Formal Ontology in Information Systems
M. Donnelly and G. Guizzardi (Eds.)
IOS Press, 2012

doi:10.3233/978-1-61499-084-0-89

An Ontology for Skill and Competency Management

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Abstract. To stay competitive within the market, organizations need to understand the skills and competencies of their human resources in order to best utilize them. This paper focuses on the problem of modeling human resources in a dynamic environment, and presents a formal ontology for representing, inferring, and validating skills and competencies over time.

Keywords. expert profiling, skills and competency management, skills ontology

Introduction

In today's dynamic environment, many companies have transformed their traditionally hierarchical organizations to flatter and flexible structures based around teams (Kodama, 2007) in order to better engage with multiple and changing clients. In such environment, proper and flexible human resources management approaches for more effective resource allocation and team staffing are of utmost importance. Companies need to accurately understand the skills and competencies of their human resources to better utilize them and more effectively respond to internal and external demands for skills and competencies.

In order to facilitate the management of available human resources' skills and competencies, international specifications for competency description (e.g., IEEE RCD, 2004; HR-XML, 2006), and totally or partially automated techniques for construction of expert profiles (Stankovic et al., 2010; Yimam-Seid and Kobsa, 2003) have been proposed in recent years. A careful examination of the related literature (Section 1), however, suggests that important issues regarding modeling and evaluating human resources over time have not so far received much attention. In particular, previous works have not (completely) answered the following questions: what are the criteria for determining whether an individual actually possesses a skill at a level of proficiency, what are the different types and sources of information that can be used to infer and validate skill statements, what is the degree of belief in an individual's skills and competencies, and how should dishonest behaviors in exchanging skills and competency information about oneself or others be detected and verified. In order to respond to these shortcomings, one needs to focus on how skills and competencies should be represented and evaluated, how

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skill statements about an individual should be modeled, and how trust and belief in skill statements and the sources of information should be represented and modified. To this end, this paper presents a formal ontology for modeling human resources in a dynamic environment. The ontology specifies skills at particular levels of proficiency as what enable the performance of activities, and skill statements as properties that have degrees of belief associated with them and that can change over time.

The remainder of this paper is organized as follows: A presentation of motivating scenarios is followed by a brief discussion of related work. The ontology for representing and measuring skills and competencies and our approach for profiling experts over time are presented. Finally, the paper is concluded with a discussion of areas of future work.

1. Motivating Scenarios

There are many different use cases that motivate and illustrate the need for accurately profiling human resources over time. These range from locating and matching individuals and requirements, to composing teams, conducting gap analysis, and human resource development, and include activities such as queries about individual human resources and teams of experts, development history, and believability of a certain piece of information. In the following we consider two use case scenarios.

Activity Assignment: Suppose that Mary is a project manager working at an IT consulting company, responsible for selecting individuals to work on specific projects for industry clients. To do her job well, Mary needs to know the competencies of available human resources to match them with the existing requirements, and determine if the company needs to hire a new employee or outsource the project. It is often the case, however, that this information is either not explicitly available, is unreliable, or out-of-date. As such, she needs to gather skills and competency related information from different sources and judge whether they are relevant to the requirements. In order to identify the best person for the job, Mary also considers previous projects each potential candidate worked on and evaluates their performance and the quality of produced outcomes related to the required skills and competencies. To this end, she considers performance appraisals, where the employees are reviewed by their immediate managers, and 360-degree reviews, where a combination of self, supervisor, and peer ratings are considered. This process can be very frustrating since she has to base her decisions on inaccurate, incomplete, or out-of-date data about employees' competencies gathered from different sources. The same process also applies, more or less, to the problem of outsourcing work to other companies or a crowd where a set of experts processes assigned activities on demand.

Human Resource Recruitment: Assume that for one of the projects, Mary needs to hire a new employee. As such, she posts a job advertisement on the company website and asks all potential candidates to submit their curriculum vita and provide references. Once an applicant pool has been formed, Mary grades candidates according to specific criteria and degree of match to the requirements and considers their references. The difficulty in this stage is in matching and relating individual's declared skills and competencies, acquired and assessed skills and competencies as suggested by their credentials and certificates, and applied skills as suggested by their previous work experience to job requirements. For example, same position titles in two different companies may refer to different responsibilities and set of skills. In verifying individual's competencies, references may also be dishonest in exchanging information or not sufficiently competent or consistent in providing accurate evaluations. Once Mary selects the viable candidates, she asks them to attend an interview. The goal of the interview is to assess the level of proficiency for some of the required skills and competencies from observable performance.

2. Background and Related Work

In order to facilitate the interchange of competency descriptions between systems, international specifications for competency description such as the Reusable Definition of Competency or Educational Objective (IMS RDCEO, 2002), the IEEE Reusable Competency Definitions (IEEE RCD, 2004), and the HR-XML Competencies (HR-XML, 2006) have been proposed in recent years. These specification provide: (a) identification of the competence, (b) title of the competence, (c) description of the competence, (d) definition of the competence, (e) taxonomy of the competence, (f) personal information (Sampson, 2009). The IEEE RCD defines competency as "any aspect of competence, such as knowledge, skill, attitude, ability, or learning objective" that can be described in a context of learning, education or training. This definition ignores two important dimensions related to competence definition, namely, context and proficiency level (De Coi et al., 2007; Prins et al., 2008; Sampson, 2009). The HR-XML consortium attempts to extend the previous definition and defines competency as "a specific, identifiable, definable, and measurable knowledge, skill, ability and/or other deployment-related characteristic (e.g. attitude, behavior, physical ability) which a human resource may possess and which is necessary for, or material to, the performance of an activity within a specific business context." This definition is more appealing for its emphasis on measurable characteristics and the connection between competencies and activity performance. However, context is captured only implicitly and is still excluded from the schema (Prins et al., 2008). In addition, although elements for measurable evidence and measurable weights and importance levels are added to the schema, there are no clear semantics of what a value actually means nor are there restrictions on the values of these scales.

Researchers and organizations interested in expert locator systems have also considered different methods of representing skills and expertise of individuals. To this end, non-ontology-based approaches use databases as skill repositories in which user profiles are expressed by data structures or weighted vectors of terms (Colucci et al., 2003). In recent years, enterprise social networking has also been considered as a different approach to employee profiles. The resulting profiles, however, lack commitment by the organization, especially with respect to the vocabulary used. Another limitation is the lack of mechanisms for reasoning about individual's skills and proficiency and inferring skills that were not explicitly mentioned. To address these limitations, ontology-based approaches have been proposed. Previous works in this regard have primarily focused on building and maintaining skill catalogs in a domain of interest. In the KOWIEN project, research to build up and maintain a detailed ontology-based skill catalog is carried out (Dittmann, 2003). (Mochol et al., 2007) and (Gomez-Perez et al., 2007) develop HR ontologies by integrating existing standards and classifications for supporting the recruitment process. (Biesalski and Abecker, 2006) discusses the integration of HR processes with ontologies in a project at DaimlerChrysler AG. The results are modeled in a competence catalog that represents knowledge over all areas of production, management, and administration. (Schmidt and Kunzmann, 2006) and (Dorn et al., 2007) describe ontologies that integrate concepts from skill management and learning. (Aleman-Meza et al., 2007) describes the integration of existing vocabularies for expertise finding. (Colucci et al., 2003) uses description logic inferences for finding the best individual for a given task, based on profiles sharing a common ontology.

For constructing expert profiles, different sources of information have been used in previous works (Stankovic et al., 2010; Yimam-Seid and Kobsa, 2003). Skill statements can be declared by individuals about themselves or by others, and/or can be derived from 1) activities performed by the individual either online or offline including enrolment in learning activities, experiences related to the workplace, generating content both within the organization and on the Web, and question-answering in online forums; 2) recommendations and “wisdom of the crowd”; and 3) assessments in the form of various tests or evaluation in the form of 360 reviews or performance appraisal. It is important to recognize that these sources and the information they provide vary in degrees of trust and validity, respectively. For example, self declarations of skills can be incorrect, inaccurate, or insufficient. People may not be aware of having a certain skill at a level of proficiency or they may lie on their descriptions of what they contributed or accomplished. Using automatic creation of profiles based on user generated content, we need to consider that some of the individuals’ expertise may not be represented in their digital trace. In addition, it is not always easy to relate the author of a particular content with the domains of expertise that it identifies (Stankovic et al., 2010). Furthermore, although generated content may indicate expertise in a field of interest, it is very difficult to determine the proficiency level of the individual. It is also important to note that competencies are dynamic and an individual’s knowledge and experience change over time.

The focus on the syntax of the data exchange and the lack of adequate semantic underpinning (Jarrar et al., 2007) have restricted the usefulness of the standards and representations presented in this section. For example, it is not clear what can be expected of someone who possess a skill, how an individual should be evaluated against a skill, how different sources of information can be used to infer and validate skills and competencies, and how the changing nature of individual’s skills should be represented. As such, it is necessary to extend these specifications. In the remainder of this paper, we present an ontology to address these issues and focus on measurable skills and use skill and competency interchangeably.

3. Methodology

For the development of the ontology, we use the ontology design and evaluation methodology of (Gruninger and Fox, 1995). We specify the ontology in four steps: (1) provide a motivating scenario; (2) define informal questions to capture the scenario (i.e. scope); (3) define the terminology (i.e. predicates); and (4) define the axioms (i.e. semantics).

3.1. Informal Competency Questions

The key concepts abstracted from the scenarios described in Section 1 are the following:

C-1 There must be a systematic way of identifying skill requirements for successful performance of the required activities and determining whether an individual possesses a particular skill.

C-2 The ability of individuals to perform the activities enabled by a particular skill may vary. There must be a systematic way of assessing activity performance and evaluating the quality of outcomes produced.

C-3 Different sources and the information they provide about individual's skills and competencies vary in degrees of trust and validity, respectively. Statements about individual's skills and competencies must be updated only based on credible new information.

C-4 Individuals are not always honest in exchanging information about themselves or others, and may engage in collusive behaviors with others.

In this paper, we focus on C-1 to C-3. To elaborate C-1 and C-2, we need to focus on the connection between skills and activity performance and the relation between skills. A skill suggests the possibility of performing an activity. The following are informal competency questions about skills:

Q-1 What skills are needed to perform the required activities?

Q-2 What is the relation between two skills? Does having one imply having the other?

Not everyone possessing a skill, however, can perform all the activities it enables, thus, it is also necessary to specify the level of proficiency that is required. Proficiency in a skill may depend on different factors such as familiarity with the subject, the span of the activities that one can perform, how much experience one has in performing the activities, etc. Different measurement scales exist for evaluating an individual against a skill. Rating scales, consisting of a numeric scale with a brief description of each number's corresponding meaning, are the most widely used. Their disadvantage, however, lies in their inconsistent interpretations across users of a scale (Moyer, 2001). Domain-specific metrics, such as number of errors found in a code for a programmer or number of failed projects for a contractor, are other metrics that can be used. The following are some questions for representing and measuring proficiency:

Q-3 What are the proficiency reference levels for evaluation against a skill?

Q-4 What are the criteria for determining whether an individual possesses a skill at a level of proficiency?

- Q-4.1 What are the activities that the individual should be able to perform?
- Q-4.2 What are the attributes related to that skill that can be measured?
- Q-4.3 What is the unit of measurement for an attribute related to a skill?
- Q-4.4 What ought to be the measured value to be ranked at a level of proficiency?

In order to elaborate C-3, we take into account the different sources of information that can be used to infer and validate individual's skills as mentioned in Section 2. The following are some questions about skill statements about individuals:

Q-5 What evidence suggests that an individual has a skill at a level of proficiency?

Q-6 Should a source be trusted with respect to the information it is providing?

Q-7 Does new information confirm what is already believed about an individual's skill?

Q-8 Or, should belief in a skill statement be updated based on new information?

Q-9 What are the skill statements about an individual?

- Q-9.1 What are the *demonstrated* skills of an individual at a given time point?

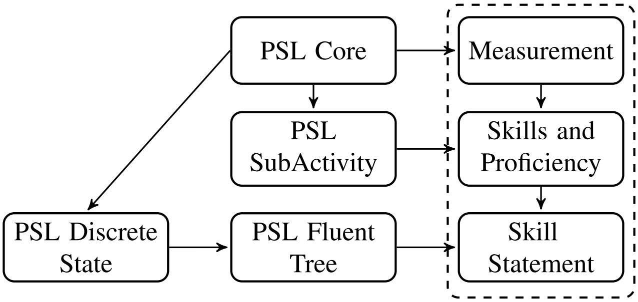

Figure 1. Modules of the ontology.

Q-9.2 What are the suggested skills of an individual at a given time point, i.e. those skills that have not been observed but the individual may possess?

Q-9.3 What are the *refuted* skills of an individual at a given time point, i.e. those skills that the individual does not have?

3.2. Approach Outline

We use first-order logic (FOL) as the basis of our representation because of its expressive and declarative capability. In particular, our ontology is an extension of the Process Specification Language (PSL) (Gruninger and Menzel, 2003) which provides predicates and axioms that enable representation of and reasoning about fluents, activities, activity-occurrences, and values of fluents before and after activity-occurrences. The Activity-Occurrence Extension of PSL defines relations that allow the description of how activity-occurrences relate to one another with respect to the time at which they start and end; and the State Extension introduces the concept of state (before an activity-occurrence) and post-state (after an activity-occurrence). Figure 1 illustrates the overall relationship between the modules of our ontology and the modules used from PSL. Table 1 presents

Table 1. PSL predicates used in this paper (Schlenoff et al., 2000)

Predicate	Informal Definition
$activity(A)$	A class or type of action. Intuitively, activities can be considered to be reusable behaviors within the domain.
$activity\text{-}occurrence(O)$	An event or action that takes place at a specific place and time. An instance or occurrence of an activity.
$object(X)$	Anything that is not a timepoint, nor an activity, nor an activity-occurrence.
$state(F)$	Intuitively, states represent properties and relationships in the domain that can change as the result of the occurrence of activities.
$occurrence\text{-}of(O,A)$	The activity-occurrence is a particular occurrence of the given activity.
$subactivity(A_1,A_2)$	This relation defines a partial ordering over the set of activities with respect to aggregation and decomposition.
$participates\text{-}in(P,O)$	P plays some role in the activity-occurrence.
$holds(F,O)$	The state (fluent) F is true after the activity-occurrence O.
$prior(F,O)$	The state (fluent) F is true before the activity-occurrence O.
$achieved(F,O)$	A state is achieved by the activity-occurrence if and only if it does not hold before the occurrence, but it does hold after the occurrence.

the PSL predicates used in this paper. Note that in the formal PSL ontology, the notion of activity is a basic construct, which corresponds intuitively to a kind of activity. An activity may have associated occurrences, which correspond to individual instances or executions (from start to finish) of the activity.

4. Representing and Measuring Skills and Competencies

A skill at a particular level of proficiency enables a set of activities:

S-1: $\forall s\ skill(s) \equiv (\exists a,l,f\ activity(a) \wedge proficiency\text{-}level(l) \wedge knowledge\text{-}field(f) \wedge enables(s,l,a) \wedge in\text{-}field(s,f))$.

The *in-field* predicate relates a particular skill to the *knowledge-field* that it belongs to, and is later used for asserting skill statements about an individual using information from sources that are trusted in the related knowledge field. Level of proficiency refers to the ranking of the ability of an individual to perform the activities enabled by a particular skill. We consider proficiency as determined by the successful performance of activities the skill enables. We also consider attributes related to that skill that can be measured. For example, recency, years of experience, and average number of errors found are some of the attributes that can be used to measure proficiency in programming. This provides the means for reducing fluctuations in competency measurement. We define the ordering between *proficiency-levels* referring to a skill by the *dominates* relation which is transitive and antisymmetric.

S-2: $\forall s,l_1,l_2,a_1,a_2\ (enables(s,l_1,a_1) \wedge enables(s,l_2,a_2) \supset (l_1 = l_2) \vee dominates(l_1,l_2) \vee dominates(l_2,l_1))$.

If a skill enables an activity at a particular level of proficiency, then it also enables that activity at higher levels of proficiency (i.e. an individual having the skill at a level of proficiency can perform all the activities associated with the skill at lower levels).

S-3: $\forall s,l_1,a\ enables(s,l_1,a) \supset (\forall l_2\ (dominates(l_2,l_1) \supset enables(s,l_2,a)))$.

As mentioned earlier, in addition to the span of activities that one can perform, attributes related to a particular skill that can be measured (*measured-attribute*) are also useful for determining the level of proficiency. These attributes are input to the model (primitive types), and can be categorical or numeric. Each *measured-attribute* takes up values from a specification set (*has-spec*) which is either defined by its elements and an ordering between the elements, or over an interval. All measured attributes must have a unique specification set and a unit of measurement. For brevity, relations, functions, and axioms related to non-empty sets and intervals are omitted (in the following we use *lesser* and *lesserEq* to compare values of sets or intervals when needed).

P-1: $\forall m\ measured\_attribute(m) \supset (\exists sp,u\ (specification\_set(sp) \wedge has\_spec(m,sp) \wedge measurement\text{-}unit(u) \wedge has\text{-}unit(m,u)))$.

P-2: $\forall m,sp_1,sp_2\ ((has\text{-}spec(m,sp_1) \wedge has\text{-}spec(m,sp_2)) \supset (sp_1 = sp_2))$.

The required value of a particular *measured-attribute* *m* related to a skill *s* is identified for different levels of proficiency *l* using *requires-value(s, l, m, x)*, where *x* is the required value. The required value for an attribute at a level of proficiency is unique and must be an element of its specification set:

S-4: $\forall s,l,m,x_1\ requires\text{-}value(s,l,m,x_1) \wedge requires\text{-}value(s,l,m,x_2) \supset (x_1 = x_2)$.

S-5: $\forall s,l,m,x\ requires\text{-}value(s,l,m,x) \supset \exists sp\ has\text{-}spec(m,sp) \wedge$

$(set\text{-}memeber(x,sp) \vee (\exists u,w\ (min\text{-}value(sp) = u \wedge max\text{-}value(sp) = w \wedge$
$lesser(u,x) \wedge lesser(x,w)))).$

If a value is required for a measured attribute at a level of proficiency, the same or a higher value is required for higher levels:

S-6: $\forall s,l_1,m,x_1\ requires\text{-}value(s,l_1,m,x_1) \supset (\forall l_2\ (dominates(l_2,l_1) \supset$
$(\exists x_2\ requires\text{-}value(s,l_2,m,x_2) \wedge (x_1 = x_2 \vee lesser(x_1,x_2))))).$

In many domains of interest, it is also possible to assume a taxonomy of skills with specialization of skills defined using the *subskill-of* relation. This relation is reflexive, transitive, and asymmetric. A skill enables all the activities its super skill enables at the same or higher level of proficiency, and inherits the required values of its parent for a measured attribute, if it does not explicitly have a required value assigned.

S-7: $\forall s_1,s_2,l,a\ subskill\text{-}of(s_1,s_2) \wedge s_1 \neq s_2 \wedge enables(s_2,l,a) \supset$
$\exists l_2\ (enables(s_1,l_2,a) \wedge (dominates(l_2,l) \vee l_2 = l)).$

S-8: $\forall s_1,s_2,l,m,x\ subskill\text{-}of(s_1,s_2) \wedge s_1 \neq s_2 \wedge requires\_value(s_2,l,m,x) \wedge$
$\neg(\exists x_1\ requires\text{-}value(s_1,l,m,x_1)) \supset requires\_value(s_1,l,m,x).$

We also define the *related-to* relation between two skills indicating that they are highly related to each other in the domain of interest (i.e., having one usually implies having the other). For example, software development skills are *related-to* programming skills. Put formally, two skills are related if they enable the same activity, or if they enable different subactivities of the same activity:

S-9: $\forall s_1,s_2\ related\text{-}to(s_1,s_2) \equiv skill(s_1) \wedge skill(s_2) \wedge s_1 \neq s_2 \wedge (\exists a,l_1,l_2$
$((enables(s_1,l_1,a) \wedge enables(s_2,l_2,a)) \vee (\exists a_1,a_2\ (subactivity(a_1,a) \wedge$
$subactivity(a_2,a) \wedge enables(s_1,l_1,a_1) \wedge enables(s_2,l_2,a_2))))).$

The *related-to* relation is symmetric. Furthermore, a skill is related to the skills that its super skill is related to.

S-10: $\forall s_1,s_2\ related\text{-}to(s_1,s_2) \supset related\text{-}to(s_2,s_1).$

S-11: $\forall s_1,s_2,s_3\ subskill\text{-}of(s_1,s_2) \wedge s_1 \neq s_2 \wedge related\text{-}to(s_2,s_3) \wedge$
$s_1 \neq s_3 \supset related\text{-}to(s_1,s_3).$

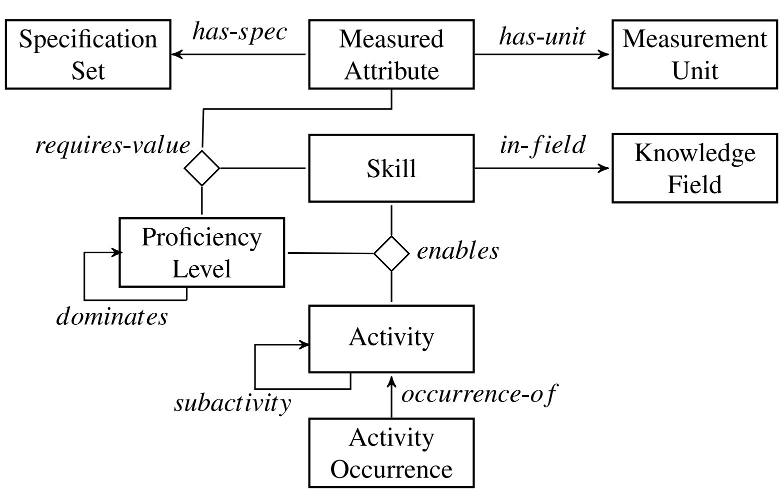

Figure 2. Concepts and their relations in the static representation

Figure 2 summarizes the overall relations between skills, proficiency levels, and activities. Using the terms described above, competency questions 1 to 4 of Section 3 are formally expressed. Next we focus on representing and inferring skill statements.

5. Skill Statements

The unit of skills information about the individual that we consider is a *skill statement* which states that "individual *p* has skill *s* at level of proficiency at least *l*." Each human resource will have a profile composed of a set of such skill statements. The degree to which we can believe a skill statement depends on the evidence that supports it and how it was changed over time. For example, in many organizations workflow management systems are used to track employees' daily activities. If it is recorded that an individual has performed all the activities which a skill enables at a level of proficiency, then we can be sure that the individual in fact has the skill. On the other hand, if the only support for a skill statement is self declaration, the credibility of the statement cannot be precisely determined. To take these factors into account, we define different states for skill statements (Table 2). These states are core to how the understanding of skills evolves. Starting with less than accurate information about the individual, skill statements can be suggested or refuted as information becomes available until they are demonstrated.

To see how skill evaluation changes over time, consider the simple example of Mary declaring that she is proficient in object-oriented programming. Since this is a self-declaration, we can only acknowledge that she possibly has the skill. However, if we know that she has previous experience as Java Developer which requires object-oriented programming at least at the proficient level and her former manager recommends her, we can infer that she probably has the skill. As more information becomes available on activities performed by Mary, proficiency is measured and it is noticed that she does not meet one of the required criteria for being proficient in object-oriented programming, thus, the skill statement is refuted. Nevertheless, Mary may have the skill at a lower level of proficiency. Thus, a statement referring to this skill at a lower level is added to the knowledgebase. Since she has performed all the activities required for this level, we can be sure that Mary in fact has the skill at the level.

Table 2. States of skill statements

Fluent	Definition
demonstrated(skill-statement(p, s, l))	Relational fluent. Agent *p* has demonstrated skill *s* at level of proficiency at least *l*.
probable(skill-statement(p, s, l))	Relational fluent. It is highly probable that agent *p* has skill *s* at level of proficiency at least *l*. Degree of belief *d* in *skill-statement(p, s, l)* is $\varepsilon \leq d < 1$.
possible(skill-statement(p, s, l))	Relational fluent. It is possible that agent *p* has skill *s* at level of proficiency at least *l*. Degree of belief *d* in *skill-statement(p, s, l)* is $0 < d < \varepsilon$.
refuted(skill-statement(p, s, l))	Relational fluent. Agent *p* does not have skill *s* at level of proficiency at least *l*.
asserted(skill-statement(p, s, l))	Relational fluent. *skill-statement(p, s, l)* is *demonstrated*, *probable*, or *possible*.

To this end, the states extension of PSL provides the concepts for relating states of the world to activity occurrences. At any point in time a skill statement can be in one and only one of four states: *demonstrated*, *probable*, *possible*, or *refuted* (Table 2). For inferring and validating skill statements, we also use an extension of the Organization Ontology (Fox et al. 1996) which formalizes the organizational structure. An organizational agent (or in short *agent*), for example, is an entity which plays one or more *roles* in the organization. Due to space limitation, not all axioms are included in this paper. If a skill statement at a particular level of proficiency is in any of the states except for *refuted*, then it is also in that state at lower levels if no information about lower level is available. On the other hand, if a skill statement is *refuted* at a level of proficiency, it is also *refuted* at higher levels. If a skill statement is in any of the states except for *refuted* then it is *asserted.*

$$\textbf{T-1}: \forall o,p,s,l\ holds(asserted(skill\text{-}statement(p,s,l)),o) \equiv (holds(demonstrated(skill\text{-}statement(p,s,l)),o) \lor holds(probable(skill\text{-}statement(p,s,l)),o) \lor holds(possible(skill\text{-}statement(p,s,l)),o)).$$

If the state of a skill statement changes, its previous state does not hold any longer. For example:

$$\textbf{T-2}: \forall o,p,s,l\ achieved(demonstrated(skill\text{-}statement(p,x,y)),o) \land prior(probable(skill\text{-}statement(p,s,l)),o) \supset \neg holds(probable(skill\text{-}statement(p,s,l)),o).$$

5.1. Skill Demonstration and Assessment

In order to verify whether individuals actually possess a skill, they are observed and/or assessed over time. If an individual is observed to perform all the activities which a skill enables at a level of proficiency and satisfies all the measured attributes, then it is the case that he or she has demonstrated that skill. Here, the order in which the activities have been performed is not important, and once all the enabled activities have been performed, the conclusion can be made. As such, we define the *enabling-suite* of a skill at a level of proficiency (i.e., the complex activity including all the activities enabled by that skill at this particular level) as:

$$\textbf{T-3}: \forall s,l,a\ enabling\text{-}suite(s,l,a) \equiv (\forall a_1\ enables(s,l,a_1) \supset subactivity(a_1,a)).$$

Using this definition, and considering the attributes that are measured and the actual measured values (*measurement-pt*) for an agent, we can write the above intuition as:

$$\textbf{T-4}: \forall o,p,s,l,a\ enabling\text{-}suite(s,l,a) \land (\forall a_1 subactivity(a_1,a) \supset (\exists o_1\ occurrence\text{-}of(o_1,a_1) \land participates\text{-}in(p,o_1)) \land leaf(o,a)) \land (\forall m,x\ requires\text{-}value(s,l,m,x) \supset (\exists x_1\ measurement\text{-}pt(p,m,x_1) \land lesserEq(x,x_1))) \supset achieved(demonstrated(skill\text{-}statement(p,s,l)),o).$$

where, *leaf(o, a)* is true when *o* is a leaf of the activity tree for *a* as defined in the formal PSL ontology. An activity tree consists of all possible sequences of atomic subactivity occurrences beginning from a root subactivity occurrence.

Observing individuals to determine all their skills can be costly. We can use the *subskill-of* and *related-to* relations to infer further knowledge about individuals' skills in the absence of explicit data. In addition, nowadays, many organizations are using different types of online and offline tests for inferring and validating individuals' skill set. Assessment tools are particularly useful before an individual is hired and for filtering the applicant pool. These tests are, of course, meaningful when reliable, i.e. they measure skills correctly. We define a *test* as an object which measures the level of proficiency in at least one skill. Here we do not consider tests which include performing activities related to a particular skill since those are covered by direct observations.

T-5: $\forall t\ test(t) \equiv (object(t) \wedge (\exists s,l\ measures\text{-}skill(t,s,l)))$.
T-6: $\forall t,s,l\ measures\text{-}skill(t,s,l) \supset test(t) \wedge skill(s) \wedge proficiency\text{-}level(l)$.

We define two activities related to tests: *passes* and *fails*. If an individual *passes* a test, then he or she probably has the skills which the test measures at a level of proficiency if they were not refuted prior to the test. Otherwise, the skill statements are refuted.

T-7: $\forall o,p,t\ occurrence\text{-}of(o,passes(p,t)) \supset (\forall s,l\ measures\text{-}skill(t,s,l) \wedge$
$\neg prior(demonstrated(skill\text{-}statement(p,s,l)),o) \wedge$
$\neg prior(refuted(skill\text{-}statement(p,s,l)),o) \supset$
$achieved(probable(skill\text{-}statement(p,s,l)),o))$.
T-8: $\forall o,p,t\ occurrence\text{-}of(o,fails(p,t)) \supset (\forall s,l\ measures\text{-}skill(t,s,l) \supset$
$achieved(refuted(skill\text{-}statement(p,s,l)),o))$.

5.2. Other Sources of Skill and Competency Information

As mentioned earlier, there are many different sources of information that can be used for constructing expert profiles (Figure 3). These sources and the information they provide vary in degrees of trust and validity, respectively. Consideration of all these sources is beyond the scope of this paper because of length restrictions. In what follows, we give an example of individuals as sources of skill and competency information.

Individuals can declare positive or negative skill statements about themselves or others. We represent this by activities *declares(r, p, s, l)*, indicating agent *r* has stated that agent *p* has skill *s* at level of proficiency at least *l*, and *declares-neg(r, p, s, l)*, indicating a negative declaration. Skill declarations by others are only credible when the individual is trusted in the related knowledge field. In this regard, we use the Ontology of (Huang and Fox, 2006; Huang, 2008). In particular, the *trusted-in* predicate is used which denotes that an agent (the organization in our case) trusts an information creator on producing

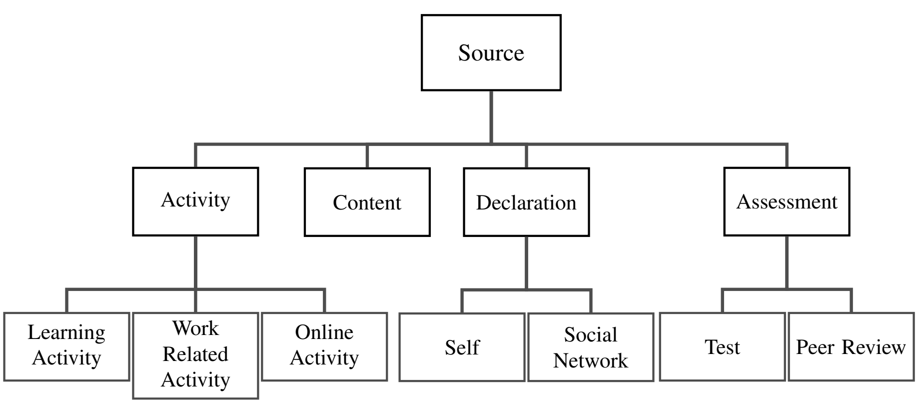

Figure 3. Sources of skill and competency information

information in a particular knowledge field at particular point in time. This predicate corresponds to an external process to make trust judgments. If the trust relationship holds, then process returns true, otherwise returns false. In this case, if the individual is trusted to make judgments about the skill, when the recommendation is positive, the state of a skill statement is set to *probable* (T-13), otherwise, it is set to *possible* (T-14).

T-9: $\forall o, r, p, x, l\ occurrence\text{-}of(o, declares(r, p, s, l)) \wedge r \neq p \wedge in\text{-}field(s, f) \wedge$
$trusted\text{-}in(r, f) \wedge \neg prior(demonstrated(skill\text{-}statement(p, s, l)), o) \wedge$
$\neg prior(refuted(skill\text{-}statement(p, s, l)), o) \supset$
$achieved(probable(skill\text{-}statement(p, s, l)), o).$

T-10: $\forall o, r, p, x, l\ occurrence\text{-}of(o, declares(r, p, s, l)) \wedge r \neq p \wedge in\text{-}field(s, f) \wedge$
$\neg trusted\text{-}in(r, f) \wedge \neg prior(asserted(skill\text{-}statement(p, s, l)), o) \wedge$
$\neg prior(refuted(skill\text{-}statement(p, s, l)), o) \supset$
$achieved(possible(skill\text{-}statement(p, s, l)), o).$

5.3. Competency Questions Revisited

The informal competency question 5 to 9 of Section 3 are presented in the following using the terminology developed in Section 5[2].

Q-5. What evidence suggests that individual P has skill S at level of proficiency L?

$achieved(asserted(skill\text{-}statement(P, S, L)), o) \wedge participates\text{-}in(P, o).$

Q-6. Should a source X be trusted with respect to information about skill S?

Example 1: $\exists f\ trusted\text{-}in(X, f) \wedge in\text{-}field(S, f).$
Example 2: $\exists l\ measures\text{-}skill(X, S, l).$

Q-7. Does new information confirm what is already believed about an individual P's skill S at level L?

$\exists o, a\ occurrence\text{-}of(o, a) \wedge ((\exists t, l\ a = passes(P, t) \wedge measures\text{-}skill(t, S, l)) \vee$
$(\exists r, l\ a = declares(r, P, S, l)) \vee ...) \wedge prior(asserted(skill\text{-}statement(P, S, L)), o).$

$\exists o, a\ occurrence\text{-}of(o, a) \wedge ((\exists t, l\ a = fails(P, t) \wedge measures\text{-}skill(t, S, l)) \vee (\exists r, l$
$a = declares\text{-}neg(r, P, S, l)) \vee ...) \wedge prior(refuted(skill\text{-}statement(P, S, L)), o).$

Q-8. Or, should belief in a skill statement be updated based on new information?

$\exists o, a\ occurrence\text{-}of(o, a) \wedge ((\exists t, l\ a = passes(P, t) \wedge measures\text{-}skill(t, S, l)) \vee$
$(\exists r, l\ a = declares(r, P, S, l)) \vee ...) \wedge prior(refuted(skill\text{-}statement(P, S, L)), o).$

$\exists o, a\ occurrence\text{-}of(o, a) \wedge ((\exists t, l\ a = fails(P, t) \wedge measures\text{-}skill(t, S, l)) \vee (\exists r, l$
$a = declares\text{-}neg(r, P, S, l)) \vee ...) \wedge prior(asserted(skill\text{-}statement(P, S, L)), o).$

Q-9.1. What are the *demonstrated* skills of individual P at given timepoint T?

$holds(demonstrated(skill\text{-}statement(P, x, l)), o) \wedge beforeEq_{psl}(end\text{-}of_{psl}(o), T).$

Q-9.2. What are the suggested skills of individual P at given timepoint T?

$(holds(probable(skill\text{-}statement(P, s, l)), o) \vee$
$holds(possible(skill\text{-}statement(P, s, l)), o)) \wedge beforeEq_{psl}(end\text{-}of_{psl}(o), T).$

Q-9.3. What are the *refuted* skills of individual P at given timepoint T?

$holds(refuted(skill\text{-}statement(P, s, l)), o) \wedge beforeEq_{psl}(end\text{-}of_{psl}(o), T).$

[2]For the evaluation of the ontology, consistency checking was also carried out using the Mace4 (McCune, 2003) model builder.

6. Summary and Conclusion

To stay competitive within the market, organizations need to accurately grasp the competency of their human resources. This is particularly important for organizations that engage with multiple and changing clients such as consulting firms and software development companies since these organizations need to be able to flexibly respond to internal and external demands for skills and competencies. To this end, this paper presented a formal ontology for representing and reasoning about skills and competencies in a dynamic environment. We related proficiency levels to the span of activities that one can perform in addition to measurable attributes related to skills in order to specify what can be expected of someone who possess a skill. This provides the means for reducing fluctuations in competency measurement and evaluation by ensuring a consistent interpretation of the meaning of proficiency. Furthermore, we identified different sources of skills and competency information and discussed how information from a source can change our belief about the skills of an individual. The expert profiles constructed in this fashion can be used to determine whether an individual satisfies a set of requirements, or to conduct gap analysis in order to determine who to train and what training programs to offer.

Future work will focus on evaluating different sources with respect to the quality and accuracy of the information they provide. Revising trust and belief in the sources of information is an important topic of future work. In real world settings, most of the information provided, especially at the beginning, are from untrusted sources which are mainly useful for stating the possibility of having a skill, and are not very useful for state transitions. We can adjust trust and belief in the sources over time as observations are made. In addition, if many untrusted sources are stating the same information, we need to reconsider our belief and trust in those sources. However, in this regard, it is important to also consider the chances of dishonest behavior, namely, lying and collusion. Considering the cost of gaining information is another interesting topic for future work.

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