Medical Knowledge Morphing via a Semantic Web Framework

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Abstract

Clinical decision-making involves an active interplay between various medical knowledge modalities. Medical knowledge morphing aims to support clinical decision support by mimicking the interplay between knowledge modalities, as per the problem description, to derive a holistic knowledge-base. We leverage the Semantic Web technology suite to pursue knowledge morphing. We present a Knowledge Morphing framework that involves ontologies to represent the domain and knowledge artifacts, annotation of knowledge artifacts based on the respective ontological model, and ontology mediation activities to knowledge morphing.

1. Introduction

Clinical decision-making is a complicated activity because it involves a complex, multi-faceted and dynamic interplay between patient parameters that evolve along a temporal axis, medical knowledge withheld by the practitioner, procedural and operational constraints defining the care environment, and health outcomes metrics [1, 2]. If one just considers the medical knowledge component of clinical decision-making, then the complexity of the task can be gauged by studying the underlying complex interplay between heterogeneous medical knowledge modalities, such as (a) the tacit knowledge of a healthcare practitioner in terms of problem-solving skills, judgment and intuition; (b) clinical experiences and lessons learnt; (c) collaborative clinical discussions between practitioners; (d) published medical literature and clinical practice guidelines; (e) operational clinical protocols and pathways; (f) practitioner educational content; (g) patient education content; (h) formal decision support knowledge encapsulated as decision logic/rules; (i) social knowledge eliciting knowledge of a community of practice; and (j) data-mediated knowledge—i.e. clinical observations, diagnostic tests and therapeutic interventions captured within an EMR.

Clinical reasoning and decision-making by human practitioner involves the mental *morphing* of multiple knowledge resources—i.e. synthesizes of the practitioner's tacit knowledge with experiential, explicit and/or social knowledge. Put simply, when confronted with a clinical problem, human practitioners seek knowledge from different sources, synthesize it to develop a broader understanding of the problem at hand and then reason over the entire knowledge to derive knowledge-based solutions. Most interestingly, the solution cannot be traced to a specific knowledge source, rather it is consequence of a seamless *morphing* of different knowledge modalities, where the different knowledge sources both extend and constrain the eventual knowledge-base used to solve the problem.

We posit that, if Clinical Decision Support System (CDSS) are expected to provide quality and pragmatic decision support and care planning interventions, then the traditional approach of leveraging a single knowledge modality, as the knowledge-base, may not suffice. Rather, what is needed is the seamless morphing of various knowledge resources (even in different modalities) to dynamically create a problem-specific *holistic* knowledge-base that can competently interpret a complex clinical scenario and in turn recommend an action that is grounded in both evidence and experience.

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Knowledge morphing is defined by Abidi [3] as "the intelligent and autonomous fusion/integration of contextually, conceptually and functionally related knowledge objects that may exist in different representation modalities and formalisms, in order to establish a comprehensive, multi-faceted and networked view of all knowledge pertaining to a domain-specific problem". Knowledge morphing is necessitated due to the dispersion of medical knowledge across different knowledge modalities, and the need to synthesize these modalities to effectuate holistic medical knowledge for clinical decision support. We pursue knowledge morphing as a complex knowledge modeling activity that establishes a *knowledge link* between two or more knowledge resources that are both contextually and functionally compatible. For clinical decision support purposes the morphed knowledge resource, encapsulating multiple perspectives of the healthcare knowledge for a particular health issue, can be operationalized through logic-based reasoning formalisms to infer problem-specific and patient-centered clinical actions/recommendations.

In this paper, we extend our original concept of medical knowledge morphing [3]. We present a semantic web based knowledge morphing framework (as shown in Figure 1), that focuses on ontology-based knowledge representation and morphing of heterogeneous knowledge modalities through logic-based reasoning involving ontology mediation.

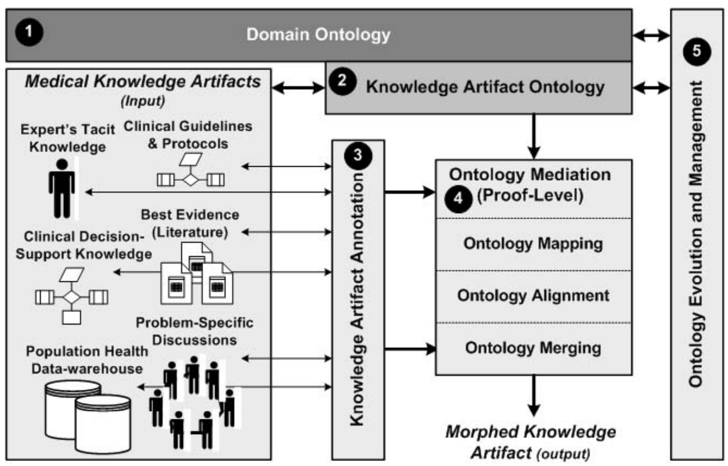

Figure 1. Medical Knowledge Morphing Framework

2. Knowledge morphing via a Semantic Web framework

Knowledge morphing requires a high level abstraction of the domain that on the one hand extends across heterogeneous knowledge resources that may differ in origin, content, function and modality, and on the other hand conceptualizes the domain along the lines of declarative and procedural knowledge that can be further classified in terms of continuant and occurrent entities at the mereological level [4, 5].

The *Semantic Web* purports methods and formalisms to achieve a high-level semantic modeling—i.e. interpretation, abstraction, axiomatization and annotation—of domain knowledge in terms of classes, properties, relations and axioms [6]. More specifically, the Semantic Web offers a logic based framework to (a) model the procedural and declarative medical knowledge as ontologies that represent the underlying domain concepts and their relationship; (b) annotate the heterogeneous medical knowledge resources, based on their respective ontologies; (c) determine similar semantic patterns between multiple ontologies in order to facilitate the interoperability between and merging of multiple ontologically defined medical knowledge resources to realize a *holistic* knowledge resource; (d) maintain domain knowledge consistency by active

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ontology evolution and management processes; and (e) operationalize the abstracted knowledge via proof engines, employing logic-based reasoning methods, to infer 'trusted' solutions from morphed knowledge. The orchestration of these activities is to be achieved by our Semantic Web based *Knowledge Morpher* for healthcare knowledge.

3. Medical knowledge representation via ontologies

As a first step to medical knowledge morphing we need to pursue medical knowledge formalization in order to support domain-specific argumentation based on (a) *medical (declarative) knowledge* that describes the domain, potential problems and probable solution; this knowledge can be causal, qualitative, descriptive or quantitative; and (b) *procedural knowledge* that describes how to apply the medical knowledge to actually solve clinical problems for a specific patient, whilst taking into account the unique health delivery constraints of a healthcare institution.

In line with the Semantic Web approach, we pursue medical knowledge representation using ontologies that allows (i) formalization of medical knowledge; (ii) characterization of the knowledge along declarative and procedural dimensions; (iii) annotation of the knowledge resources based on an ontological model; (iv) re-use and evolution of the knowledge; (v) use of standard terms and concepts; and (vi) identification of contextually and functionally similar knowledge objects/constructs to allow knowledge morphing [7].

For medical knowledge representation we distinguish two different ontologies—(a) a high-level *domain ontology* describing the fundamental medical concepts of the domain—i.e. declarative knowledge; and (b) a lower-level *knowledge artifact ontology* that captures both the structure and content of a particular knowledge artifact—such as a clinical practice guideline, clinical pathway, clinical cases and so on. It also entails procedural knowledge in terms of procedural and operational parameters that specify the constraints for the application of the medical knowledge in a given healthcare environment.

3.1. Domain Ontology

The domain ontology serves two purposes: (i) it provides a formal and consensual understanding of the problem domain, thus ensuring a high-level standardization of generic domain-specific concepts and relation; and (ii) it facilitates the establishment of abstract knowledge links between contextually and functionally congruent knowledge constructs across different knowledge artifact ontologies.. The domain ontology is built by abstracting the declarative medical knowledge from an assortment of medical knowledge resources, with the net effect that the emergent domain ontology encapsulates knowledge structures that maybe common across multiple knowledge resources. Notwithstanding the fact that the development of a problem-specific domain ontology is a major undertaking, yet it allows to (a) model the different types of knowledge along a standard structure, and (b) to modularize the domain knowledge along salient domain aspects to facilitate context-specific merging of specific knowledge elements. In our *Knowledge Morpher*, the domain ontology not only logically represents the domain concepts, but upon execution aligns multiple knowledge constructs, even in heterogeneous modalities, that share a discrete notion of contextual compatibility to support knowledge morphing.

3.2. Knowledge Artifact Ontology

We recognize the need to distinguish between different knowledge modalities, as each knowledge modality entails idiosyncratic properties and functions that bring a unique perspective to a problem's solution. As such, heterogeneous knowledge resources/modalities represent knowledge in an artifact-specific manner, despite the fact that they share contextual and functional characteristics with other knowledge resources. For all intents and purposes, knowledge artifacts can be seen as collections of medical argumentations, albeit each knowledge artifact may exercise different knowledge structures, procedural constraints, specificity, adequacy and operational efficiency, determined by the intended function of the knowledge resource. Since all knowledge artifacts support medical argumentation, therefore they can be represented through a common formalism—i.e. a knowledge artifact ontology.

In our Knowledge Morphing framework, we propose a set of knowledge artifact ontologies—i.e. one each for a specific knowledge modality—to structure and represent modality-specific knowledge. Each knowledge artifact ontology models the semantic relations inherent in the modality-specific knowledge resource and characterizes the procedural knowledge as a sequence of control structures—each control structure identifies actions, rationalization of actions, ordering of actions, execution of actions and quantification of action effects. Our Knowledge Morpher, guided by the domain ontology, establishes knowledge interoperability links between different knowledge artifacts, based on contextual and functional similarities, to effectuate knowledge morphing.

4. Ontology-based annotation of knowledge artifacts

The formalization of the domain and artifact knowledge as ontologies, as described earlier, is to be followed by ontology-based annotation of the knowledge contents within the different knowledge artifacts. The objective of the knowledge annotation activity is to characterize the content of the knowledge artifacts, as per the ontological models, to establish *morphing constructs* that are used to formally align knowledge artifacts for morphing purposes. In principle, a morphing construct is a tuple that contains context-specific knowledge content and operators; the knowledge content typically entails procedural knowledge (defined by the knowledge artifact ontology) pertinent to a medical context that in turn is defined via the domain ontology. Within a knowledge artifact, we need to identify and annotate the possible morphing constructs as they serve as the both the 'hooks and glue' to morph different knowledge artifacts—i.e. two knowledge artifacts that contain contextually and functionally similar morphing constructs can potentially be morphed to form a multi-faceted and comprehensive knowledge artifact. Given below are sample of morphing constructs:

[medical_action, relation_operator, disorder], [intervention, rationale_operator, outcome]
[intervention, choice_operator, outcome], [medical_context, relation_operator, medical_action]
[medical_action, observation_operator, medical_action], [medical_disorder, temporal_operator, medical_action]

The knowledge annotation exercise will annotate the: (a) declarative and procedural knowledge within an artifact; and (b) morphing constructs within an artifact. The activity is expected to take as input a knowledge artifact, under the guidance of the domain and knowledge artifact ontologies, and accordingly annotate its content. At the conclusion of the annotation exercise, a knowledge engineer might be required to check and approve the annotated knowledge artifact prior to subjecting them to the knowledge morphing process.

5. Medical knowledge morphing via proof-level ontology mediation

Ontology mediation is the process of reconciling differences between heterogeneous ontologies in order to achieve interoperability between ontologically defined knowledge sources [8]. In our Knowledge Morphing framework, we introduce the concept of Proof-level Ontology Mediation (POM) to allow 'morphing' of ontologically defined knowledge sources at the proof-level—i.e. beyond structural level ontology mediation—through the activities of Ontology Mapping, Ontology Alignment and Ontology Merging [8]. For knowledge morphing purposes, the *ontology mapping* activity is deemed to

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(a) identify similar concepts or relations from different morphing constructs based on shared ontologies. Subsequently, an *ontology alignment* activity will reconcile these two knowledge artifacts to potentially align the candidate morphing constructs. Next, the *ontology merging* activity will lead to the merging of candidate knowledge artifact ontologies to project a merged knowledge artifact ontology that effectuates knowledge morphing leading to a holistic knowledge artifact. We formally describe our concept of *proof-level ontology* :

Definition 1 (Ontology): Let V be the set of structured vocabulary, and Ax be the set of axioms about V, which are formulated in formal language L. An ontology is a sign-system $Ont = (L, V, Ax)$, where: the symbols of V denote categories, and relations between categories or between their instances; and L is a formal language associated to a vocabulary V and used to declare a set of $L(V) = Ax$, which are usually a declarative formulae.

It is also assumed that: $V \subseteq V1 \Rightarrow L(V) \subseteq L(V1), and\ L(L(V)) = L(V)$.

Definition 2 (Ontology Instance Triples): Let $O = (L, V, Ax)$ be an ontology, and $s, p, o \in V$. Ontology Instance Triples $\mathbb{I}(O)$ is the set of triples $< s, p, o >$, where p is a relation between two category instances s and o. Furthermore, Morphing Constructs Triples $\mathbb{M}(O)$ are set of triples $< s, p', o' >$ in O, where s denotes category instance in Ontology O, and p' denotes an operator that specifies a contextual relation between a category instance s with a category instance o' in a domain ontology.

Definition 3 (Proof-level Ontology): Let $\mathbb{O} = \{O_1, \cdots, O_n\}$ be the set of ontologies, and $\mathbb{T} = \bigcup_{i=1}^{n} \mathbb{I}(O_i)$ be the set of all *Ontology Instance Triples*. An ontology $O \in \mathbb{O}$ is called a Proof-level Ontology iff: $\forall\, T \in \mathbb{I}(O), \exists \mathbb{T}' \subseteq \mathbb{T}.$ such that $\mathbb{T}' \vDash T$

As defined above, a proof-level ontology is an ontology where each of its instance triples are entailed by triples that are not necessarily from the same ontology. An ontology can be seen as a proof-level ontology where each of its instance triples are asserted facts and are entailed by *null* (denoted as $\bot \vDash T$). An ontology at the proof-level also represents the justifications behind inferred instances based on ontology-based and user-defined axiomatic systems (that are modeled in $L(V) = Ax$).

We argue that proof-level ontologies can be better candidates for ontology mediation process. If the ontology mapping is established among two (inferred) triples $T_1$and T_2 from two proof-level ontologies along their proofs ($\mathbb{T}' \vDash T_1$ and $\mathbb{T}'' \vDash T_2$, where $\mathbb{T}', \mathbb{T}'' \subseteq \mathbb{T}$), then their justifications (modeled as set of instance triples $\mathbb{T}', \mathbb{T}'' \subseteq \mathbb{T}$) behind $T_1$and T_2 can support further mediation steps to ensure that $\mathbb{T}'$and $\mathbb{T}''$ must be either mapped or integrated in the final merged ontology, such that the merged ontology will be generated based on semantic similarity, and also be consistent with 'trusted' results in the source ontologies.

At the proof-level, ontologies are comprised of their asserted/inferred facts, underling to their logical, structural and user-defined axioms. We argue that asserted/inferred facts together their justifications/proofs based on their respective axioms can potentially improve ontology mediation, and can find better consistent and 'trusted' mapping between ontologies.

Our POM architecture aims to find mappings between two or more proof-level ontologies, based on similar morphing constructs (denoted as $\mathbb{M}(O)$). The rationale for controlling similarity matching activity by morphing constructs is because morphing constructs triples define the context under which two knowledge sources can be morphed. POM employs an ontology management and evolution module (as described later) that can identify structural, logical and user-defined inconsistencies occurred due to ontology mapping, whilst generating maximal consistent and minimal inconsistent sub-ontologies [9]. Next, POM proceeds with the merging and alignment rules, and generates a merged ontology.

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6. Ontology evolution and management

Medical knowledge evolves at a rapid pace, so we account for medical knowledge evolution by periodically updating both the domain and knowledge artifact ontologies. We ensure that the changes to the ontologies are consistent with user-defined structural, conceptual and functional parameters [9]. We plan to use Stojanovic's Ontology Evolution and Management Process [10], which comprises six phases.

7. Concluding Remarks

There is a growing demand for medically sound, pragmatic, proactive, multi-faceted and comprehensive recommendations from knowledge-based clinical decision support and care planning systems. On the face of it this demand by health practitioners, though valid, is not achievable because (a) current knowledge based systems place an insatiable demand for medical knowledge; and (b) the apparent lack of the desired quality and quantum of medical knowledge in a single knowledge resource. One potential solution is to aggregate the available medical knowledge that may exist across heterogeneous knowledge modalities/resources. The proposed *medical knowledge morphing* framework is a first step towards the generation of a holistic knowledge resource to address the demands.

In this paper we presented the conceptual overview of our medical knowledge morphing framework that is grounded in the Semantic Web approach. Our knowledge morphing approach comprises: (i) formalizing the knowledge in terms of semantic models—i.e. ontologies; (iia) annotating the knowledge artifacts based on the ontologies; (iib) identifying the morphing constructs (i.e. potential concepts shared across artifacts) within the knowledge artifacts; (iii) using proof-level ontology mediation to morph the candidate knowledge artifacts; (iv) establishing 'trust' in the morphed knowledge through proof-level justifications; and (v) managing the evolution of the knowledge through ontology evolution and management processes. We are currently implementing our medical knowledge morphing framework and will report our results in follow-up publications.

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References

[1] M. Fieschi, J. C. Dufour, P. Staccini, J. Gouvernet, and O. Bouhaddou. Medical decision support systems: old dilemmas and new paradigms? *Methods Inf Med.*, 42(3):190–198, 2003.

[2] E. Coiera. *The Guide to Health Informatics (2nd Edition)*. Arnold, London, October 2003.

[3] S. S. R. Abidi. Medical knowledge morphing: Towards the integration of medical knowledge resources. *18th IEEE Intl. Symposium on Computer-Based Medical Systems*, Dublin, 2005.

[4] P. Simon P. Parts: a study in ontology. Oxford: Clarendon Press; 1987.

[5] S. Schulz, U. Hahn. Part-whole representation and reasoning in biomedical ontologies. Artificial Intelligence in Medicine, 34(3), 2005.

[6] T. Berners-Lee, J. Hendler, and O. Lassila. The semantic web. *Scientific American*, 284(5):34–43, 2001.

[7] S. Schulz, A. Kumar, T. Bittner. Biomedical ontologies: What part-of is and isn't. *Journal of Biomedical Informatics*, 39: 350–361, 2006.

[8] L. Predoiu, C. Feier, F. Scharffe, J. de Bruijn, F. Martn-Recuerda, D. Manov, and M. Ehrig. State-of-the-art survey on ontology merging and aligning v2. Technical Report D4.2.2, Digital Enterprise Research Institute, University of Innsbruck, December 31 2005.

[9] P. Haase and L. Stojanovic. Consistent evolution of OWL ontologies. In A. Gmez-Prez and J. Euzenat, editors, *2nd European Semantic Web Conference, Heraklion, Greece,* pp. 182–197. Springer Verlag, 2005.

[10] L. Stojanovic. *Methods and Tools for Ontology Evolution*. PhD thesis, Universität Karlsruhe (TH), Universität Karlsruhe (TH), Institut AIFB, D-76128 Karlsruhe, 2004.

0-7695-2905-4/07 $20.00