

Grounding of Relations and Abstract Symbols in the Decision Unit of an Embodied Agent

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Abstract — This paper is about problems in the area of the artificial intelligence (AI) of an embodied agent, i.e. a robot or any other autonomous machine, whether simulated or real. We discuss the necessity of grounding the concepts that form relations between symbols in the decision unit of such an agent. We explore existing concepts for knowledge engineering in the field of the Semantic Technologies to determine which grounded base vocabulary might be necessary, we detect that besides bodily experienced basics intelligence also deals with mental experiences and show a possible way to ground the concept for subclass as an example.

Keywords — artificial intelligence; symbol grounding; semantic knowledge base, cognitive automation, cognitive architecture, artificial recognition system

I. INTRODUCTION

In cognitive science, the knowledge base of an artificial intelligence machine is commonly described and implemented as a network of interrelated symbols [1]. Each symbol describes a relevant concept and is related to other concepts via associations. “Learning” in this context is done by including new symbols and relating them to existing ones, building an increasingly large and dense network. Hence, to be able to integrate new concepts, a relation to existing symbols has to be found. This can be compared to human interaction or dictionaries, where an unknown word is explained by using other words.

Already in 1990, HARNAD [2] pointed out a major flaw in this concept: the foundation of the knowledge base cannot be related to anything but itself. He describes this with trying to learn Chinese with only a Chinese/Chinese dictionary: even if you know how to use the dictionary, looking up a word would only return other Chinese words that need to be looked up only to return unfamiliar Chinese words yet again. To overcome this inherent loop, he proposed the “grounding” of symbols via sensorimotor experience. This concept has since been successfully applied in several projects [3].

When it comes to relations between these symbols that allow deriving the semantic meaning of a non-grounded symbol, set theory seems to be a viable candidate: using concepts like equality, subsets or intersections, logically sound and technologically accessible ontologies can be built. For this reason, the Semantic Technologies community [4] also mainly

focuses on this approach, and has introduced a set of languages, whose concepts might also be interesting for cognitive science. The next Chapter will give an overview and introduce the relevant concepts and vocabulary to allow an evaluation for the field of artificial intelligence. If the same or similar concepts can be transferred to cognitive science, this would make the Semantic Web a ‘dictionary’ for artificial intelligence machines. Combined with a basic, grounded vocabulary, this could lead to potent new methods for training artificial intelligence machines.

However, we believe that the mechanisms, i.e. the basic vocabulary used to describe the relations between symbols, must also be grounded. Up to now, these relations have been merely regarded as an auxiliary syntax that does not carry any meaning by itself and can be pre-defined and built into the artificial intelligence machine. However, in Semantic Technologies, new types of relations can be defined with reference to existing relations in the same way new symbols are defined. Any compatible knowledge base must therefore also support this concept. Following the same argumentation used for symbols [2], this therefore makes it necessary also to ground the basic types of relations in some way.

The grounding of this vocabulary only makes sense in the context of a decision unit of an embodied agent. In particular, we developed our considerations in the context of the Artificial Recognition System (ARS) [5], [6]: a cognitive architecture based on the Freudian theory of psychoanalysis [7]. It is used as the structure for the control software of intelligent agents – both embedded in a simulation or in a robot in the real-world [5].

FREUD’S second topical model describes the Id, the Ego and the Super-Ego as functional blocks of the mental apparatus (aka the psyche). Here, roughly speaking, the Ego has to resolve conflicts between the competing demands of the Id as the instance of physical needs, and the Super-Ego as the instance of social requests. Following a top-down design, the ARS architecture identifies a number of mental functions processing psychic contents. The data representing these contents can be separated into data of the so-called primary processes, i.e. the part of information processing dealing with unconscious data, and the secondary process, the part that deals with preconscious and conscious data [8]. Thing presentations (TPs) are the most essential data structures in the

primary process, while the secondary process uses mainly word presentations (WPs).

“TPs represent environmental, bodily and homeostatic information as well as automated motion sequences. TPs do not possess any logical structure [9].”

“A WP is the description of an object by the use of a set of symbols [9].”

So while thing presentations have to be understood as the symbolic representation of the agent’s bodily experiences, word presentations build the expressions of these experiences in various symbolization systems, of which the most prominent is natural language. TPs are linked to each other via associations. This puts them into context and gives them a meaning beyond that immediately represented by them alone. TPs are also associated with the WPs which make it possible to talk about them. WPs are connected associatively with TPs representing their content on the one hand, and on the other with TPs representing different images used to articulate the word (visually, kinesthetically, or acoustically) (Fig. 1).

It is essential to our understanding, that, according to FREUD’S theory, any rational activities of the mental apparatus – that is language processing as well as logical reasoning or dealing with time dependencies – can only be performed on word presentations in the secondary process [9]. It is not possible to do this using the associations between TPs alone.

If we map the considerations of FREUD and HARNAD we detect that the role of TPs and WPs in FREUD’S considerations is the same as that of symbols in HARNAD’S work. TPs can be grounded by means related to connectionism, as Rosemarie VELIK has proven [10]. This is because they represent what we usually call ‘concrete’ objects or observations. However, if we are looking for the grounding of basic vocabulary, which is needed to describe the relations between derived words and their grounded base, we deal with highly abstract concepts not coupled with any immediate bodily experience.

In this paper we introduce a mechanism that allows grounding one element of this basic vocabulary: subclasses. We also present the state of the art in the Semantic Technologies to outline how this concept is used there, and to determine if further research could lead to the use of the Semantic Web as a dictionary for artificial intelligence machines.

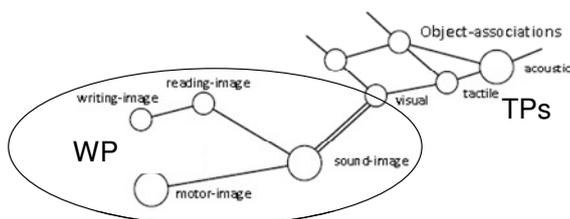


Fig. 1. Word Presentation (WP) and Thing Presentations (TPs, originally called Object-associations by FREUD). Drawing under usage of [8] based on [7].

II. SEMANTIC TECHNOLOGIES

A. Languages of the Semantic Web

The Semantic Web was proposed by Tim BERNERS-LEE as the next evolutionary step of the World Wide Web [11]. There, the information that is currently only available for a human user will also be available for machines. This allows creating services that can use the internet as a huge database and extract information on-demand and call other services. For example, an agent could collect offers for a business trip including a hotel room, flight, rental car and recommendations for restaurants. The user could choose from this shortlist and the agent would then perform all necessary actions like booking the flights and reserving a dinner table.

To realize this vision, the World Wide Web Consortium, of which Tim BERNERS-LEE is currently the director, has published a roadmap that resembles a stack of necessary technologies and languages [12]. The base of this stack is formed by purely technical mechanisms that define the character encoding (Unicode), references (URI – Uniform Resource Identifiers), and basic scheme of serialization (XML – eXtensible Markup Language). On top of these, the following family of semantic languages is defined¹:

- Resource Description Framework (RDF)
- Resource Description Framework Schema (RDFS)
- Web Ontology Language (OWL)
- Rule Interchange Format (RIF)
- SPARQL Protocol And RDF Query Language (SPARQL)

While SPARQL [13] could be the language an artificial intelligence agent uses to access the data, and while modeling information in the form of rules using RIF [14] could also be of considerable interest, we will focus on the ontological form of information representation for now.

The first language, RDF [15], defines the data model: a fact is represented in RDF as a triple consisting of a subject, a predicate and an object. The subject and predicate are both resources defined by their unique identifier (URI), while the object can either be also a resource or a literal value, e.g. a date or numeric value. This basic schema allows expressing any fact about a resource such as “cake - is a subtype of - baked goods”. A group of such interrelated triples form a graph where the resources used as subject and object are the nodes, while the predicates resemble the edges. RDF itself only introduces this data model and defines the relevant vocabulary for describing it (e.g. `rdf:Property`, `rdf:type`, ...).

RDFS [16] enhances this vocabulary by defining a set of terms that allow creating very basic ontologies. Particularly, the concept of classes is introduced, resembling the set in set theory. RDFS also defines the properties `subClassOf` and `subPropertyOf`, which form the basic mechanism for relating sets to each other. Using this mechanism, several

¹ See <http://www.w3.org/2001/sw/Specs> for details on these standards

other relations can be derived without introducing any new concepts [17]:

- Intersection: if A is a subclass of B and A is also a subclass of C, any element of A is an element of the intersection of B and C.
- Union: if A is a subclass of C and B is also a subclass of C, any element of either A or B is an element of C.
- Equivalence: if A is a subclass of B and B is a subclass of A, A and B are equivalent or both are empty sets.

It should be noted that these concepts are only approximations of the propositions disjunction and conjunction, since the inference only works in one direction, i.e. given the definition for the intersection one cannot infer that any member of B and C is also a member of A as a proper conjunction would, only the opposite conclusion given above is valid.

Finally, the Web Ontology Language OWL [18] introduces further relations that allow to create more complex and sound ontologies, such as `owl:sameAs`, `owl:inverseOf`, `owl:intersectionOf`. It comes in three flavors:

- OWL Full allows unrestricted use of the language specification.
- OWL DL is a restricted subset, which ensures that all conclusions can be computed and all computations will finish in finite time.
- OWL Lite is even further restricted, and was defined to resemble a simple and easy to implement subset, while still having enough expressive power to define hierarchies and simple constraints.

B. The Linked Open Data Initiative

The family of languages introduced above allows creating distributed ontologies where facts are given in the form of triples relating a resource to another resource or asserting a literal value. For the context of this paper, the relations between resources, especially taxonomic relations are of interest, since they can be used to define new symbols for an artificial intelligence machine by relating it to existing grounded symbols. In the Semantic Web, the property `owl:sameAs` can be regarded the most important taxonomic relation, since it allows creating a “Semantic Bridge” [19] also called RDF Link [20] between two resources. This mechanism can be used to link two ontologies, for example factual information about Vienna from dbPedia `<http://dbpedia.org/page/Vienna>` to geographic information about Vienna in the open semantic database Geonames `<http://www.geonames.org/2761369>`.

This results in an extensive ontology consisting of smaller interrelated ontologies. The largest organized project of this type is the Linked Open Data cloud. The size of these interlinked datasets was estimated to be 4.7 billion RDF triples as of 2008 [20], and in a talk in 2011, the same author stated

that in 2010 it was already at 26 billion triples with an average yearly growth rate of 300% for the past 3 years [21]. Developing reliable methods for tapping this information source by including it into the models of artificial intelligence machines, could pose considerable advantages for both learning and modeling knowledge in the field of cognitive science.

C. Exploratory Example

The WordNet [22] ontology, which is part of the Open Linked Data cloud, is a lexical database for English. It groups nouns, verbs and adjectives into what they call “synsets”, which are sets of synonyms expressing a distinct concept. It also sets these concepts into relation to other concepts by defining hypernyms/holonys. Both of these classes of relations can be approximated using the `subClassOf` property as was shown in the previous section. The main purpose of this database is to serve as a repository for Natural Language Processing applications and other related tools. However, we assume that the same database can also be used to derive information that might be useful for an artificial intelligence machine. To illustrate this, let us assume that an artificial intelligence agent is set with the task of finding food in some arbitrary simulation. The symbol for food is grounded and possible operations like eating are associated with it. In the simulation, the agent discovers a ‘schnitzel’ which it can identify as such as it is associated with a thing presentation identified in a process of perception based on the schnitzel’s shape. However, at this stage the agent cannot relate to the object. It doesn’t have any former experiences with this object, and hence does not know that it could satisfy hunger. Thus it could only link the schnitzel to existing knowledge by discovering other properties it may be able to recognize (e.g. texture, color) or by trial and error interaction (e.g. try moving it, try eating it, ...). An alternative solution could be to look up the concept in a dictionary like WordNet. Here the resource `<http://wordnet.rkbexplorer.com/id/synset-schnitzel-noun-1>` is linked to the following chain of hypernyms: `schnitzel → dish → nutriment → food`, and hence relates the formally completely unknown entity to the symbol for food, which is grounded with the action of eating. The agent may accept this directly, or maybe only use it as a hint on how to continue its course. It could also look up the term in dbPedia via a semantic link to discover that it is meat which it may already have some knowledge about that could also change its course of action (e.g. a vegetarian agent might not regard meat as food ...).

III. GROUNDING OF RELATIONS

The exemplary task of our agent as described in the end of section II.C is to identify the schnitzel as the member of a subclass of food, so that it can draw the conclusion, that the schnitzel can be eaten and would satisfy its hunger. To perform tasks like this, which are based on relations between symbols, the agent needs to understand a minimal set of abstract concepts. To “understand” means to have them grounded. But they cannot be grounded in bodily experience in the same way as symbols denoting concrete objects can. They rather have to be grounded in the activities of the mind.

A. Basic Considerations About the Grounding of Abstract Symbols

When we talk about abstract symbols – or more precisely concepts about symbols with abstract meaning - we may distinguish between different degrees of abstractions. In principle, drawing classes from individuals or creating super and sub classes are steps of abstraction. As long as the defining predicates of the classes that are to be created rely on sensorimotor experiences the degree of abstraction is rather low.

A higher degree of abstraction is reached, if a certain concept is part of a system derived as target by drawing analogies from a source. But still, bodily grounding is given. For the concepts we are interested in, a physical base is not visible so their abstraction level is much higher. They also cannot be derived from other concepts by means of language as they themselves build the foundation to formulate explanations or definitions.

In particular we are looking for a grounding of logical operations, quantifications, axioms and inference rules, as they form a basic set to build descriptions of other new words. They might not be the building blocks used by humans in real life, but they might work as examples for those. Besides the elements of predicate calculus, those of OWL (classes, properties, operations etc.), the elements of set theory, or the concepts to draw analogies could be sets of abstractions of that kind.

In any case, the abstractions to be investigated are parts of a language with syntactic, semantic, and pragmatic rules, and the afore mentioned restriction, that rational processing of language according to FREUD can only take place based on word presentations, makes it clear that in the context of ARS only WPs can be adequate data structures to represent them. Associations between WPs are not just of the kind ‘thinking of A, I also recall thinking of B’, as between TPs, and where the reasons why A reminds me of B are not quite clear and buried deeply in the history of my psyche. Instead of that, the links between WPs might also have an inner structure. This is permitted in the secondary, but not in the primary process. Associations between TPs are unordered pairs, while associations between WPs and between a TP and a WP are ordered. In the secondary process, associations between the constituents play a role: there is a left element, a right element, which can be clearly distinguished, and the relation itself also has a distinguishable direction. More than that, ordered pairs are the basic elements of sequences, as any sequence can always be understood as an ordered pair, consisting of a first element and the rest of the sequence. Thus it is an essential property of WPs, that they can appear in sequences, and such word presentation sequences (WPS) build the fundamental structures of language: phrases and sentences.

The fact that language expressions often are sequences – sequences of phonemes in speech, such of graphical signs in written text – seems to be an essential characterization of many languages. In contradiction to pictures, where different elements are more or less evenly distributed over the plain or space, the parts of an acoustic or symbolic stream are well ordered. This is the same kind of difference as we observe it

between the complex number field and the number line. It seems to be a consequence of the fact that speech needs acoustic variations over the time line, one phoneme strictly has to follow the other to transport meaning. That doesn’t imply that the order of words necessarily always matters nor that a certain order always expresses meaning, but it makes it possible to process language by algorithms accepting the elements one by one.

The interconnection between order and time is very tight. If we want to investigate an area or a space we usually serialize it, i.e. we walk through it along an imaginary path where we touch one point *after* the other, and in the ordered pair we check the first element before the second when reading from left to right. That is because to gain order we need an asymmetric relation between the elements - the condition of anti-symmetry is what distinguishes order relations from symmetric equivalence relations in mathematics - and naturally we find dissymmetry in time: while we can recall the past we cannot do this in the same way when anticipating future. We map our intuitive recognition of order in time to orders in any kind of sequence, even to ordered pairs.

Independent of the order, a fundamental ability of the human mind is pattern recognition. It employs a wide field of research in artificial intelligence [23] Our first suggestion regarding the grounding problem of abstract symbols is to understand this human ability (pattern recognition) as one of the congenital skills, which enable human beings to apply logical dependencies between concepts. But in our context we are looking at a very special variant of this general mental competence, namely the recognition of patterns in sequences of word presentations (WPS).

Following this model, the act of thinking is the task of replacing a pattern of WPs with a different WPS. We can define this act as an ordered pair of WPS: the original sequence (the pattern) and the target sequence (which replaces the pattern). This is the same as deriving a rule in formal language [24], and we again observe that order matters. It is a common property of rules, both in natural language (syntax, semantics) and in systems of logic and related processing (programs, calculi, instruction sheets, check lists), that they rely on sequences where order matters. To avoid any misunderstanding, it should be emphasized that order always matters in rules, but not necessarily in the pattern on which the rule is applied. That is because they all describe acts, and acts transform a given situation (in the context of ARS that is modeled by an image) into a different one by performing a motion [9].

There is a tight connection, not only between order and time as mentioned above, but in consequence between those two and additionally language and logical reasoning, which may explain that all these fields of activity of the psyche have been assigned to the system ‘conscious-preconscious’ by FREUD, i.e. the secondary process [9].

Summarizing all this, we suggest that the ability of logical reasoning and thus the grounding of the abstract concepts of logic, which are the basis to derive words from others, are grounded in experience, based on

- The ability to recognize patterns in WPS as a special variant of the more general skill to detect patterns, and
- The ability to replace patterns of WPs by other WPS as an activity similar to the performance of a motion.

As acts in the ARS system cannot be anything else than word presentations themselves [9], we further suggest that the activity of replacing WPSes should be represented by a word presentation itself. For the SW agent, such an act is not only grounded in a similar way as its ability to lift an arm or a leg, to move, eat or speak, but more than that it is an aptitude within its own original domain: manipulation of symbols. The question whether it has to be represented by a TP as the grounding base of a WP or whether it can be represented by only a WP needs further investigation.

Once we have a WP for denoting an act of logical thinking, this act itself can become substance of the agent's cogitation and can appear as an element of a plan.

B. The Relation of Subclass and Implication

It is evident that the concepts of subclass and implication are strongly coupled. The definition of a subclass in formal notation is

$$(A \subseteq B) \leftrightarrow \forall x(x \in A \rightarrow x \in B). \quad (1)$$

This means that A is a subset of B exactly if for any object holds that when it is an element of A, then it also is an element of B. So we can derive the concept of a subset or a subclass directly from the concept of implication. It has been suggested to ground mathematical ideas via analogies with the physical world (e.g. using the similarities between sets and boxes) [25], but that doesn't help much as long as the logical principles are not grounded. So instead of founding the agent's idea of a subset on its idea of sections in boxes we prefer to search for the underlying presentations of the implication.

What holds for all these concepts of logic also holds for the variants of "if ... then": we need to observe the difference between the phrases, i.e. the WPs, which express the relation between the two statements (propositions, basic sentences) such as "if ... then", "therefore", "for that reason", and the act of formulating the implication. This act is not a step of reasoning, but just a 'movement' to formulate a sentence. The rule to be executed in performing it could be

$$\langle \text{sentence 1} \rangle, \langle \text{sentence 2} \rangle ::= \langle \text{sentence 1} \rangle \text{ therefore } \langle \text{sentence 2} \rangle, \quad (2)$$

where $\langle \dots \rangle$ indicates a word presentation sequence, 'sentence 1' and 'sentence 2' are WPS constructed according to the rules for building propositions, the symbol '::=' indicates the act of replacing the set of WPS on the left side by the WPS on the right and 'therefore' is a WP on its own.

The interesting question is under which conditions this act might be executed in the agent's decision unit. According to the ARS concept it is always a drive – a concrete bodily or psychic need – that provides the necessary psychic intension, which then finally leads to the creation of plans in order to

reduce drive tension. There is always an amount of psychic intensity of the need to do something and at least to do reasoning as a result of the tension permanently produced by drives. In order to reduce this tension a child would just keep on moving while a 'grown up' agent would apply the action, which best matches positive memories of a previous, similar situation. To select the 'build implication' task it therefore needs a number of memory traces in good experiences with building sentences in general, and trying implication in particular. The 'good experiences' are stored as weights of associations between the image modeling the current situation and the one showing the remembered past. These weights are nothing else than the amount of drive tension that has been reduced when applying the act in the past.

The implication is thus grounded in two steps: We may say the agent 'understands' the act of formulating an implication as the agent's original ability to modify WPS. And it 'understands' why to apply an implication in particular in the current situation, as this situation is linked with earlier successful applications of performing an implication by strongly cathected – that is equipped with high psychic intensity – memory traces.

As mentioned above this grounding of the act to construct an implication is not the same as the grounding of the phrases on which this is applied, e.g. "if ... then", which is a totally different question. To find reliable answers to it needs some more research in the fields of psychoanalysis of children, developmental psychology and related fields. A first guess would be that it has to do with the child's early experience of being an actor. 'If I do *that*, then *this* is happening.'

Tightly joined with the implication is the reasoning rule of the modus ponens. It is only this rule which makes the implication applicable. In our approach it has the same status as the act to create an implication. The corresponding rule can have one of the two shapes (3) or (4):

$$\langle \text{sentence 1} \rangle, \langle \langle \text{sentence 1} \rangle \text{ therefore } \langle \text{sentence 2} \rangle \rangle ::= \langle \text{sentence 2} \rangle, \quad (3)$$

or

$$\langle \langle \text{sentence 1} \rangle \text{ and } \langle \langle \text{sentence 1} \rangle \text{ therefore } \langle \text{sentence 2} \rangle \rangle ::= \langle \text{sentence 2} \rangle. \quad (4)$$

The difference between (3) and (4) on the one hand and (2) on the other is the situation in which the agent tries to apply it. While (2) formulates an act to create a new sentence (containing implication), (3) or (4) would be executed if the goal is to derive a true result given true premises. So it depends on the perceived image whether it is associated with the one or the other act as a possible plan towards the goal of reduction of current drive tension.

In our example situation with the schnitzel, the agent would get the WPS (in this case a sentence)

$$\langle \text{object 1} \rangle \text{ is_a schnitzel} \quad (5)$$

from its perception, where ‘object 1’ is a variable (variables are another category of concepts, which have to be investigated in the project ARS). Without other information about ‘schnittzel’, the agent could look up the concept on the internet, resulting in

*<<object 1> is_a schnitzel> therefore
<<object 1> is_a food>.* (6)

The simultaneous appearance of a WPS with ‘schnittzel’ and an implication with ‘schnittzel’ in the premises matches sufficiently enough with an image working as a precondition for the application of modus ponens and therefore would activate this act of reasoning with the result

<object 1> is_a food. (7)

In consequence the agent would consider object 1, viz. the schnitzel, as edible and use this information for further action planning, possibly resulting in going there and eating it.

IV. CONCLUSION AND OUTLOOK

In this paper we proposed a possible method for grounding abstract concepts, using subset and implication as an example in the context of the cognitive architecture of ARS. What remains to be done is to implement the acts of reasoning in general and the acts of applying implication and modus ponens in particular as WPS in the decision unit software of the ARS project. Further work has also to be done to investigate the role of other concepts of logic and set theory as word presentations in the mental apparatus of an embodied agent.

If a working set of grounded symbol relations can be developed that is compatible with existing languages already used in knowledge engineering, for example in the field of the Semantic Technologies, new strategies for training artificial intelligence machines could be developed, and maybe, vice versa, also possible new applications of artificial intelligence concepts in those fields.

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