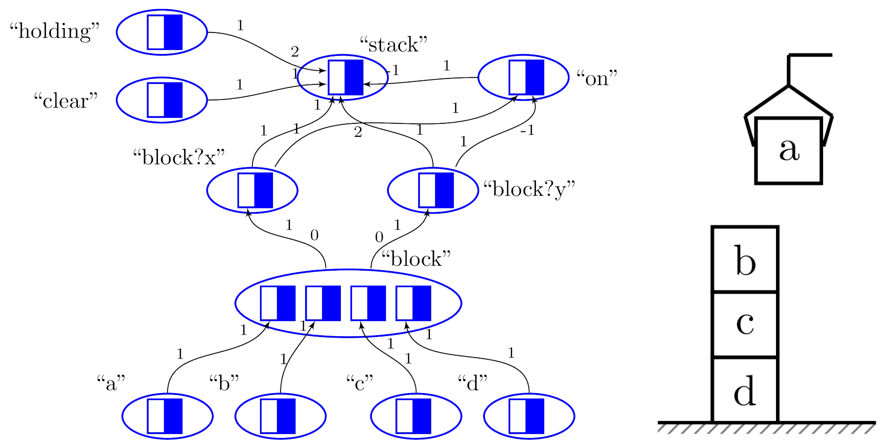

Figure 7: Fragment of the causal network: representation of the action *stack*.

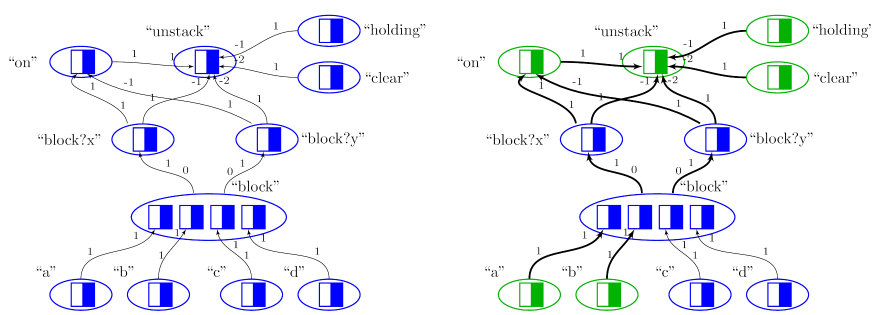

Figure 8: Spreading activity in the significance network, generation of personal meaning of the sign *unstack*.

Figure 5. The set of significances M^* will include the significances of the signs representing blocks a,b,c,d — these all are procedural sign associated with them within meaning network *stack*, *unstack*, *pick-up*, *put-down*. Left part of Figure 8 shows a fragment of causal network for significances, which includes procedural causal matrix *unstack*. To activate causal matrix *unstack* by matrix a, it is enough to use value of three edges as constant d_m.

At A-stage, generation of new causal matrices $\hat{A}_{gen}$ occurs in personal meaning network by propagating activity downward the network of significances. An example of this propagation, which results in a new causal matrix of sign *un-*

stack, is shown at the right part of Figure 8. The new causal matrix of personal meaning matrix is a copy of corresponding matrix for network of significances with references pointing to role signs, replaced with references pointing to object non-abstract signs representing blocks. In our example, a matrix corresponding to action $unstack(a,\ b)$ — remove block a from block b will be generated. At this stage, four matrices for each single-place actions will be generated and twelve — for two-place actions.

A-stage is completed with testing of effects of the generated procedural matrices for applicability in the current situation and among applicable actions those satisfying a certain meta-cognitive (heuristic) rule θ_a are selected. In our example, of all the generated variants the action $unstack(a,b)$ will be the only applicable action. As the heuristic rule, the following greedy rule may be used: select actions that bring success the fastest (the new situation has more common features with the target situation).

At the end of iteration, at P-stage, new causal matrix z_{next} is generated in personal meaning network of the sign representing the next planning situation. In our example, the new current situation will coincide with the previous with the exception that block a is now held by manipulator and there is nothing on block b. A pair $\langle z_{cur}, z_a \rangle$ of causal matrices of the current situation and the selected action is added to the current $Plan_{cur}$ plan. Since the new situation does not include starting situation, we will begin a new iteration.

In our example, as the result of activity of MAP algorithm the following plan of 6 actions will be generated: $pick\text{-}up(c)$, $stack(c,d)$, $pick\text{-}up(b)$, $stack(b,c)$, $pick\text{-}up(a)$, $stack(a,b)$. After the agent completes working on this problem, it saves planning precedent in its world model: it saves the initial and the final situation in the form of new signs and generates a new procedural sign, which could be called "build a tower". The initial situation will be the only feature in condition column of this sign and the target situation will be the only attribute in effect column. After that, the intelligent agent will be able to solve the same problem by finding at S-stage the required action that will lead to the solution immediately. The same situation my occur while solving another problem leading to reduction of applicable action search space.

6. Conclusion

In the classical symbol planning problem definition, Artificial Intelligence faces the problem of combining symbol planning algorithms with the methods of learning, which allow both to preserve planning experience and adapt to new conditions. This problem overlaps with symbol grounding problem — the problem of associating symbols used in the classical method of knowledge representation with real objects, processes, and properties of external environment. These problems are very vividly manifested in the area of implementing learning robotics systems, for which it is important to associate the symbols used in conceptual planning and the data obtained by sensors. It should be noted that when complex technical system is presented with a planning problem in a broad spectrum of conditions, including cooperative, approaches using a preset, albeit replenished knowledge base, prove to be inefficient. A method of representing knowledge serving as the basis for the functions of control of an intelligent agent should inherently support the possibility to associate symbols with sensor data, as well as support the representation of both internal information and generalized information coordinated between other participants of the group. This article solves the said problems by using sign world model. We present an original planning method (MAP algorithm), which uses and maintains the precedent information in the process of plan generation. The four-component world model component (sign) used allows coding both the information of external environment and internal attributes, motivation and need properties, as well as general collective knowledge. The algorithm presented may also be used for the generation of cooperative plans. To demonstrate MAP Planner, a model example of generation as to the plan for one of the "block world" problems is presented. Software support and model experiments may as well be found at https://github.com/cog-isa/map-planner.

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