Information systems. Computer sciences. Issues of information security

Информационные системы. Информатика. Проблемы информационной безопасности

UDC 004.825
https://doi.org/10.32362/2500-316X-2022-10-5-7-15

RESEARCH ARTICLE

Structure of associative heterarchical memory

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Abstract
Objectives. Since the 20th century, artificial intelligence methods can be divided into two paradigms: top-down and bottom-up. While the methods of the ascending paradigm are difficult to interpret as natural language outputs, those applied according to the descending paradigm make it difficult to actualize information. Thus, natural language processing (NLP) by artificial intelligence remains a pressing problem of our time. The main task of NLP is to create applications that can process and understand natural languages. According to the presented approach to the construction of artificial intelligence agents (AI-agents), processing of natural language should be conducted at two levels: at the bottom, methods of the ascending paradigm are employed, while symbolic methods associated with the descending paradigm are used at the top. To solve these problems, the authors of the present paper propose a new mathematical formalism: associative heterarchical memory (AH-memory), whose structure and functionality are based both on bionic principles and on the achievements of top-down and bottom-up artificial intelligence paradigms.
Methods. Natural language recognition algorithms were used in conjunction with various artificial intelligence methods.
Results. The problem of character binding as applied to AH-memory was explored by the research group in earlier research. Here, abstract symbol binding was performed using multi-serial integration, eventually converting the primary symbols produced by the program into integrated abstract symbols. The present paper provides a comprehensive description of AH-memory in the form of formulas, along with their explanations and corresponding schemes.
Conclusions. The most universal structure of AH-memory is presented. When working with AH-memory, a developer should select from a variety of possible module sets those AH-memory components that support the most successful and efficient functioning of the AI-agent.

Keywords: artificial intelligence, natural language processing, associative heterarchical memory, AI-agent, abstract symbols, hypernet, predicate symbol control model, actant role classifier, hypergraph

• **Submitted:** 16.03.2022 • **Revised:** 13.07.2022 • **Accepted:** 12.09.2022

For citation: Dushkin R.V., Lelekova V.A., Stepankov V.Y., Fadeeva S. Structure of associative heterarchical memory. *Russ. Technol. J.* 2022;10(5):7–15. https://doi.org/10.32362/2500-316X-2022-10-5-7-15

Financial disclosure: The authors have no a financial or property interest in any material or method mentioned.

The authors declare no conflicts of interest.

НАУЧНАЯ СТАТЬЯ

Структура ассоциативно-гетерархической памяти

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Резюме

Цели. Начиная с XX века методы искусственного интеллекта разделяют на две парадигмы – нисходящую и восходящую. Методы восходящей парадигмы сложно интерпретировать в виде вывода естественного языка, а в методах нисходящей парадигмы затруднена актуализация информации. Обработка естественного языка (NLP, от англ. Natural Language Processing) искусственным интеллектом остается актуальной проблемой современности. Основная задача NLP – создание программ, способных обрабатывать и понимать естественные языки. С учетом авторского подхода к построению агентов искусственного интеллекта (ИИ-агентов) обработка естественного языка должна также вестись на двух уровнях: на нижнем – при помощи методов восходящей парадигмы и на верхнем – при помощи символьных методов нисходящей парадигмы. Для решения этих задач авторами предложен новый математический формализм – ассоциативно-гетерархическая память (АГ-память), структура и функционирование которой основаны как на бионических принципах, так и на достижениях обеих парадигм искусственного интеллекта.

Методы. Использованы методы искусственного интеллекта и алгоритмы распознавания естественного языка.

Результаты. Ранее авторским коллективом была исследована проблема привязки символов в приложении к АГ-памяти. В ней привязка абстрактных символов осуществлялась с помощью мультисенсорной интеграции. При этом первичные символы, получаемые программой, преобразовывались в интегрированные абстрактные символы. В данной статье приведено полное описание АГ-памяти в виде формул, пояснений к ним и соответствующим схемам.

Выводы. В статье представлена максимально универсальная структура АГ-памяти. При работе с АГ-памятью из множества возможных модулей следует выбирать те части АГ-памяти, которые обеспечивают успешное и эффективное функционирование ИИ-агента.

Ключевые слова: искусственный интеллект, обработка естественного языка, ассоциативно-гетерархическая память, ИИ-агент, абстрактные символы, гиперсеть, модель управления предикатного символа, классификатор ролей актантов, гиперграф

• **Поступила:** 16.03.2022 • **Доработана:** 13.07.2022 • **Принята к опубликованию:** 12.09.2022

Для цитирования: Душкин Р.В., Лелекова В.А., Степаньков В.Ю., Фадеева С. Структура ассоциативно-гетерархической памяти. *Russ. Technol. J.* 2022;10(5):7–15. https://doi.org/10.32362/2500-316X-2022-10-5-7-15

Прозрачность финансовой деятельности: Авторы не имеют финансовой заинтересованности в представленных материалах или методах.

Авторы заявляют об отсутствии конфликта интересов.

Glossarium

Artificial intelligence (AI) is a set of technological solutions for simulating human cognitive functions (including self-learning, finding solutions without a predetermined algorithm, and obtaining insights) and yielding specific, practically significant results that are at least comparable with those gained through human intellectual activity.

Natural language processing is a subfield of computer science and AI dedicated to the analysis of natural (human) languages using computers.

AI-agent is a fully-fledged cybernetic machine encompassing a control system that continuously receives information from its sensory systems and operates on its environment by means of actuators.

INTRODUCTION

Artificial intelligence methods [1] can be divided into two paradigms: top-down and bottom-up [2]. Methods associated with the bottom-up paradigm are used to build models of cognitive processes that rely on large amounts of data. Thus, while the accuracy of results from the thus constructed "black box" model can be brought to the required value, the relevant decision-making processes are difficult (or even almost impossible) to interpret from a human point of view [3]. Conversely, when using knowledge-based "white-box" models generated according to the top-down paradigm, difficulties arise in maintaining the relevance of the state when the structure of the problem area changes; moreover, the construction of such models is an inherently complex and time-consuming process [4].

Thus, natural language[1] processing (NLP) by artificial intelligence remains an urgent problem [5, 6]. The main challenge for NLP is to create applications for processing and understanding natural languages. Taking into account the presented approach to the construction of AI-agents [7], natural language processing should be carried out at two levels: (1) at the lower level using methods of the ascending paradigm (deep learning neural networks for solving linguistic problems); (2) at the upper level using symbolic methods of the descending paradigm (semantic networks and an associated ontology for knowledge representation and machine inference).

To solve these problems, the authors propose a novel mathematical formalism referred to as associative heterarchical memory (AH-memory), whose structure and functionality are based both on bionic principles and on the achievements of both paradigms of artificial intelligence. AH memory is based on this understanding of the structure of the *cognitome*. In terms of its structure, it comprises a hypergraph [8], in which nodes are comprised of symbols, while links and hyperlinks between symbols represent a mapping of relationships between concepts.

This article presents a complete description of the set-theoretic structure of AH-memory.

STRUCTURE OF ASSOCIATIVE HETERARCHICAL MEMORY

AH-memory comprises a tuple, i.e., an ordered set of elements of a fixed length, further presented in formula (1), between whose elements are five sets of links shown in Fig. 1 in the form of a graph [9].

[1] Natural language is a language that human beings speak or write.

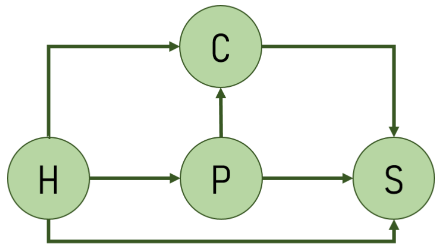

Fig. 1. Graph of links between AH-memory objects

A link between two sets on a graph denotes the entire set of associative links between their objects.

$$AG = <S, C, P, H, L>,$$

where S is the set of abstract symbols, whose formation scheme is shown in Fig. 2; C is the AG-hypernetwork of general knowledge; P is the AG-hypernetwork of particular knowledge; H is the AG-hypernetwork of personal history; L is the set of associative links between the objects of the sets S, C, P, and H.

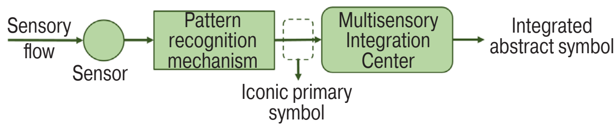

Fig. 2. Scheme for the formation of an abstract symbol

The formation of an abstract symbol takes place as follows:

1. The sensory channel input of the AI agent receives a discrete or continuous sensory data stream, which is filtered by the corresponding sensor and sent for processing to the image recognition mechanism.
2. After selecting and isolating the perceived images from the sensory stream, the image recognition mechanism of the corresponding sensory modality sends them to the multisensory integration center. Sensory modalities may consist of one or more sensory systems, each consisting of one or more sensory channels [10].
3. The multisensory integration center collects selected and recognized images from all sensory modalities of the AI agent and builds an integrated abstract symbol associated with all recognized sensory perception images. Thus, the AI agent solves the problem of symbol binding [11].

The S object represents the following structure:

$$S = \{s_i\}_{i=1}^{N},$$

where s_i is an abstract symbol with identifier i having N abstract symbols in the set S. Moreover, each abstract symbol s_i is the following object:

$$s_i = <UID, R>,$$

where s_i is an arbitrary unique sequence of characters from the selected alphabet V; *UID* is a unique identifier [12] of an abstract symbol; R is a labeled set of primary sensory symbols to which the abstract symbol s_i is attached.

$$R = \bigcup_{i=1}^{K} R_i, \text{ wherein } R_i \cap R_j = \emptyset, \text{ if } i \neq j.$$

The AI-agent has *K* sensory modalities; the sets R_i ($i = 1, ..., K$) are the sets of primary sensory symbols for each sensory modality *i*. From a mathematical standpoint, the AH-hypernets C, P, and H comprise hypergraphs [13], i.e., generalized cases of a graph, in which any subset of vertices can be connected by an edge. AH memory elements C, P, and H comprise the following tuple:

$$e = <(s^*|m|m^*|g|k|T|N), x, f>, \quad (2)$$

where *N* is a hyperlink between AH-memory objects from sets C, P, or H; *x* is the current level of excitation of the AH-memory element; *f* is the activation function of the AH-memory element; *m* is a second-order abstract symbol $m = <UID, Pr, Mt>$, where *UID* is a unique symbol identifier; Pr and Mt are sets of properties and meta-properties of symbols, respectively; s^* and m^* are a link to an abstract symbol from the set S and a link to an abstract symbol of the second order from the sets C, P and H, respectively, which are symbol identifiers with additional information by which you can identify the link type and the link itself:

$$s^* = <S', UID, UID^*>, m^* = <M', UID, UID^*>.$$

Here *S'* and *M'* are labels confirming the relevance of links; *UID* is the unique identifier of *s* and *m*, to which there is a corresponding link; UID^* is the unique identifier of the link itself.

Meta-properties from the set Mt comprise a semantic set of properties reflected in the patterns of the AI agent and directly embedded in the code. Properties from the Pr set are purely syntactic constructions, whose semantics are unknown to the AI agent at the program level and which are revealed only during the functioning of the AH memory, taking into account the binding of all symbols to sensory information. Both sets comprise a set of elements of the following form:

$$p = <name, value, type, unit>,$$

where all the objects that make up the *p* property are strings: *name*—name of the property; *value*—the value of the property must be non-empty; *type*—the type of the property; *unit*—the unit of measurement of the property (value can be empty).

A property of a particular AH-memory element can be identified by a unique identifier such as UID.name, i.e., there cannot be two properties having the same name in a single element of AH-memory.

In (2) *g* is a functional symbol designated for those elements of knowledge of the AI-agent that have special behavioral responses or special processing procedures, such as quantifiers or logical propositional connectives (conjunctions "and," "or," etc.). Function symbols used to describe arbitrary relationships between some elements of the AH-memory represent the following tuple:

$$g = \left\langle UID, ID, \{e_i^*\}_{i=1}^{Z} \right\rangle,$$

where *UID* is the unique identifier of the functional symbol; *ID* is the identifier of the type of functionality, necessary to indicate which behavioural pattern of the AI agent corresponds to the selected functional symbol; e_i^* is the *i*th reference to the AH-memory element from the set of operands (value, variable or expression located to the left or right of the operator) of the function symbol; *Z* is the number of operands of the function symbol.

The symbol k in (2) denotes a list of AH-memory elements for grouping AH-memory elements into a single object: this is necessary for the formation of hierarchies and heterarchies. In actuality, k is an identified and ordered set of references to arbitrary AH-memory objects, expressed in the following tuple:

$$k = <UID, \{e_i^*\}_{i=1}^{Y}, Pr, Mt>,$$

where *UID* is a unique identifier of the list of AH-memory elements; e_i^* is the *i*th link to the AH-memory element; *Y* is the number of elements in the list; Pr and Mt are sets of properties and meta-properties of the list of AH-memory elements, respectively, defined similarly to symbol *m*.

In (2), the control model template of the predicate symbol T [14] is the following tuple:

$$T = <UID, s^*, A>,$$

where *UID* is the unique ID of the predicate symbol control model template; s^* is a reference to an abstract symbol from the set S, which corresponds to the predicate of the described control model template; $A = \{a_i\}_{i=1}^{Q}$ is the set of actants in the control model of the predicate symbol, consisting of the *i*th number of actants of valence *Q* (the total number of actants) of the predicate symbol. The actant in the control model of the predicate symbol *a* represents the role of the element that occupies a vacant place in the case of the implementation of the control model template [15].

For a specific AI-agent, a classifier of the roles of elements in control models of predicate symbols should be compiled. The proposed classifier of the roles of actants (language expressions that fill the valence of a predicate symbol), which solves the problems of natural language processing, is given as follows:

1. SUBJECT is the actant role that performs the action of a predicate symbol, whose control model is described by a template. In natural language, this can be expressed as a subject in the syntactic construction of a predicate.
2. OBJECT is the actant role on which the action of the predicate symbol is performed, whose control model is described by the template. In natural language, this can be expressed as a direct object in the syntactic construction of the predicate.
3. LOCATION is the actant role indicating the place of the action execution of the predicate symbol, whose control model is described by the template. In natural language, this can be expressed as an adverbial place in the syntactic construction of the predicate, or as an object in some grammatical locative. This role can also be divided into several sub-roles, among which there can be such frequently used ones as LOCATION-FROM (LOC-FROM) and LOCATION-TO (LOC-TO), denoting places—source and destination—of the motion realized by the action of the predicate symbol.
4. TIME is the actant role indicating the execution time of the action of the predicate symbol, the control model of which is described by the template. In natural language, this can be expressed as a time circumstance in the syntactic construction of the predicate.
5. CAUSE is the actant role indicating the reason for the execution of the action of the predicate symbol, whose control model is described by the template. This is usually expressed in natural language as a subordinate syntactic construction that introduces causal relations into the statement.
6. PURPOSE is the actant role indicating the purpose of performing the action of the predicate symbol, the control model of which is described by the template. In natural language, this can be expressed as a subordinate syntactic construction that introduces causal relations into the statement. In this case, the predicate itself, describing the action, acts as a reason for the actant-goal.
7. TOOL is the actant role indicating the method (tool) for performing the action of the predicate symbol, whose control model is described by the template. In natural language, this can be expressed as an indirect object in the syntactic construction of the predicate in the instrumental grammatical case.
8. MATERIAL is the actant role indicating the material from which the object is produced during the execution of the action of the predicate symbol, whose control model is described by the template. In natural language, this role can be expressed by means of an indirect object in the prepositional case using prepositions such as "of" (or similar grammatical constructions in other languages).
9. IMAGE OF ACTION (HOW-TO) is the actant role, which indicates the method (attribute) of performing the action of the predicate symbol, the control model of which is described by the template. Usually, in natural language it is expressed using an adverb referring to the predicate in the sentence describing the fact.

Here, the action also means the state of the subject or the change of such a state; this can also be expressed by predicate symbols in natural language.

Since the predicate with its control model is a description of the fact about the existence of an AI being, the presented classifier of the roles of actants in the control model holistically and fully describes the possible situations in which an AI-agent finds itself within the framework of various facts of its personal history.

For a particular predicate, the control model template may contain a subset of distinguished actants. At the same time, almost any predicate must comprise in its control model actants with the roles of SUBJECT and OBJECT.

As an example, consider the CREATE predicate. Its template will have 7 actants listed in the presented actant role classifier. Figure 3 shows the scheme of the CREATE predicate template.

Here, it should be noted that not all vacant roles of actants can be filled when implementing the predicate symbol template.

The hyperlink N between AH-memory objects from the sets C, P, or H is a specific implementation of the predicate symbol control model. Each hyperlink in AH-memory is a predicate symbol describing some fact from the personal history of the AI-agent. Thus, the hyperlink N comprises the following object:

$$N = <UID, w, t^*, \{s_i^* \mid e_i^*\}_{i=1}^{Q}>,$$

where UID is a unique hyperlink identifier; w are all hyperlink activations ($w \in [0,1]$); t^* is the reference to the control template of the predicate symbol; $s_i{}^*$ is a reference to the abstract symbol of the set S, replacing the vacant role i in the control model of the predicate symbol; e_i^* is a reference to an element of the sets C, P, or H, replacing the vacant role i in the control model of the predicate symbol.

The most interesting option from the presented possibilities for replacing the vacant actant of the control model of the predicate symbol is the element of e_i^* type, since this actually allows any other element of the sets C, P or H to act as an actant of the predicate, including hyperlinks *N*. Since any actant can be another fact from personal history, this makes the AG-hypernetwork very flexible for describing facts from the personal history of an AI-agent; thus, the AH-hypernet becomes a hypergraph from a mathematical standpoint. This structure allows a very flexible processing of facts as revealed in natural language texts describing the personal history of an AI-agent.

Finally, the set of associative links L consists of objects of the following form:

$$l = <UID, ID, w(e_1^*, e_2^*)>,$$

where *UID* is a unique identifier for a specific connection; *ID* is a non-unique identifier (type) of the connection; *w* is the connection activation weight ($w \in [0,1]$); e_1^* and e_2^* are the references to elements of sets C, P, or H. (In this case, the link *l* is directed and goes from element e_1^* to element e_2^*.)

For a specific manifestation of an AI-agent, it is necessary to create an exhaustive set of possible link identifiers, the semantics of which can be written at the level of the program code of a specific AI-agent.

It remains to note that the activation weight $w[0,1]$ used in AH-memory links and hyperlinks, the level of excitation of the element *x* and the activation function of the AH-memory element *f* are used in the procedures of knowledge processing and inference on the facts recorded in the AH-memory, which will be described in detail in subsequent articles.

A summary diagram of the structure of the AH-memory is shown in Fig. 4.

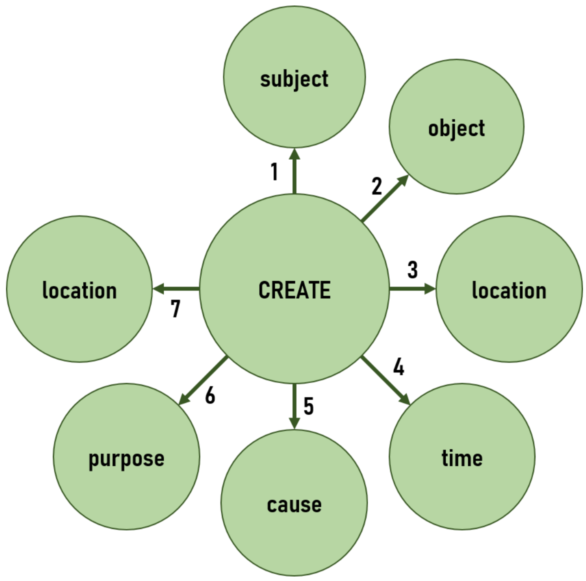

Fig. 3. Template of the control model of the CREATE predicate symbol

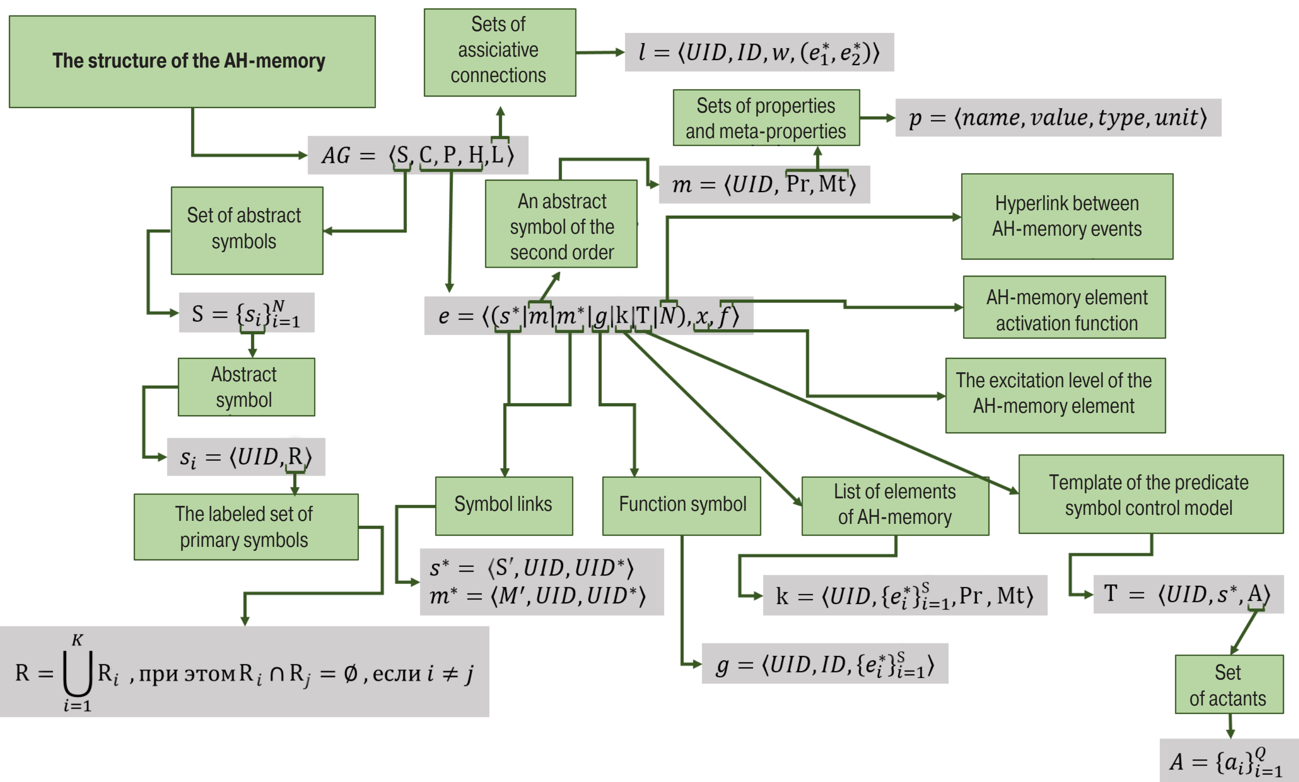

Fig. 4. Structure of AH-memory

CONCLUSIONS

When implementing a specific AI-agent, the designer and developer must select those elements of the AH-memory from those required for the successful and efficient functioning of this particular AI-agent. Although the most universal structure of the AH-memory has been presented in this article, it is necessary to decide which specific components are to be used in each specific case.

Authors' contributions

R.V. Dushkin—development of AG-memory, presentation of theoretical basis for implementation in the form of an article.

V.A. Lelekova—analysis of theoretical scientific materials, writing the text of the article.

V.Y. Stepankov—development of AG-memory, consultations on technical details of AG-memory.

S. Fadeeva—analysis of theoretical scientific materials, editing the text of the article.

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Translated from Russian into English by Evgenii I. Shklovskii
Edited for English language and spelling by Thomas A. Beavitt