AD-A207 042

REPORT NO. UIUCDCS-R-88-1421

UILU-ENG-88-1726

The SME User's Manual
(SME Version 2E)

by

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December 1988

DEPARTMENT OF COMPUTER SCIENCE
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN · URBANA, ILLINOIS

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; Distribution unlimited
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UIUC-DCS-88-1421	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION University of Illinois Dept. of Computer Science 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Office of Naval Research Cognitive Science Division (Code 1142CS)
6c. ADDRESS (City, State, and ZIP Code) 1304 W. Springfield Ave. Urbana, IL 61801	7b. ADDRESS (City, State, and ZIP Code) 800 N. Quincy St. Arlington, VA 22217-5000
8a. NAME OF FUNDING / SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-89-J-1272
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 6115N; PROJECT NO.; TASK NO.; WORK UNIT ACCESSION NO NR 442f-007

11. TITLE (Include Security Classification)
The SME User's Manual (SME Version 2E)
(Approved for public release; Distribution unlimited)

12. PERSONAL AUTHOR(S)
Brian Falkenhainer

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical Report	FROM 89-1-1 TO 91-12-31	12-30-88	

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Structure-mapping engine analogical processing
05		10	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. James Lester	22b. TELEPHONE (Include Area Code) 202-696-4503 22c. OFFICE SYMBOL ONR 1142CS

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

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(SME Version 2E)

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Abstract

This paper documents the *Structure-Mapping Engine* (SME), a general-purpose program for studying analogical processing. It provides a comprehensive description of the program and instructions for using it, including techniques for integrating it into larger systems. One section demonstrates methods for configuring SME to a variety of mapping preferences and suggests the range of theoretical variations available.

This research is supported by the Office of Naval Research, Personnel and Training Research Programs, Contract No. N00014-85-K-0559.

Contents

1 Introduction

The Structure-Mapping Engine (SME) is a general tool for performing various types of analogical mappings. SME was originally developed to simulate Gentner's *Structure-Mapping* theory of analogy [12,13,14]. It was hoped that the developed system would also be able to model the other types of similarity comparisons sanctioned by Gentner's theory, such as *literal similarity* and *mere appearance*. What ended up being developed was an extremely flexible and efficient system. Most theoretical assumptions are left out of the program and are supplied through match rules. Thus, while SME was originally designed to simulate the comparisons of structure-mapping theory, it may simulate many others as well. Given a set of theoretical restrictions on what constitutes a reasonable analogical mapping, one may implement these restrictions in the form of rules and use SME to interactively test their consequences. This report is intended to make that task easier.

This paper is designed for those interested in using SME for studying analogical processing, testing alternate theories, or as the mapping component in a larger system. It describes the options and user support provided in SME, how to use it for testing theories, and how to integrate it with other programs. For a discussion of the theory behind SME, the general algorithm, and descriptions of the program in operation, one should consult [8,9] prior to reading this manual. Descriptions of the use of SME in various research projects may be found in [4,5,6,7,13,15,23], while descriptions of Gentner's Structure-Mapping theory appear in [11,12,13,14,10,9].

1.1 Conventions

Throughout this guide, a few conventions will be used which should be explained at this time.

1. *CommonLisp Packages.* The SME system resides in its own package, SME, which is defined to use CommonLisp. As a result, any reference to an SME function or variable must specify the SME package, as in the function `sme:define-predicate`. To simplify the discussion, we will omit the package prefix when describing SME functions, macros, and variables. In addition, while the SME routines reside in the SME package, the structures it manipulates reside in the general `USER` package.

2. *The declarative interface.* In general, the routines used to present data items to SME, such as predicate definitions and concept descriptions, appear in two, functionally-equivalent forms. These two types have a naming convention associated with each. The most common type is the *declarative* or macro interface. The declarative routines do not evaluate their arguments and match the syntactic form `def`*routine-name*. For example, to define the entity sun declaratively, one writes `(defEntity sun)`. The second type is the *functional* interface, which is present to support declarations by external programs. These routines evaluate their arguments and match the syntactic form `define-`*routine-name*. For example, to define the entity sun functionally, one writes `(define-entity 'sun)`.

1.2 File Organization

SME is contained within the following twelve files:

config.lisp The declarations for site specific parameters.

defs.lisp The basic structure definitions and macros used throughout SME.

bits.lisp Routines for creating and manipulating bit vectors.

bms.lisp The belief-maintenance system (BMS) - a probabilistic TMS.

bms-tre.lisp The rule system and problem-solver front end for the BMS.

sme.lisp The SME top-level routines, such as initialization, defining facts about a concept, and fetching and storing facts and concept descriptions.

match.lisp The SME mapping algorithm.

match-rules-support.lisp A few functions useful for writing SME match rules.

display.lisp Machine independent output routines.

windowing.lisp Symbolics dependent interface routines.

batch.lisp Routines to enable execution in *batch* mode with a final report generated.

generalize.lisp Inductive generalization support.

2 System Review

The Structure-Mapping Engine can simulate a class of ***structural approaches*** to analogical mapping. In these approaches, there is a distinct stage of matching and carryover of predicates from one domain (the *base*) into another (the *target*) within the larger analogy process. Furthermore, although there are a number of differences, there is widespread agreement among these techniques on one fundamental restriction [1,2,16,19,20,21,22,25]:

1. *Structural consistency.* If a final analogical mapping includes a predicate in the base paired with a predicate in the target, then it must also include corresponding pairings between each of their arguments. This criterion simply asserts that an analogical mapping must not produce syntactically meaningless predicate calculus forms.

In SME, this restriction was enforced by the requirement of simulating Structure-Mapping theory; its impact on the algorithm is described in [9]. However, this restriction is only part of that theory and alone does not uniquely define a matching algorithm. Additional theoretical restrictions must be supplied through *match rules*. This enables SME to be used in exploring the space of theories consistent with this single criterion. An additional restriction is enforced by default:

- *One-to-one mapping:* No base item (predicate or object) may be paired with multiple target items. Likewise, no target item may be paired with multiple base items.

Enforcement of the one-to-one restriction is a global parameter which may be disabled. Support is provided to implement variations of one-to-one within the match rules.

Match rules specify what pairwise matches are possible and provide local measures of evidence used in computing the evaluation score. These rules are the key to SME's flexibility. To build a new matcher one simply loads a new set of match rules. This has several important advantages. First, we can simulate all of the types of comparisons sanctioned by Structure-Mapping theory with one program. Second, the rules could in theory be "tuned" if needed to simulate particular kinds of human performance. Third, a variety of other analogical mapping systems may be simulated for comparison and theoretical investigation. The breadth of the space of these structural approaches is suggested by the examples in Section 4.

In this section, the SME matching algorithm is briefly reviewed, followed by a short discussion of how theoretical guidelines may be added to the general mechanism. It is a summary of the algorithm description appearing in [9], annotated with the SME functions that carry out each step.

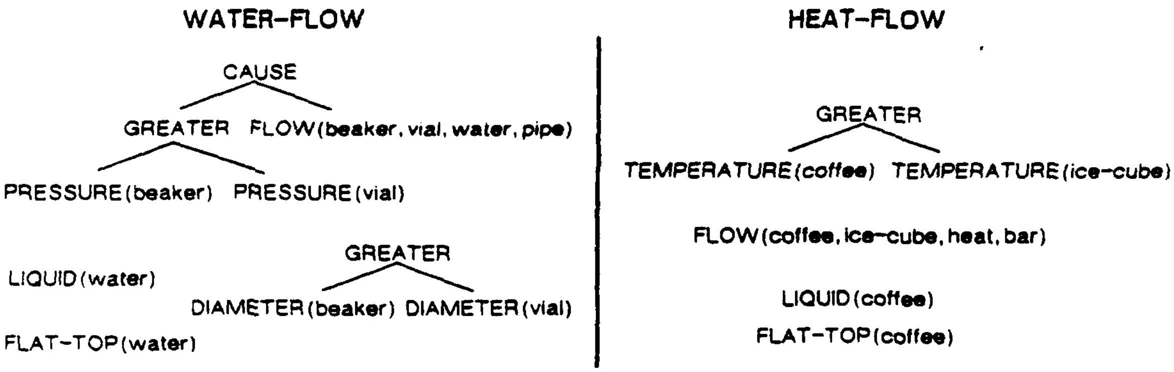


Figure 1: Simplified water flow and heat flow descriptions.

2.1 Algorithm Review

Given descriptions of a base and a target (called Dgroups), SME builds all structurally consistent interpretations of the comparison between them. Each interpretation of the match is called a *global mapping*, or *Gmap*. Gmaps consist of three parts:

1. *Correspondences:* A set of pairwise matches between the expressions and entities of the two dgroups.

2. *Candidate Inferences:* A set of new expressions which the comparison suggests holds in the target dgroup.

3. *Structural Evaluation Score:* (Called *SES* for brevity) A numerical estimate of match quality.

For example, given the descriptions of water flow and heat flow shown in Figure 1, SME might, depending on the current theoretical configuration, offer several alternative interpretations for this potential analogy. In one interpretation, the central inference is that water flowing from the beaker to the vial corresponds to heat flowing from the coffee to the ice cube. Alternatively, one could map water to coffee, since they are both liquids.

The SME algorithm (see Figure 2) is logically divided into four stages:

1. *Local match construction:* Finds all pairs of (*BaseItem*, *TargetItem*) that potentially can match. A *Match Hypothesis* is created for each such pair to represent the possibility that this local match is part of a global match.

2. *Gmap construction:* Combines the local matches into maximal consistent collections of correspondences.

3. *Candidate inference construction:* Derives the inferences suggested by each Gmap.

4. *Match Evaluation:* Attaches evidence to each local match and uses this evidence to compute structural evaluation scores for each Gmap.

- Run MHC rules to construct match hypotheses (create-match-hypotheses).
- Calculate the *Conflicting* set for each match hypothesis (calculate-nogoods).
- Calculate the *EMaps* and *NoGood* sets for each match hypothesis by upward propagation from entity mappings (generate-justifications and propagate-descendants).
- During the propagation, delete any match hypotheses that have justification holes (propagate-death).
- Merge match hypotheses into Gmaps (generate-gmaps).
  1. Interconnected and consistent (generate-structure-groups).
  2. Consistent members of same base structure (merge-base).
  3. Any further consistent combinations (full-gmap-merge).
- Calculate the candidate inferences for each GMap (gather-inferences).
- Score the matches (run-rules).
  1. Local match scores.
  2. Global structural evaluation scores.

Figure 2: Summary of SME algorithm.

Each computation will now be reviewed, using a simple example to illustrate their operation. In this example, the rules of structure-mapping theory are in use. It is important to distinguish the general SME system from its behavior when using the rules of a particular theory. Hence, when using the rules of structure-mapping theory, it will be called SME_{SMT}.

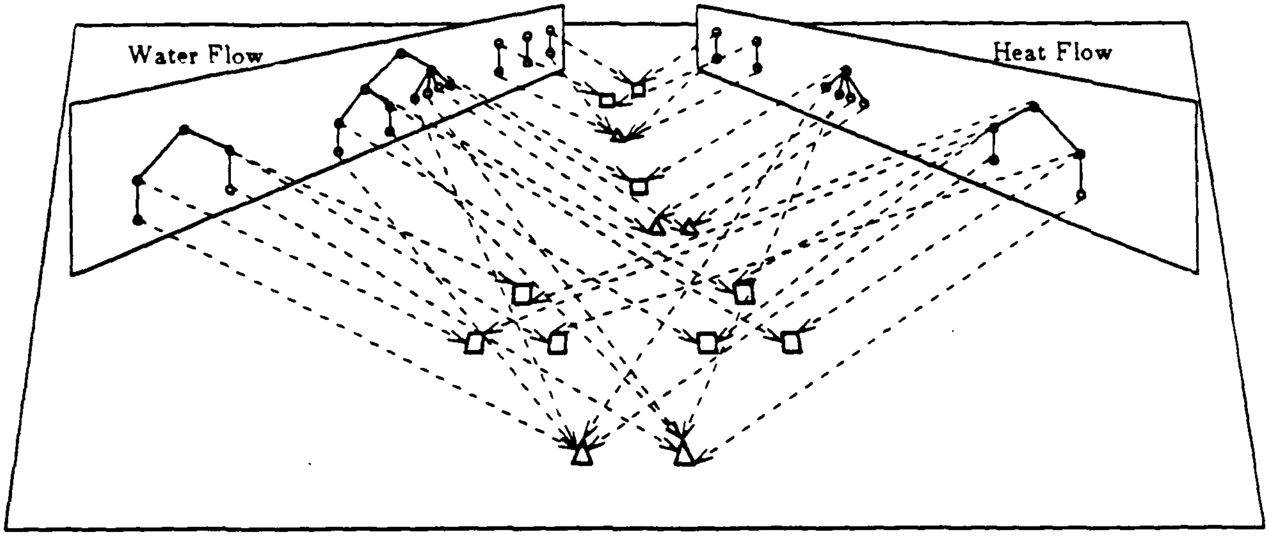
2.1.1 Step 1: Local match construction (create-match-hypotheses)

SME begins by finding for each entity and predicate in the base the set of entities or predicates in the target that could plausibly match that item (see Figure 3). Plausibility is determined by *match constructor* rules, which are of the form:

```
(MHCrule (⟨Trigger⟩ ⟨BaseVariable⟩ ⟨TargetVariable⟩
                    [:test ⟨TestForm⟩])
   ⟨Body⟩)
```

The body of these rules is run on each pair of items (one from the base and one from the target) that satisfy the condition and installs a *match hypothesis* which represents the possibility of them matching. For example, to state that an expression in the base may match an expression in the target whose functor is identical, we write:

```
(MHC-rule (:filter ?b ?t :test (equal (expression-functor ?b)
                                      (expression-functor ?t)))
      (install-MH ?b ?t))
```



□ - MH between predicates
△ - MH between entities (Emap)

Figure 3: Local Match Construction. The water flow and heat flow descriptions of Figure 1 have been drawn in the abstract and placed to the left and right, respectively. The objects in the middle depict match hypotheses.

The likelyhood of each match hypothesis is found by running *match evidence* rules and combining their results. The evidence rules provide support for a match hypothesis by examining the structural and syntactic properties of the items matched. For example, the rule

```
(MHErule ((:intern (MH ?b ?t) :test (and (expression? ?b) (expression? ?t)
                                          (eq (expression-functor ?b)
                                              (expression-functor ?t))))
    (assert! (implies same-functor (MH ?b ?t) (0.5 . 0.0))))
```

states "If the two items are expressions and their functors are the same, then supply 0.5 evidence in favor of the match hypothesis." The rules may also examine match hypotheses associated with the arguments of these items to provide support based on systematicity. This causes evidence for a match hypothesis to increase with the amount of higher-order structure supporting it.

The state of the match between the water flow and heat flow descriptions of Figure 1 after running these first two sets of rules is shown in Figure 4. There are several important things to notice in this figure. First, there can be more than one match hypothesis involving any particular base or target item. Second, our rules required predicates to match identically while they allowed entities to match on the basis of their roles in the predicate structure. Thus while TEMPERATURE can match either PRESSURE or DIAMETER, IMPLIES cannot match anything but IMPLIES. Third, not every possible correspondence is created. Local matches between entities are only created when justified by some other identity. This significantly constrains the number of possible matches in the typical case.

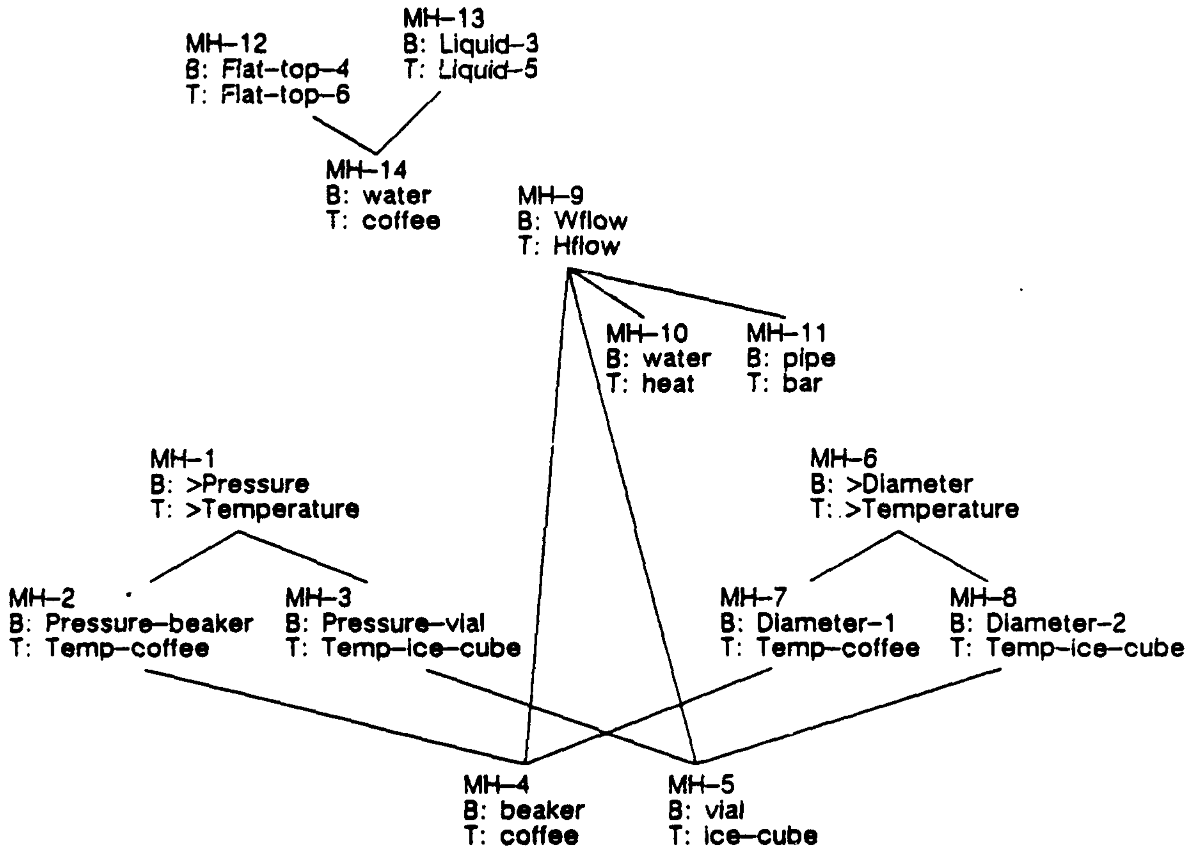


Figure 4: Water Flow / Heat Flow Analogy After Local Match Construction. Here we show the graph of match hypotheses depicted schematically in Figure 3, augmented by links indicating expression-to-arguments relationships. Match hypotheses which are not descended from others are called *roots* (e.g., the matches between the `GREATER` predicates, `MH-1` and `MH-6`, and the match for the predicate `FLOW`, `MH-9`). Match hypotheses between entities are called *Emaps* (e.g., the match between beaker and coffee, `MH-4`). Emaps play an important role in algorithms based on structural consistency.

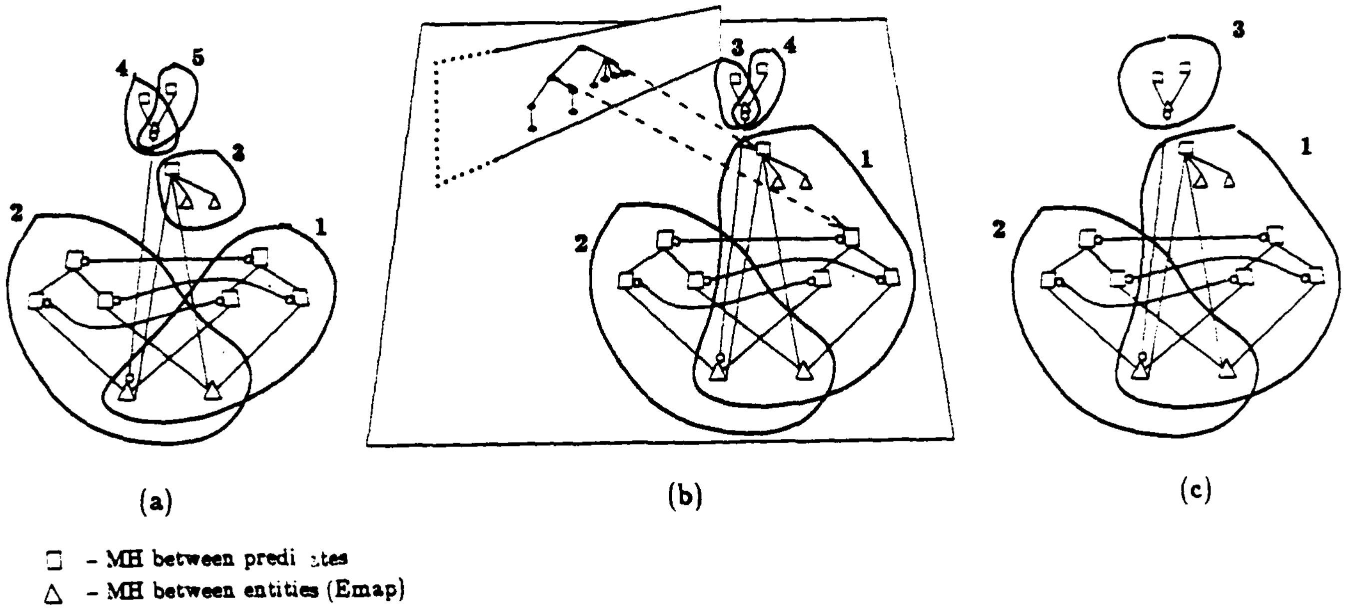


Figure 5: Water Flow - Heat Flow analogy after computation of *Conflicting* relationships. Simple lines show the tree-like graph that the grounding criteria imposes upon match hypotheses. Lines with circular endpoints indicate the *Conflicting* relationships between matches. Some of the original lines from MH construction have been left in to show the source of a few *Conflicting* relations.

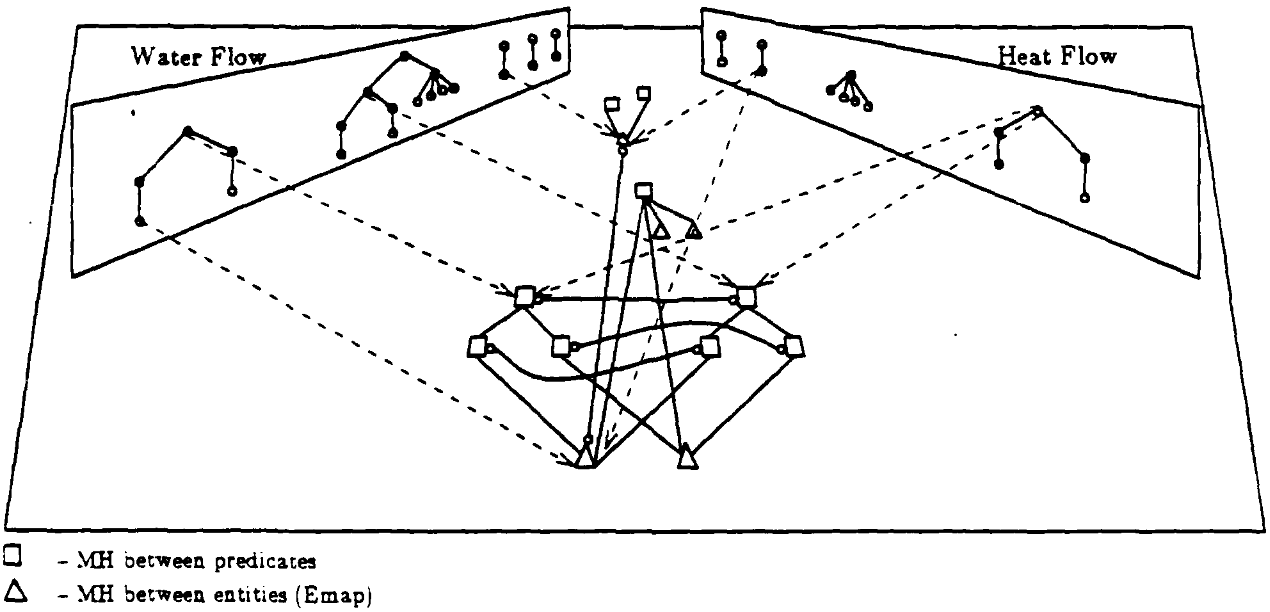


Figure 6: GMap Construction. (a) Merge step 1: Interconnected and consistent. (b) Merge step 2: Consistent members of the same base structure. (c) Merge step 3: Any further consistent combinations.

2.1.2 Step 2: Global Match Construction

The second step in the SME algorithm combines local match hypotheses into collections of global matches (Gmaps). Intuitively, each global match is the largest possible set of match hypotheses that depend on the same one to one object correspondences.

More formally, Gmaps consist of ***maximal, structurally consistent*** collections of match hypotheses. A collection of match hypotheses is structurally consistent if it satisfies two criteria:

1. *One-to-one:* No two match hypotheses assign the same base item to multiple target items or any target item to multiple base items.

2. *Support:* If a match hypothesis MH is in the collection, then so are the match hypotheses which pair up all of the arguments of MH's base and target items.

The preservation criteria enforces strict one to one mappings. The grounding criteria preserves connected predicate structure. A collection is maximal if adding any additional match hypothesis would render the collection structurally inconsistent.

The formation of global matches is composed of two primary stages:

1. *Compute consistency relationships* (`calculate-nogoods`)*:* Here we generate for each match hypothesis the sets of entity mappings it entails, what match hypotheses it locally conflicts with, and which match hypotheses it is structurally inconsistent with. This information simplifies the detection of contradictory sets of match hypotheses, a critical operation in the rest of the algorithm. The result of this stage of processing appears in Figure 5.

2. *Merge match hypotheses* (`generate-gmaps`)*:* Compute Gmaps by successively combining match hypotheses as follows:

   (a) *Form initial combinations* (`generate-structure-groups`)*:* Combine interconnected and consistent match hypotheses into an initial set of Gmaps (Figure 6a).

   (b) *Combine dependent Gmaps* (`merge-base`)*:* Since base and target dgroups are rarely isomorphic, some Gmaps in the initial set will overlap in ways that allow them to be merged. The advantage in merging them is that the new combination may provide structural support for candidate inferences (Figure 6b).

   (c) *Combine independent collections* (`full-gmap-merge`)*:*[1] The results of the previous step are next combined to form maximal consistent collections (Figure 6c).

A parameter option allows the support criterion to be weakened so that it does not cross the boundaries of a ***relational group*** [7]. A relational group is distinguished as an unordered collection of relational structures that may be collectively referred to as a unit. They correspond to the abstract notion of a "set" and are associated to predicates taking any number of arguments. For example, a set of relations joined by the predicate AND defines a relational group. Other examples include the axioms of a theory, a decomposable compound object, or the relations holding over an interval of time. Intuitively, we would like to say that two groups correspond without requiring that their contents are exhaustively mapped.

If base and target propositions each contain a group as an argument, the propositions should not be prevented from matching if the groups' members cannot be exhaustively paired. For example, the set of relations

[1] These two merge steps (b and c) are called by `merge-gmaps`, which is in turn called by `generate-gmaps`.

```
B:   Implies[And(P1,P2,P3), P4]          (1)
T:   Implies[And(P'1,P'2), P'4]
```

$$\text{B: Implies[And}(P_1,P_2,P_3),\ P_4] \qquad (1)$$
$$\text{T: Implies[And}(P'_1,P'_2),\ P'_4]$$

should match better than the set of relations

$$\text{B: Implies[And}(P_1,P_2,P_3),\ P_4] \qquad (2)$$
$$\text{T}': P'_1,\ P'_2,\ P'_4$$

The original model of structural consistency would score (1) and (2) equally, since the Implies relations of (1) would not be allowed to match. This is a particularly important consideration when matching sequential, state-based descriptions (e.g., the behavior of a system through time). The set of relations describing a pair of states often do not exhaustively match or are of different cardinality. Yet, higher-order relations over states, such as temporal orderings, are vital and must appear in the mapping.

2.1.3 Step 3: Compute Candidate Inferences (gather-inferences)

Associated with each Gmap is a (possibly empty) set of candidate inferences. Candidate inferences are base predicates that would fill in structure which is not in the Gmap (and hence not already in the target). If a candidate inference contains a base entity that has no corresponding target entity (i.e., the base entity is not part of any match hypothesis for that gmap), SME introduces a new, hypothetical entity into the target. Such entities are represented as a skolem function of the original base entity (i.e., (:skolem base-entity)).

In Figure 7, Gmap #1 has the top level CAUSE predicate as its sole candidate inference. In other words, this Gmap suggests that the cause of the flow in the heat dgroup is the difference in temperatures. If the FLOW predicate was not present in the target, then the candidate inferences for a Gmap corresponding to the pressure inequality would be both CAUSE and FLOW. Note that GREATER-THAN[DIAMETER(coffee), DIAMETER(ice cube)] is not a valid candidate inference for the first Gmap because it does not intersect the existing Gmap structure.

2.1.4 Step 4: Compute Structural Evaluation Scores (run-rules)

Typically a particular pair of base and target will give rise to several Gmaps, each representing a different interpretation of the match. Often it is desired to select only a single Gmap, for example to represent the best interpretation of an analogy. Many of these evaluation criteria (including validity, usefulness, and so forth) lie outside the province of Structure-Mapping, and rely heavily on the domain and application. However, one important component of evaluation is *structural* — for example, one Gmap may be considered a better analogy than another if it embodies a more systematic match. SME provides a programmable mechanism for computing a *structural evaluation score* (SES) for each Gmap. This score can be used to rank-order the Gmaps in selecting the "best" analogy, or as a factor in a more complex (but external) evaluation procedure. In SME_{SMT}, the structural evaluation score is currently computed by simply adding the belief of each local match hypothesis to the belief of the Gmaps it is a member of.

Returning to Figure 7, note that the "strongest" interpretation (i.e., the one which has the highest structural evaluation score) is the one we would intuitively expect. In other words, beaker maps to coffee, vial maps to ice-cube, water maps to heat, pipe maps to bar, and PRESSURE maps to TEMPERATURE. Furthermore, we have the candidate inference that the temperature difference is what causes the flow.

```
Rule File: literal-similarity.rules     Number of Match Hypotheses: 14

Gmap #1: { (>PRESSURE  >TEMPERATURE)  (PRESSURE-BEAKER  TEMP-COFFEE)
           (PRESSURE-VIAL  TEMP-ICE-CUBE)  (WFLOW  HFLOW) }
    Emaps:  { (beaker coffee)  (vial ice-cube)  (water heat)  (pipe bar) }
    Weight:  5.99
    Candidate Inferences: (CAUSE >TEMPERATURE HFLOW)

Gmap #2: { (>DIAMETER  >TEMPERATURE)  (DIAMETER-1  TEMP-COFFEE)
           (DIAMETER-2  TEMP-ICE-CUBE) }
    Emaps:  { (beaker coffee)  (vial ice-cube) }
    Weight:  3.94
    Candidate Inferences:  { }

Gmap #3: { (LIQUID-3  LIQUID-5)  (FLAT-TOP-4  FLAT-TOP-6) }
    Emaps:  { (water coffee) }
    Weight:  2.44
    Candidate Inferences:  { }
```

Figure 7: Complete SME interpretation of Water Flow - Heat Flow Analogy.

2.2 Adding Theoretical Constraints

Given the general program, we may then add theoretical constraints in the form of rules. For instance, the example just presented used the *literal similarity* rules of structure-mapping theory. These rules augment SME's one-to-one mapping and structural consistency criteria with two additional restrictions. First, evidence is computed according to *systematicity*, that is, highly interconnected systems of relations are preferred over independent facts. Second, only identical relations are allowed to match (i.e., CAUSE is not allowed to match GREATER-THAN). Had another set of rules been used, the results might have been substantially different. For example, the *mere appearance* rules of structure-mapping theory would have determined that the water to coffee mapping was the best, due to their superficial similarity.

3 Declarations

The *descriptions* given to SME are constructed from a user-defined vocabulary of entities and predicates. This section discusses the conventions for defining languages for SME's use.

3.1 Declaring Predicates

defPredicate *name argument-declarations predicate-class* [*Macro*]

```
             &key :expression-type logical-type
                  :commutative?  {t | nil}
                  :n-ary?  {t | nil}
                  :documentation descriptive-string
                  :eval procedural-attachment  )
```

define-predicate *name argument-declarations predicate-class ...* [*Function*] *predicate-class* is either `function`, `attribute`, or `relation`, according to what kind of predicate *name* is. The *argument-declarations* allows the arguments to be named and typed. For example, the declaration:

```
(defPredicate CAUSE ((antecedent event) (consequent event)) relation)
```

states that `CAUSE` is a two-place relational predicate. Its arguments are called `antecedent` and `consequent`, both of type `event`. The names and types of arguments are for the convenience of the representation builder and any external routines (including the match rules), and are not currently used by SME internally. Likewise, the predicate class may be very important to the theoretical constraints imposed in the rules, but is ignored by SME internally.

The optional declaration `:expression-type` indicates the logical type of an expression headed by the given predicate. For example, the predicate `throw` may represent a kind of `action`, while the predicate `mass` may represent an `extensive-quantity`.

The optional declarations `:commutative?` and `:n-ary?` provide SME with important syntactic information. `:commutative?` indicates that the predicate is commutative, and thus the order of arguments is unimportant when matching. `:n-ary?` indicates that the predicate can take any number of arguments. Examples of commutative nary predicates include `AND`, `SUM`, and `SET`.

The `:documentation` option allows one to attach a descriptive string to a predicate. This documentation may then be accessed through the lisp machine supplied interface (`C-Shift-D`) or some externally written routine. If no documentation is supplied, the list of argument names is used. Another option provided strictly for potential user routines is the optional `:eval` parameter. This allows one to declare a procedural attachment for a predicate.

3.2 Declaring Entities

`defEntity` *name* `&key type constant?` [*Macro*]
`define-Entity` *name* `&key type constant?` [*Function*]

Entities are logical individuals, i.e., the objects and constants of a domain. Typical entities include physical objects, their temperature, and the substance they are made of. Primitive entities are declared with the `defEntity` form (a non-primitive entity would be `(temperature sun)`, which is a functional form representing a particular numeric temperature entity). Primitive entities declared in this way represent global entity types, that is, they represent a class of entities rather than an actual instance of an entity. When an entity type is actually used in a domain description, a unique entity instance is created for that type (e.g., `Mary` is translated to `Mary43`).

Since the language is typed, each entity type can be declared as a subtype of an existing type using the `:type` option. For example, we might have

```
(defEntity star :type inanimate)
(defEntity Sun :type star)
```

to say that stars are inanimate objects, and our Sun is a particular star. Constants are declared by using the `:constant?` option, as in

```
(defEntity zero :type number :constant? t)
```

3.3 Declaring Description Groups

`defDescription` *description-name* [*Macro*]
`entities` (*entity*$_1$, *entity*$_2$, ..., *entity*$_i$)
`expressions` (*expression-declarations*)

`define-description` *description-name entities expressions* [*Function*]

For simplicity, predicate instances and compound terms are called *expressions*. A *Description Group*, or *Dgroup*, is a collection of primitive entities and expressions concerning them. Dgroups are defined with the `defDescription` form, where *expression-declarations* take the form

expression or
(*expression* `:name` *expression-name*)

For example, the description of water flow depicted in Figure 1 was given to SME as

```
(defDescription simple-water-flow
      entities (water beaker vial pipe)
      expressions (((flow beaker vial water pipe) :name wflow)
                   ((pressure beaker) :name pressure-beaker)
                   ((pressure vial) :name pressure-vial)
                   ((greater pressure-beaker pressure-vial) :name >pressure)
                   ((greater (diameter beaker) (diameter vial)) :name >diameter)
                   ((cause >pressure wflow) :name cause-flow)
                   (flat-top water)
                   (liquid water)))
```

All entities must have been previously defined and every entity referred to in the Dgroup's expressions must appear in the `entities` list of the `defDescription`.

3.4 Adding new expressions

`expression` *form dgroup-name* `&key expression-name update-structure?` [*Function*]

Expressions are normally defined as a side effect of creating a description group (Dgroup). However, the facility is provided for dynamically adding new expressions to a Dgroup. The syntax is essentially the same as for expressions declared within a `defDescription`. The expression's *form* may refer to the names of existing Dgroup expressions and the form may be given a name. When `expression` is used to add expressions to an existing Dgroup, the `update-structure?` keyword must be invoked with a non-nil (e.g., `T`) value. This keyword indicates that the Dgroup's structure must be reexamined, since the known structural roots will change as a result of this new expression.

3.5 Typed Logic

A mechanism exists for attaching types to predicates and their arguments (see `defPredicate`). This facility is designed to constrain the operation of SME, particularly candidate inference generation. However, it has not been extensively used to date. The ability to attach types may be useful for consistency checking by external systems.

4 Using the rule system

The rule system is the heart of SME's flexibility. It allows one to specify what types of things might match and how strongly these matches should be believed. This section describes the required syntax for a rule set and different strategies for rule specification.

4.1 Rule file syntax

A rule set, or rule file, consists of a *declaration*, a set of *match constructor* rules, and a set of *match evidence* rules. In order to describe each, we will examine the syntax and functionality of each part of the *smt-analogy* rule file.

4.1.1 File declarations

`sme-rules-file` *identification-string* [*Function*]

Each rule file must begin with the initialization command `sme-rules-file`. This function clears the rule system in preparation for a new set of rules (rules are cached for efficiency) and stores the name of the rule set for output identification purposes. For example, our sample rules file begins with:[2]

```
(sme-rules-file "smt-analogy.rules")
```

The rule file must then end with the `tre-save-rules` command:

`tre-save-rules` [*Function*]

4.1.2 Match Constructor rules

`MHC-rule (`*trigger ?base-variable ?target-variable*
`[:test` *test-form*`])`
body [*Macro*]

`install-MH` *base-item target-item* [*Function*]

SME begins by finding for each entity and predicate in the base the set of entities or predicates in the target that could plausibly match that item. Plausibility is determined by *match constructor* rules, which are responsible for installing all match hypotheses processed by SME. There are two types of constructor rules, each indicated by a different value for *trigger*. The first type of rule is indicated by a `:filter` trigger. These rules are applied to each pair of base and target expressions, executing the code in *body*. If the `:test` option is used, *test-form* must return true for the body to be run. For example, the following rule states that an expression in the base may match an expression in the target whose functor is identical, unless they are attributes (a structure-mapping *analogy* criterion):

```
(MHC-rule (:filter ?b ?t :test (and (eq (expression-functor ?b)
                                        (expression-functor ?t))
                                    (not (attribute? (expression-functor ?b)))))
      (install-MH ?b ?t))
```

The second type of MHC rule is indicated by a trigger of `:intern`. These rules are run on each match hypothesis as it is created. Typically they create match hypotheses between any functions or entities that are the arguments of the expressions joined by the match hypothesis that triggered the rule. The following is one of two that appear in smt-analogy.rules:

[2] Notice the file extension *.rules. While rule files are not required to end in ".rules", all user interface facilities for simplifying the loading of rule files depend upon this extension. Another useful point is that rule files are typically defined to be in the SME package to avoid having to use `sme:` throughout the rule set.

```
(MHC-rule (:intern ?b ?t :test (and (expression? ?b) (expression? ?t)
                                     (not (commutative? (expression-functor ?b)))
                                     (not (commutative? (expression-functor ?t)))))
    (do ((bchildren (expression-arguments ?b) (cdr bchildren))
         (tchildren (expression-arguments ?t) (cdr tchildren)))
        ((or (null bchildren) (null tchildren)))
      (cond ((and (entity? (first bchildren)) (entity? (first tchildren)))
             (install-MH (first bchildren) (first tchildren)))
            ((and (function? (expression-functor (first bchildren)))
                  (function? (expression-functor (first tchildren))))
             (install-MH (first bchildren) (first tchildren)))
            ((and (attribute? (expression-functor (first bchildren)))
                  (eq (expression-functor (first bchildren))
                      (expression-functor (first tchildren))))
             (install-MH (first bchildren) (first tchildren))))))
```

Notice that the third test allows identical attributes to match, whereas the previous MHC rule did not allow such matches. This design does not allow isolated attributes to match, but recognizes that attributes appearing in a larger overall structure should be matched.

4.1.3 Match Evidence rules

`rule` *nested-triggers body* [*Macro*]
`rassert!` *expression* `&optional` (*belief+* `1.0`) (*belief-* `0.0`) [*Macro*]
`assert!` *expression* `&optional` (*belief+* `1.0`) (*belief-* `0.0`) [*Function*]
`initial-assertion` *assertion-form* [*Macro*]

The structural evaluation score is computed in two phases. First, each match hypothesis is assigned some local degree of evidence, independently of what Gmaps it belongs to. Second, the score for each Gmap is computed based on the evidence for its match hypotheses. The management of evidence rules is performed by the *Belief Maintenance System* (BMS) [3]. A BMS is a form of Truth-Maintenance system, extended to handle numerical weights for evidence and degree of belief (see [3] for a description of what the weights mean). Pattern-directed rules are provided that trigger on certain events in the knowledge base.

The following is a simple rule for giving evidence to match hypotheses between expressions that have the same predicate:

```
(initial-assertion (assert! 'same-functor))

(rule ((:intern (MH ?b ?t) :test (and (expression? ?b) (expression? ?t)
                                       (eq (expression-functor ?b)
                                           (expression-functor ?t)))))
   (if (function? (expression-functor ?b))
       (rassert! (implies same-functor (MH ?b ?t) (0.2 . 0.0)))
       (rassert! (implies same-functor (MH ?b ?t) (0.5 . 0.0)))))
```

There are two things to notice here in addition to the evidence rule. First, the proposition `same-functor` was asserted to be true (a belief of 1.0) and then used as the antecedent for the implication of evidence. In this way, the source of this particular piece of evidence is identified and is available for inspection. Second, the assertion of `same-functor` was placed *inside* the `initial-assertion` form. Since SME caches the current rule file, it must be told if there are any functions embedded in the rule file that must be invoked each time SME is initialized.

`children-of?` *base-child target-child base-expression target-expression* [*Function*]

Nested triggers within an evidence rule may be used to locate interdependencies between different match hypotheses. For example, structure-mapping's systematicity principle is implemented in a local fashion by propagating evidence from a match hypothesis to its children:[3]

```
(rule ((:intern (MH ?b1 ?t1) :test (and (expression? ?b1) (expression? ?t1)
                                        (not (commutative? (expression-functor ?b1)))))
       (:intern (MH ?b2 ?t2) :test (children-of? ?b2 ?t2 ?b1 ?t1)))
     (rassert! (implies (MH ?b1 ?t1) (MH ?b2 ?t2) (0.8 . 0.0))))
```

Evidence for a Gmap is given by:

```
(rule ((:intern (GMAP ?gm) :var ?the-group))
   (dolist (mh (gm-elements ?gm))
      (assert! '(implies ,(mh-form mh) ,?the-group))))
```

The BMS allows a set of nodes to be declared special and will treat evidence to these nodes differently. An `additive-nodes` function is provided which takes a set of BMS nodes and modifies them so that their evidence is added rather than normalized using Dempster's rule. SME automatically invokes `additive-nodes` on the derived set of Gmaps once they are created. Thus, when the above Gmap rule is executed and the `implies` statement is used to supply evidence from each match hypothesis to the Gmap, that evidence is simply automatically added to the total Gmap evidence rather than propagated using Dempster's probabilistic sum.

The following destructive rule is often used instead of the previous one to give a significant speed up:

```
(rule ((:intern (GMAP ?gm) :var ?the-group))
    (setf (node-belief+ (gm-bms-node ?gm)) 0)
    (dolist (mh (gm-elements ?gm))
       (incf (node-belief+ (gm-bms-node ?gm))
             (node-belief+ (mh-bms-node mh)))))
```

This rule bypasses the BMS entirely, thus increasing speed by not creating justification links. It also renders the `additive-nodes` distinction irrelevant. However, such rules must be used with extreme caution. For example, the source of a Gmap's evidence cannot be inspected when using this type of operation (see Section 6.5).

4.2 Making SME simulate structure-mapping theory

The previous section examined the general structure of an SME rule file. In the process, the basic elements of the *structure-mapping-theory analogy* rule set were presented. The *literal similarity* and *mere-appearance* rules are essentially the same as the *analogy* rules. They differ in the first match constructor rule. The *analogy* rule set has the test `(not (attribute? (expression-functor ?b)))` which is absent from the corresponding *literal similarity* rule. Conversely, the corresponding *mere appearance* rule forces the opposite condition `(attribute? (expression-functor ?b))`. One should consult Appendix A of [9] for listings of all three structure-mapping rule sets.

[3] A number of functions (e.g., `children-of?`) are provided to simplify the writing of rules. These appear in the file `match-rules-support.lisp`.

4.3 Making SME perform as SPROUTER

The SPROUTER program [17] was developed as an approach to the problem of inductively forming characteristic concept descriptions. That is, given a sequence of events (e.g., a list of pictures), produce a single, conjunctive description which represents a generalized, characteristic description of the sequence. SPROUTER generalized a sequence of N descriptions by finding the commonalities between the first two descriptions, generalizing these common elements (i.e., variablize the literals), and then repeating the process using this generalized description and the next, unprocessed description. These steps would be repeated until the generalization had propagated through the entire list of input descriptions.

SME may be used to implement SPROUTER's *interference matching* technique by giving it a set of match constructor rules which require all matching predicates to have the same name (i.e., the *literal similarity* rules without the condition that allows functions with different names to match). The SPROUTER generalization mechanism may then be implemented with the following algorithm:

```
Procedure SPROUTER (event-list)
   begin
     generalization := pop(event-list)
     while event-list
        pairwise-match := match(pop(event-list), generalization)
        generalization := generalize(pairwise-match)
     return generalization
   end
```

4.4 Relaxing the identical predicates constraint

The current structure-mapping theory rules are sensitive to representation by requiring that relational predicates match only if they are identical. This is an important restriction that ensures the structures being compared are semantically similar. However, it can also be overly restrictive. We are currently exploring different methods to relax the identicality requirement while still maintaining a strong sense of semantic similarity. One approach, called the *minimal ascension principle*, allows relations to match if they share a common ancestor in a multi-root is-a hierarchy of expression types [7] (i.e., the identicality test in the match constructor rule is replaced by a call to `predicate-type-intersection?`). The local evidence score for their match is inversely proportional (exponentially) to the relations' distance in the hierarchy. This enables SME to match non-identical relations if such a match is supported by the surrounding structure, while still maintaining a strong preference for matching semantically close relations. This is similar to approaches used in [1,16,24].

Problems with an unconstrained minimal ascension match technique are discussed in [7]. A mapping approach which considers the current context when determining pairwise similarity is also discussed.

4.5 Pure isomorphisms

While it is important to assure that the structures being compared are semantically similar, one can in principle remove all semantic comparisons. This would allow match creation to be guided strictly by SME's structural consistency and 1-1 mapping criteria and match selection to be based strictly on systematicity.

Consider the isomorphic mapping between the formal definitions of numeric addition and set

Addition	Union
`N1 + N2 = N2 + N1`	`S1 ∪ S2 ≡ S2 ∪ S1`
`N3+(N4+N5) = (N3+N4)+N5`	`S3 ∪ [S4 ∪ S5] ≡ [S3 ∪ S4] ∪ S5`
`N6+0 = N6`	`S6 ∪ ∅ ≡ S6`

Figure 8: Formal descriptions for addition and union.

union shown in Figure 8.[4] These formal descriptions may be given to SME in the standard manner, as in `(plus N3 (plus N4 N5))` for the left side of the associativity rule (the representation `(plus N4 N5 result45)` also works, although it results in a slightly longer run time due to the flattening of structure). When presented as formal definitions, the concepts of addition and union are structurally isomorphic, independent of the meaning of the predicates. Thus, while it could be argued that the predicates `plus` and `union` share a certain degree of semantic overlap, this example demonstrates that it is possible to make SME ignore predicates entirely and simply look for isomorphic mappings. The rule set for isomorphic mappings is shown in Figure 9. (This is called the *ACME* rule set, as it configures SME to emulate the ACME program on this example [18]). The only constraint this rule set enforces is that each predicate has the same number of arguments. While it includes the Structure-Mapping notion of systematicity to prefer systems of relations, it does not enforce identicality of predicates. Using this rule set, SME produces the unique best mapping that we would expect between the formal definitions of addition and union.

Since SME enforces the "same number of arguments" restriction by defeating any match hypotheses that are not structurally sound, we could in principle effectively remove the rule file entirely. This could be done with one match constructor rule to match everything with everything and one evidence rule to measure systematicity. When this *free-for-all* rules file was given to SME, the same single best Gmap was produced, but at the expense of increasing the run time from 13 seconds to 3.25 minutes.

4.6 Imposing externally established pairings

In certain situations, a number of entity and predicate mappings may already be known prior to invoking SME. These mappings may have been provided as an analogical hint from an instructor or derived by the application program during earlier processing. For example, PHINEAS [4,5] uses SME to analogically relate observed physical phenomena to known theories of the world. PHINEAS uses two analogical mappings to learn about a new physical process. First, behavioral correspondences are established (i.e., what entities and quantities are behaving in the same manner). Second, the relevant base theories are analogically mapped into the new domain, guided by the behavioral correspondences. The two-stage mapping process solves the problem of using analogy in cases where one does not have a pre-existing theory, as occurs with truely novel learning. The assumption made in PHINEAS is that similar behaviors will have similar theoretical explanations. The first mapping provides the correspondences between entities and functions required to guide the importation of an old theory to explain a new domain in the second mapping.

SME includes facilities to simplify writing PHINEAS-like programs, by enabling the results of earlier processing to constrain subsequent mapping tasks. These routines are divided into two

[4] This example is taken from an advance copy of a paper by Holyoak and Thagard [18]. I include it here simply to demonstrate the range of matching preferences available in SME.

```
(MHC-rule (:filter ?b ?t :test (= (numargs (expression-functor ?b))
                                  (numargs (expression-functor ?t))))
    (install-MH ?b ?t))

;;; Intern rule to match entities (non-commutative predicates)
(MHC-rule (:intern ?b ?t :test (and (expression? ?b) (expression? ?t)))
    (do ((bchildren (expression-arguments ?b) (cdr bchildren))
         (tchildren (expression-arguments ?t) (cdr tchildren)))
        ((or (null bchildren) (null tchildren)))
      (if (and (entity? (first bchildren)) (entity? (first tchildren)))
          (install-MH (first bchildren) (first tchildren)))))

;;; Give a uniform initial priming to each MH
(initial-assertion (assert! 'initial-priming))

(rule ((:intern (MH ?b ?t)))
   (rassert! (implies initial-priming (MH ?b ?t) (0.2 . 0.0))))

;;;propagate interconnections - systematicity
(rule ((:intern (MH ?b1 ?t1) :test (and (expression? ?b1) (expression? ?t1)))
       (:intern (MH ?b2 ?t2) :test (children-of? ?b2 ?t2 ?b1 ?t1)))
   (rassert! (implies (MH ?b1 ?t1) (MH ?b2 ?t2) (0.8 . 0.0))))

;;; Support from its MH's
(rule ((:intern (GMAP ?gm) :var ?the-group))
   (dolist (mh (gm-elements ?gm))
      (assert! `(implies ,(mh-form mh) ,?the-group))))
```

Figure 9: Rule set for forming general isomorphic mappings.

categories, *declaration* and *test*. The declaration routines tell SME what predicate and entity correspondences are known *a-priori*. The test routines enable the match constructor rules to adhere to these imposed constraints. Known mappings are declared through the following functions:

defGiven-Mappings [*Macro*]
  entities ((*base-entity*$_1$ *target-entity*$_1$)
    (*base-entity*$_i$ *target-entity*$_j$) ...)
  predicates ((*base-predicate*$_1$ *target-predicate*$_1$)
    (*base-predicate*$_i$ *target-predicate*$_j$) ...)

declare-given-mappings *entities predicates* [*Function*]

clear-given-mappings [*Function*]

Both defGiven-Mappings and declare-given-mappings have identical functionality. The first does not evaluate its arguments while the second one does. Disjunctive constraints may be imposed by including all of the possible pairings (e.g., defining both (*base-entity*$_i$ *target-entity*$_j$) and (*base-entity*$_i$ *target-entity*$_k$)).

Once a set of given mappings has been declared, the following test routines may be used within the match constructor rules to enforce these mappings:

`sanctioned-pairing?` *base-item target-item* [*Function*]
`paired-item? &key base-item target-item` [*Function*]

`sanctioned-pairing?` tests if the given pair is one of the *a-prior* pairings. `paired-item?` takes either a base item or a target item and returns true if the mapping for that item has been externally determined.

These functions help in writing rules which respect established mappings. For example, the following two rules are used in the PHINEAS system to allow observed behavioral correspondences to constrain the mapping of the relevant theory:

```
(MHC-rule (:filter ?b ?t :test (and (eq (expression-functor ?b) (expression-functor ?t))
                                    (not (paired-item? :base-item (expression-functor ?b)))
                                    (not (paired-item? :target-item (expression-functor ?t)))))
    (install-MH ?b ?t))

(MHC-rule (:filter ?b ?t :test (sanctioned-pairing? (expression-functor ?b)
                                                    (expression-functor ?t)))
    (install-MH ?b ?t))
```

When an analogy is being made between two behaviors, `clear-given-mappings` is used to make SME perform in normal analogy mode. The discovered entity and function correspondences are then given to `declare-given-mappings` prior to using SME to map the relevant theory.

5 Representation Issues

The proper representation becomes an issue in SME due to its significant impact on speed performance. Hierarchical representations provide an important source of constraint on generating potential matches. They tend to make the semantic interrelations explicit in the structure of the syntax. For example, Section 4.5 described a comparison between the laws of addition and union. There it was noted that part of the additive associativity rule may be represented as `(plus N3 (plus N4 N5)` or as the pair `(plus N4 N5 result45)` and `(plus N3 result45 result3-45)`. The latter "flat" representation takes more time for SME to process, sometimes a significant difference for large domain descriptions. This is because the functional representation makes the associativity rule structurally explicit, while the flat representation buries it among the tokens appearing as arguments to `plus`. However, it is important to note that SME is able to process domain descriptions in any predicate-based format. It is simply speed considerations that render standard, flat forms of representation undesirable.

Due to SME's ability to accept commutative, n-ary predicates, it is able to match arbitrary sets (which must be of equal size at this time). This has two consequences. First, the explicit use of sets becomes a viable form of representation. Thus, a theory might be represented concisely as

```
(Theory T1 (SET axiom-8 axiom-14 ...))
```

rather than as `(Axiom-of T1 axiom-8)`, etc. Second, sets may be used to add structure to descriptions. For example, the set representation for theories results in greatly reduced run times compared to the non-set representation.[5] I am currently investigating the use of a similar representation for temporal states, as in:

[5] The difference in speed is due to the operation of merge step 2, which combines matches sharing a common base structure. The set notation for theory T1 enables merge step 2 to know that matches for `axiom-8` and `axiom-14` should be placed in the same gmap, thus reducing the number of possibilities in merge step 3.

```
(Situation S1 (SET (Increasing (Amount-of water1))
                   (Increasing (Pressure water1))
                   o o o ))
```

A PHINEAS problem which took SME 53 minutes (using `(Increasing (Amount-of (at water1 S1)))`) was reduced to 34 seconds using this more structured representation.

6 Using SME

This section describes how to install SME on your machine, load it, and operate it.

6.1 Installing SME

`*sme-language-file*` [*Variable*]
`*sme-default-rules*` [*Variable*]
`*sme-rules-pathname*` [*Variable*]
`*sme-dgroup-pathname*` [*Variable*]

To configure SME to a particular site, a handful of variables storing system directory information must be edited and set to the appropriate values. These variables appear in `config.lisp`, a separate file for this purpose. Of primary importance are `*sme-language-file*` and `*sme-default-rules*`. These are used by `sme-init` to initialize the language and rule systems. The two variables storing the rules and dgroup pathnames are used by the user interface routines.

`*the-lisp-package*` [*Variable*]
`*the-user-package*` [*Variable*]

In most Common Lisp implementations, one package exists for general user definitions and another exists for the lisp implementation. It is important to notify SME what these are for the Common Lisp in use. For example, on a Symbolics (version 6.2), the lisp package is called `common-lisp` and the user package is called `cl-user`. These are the default settings.

`*sme-system-pathname*` [*Variable*]
`*sme-files*` [*Variable*]

These variables are used to automate compiling and loading. If the system is being loaded on something other than a Symbolics or TI Explorer, the file `windowing` should not be included in the list `*sme-files*`. Otherwise, it should be left in the list of SME files, which is the default.

The SME routines assume a set of naming conventions on domain description and rule files. The names of files containing domain descriptions (`defDescription`) should end with a `*.dgroup` extension. The name of a file containing a rule set should end with the `*.rules` extension.

6.2 Running SME

`sme-init &optional` (*initialize-language?* T) (*initialize-rules?* T) [*Function*]

This section gives a brief overview of the process of using SME for matching, generalization, and inspection tasks.

```
> (sme:sme-init)
Initializing SME...
   Loading default language file: prof:>falken>sme>language
   Loading default rules file: prof:>falken>sme>literal-similarity.bin
Complete.
T
> (load "prof:> falken> sme> simple-water-flow.dgroup")
Loading PROF:>falken>sme>simple-water-flow.dgroup into package USER
#P"PROF:>falken>sme>simple-water-flow.dgroup"
NIL
> (load "prof:> falken> sme> simple-heat-flow.dgroup")
Loading PROF:>falken>sme>simple-heat-flow.dgroup into package USER
#P"PROF:>falken>sme>simple-heat-flow.dgroup"
NIL
> (sme:match 'swater-flow 'sheat-flow T)
              SME Version 2E
    Analogical Match from SWATER-FLOW to SHEAT-FLOW.

Rule File: literal-similarity.rules
----------------------------------------------------------------------------
                   | # Entities | # Expr. | Maximum order | Average order |
  Base Statistics  |     4      |   11    |       3       |     1.36      |
Target Statistics  |     4      |    6    |       2       |     1.17      |
----------------------------------------------------------------------------
# MH's | # Gmaps | Merge Step 3 | CI Generation | Show Best Only |
   14  |    3    |    ACTIVE    |    ACTIVE     |      OFF       |
--------------------------------------------------------------------
Total Run Time:     0 Minutes,  0.821 Seconds
BMS Run Time:       0 Minutes,  0.530 Seconds
Best Gmaps:  3

Match Hypotheses:
    (0.6320  0.0000)  (PIPE4 BAR7)
    (0.7900  0.0000)  (FLAT-WATER FLAT-COFFEE)
      o      o        ;a number of match hypotheses appeared here
    (0.8646  0.0000)  (WATER1 COFFEE5)
    (0.7900  0.0000)  (LIQUID-WATER LIQUID-COFFEE)

Gmap #1:    (BEAKER2 COFFEE5)  (DIAM-BEAKER TEMP-COFFEE)  (VIAL3 ICE-CUBE6)
            (DIAM-VIAL TEMP-ICE-CUBE)  (>DIAMETER >TEMP)
  Emaps:  (BEAKER2 COFFEE5) (VIAL3 ICE-CUBE6)
  Weight: 3.937660
  Candidate Inferences:

      o      o        ;Gmap #2 appeared here...

Gmap #3:    (>PRESSURE >TEMP)  (PRESS-VIAL TEMP-ICE-CUBE)  (PRESS-BEAKER TEMP-COFFEE)
            (BEAKER2 COFFEE5)  (VIAL3 ICE-CUBE6)  (WATER1 HEAT8)
            (PIPE4 BAR7)  (WFLOW HFLOW)
  Emaps:  (BEAKER2 COFFEE5) (VIAL3 ICE-CUBE6) (WATER1 HEAT8) (PIPE4 BAR7)
  Weight: 5.991660
  Candidate Inferences:  (CAUSE >TEMP HFLOW)
```

Figure 10: Initializing and running SME.

1. *Loading the files.* To load or compile SME, the file `config` should be loaded and then `(load-sme)` or `(compile-sme)` called. A `defSystem` definition is provided in `system.lisp` for Symbolics machines.

2. *System startup.* This stage is only appropriate for full, lisp machine startup. The SME window environment may be created with Select-S on a Symbolics or System-S on a TI Explorer.

3. *Initialization.* The function `sme-init` should be called to initialize the database. If *initialize-language?* is non-nil, the default language file (predicate definitions) will be loaded. If *initialize-rules?* is non-nil, the default rules file will be loaded. Prior to operating SME, the language and rule systems must be established.

4. *Loading Dgroups.* Any description groups that are to be matched must be declared. These declarations are typically stored in files, with the extension `*.dgroup`. If the windowing system is active, the command `Load Dgroup` will offer a menu of all `*.dgroup` files in `*sme-dgroup-pathname*` to select what to load.

5. *Analogical mapping.* The function `match` may be called to form a mapping between two given Dgroups. This is discussed in Section 7.2.3. If the windowing system is active, the command `Match` will offer a menu to select base and target Dgroups. It is prior to this step that one might want to think about wether to modify any system parameters (e.g., print the match hypotheses, print only the best Gmaps, generate candidate inferences, etc.).

6. *Describing Dgroups.* Once Dgroups are defined, the `describe-dgroup` facility will provide a description of any particular Dgroup.

7. *Graphically displaying Dgroups.* If the windowing system is active, Dgroups may also be displayed graphically, through the `Display Dgroup` utility.

8. *Generalizing.* Once a mapping is formed, it may be generalized using the `generalize` function or the `Generalize` command in the system menu.

9. *Saving the results of a session.* If the windowing system is active, the results of commands like `Match` and `Generalize` are sent to the scroll window by default. These results may be written to a file using the `dump-scroll` system utility.

10. *Comparing two apparently identical Gmaps.* When two Gmaps are formed that appear to be identical, their differences can be identified using the `compare-gmaps` system utility.

A trace of SME performing the basic mapping task is given in Figure 10. Each of the other options are described in greater detail in the following sections.

6.3 Batch mode

`run-batch-file` *pathname* `&key (`*gmap-display* `:all) (`*gmap-statistics* `:none)` [*Function*]
`language-file` *pathname* [*Macro*]
`dgroup-directory` *pathname* [*Macro*]
`dgroup-file` *file-name* [*Macro*]
`rule-directory` *pathname* [*Macro*]
`rule-file` *file-name* [*Macro*]
`rule-sets &rest` *rule-file-names* [*Macro*]

```
(sme:Dgroup-Directory "prof:>falken>sme>")

(sme:Dgroup-File "solar-system")
(sme:Dgroup-File "rutherford")
(sme:Dgroup-File "simple-water-flow")
(sme:Dgroup-File "simple-heat-flow")

(sme:Rule-Directory "prof:>falken>sme>")

(sme:Rule-Sets "literal-similarity" "true-analogy" "attribute-only")   ; iterate over each rule set

(sme:Report-Comments "Sample run of SME to demonstrate batch mode.")

(sme:Send-Report-To "heath:>falken>sample.dmp" :text-driver :LATEX)

(sme:Run-Matcher-On solar-system rutherford-atom)     ; map this pair once for each rule set
(sme:Run-Matcher-On swater-flow sheat-flow)           ; map this pair once for each rule set
```

Figure 11: Sample SME batch file.

`report-comments` *string* [*Macro*]
`send-report-to` *pathname* &key (*text-driver* :LPR) (*style* :STANDARD) [*Macro*]
`run-matcher-on` *base-name target-name* [*Macro*]
`defPostMatcher` *function* [*Macro*]

SME is normally used as an interactive utility or as a module to some larger program. However, when performing statistical analyses across a broad space of matching preferences (i.e., rule sets) and domain descriptions, an interactive format soon becomes inconvenient. Utilities are provided so that a file of SME instructions may be defined and then executed using `run-batch-file` (e.g., Figure 11). This would instruct SME to perform a series of matches, potentially over a variety of rule sets and domain descriptions, and generate a detailed report of the execution and a summary of the results. When a single rule set is specified using `rule-file`, all subsequent matches (invoked by `run-matcher-on`) will use this rule file until another one is specified. Using `rule-sets`, one may instead specify a series of rule files to be used, so that a single `run-matcher-on` command will cause SME to run once for each rule file in the list. If a user-defined function name is given to `defPostMatcher`, this function will be called after each match is performed, in case special post-match routines are desired or extra information is to be added to the report being generated. A variety of text drivers are supported for report generation (`send-report-to`), such as `:lpr` (line printer), `:latex`, and `:troff`.

6.4 Generalization mechanism

`generalize` *gmap* [*Function*]

The `generalize` function takes a global mapping structure and returns three alternate generalizations (using the Common-Lisp `values` protocol), each one successively larger than the previous:

1. *Literally common aspects only.* This generalization locates those sub-structures which are identical in both base and target Dgroups. This is a type of generalization typically found in

```
Generalizations for Match from SWATER-FLOW to SHEAT-FLOW:

    Generalization #1 (Literally Common Aspects Only):
        (FLOW ENTITY6 ENTITY8 ENTITY13 ENTITY14)

    Generalization #2 (All Common Aspects Only):
        (FLOW ENTITY6 ENTITY8 ENTITY13 ENTITY14)
        (GREATER (FUNCTIONO ENTITY6) (FUNCTIONO ENTITY8))

    Generalization #3 (Maximal Generalization):
        (CAUSE (GREATER (FUNCTIONO ENTITY6) (FUNCTIONO ENTITY8))
               (FLOW ENTITY6 ENTITY8 ENTITY13 ENTITY14))
```

Figure 12: SME generalizations for the simple water flow – heat flow analogy.

inductive generalization programs.

2. *All common aspects only.* In addition to common, identical substructures, this generalization includes cases where functions of a different name were allowed to match. Where this occurs in the common structure, a skolemized function predicate is created.

3. *Maximal generalization.* The largest generalization (in terms of amount) includes all candidate inferences sanctioned by the Gmap, as well as the common substructure of generalization mode 2. This represents the entire shared structure between the two Dgroups under the assumption that the candidate inferences are valid.

For example, given the best Gmap from the simple water flow – heat flow analogy described in Section 2.1 and shown in Figure 7, SME will produce the set of generalizations shown in Figure 12. The first generalization indicates that the only thing in common between the two situations is the existence of flow. The second generalization loosens the meaning of "in common" to include the fact that a quantity associated with the source of flow was greater than the same quantity measured for the destination. The final generalization assumes that this inequality, which was the cause of flow in the water flow domain, is actually the cause of flow for both situations.

6.5 Inspecting MH and Gmap evidence

`match-evidence-inspector` [*Function*]

When developing a theory about what types of rules should be used and how much evidence for a particular match they should provide, it is often useful to explicitly see what the different sources of evidence were for a particular match item. The system utility `match-evidence-inspector` may be used to display a trace of the entire evidence facility or just the evidence for a particular match hypothesis or Gmap. For example, the following information was printed out about the `pressure` to `temperature` match hypothesis in the water flow – heat flow analogy:

```
(MH F#PRESS-BEAKER F#TEMP-COFFEE) has evidence (0.7120, 0.0000) due to
   IMPLICATION((MH F#>PRESSURE F#>TEMP))  (0.5200, 0.0000)
   IMPLICATION(CHILDREN-POTENTIAL)  (0.4000, 0.0000)
```

While the following information appears for the best Gmap in this analogy:

```
(GMAP #GM3) has evidence (5.9917, 0.0000) due to
    IMPLICATION((MH F#WFLOW F#HFLOW)) (0.7900, 0.0000)
    IMPLICATION((MH I#PIPE20 I#BAR23)) (0.6320, 0.0000)
    IMPLICATION((MH I#WATER17 I#HEAT24)) (0.6320, 0.0000)
    IMPLICATION((MH I#VIAL19 I#ICE-CUBE22)) (0.9318, 0.0000)
    IMPLICATION((MH I#BEAKER18 I#COFFEE21)) (0.9318, 0.0000)
    IMPLICATION((MH F#PRESS-BEAKER F#TEMP-COFFEE)) (0.7120, 0.0000)
    IMPLICATION((MH F#PRESS-VIAL F#TEMP-ICE-CUBE)) (0.7120, 0.0000)
    IMPLICATION((MH F#>PRESSURE F#>TEMP)) (0.6500, 0.0000)
```

The inspection facility will not work for Gmaps if their scores were produced by an external (to the BMS), destructive operation. One such destructive rule appeared at the end of Section 4.1.3.

6.6 Windows

`dump-scroll-menu` [*Function*]
`dump-scroll` *output-pathname* [*Function*]
`clear-scroll` [*Function*]
`select-windowing-configuration` [*Function*]
`select-scroll` [*Function*]
`select-double-scroll` [*Function*]
`select-graphics` [*Function*]
`select-large-graphics` [*Function*]
`select-split` [*Function*]
`*sme-frame*` [*Variable*]
`*graphics-pane*` [*Variable*]
`*scroll-pane*` [*Variable*]
`*spare-scroll-pane*` [*Variable*]
`*lisp-pane*` [*Variable*]

The windowing system is lisp machine dependent and appears in the file `windowing.lisp`. The loading of this file is optional. When the windowing system is used, a number of window configurations are possible, such as having a single scroll window, two side by side, a single graphics window, or a scroll and graphics window side by side. These configurations may be selected through their individual functions (e.g., `select-scroll`), or through the central configuration facility `select-scroll-graphics`. By default, when the windowing system is active, all SME output is sent to the primary scroll pane. When both scroll windows are in use, the configuration facility allows one to specify which scroll window is currently active. The two scroll dumping routines write the contents of the primary scroll window to a specified file. Output sent to the secondary (*scratchpad*) scroll pane is for observation only and cannot be written to a file.

6.7 System parameters

`*sme-parameters*` [*Variable*]
`*parameter-menu-options*` [*Variable*]
`defSME-Parameter` *variable-name string-description type* `&optional` *type-choices* [*Macro*]

The `defSME-Parameter` form adds a new variable to the list of known SME parameters. This list is used by the windowing interface routines to query the user about possible parameter settings. It is provided primarily for application programs wanting to use the standard SME parameter

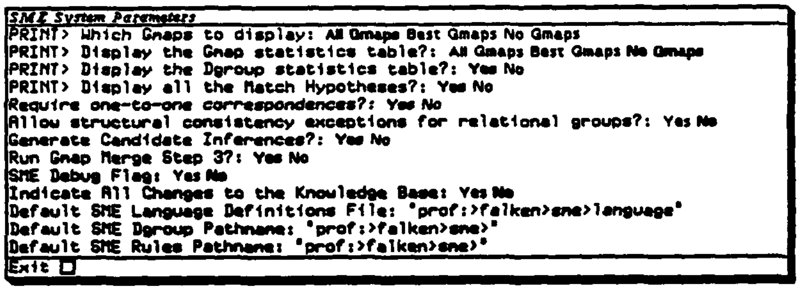


Figure 13: SME System Parameters.

setting facility. The arguments to **defSME-Parameter** correspond to the appropriate definitions for the **choose-variable-values** function of your particular machine. For example, the following declaration appears in **match.lisp**:

```
(defSME-Parameter *display-all-MH* "Display all the Match Hypotheses" :boolean)
```

change-parms *[Function]*

The windowing system provides a menu facility for viewing and changing the current values of system parameters. This menu is shown in Figure 13.

6.8 System utilities

system-utilities-menu *[Variable]*
defSME-Utility *string-name lisp-form* *[Macro]*
menu-utilities *[Function]*
get-dgroup *[Function]*
get-rules *[Function]*

The SME system utilities are the options that appear when the **Utilities** command is evoked, the right mouse button is pressed, or the function **menu-utilities** is called. These utilities include changing the system parameters, choosing to load a Dgroup or rule file from those in the defined directories, and clearing or writting to file the contents of the scroll window. These routines are lisp machine dependent. The following declaration appears in **match.lisp**:

```
(defSME-Utility "Inspect Evidence" (match-evidence-inspector))
```

7 User Hooks

This section describes the global variables and routines that are available to the user and application programs for the creation and inspection of analogical mappings.

7.1 Applications control over display

sme-output-stream *[Variable]*
windowing? *[Variable]*
sme-graphics-output *[Variable]*

All SME textual display routines send their output to `*sme-output-stream*`. By default, the value of this variable is `T`, which causes output to be sent to `*terminal-io*`, CommonLisp's default pointer to the user's console. When `*sme-output-stream*` is a scroll window (determined by the presence of an `:append-item` handler), the appropriate scroll window routines for sending display items are invoked. Otherwise, text is sent to the current output stream using `format`. Text routines are machine independent.

In a similar manner, all SME graphics output is sent to the current `*sme-graphics-output*` window. Graphics output is lisp machine dependent and relies on the ZGRAPH graphics system.

When the SME windowing system is in operation, `*sme-output-stream*` is set to the primary SME scroll pane (`*scroll-pane*`), `*sme-graphics-output*` is set to the SME graphics pane (`*graphics-pane*`), and `windowing?` is set to `T`.

`sme-format` *format-string* `&rest` *format-args* [*Macro*]
`sme-print` *string* [*Function*]
`sme-terpri` `&optional` (*N* 1) [*Function*]

These routines provide a general interface for sending textual output to the current SME output stream. `sme-format` is equivalent to CommonLisp's `format` routine, except that the printed output is always followed by a newline. The `sme-print` routine is provided for simple situations where only a string is printed or for situations requiring the standard use of `format`, as in building up a line of text through multiple invocations. The printed output of `sme-print` is followed by a newline. When the routine is used for multiple calls of `format`, it should be used in conjunction with CommonLisp's `with-output-to-string`, as in:

```
(sme-print
  (with-output-to-string (stream)
    (format stream "~%Beginning of a line...")
    (format stream "  middle of a line...")
    (format stream "  end of a line.")))
```

When a whole set of operations are carried out within the context of a single `sme-print`, one must be careful not nest calls to `sme-print` (e.g., calling a function in the context of an `sme-print` which itself invokes `sme-print`). Such nesting will cause output to appear backwards from what was intended and may cause the output stream to close improperly.

7.2 Useful miscellaneous functions

Data exists within SME in three forms: (1) local items such as entities, predicates, and expressions, (2) description groups (Dgroups), and (3) analogical mapping information. The routines to create and query these items are described in the following sections.

7.2.1 Entities, predicates, and expressions

`entity?` *item* [*Function*]
`entity-type?` *item* [*Function*]
`entity-name?` *symbol* [*Macro*]
`fetch-entity-definition` *symbol* [*Macro*]
`entity-domain` *symbol* [*Macro*]
`constant-entity?` *symbol* [*Macro*]

Entities declared through `defEntity` represent global entity types, that is, they represent a class of entities rather than an actual instance of an entity. When an entity type is used in the definition of a description group, a unique entity instance is created for that type (e.g., `beaker` is translated to `beaker73`). Thus, a given entity token will represent either a type or an instance. The structure predicate `entity?` returns true if the given item is an entity-instance structure, while `entity-type?` returns true if the item is an entity-type structure. The macro `entity-name?` returns true if the given symbol represents either an entity type or instance. `fetch-entity-definition` will return the entity-type structure for an entity type token or the entity-instance structure for an entity instance token. The routines `entity-domain` and `constant-entity?` refer to the type and `constant?` keyword values given to `defEntity` when the corresponding entity type was created.

`*sme-predicates*` [*Variable*]
`fetch-predicate-definition` *predicate-symbol* [*Macro*]
`predicate?` *symbol* [*Macro*]
`predicate-type` *predicate-symbol* [*Macro*]
`relation?` *predicate-symbol* [*Macro*]
`attribute?` *predicate-symbol* [*Macro*]
`function?` *predicate-symbol* [*Macro*]
`commutative?` *predicate-symbol* [*Macro*]
`n-ary?` *predicate-symbol* [*Macro*]
`arg-list` *predicate-symbol* [*Macro*]
`numargs` *predicate-symbol* [*Macro*]
`expression-type` *predicate-symbol* [*Macro*]
`eval-form` *predicate-symbol* [*Macro*]

These routines provide the facility to access the various predicate properties defined with the `defPredicate` form. `fetch-predicate-definition` returns the actual sme-predicate structure containing all the information about a given predicate.

`fetch-expression` *expression-name dgroup* `&optional (`*error-if-absent?* `T)` [*Function*]
`expression-functor` *expression-structure* [*Function*]
`fully-expand-expression` *expression-structure dgroup* [*Function*]
`fully-expand-expression-form` *expression-form dgroup* [*Function*]

An "expression" represents an actual predicate instance within a Dgroup. Notice that this includes terms corresponding to function applications as expressions. Each use of a predicate gets its own expression with its own name, so that a higher-order relation gets translated into several expressions, with some having expressions as arguments. These routines allow one to retrieve and inspect expressions in the database. `fetch-expression` returns the expression structure with the given name.

The routines `fully-expand-expression` and `fully-expand-expression-form` are useful for examining the form of an expression. Typically, the expression `(greater-than (diameter beaker) 5)` is stored as the expression `greater-than23`, which has the form `(greater-than diameter24 5)`. These routines return a fully expanded expression form, where all expression names are replaced by their corresponding forms.

7.2.2 Dgroups

`fetch-dgroup` *dgroup-name* `&optional` *create?* [*Function*]
`return-dgroup` *dgroup-or-dgroup-name* [*Function*]

Description groups (Dgroups) are stored in a simple data base managed primarily by routines in `sme.lisp`. The general procedures for Dgroup and expression creation were described in sections 3.3 and 3.4. A Dgroup may be retrieved by name using `fetch-dgroup`, or created if *create?* is non-nil and no Dgroup with the given name currently exists. `return-dgroup` is designed for routines that may take either an actual Dgroup or simply a Dgroup name (e.g., `fetch-expression`). It will cause an error if the Dgroup does not previously exist.

`describe-dgroup` *dgroup* [*Function*]
`menu-display-dgroup` [*Function*]
`menu-display-pairs` [*Function*]

A Dgroup may be textually described using `describe-Dgroup`, which writes to the SME output stream. Graphical display is provided in the windowing system by `menu-display-dgroup` for a single Dgroup or `menu-display-pairs` for a display of two Dgroups side by side.

7.2.3 Creating and inspecting global matches

`match` *base-name target-name* `&optional` *display?* [*Function*]
`best-gmaps` `&optional` (*gmaps* `*gmaps*`) (*percentage-range* `0.02`) [*Function*]
`display-match` *base target* `&optional` (*total-run-time* `0`) (*bms-run-time* `0`) [*Function*]

The `match` function is the central SME procedure. Given the names of two Dgroups, it forms the complete set of global mappings between them. If *display?* is non-nil, a description of the results will be sent to the current SME output stream. The function itself returns two values, the total run time of the match process in seconds and the subset of that time spent running the BMS evidence rules. The analogical mapping results are stored in the following global variables, which are then accessible by the user or application program.

`*base*` [*Variable*]
`*target*` [*Variable*]
`*match-hypotheses*` [*Variable*]
`*gmaps*` [*Variable*]

The Gmap(s) with the highest evaluation score are retrieved by `best-gmaps`, which returns all Gmaps having a score within a given percentage (default is 2%) of the highest score. `best-gmaps` returns two values: the list of best Gmaps and the actual real-valued highest score.

`compare-gmaps` *gmap1 gmap2* `&optional` *display?* [*Function*]

Occasionally, SME will produce two or more "best" Gmaps that appear to be identical yet have been classified as distinct. When these Gmaps are large, the "here's the set of match hypotheses" output format can make it frustrating to find what the slight differences are between a pair of Gmaps. When given two Gmap structures, `compare-gmaps` will return (using `values`) the list of the match hypotheses that are uniquely part of the first Gmap and a list of match hypotheses that are uniquely part of the second Gmap (i.e., (*gmap1* - *gmap2*) and (*gmap2* - *gmap1*)). When the windowing system is active, this option is available through the system utilities menu.

8 Algorithm Internals

This section quickly describes a few internal points of the program in case one has specialized needs for interfacing to the code. It assumes knowledge of CommonLisp and the realization that for many questions, the only feasible answer must be to examine the SME program.

8.1 The Match Function

`create-match-hypotheses` *base-dgroup target-dgroup* [*Function*]
`run-rules` [*Function*]
`calculate-nogoods` *base-dgroup target-dgroup* [*Function*]
`generate-gmaps` [*Function*]
`gather-inferences` *base-dgroup target-dgroup* [*Function*]
`intern-gmaps` [*Function*]

The function `match` is primarily a sequence of calls to these functions. `create-match-hypotheses` runs the match constructor rules to form the individual match hypotheses. The BMS evidence rules are then run on these match hypotheses (`run-rules`) and their dependence and inconsistency relationships are determined (`calculate-nogoods`). The function `generate-gmaps` executes the three merge steps, resulting in the set of complete global mappings being placed in the variable `*gmaps*`. The candidate inferences each Gmap sanctions is then calculated (`gather-inferences`) and additive BMS nodes for each Gmap are formed (`intern-gmaps`), allowing the evidence rules to run on each Gmap.

8.2 Match Hypotheses

`match-hypothesis` [*Defstruct*]
`mh-form` *match-hypothesis* [*Subst*]
`mh-base-item` *match-hypothesis* [*Subst*]
`mh-target-item` *match-hypothesis* [*Subst*]
`mh-bms-node` *match-hypothesis* [*Subst*]
`node-belief+` *bms-node* [*Subst*]
`mh-plist` *match-hypothesis* [*Subst*]
`*match-hypotheses*` [*Variable*]

Most programs using SME will need to interact with the *match hypothesis structures*. Slots to this structure type use the `mh-` prefix. There are several slots that might be important. The MH form, which is a list of (MH <*base-item*> <*target-item*>), is found using `mh-form`. This is the form used for triggering the MH evidence rules, and is asserted in the BMS for each match hypothesis. The base and target items are expression or entity structures. The base item or target item may be obtained directly using `mh-base-item` and `mh-target-item`, respectively. The BMS node for each match hypothesis is found by `mh-bms-node`. In turn, the weight for that node may be obtained using `node-belief+`. Finally, each match hypothesis structure has a property list slot (`mh-plist`) which may be useful for various purposes.

8.3 Global Mappings

`global-mapping` [*Defstruct*]
`gm-id` *global-mapping* [*Subst*]

`gm-elements` *global-mapping* [*Subst*]
`gm-emaps` *global-mapping* [*Subst*]
`gm-base` *global-mapping* [*Subst*]
`gm-target` *global-mapping* [*Subst*]
`gm-inferences` *global-mapping* [*Subst*]
`gm-bms-node` *global-mapping* [*Subst*]
`gm-plist` *global-mapping* [*Subst*]
`*gmaps*` [*Variable*]

Each Gmap is stored as a *global-mapping structure*. Slots to this structure type use the `gm-` prefix. Each Gmap is assigned a unique integer identifier, found through `gm-id`. The Gmap form used by the BMS is not explicitly available, but is asserted as `(Gmap` <*gmap-structure*>`)`. The match hypotheses associated with a Gmap are stored in `gm-elements`, while the subset of these that are entity mappings is stored in `gm-emaps`. The candidate inferences sanctioned by the Gmap appear in `gm-inferences` and are stored as a simple list data type, using the syntax defined in Section 3.3 for description group expressions.

8.4 Candidate Inference Generation

The original candidate inference generator, as described in [8], will take any base structure "intersecting the Gmap structure". The newer (V. 2) edition only takes base structure "intersecting a Gmap root". Thus, the newer edition is more cautious and far more efficient than the older edition. Both versions of the code are available (in `match.lisp`), with the default being the newer, more cautious version. There are theoretical arguments for and against each approach. For example, one might want to use only the inferences from the newer, more cautious approach at first since they are supported by more target knowledge and thus more likely valid. If an analogy proves fruitful, one may want to relax these constraints, and use the older version to find out what additional inferences might be made.

8.5 Rule System

`tre-rules-file` [*Function*]
`tre-save-rules` [*Function*]
`tre-init` [*Function*]
`restore-rules` [*Function*]
`run-rules` [*Function*]
`*tre-rules-saver*` [*Variable*]
`*initial-assertions*` [*Variable*]

When a new rules file is loaded, the sme-rules-file command at the top of the file initializes the BMS rule system prior to loading the new set of rules. At the bottom of the rules file, the fresh, just-loaded set of rules are saved in the global variable *tre-rules-saver* by the command tre-save-rules. This variable saves the status of the rule counters and the list of initial rules. A similar variable, `*initial-assertions*`, is used to store all assertions appearing in the rules file. When the BMS is run, new rules may be created and added to the known set of rules. As a result, each time `match` is invoked, the BMS is reinitialized to its status just after loading the rule file, that is, it is restored to the status indicated in `*tre-rules-saver*`.

This facility may be used by application programs to save different rule sets in memory and swap them as needed, without having to load rule files each time. For example, suppose SME is invoked, which will cause it to run the current rule set for Gmap scoring. If a second scoring criterion is then desired, a second set of rules may be invoked using code of the form:

```
(let ((save-rules sme:*tre-rules-saver*)            ;save the previous rule set
      (save-assertions sme:*initial-assertions*))
  (setq sme:*tre-rules-saver* *my-other-rules-set-rules*)
  (setq sme:*initial-assertions* *my-other-rules-set-assertions*)
  (sme:tre-init)                                    ;initialize with new rules
  (sme:run-rules)                                   ;run the new rule set
  (setq sme:*tre-rules-saver* save-rules)           ;restore the original rules
  (setq sme:*initial-assertions* save-assertions))
```

This saves SME's normal rule set, runs a different one, and then restores the rule set to its previous value. In this example, `tre-init` was used, which fully initializes the BMS. If the desire is simply to supply additional rules without destroying the current BMS state, `restore-rules` should be used in place of `tre-init`. The variables corresponding to "my-other-rules-set" may be initialized by a similar program which saves the current rule set, *loads* the desired "other rule set" file, sets the "my-other-rules-set" variables from `*tre-rules-saver*` and `*initial-assertions`, and then restores the original rule set.

9 Summary

The SME program has been described from the perspective of how to actually use it. A number of methods have been presented about how to configure SME to perform a variety of different types of matches. It is hoped that SME may serve as a general mapping tool for research on analogical mapping, allowing researchers to focus on the more substantive issue of general theories of analogical mapping, as opposed to worrying about implementation details. The latter has the unfortunate effect of producing the repeated scenario in which analogy researcher A goes to analogy researcher B and says "My program can do X, which yours cannot", followed by researcher B returning a month later with this simple modification added. By testing different theories within the same program, we may now compare the more critical "This is a logical consequence of my theory". A program does not a theory make. It can, however, function as a useful analytical tool.

Of course, not all of the problems of implementing analogical mapping have been solved. Most critical is redesigning the potentially combinatoric merge step 3, perhaps using either a heuristic search or connectionist relaxation network as suggested in [9]. Of theoretical relevance is the appropriateness of the abstract structural approach which SME embodies.

10 Acknowledgements

The development of SME has been a collaborative effort with Ken Forbus and Dedre Gentner, with significant influence provided by Janice Skorstad. This work has also benefited from discussions with Steve Chien, John Collins, and Ray Mooney.

This research is supported in part by an IBM graduate fellowship and in part by the Office of Naval Research, Contract No. N00014-85-K-0559.

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