A Knowledge Creation Info-Structure to Acquire and Crystallize the Tacit Knowledge of Health-Care Experts

Syed Sibte Raza Abidi, Yu-N Cheah, and Janet Curran

Abstract—Tacit knowledge of health-care experts is an important source of experiential know-how, yet due to various operational and technical reasons, such health-care knowledge is not entirely harnessed and put into professional practice. Emerging knowledge-management (KM) solutions suggest strategies to acquire the seemingly intractable and nonarticulated tacit knowledge of health-care experts. This paper presents a KM methodology, together with its computational implementation, to 1) acquire the tacit knowledge possessed by health-care experts; 2) represent the acquired tacit health-care knowledge in a computational formalism—i.e., clinical scenarios—that allows the reuse of stored knowledge to acquire tacit knowledge; and 3) crystallize the acquired tacit knowledge so that it is validated for health-care decision-support and medical education systems.

Index Terms—Knowledge acquisition, knowledge management (KM), medical decision-making, tacit knowledge.

I. INTRODUCTION

Health care is facing exceptional challenges to keep pace with demands for “actionable” health-care knowledge in the face of new treatments, procedures, guidelines, and delivery practices vis-à-vis more stringent service-quality and outcome-measurement criterion [1], [2]. Health care is a knowledge-rich domain. Yet, due to various operational and technical reasons, the various modalities of health-care knowledge are not entirely harnessed and put into practice, thus giving the false impression of paucity of health-care knowledge [3]. Traditionally, the main source and volume of health-care knowledge is published best evidence in terms of journal articles, structured reviews, clinical practice guidelines, and so forth [4]. But, from a knowledge-management (KM) perspective, health-care knowledge exists beyond published best evidence [5]. In fact, a significant quantum of extremely vital and viable health-care knowledge exists in rather tacit forms, for instance the working knowledge of health-care experts [6], [7]; the social knowledge ingrained in collaborative problem-solving [8] or educational discussions [9] between health-care practitioners; the communication patterns between a community of practitioners leading to the manifestation of an expert network that depicts hubs and consumers of knowledge [10]; and even within clinical episodes recorded in electronic patient records [11]. Even though not “evidence-based” by the traditional definition, such tacit health-care knowledge is omnipresent, and is recognized as valid, valuable, and essential to health-care practice [12].

Tacit health-care knowledge, though an undercapitalized resource, can play a significant role in improving the quality and delivery of health care, of course in tandem with the overcapitalized explicit (published) health-care knowledge [13]. Given the ever-evolving dynamics of health-care delivery practices, health-care practitioners are routinely confronted with knowledge gaps—either due to the lag in relevant evidence being published or due to the lack of published evidence for an unusually complex and novel clinical problem. For instance, many relatively rare medical problems and treatments are not adequately represented in medical literature to support evidence-based clinical decision-making, and even if evidence is available, it is not always likely for a subspecialist in the field to have personal experience with all possible syndromes and conditions to make the right decisions [5], [14]. We argue that, to address knowledge gaps experienced during professional practice, there is a strong case for leveraging the unexploited tacit modalities of health-care knowledge—in particular, the clinical experiences and intuitive problem-solving strategies of health-care experts—to provide novice health-care practitioners with auxiliary actionable health-care knowledge. More specifically, the tacit knowledge of health-care experts can assist novice clinicians by imparting practical insights into what solution will work, why it will work, and how to make it work [15]. It is interesting to note that on the one hand, tacit health-care knowledge is widely omnipresent in clinical practice, yet on the other hand, it is extremely difficult to articulate, describe, and disseminate [5], [12]. Hence, from a health-care KM perspective, it is not only essential but also challenging to harness and operationalize the tacit modalities of health-care knowledge.

The emergence of KM as a discipline and its profuse application to health care can resolve the current operational and technical barriers toward the recognition, acquisition, dissemination, and utilization of actionable health-care knowledge [1], [3], [16]–[19]. KM theory and practice provides the necessary philosophical basis, psychological underpinnings, management strategies, and technical methods to undertake the unique challenges faced by the health-care community pertaining to the efficacious creation, management, dissemination, and operationalization of health-care knowledge in order to ostensibly support the knowledge consumption needs and demands of the various

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health-care constituencies, i.e., practitioners, patients, communities, administrators, and policy makers [20], [21].

This paper presents a KM methodology, together with its computational implementation, to 1) explicate and acquire the nonarticulated tacit knowledge of health-care experts [15], [21]; 2) represent acquired tacit health-care knowledge in a computational formalism that structures knowledge in terms of clinical scenarios; and 3) crystallize the acquired tacit knowledge so that it can be amalgamated with existing knowledge info-structures that are used by front-end health-care decision-support and medical education systems [22]. Through a combination of KM techniques, we have developed a Tacit Knowledge Acquisition Info-structure (TKAI) that provides tools to capture tacit health-care knowledge and to crystallize the acquired tacit knowledge in a computational formalism.

The discussion proceeds as follows. In Section II, we highlight the nature of tacit knowledge and the kind of questions that need to be addressed to harness this rather untapped knowledge resource. In Section III, we present our approach for tacit knowledge acquisition that reuses an expert’s articulated basic experiential knowledge to challenge him/her to solve a clinical problem and in the process explicate his/her nonarticulated and complex tacit knowledge. A novel knowledge representation construct, termed scenarios, is central to the tacit knowledge acquisition process and is next introduced in Section IV. Having set the necessary background for tacit knowledge acquisition, in Section V, we discuss the process of tacit knowledge acquisition, whereas in Section VI, we discuss the process of knowledge crystallization. Section VII provides concluding remarks and some thoughts for the future of KM in health care.

II. NATURE OF TACIT HEALTH-CARE KNOWLEDGE

Health-care knowledge can be differentiated along the lines of explicit and tacit knowledge [5], [23]. Explicit knowledge is about how things should work and can be described as canonical knowledge presented as clinical guidelines, studies, methods, reviews, and analysis as reported in published medical literature. Tacit knowledge is the innate knowledge of health-care experts that is not yet articulated and made explicit; it embodies their experiential know-how, personal skills, and intuitive judgment, i.e., what really works and how to make it work [15], [23], [24]. Tacit knowledge can be further distinguished as follows: 1) Basic tacit knowledge or routine experiential knowledge, that is amenable to articulation simply during casual peer discussions or when answering questions—it encompasses ones theoretical know-how, evidence-based interpretation, and experiences related to typical and everyday clinical problems; (b) complex tacit knowledge or intuitive experiential knowledge, that is progressively accumulated as the expert responds to atypical and high acuity clinical problems—it is deeply embedded and, hence, not easily articulated, yet it manifests as the expert’s intuitive judgment in challenging clinical situations. It is contended that essential strategic and practical knowledge is tacit rather than explicit; health-care experts with profound clinical experience inherently withhold strategic medical knowledge that goes beyond the published or “explicit” modalities of medical knowledge.

Patel et al. [12] have elucidated the principles of expertise and tacit knowledge in health care. An expert is someone who surpasses competence in a domain and who, in general, can assess problems more rapidly and completely than can a novice, using pattern recognition as well as compilations of facts. Real-world performance results from both tacit knowledge acquired through clinical experience, as well as explicit “textbook” or evidence-based knowledge. But, due to the intuitive, implicit, and personal nature of tacit knowledge, it is difficult, if not impossible, to capture and formalize tacit knowledge in terms of procedures, algorithms, or guidelines.

III. TACIT KNOWLEDGE ACQUISITION: OUR APPROACH AND METHODOLOGY

Our approach for tacit knowledge acquisition focuses on the second phase of Nonaka’s organizational knowledge creation framework—the so-called creating concepts phase [25]. We believe that the creating concepts phase of knowledge creation is highly relevant to the acquisition of tacit knowledge of health-care experts as it features an externalization process, whereby tacit knowledge is externalized into explicit knowledge. Subsequently, the acquired tacit knowledge undergoes a crystallization process during which it is assessed and validated by experts and practitioners, and finally made available for downstream knowledge sharing and utilization.

Tacit knowledge acquisition is broadly defined as the transfer of problem-solving expertise from a knowledge source, say a domain expert, to a computational formalism. Traditional knowledge acquisition approaches, grounded in knowledge engineering methods, have resulted in a number of methods and tools, for instance repertory grids, system thinking, 20 questions, concept maps, semantic nets, causal and fault analysis, cognitive agents, semantic networks, and so forth [26], [27]. These indirect or contrived knowledge acquisition methods aim to understand the deep mental models of domain experts, but their efficacy is contingent on the provision of the right context and stimulus [24].

A recent shift in the role of knowledge, from problem solving to strategic value creation, has instigated KM research in capturing tacit knowledge for retention, enterprise-wide learning, consulting, and innovation [28]. Knowledge is deemed to exist across the enterprise in a variety of interoperable modalities, and for that matter contextualized tacit knowledge is created, explicated, crystallized, and disseminated via a variety of interactions between communities of domain experts. Emerging strategies include formal concept analysis [29], the reuse of experiences [30], case-based reasoning-based capture of contextualized tacit knowledge as ripple down rules [31], [32], and cognitive maps of tacit knowledge [33]. We note with interest the various perspectives of KM research in tacit knowledge and in this regard our work builds upon the various research threads mentioned above.

It is widely contended that a health-care expert accumulates his/her tacit knowledge in an indirect manner as a consequence of his/her profound clinical experiences, some experiences being routine while others being more complex. These clinical experiences provide the necessary stimulus to the activation
and application of tacit knowledge—for everyday clinical problems, tacit knowledge characterized as routine experiential knowledge may suffice, whereas, for more complex clinical problems, experts may respond using their complex experiential knowledge and in turn may even learn from their actions [5], [15]. Given that tacit knowledge is progressively “learned” via clinical experiences, a plausible strategy to acquire the deeply embedded and nonarticulated tacit knowledge is to explicate it through the same kind of clinical scenarios that were the basis for its origin.

We posit that the explication of a health-care expert’s tacit knowledge is made possible by subjecting him/her to a hypothetical clinical experience, i.e., we ask the health-care expert to solve simulated clinical problems or scenarios that reflect atypical and novel diagnostic situations featuring rather unusual patient and contextual constraints. We know that health-care experts are able to conveniently address typical clinical problems using routine experiential knowledge. However, if and when health-care experts are confronted with a challenging clinical situation, they need to leverage all their knowledge; health-care experts, therefore, invoke and exercise their deeply embedded complex tacit knowledge to first comprehend the dynamics of the challenging situation with respect to what they already know, and then second, to infer possible pragmatic solutions, i.e., *what really will work and how to make it work*, on the basis of their clinical experiences, intuitions, judgments, rules of thumb, and practice know-how [34]. Given the presence of a knowledge “ecosystem,” a clinical challenge, therefore, acts as a stimulus to activate and explicate an expert’s innate complex tacit knowledge, and in turn, acquires and represents it in a predefined computational formalism. This approach is in contrast to passive interviews with an expert.

Acquisition of tacit knowledge is a challenging task because it demands the capture and structuring of an expert’s mental model [35]—where the mental model may comprise an unstructured collection of beliefs, assumptions, feelings, biases, intuitions, memories, etc. [34]—that is configured in response to an expert’s individual experiences and problem-solving strategies. We argue that a more effective strategy to seek individualized tacit knowledge will be to provide 1) a controlled knowledge explanation environment that is more closely related to an expert’s mental model of practice and problem-solving and 2) a knowledge explanation stimulus that provokes the expert to act and apply his tacit knowledge. Again, for maximum efficiency, the stimulus should be with respect to the expert’s explicated mental model of practice and problem-solving, i.e., routine experiential knowledge. This position leads to our tacit knowledge acquisition approach that leverages a domain expert’s previously explicated routine experiential knowledge, i.e., knowledge that is representative of the expert’s basic mental model, as a catalyst to “explicate” the expert’s more complex and deeply embodied tacit knowledge. Here, the explicated experiential knowledge serves as an individualized frame of reference to which the domain expert can easily relate to and in turn use it to access and establish a conscious relationship with his/her inherent complex tacit knowledge. In conclusion, setting up the right context and stimulus is paramount to effectuate the effective acquisition of tacit knowledge from a domain expert.

The tenets of our multistep tacit knowledge acquisition methodology, therefore, are as follows: 1) Establish a basic individualized mental model of a health-care expert depicting his/her routine experiential knowledge. Given that a clinical situation (in terms of predefined attributes and parameters) is represented as a scenario construct, therefore, an explicated-scenario represents the explicated experiential knowledge of an individual health-care expert. 2) Design a challenge, i.e., an atypical problem situation, to explicate the health-care expert’s tacit knowledge. Given an explicated-scenario, modifications to it by health-care experts can introduce a degree of challenge for a health-care expert, hence, the formulation of a challenge-scenario. 3) Acquire the health-care expert’s tacit knowledge when it is explicated in response to solving the challenge-scenario. Given that a challenge-scenario demands a health-care expert to respond to premeditated questions, the health-care expert’s response recorded in relation to the challenge-scenario realize a solved challenge-scenario that incorporates a) specification of the problem situation; b) tacit knowledge explicating questions at specific points of interrogation; and c) most importantly, the health-care expert’s complex tacit knowledge in terms of responses to the challenge-defining questions. 4) Finally, validate the quality and applicability of the acquired tacit knowledge. Given that the acquired tacit knowledge needs to be validated with respect to existing domain knowledge, the crystallization of the acquired tacit knowledge allows for it to be classified and amalgamated with previously validated (by domain experts) domain knowledge, thus leading to a crystallized-scenario.

In summary, our approach stipulates a sequence of KM activities that eventually lead to the explication and acquisition of a health-care expert’s tacit knowledge, whereby, the solved challenge-scenario is the container of the health-care expert’s tacit knowledge. The proposed cycle purports knowledge creation where tacit knowledge is converted to and from explicit knowledge [25].

IV. SCENARIOS: A TACIT KNOWLEDGE REPRESENTATION AND ACQUISITION CONSTRUCT

Knowledge acquisition techniques go hand in hand with knowledge representational issues as the manipulation of the acquired knowledge largely depends on how the knowledge is represented to reflect the expert’s mental model [36]–[38].

We present a novel knowledge representation construct, known as scenarios, that offers a goal-oriented description of the problem situation, i.e., environmental context; the problem description in terms of actors, role of actors, temporal events and inputs; and the problem’s solution in terms of the expert’s interventions and outcomes. A health-care scenario has the following functionalities: 1) to depict a temporal sequence of distinct actions that need to be taken in order to accomplish a particular health-care task and 2) to detail the temporal sequence of interactions by health-care experts to fulfill the goal. This may comprise an exchange of messages and responses to intermediate outcomes, performed or experienced by health-care experts while solving a problem. 3) To capture and store the acquired tacit knowledge and 4) to serve as the medium for explicating tacit knowledge, i.e., the knowledge...
representation construct enables the domain expert to manifest and explicate his/her inherent tacit knowledge.

### A. Representation of Scenarios

Health-care scenarios comprise four main components: meta-scenario, scenario-construct, health-care-episode, and health-care-event (as shown in Fig. 1).

The meta-scenario component implements a two-level categorization of scenarios, termed Class and Sub-Class. The Class ID and Class Name identify the class of the scenario. Each class is further classified into subclasses identified by Sub-Class-List. This component enables the grouping of scenarios based on a predefined classification of health-care concepts.

The scenario-construct component stores the description of individual scenarios in terms of a sequence of episodes that are arranged in chronological order to mimic the temporal characteristics of the scenario. The scenario-construct comprises four “conceptual” parts [39]. The identification/context block that contains a scenario’s unique identification number, background description, contextual information, keywords, and the time frame in which the situation occurred. Contextual information (or context) refers to an environmental or situational description in which the scenarios were either conceived or are to be presented to an expert. A trigger event defines the reason for the existence of a particular scenario. The episodes are the main body of the scenario. Each episode divides the scenario into more meaningful chunks and consists of a sequence of events. A concluding event highlights the last event in the scenario. The health-care episode details an event list that stores the sequence of events that make up an episode in a scenario. Each episode is assigned a unique Episode ID and its description is provided in the Episode Description field. Each episode is generic and can be reused with multiple scenarios. The health-care event stores information about individual events which in turn provide details of the scenario through the parameter-value-list which provides detailed descriptions of what goes on in a scenario. Each event is characterized as three types: normative—events that are expected to occur on a normal basis; obstacle—events that hinder the progress of the task; and action—events that define the course of action undertaken by an actor.

### B. Different Roles of Scenarios

The novelty of our scenario-mediated knowledge acquisition approach is that the role and composition of a scenario changes as the knowledge creation process progresses (also shown later in Fig. 3).

Role 1: A scenario is a specialized knowledge representation structure that comprises slots to hold the domain knowledge.

Role 2: When an expert’s explicated experiential knowledge is added to the various slots of a scenario, it transforms into an explicated-scenario.

Role 3: Knowledge contained in an explicated-scenario serves as a catalyst to acquire an expert’s more complex tacit knowledge. To achieve this end, selective modifications to specific segments of an existing explicated-scenario realizes a challenge situation depicting a clinical situation with atypical or novel characteristics. We regard such modified explicated-scenarios as a challenge-scenario, which has the potential functionality to explicate complex tacit knowledge.

Role 4: A health-care expert’s response to a challenge vis-à-vis a challenge-scenario is deemed as the manifestation of his/her complex tacit knowledge, which is recorded within the scenario construct to yield a solved-challenge-scenario, i.e., a scenario encapsulating complex tacit knowledge of an expert.

Role 5: A health-care expert’s tacit knowledge encapsulated in a solved-challenge-scenario is subjected to validation via a knowledge crystallization process, whereby, the solved-challenge-scenario is compared, repaired, and categorized with respect to a priori validated knowledge. The outcome of this process is a crystallized-scenario that holds the validated tacit knowledge of a health-care expert.

Hence, throughout the workflow of tacit knowledge acquisition, the term scenario changes its characteristics and functionality, from scenario to explicated-scenario to challenge-scenario to solved-challenge-scenario, and finally to crystallized scenario. We would like to point out that our scenario approach is quite close to that proposed by Busch [32] and Stenmark [28], with the exception that the formulation of a knowledge-explicating scenario is achieved by a health-care expert who modifies the various parameters of an existing scenario in order to create a challenge that may instigate the explication of tacit knowledge.

### C. Incorporating an Ontology With Scenarios

Ontology is regarded as the definition of a standard vocabulary and a body of knowledge of some domain, typically built using the defined standard vocabulary. For the purposes of tacit knowledge acquisition, ontologies are highly relevant as they provide a taxonomic representation of domain knowledge in a form that can be easily exploited by computer programs. We incorporate a medical ontology within the scenario construct to address two standardization issues [11].
Terminology Interoperability: Health-care experts have diverse perspectives and approaches for solving a clinical situation. The choice of vocabulary used by an expert may lead to the belief that two solutions are different yet in reality they are not; for instance, the use of “myocardial infarction” in one scenario and “coronary thrombosis” in another scenario can be incorrectly taken to mean two different concepts. The application of a medical ontology over the contents of a scenario allows terminology interoperability, whereby, we are able to recognize the similarities between different scenarios by resolving synonymy of medical terms across different scenarios.

Semantic Interoperability: Much like terminological variations between health-care experts, it is quite likely that they also have orthogonal semantic models that characterize knowledge at different levels of abstraction, i.e., one concept is the specialization/generalization of the other. A medical ontology depicts a semantic parent-child relationship between concepts which can form the basis for matching two concepts; for instance, the concepts orthopnea and hypercapnia can be deemed conceptually equivalent since, orthopnea is the parent of dyspnea which is the parent of hypercapnia. The use of a medical ontology provides a vehicle for medical knowledge standardization that allows the multiple semantic models of health-care experts to coexist within a single framework.

For our medical ontology requirements, we use the National Library of Medicine’s Unified Medical Language System (UMLS) that includes a metathesaurus, which is a compilation of medical terms drawn from over 30 controlled vocabularies (such as MeSH, SNOMED, CPM93, CPT98, and ICD-10), and a Semantic Net which contains the semantic types used to categorize Meta concepts and the semantic relations to connect them. As such, the UMLS has served as a unifying paradigm by providing appropriate links among equivalent entities that are used in different contexts or for different purposes [40].

V. TACIT KNOWLEDGE ACQUISITION IN ACTION: INFO-STRUCTURE AND PROCESS

A. TKAI

In line with our multistep tacit knowledge acquisition methodology, we present a KM info-structure—called TKAI—that automates the overall process of tacit knowledge acquisition and its operationalization within an enterprise context (see Fig. 2).

Within TKAI, the central tool is a Scenario Composer that models the various roles of our scenario construct, by systematically presenting to the health-care expert/user a series of electronic forms whose attributes correspond to the components of a scenario. The scenario composer provides users the functionality to 1) record the routine experiential knowledge of an expert with respect to the structure of the scenario construct, i.e., to create an explicated-scenario; 2) modify an a priori created explicated-scenario to create a tacit knowledge explicating challenge for the health-care expert, i.e., a challenge-scenario; and 3) record the health-care expert’s tacit knowledge-based responses to the challenge-scenario, leading to the generation of a solved-challenge-scenario. The scenario composer is based on the client-server model, which means that health-care experts can individually and remotely interact with it from their workplace/home. Furthermore, while solving a given challenge-scenario, each health-care expert views only his/her individualized workspace which comprises electronic forms that he/she has completed or have in progress. This ensures that a health-care expert works in private and at a pace convenient to him/her. The UMLS-based medical ontology is built into the electronic forms representing the various types of scenarios depending on the different stages of tacit knowledge acquisition. The different scenario constructs are represented using XML, where the DTD tags correspond to the attributes of the different scenario constructs. The different scenarios are stored in a scenario-base, which maintains an ontological classification of knowledge.

B. Tacit Knowledge Acquisition Process

The systematic acquisition of tacit health-care knowledge from domain experts takes place in three stages (shown in Fig. 3) and is orchestrated by a tacit knowledge acquisition committee (TKAC)—a core group of health-care practitioners who identify a health-care topic/issue/situation for which the complex tacit knowledge of relevant health-care experts is deemed important.

In brief, TKAC identifies either a group of related health-care experts or just an individual health-care expert if the topic is too focused. From our experiences, we concluded that it is best to approach health-care experts who work within the same institution, who are familiar with the overall process of tacit knowledge acquisition, who understand the time commitments, and who are comfortable with sharing their tacit knowledge amongst a known set of practitioners for a predefined purpose. Our policy is that, if multiple health-care experts are working on a similar topic, then we do not provide simultaneous access to the work of other experts (both work in progress and completed work) until all the experts have completed and submitted their final solved-challenge-scenario. The idea is to ensure that the response of an expert is not influenced by the opinions of his/her peers, though at a later knowledge crystallization stage we do determine the degree of similarity between different opinions.

[Image: TKAI]
**Stage 1—Acquisition of Explicated-Scenarios:** Explicated-scenarios reflect actual situations that are routinely encountered and solved by health-care experts. There are two possibilities for acquiring the explicated-scenario: 1) through health-care experts and 2) through TKAC. In the former case, the meta-scenario details, i.e., scenario classification and scenario description, are concluded by TKAC, and subsequently the health-care expert is required to complete the remaining components of the explicated-scenario. The scenario composer is designed to present electronic forms representing the scenario-construct, episode, event and parameter-list components of the explicated-scenario. The scenario composer guides the user by presenting forms in a sequence that conform to the hierarchical scenario structure (as shown in Fig. 1), however, users are able to go back to view and edit their responses and go forward to view what information would be required later. In interacting with the scenario composer, health-care experts/professionals provide values to the various scenario-defining attributes, for instance, Definition of Trigger Event, Episodes, Events, Concluding Event, Keywords, etc.

**Stage 2—Derivation of Challenge-Scenarios:** Challenge-scenarios are derived from existing explicated-scenarios by modifying the values of certain attributes to create an atypical or novel clinical situation. Given a selection of explicated-scenarios stored in the scenario base, the TKAC selects a scenario and identifies the relevant expert(s) who will be asked to solve the challenge. Once an agreement is made with the selected expert(s), they are assigned the challenge-scenario which they can access from the TKAI server with user authentication assigned by the TKAC.

The challenge-scenario is created by the TKAC by 1) changing the parameters of the original explicated-scenario and 2) by introducing specific points of knowledge explication (POKE) within the explicated-scenario to prompt health-care experts to record their solution strategy from that point onwards. A challenge is created by introducing a POKE after the event type obstacle or normative; the follow-up event type after a POKE is usually an action and it is here that the expert’s tacit knowledge that is explicated in response to the obstacle event (i.e., the POKE) will be recorded. The portion of the scenario from the trigger event to the POKE is deemed as the challenge. Since an explicated-scenario may comprise multiple obstacle or normative events, we can derive multiple challenges by placing multiple POKEs within the explicated-scenario and, hence, create multiple challenges.

**Stage 3—Acquisition of Solved-Challenge-Scenarios:** In the last stage, the health-care expert responds to the given challenge-scenario by 1) defining new episodes and events; 2) suggesting the sequence of episodes and events; and 3) providing values to the various scenario defining attributes. The scenario composer presents each challenge to the health-care experts together with electronic forms to record their responses.

The expert’s responses are normalized to MeSH compliant vocabulary; the scenario composer automatically presents conceptual and terminological synonyms for a noncompliant term to the health-care expert who can either choose the best representative synonym or ask to retain the specialized term used by him/her.

Finally, we argue that a health-care expert’s tacit knowledge is captured within the set of action events that manifest his/her problem-solving decisions and actions. The completed solved-challenge-scenario is retained in the scenario-base.

**C. Using TKAI in a Health-Care Setting**

A project is currently underway in the pediatric emergency department at IWK Hospital (Halifax, Canada) that leverages the TKAI process to support an orientation program for nurses advancing to the role of triage nurse in the emergency department. The triage nurse is the first stop in any emergency department and her task is to complete a rapid advanced assessment of each patient entering the department and based on this assessment assign the child to one of five categories in the Canadian Triage and Acuity Scale (CTAS). The CTAS tool is intended to prioritize patient care requirements and to ensure that the "sickest" patients are attended first [41]. Expertise in this instance is enhanced through exposure to a large repertoire of cases in which problem solving can be exercised [42]. Scenario-mediated problem specification and solving is used to both introspect and acquire the tacit knowledge of the triage nurse. The idea is that TKAI will guide the development and validation of “problem-specific” scenarios for use in simulations for the orientation and training process. For instance, we present a sequence of scenarios—the initial explicated-scenario describes a child presenting in the emergency department with an uncom-
Fig. 4. Script of explicated-scenario with possible POKE.

Fig. 5. Challenge-scenario showing the challenge part, where italics bold shows added atypical aspects. The action part records the expert’s response.

We believe that such scenario-based simulations using TKAI will allow the novice nurse to observe the impact of their choices without the outcomes having any impact on the patient or the real operation of the emergency department. TKAI has been fully implemented and the components of TKAI have been tested with success in controlled environments. In a real-life setting, i.e., the emergency department, the impact of TKAI has not yet been evaluated. At this stage, our concerns are with the incorporation and potential usage of TKAI by nurses. Although we have received positive responses from the participants, we anticipate that it will take at least a year for us to gather enough data and observations to perform a systematic evaluation.

VI. SCENARIO-BASED KNOWLEDGE CRYSTALLIZATION

Knowledge crystallization is an integral process in the knowledge creation cycle, whereby, domain experts in an enterprise jointly validate the interoperability, quality, and applicability of the acquired tacit knowledge. In Nonaka’s terms [25], this is the social-oriented view of knowledge creation where users can express their support for a particular knowledge or concept. The notion of knowledge crystallization is best understood in attempts to integrate knowledge acquired from multiple domain experts in order to create “consensual knowledge.” To meet this end, Shaw [26] presented an excellent four-quadrant model of knowledge integration which formed the basis for later methods that involved, choosing one consensual source to focus on (avoidance) [43], replacing conflicting knowledge (abandonment), a priori alignment using negotiation strategies, comparison of knowledge graphs, constructive modeling [18], semantic
networks of expertise [44], and allowing domain experts to build their own knowledge bases and subsequently use a reconciliation process to synthesize the acquired knowledge [31]. Our knowledge crystallization approach is in concert with Richard’s [31]; we allow domain experts to develop and populate their own scenarios which are subsequently crystallized through a collaborative critiquing strategy involving both domain experts and content similarity measures using information retrieval methods and analogical reasoning for knowledge repairing.

We have devised a novel scenario-based knowledge crystallization strategy that leads to the formation of epistemologically sound knowledge crystals derived via the systematic synthesis of an ensemble of knowledge items based on their conceptual similarity and/or prespecified business rules. In this way, we are able to not only verify the goodness of knowledge contained within individual scenario components, but also establish a network of related scenario components which can be jointly used to solve complex tasks, i.e., using the health-care episodes from different scenarios to solve divergent aspects of a complex problem. Our knowledge crystallization strategy models the processes of crystallization in chemistry and annealing in thermodynamics, i.e., solidifying and internally arranging atoms/molecules according to predefined criteria to form stronger structures or crystals.

A. Knowledge Nucleation

The knowledge nucleation subprocess involves the nucleation (i.e., collection) of similar knowledge items. This is achieved via the creation of knowledge seeds and their release into the scenario-base as a prelude to the follow-up knowledge growth subprocess. A knowledge seed is a specification of the criterion for establishing similarity between different scenarios, serving both as a catalyst for the formation of a knowledge crystal and also the nuclei around which the knowledge crystal is to be created. The TKAC designs the knowledge seed. Practically, there are three types of knowledge seeds: 1) structural knowledge seed synthesizes multiple scenario items on the basis of structural equivalence; 2) contextual knowledge seed synthesizes multiple scenario items on the basis of contextual equivalence; and 3) hybrid knowledge seed synthesizes multiple scenario items on the basis of both structural and contextual equivalence.

B. Knowledge Growth

The knowledge growth subprocess involves the automated attraction of scenarios toward the knowledge seed, the so-called nuclei of the knowledge crystal, based on how well the scenarios in question match the predefined knowledge seeds. Amalgamation of multiple scenario-items leads to the formation of a knowledge crystal. In Fig. 7, we illustrate the knowledge crystallization process where two crystals are formed with two different knowledge seeds. The scenario with contexts “1, 2” and keywords “C, D” is shown linking with the crystal on the left as the scenario’s contexts and keywords are subsets of those of the knowledge seed. Also shown are two free scenarios that exist independently as there are no crystals with which they can attach.

C. Knowledge Crystallization Strategy

Below we present the tenets of our knowledge crystallization strategy (illustrated in Fig. 8).

**Step 1: Voting of events, episodes, and scenario-constructs**: The knowledge growth subprocess relies on the measurement of the scenario components’ quality.
To begin with, a group of experts screen the scenario components on the basis of their user-acceptance, correctness, appropriateness, and applicability. This is achieved through a voting process on the scenario’s events, episodes, and the scenario-construct.

**Step 2: Calculation of Event, Episode, and Scenario Crystallization Factors:** The votes cast by experts lead to the calculation of an individual scenario crystallization factor (SCF)—analogous to the energy-level in an annealing process—for each event, episode, and scenario-construct. SCF is a measure determining the crystallization ability, such that scenarios with an SCF exceeding the crystallization threshold are considered as “knowledge crystal candidates.”

**Step 3: Knowledge Nucleation:** In this step, knowledge seeds are defined and released into the scenario-base to serve as the nuclei for the attraction of scenarios in a knowledge crystal-forming paradigm. Note that during a single nucleation exercise, multiple knowledge seeds can be released.

**Step 4: Calculation of Scenario Attraction Factor:** Knowledge crystal candidates are checked to see how well their context, keywords, and structure match with the knowledge seed. A similarity-based scenario attraction factor (SAF) determines how “crystallizable” each scenario is with a given knowledge seed. Note that each scenario will have different SAF for different knowledge seeds.

**Step 5: Knowledge Attraction:** In this final step, scenarios with an SAF exceeding the predetermined attraction threshold are attracted or bound to their respective knowledge seeds to form knowledge crystals. This step simulates growth in the chemical crystallization paradigm. Note that it is possible for a scenario to be part of different knowledge crystals if the scenario’s SAF for the different knowledge seeds exceed the attraction threshold.
traction threshold. It may be noted that scenarios (and their constituents) are mutually exclusive and, hence, do not lose their original identity due to crystallization. Rather, they contribute toward the formation of multiple knowledge crystals as and when the opportunity arises. In this regard, the crystallized knowledge is a more consolidated, yet separate, entity.

VII. CONCLUDING REMARKS: THE WAY FORWARD

For all practical purposes, health-care knowledge needs to be recognized as a vital organizational capital, operational resource, and its management as a strategic policy. With a fair degree of agreement amongst health-care practitioners on the efficacy of incorporating KM strategies and applications, there is a premium in setting an overall agenda for KM in health care which should reflect initiatives to 1) capture and representation of all possible modalities of health-care knowledge existent within the health-care enterprise; 2) sharing and distribution of the right health-care knowledge at the right time to the right person; and 3) the operationalization of available medical knowledge to improve health-care awareness, education, delivery, services, practices, policy, and administration. We suggest that any health-care KM strategy should involve an active interplay between both explicit and tacit knowledge resources. From a practitioner’s perspective, the use of a particular knowledge modality is largely determined by the perceived knowledge consumption needs and the knowledge gaps with respect to the severity of the task at hand. For instance, routine clinical cases are more likely to be resolved using evidence derived from explicit knowledge within published medical literature, whereas, complex clinical cases with a higher degree of acuity may demand the kind of intuitive judgment that is exercised by experts and is encapsulated within tacit modalities of the acquired health-care knowledge. Notwithstanding the distinctive usage of both explicit and tacit health-care knowledge, it is realistic to pursue a KM strategy that accords proportional importance and resources to provide explicit knowledge and pursue tacit knowledge in accordance to an audit of the existing knowledge resources versus the knowledge demands within the health-care enterprise.

Health-care knowledge is an asset of the parent enterprise. But, to maintain the value of this asset, it is imperative to promote and practice an enterprise-wide learning culture, i.e., putting into place effective (tacit) knowledge creation...
mechanisms. We believe that our tacit knowledge acquisition strategy, together with its computational implementation, provides a possible technical solution to forging a knowledge elicitation, collection, and dissemination culture. Yet, we feel that the success of any tacit knowledge program may need to take into account certain human and operational factors such as: 1) the motivation for domain experts to share their knowledge—maybe certain knowledge sharing incentives may serve as a motivation; 2) intellectual ownership needs to be addressed in advance as domain experts may have reservations toward disclosing their tacit knowledge due to the fear of losing their intellectual competitive edge, value, and utility; and 3) the availability of a critical-mass of knowledge to enable the efficacious application of knowledge acquisition techniques. The work reported here demonstrates a viable methodology for accessing the tacit knowledge of health-care experts, and the accompanying KM tools provide the technical framework to practically achieve the same. A critical evaluation of the approach and its operational constraints are yet to be determined, as this is contingent on the establishment of a learning culture. We are working on achieving the same by demonstrating localized and individual knowledge acquisition exercises with collaborating health-care experts.

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