An Integrated Analogy Model for Creative Reasoning

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1. Introduction

Analogical reasoning is a ubiquitous process playing a pivotal role in many disparate cognitive processes from induction, through metaphor interpretation, to creativity. We examine the role of analogy in creative reasoning highlighting the many similarities between both reasoning mechanisms. We interpret creativity as the search for some source analogue with which to reinterpret a given target domain. Such a mapping has the attractive quality that it explains anomalies in the current target interpretation. We have chosen as a basis for a detailed examination, creativity within the science domain as we feel that this offers the best opportunity for computational modelling.

To support creative reasoning we require great flexibility in the retrieval and mapping phases, to support the formation of semantically distant mappings. However, this flexibility will inevitably result in the generation of invalid analogies, which should be rejected as early in the validation stage as possible. In this paper we focus on retrieval and mapping and particularly their influence upon the validation mechanism. We also review previous work which may be complementary to our retrieval, mapping and validation procedures.

While the full extent of creativity encompasses many domain specific processes beyond the scope of analogy, we focus on processes related to background knowledge - or Long Term Memory (LTM). We feel that an examination of the effects and influences of an LTM provides some valuable insights into the analogical process, and thus creativity itself. The overall aim of this paper then, is the development of a computational model capable of supporting creative reasoning, and in pursuit of this goal we avail of previous work in the area of analogical reasoning.

We feel that no stage of analogical reasoning or creativity may be adequately modelled free from the influences of the other stages. Our integrated model examines analogy as a form of memory embedded reasoning, and results directly from a holistic view of analogy. The operation of each stage depends directly upon the information supplied by the preceding stage, and on the underlying memory contents. Focusing on an individual stage eliminates the influence of interactions between stages, significantly reducing the scope and complexity of that individual stage. Furthermore, indirect interactions between non-sequential stages may not be identified by the constrained models, such as the requirements placed upon retrieval by the validation process..

We focus on scientific rather than artistic creativity because its well structured and identifiable concept boundaries lend themselves more readily to computational modelling. Secondly, scientific creativity generally addresses specific limitations with the accepted understanding of some concept. Finally, an identified problem area can be used as a target domain, serving as the basis for a search for a suitable source. Thus, we might utilise the results of years of work in analogical reasoning to develop a useful model of this creative process.

2. Creativity

True creativity is sometimes said to lie not in seeing new things, but in having new eyes. Thus, we see the familiar afresh, gaining a new understanding or appreciation of it. For example, we might view a triangle as a planar object with three sides, or as a planar object with three angles; with each interpretation highlighting different aspects of it. Scientific creativity is required where existing analogies which are used to structure and understand some domain, are found to have specific limitations. This identifies certain facts which lie outside the existing understanding, as anomalous information within the general theory, if you will. The current analogy lacks the descriptive power to cover all relevant factors of the domain. Sometimes even, those factors which lie beyond the analogy are reasonably well known in their own right. Kekulé's original carbon chain analogy for example, explained many molecular structure but couldn't explain the structure of the C_6H_6 molecule. This was a well documented molecule, but its observed behaviour was contradictory to that predicted by the Carbon Chain analogy (which predicted a highly reactive substance due to all the unused Carbon bonds). A new interpretation which resolved the apparent anomalies was required.

Creativity is usually examined as a search for inspiration, wherein we look for new analogies with which to restructure or reinterpret old knowledge (Boden, 1994). Viewing sound as waves upon the water or the heart as a pump introduces new ways of understanding old, though ill-understood concepts. Hadamard described Creativity as being composed of the following stages :

i) Preparation
ii) Incubation
iii) Illumination
iv) Verification

As we shall see, each of these stages has a parallel in Analogical Reasoning. We shall focus on the *incubation*, *illumination* and *verification* phases, which we liken to the *retrieval, mapping,* and *validation* phases of analogy. It is this similarity between analogy and creativity which we use as the basis for a realisable computational model of creative reasoning.

There are a great number of possible source analogues which could have served as inspiration for Kekulé's carbon ring; from buckling his trouser belt in the morning, or repairing a bicycle chain, to collaring his dog for a walk at night. We require a method of discovering the required structural similarity between some problem domain and any appropriate source domain. However, to achieve this we must also have a method of rejecting invalid source domains, preferably with minimal computational expense. It is one of our basic premises that not every domain which bears a structural similarity to a given target domain, can act as the source of creative insight. Indeed, we partly adopt an opposite but complementary position;. that is how do we identify source domains which although they have the required systematicity, cannot support valid creative insight.

A source domain of six clouds could, conceivably, have served as Kekulé's source of inspiration, each cloud being mapped to a CH group (Figure 1), and the clouds then adopting the appropriate formation. However, the source domain might also include information whereby these clouds coalesce, forming one large cloud with the original entities vanishing in favour of the new entity. Any attempt to transfer the "coalesce" predicate to the target should result in the validation mechanism rejecting the inter-domain mapping. The coalesce predicate could be rejected as any combination of the target atoms could not result in their identities being lost. Coalesce would be restricted to mass nouns and the use of non-mass nouns with this predicate would be trapped as a validation failure. This restriction on predicate applicability applies not just to coalesce, but to all predicates. Differentiating between useful and useless source analogues is a prime consideration of this paper.

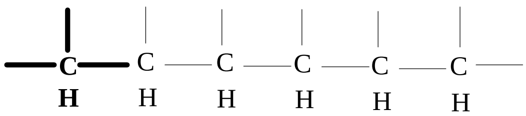

Figure 1 : *The Carbon Chain*

We now examine some existing models of analogical mapping, as it is this phase which is the driving force behind structure based reasoning. This will serve to highlight the requirements of the retrieval phase, while also determining the types of validation required once inter-domain mappings have been generated.

3. Analogy Models for Creative Reasoning

Metaphor and analogy have been studied since the days of Aristotle, with Lakoff and Johnston (1980) highlighting its ubiquity in cognition. It was Gentner's (1983) identification of the central role of the inter-domain mapping which sparked the development of comprehensive computational models of this process. These models take domains represented by predicate calculus assertions, and attempted to identify the best set of 1-to-1 mappings between domains. This stage could be described as the heart of analogy, as structural similarity is the guiding force behind the formation of analogies. Typically, analogical reasoning is divided into a number of successive steps, as follows (from Keane, Ledgeway and Duff, 1994) :

i) *Representation* of problem knowledge *ii)* *Retrieval* of required information

iii) *Mapping* between domains

iv) *Transfer* of new information

v) *Validation* of the inter-domain mapping

vi) *Induction* of new information in target domain

Representation of the appropriate knowledge can be seen as preparing for creativity, and may include acquiring relevant information about the target domain. Retrieval is similar to incubation in that we await suitable inspiration by conscious and sub-conscious processes, or as prompted by external events. Illumination is best described as the phase wherein the new analogy is specified, which transforms our understanding of the problem domain. This is the stage during which Kekulé generated the famous analogy between the carbon chain and the snake with its tail in its mouth. The Illumination phase generates a whole new conceptual space which can then be explored.

Our computational model of creative reasoning becomes a three stage process (Figure 2). This separates the purely creative element, from reasoning within the target domain about the new interpretation. This can be seen as splitting the validation phase in two, the first part validates the structure of the transferred knowledge, and the second half requires domain specific expert reasoning within the target domain using the transferred knowledge.

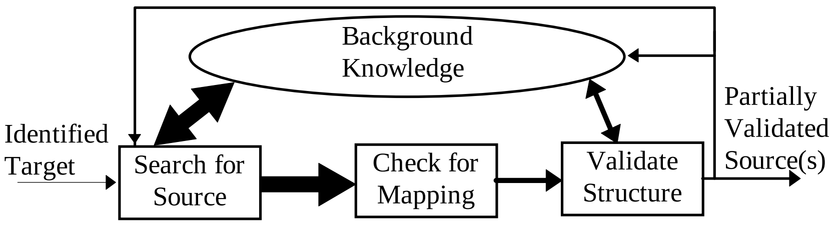

Figure 2 : *The Integrated Model of Analogy*

Clearly creativity is a time consuming process, requiring many iterations through the filtering mechanism outlined in Figure 2. The output of each iteration is some new interpretation of the problem domain, but may prove to be one with no discernible advantage over previous interpretations. However, such apparently fruitless interpretations may ultimately prove useful by providing the inspiration for a further retrieval episode which delivers an all encompassing explanation. Thus the "beacon search" mechanism iteratively focuses in on the required domain description. (as described below).

3.1. Mapping

The most widely analysed phase of analogy is mapping, with most models treating this as the real core process in analogy. An early and notable model of analogy is SME, the Structure Mapping Engine (Falkenhainer, Forbus and Gentner, 1986), which performs a depth-first search for the optimal set of inter-domain mappings. As with most models, the mapping phase plays the most important part, with the other phases receiving little attention. SME validated the importance of systematicity by computationally reproducing some results of observed human behaviour for a variety of problems. It also helped to highlight the importance of numerous other factors which also influence the overall process. Falkenhainer and Oblinger (1990) addressed SME's computational efficiency problems by including a pragmatic "hill-climbing" heuristic in the search mechanism.

Holyoak and Thagard's (1987) Analogical Constraint Mapping Engine (ACME) is a neural network for parallel constraint satisfaction which generates sub-optimal inter-domain mappings. ACME spawns a new "tumour" of solution nodes for every mapping problem, disappearing once the solution has been computed. It does however include pragmatic and other constraints upon the mapping process. Keane, Ledgeway and Duff's (1994) Incremental Analogy Machine (IAM) is a more psychologically plausible model of reasoning, reflecting the way in which inter-domain mappings are compiled incrementally, rather than being identified in a single operation. A new version of SME called Incremental-SME (I-SME) was developed (Forbus *et al*, 1994), growing the inter-domain mapping in an incremental manner.

An important and frequently overlooked constraint upon models of analogy is their computational feasibility, especially because identifying the optimal inter-domain mapping in the set of NP-Complete problems (Veale *et al*, 1996). Any model attempting to find an optimal solution to an NP-Complete problem, can not be considered a practical and scaleable problem solving tool. For a comparison of the computational feasibility of SME, ACME and Sapper, see Veale *et al* (1995). The Sapper model (Veale, 1997) is a very efficient model for identifying inter-domain mappings, scaling approximately linearly with problem size. It is a joint localist-connectionist and symbolic model which uses spreading activation as a basis for identifying mappings between two concepts stored in an integrated memory. In common with other sub-optimal algorithms, this is achieved by guaranteeing the systematicity of the final mapping, but not its optimal size. Sapper highlights the advantage to be gained by the efficient use of a localist-connection representation.

It should be noted that there are a wide variety of constraints upon the Analogical Reasoning process which have yet to be modelled in detail. See Holyoak *et al* (1996) for a comprehensive list of these factors, although the exact interplay between these constraints during the problem solving process is anything but clear. This in part, prompted the development of models like LISA (Hummel and Holyoak, 1996), which focus on the role of analogy in Induction more than on the mapping problem itself. A great deal of simulation and analysis will have to be completed to understand the interactions between these factors, and before any comprehensive model of analogy can emerge

This paper describes a new model of analogical reasoning which attempts to address a broader range of issues, focusing on mapping but also addressing validation issues. This model is broadly in line with the Sapper model for metaphor interpretation (Veale, 1997), in using a localist-connectionist memory model and a symbolic matching component. The inter-domain mapping is built-up from partial mappings derived from the domain description. Additionally these description are stored in an integrated store of background knowledge which includes the domain descriptions. Our model uses this integrated memory as the store of “hidden” creative analogues, and also as the knowledge structure against which to validate new creative interpretations.

Mapping the multiple carbon atoms of the simple carbon cluster (Figure 1, in bold) to the snakes body, we close the loop just as the snake bites its tail. Kekulé’s famous analogy however does not automatically and uniquely lead to the generation of a ring of 6 Carbon atoms. The smallest such ring structure is the triangle (Figure 3a) - assuming that the mapping occurs between the carbon chain and the snakes body, and not between the hydrogen atoms and the snakes body. However, we are left with a number of inferences in the target domain which are implicit within this mapping, and which lie contrary to a consistent new explanatory model of our C_6H_6 domain. Since Kekulé's focus was C_6H_6 not C_3H_3, Figure 3a might have scaled up to the construct in Figure 3b, but here too we are left with inferences in the target domain which contradict our basic requirements (as stored in long term memory). Validation rejects some source domains (though not all invalid sources can be rejected without reasoning in the target domain), as transferred knowledge "clashes" with structural requirements target domain requirements.

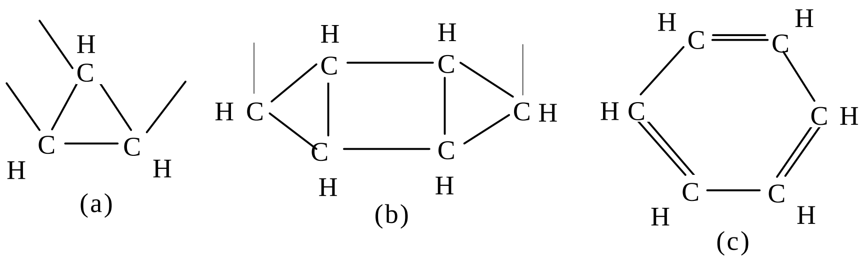

Figure3 : *Alternative Interpretations of Kekule's Carbon*

There being little semantic similarity between carbon atoms and a snakes body, creativity requires a flexible mapping process. We cannot rely on predicate identicality to constrain the number of mappings which must be entertained, and even predicate similarity may fail to retrieve useful source domains. Thus the validation stage must assume most of the responsibility for accepting or rejecting potential sources, preferably rejecting invalid sources as soon as possible. This factor in particular indicates that Gentner's predicate identicality constraint is less significant in creative analogies than those used for learning, description, or explanation.

3.2. Retrieval

Finding a new interpretation of a given domain will require a great deal of searching, but any suitably structured source domain can serve the creative need. Previous work in analogue retrieval has served to highlight the difficulty and computational expense of discovering a suitable source for any given target. Searching is the driving force behind our model of creativity, and therefore it will have a definite impact upon the mapping and validation stages.

Thus, we need to examine structure-based searching before proceeding to the latter stages. Typically in the science domain, there is a notion of what lies within the problem domain, though its exact boundaries may be unclear. Kekulé for example, knew his problem centred around the C_6H_6 molecule. Target domain contents then, can serve as the basis for the creative search.

Two notable retrieval models are MAC/FAC and ARCS with both operating in a two stage manner. MAC/FAC "Many Are Called but Few Are Chosen" (Gentner and Forbus, 1991) uses the identicality constraint as a basis for selecting multiple alternative source domains from an extensive memory base. These domains are then assessed for structural similarity to the target, as performed by SME (Falkenhainer, Forbus, and Gentner, 1989). The best domain identified is selected as the favoured source for the given target analog. ARCS (Thagard *et al*, 1990) first identifies potential sources using a similarity metric being based on WordNet. Each identified source is assessed for structural similarity to the target using an ACME (Holyoak and Thagard, 1989), identifying the largest systematic domain. MAC/FAC and ARCS employ identicality and similarity-based constraints to reduce the number of potential source domains to be analysed. Creative reasoning however often relies on between-domains mappings, lying beyond the scope of identicality and similarity constraints. Creativity would be better served by a retrieval operation which traverses memory seeking out successively more distant domains until a suitable source is found.

Case Based Reasoning has also addressed the issue of retrieving semantically distant and local source domains, given some target description. KDSA Knowledge Directed Spreading Activation (Wolverton, 1995) system however, has successfully been used to retrieve semantically distant sources from a case base represented as an integrated semantic network. This technique relies on a “beacon search” to iteratively traverse the semantic network, each step identifying a new “beacon” from which searching may proceed. The attractive feature of KDSA is that not every beacon represents a maximum of the corresponding heuristic evaluation function enabling the retrieval of semantically distant analogues. KDSA does retrieve a great many analogues during its search process, each of these being filtered out by a validation mechanism. Validation also facilitates retrieval by selecting or rejecting a beacon for the next search. Any creativity model similarly, must expect to retrieve a great many source domains before a useful one is discovered. Thus, after the retrieval and mapping stages, we will need to filter out invalid sources as quickly and efficiently as possible.

As pointed out by Johnson-Laird (1989) analogue retrieval is essentially an intractable problem. In common with approaches to solving NP-complete problems like the Travelling Salesman Problem, the focus lies on the usefulness of a generated solution and not on the difficulty with which solutions are found. The aim then is not to create an algorithm which is guaranteed to produce profound novel analogies within a given time-frame, but to produce algorithms which are capable of generating a creative product. The problem then becomes an effort to reduce the potential search space to more manageable proportions.

Using target knowledge lying outside the current interpretation as a basis for search is as likely to exclude currently understood information as create a useful mapping. Thus we must rely on at least some domain knowledge to constrain the search space. We may choose to move between "high level" domains of interpretation to find a novel source, as semantic distance from the current interpretation is the only quality which can be expected of a novel interpretation. Many retrieval algorithms lack this ability to retrieve semantically distant analogues, and thus may have limited applicability within creative retrieval.

Creativity requires finding new interpretations of old data, and accordingly old interpretations should play no part in this process. Creative search should use as “inspiration” pure target domain information and not our current interpretation of it, thereby de-conceptualising (Indurkhya, 1997) the target domain. Standard reasoning benefits greatly from multiple interpretative analogies supporting multiple manipulations of the problem domain (a triangle has three sides, or a triangle has three angles, it encloses an area). During creative reasoning however, dropping these interpretative analogies allows only "pure" problem domain information to influence the analogical processes. The ability to remove current interpretations may be easier to model computationally that for humans to achieve, indicating that computers may have a greater potential for creativity than humans.

The attributes and predicates of a standard chain description for example, should play no part in determining our new interpretation of C_6H_6. Thus we should not think of the chain in Kekulé's carbon chain, but rather about the carbon and hydrogen atoms and the bonds they form. Had Kekulé thought of chains, he might never had his snake inspired analogy. Only the information previously transferred to the problem domain (such as its structure) and all other same domain data should be involved. Determining domain boundaries and eliminating the current interpretation of the problem may prove a difficult task in scientific creativity, and perhaps an impossible one for models of artistic creativity.

As previously stated, numerous source domains could have filled Kekulé's requirements. For example tying his trouser belt or fixing a bicycle-chain involves the necessary transition from open to closed geometric space, or from linear to circular shape. Such domains may be retrieved by exploring the chain domain or noting that both the carbon chain and trouser belt ha a number of common features. The resultant mapping might be driven by and based upon mapping the ends of the carbon chain to the ends of the belt, and the belt notches to the carbon chain. Then closing the belt becomes attaching the two unused carbon bonds together, forming a carbon ring with six instead of eight unused carbon bonds. This may then be completed by allowing multiple bonds exist between two carbon atoms.

Because of the diversity of inspiration which can usefully serve the purpose of creativity, almost any retrieval mechanism could be usefully employed. However, the use of a "beacon search" technique allows a greater range to the search, enabling the discovery of semantically distant analogues. This iterative model of analogue retrieval allows feedback from an unsuitable source domain to influence succeeding retrieval episodes. Retrieving a non-linear source domain may not result in the required creative analogy, but may map a larger subset of target information than linear sources indicating that we are in a potentially more useful domain than before. Having sufficiently diverse contents within in long term memory however, may be far more critical than the search mechanism operating on that memory.

3.3. Validation of Transferred Knowledge

The need for validation is rooted in the realisation that not every structural similarity can form the basis of creative insight. The mere act of seeing something in a new way can be no guarantee that this new perception will support new and useful inferences. It is even less likely that the new perception will explain all previously understood knowledge, and additionally explain any previously inexplicable facts. The problem then is to counteract increase retrieval flexibility with a mechanism that will readily reject invalid sources, allowing potentially useful sources to propagate through to later stages of processing. Ideally we would like to validate each mapping as early as possible avoiding unnecessary reasoning about the new target interpretation. Validating the mapping itself seems impossible because, as already stated, we require maximum flexibility in the mapping stage. We require some other way of rejecting impotent sources, preferably without exploring the entire new conceptual space.

Structural validation can be achieved in a number of ways, such as validating the retrieval by ensuring the required structural similarity exists. The n-ary restriction is frequently used as a basis for restricting the complexity of the mapping process, however the LISA model (Hummel and Holyoak, 1996) allows n-ary violation (i.e. multiple binary predicates may map onto a single n-ary predicate -a kind of mental array). In this paper we focus mainly on ensuring the compositional integrity of predicates, as it is predicate structure which is integral to analogical reasoning, and thereby to creativity. Our particular interest lies with the transferred information and its interaction with background knowledge. The earliest identifies invalid transfers, basing rejection on the fact that they induce structural errors in the target domain. The latter and more expensive validation requires general reasoning about target domain knowledge, but the first clearly lies within the realm of analogy and can be performed relatively inexpensively.

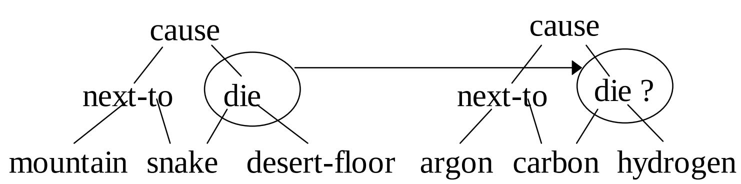

Figure 4 : *Invalid Knowledge Transfer*

Using Kekulé's analogy between the carbon chain and the snake, we could envision the snake dying and perhaps decaying on the desert floor (perhaps the Hydrogen atoms are mapped to the desert floor). However, any attempt to transfer a "die" predicate to the chemistry domain should be trapped as an invalid knowledge transfer (Figure 4). The dying relationship as used within the knowledge base applies to living things, so the validation mechanism can quickly reject an attempt to apply this predicate to inappropriate arguments.

We use a similarity based transfer validation mechanism, wherein the transferred knowledge has to be sufficiently similar to background knowledge for validation. This avoids the generation of anomalies within the knowledge base, such as the dying Carbon atoms. To determine whether a transferred predicate is sufficiently similar to previous usage, we use a simple similarity metric which is relatively inexpensive to compute (Tversky's, 1977). Validation is a binary mechanism which ensures that the target domain has sufficient features to support the transferred predicate as used in the target domain.

$$F(a \cap b) > F(a - b) + F(b - a)$$

A typical source predicate connects two objects, and when transferred will also connect two target domain objects. Each argument of the predicate must be validated before the transferred knowledge is added to the target domain. In the previous analogy between the carbon chain and a dying snake, the predicate "die (Carbon, Hydrogen)" may be available for transfer. The validation mechanism must ensure that the "die" predicate is not anomalous in the target domain, by first examining the similarity between carbon and snake, and then the similarity between hydrogen and desert-floor. A failure to validate any part of the transferred knowledge causes a failure of the validation mechanism, and a rejection of the inter-domain mapping.

If no features are available in the target domain the transfer is assumed to be valid. Of course, real reasoning integrates many different forms of knowledge such as prototypes and rules, but herein we only use prototype features for validation. This validation mechanism is just one of a number of levels of validation which are necessary within any such model, but is one which can be implemented with relative ease and efficiency. It has the added computational advantage that is reuses the knowledge which has been retrieved from long term memory by the previous mapping stage, reducing the computational expense of validation.

4. Conclusion

We examine scientific creativity as the search for novel interpretative analogies, which account for information lying outside the current interpretation. The necessity for a memory based approach to modelling analogical reasoning is assessed, and we analysed the requirements placed on analogy by the memory component. We examine a memory embedded model of analogy encompassing the phases of retrieval, mapping, transfer and validation. The potential of this, or any other model, to generate a creative output is assessed, and the requirements placed by it on the underlying analogy mechanism are assessed. Indeed, computers may be more suited to creativity than humans because an unbiased analogy search is more practicable for computers, overcoming the human prejudice favouring existing interpretations.

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