ANALOGICAL REASONING TECHNIQUES IN INTELLIGENT COUNTERTERRORISM SYSTEMS

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Abstract: The paper develops a set of ideas and techniques supporting analogical reasoning throughout the life-cycle of terrorist acts. Implementation of these ideas and techniques can enhance the intellectual level of computer-based systems for a wide range of personnel dealing with various aspects of the problem of terrorism and its effects. The method combines techniques of structure-sensitive distributed representations in the framework of Associative-Projective Neural Networks, and knowledge obtained through the progress in analogical reasoning, in particular the Structure Mapping Theory. The impact of these analogical reasoning tools on the efforts to minimize the effects of terrorist acts on civilian population is expected by facilitating knowledge acquisition and formation of terrorism-related knowledge bases, as well as supporting the processes of analysis, decision making, and reasoning with those knowledge bases for users at various levels of expertise before, during, and after terrorist acts.

Keywords: analogical reasoning, structure-mapping theory, associative-projective neural networks, knowledge bases, terrorism, terrorist acts, antiterrorism, counterterrorism, SMT, SME, APNN

Introduction

Since September 2001, the world has awakened to a new danger - the threat of international terrorism. Combating terrorism has become a high priority in international cooperation. A key component of counterterrorism measures is going to be the creation of tools that can supplement human reasoning to handle the vast amount of data that is being generated by counterterrorism measures. Technologies from computer science will play an important role in endeavors ranging from intelligence, prevention, preparedness planning, response training - to crisis management, reaction, mitigation, and recovery (e.g. [SAIC]). Computer-based systems to assist expert and nonexpert personnel to reason about terrorist activities (henceforth referred to as terracts) will benefit from further development of such systems. The key to these enhancements, as we propose, is the integration of existing tools and the creation of new computer-based counterterrorism systems using analogical reasoning techniques. The resulting analogical processing tools working with data and knowledge bases (KB) of experience accumulated from known terracts will provide new capabilities to counterterrorism systems. This approach can be used to support reasoning, prediction, assessment, analysis, decision-making, problem solving, planning, response actions throughout life-cycle of terrorist incidents.

Ultimately, such systems should be able to reason and learn from examples in the area of terrorism and other complex real-wold domains in the same manner as humans, who are capable of accumulating knowledge and experience by assimilating examples, working through problems, and reusing examples to solve new problems. However, humans have well-known limitations of their abilities. In particular, human memory tends to preserve the gist of prior situations, without necessarily providing access to detailed descriptions of past situations. In addition, humans often do not work efficiently under stress and time pressure. Therefore, it would be useful to have a system that supplements human reasoning and addresses people's shortcomings. Furthermore, such a system must be compatible with human reasoning processes in order to facilitate integration of a computer system's recommendations with ideas of a human user.

Analogical reasoning is an excellent candidate for serving such a function. In analogy, one situation is viewed as similar to another on the basis of relationships among the objects and actors in the situation. Once two situations are seen to be similar, predictions can be generated by carrying over information from one domain to another. In this paper, we discuss Structure-Mapping Theory (SMT; [Gentner, 1983]), which is the most prominent theory of analogical reasoning in the cognitive science literature. This theory has been implemented in a number of computational models. We discuss two implementations of SMT, the Structure Mapping Engine (SME; [Falkenhainer et.al., 1989]) and Associative-Projective Neural Networks [Rachkovskij, 2001]. We explore how these implementations can be used to supplement human reasoning in the domain of counterterrorism.

Analogical vs case-based reasoning

Past experience provides an important source of information for reasoning about terracts. In particular, it is important to recognize when a new situation is sufficiently like some previous situation that some action ought to be taken.

One approach to the use of prior knowledge involves expert systems in which domain experts are asked about the rules they use to reason. Unfortunately, experts are rarely able to articulate complete and correct general-purpose rules that they use to reason. Also, expert systems that use the rules obtained from experts often have difficulty with new cases that are not an exact match to those for which the rules were constructed.

Two other approaches apply information about specific known episodes to new situations. The first is case-based reasoning (CBR). On this approach, a KB is developed that consists of descriptions of cases that are indexed by key aspects of the environment such as the goals that the case is designed to solve. New situations with the same index call up prior cases. The prior cases are then examined for their appropriateness by determining whether the differences between the new situation and the old one are critical. If the differences are not important, then the old case is tweaked to allow it to be applied to the new situation. CBR has been applied in a number of domains [Kolodner, 1993; Schank, Kass, & Reisbeck, 1994], but it has a number of limitations including:

- it cannot deal with complex structured knowledge. Representations of cases are usually unstructured sets of attributes, without relational information;
- it is not so flexible as human reasoning. The indexing scheme that allows new cases to be accessed based on prior cases needs hand-tailoring;
- it lacks robust, domain-independent algorithms for finding similarity and applying information from a previous case to generate advice specific to the current case.

Analogical reasoning is one of the most commonly encountered and vivid cognitive processes. That is why a lot of work is devoted to the development of theories and computational models of analogy. (For an introduction, see, e.g., [Gentner & Markman, 1995, 1997; Holyoak & Thagard, 1989; Hummel & Holyoak, 1997; Thagard et. al, 1990; Eliasmith & Thagard 2001] and references therein).

Analogical reasoning provides the flexibility to reason on-the-fly given a knowledge base of historical cases by supporting comparisons between known episodes and current conditions. Counterterrorism requires the ability to flexibly extend existing ideas to new situations, and so analogical reasoning is a good match for it.

The analogical reasoning account supports a number of important sub-processes:

- finding relevant episodes in the KB and comparing them taking structure into account, as in human reasoning [Gentner, Rattermann, & Forbus, 1993];
- inferring new information in order to generate predictions [Clement & Gentner, 1991; Markman, 1997];
- retrieving and adjusting associated information in order to create action plans [Keane, 1996];
- reasoning with, learning and generalizing from examples and applying knowledge appropriately to the case situation [Forbus et al., 1999];
- providing the ability to understand analogies and metaphors in natural language texts [Fauconnier, 1997].

The ways to overcome the limitations of CBR using analogical reasoning are investigated in large-scale DARPA projects, High Performance Knowledge Bases [HPKB] and Rapid Knowledge Formation [RKF], that deal with construction of and reasoning over a large KB. As evidenced by those programs, analogical reasoning tools can serve as a basis for new AI technologies, with such applications as, e.g., crisis management or getting expertise in weapons of mass destruction.

Thus, introducing analogical reasoning to KB and expert system enables:

- a more advanced, human-like reasoning about the world (as in the HPKB project);
- support for creation of KBs (as in the RKF project);
- help in human interaction with KB, using natural language, examples and generalization;
- overcoming some limitations of human reasoning (such as the limited span of working memory, inability to extract precise description of past situations, limitations of input and exchange information channels, "standard" human thinking that limit the possibilities of creativity),
- overcoming other human limitations (such as the inability to work efficiently and to make decisions under pressure, the need to discuss with somebody, the difficulty to take responsibility, vigilance loss, etc.).

The Structure Mapping Theory and its symbolic implementation

The most advanced and elaborated theory of analogical reasoning is Gentner's Structure-Mapping Theory (SMT) of analogy and similarity [Gentner, 1983], further developed in [Gentner & Markman 1995, 1997; Markman 1997, Markman & Gentner, 2000]. The theory explains analogy and similarity in terms of comparisons involving structured representations, not just lists of features.

In an analogy, a base domain, which is the one people typically know more about, is compared to a target domain, which is typically the new situation to be reasoned about. The base and target are represented using structured hierarchical representations consisting of entities (the objects in the domain), attributes (one-place predicates that describe objects) and relations (two- or more-place predicates that relate entities, attributes, and other relations. Finding an analogy between two domains involves finding overlapping relational structure between the domains.

Two domains have overlapping relational structure if their representations contain some identical relations (i.e., they share semantic similarity), if matching relations have matching arguments (i.e., they display parallel connectivity), and if each element in one domain matches to at most one element in the other domain (i.e., there is a one-to-one mapping). Considerable psychological evidence is consistent with the operation of these constraints in human analogical reasoning [Gentner & Markman, 1997].

Unlike CBR, analogical reasoning does not require that cases be indexed for later retrieval. Instead, access is mediated by retrieval algorithms that find base domains in memory that share similarity with a target probe. Retrieval involves two stages. First, the contents of memory are filtered to include only those domains that share substantial semantic similarity with the target. This stage does not require attention to the structure of the domain (i.e., to parallel connectivity or one-to-one mapping) and hence can be done in a computationally efficient manner. Furthermore, recent work suggests that the semantic similarity component of retrieval can be done using high-dimensional semantic space models of the lexicon, which eases the process of developing domain representations (Ramscar & Yarlett, 2003). Those domains that pass through the initial stage of retrieval are given a structural comparison to the target domain, and those domains with a good structural match are retrieved from memory and made available for further reasoning.

There is quite a bit of psychological support for the basic principles of SMT. For example, [Clement and Gentner, 1991] observed that people show a preference for systematicity in that the prefer analogies that have deeply connected relational structures to analogies that preserve only a limited set of disconnected matches. Furthermore, Markman (1997) demonstrated that one-to-one mapping is critical for the formation of analogies. In other work, Markman & Gentner [1997] have extended structure-mapping theory from analogies to comparisons in general, and have created a number of experimental methods for gathering evidence about the way people make comparisons. This theory provides the scientific basis for developing systems that approach the flexibility of human analogical reasoning, for analyzing and predicting of human behavior, for natural interaction with humans.

This psychological theory has been implemented in a number of computational models (e.g., Falkenhainer et al., 1989; Hummel & Holyoak, 1997; Keane, et. al., 1994). The most prominent model is the Structure Mapping Engine (SME) [Falkenhainer et. al.,1989], that has been used successfully in a number of state-of-the-art large scale AI (knowledge-related) projects, such as [HPKB; RKF]. SME is implemented as a symbolic model. The representations given to SME consist of predicate-argument representation structures that can be represented as directed acyclic graphs. Thus, the problem of finding an analogy between domains is computationally intractable in general, and so heuristics and limitations imposed by the SMT must be used to find analogical matches efficiently.

SME makes the analogy process computationally tractable by using a local-to-global match algorithm in which predicates in one domain are first matched to those in the other domain when they have identical semantics. After this initial sequence, matching predicates are assessed to determine whether they have matching arguments, and each set of matching predicates is checked to ensure that matches are one-to-one. This model requires manual construction of representations of items and structures based on them.

SME is also incremental. An initial correspondence between the base and target domains can be extended when more information is obtained about the domains. If analogy were only able to find correspondences between domains, it would be limited in its usefulness to counterterrorism situations. However, SME also generates candidate inferences by carrying over information from the base domain to the target when that information is connected to the correspondence between the domains and is structurally consistent with it.

The central mechanisms embodied in SME are all consistent with what is known about the way people process analogies.

SME is one tool that can be used for the development of counterterrorism tools. The symbolic algorithm can be set up to operate with a KB of prior terracts and other relevant information. A second technique for analogical mapping is the APNN architecture. We describe it in the next section.

Analogical reasoning with APNNs

Associative-Projective Neural Networks [Kussul,1992; Kussul et.al. 1991] are based on a scheme for sparse binary distributed representations of information. These "structure-sensitive" distributed representations take into account both semantic and structural aspects of similarity. This approach provides an opportunity to combine the advantages of connectionist networks (semantic sensitivity, parallelism) and symbolic representations (compositionality, systematicity).

Traditional distributed representations allow a natural representation and computation of gradual similarity and make an efficient use of representational resources. Similar items are represented by correlated codevectors where similarity can be estimated using the dot product. A large information capacity is provided by the possibility to represent exponentially many items by different codevectors of the same dimensionality. Distributed representations are robust and neurobiologically plausible. Also, they allow unsupervised learning of similar representations for similar items using such methods as Learned Vector-Space Models (Latent Semantic Analysis, Context Vectors, Random Indexing, etc. [Caid et. al., 1995; Kanerva et. al., 2000]).

However, it was thought that distributed representations cannot represent nested (recursive) structures because of superposing pairs of vectors would lead to the loss of information about the relationship between elements and their arguments, see [Rachkovskij & Kussul, 2001] for discussion and references). In APNNs, Holographic Reduced Representations (HRRs) [Plate 1995; 2000], Binary Spatter Codes (BSCs) [Kanerva 1996, 1998], the scheme of [Gayler & Wales, 1998], it has been possible to create on-the-fly (without any training) distributed representations of recursive compositional structures with codevectors of the same dimensionality for arbitrary (even novel, non-similar) items.

Complex structures are chunks of a small number of component (sub)structures. The codevectors for more complex structures are built from the set of component codevectors. Because each component may itself be a complex compositional (sub)structure, structures of arbitrary complexity can be represented. To preserve grouping of components in chunks of various compositional levels, binding by Context Dependent Thinning [Rachkovskij & Kussul, 2001] is used in APNNs for component codevectors of each chunk. This allows an on-the-fly construction of a composite bound codevector from its component codevectors.

APNNs encode items of any nesting level, elementary or compositional, are represented by large codevectors of the same dimensionality. The codevectors are binary (with 0 or 1 elements) and sparse (with small fraction of 1s), e.g., with N=100,000 elements representing neurons and M=1,000 of 1s. To build APNN representations of the episodes, it is necessary to encode the entities and relations using base-level codevectors of the lowest composition level. Random independently generated codevectors were used for base-level codevectors in [Rachkovskij, 2001], though correlated codevectors for similar items are possible. Similar items are represented by codevectors with a more-than-random overlap of 1s.

Thus, distributed representations of structures can be constructed that carry immediate information on both the set of structural components of various hierarchical levels and their structural organization. Similarity of resulting bound representations is influenced both by the set of components and their arrangements. So, similar structures are encoded by similar codevectors. Therefore, it is not necessary to search for the match between the elements of two structures in order to estimate their overall similarity by dot product of their codevectors. Similarity found by one-shot dot product of APNN codevectors takes into account both semantic and structural similarity of episodes. Such representations exemplify "reduced descriptions" [Hinton, 1990] or "meaningful symbols" [Kanerva, 2000] that are central to analogical reasoning.

A mapping process has been defined for APNNs that uses alternating sequential and parallel steps to find structural correspondences between pairs of representations [Rachkovskij, under revision]. Processing is based on similarity preservation in reduced representations and includes finding similarity between elements of the same hierarchical level for mapping, and between elements of different levels for structure traversing.

In order to map two analogs, first their elements (chunks of all hierarchical levels) must be encoded by codevectors. Then, the simplest mapping technique involves placing in correspondence the analogical elements of the same hierarchical level having the largest overlap of codevectors. For interpretation of more formal analogies, a technique with synchronous traversal of hierarchical representations may be required, such as finding the corresponding roles and putting into correspondence their fillers. The consistency of mapping can be verified by checking if both techniques produce the same results. Using various attribute structures and representation schemes, and even changing them in the process of mapping may be required for mapping of more difficult analogies.

Usage of distributed associated memories with fast or even one-shot storage and fast retrieval of the most similar episodes [Frolov et.al, 2002] is also facilitated by sparse and binary character of the APNN representations. These features provide APNNs with a scaling potential and flexibility necessary for analogy-processing for large-scale real-world problems emerging at various stages of counterterrorism activity.

Application of analogical reasoning to antiterrorism tasks

Analogical reasoning can facilitate efforts to minimize the effects of terrorist acts by allowing the use of past episodes to influence the interpretation of current events. There are three stages at which analogical reasoning can be used: prevention of new acts, reasoning about the course of ongoing terrorist activity, and reasoning about the consequences of a new act.

Before terrorist acts, the task is to *prevent* them and *prepare* countermeasures. These include: revealing terrorist groups and individuals; prediction of terracts; preparation of countermeasures (general and specific); full-spectrum assessment of and preparation for threats, effects, and consequences; specialized training of personnel and people (from preventing to responding to an incident); action planning and executing in view of a potential terract. *Within* and *after* terrorist acts, the task is to *interdict*, *mitigate*, *learn*, and *prevent new* terracts, including: optimal response to acts of terrorism; evacuation and emergency medical aid; assess the affected population and damage; emergency and consequence management; prevention of follow-up terracts; study of the terract and its effects.

Applications of analogical reasoning in computer-based systems dealing with various aspects of the life-cycle of terrorist acts for minimizing their effects on civilian populations may include, but are not exhausted, by the following:

- constructing case libraries or KB of life-cycles of known terrorist attacks in order to develop countermeasures to them, to analyze what novel terracts may be and prepare to them;
- inclusion in the KB of information about previous cases that can be used for predicting terracts;
- inclusion of information about what was done after the previous terracts, including errors and correct actions, and giving action planning proposals for the current terract;
- generation of new terract scenarios by analogy to prior attacks, given an initial set of conditions, e.g., a terrorist group, its assets, information about potential targets, etc. These scenarios could then be used to test current anti-terrorist measures as well as emergency response preparations;
- supporting analysis and expert decision making for various scenarios of terracts, from prediction through the course to response;
- inventing new schemes or some aspects of terracts by relaxing some constraints on human analogical reasoning or otherwise changing real cases thus simulating reasoning of terrorists learning from previous attempts of terracts and using this information for analysis and developing countermeasures;
- a better understanding of the way people behave after a terrorist attack, in particular how people make plans by drawing analogies to that attack, such as avoiding doing things that can lead to getting into situation similar to that of a recent terract.

When performing analytic tasks, analysts use analogies in at least four ways

-for organizing and understanding information arriving about a new, emerging or otherwise unfamiliar situations;

-to sharpen understanding of a current situation by comparing it to past situations;

-to help test assumptions about new situations;

-to test for projection of our own biases, goals, values and thought systems into uncertain situations.

Consider the case of generating a prediction for a new terract. There is good evidence that when people generate new ideas, they do so by analogy to known ideas (e.g. [Gentner, et al., 1997; Moreau, Markman, & Lehmann, 2001; Ward, 1994]. Using analogical reasoning, a known incident can be combined with a new set of conditions to predict a new incident. For example, the 1972 hostage crisis at the Munich Olympic games can be combined with the conditions predicted to exist at the 2004 Summer Olympic games in Athens to create a novel scenario for these games. Scenarios generated in this way can be used to test readiness of Civil Defense personnel and to suggest potential suspicious activities that might alert authorities of possible terracts. Different patterns of terracts such as homicide bombers, hijacking planes, and the attempted bombing of the WTC at the beginning of 1990 could provide analogy to the Sept. 11 attack.

Implementation issues

We propose the following scheme to implement and test this approach. The analogical reasoning tools for analogical access, mapping, and inference operating with complex structured episodes should be implemented based the techniques and algorithms of the APNN system. Then the system should be tested on terrorism-related episodes from a KB developed for this purpose. These require:

(1) Finding, constructing, and adapting benchmark episodes that describe the life-cycle of terrorist acts for elaborating and testing analogical reasoning techniques in counterterrorism-related tasks. These benchmark episodes can be constructed by the researchers, with the help of experts where appropriate, based on information that is readily available from public-domain sources (e.g., newspapers, historical records, Internet [Terrorism-related resources]). Obviously, more detailed scenarios can be constructed using information that is not typically publicly available (e.g., military intelligence). The principles of APNNs described here will provide more detailed predictions for new situations when the base domains where they are given are similarly detailed.

(2) Implementing reasoning tools using APNNs:

- parsing of input symbolic representations and its transformation into internal XML-based format of episodes;
- setting the schemes for relational representations; distributed encoding of analogical episodes; analogical access, mapping, inference.

These tools will enable retrieval of previously supplied episodes of terracts and their usage for solving problems concerning new terracts. Then the system can be tested with the constructed complex episodes and situations describing the life-cycle of terrorist acts, such as preparations, execution, consequences. These sample terrorism-related benchmark episodes are meant to be demonstrations of the utility of this approach. Of particular interest is the degree to which descriptions of prior terracts can be used to generate predictions of new scenarios.

Conclusion

Thus, our approach consists in using techniques of Computer Science, specifically Artificial Intelligence and Neural Networks, and combining them with knowledge obtained through the progress of cognitive science in order to create analogical processing tools that provide new quality to counterterrorism systems.

The main goal is twofold:

- to develop the set of ideas and techniques supporting terrorism-related analogical reasoning using structure-sensitive distributed representations within the architecture of Associative-Projective Neural Networks;
- to implement software components and a prototype of an analogical processing toolkit that can potentially enhance the intellectual level of computer-based systems for a wide range of personnel dealing with various aspects of the pressing problem of terrorism and its effects.

The new methods and techniques of analogical reasoning with meaning- and structure-sensitive distributed representations should be developed, investigated, and applied to the problem of counterterrorism. They combine the advantages of distributed representations (possibility to be learnt, natural representation and estimation of similarity, an efficient use of representational resources, generalization potential, etc.) with the necessity of complex structured representations to describe adequately the real-world situations, such as terrorist incidents and associated scenarios, plans, analyses, predictions, countermeasures, etc.

This new knowledge will have a substantial impact on the efforts to minimize the effects of terrorist acts on civilian populations by facilitating knowledge acquisition and formation of terrorism-related knowledge bases, as well as supporting the processes of analysis, decision making, and reasoning with those KBs for users at various levels, from expert to usual personal, before, in the process, and after terracts.

This technology has a potential commercial value at the market place by enhancing intelligence level of existing computer systems, as well as providing a basis for development of a new generation of such systems, that help to provide technological solutions to the threat of terrorist acts, as well as other KB systems. This technique can also provide a basis for developing a psychological theory of human analogical reasoning that is consistent with behavioral data and is also neurally plausible.

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