Computability as a Limiting Cognitive Constraint:

Complexity Concerns in Metaphor Comprehension about which Cognitive Linguists should be Aware

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1. Introduction

If metaphor is to be viewed as a fundamental cognitive agency, as recent work suggests, what ramifications does this view have for a model of semantic memory? This paper presents a computational treatment of metaphor comprehension, named Sapper (see Veale & Keane. 1993, 1994; Veale et al. 1995, 1996), which is built upon a parallel, adaptive, and learning network model of semantic memory. Sapper is a hybrid symbolic connectionist model which views the interpretation of novel metaphors as a process of connectionist *bridge-building*, a process which subsequently alters the activation dynamics between different conceptual schemata in semantic memory, thereby causing these schemata to *interact* (following Black, 1962) in a *representationally dynamic* fashion.

Sapper employs a bottom-up approach to metaphor comprehension, one which encourages the existing structure of semantic memory to shape and accommodate the most consonant interpretation for each concept juxtaposition. In this way, the entirety of contingent background knowledge is brought to bear on the interpretation process. However, the Sapper mechanism combines the base-filtering stage of interpretation with the formation of initial match hypotheses in a single connectionist phase, thereby significantly curtailing the sweep of the matching process and side-stepping the factorial death that models such as SME, the *Structure Mapping Engine* (see Gentner 1983) and ACME, the *Analogical Constraint Mapping Engine* (see Holyoak & Thagard 1989) can all too easily fall victim to. Such factorial demise occurs because of the inherent unscalability of these models: as the problem at hand grows larger, the computational resources demanded by such models also grows, but at an exponential rate, quickly outstripping even the most generously equipped machines, and in theory, outpacing even the computational power of the human brain. In fact, this paper will provide empirical evidence that SME and ACME are fundamentally unsuited to the interpretation of a broad class of metaphors that rely on an object-centred, as opposed to predicate-centred, representation. These metaphors, which often find linguistic expression as *noun: noun* comparisons, depend mainly upon the adequate representation of object partonomies and taxonomies, rather than the representation of actions and events toward which models such as these are inherently biased. This evidence casts grave epistemological doubts on the validity of these models as cognitive theories of human metaphor comprehension.

1.1. Structure of This Paper

This paper addresses a single, but broadly sweeping, question: What representational and computational demands are placed upon a model of semantic memory by a theory that views metaphor as a dynamic conceptual agency, and what constitutes good and bad solutions to these demands? This paper provides an answer in the form of a hybrid model of memory which marries the complementary strengths of both the symbolic and connectionist paradigms. Our discussion of this model will observe the following course: section two presents the motivations and guiding metaphors for this work, while section three outlines the principles and mechanics of a hybrid model of semantic memory, emphasizing the connectionist mechanics of network representation, and providing an elegant computational account of that appealing but infinitely nebulous view of metaphor, Black's *Interaction View*; various epistemological issues in metaphor and analogy are raised by this style of bottom-up analysis, and a discussion of such issues is presented in section four. A quantitative evaluation of the model is then presented in section five, where a comparative analysis with the SME and ACME models is reported, and epistemological conclusions are drawn that should, we suggest, be of some concern to practitioners of cognitive linguistics. The paper then concludes with an overall summary in section six.

2. Motivations & Guiding Metaphors

Metaphor has traditionally received short shrift from the linguistics community, who, in their efforts to formalize the study of language by narrowly concentrating on its structural makeup, seem unwilling to accommodate a phenomenon which is so deeply entwined with wider issues of general cognition. It would not be contentious to claim that the major achievement of modern structural linguistics is its formal treatment of syntax (see for instance Chomsky 1957), and that the study of semantics and meaning is somewhat unimpressive by comparison. The effects of this stance are clearly demonstrated in the severe limitations of the Aarts & Calbert approach (1979), which is rooted in the linguistic framework of *generative semantics*. Linguistics has pressed the syntactic advantage and given the study of meaning a back seat, rather like the man who searches for missing car keys under a street lamp, not because he suspects he may have lost them there, but because it is the major source of illumination available.

But as readers of this volume will doubtless already know, a branch of linguistic study has recently developed which concerns itself deeply with issues of cognition and conceptualization. *Cognitive Linguistics* may be considered the cognitive science of linguistics, and as such, brings the full, interdisciplinary range of issues, vocabularies, frameworks and methodologies to the study of language as was previously available to the cognitive scientist. Linguistics is now in a position to properly tackle the issues of metaphor comprehension without first under-estimating its power. Language is no longer seen simply as a formal language of abstract symbols such as NP, VP and PP, but as a grounded system of schemas which relate to how we are situated in the world. This approach, which may be called the *Cognitive Grammar* approach, is epitomized by the work of Langacker (1991), who strives to describe traditional syntactic notions such as nouns and verbs not in hollow formal terms, but in terms of the cognitive processes that underlie them.

However, if one has a criticism of this new flank of linguistic advance, it must be its lack of computational sensibility. Gardner (1987) argues that computation is a fundamental concern of cognitive science, yet it would seem to have little sway in the new field of cognitive linguistics. An analysis of the 1995 proceedings of the *International Cognitive Linguistics* conference, for instance, whose main theme was metaphor, shows the major methodology in the field to be the *Lakoffian analysis*, whereby the dominant families of metaphors in a new domain are recognized (e.g., Rohrer 1995 discusses the metaphors underlying the public's conception of the internet), and their systematic interactions noted. However, the importance of computational simulation to a new metaphor theory cannot be over-emphasized, as will be demonstrated by the findings reported later in this paper. For if we accept Gardner's *charter* of cognitive science, which stresses the fundamental role of computers in the study of mind, we must also accept such computational results to pose a serious and rigid psycholinguistic constraint.

2.1. Conceptual Bridges as Conduits for Metaphoric Activity

So powerful and cognitively-entrenched is the metaphor phenomenon that we frequently need to employ metaphor to describe itself, as no other descriptive tool seems to suffice. For example, one frequently uses the metaphor of *seeing* to elucidate the process of metaphoric comprehension: we speak of *seeing one domain through the lens of another*, which is itself an extension of Kant's category metaphor (see Kant 1933), who described our innate categories as the conceptual spectacles through which we rationalize the world. Max Black (1962) has also advocated the notion of metaphor as *an etched plate of smoked glass*, through which we visualize connected portions of another domain.

The work described in this paper is founded upon another metaphor -- which though perhaps less commonplace, is certainly more amenable to the computational elucidation of metaphor -- that of the *conceptual bridge*. A bridge is a relational linkage that connects concepts from two different domains of discourse, and may best be described as a form of *family resemblance*, or more computationally, a *fuzzy membership* relation. This metaphor is an extension of one that is seen as basic in connectionist modelling, one which views memory as a *contoured semantic terrain*, whereby contours in this space correspond to relationships, or perhaps energy potentials, between the points so linked (see Quinlan 1991).

The addition of a bridge to such a terrain establishes, in effect, a new linkage between two points on the terrain, in much the same way as does a conceptual relation. However, the emergent power of a metaphor is linked to the construction of new conceptual bridges in much the same way that regional industry is dependent upon local infrastructure: for just as the construction of new roads and bridges provides a framework for the increased flow of traffic, and thus indirectly entices new industry, the augmentation of memory with new conceptual bridgework provides the means for previously unrelated schemata to interact, giving rise in turn to new and unexpected metaphors. This guiding idea shall be given computational expression in this paper, and will be argued to provide both a solid explanation of the emergent character of metaphor whilst also grounding Black's interaction theory in an unambiguous algorithmic form.

2.2. Three Cognitive-Mapping Theories of Analogy & Metaphor

The three theories described in this paper each represent a distinctly different approach (and ideology) to the problem of cognitive mapping.

SME, the *Structure Mapping Engine*, occupies one extreme of a functional continuum, and may be described as an exhaustively *optimal* and *maximal* approach. For SME tirelessly produces all possible interpretations of a given analogical mapping, each alternate interpretation deemed maximal in the sense that no additional correspondence can be added to it without destroying its internal *systematicity* and coherence. Additionally, SME is optimal in the sense that it scores each alternate interpretation, and indicates the best mapping according to a predefined systematicity metric.

A systematic collection of inter-structure correspondences is termed a *gmap* (global mapping) in SME parlance. Initially, a set of *root gmaps* is constructed by systematically comparing the corresponding arguments of identical predicates in each structure. This set is grist for the core of SME, a factorial process which then produces successively larger combinations of these partial gmaps until maximal global mappings are generated. Clearly, the size of the initial root set is a key factor in the tractability of the combination process; SME employs the notion of *structural support* to limit the size of this set, exploiting systematicity across the nested organization of predications in each structure as an evidential basis for generating new roots. It is such *support* then that stands between SME and a sticky factorial demise.

ACME, the *Analogical Constraint Mapping Engine*, also places great emphasis on the property of mapping *systematicity*, or *isomorphism*, but eschews the exhaustively optimal and maximal strategy pursued by SME. Instead, ACME constructs a constraint network for each new analogical problem, to model the various pressures of similarity, context and isomorphism which shape the final interpretation. This network is the subject of a parallelized constraint relaxation process, from which a sole interpretation emerges, one that is neither guaranteed to be optimal, or maximal, or for that matter, even wholly systematic. Unlike SME, ACME guarantees *nothing*, representing a heuristic rather than complete approach to the problem. ACME pursues what may be called a *natural* or *evolutionary* model of computation, in which environmental forces pressurize a system into converging toward a *good*, rather than optimal, solution to a problem.

Like SME, ACME is a structure matcher which compares two domain descriptions in a predicate-calculus-style representation. Hierarchical structure in such descriptions, which is originally expressed via nesting of predications, is translated into a series of inhibitory and excitatory linkages in the ACME network. Nodes in this network correspond to possible entity correspondences between the source and target domains; once the network is activated, the activation levels of these nodes gradually converge toward asymptotic values as the network proceeds through a succession of epochs before eventually *settling*. An ACME network is deemed to have settled when a certain large proportion of its nodes have reached their asymptote. Yet while being neither maximal or optimal, ACME nevertheless seems slower than SME, and is certainly less systematic; this puzzling result, borne out in section five, would seem to support to the case for exhaustive interpretation.

Sapper, like ACME but unlike SME, is a model which claims to be neither optimal or maximal; but in contrast to ACME, Sapper *is* wholly systematic. Sapper is a network model which employs spreading activation with a fixed horizon to delimit the extent of its search. However, unlike ACME's dedicated network model, which is constructed anew for each individual metaphor, Sapper is *memory-situated* -- as will be described in the next section, spreading activation is used to highlight those elements of long-term memory which may be relevant to the current interpretation, and where it is best to lay down new conceptual bridges.

2.3. Issues of Complexity Analysis

Each of the above theories has been implemented on a computer and thereby used to generate empirical results; such implementations indicate experimentally what the structural requirements of each theory are (i.e., how best should our domain descriptions be structured), whilst revealing the performance/competence trade-offs that are embodied in each theory. In an important sense, structure mapping is thus an excellent example of cognitive science at work, being a domain that relates directly to issues of human cognition, and one that is readily modelled on a computer. More importantly, if one accepts the charter of the discipline as outlined by Gardner (1984), the use of computational modelling is a fundamental element in the execution of cognitive science. Our working models are more than toys then, as fundamental limitations of computation that become apparent in such implementations may have dire theoretical consequences for the originating theory. That is, computational limitations often become cognitive limitations.

If complexity analysis is considered unpopular in the computationally oriented sub-fields of cognitive science, drenched as it is in functional pessimism, this perception is even stronger in cognitive linguistics. However, although usually overlooked for this reason, complexity analysis is vital to cognitive theories which rely on highly combinatoric algorithms, such as cognitive mapping. In this sense, complexity serves as the ultimate cognitive science constraint.

One should not look upon complexity analysis then as solely the grim harbinger of the worst case scenario; when combined with systemic experiments, such analyses provide valuable insights into those areas of the performance curve where an NP-hard problem (i.e., one which is *non-deterministically polynomial*, and one for which most computer scientists suspect brutish, exhaustive, search is the only optimal strategy) will perform well, and also those areas where the problem is likely to factorially blow-up in our faces (i.e., rapidly outscaling even our best hardware). Believing that fore-warned is fore-armed, this paper presents an empirical analysis of cognitive mapping, in an attempt to systematically reveal precisely where a theory derives its power, and similarly, to determine the exact price a theory pays for this power.

3. Sapper: A Hybrid Model of Metaphor Interpretation

The Sapper framework, as described in Veale & Keane (1993), is a hybrid symbolic / connectionist model, embodying a basic philosophy which views the interpretation of novel metaphor as a process of connectionist *bridge-building*. From the Sapper perspective, metaphor comprehension involves the construction (or more accurately, the *awakening*) of new cross-domain linkages, which serve as bridges to bind the *analog-pairs* established by the metaphor. The novelty of a metaphor may be measured by the extent to which it adds to the structure of the network, as it is accommodated by the system. This philosophy thus views metaphor as a dynamic, constructive, conceptual phenomenon, which evokes a response in a reactive fashion from an adaptive and accommodating knowledge-base.

3.1. Memory Organization

A Sapper network is essentially a localist graph in which nodes represent concepts, and where arcs represent semantic relations between these concept nodes. While localism is often pejoratively labelled *grandmother-cell coding*, two significant architectural features arise out of a localist rather than distributed architecture: (i) *knowledge isomorphism* - the structure of a localist network directly mirrors the semantic composition of the knowledge represented therein; and (ii) *knowledge parallelism* - in a localist network any number of different concepts (i.e., nodes) may be co-active simultaneously. Now, while this first feature is simply a matter of design convenience, the second is arguably fundamental to the operation of metaphor, the heart of which is the apt juxtaposition of different concepts (see Harnad 1982). Sapper exploits knowledge parallelism to enable the creative reconciliation of different concept domains to occur, in a bottom-up fashion, by inferring cross-domain linkages, or *bridges*, where previously none existed (e.g., if generals are surgeons, then an operating theatre can be seen as a battlefield!).

New cross-domain bridges are laid down along *dormant* inter-concept connections, which have been established a priori by the rule-based component of the model. These dormant connections provide the possible routes along which metaphor creativity can arise. The primary role of the rule-based, symbolic, component is therefore the analysis of the network organization for particular consistencies of structure, and the augmentation of the network with new (but dormant) connections on the basis of these consistencies. Such dormant network linkages represent merely *plausible*, rather than fully *established*, semantic relations, and are thus not operative carriers of activation. The connectionist component of Sapper is responsible for the controlled propagation of activation energy, or *zorch* (see Hendler 1989), throughout the network, as it flows from the matriarch concept nodes as evoked by the metaphor. The matriarch concepts of a metaphor, following Richards (1936), are known as the *tenor*, or metaphorized subject, and the *vehicle*, or metaphorizing object. The task of the connectionist component, then, is to predict which dormant linkages should eventually be *awakened*, to become active bridges linking the domains of the tenor and vehicle concepts.

Figure 1 depicts such a scenario during the interpretation of the metaphor "Composers are Generals" (or vice versa). Whenever waves of competing activation meet at a dormant linkage, that linkage forms the basis of an initial match hypothesis. Because dormant linkages are laid down by the rule-based component on the basis of local consistencies of structure, the hypothesis stage is thus, in a strong sense, driven by both literal similarity and higher-order structural constraints. And because activation originates at the concept nodes of the tenor and vehicle, the connectionist phase integrates the base-filtering and hypothesis formation stages of processing.

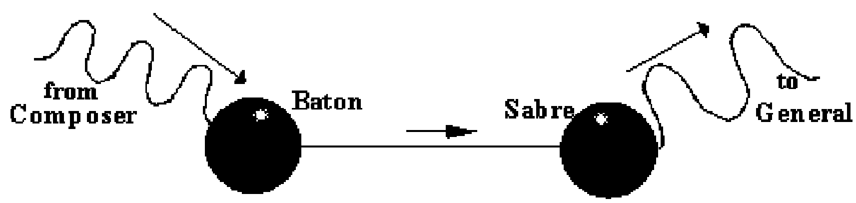

Figure 1: A dormant linkage between the concepts Baton and Sabre is deemed to provide a plausible match hypothesis when it becomes a cross-over path for competing activation waves from the tenor and vehicle concept nodes.

Returning to our current metaphor example, the Sapper system awakens a range of initial cross-domain bridges in response to the juxtaposition of Composer and General, some of which are eventually recognized to be globally inconsistent, and therefore returned to a dormant state. The bridges that survive produce the following mappings:

[.86] If **Composer** is like **General**

[.25] *Then* **Concert-Theatre** is like **Battle-Theatre**

[.75] *and* **Orchestra** is like **Army**

[.94] *and* **Musician** is like **Soldier**

[.98] *and* **Musical-Instrument** is like **Musket**

[.95] *and* **Baton** is like **Sabre**

[.92] *and* **Musical-Score** is like **Battle-Plan**

[.93] *and* **Percussion** is like **Artillery**

[.96] *and* **Drum** is like **Cannon** *etc.*

The number specified in square brackets to the left of each mapping is a numeric measure, between -1 and +1, of the perceived similarity of the related concepts *after* the metaphor has been comprehended. This measure combines a metric for both the literality similarity of the related items (e.g., Drums and Cannons are loud and booming), and the higher-order similarity that is now seen to exist between the two (e.g., the relation between Drum and Cannon supports the second-order mapping Percussion: Artillery, which in turn supports the mapping Orchestra: Army).

The Sapper rule component employs two distinct constructor rules to augment the knowledge-base with dormant conceptual bridges --- the *Triangulation Rule* and the *Squaring Rule*. In essence, these rules compile into the knowledge-base the top-down knowledge that is necessary to infer systematic cross-domain binding; and because this knowledge is automatically pre-compiled into the network, the connectionist phase is spared the necessity of performing global structural analysis, and is therefore adequately modelled as a spreading activation process. The *Triangulation* rule is invoked whenever two concept nodes share a common association or superclass, as is the case with the concepts Musical-Instrument:Musket & Hand-held, Drum:Cannon & Loud, Baton:Sabre & Long, Battle-Theatre:Concert-Theatre & Theatre, and Stave:Contour & Line, laying down dormant linkages between the schemata Musical-Instrument and Musket, Drum and Cannon, Baton and Sabre, Battle-Theatre and Concert-Theatre, and Stave and Contour. The *Squaring* rule, which is a *second-order constructor* -- inasmuch at it may act upon the linkages laid down by the triangulation rule -- is used to build (or *reinforce)* the bridges Orchestra:Army, Percussion: Artillery, Musical-Instrument: Musket, and Musical-Score:Battle-Plan. The Squaring rule thus builds bridges upon bridges, each new linkage extending the inter-domain *reach* of the last; in this way Sapper accounts for the phenomenon of *domain incongruence* -- the non-literal sharing of attributes between domains (see Tourangeau & Sternberg 1981). The mechanics of these two rules are illustrated in Figure 2:

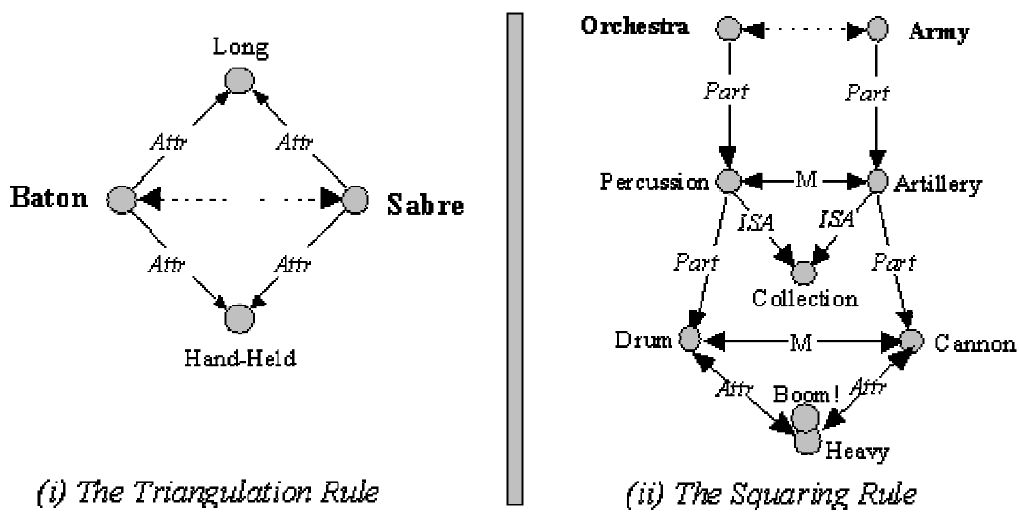

Figure 2: The Triangulation Rule (i) and the Squaring Rule (ii) augment the knowledge base with additional dormant structures, precompiled pathways that may later be used to form cross-domain analog bindings. The Triangulation rule infers new structure on the basis of shared associations, while the squaring rule employs shared metaphoric bridges (previously awakened dormant bridges, or established metaphors) as an evidential basis.

The Sapper memory network fragment corresponding to the Composer: General metaphor is illustrated below in Figure 3:

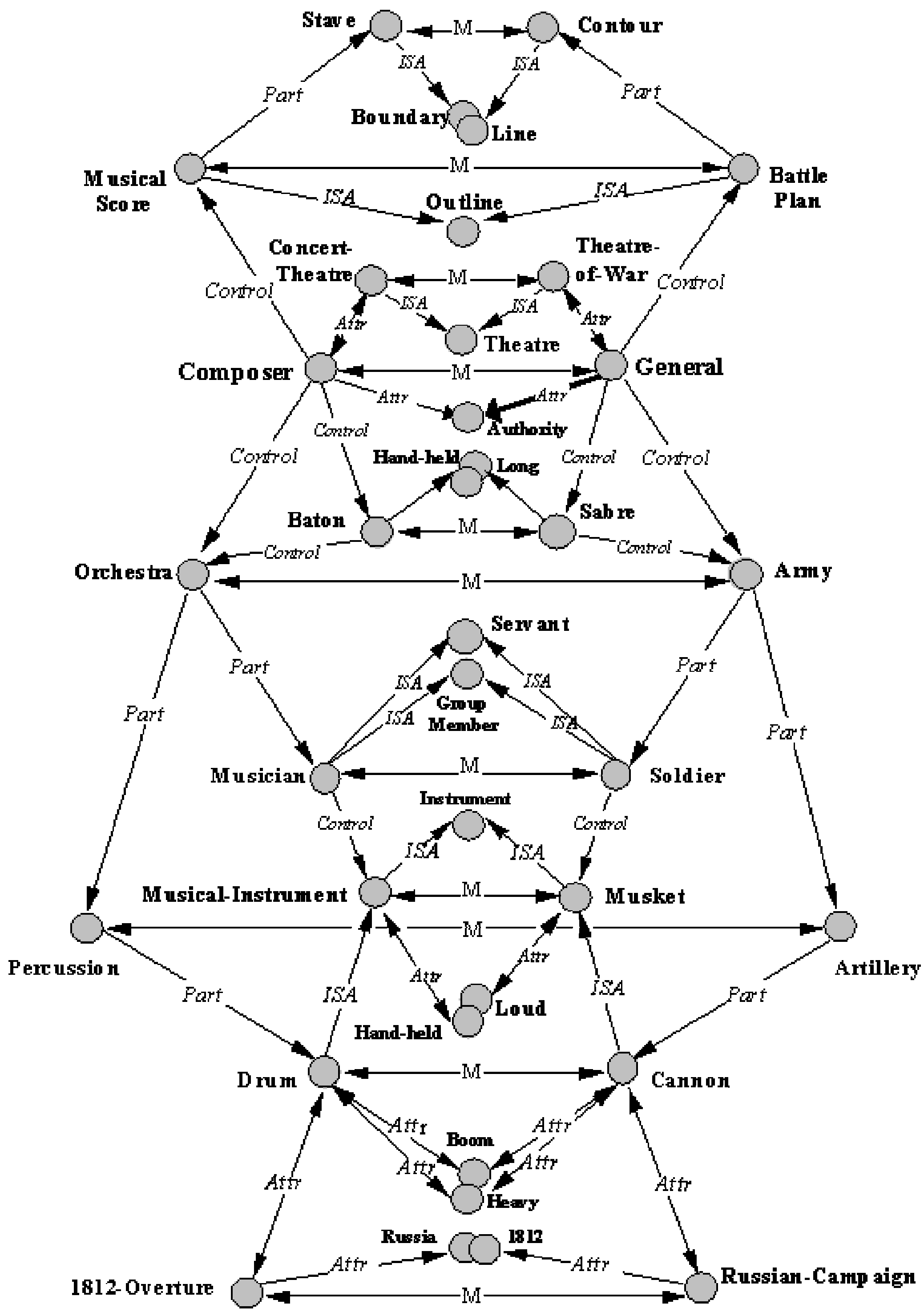

Figure 3: Sapper description of the metaphor "Composers are Generals".

Note that the triangulation and squaring rules are wholly independent of any particular comprehension task. Full metaphor comprehension is only initiated once the matriarch nodes corresponding to the tenor (Composer) and vehicle (General) have been *clamped*, and the connectionist component proceeds to propagate activation from these source nodes; in our current example, this causes the dormant linkages between Composer: General, Baton: Sabre, Percussion: Artillery, scalpel:Cleaver, and Concert-Theatre: Battle-Theatre to be recognized as initial match hypotheses. Sapper then directs these linkages to be *provisionally awakened*, thereby providing an basis for the squaring rule to infer even higher-level structural hypotheses.

3.2. Metaphor Interactivity

The opening of these bridges allows activation to flow freely between the tenor and vehicle domains, altering the activation dynamics of the network in such a way that the tenor *actually* interacts with the vehicle at a conceptual level. This network effect is illustrated below in Figure 4:

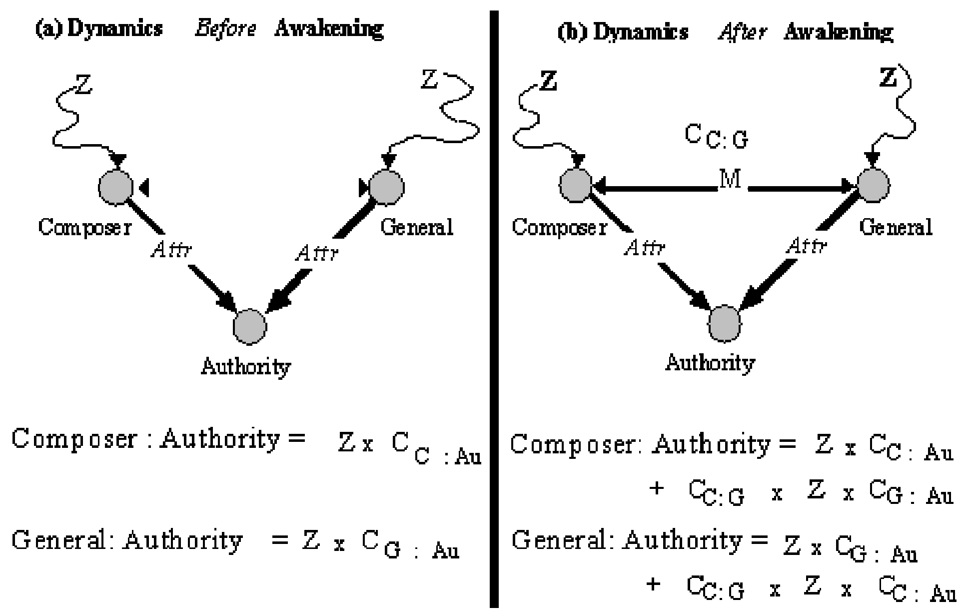

Figure 4: The awakening of a new bridge alters the activation dynamics of the network, allowing zorch (Z) to flow freely between two domains.

The *hard* activation patterns of General, Battle, Artillery, Musket and Cannon interact with the *softer* patterns of Composer, Music-Composition, Percussion, Musical-Instrument and Drum to produce a response to the metaphor. Overall, a Composer is seen, through the lens of the metaphor, to be an altogether more authoritative and commanding figure, leading loyal musicians into the fray, while amidst the booms and swells of performance, wielding a conductors baton to dictate the course of the action. A fancifully graphic interpretation to be sure, but one that, in following the interaction view of Richards (1936) and Black (1962), operates both ways. The metaphor toughens composers, but softens generals, who are now seen to be that much less hardened and impassionate, and altogether more artistic and romantic.

4. Epistemological Issues in Metaphor Comprehension

Linguistic metaphors come in different syntactic guises: qualification metaphors of the adjective: noun variety, object-centred metaphors of the noun: noun variety, and predicate-centred metaphors of the verb: verb variety. While it is to be expected that each form is interpreted relative to the same knowledge structures, full comprehension of each form may stress different aspects of those structures than others, and overall, adopt a different epistemological perspective on the organization of memory.

Surprisingly, even metaphor theories which claim to be generalized structure matchers, such as SME, the *Structure Mapping Engine* of Falkenhainer, Forbus and Gentner (1989), embody hard-wired epistemological biases which make them more suited to one guise of metaphor over another. SME is essentially a symbolic graph matching mechanism, which is nevertheless claimed to model the metaphor comprehension process in Gentner, Falkenhainer & Skorstad (1989). This section will set the stage for the empirical demonstration in the next, arguing that objected-centred metaphors of the *noun: noun* variety comprise a significant Achilles' heel of SME. As our analysis will reveal, this weakness derives from an epistemological bias in SME's design, which leads the unwary matcher to a factorial demise for certain types of domain structure in which hierarchical organization is present but implicit. This factorial demise is also exacerbated by SME's refusal to employ literal similarity as a constraint on the creation of initial match hypotheses. The empirical results also suggest that such a refusal to effectively limit the number of initial match hypotheses also ham-strings the connectionist-flavoured ACME model of Holyoak & Thagard (1989). ACME, the *Analogical Constraint Mapping Engine*, builds a new constraint network for each metaphoric comparison, and allows this network to iteratively converge from an initial random state toward an ordered final state that encodes a suitable domain mapping. The evidence presented here casts serious epistemological doubts on the validity of these models both as generalized matching systems, and as cognitive theories of human metaphor comprehension.

4.1 Object-Centred Representations

Metaphors which contrive the juxtaposition of two object concepts, such as Surgeon & Butcher, or Car & Rocket, will more readily exploit the object-centred aspects of these concepts in memory. That is to say, those aspects of conceptual representation which emphasize objects and entities over actions and events, such as meronomic, taxonomic and associational structures — how an object is defined in terms of its own behaviour, rather than the higher-order actions and events in which it participates — make the greatest contribution to the analysis of *noun: noun* metaphors. For instance, the physical properties of an entity — such as its size, weight, component structure, etc. — contribute toward the object-centred view of that entity, while the historical character of an entity — who it married, what it does on Sundays, etc. — constitute the *predicate-centred or event-centred* view of that entity. This form of representation is illustrated in the example metaphor of Figure 5:

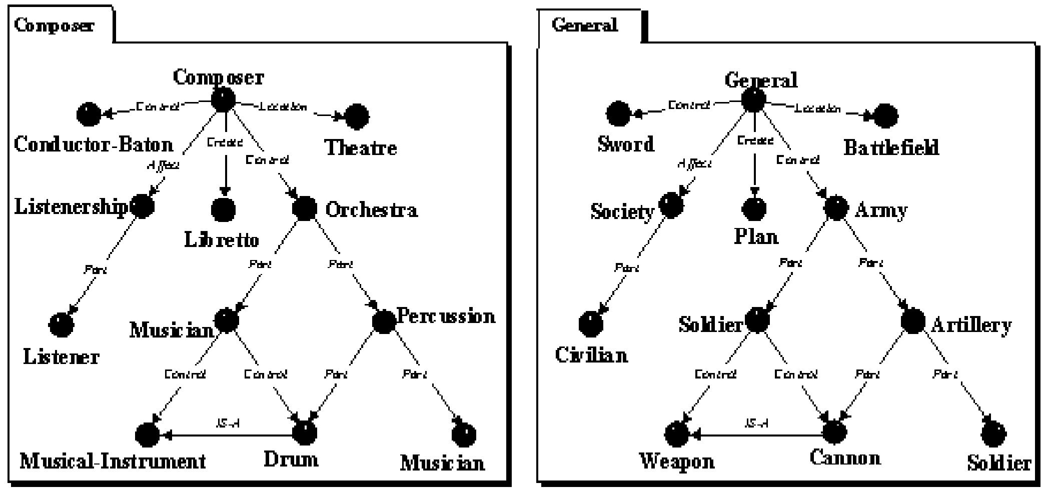

Figure 5: Object-Centred Representations for the concept schemata of Composer and General. Notation: The labelling scheme differs from that employed in previous diagrams, as our discussion is to be a general one concerning representation issues, and is not specific to the Sapper mechanism.

The epistemological style of Figure 6 may be considered object-centred inasmuch as object/entity nodes establish the foreground of the representation, while inter-concept relations are strung between these nodes like tinsel on a Christmas tree. The significant point to note about this representational form is that linkages as well as nodes are labelled, and thus, both types of graph component may be considered to be *first-class* representational elements. As illustrated earlier in Figures 3 and 4, this is the representational form adopted by Sapper, for reasons that will become clearer later in this paper.

4.2. Scenario-Centred or Predicate-Centred Representations

Whereas object-centred metaphors tend to focus upon the entities of a domain, scenario-based or predicate-centred metaphors are naturally more disposed toward the relational structure that exists between these entities. Curiously enough, this shift in emphasis is achieved by denying labelling privileges to the linkages which connect the nodes of the representation, forcing the knowledge-base to encode both actions and objects as nodes. The linkages of a predicate-centred representation exist only to tie the argument nodes of a predicate to the predicate node itself, in effect then establishing a graph notation for the predicate calculus. For in much the same way that arguments go unlabelled in a predicate calculus expression, relying wholly upon ordering constraints to define their relationship to the governing predicate, the nodes of a predicate-centred representation also rely upon surface ordering to convey implicit deep relationships. This style of representation is illustrated in Figure 6 below, in expressing the oft-employed Karla the Hawk story which typifies the SME/ACME approaches to analogy:

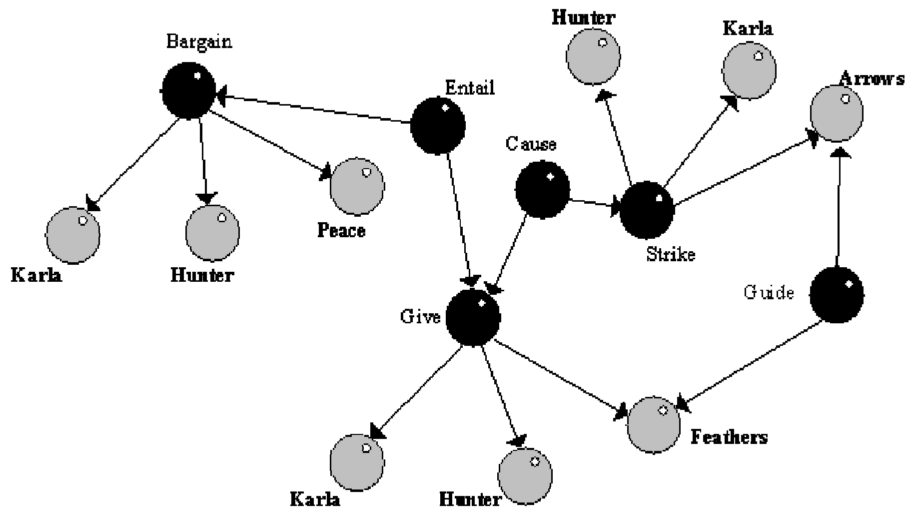

Figure 6: The Karla the Hawk story. (a) illustrates a representation of this predicate-centred domain in which nodes only are labelled (following the SME approach). Notation: Black nodes represent predicates, and grey nodes represent entities.

It is toward this form of domain that predicate-centred representations are best suited, problems where one hierarchical relational structure, essentially a nested predication, is matched with another. In a predicate-centred model of analogy such as Gentner's SME, predicate nodes (depicted in black) are mapped under a strict identicality constraint, while entity nodes (depicted in grey) may conceivably map onto any entity node in the target domain, provided the 1-to-1 coherence of the overall mapping is preserved. Entity nodes are therefore almost incidental to the mapping process in a predicate-centred representation, as it is the predicates and their relationship to each other that ultimately determine the basis of the analogy.

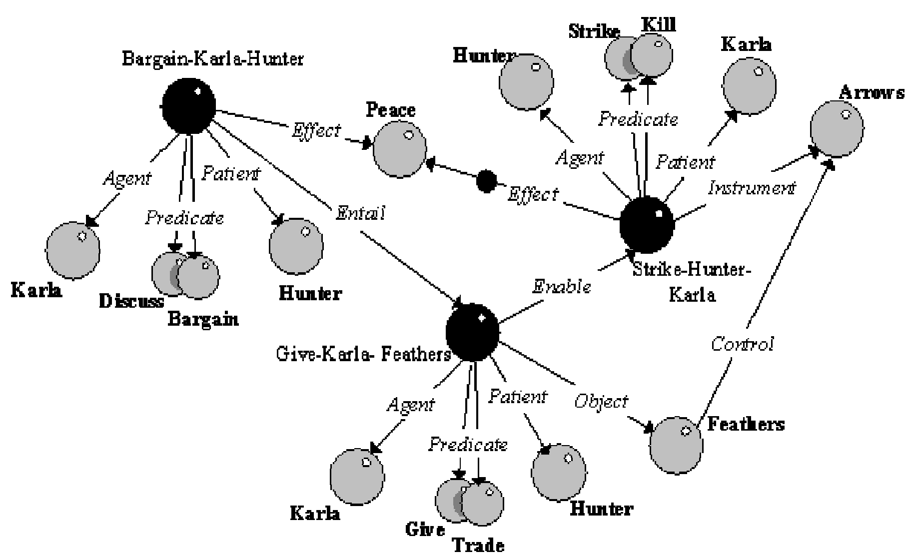

Figure 7: An object-centred representation can nevertheless neatly express the meaning of a predicate-centred domain , while labelling both nodes and links.

As illustrated in Figure 7 above, however, an object-centred representation is equally capable of expressing predicate-centred domains. In fact, to our minds, the above representation is preferable to that of Figure 6, as the role of each entity (grey node) is explicitly annotated with a case-role labelling. In addition, the use of a predicate case role which can take several values means that more than one predicate can be assigned to a particular action; thus, the act of bargaining can be described as both an instance of a Discuss and Bargain predication, providing greater scope for matches with other, analogous events (e.g., allowing a match between a Placate and Bargain action).

4.3. Support Relations

While different models of metaphor and analogy may place different degrees of significance on the role of structural isomorphism, most theories (such as SME, ACME and Sapper) ultimately acknowledge that analogy and metaphor are, by and large, structure-preserving processes. Philosophically, this is an unavoidable, indeed almost tautological, position to assume, for in any formal/computational system, meaning is necessarily explicated in structural terms, so where structure is not respected, neither is meaning. In the ACME approach, the structure of the tenor and vehicle domains dictates the structure of the constraint network that is especially constructed for the interpretative task at hand; the conceptual structure of the tenor and vehicle is thus the major source of constraints upon the mapping process. In the Sapper approach, the conceptual structure of the tenor and vehicle domains not only provides the evidential basis of the triangulation and squaring rules, but also defines the pathways along which activation energy will flow to awaken new cross-domain bridges. And in the SME approach, the hierarchical structure of the tenor and vehicle domains is used to constrain, in a top-down fashion, the combinatorial possibilities of cross-domain entity mappings. Each model therefore, in its own way, looks to the structural make-up of the tenor and vehicle to indicate what partial mappings support other partial mappings, and which partial mappings are irreconcilable with each other.

A metaphor interpretation system must, therefore, take its support relations wherever it can find them. However, certain models, such as SME and ACME, place far too much emphasis on the importance of hierarchical support as manifested by nested predicate structures, to the detriment of other forms of support relation. These models exhibit a serious *epistemological blind-side*, an oversight which makes them inherently unsuited to the interpretation of noun: noun metaphors and any other form of comparison that requires an object-centred representation. To see why this must be so, consider the predicate-centred re-representation of a domain that is more amenable to object-centred organization, as illustrated in Figure 8 on the following page.

The most striking quality of the representations in Figure 8 must surely be the obvious lack of hierarchical depth - gone are the tree structures of Figure 6, rich in vertical support relations, to be replaced by a shallow and un-nested representation that favours horizontal rather than vertical expansion. However, all that has been performed here is an alternative depiction of the same knowledge structures - a graph re-labelling in which no knowledge has been added or removed - and thus, on a syntactic level, the form may have changed but the meaning has been preserved.

Effectively, the reader will observe that the support structures which found vertical expression in an object-centred representation have simply been *sheared* to find horizontal expression in a predicate-centred representation, while the support relations which were manifest hierarchically in the former are now present in the latter in a *sideways systematic* fashion. However, models such as SME and ACME which are locked into a particular form of processing, and are algorithmically predisposed to seeking support structure in hierarchical rather than horizontal organization, fail completely to acknowledge this sideways systematicity.

In the terminology of SME, each predicate node in Figure 8 (illustrated in black) comprises a *root mapping* in the overall analogy, inasmuch as each predicate is ungoverned by a higher-order relation (in contrast, say, with the structures of Figure 7). Unfortunately, the SME algorithm includes a *root merging* stage whose complexity is factorially dependent upon the number of such roots (this merge stage is described in Falkenhainer, Forbus, & Gentner 1989). Clearly, if every predicate in the tenor and vehicle domain is to be considered a root, then SME quickly descends into factorial hell. Likewise, the excitatory and inhibitory linkages which codify the support relations in an ACME constraint network are laid down on the basis of hierarchical support; if this support is not perceived in a sideways fashion, the constraint network may become underdetermined.

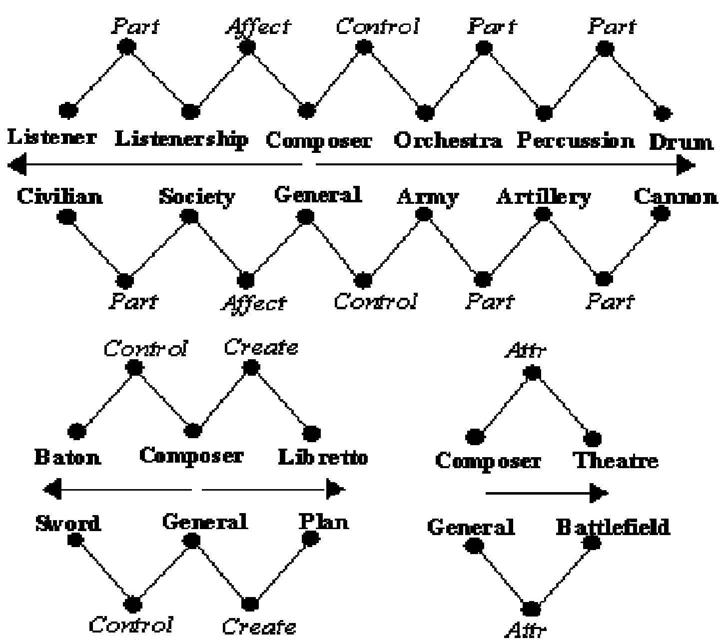

Figure 8: A Predicate-centred view of the domains of Composer and General. Arrows are provided to indicate the direction in which predicate arguments should be read. Compare these flat structures with the hierarchical depth of the equivalent object-centred views illustrated in Figure 6.

However, unlike the structure-bound SME, the connectionist ACME employs a form of spreading activation which can horizontally *cut across* structures, thereby enforcing in some astructural manner the sideways systematicity inherent in the representation. In effect, spreading activation facilitates a form of *lateral thinking*, in which one part of the network may reinforce another, even when these regions are not connected by some overarching hierarchical relation. Consider again the example of Figure 8: activation may propagate upwards and sideways, allowing the network to transcend the limitations of simple vertical support, to additionally exploit horizontal support relations. However, while more epistemological sure than SME, a more secure case against ACME can nevertheless be made on grounds of scalability, and such a case is addressed in the next section.

4.4. Epistemological Commitments

In the final analysis, then, noun: noun metaphors demand an object-centred representation if the support relations manifest in the structural make-up of the tenor and vehicle domains are to be made explicit. If the sample metaphor of Figure 7 illustrates the suitability of a predicate-centred representation for verb: verb comparisons, the example of Figure 8 clearly demonstrates the error of shoehorning noun: noun metaphors into such a representation. Indeed, while an object-centred representation is readily augmented to accommodate verb: verb metaphors, no simple additions can be made to a predicate-centred representation to accommodate noun: noun metaphors. Any such changes would shake at the very roots of the host theory, and substantially reformulate that theory to the extent that it bore no resemblance to the original. It would seem then that the representation of choice in the Sapper model, an object-centred localist network, is best suited to the rigours of a metaphor interpretation system that is to tackle figurality in its variety of linguistic forms. This view is borne out in the experimental evaluation described in the next section, in which such doubts regarding the epistemological foundations of SME and ACME are given quantitative form.

5. Quantitative Evaluation and Analysis

The quantitative evaluation of Sapper described in this section was carried out within a sample memory network containing 284 concept nodes and 1597 user-specified inter-concept relation links. This network represents a description of the profession domain, and contains conceptual schemata for fifteen different profession types, such as Surgeon, Composer, Butcher, General, Scientist, and so on. The total number of automatic inferences generated by Sapper while assimilating this network description is 2299 dormant conceptual bridges, all of which are created using the triangulation rule, as higher-order inferences only occur during metaphor comprehension. On average then, each profession schemata comprises 19 localist concept nodes, and 106 inter-node linkages. Of these linkages, 36 codify high-level relations (such as Cause and Depend), and 70 codify attributions and taxonomic orderings; while this distinction is an artificial one which means nothing at all to Sapper, the distinction is nevertheless considered valid in the context of SME. The following profession types are defined in this network:

Surgeon	*Butcher*	*General*	*Priest*	*Scientist*
Architect	*Politician*	*Criminal*	*Hacker*	*Chef*
Accountant	*Author*	*Magician*	*Composer*	*Sculptor*

The following network linkages are used to encode semantic relations within and amongst these conceptual schemata:

Attribute	*Control*	*Part*	*Substance*	*Purpose*	*Effect*
Instrument	*Predicate*	*Aspect*	*Perform*	*Affect*	*Create*
Connect	*Disconnect*	*Up*	*Down*	*Manner*	*Source*
Target	*Method*	*Agent*	*Patient*	*Event*	*Character*
Metaphor					

The linkages Effect, Manner, Method, Target, Purpose, Event, Character, Agent, Patient and Instrument are provided for the description of verb-centred scenarios, for example, the J.F.K. political setting, or the King Arthur legends (the latter yielding good metaphors for the former), while the linkage Metaphor is provided to allow the knowledge engineer to encode conventional metaphors into the network (such as the *Family Tree* and *Gene Pool* metaphors).

5.1. A Quantification of Automatic Inference

Given such a test-bed environment, the scene is set to ask some basic empirical questions regarding the profligacy of automatic inference, as performed by the triangulation and squaring rules. For instance, what kind of worst-case and average-case scenarios can be imagined here? Even if Sapper were to push the limits of prodigality in the creation of dormant linkages, the worst case scenario involves the generation of n*(n-1)/2 dormant linkages, where n is the number of localist nodes in semantic memory; large to be sure, but hardly nightmarish in its extent. And as it happens, the average case performance is much lower than this ceiling, the effect of well-defined domain structure being to considerably reduce the possibilities of inter-node bridging. This situation is illustrated in Figure 9 following, in which the bridging overhead of our profession test-bed network is graphed.

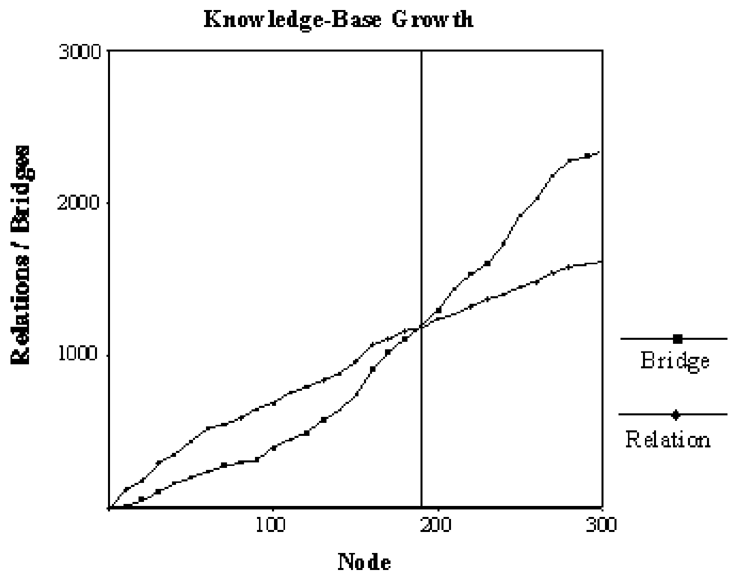

Figure 9: Number of user-specified concept relations graphed against number of system-inferred bridges.

Note that the network seems to reach a critical mass at just under 200 nodes, at which point the system begins to out-produce the knowledge-engineer in adding linkages to the network. But when the network reaches 300 concept nodes in size, the worst-case model predicts that 44850 dormant linkages will have been automatically inferred, while the real situation presents a more tractable picture: just over 2000 such linkages, less that five percent of the worst case scenario, are actually added to the network. Sapper thus seems to exhibit remarkable thrift in its automatic inference capabilities.

Of course, these bridges do not necessarily have to be held in the system until they are used, if ever; rather, they might be created dynamically as the metaphoric context dictates. This is achievable by delaying application of the triangulation rule until the spreading activation phase of metaphor interpretation - as each node is newly activated, the triangulation rule is applied to that node and to those other nodes which are currently active within the scope of the rule. This is the classic computational trade-off in space versus time, whereby the storage costs of maintaining many, potentially useless, bridges is translated into processing costs at run-time.

5.2. An Experiment

This profession network provides a suitable test environment in which to perform a comparative evaluation of Sapper, SME and ACME; disregarding issues of metaphor symmetry, focusing instead on the concerns of structural consistency and mapping coherence, fifteen different concept descriptions yield one hundred and five different figurative comparisons. Running upon this pool of 105 test metaphors, Sapper achieves a respectable average interpretation time of 12.5 seconds per metaphor. The incremental case, wherein the same metaphors are presented to the system a second time, shows that this time drops to less than six seconds for metaphors that have been previously encountered. Of course, since Sapper is the only model of the three which incorporates any real notion of long-term memory in comprehension, it is the only model to exhibit this effect. Moreover, neither SME or ACME provide any concrete results whatsoever, for any of the test metaphors, even when they are allowed to run for days at a time, yielding an effective *destruct-test* of Allegro Common Lisp but little else. Eventually then, unable to obtain performance ratings for SME or ACME on this test network, a tabulation the number of initial match hypotheses generated by each model is instead provided. This data proves to be revelatory in clearly demonstrating the cause of failure in SME and ACME -- too many initial match hypotheses cause each model to become intractable in later stages of processing. This finding is illustrated in Figure 10 on the following page. Note that Sapper's average *mapping competence* has been determined by running a time consuming exhaustive-search variant of the basic Sapper algorithm to obtain the perfect mapping score for each test metaphor; the mapping score awarded by the standard Sapper algorithm is then compared to this optimum to obtain an average measure of Sapper's expected competence.

As can be seen in Figure 10, Sapper on average generates considerably less match hypotheses than SME (18 versus 386), while SME in turn is significantly more thrifty than ACME (386 versus 12657). Sapper's hypothesizing thrift arises from its dependence on conceptual bridges, which are only ever created when there exists a first-order (literal) or higher-order (creative) similarity between two concepts. SME, however, employs no such notion of similarity and instead prefers to temper match selection using the notion of predicate identicality. ACME is the prodigal son of the trio, eschewing even predicate identicality and instead favouring the weaker constraint of arity-matching. No wonder then that ACME fails to generate a mapping for any metaphor; while not as prone to the epistemological blind-sight that so afflicts SME, ACME instead suffers from *network bloat* - the constraint network developed for each metaphoric comparison is simply to large to be resolved in any reasonable amount of time.

Aspect / System	**SME**	**ACME**	**Sapper**
System Competence	Optimal	N/A (sub-optimal)	98% of optimal
Match Hypotheses (M.H)	386	12657	18
M. H. Incremental Case	Unchanged	Unchanged	7
Time per Metaphor	Worst case O(2^{386}) seconds	N/A	12.5 seconds
Time Incremental Case	N/A - Unchanged	N/A - Unchanged	5.8 seconds

Figure 10: Comparative evaluation of Sapper, SME and ACME as determined within the Profession test network. Note that the unavailability of time figures for SME and ACME reflects the inability of these models to generate a result in real time.

5.3. Factorial Death

Although considerably less prodigal than ACME in generating match hypotheses, SME is nevertheless inherently factorial in its root global mapping (gmap) merge stage of processing. Now, because of its inability to determine sideways support relations in an object-centred domain (of which the profession test-bed is an exemplar), each linkage in every concept description forms the basis of a root gmap, and thus, SME is combinatorial over the number of linkages in each concept description. To appreciate the complexity implications of this, consider the metaphor General as Surgeon - which causes SME to generate 398 distinct root gmaps. The worst case scenario for the merge stage thus necessitates the consideration of as many as 2398 mapping combinations, a scenario of truly nightmarish proportions. To further appreciate the enormity of this number, consider that if a dedicated *analogy machine* (or *engine*, as SME and ACME are viewed by their creators) were capable of performing a generous one trillion gmap merges a second, the General-Surgeon example might still occupy this machine for over U5 years, where U is a conservative estimate of the age of the universe at fourteen billion years. Clearly, this is a hole from which even massive parallelism is powerless to rescue a theory.

5.4. A.C.M.E: Return to Sender?

ACME is an intriguing acronym, but one which perhaps has too many evocations of the classic *Loony Tunes* animation of Chuck Jones than any one theory should have to bear. As with those infamous packages marked A.C.M.E. which constantly promise instant *Road-runner doom* but which instead boomerang on an ever-unsuspecting Wile E. Coyote, the analogical model ACME would also seem to advertise much more than it delivers. Perhaps the comparison is undeserved (though irresistible!) inasmuch as ACME offers a connectionist perspective on metaphor analysis, which as this paper argues, is needed if all of contingent world knowledge is to be opportunistically made available to the comprehension process. However, ACME spurns this advantage of connectionism by necessitating the construction of a dedicated network for each metaphor analysis, in effect a priori separating ACME from this wealth of experiential knowledge in long-term memory. Thus, an ACME network is not so much a representation of that subset of the mental landscape in which the metaphor is interpreted, but a meta-representation of such representations that has to be constructed on the fly. Connectionism in this context should thus grant no biological kudos; indeed, if its creators hope to claim neurological plausibility with connectionism, one must view such dedicated construction as the computational equivalent of *tumour growth!*

As stated in section 5.2, no final results were forthcoming from our profession domain tests on ACME, as the scale of its network operation simply overwhelmed our test environment (a SPARC 2 running Allegro Lisp with 64 megabytes of RAM). To obtain some real data, ACME was run with a subset of the profession domain metaphors, each run evaluating metaphoric comparisons of successively larger predicate count (in the region of 5 ... 30 predicates for each tenor); Figure 11 following graphs the average number of nodes in each network so created against the average convergence time for each network.

Though prediction of network convergence times is in general a black and highly non-deterministic art, our experience with ACME on the larger test suite suggests that convergence time is exponentially related to network size; this intuition is borne out by Figure 11, which illustrates the closeness of an exponential fit to the actual results. ACME thus succumbs to the same factorial fate as SME, a victim of its own spendthrift nature and tendency toward network bloat.

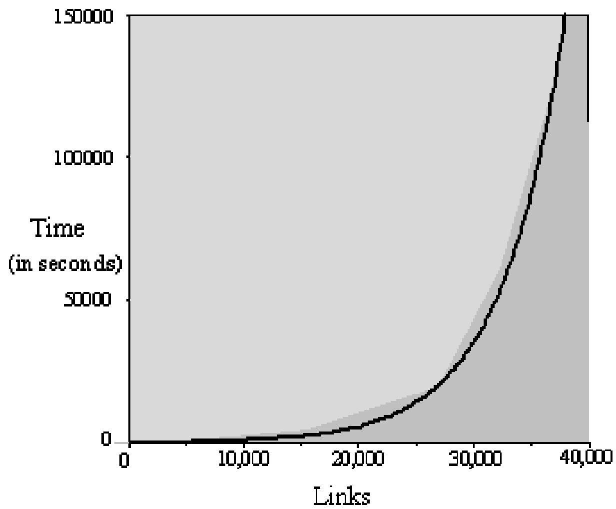

Figure 11: Graph of average ACME network convergence times versus size of network in links, as derived from a representative subset of metaphors from the professions domain. The jagged outline area records the experimental results, whilst the black curve is an exponential fit for these results.

5.5. Counter-Arguments from the SME Camp

Consider the following rebuttal: SME does not work upon these profession examples simply because they are structurally-impoverished and causally-deficient. In short, the test metaphors are contrived and thus invalid because any hierarchical causal structure has been removed, but if causal structure were correctively added to these examples, SME would perform adequately upon them. This line of argument is fallacious for the following reasons:

> **(i)** In no way should these object-centred domains be considered structurally or causally lacking. The network linkages Effect, Control, Perform, Method, Purpose and so on are provided to explicitly represent causal relations, and these may be stringed together, in a sideways fashion, to construct complex causal structures.
>
> **(ii)** A suitable graphical representation in which both nodes and links are labelled demonstrates that there is indeed hierarchical structure inherent in

these object-centred domains. It is simply a matter for the analogy system in question to seek out this structure using the correct *filter* (e.g., vertical versus horizontal support).

(iii) Even if these examples *were* structurally impoverished, would this excuse SME's apparent ultra-sensitivity to representation? No, at best the SME theory should provide an algorithmic basis for determining the suitability of its inputs in advance, rather than having to spend geological time demonstrating the deficiency of the representation.

(iv) An empirical demonstration of the presence of this structure, and its sufficiency for analogical mapping, is provided by the Sapper mechanism and its ability to recognize and map this structure.

In summary then, these results show the SME approach to be seriously lacking in mapping competence, and not at all the general-purpose matching algorithm it purports to be (see Falkenhainer, Forbus & Gentner 1989).

6. Summary and Conclusions

This paper has presented both the driving motivations and basic philosophy underlying the Sapper model of memory for metaphor comprehension. As stated in the introduction, a computational treatment of metaphor as a first-class cognitive phenomenon, which addresses the various signature phenomena debated in the literature, raises a number of interesting issues concerning knowledge representation. Namely, how is systematicity among different conceptual schemata from different domains to be enforced? How best should these schemata be organized to ensure that the most natural interpretation of a metaphor emerges from, or is shaped by, the existing knowledge-base, rather than being eked out by a dedicated metaphor processor? What characterizes *learning* in the interpretation of novel metaphors, and how should this learning be constrained to occur in a systematic manner? How can metaphors be reified to the status of active conceptual entities, such that they dynamically strive to impose themselves upon incoming schemata, and in doing so elaborate themselves further?

A hybrid model has been presented to address these issues, marrying the complementary strengths of the symbolic and connectionist paradigms to combine both high-level structural inference with low-level opportunistic activation flow. The Sapper model of connectionist bridge-building, it is argued, provides a computational framework that is truest to the interaction view of metaphor, as advocated by Richards and Black, while explicating the manner in which metaphors move from *attention-winning* novelty to trite *conventionality*. Sapper operates in a bottom-up fashion, and thereby complements the top-down strategy of conceptual scaffolding developed in Veale & Keane (1992a,b) to yield a comprehensive account of the metaphor phenomenon, at both a lexical semantics and a deep conceptual level.

Sapper also provides a computational account of metaphor creativity that is essentially based upon the exaggeration of domain incongruences. Local similarities of a literal nature, initially established using the triangulation rule, are magnified by repeated application of the squaring rule, in the appropriate network contexts, to generate higher-order similarities that simply did not exist before interpretation of the metaphor. In this way, Sapper offers a cognitively appealing view of metaphor as a creative force that invents, rather than simply observes, new associations between concepts.

Sapper also provides a flexible network model that is amenable to the interpretation of metaphors in different linguistic guises, whether noun: noun, adjective: noun or verb: verb. Each of these forms are interpreted relative to an object-centred representation which highlights some epistemological concerns about the structural foundations of the SME and ACME models. While Sapper is capable of handling metaphors that prefer object-based descriptions (such as General: Surgeon) and predicate-based descriptions (such as *Karla the Hawk* story analogies), SME is shown to be competent with the former only, becoming factorially unhinged when expected to deal with metaphors of the latter variety. This result casts a shadow not only over SME's claim to be a generalized structure-mapping engine, but also upon any serious pretensions to cognitive plausibility its creators may entertain.

To conclude, should the reader wish to examine the experimental data for his or herself, it may be obtained (in Sapper, SME and ACME formats) from the Metaphor Home Page: *http://www.cs.tcd.ie/www/raveale/metaphor.html*.

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