Processes and Problems in the Formative Evaluation of an Interface to the Foundational Model of Anatomy Knowledge Base

LINDA G. SHAPIRO, PhD, EMILY CHUNG, BSc, LANDON T. DETWILER, BSc, JOSE L. V. MEJINO, JR., MD, AUGUSTO V. AGONCILLO, MD, JAMES F. BRINKLEY, MD, PhD, CORNELIUS ROSSE, MD, DSc

Abstract The Digital Anatomist Foundational Model of Anatomy (FMA) is a large semantic network of more than 100,000 terms that refer to the anatomical entities, which together with 1.6 million structural relationships symbolically represent the physical organization of the human body. Evaluation of such a large knowledge base by domain experts is challenging because of the sheer size of the resource and the need to evaluate not just classes but also relationships. To meet this challenge, the authors have developed a relation-centric query interface, called Emily, that is able to query the entire range of classes and relationships in the FMA, yet is simple to use by a domain expert. Formative evaluation of this interface considered the ability of Emily to formulate queries based on standard anatomy examination questions, as well as the processing speed of the query engine. Results show that Emily is able to express 90% of the examination questions submitted to it and that processing time is generally 1 second or less, but can be much longer for complex queries. These results suggest that Emily will be a very useful tool, not only for evaluating the FMA, but also for querying and evaluating other large semantic networks.


The University of Washington Digital Anatomist (UWDA) vocabulary was initially established to facilitate the correlation of anatomical concepts within the National Library of Medicine’s Unified Medical Language System (UMLS).2 UWDA’s domain encompasses macroscopic and microscopic anatomy for all parts of the body and also includes, in a consistent and continuous semantic structure, extensive representations of subcellular and macromolecular anatomical entities. The latest UWDA version contains nearly 70,000 classes of anatomical entities associated with nearly twice as many terms. The authors have defined a high-level scheme for the UWDA knowledge base, enhanced it with 150 new kinds of relationships, and transformed it into a disciplined, expressive ontology. This enhanced, computable, anatomical knowledge source is known as the Digital Anatomist Foundational Model of Anatomy (FMA for short) (available at http://fma.biostr.washington.edu).3–5

Affiliation of the authors: Structural Informatics Group (LGS, EC, LTD, JLVM, AVA, JFB, CR), Department of Biological Structure (LTD, JLVM, AVA, JFB, CR), Department of Medical Education and Biomedical Informatics (LGS, JFB), Department of Computer Science and Engineering (LGS, EC, JFB) and the Department of Electrical Engineering (LGS), University of Washington, Seattle, WA.

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The name Emily is in honor of the second author, Emily Chung, who developed the initial prototype of this program as a summer undergraduate project.

Correspondence and reprints: Linda G. Shapiro, PhD, Box 352350, Computer Science and Engineering, 634 Paul Allen Center, University of Washington, Seattle, WA 98195; e-mail: <shapiro@cs.washington.edu>.

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The FMA is a resource for many different groups of users. Anatomists may want to compare it with their own terminologies or other published compendia. Scientists studying other species can use it as a basis for comparison. Students of anatomy and the general public can use it to help them learn about the human body at their desired level of complexity. However, to be maximally useful, the FMA must be evaluated for accuracy and comprehensiveness.

Evaluation of the FMA presents challenges distinct from those described in published evaluations of UMLS and other controlled medical terminologies, which have largely focused on the comprehensiveness of concepts.6–8 By contrast, evaluation of the FMA must also include assessment of the comprehensiveness and validity of the relationships that the FMA explicitly models. To ensure optimal results, evaluation must include participation of domain experts, in this case, anatomists. With a knowledge base the size of the FMA, it is not feasible to simply ask the experts to examine the entire model, paying particular attention to its relationships.

The FMA has been implemented in the Protégé-2000 frame-based system,10,11 which has proved advantageous for authoring and curating the knowledge base. However, given the size of the knowledge base, it would be time-consuming and problematic for FMA-naive users to gain proficiency in the navigation of Protégé-2000. Furthermore, Protégé-2000 provides only a browsing interface, not a full query interface. Evaluators must therefore have access to an intuitive, easy-to-use query interface that allows them to ask systematically designed questions of the knowledge base. To meet this need, the authors have developed a simple and intuitive graphical user interface, called Emily, which allows the submission of queries composed of any combination of entities and relationships represented in the knowledge base. Formative evaluation of Emily shows that it is capable of expressing most
queries given to it, it is easy to use by domain experts, and its response time is adequate for use in an evaluation study.

In the remainder of this paper, we describe the interface and its formative evaluation. We conclude that, with only small additions, the interface will become a useful evaluation tool, not only for the FMA, but also for other large semantic networks.

**Background**

The FMA, constructed using Protégé-2000, explicitly defines classes of anatomical entities and relationships necessary for consistently representing the structure of the idealized human body. Protégé-2000 represents this knowledge, which is a semantic network, in a frame-based system. Population of the FMA with terms that refer to anatomical entities is guided by a high-level abstraction composed of knowledge elements that the authors consider necessary for comprehensively modeling the structural organization of the human body. These knowledge elements include the following:

- **Anatomy Taxonomy** (AT), an inheritance type hierarchy of anatomical entities;
- **Anatomical Structural Abstraction** (ASA), which specifies the structural relationships of the entities represented in AT;
- **Anatomical Transformation Abstraction** (ATA), which describes the morphological transformations of the entities represented in AT during the human life cycle (including prenatal development, postnatal growth, and aging);
- **Metaknowledge** (Mk), which comprises the principles, rules, and definitions according to which relationships are to be represented in the three other knowledge elements.

The classes of the AT represent entities at all levels of the biological organization of the body from the macroscopic (e.g., brain) to the microscopic, submicroscopic, and molecular (e.g., neuron, mitochondrial cristae, alpha-tubulin). The ASA is an aggregate of structural relationships that exist between anatomical entities. The ASA includes a Dimensional Taxonomy, which defines geometric entities of 0–3 dimensions, provides a classification of three-dimensional (3-D) shapes, and describes topological relationships such as parts, containment, adjacency and qualitative coordinates, branches, connectivity, continuity, and attachment. Figure 1 illustrates a portion of the taxonomy of anatomical relationships that are currently being instantiated, and Figure 2 shows how subclasses of these relationships (italicized in the following text) are used in the frame for a single anatomical entity, the esophagus.

As shown in the frame for esophagus (right half of Figure 2), the esophagus is a 3-D entity whose inherent 3-D shape is a hollow cylinder. It is bounded-by the external surface of esophagus. Its immediate superclass is organ with organ cavity (subclass hierarchy, or AT, shown on the left); its instances (e.g., John Doe’s esophagus) are therefore excluded from the AT. It is part-of foregut and upper gastrointestinal tract and has parts wall of esophagus, lumen of esophagus, cervical part of esophagus, thoracic part of esophagus, and abdominal part of esophagus. It has no branches or tributaries. It is contained-in superior mediastinal space, posterior mediastinal space, left posterior subphrenic space, and space of anterior compartment of neck. It contains no other anatomical entities, since only anatomical spaces can have contents, and therefore its lumen contains esophageal secretion and bolus of food (which would be shown in the frame for lumen of esophagus). It is continuous-with pharynx and stomach, and it is adjacent-to trachea, thoracic vertebral column, and thoracic aorta.

This single example shows only a very small number of the 1.6 million relationships that are present in the FMA. As shown in Figure 2, it is possible to browse the FMA by clicking the values of specific relationships (e.g., clicking lumen of esophagus in Figure 2 will navigate to the frame for lumen of esophagus). It is also possible to browse the FMA over the Web using the online Foundational Model Explorer, which presents a browsing interface based on Protégé. However, the sheer size of the FMA precludes browsing as a meaningful way to evaluate its accuracy and completeness.

The authors have developed a query interface to the FMA, called OQAFMA, which accepts queries in the StruQL database query language. Although end-user applications have been built on top of OQAFMA, the StruQL query language alone is too difficult for nonprogrammers.

Other graphical query languages have been developed for Protégé knowledge bases. For example, the ShriMP (Simple Hierarchical Multi-Perspective) visualization technique has been made available to Protégé-2000 users through the Jambalaya interface. ShriMP uses a nested graph view to present the semantic Web to users. Exploring the FMA
through ShriMP/Jambalaya would only provide browsing, not querying capabilities.

Query interfaces have been developed for other large biomedical knowledge bases such as GALEN through the GRAIL concept modeling language. However, since this and many other knowledge bases are expressed in description logic rather than frames, the methods are not directly applicable to the FMA.

**Design Objectives**

The main functional objective of the Emily query interface is to allow users to submit queries concerning the many structural relationships of the ASA. Design objectives include the following: (1) the power to query both direct and closure relationships among anatomical entities, (2) the ability to ask for unknown relationships among given entities, (3) the ability to combine basic queries to ask more complex questions, and (4) a simple method for entering these queries so that nonprogrammers would require very little training to do so.

**System Description**

The Emily query interface to the FMA is a Java application, which accesses the Protégé-2000 API (a Java programming interface) to communicate with the FMA knowledge base (which itself is contained in a MySQL relational database). The Emily graphical user interface allows the user to pose basic queries that involve a single structural relationship between two anatomical entities and compound queries that involve more than one relationship. The names of anatomical entities and relationships available in Emily have all been based directly on FMA terms and relationships and include intuitive relationship name synonyms. Emily translates user-formulated queries into the appropriate method calls to the underlying Protégé-2000 library, which in turn retrieves the appropriate FMA data from the MySQL relational database. Emily reformats the values returned for display within its graphical interface.

**Types of Queries**

Emily can process two kinds of queries: basic and compound. A basic query has the form: < Subject Relation Object > where Subject and Object can be any anatomical entity or can be Unknown, and Relation specifies one of the structural relationships of the ASA or can be Unknown. The part-of relationship allows the user to submit queries for is part of (directly), which would return the terms that refer only to those entities of which a given entity is a direct part, and for is part of, which would return those terms that refer to entities of which the given entity is a part in the closure sense: the entities of which the given entity is a direct part, the entities of which those entities are direct parts, and so on. For example, wall of esophagus is part of (directly) esophagus, but esophagus is part of (directly) foregut, which is part of (directly) gut, which is part of (directly) abdomen, which is part of (directly) trunk, which is part of (directly) body. Thus, in the closure sense, wall of esophagus is part of esophagus, foregut, gut, trunk, and body (among other entities).

Examples of basic queries include the following:

1. Esophagus is contained in (directly) unknown
2. Esophagus is contained in unknown
3. Unknown is contained in lumen of esophagus

Figure 2. Structural relationships implemented within the frame of Esophagus in Protégé-2000.
4. Unknown is part of esophagus
5. Wall of esophagus is part of esophagus
6. Esophagus unknown gut
7. Wall of esophagus unknown stomach

Queries 1–4 each have one unknown and should return a set of zero or more anatomical entities. Query 5 is a yes/no question since it contains no unknowns; the response should be yes. Query 6 contains an unknown relationship between esophagus and gut. The response should be that Esophagus is part-of gut. Note from Figure 2 that Esophagus is part of Foregut, which is part of gut (not shown in Figure 2). Thus, query 5 illustrates the need to traverse relationship paths of lengths greater than 1. Similarly, query 7 asks for the unknown relationship between wall of esophagus and stomach. This query requires Emily to search through the database to produce the response that wall of esophagus is continuous with wall of stomach, which is part of stomach.

Compound queries allow the user to ask questions involving more than one relationship. They can be formulated in two different ways: (1) sets of linked queries, and (2) Boolean combinations of several queries. Sets of linked queries may generate or use variables whose values are sets of anatomical entities. Two queries can be linked by a common variable. An example is the query illustrated in Figure 3:

Unknown is part of (directly) Esophagus

generates the set {part of esophagus, Lumen of esophagus, Wall of esophagus, Cervical part of esophagus, Thoracic, Abdominal part of esophagus}. This set is then assigned to a variable, such as U1, which is automatically created and labeled by Emily. A second query (illustrated in Figure 4)

U1 is continuous with (directly) Unknown

looks for the is continuous with (directly) relationship between each separate element of U1 and other anatomical entities. The result is a tree structure that contains each element of U1 at the top level and the entities that satisfy the query as children of these top-level entities. For the above query, the tree structure contains the following information (where :: indicates children of an entity with respect to the continuous relationship).

Wall of esophagus::(Wall of stomach, Wall of pharynx)
Lumen of esophagus::(Cavity of pharynx, Cavity of stomach)
Cervical part of esophagus::(Pharynx, Thoracic part of esophagus)
Thoracic part of esophagus::(Cervical part of esophagus, Abdominal part of esophagus)
Abdominal part of esophagus::(Thoracic part of esophagus, Cardia of stomach)

Figure 3. The Emily graphical user interface: processing of a basic query. The user has selected Unknown is part of (directly) Esophagus and clicked on the query button. The query is shown as a string in the Query column of the lower portion of the interface (for use in future compound queries), and the result set is displayed to its right in the Result column. The result set has been assigned to the system-generated variable U1. This set can now be used to formulate a new query U1 is continuous with (directly) Unknown, as discussed in the text. The interface for the compound query consisting of these two linked queries is shown in Figure 4.
In addition to the tree structure displayed as the query result, another variable, U2, is assigned to the set {Wall of stomach, Wall of pharynx, Cavity of pharynx, Cavity of stomach, Pharynx, Thoracic part of esophagus, Cervical part of esophagus, Abdominal part of esophagus, Cardia of stomach}, which is the set of leaves of the tree.

For Boolean combinations of several queries, results produced by each query are combined via Boolean operators. For example, if one asks, “What is continuous with the abdominal part of the esophagus that is not part of the esophagus?”, the Emily query would be:

Unknown is continuous with (directly) Abdominal part of esophagus

and not

Unknown is part of (directly) Esophagus

The first query produces the set {Thoracic part of esophagus, Cardia of stomach}, the second produces {Wall of esophagus, Lumen of esophagus, Cervical part of esophagus, Thoracic part of esophagus, Abdominal part of esophagus}. The Boolean combination produces the set {Cardia of stomach}.

Answering “Unknown” Queries

Unknown relationship queries (such as Query 7 in the previous section) are interesting because there are many potential answers to a single query, but most of them are not very useful. Emily’s unknown-relationship strategy is threefold:

1. The system will first search for direct and closure relationships between the two entities. The database can be indexed, so that finding either of these takes constant time.

2. Next, the system will search for specific, predefined, relational sequences that have been identified as important. For example, the composite relationship described by the regular expression (has parts)*contains specifies that any number of has parts relationships should be followed by one contains relationship. This composite relationship holds between heart and blood, since heart has part right atrium, which has part cavity of right atrium, which contains blood. Since regular expression components involve only direct relationships and closure relationships, indexing can be used to accelerate searches.

3. If no direct, closure, or predefined composite relationship is found between the two selected entities, the system will resort to a depth-limited, breadth-first search. Our
current system can search four levels of the FMA structure
in an acceptable amount of time.

The Graphical User Interface
The Emily graphical user interface is shown in Figures 3 and 4.
The upper part of the screen is for entry of basic queries. The
user can select an anatomical entity or Unknown from each of
the fields: Subject, Relation, and Object. When selecting an
anatomical entity, the user can type in a term (or its synonym)
directly into the top search box labeled “Select tree to search”
or select a term by browsing through the entire hierarchy of
terms from the AT (is-a hierarchy) of the FMA. Clicking on
the Query button causes Emily to translate the query into ap-
propriate calls to the Protégé API and to then display the result
next to the representation of the query in the lower part of the
screen. A basic query is processed in Figure 3. Figure 4 shows
a compound query with its returned results. The search facility
allows wild-card searches. For example, if a user types the
string “cardiac*” into the search field, Emily returns the list
of FMA terms starting with the word cardiac (Cardiac apex,
Cardiac atrium, Cardiac border, etc.). Users can review previ-
ous results to select a prior term as a new query component.

Status Report
In this section, the authors describe a formative evaluation of
the potential for Emily to be used as a tool for evaluation of
the FMA.

To gain some independent measure of the reliability of Emily,
the authors used two of several published compendia of anat-
omy examination questions to establish whether Emily could
process items selected from them. First, nine multiple-
choice questions were selected which the authors considered
representative of the different kinds of challenges that anat-
omists might encounter in presenting examination items to
the FMA through Emily. The authors analyzed the results to
better understand Emily’s capabilities for handling items of
different levels of difficulty. Next, the authors performed a
quantitative analysis on a different, larger set of question
items, which are illustrated in detail in Appendix 1. For ex-
ample, the first case in Appendix 1 involved an easy translation of
“is continued as” from the examination item to “is continuous
with (directly)” in Emily. The second example involved more
complex translation of “supplies” to “is-nerve-supply-of” in
Emily, as well as “arises from” to “is branch of (directly)”
and “notches” to “is adjacent to.” In the fourth example, a
shortcoming of Emily was uncovered in that “lies anterior
to” and “is lateral to” in examination items could only be trans-
lated as “is adjacent to” in Emily. The FMA representation
allows attribute slots for “is adjacent to” that can hold values
such as “lateral to” and “anterior to,” but the current version
of Emily cannot access those attribute slots. Several other ex-
amples illustrate the use of synonyms by Emily.

Emily’s Ability to Return Correct Answers
This study attempted to measure the proportion of questions
for which Emily could process and provide a correct answer.
The evaluation secondarily attempted to gain insight into
causes of query failures. The questions for this exercise were
chosen from only one of the two reference texts. The first
100 questions in each of the first seven chapters of this text
were captured, considering each option in a multiple choice
item as a “separate question” (i.e., a multiple choice question
with five options counted as five separate questions for sub-
mission to Emily). In all, 700 questions were reviewed and
those that required anything other than structural knowledge
of human anatomy were removed, leaving 486 questions (see
Table 1). The authors then eliminated those questions contain-
ing relationships not found in the FMA. Finally, 100 items
were randomly selected from the remaining 412 candidate
questions. Table 1 shows the results of this component of
the study, broken down by chapters of the text.

As shown in Table 1, of the 100 questions that the authors at-
ttempted to submit to Emily, ten were answered correctly, ten
could not be formulated due to Emily’s inability to handle at-
tributed relationships, and 80 were not answered because the
required data had not been entered as yet into the FMA data-
base. However, when the authors entered the data required
by ten questions randomly selected out of the 80 unanswered
questions, Emily answered all ten of them correctly. The fol-
lowing example illustrates the process:

Question. The greater sciatic foramen transmits the following
structures, EXCEPT:
1. Superior gluteal vessels
2. Posterior cutaneous nerve of thigh
3. Piriformis muscle
4. Obturator internus
5. Inferior gluteal vessels

Answering this question through Emily first required the
translation of the active term “transmits” into a structural rela-
tionship represented in the FMA. A foramen is classified in the
FMA as an Anatomical conduit, which contains, rather than
transmits diverse anatomical structures. Therefore, the au-
thors translated this question into the following Emily query:

Greater sciatic foramen contains Unknown

Upon initially submitting this query, Emily returned an empty
result set. Inspection of the knowledge base revealed that the
values for the contains relationship in the frame of Greater
sciatic foramen had not been entered. Not surprisingly, when the query was resubmitted after entering the appropriate data, Emily returned the result set: {Superior gluteal artery, Inferior gluteal artery, Superior gluteal vein, Inferior gluteal vein, Superior gluteal nerve, Inferior gluteal nerve, Piriformis, Posterior femoral cutaneous nerve, Internal pudendal artery, Internal pudendal vein, Pudendal nerve, Sciatic nerve, Nerve to obturator internus, Nerve to quadratus femoris}.

Query Efficiency

To evaluate Emily's response time, the authors chose a set of ten representative queries, of varying degree of difficulty, and timed their processing. All efficiency tests were performed with both the Emily application and a local MySQL DBMS running on a PC with a 2.60 GHz Intel Pentium 4 processor and 1 GB of RAM. Each query was chosen because it was representative of a particular class of queries. The queries, along with a brief description, were as follows:

1. Heart has part (directly) Unknown
   This query is a simple direct query but on a heavily populated slot (32 values).
2. Heart has part Unknown
   This query is the transitive closure of query 1 and yields a highly populated result list (472 values).
3. Heart has boundary (directly) Unknown
   Like 1, this is a simple direct query but on a lightly populated slot (1 value).
4. Heart has boundary Unknown
   The transitive closure of 3, again with a lightly populated result set (1 value).
5. Heart Unknown Esophagus
   An unknown relation query where the two entities are directly related by a single edge.
6. Heart Unknown Wall of right atrium
   An unknown relation query that requires transitive closure (two edges).
7. Heart Unknown Pharynx
   An unknown relation query that requires breadth first search (mixed relations three edges deep).
8. Right eye Unknown Heart
   An unknown relation query for which there is no answer found. Queries with no answers typically take longest because Emily must search the entire tree from the subject node to a depth of 4 to determine that there is no answer.
9. Heart Unknown Right eye
   The same unknown relation query as in 8 but with the subject and object transposed. While this appears to be the same query as 8, it is interesting because it illustrates the point that the query time is a function of the branching factor of the subject tree, not the object tree.
10. Heart is adjacent to (directly) unknown AND stomach is continuous with unknown
    This query is actually a Boolean combination of two other queries: 1. Heart is adjacent to (directly) unknown, and 2. Stomach is continuous with unknown. The query time is the sum of the times to answer both subqueries (125 milliseconds for the first and 63 milliseconds for the second) plus the time it took to perform the Boolean AND operation (<1 millisecond). Processing times for these ten queries are illustrated in Table 2. Some queries were repeated to illustrate the effect of precaching data from the database (Sequential Run column).

Discussion

The formative evaluation indicates that the Emily relation-centric query interface allows anatomists who are non-programmers as well as programmers not trained in anatomy to enter both simple and relatively complex queries concerning the structural relationships among anatomical entities of the human body. About 90% of the structural queries selected from the published compendia of anatomy questions could be translated into the format required by Emily. Relatively...
simple extensions to the program should allow most, or all, of the query types to be answered if the content is present in the FMA. In addition, the response time for all but the most unlikely queries (queries 8 and 9 in Table 2) is acceptable for use in an interactive application.

However, the results also indicate a substantial need for human translation of English-language expressions into terms and relationships compatible with Emily and FMA representations. This need arises because anatomy questions in compendia of the type used in this evaluation tend to use general terms and homonyms (the meaning of which is provided by the question’s context), whereas the FMA terms are highly specific. Many of these translations require knowledge of anatomy. This requirement might not present a problem for well-trained anatomists who will be recruited to evaluate the FMA (although it might present a more substantial problem for novice students). The anatomists involved in the current formative evaluation were able to translate all options in the selected multiple choice type examination questions (see Appendix 1) into a format processable by Emily, except when these examination questions contained FMA relationships whose attributes were inaccessible to Emily. The answers to the nine translated questions in Appendix 1, derived from the results returned by Emily, were consistent in all instances with the published keys for the original questions. However, as noted, significant deficiencies in the comprehensiveness of the FMA prevented Emily from returning correct responses in 80 of 100 queries (Table 1).

These results suggest that, in the hands of domain experts, Emily may become a useful tool for evaluation of the FMA. Unless the evaluation is to be limited to low-level knowledge elements, such as comprehensiveness of content and equivalence of terms, the involvement of domain experts in the evaluations becomes inevitable. The involvement of domain experts has been advocated in the evaluation of medical informatics systems, but cautions have also been sounded about such a strategy. If domain experts, such as anatomists, look to their domain’s time-honored sources as gold standards for evaluating a machine-based knowledge system, the information they provide will be of limited value to the system’s developers. Therefore, these evaluators must be provided with insights into the different requirements for representing knowledge in traditional media versus formal systems, and they must be educated about the conceptual design of the latter systems. Meaningful input can be expected only from those participants in the analysis who have grasped the rationale accounting for the inherent differences between hardcopy and formal knowledge sources. Such an understanding will enable the evaluators to make the kinds of translations that the authors had to generate for the anatomy examination items.

The authors have learned a number of valuable lessons from this work. First, the relation-centric query format provided by Emily does allow most structural queries to be answered, but some cannot be formulated due to the inaccessibility of relationship attributes through the interface. There are many important structural questions that require attributed relationships, which the FMA provides but Emily does not yet answer. Second, the Emily interface was found to be easy to use by the anatomists who conducted the experiments. In particular, Emily allowed complex queries to be formulated that (1) could not be asked via the Protégé-2000 interface without a huge amount of search carried out interactively by a knowledgeable human and (2) could not be asked via a database query language without a large amount of knowledge about the structure of the database and some amount of programming capability. On the negative side, the authors have learned that some domain knowledge is required both for limiting queries to those that a domain-specific knowledge base can answer and for decomposing queries into the format that Emily can handle. A table that translates commonly used language into the more precise terminology of the FMA could be helpful here, but the construction of such a table is a large task and is not part of our current design plans. Finally, the biggest lesson learned was that without such a query interface, it would be very difficult to detect gaps in a knowledge base the size of the FMA.

The Emily interface is not specific to the FMA knowledge base; it could potentially be used with any large semantic network. The authors, however, are mainly interested in its use for both accessing and evaluating the FMA. To this end, Emily is being updated to handle attributed relationships and to add more power to the unknown relationship queries. A version of the program called Emily Light is being developed that can be executed from a Web site, without any downloading or installation required. This version will help the authors to identify gaps in the knowledge base and will make it easier for domain experts to evaluate the FMA, once it is more fully populated.

References


Appendix 1 ■ Examples of Translations of Exam Questions for Emily

1. The spine of the scapula is continued as the
   a. Coracoid process
   b. Angle of the scapula
   c. Infrafraglenoid tubercle
   d. Supraglenoid tubercle
   e. Acromion process
   
   Item 1 is a straightforward one for Emily; it exemplifies items requiring easy translation. The phrase “is continued as” translates directly to the ASA relationship is continuous with (directly). Thus, the query to Emily can be phrased as Spine of scapula is continuous with (directly) Unknown for which Emily returns the result set {Acromion, Body of scapula}, which indicates that the correct answer is e. This question (and most of the others) can also be solved by executing several Boolean queries, such as

   Spine of scapula is continuous with (directly) Coracoid process for which Emily will answer no.

2. The suprascapular nerve
   a. Supplies the infraspinatus muscle
   b. Arises from the lateral cord of the brachial plexus
   c. Notches the axillary border of the scapula
   d. All of the above
   e. A and B only
   
   Item 2 illustrates the need for substantial translation, calling for knowledge of anatomy and of the FMA. Options a, b, and c require the translation of the phrases “supplies,” “arises from,” and “notches” since they are absent from the Foundational Model, as such. “Supplies” is a functional relationship and was translated into is nerve supply of. “Arises from” was translated to is branch of (directly), and the term “notches” (which erroneously implies an active process) was translated as is adjacent to. Checking the validity of choices a, b, and c can be done with the following Boolean queries:

   Suprascapular nerve is nerve supply of Infraspinatus.
   Suprascapular nerve is branch of (directly) Lateral cord of brachial plexus.
   Suprascapular nerve is adjacent to Axillary border of scapula.

   The answer to the first query is yes, while the answer to the other two queries is no, which indicates that the correct answer to the examination question is choice a.

3. The thoracodorsal nerve
   a. Is a branch of the posterior cord of the brachial plexus
   b. Supplies the serratus anterior muscle
   c. Is cutaneous to dorsal surface thorax
   d. All of the above
   e. A and B only
   
   Like item 2, item 3 presents some translation challenges to deriving the appropriate relationships for Emily, resulting in a need for inferring the correct answer from the returned results. To illustrate a different strategy, the authors translated options a and b as the following queries:

   Thoracodorsal nerve is branch of (directly) Unknown
   Thoracodorsal nerve is nerve supply of Unknown.

   Anticipating that if the nerve had a cutaneous branch, Emily would return it, option c was submitted as

   Thoracodorsal nerve has branch (directly) Unknown

   For the first query, Emily returned Posterior cord of brachial plexus, indicating that option a is correct. For the second query, Emily returned Latissimus dorsi, indicating that option b is incorrect. Translation of option c remains problematic; however, Emily found no results in response to the third query, which suggests either that the thoracodorsal nerve has no branches or that no branches have been entered in the database. (The nerve, in fact, has no branches, but the FMA does not represent the absence of branches.) Regardless of the ambiguities of the translation and the results of the third query, both options d and e can be excluded on the basis of the information provided by Emily, leaving a as the correct answer, which tallies with the key. It may be of interest to note that the mechanics of many multiple-choice questions invite such reasoning from examination takers, which is independent of their knowledge of the domain that is being tested.

4. The axillary vein
   a. Is lateral to the axillary artery
   b. Is devoid of valves
c. Lies anterior to pectoralis minor
d. Is directly continuous with the brachiocephalic vein
e. None of the above

The authors selected this item to illustrate structural relationships that Emily is currently unable to handle. Options b and d are straightforward for Emily. Option d can be entered directly and the authors translate option b as

Axillary vein has part (directly) Valve of axillary vein.

Emily returns the answer no to each Boolean query. However, options a and c cannot be queried by the current version of Emily. The relationships “lateral” and “anterior” named in options a and c, respectively, are in fact attributes of the adjacent to slot of an anatomical entity. Although attributed relationships are represented in the FMA, the current version of Emily does not retrieve the attributes of relations. However, implementation of this capability is fairly straightforward and will be added to the next version.

5. The coronary sinus receives each of the following vessels EXCEPT the
   a. great cardiac vein
   b. middle cardiac vein
   c. anterior cardiac vein
   d. small cardiac vein
   e. posterior vein of the left ventricle

Item 5 illustrates the often-used examination item format that asks for an exception, which actually simplifies translation into Emily’s format. Although it requires the translation of “receives” to the ASA relation has tributary (directly), all four choices can be covered by a single query:

Coronary sinus has tributary (directly) Unknown
for which Emily returns the result set {Great cardiac vein, Posterior vein of left ventricle, Middle cardiac vein, Small cardiac vein, Oblique vein of left atrium}. This indicates that choice c is the required exception.

6. A tumor involving the fifth to twelfth thoracic vertebrae could affect each of the following structures in the posterior mediastinum EXCEPT the
   a. thoracic duct
   b. phrenic nerve
   c. azygos vein
   d. descending aorta
   e. esophagus

Item 6 is more typical of the type of questions included in anatomy examinations than the previous items. The challenge that it presents is that it does not explicitly state the relationship to be translated. The translated query is

Posterior mediastinum contains (directly) Unknown

and Emily returns the result set {Esophagus, Azygos vein, Descending aorta, Trunk of thoracic duct, Thoracic part of trunk of right vagus nerve, Thoracic part of trunk of left vagus nerve}. Since Phrenic nerve is not returned, choice b is the correct answer.

An alternative and more desirable (albeit more laborious) way to submit the question would be to query which of the structures listed in the options has an anterior adjacency in the posterior mediastinum to the fifth to twelfth thoracic vertebrae, which is the logical relationship to query. This approach, however, cannot be pursued until Emily can handle attributed relationships. Such an approach would reveal a flaw in the question, which calls for faulty reasoning. For the sake of expedience, our translation conforms to the faulty reasoning. The stem of the question restricts the options to structures located in the posterior mediastinum, yet the correct answer specified by the key can only be reasoned on the basis of a location other than the posterior mediastinum. The question provides an illustration of arriving at the right answer for the wrong reasons.

7. Each of the following is related to the lumen of the right ventricle EXCEPT the
   a. interventricular septum
   b. trabeculae carneae
   c. bicuspid valve
   d. anterior papillary muscle
   e. septomarginal band

This is a good question on which to use Emily’s unknown relationship query. Since the FMA constrains the term lumen to tubular structures, the authors need to use instead the term cavity. The FMA does not allow plural terms, and so the authors use the singular term Trabecula carneae instead of trabeculae carneae in option b. Since there is an anterior papillary muscle in both right and left ventricles, in option d, the authors use the term specific for the muscle in the right ventricle. The authors therefore translate the question into the following queries:

Cavity of right ventricle Unknown Interventricular septum
Cavity of right ventricle Unknown Trabecula carneae
Cavity of right ventricle Unknown Bicuspid valve
Cavity of right ventricle Unknown Anterior papillary muscle of right ventricle
Cavity of right ventricle Unknown Septomarginal band

Emily returns nonempty result sets for all except choice c, which is the correct answer. Options c and e illustrate the need for enabling Emily to recognize synonyms. In the FMA, “bicuspid valve” and “septomarginal band” are synonyms of the preferred names Mitral valve and Septomarginal trabecula, respectively. Emily searches synonyms and foreign language equivalents of the entities included in a query, and it always returns preferred names in the results. Option d illustrates the difference between the specificity of terms in the FMA and general anatomical discourse, a topic better addressed in relation to the next examination question.

8. The left coronary artery bifurcates into the circumflex branch and the
   a. left marginal branch
   b. left ventricular branch
   c. anterior interventricular branch
   d. right marginal branch
   e. posterior interventricular branch

For Item 8, the authors translated left coronary artery as Trunk of left coronary artery and “bifurcates into the … branch” as the has branch (directly) relationship, yielding the query

Trunk of left coronary artery has branch (directly) Unknown
which produced the result set {Trunk of anterior interventricular branch of left coronary artery, Trunk of circumflex coronary artery, Trunk of variant atrial branch of left coronary artery}; so that option c is the correct answer.
Item 8 (and also Item 7) illustrates the difference between the specificity of terms in general anatomical discourse and the FMA. The term Left coronary artery is, in fact, a homonym for two distinct entities, which are readily distinguished by the context of the English sentence in which the homonym is embedded. The FMA does not allow homonyms and uses specific terms for each entity. The meaning of the term in the stem of Item 8 is suggested by the expression “bifurcates.” The FMA’s preferred name for this entity is Trunk of left coronary artery. The other meaning of the term Left coronary artery is implied by the expression (used just as commonly in anatomical discourse) “... supplies the left ventricle, the interventricular septum,” etc. This meaning encompasses an entire arterial tree, which includes the trunk and all its branches. The preferred name of this entity in the FMA is Left coronary artery. The trunk and branches of this tree are represented in the FMA as parts of the tree, and specific branching relationships are modeled between the trunk, branches, and subbranches to symbolically represent the specific structure of the tree.

Our translation of the term “bifurcates” as “has branch (directly)” is not sufficiently specific, as indicated by the return of three rather than two branches, as a bifurcation is expected to yield. A bifurcation yields terminal branches, which are distinct from lateral branches given off along the trunk or a branch of the tree. Both terminal and lateral are attributes of the branch relationship, and as mentioned above, at the time of writing, are not processable by Emily.

Item 9 illustrates the need for composing a compound query and transitive closure because inference is required to trace the complex and remote branching relationships through which nerve fibers are transmitted from a segment of the spinal cord through a set of spinal nerves and their branches to the Greater splanchnic nerve. These relationships are shown graphically in Figure 5 to illustrate the challenge for composing the queries and to demonstrate Emily’s capabilities for tracing complex relationships.

The trunk of the greater splanchnic nerve is formed by the union of its roots, which are branches of a set of sympathetic thoracic ganglia; each of these ganglia is connected by a sequence of branches to the trunk of a spinal nerve in a particular set. The stem of the item asks which of the options is not a member of this set. The intent of the item’s author is to elicit from the examination taker (usually a student) a reasoning process that traces a nerve fiber through the structures that transmit such a fiber from a segment of the spinal cord to the trunk of the greater splanchnic nerve, as shown in Figure 5. Note, however, that to follow the fiber’s path, the student need not necessarily know the names of the structures that transmit the fiber; however, the student will not be able to arrive at the correct answer without understanding the structural (or spatial) connections shown in Figure 5.

Emily can emulate the behavior of the student who understands these connections, provided the authors recognize in formulating the query that there must be transitive continuity between the greater splanchnic nerve and the spinal cord segments that contribute nerve fibers to this nerve. Therefore, the authors formulate the query

**Greater splanchnic nerve is continuous with Unknown**

Emily returns the result set {Fifth thoracic ganglion, Sixth thoracic ganglion, Seventh thoracic ganglion, Eighth thoracic ganglion, Ninth thoracic ganglion, Tenth thoracic ganglion, Fifth thoracic nerve, Sixth thoracic nerve, Seventh thoracic nerve, Eighth thoracic nerve, Ninth thoracic nerve, Tenth thoracic nerve, T5 segment, T6 segment, T7 segment, T8 segment, T9 segment, T10 segment}.

Interpretation of the result set requires us to recognize that in the Anatomical Taxonomy of the FMA Fifth thoracic nerve is a Thoracic nerve, which is a Spinal nerve, and that Fifth thoracic nerve corresponds to the shorthand expression T5 in option a of the item. Similar translations apply to the other options. Options a, c, d, and e are found in this set (as Fifth...
thoracic nerve, Ninth thoracic nerve, Seventh thoracic nerve, and Eighth thoracic nerve, respectively), but choice b is missing, which provides the correct answer.

The same conclusion is reached if the authors submit a series of Boolean queries for the continuities of each of the options. One such query would be

Greater splanchnic nerve is continuous with Fifth thoracic nerve

and so on. Emily returns yes for the fifth, ninth, seventh, and eighth thoracic nerves (i.e., T5, T9, T7, and T8). However, if the authors pose the query

Greater splanchnic nerve is continuous with Twelfth thoracic nerve,

the answer is no, which identifies the exception called for by Item 9.

Note that the answers to any of the above queries are not represented explicitly in the FMA. Emily deduced the query results by tracing the relations represented for each structure shown in Figure 5. Note also that Emily omits from the result sets a number of structures included in Figure 5 (e.g., roots and trunk of spinal nerve, intercostal nerve, communicating ramus). The explanation is that these structures are represented in the FMA as parts of a spinal nerve tree. As in the case of the coronary artery in Item 8, the FMA distinguishes between the trunk of the spinal nerve and the entire tree, which includes the roots, the trunk, and all branches (e.g., intercostal nerve, communicating ramus) of the tree. Emily takes advantage of such knowledge embedded in the FMA and returns only the names of the neural trees since this is the level at which the most general correct answer is first encountered.