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Extending Database Capabilities: Fuzzy Semantic Model

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Résumé—This paper presents a new database model, namely Fuzzy Semantic Model (or FSM). FSM enables us to capture effectively the fuzziness and semantics of real-world and provides tools for its formalization and conceptualization within a manner adapted to human perception and reasoning. One of the novelties of FSM is that it authorizes an entity to be a member of several classes at the same time and according to different degrees of memberships that reflect the extent to which the entity verifies the attribute-based and/or semantic proprieties of these classes. The idea is to associate to each class a set of semantic and attribute-based proprieties; each one has its own membership function. These functions are then weighted in order to construct global membership functions that will be used as meant for assigning entities to classes.

Mots Clés: — Fuzzy class, Fuzzy database, Fuzzy logic, Fuzzy semantic model.

1 Introduction

Since the seminal paper of [30], fuzzy logic has experienced very successful applications in different domains. The reason for this is simply the ability of fuzzy logic to represent human perception of and reasoning about real-world. Domains to which fuzzy logic has been applied include operational research, Artificial Intelligence, decision-making, pattern recognition and computer vision, speech recognition, control and system theory, robotics, databases, etc.

In database context, there have been several tentatives to develop data models that support the fuzziness and impreciseness of real-world [25][12][18][14][28][3][9][27]. However, most of efforts have been oriented towards the extension of conventional relational database models [6][11][8][22][7] and towards the development of tools that allow for imprecise querying most often in relational database contexts [17] [2] [1] [4] [5] [15] [26] [29]. In addition, almost all of these works introduce fuzziness only at the attribute level and consider that each entity belongs to one and only one class. However, in many practical applications—such as in biology and medical sciences, archaeology and history studies, spatial data representation and modelling, archives management, cosmology research—one may come across difficulty in assigning an entity to a particular class, mainly when this entity verifies only partially the proprieties of several classes at the same time. Actually, assigning an entity to exactly one class may introduce some deformation of human perception of real-world and may eliminate several substantial information, which may be very useful in several applications.

In this paper we propose a new database model, namely Fuzzy Semantic Model (or FSM) that overcomes this limitation and authorizes an entity to be a member of several classes at the same time and according to different degrees of memberships that reflect the extent to which the entity verifies the attribute-based and/or semantic proprieties of these classes. FSM uses basic concepts of classification, generalization, aggregation and association that are commonly used in semantic modelling and supports the fuzziness of real-world at attribute, entity, class and relations intra and inter-classes levels. Hence, it provides tools to formalize and conceptualize real-world within a manner adapted to its perception and representation by humans.

The next section presents the principles and constructs of FSM and then section 3 concludes the paper.

2 PRINCIPLES OF FSM

The *space of entities*, denoted $E=\{e\}$, is the set of all entities of the *domain of interest*. A *fuzzy class* K in E is a semantic collection of *fuzzy entities*. Mathematically, K is defined as a collection of ordered pairs of fuzzy entities: $K=\{(e,\mu_K(e)): e\in E;\ \mu_K(e) > 0\}$. μ_K is a *characteristic* or *membership function* and $\mu_K(e)$ represents the *degree of membership* (or d.o.m) of fuzzy entity e in fuzzy class K. Membership function μ_K maps the elements of E to the range [0,1], where 0 implies no-membership and 1 implies full membership. A value between 0 and 1 indicates the extent to which entity e can be considered as an element of fuzzy class K. Intuitively, a fuzzy entity e may be member of many fuzzy classes according to different degrees of memberships.

The definition of a membership function is a crucial step in all applications of fuzzy logic. In our FSM, membership functions of fuzzy classes will be defined as follows. As it is underlined above, a fuzzy class is a collection of many fuzzy entities having some similar proprieties. Fuzziness is thus induced whenever an entity verifies only some or no one of these proprieties. We note by $P_K=\{p^i_K: K \subset E;\ i >=1\}$ the set of these proprieties for a given fuzzy class K. P_K forms the *extent* of class K. These proprieties may be derived from the attributes of the class and/or from common semantics. The extent to which each of these proprieties determines the class K is not the same. In fact, there are some proprieties that are more discriminative than others. To ensure this, we associate to each propriety p^i_K a normalized weight w^i_K reflecting its importance in deciding whether or not an entity e is a member of a given class K. To keep the coherence of our model, we impose that $\Sigma_i w^i_K =1$.

On the other hand, an entity may verify fully or partially extent proprieties of a given fuzzy class. Obviously, the fuzzy entity must first have at least one of the class attributes or has characteristics, which are in accordance with at least one of the semantic phrases on which extent proprieties are based. Let D^i_K be the basic domain of extent propriety p^i_K values and P^i_K is a subset of D^i_K, which represents the set of possible values of propriety p^i_K. The partial membership function of an extent propriety value is $\rho_{p^i_K}$, which maps elements of D^i_K into [0,1]. For any attribute value $v \in D^i_K$, $\rho_{p^i_K}(v) = 0$ means that fuzzy entity e violets propriety p^i_K and $\rho_{p^i_K}(v) = 1$ means that this entity verifies fully the propriety value. The number v is the value of the attribute of entity e on which the propriety p^i_K is defined. More generally, the value of $\rho_{p^i_K}(v)$ represents the extent to which entity e verifies propriety p^i_K of fuzzy class K. Accordingly, for any fuzzy entity e, the global d.o.m $\mu_K(e)$ for a fuzzy class K is equal to $\Sigma_i\, w^i_K \cdot \rho_{p^i_K}(v)$, i.e., a weighted sum of the partial membership functions.

The definition of functions $\rho_{p^i_K}$ is not the concern of this paper since our major objective here is to introduce the fuzziness at the class level. We just mention that several techniques have been proposed in the literature and all of them apply to our model and can be used to determine partial membership functions as those based on similarity relations [6][7], those based on possibility distributions [25][17][18] or those based on evidence theory [24].

This way of defining membership functions may apply better to attribute-based extent proprieties. However, analysts and/or experts may provide membership functions of extent proprieties that are based on semantic phrases.

One particular case may hold when the extent proprieties are crisply defined. In this case, for any fuzzy entity e the global d.o.m $\mu_K(e)$ for a fuzzy class K is equal to $\Sigma_i\, w^i_K \cdot b^i_K$ where b^i_K is a boolean variable defined in such a way that a value of $b^i_K = 0$ indicates that the entity violates the *ith* propriety p^i_K of class K, and a value of $b^i_K = 1$ indicates that the entity verifies this propriety. In the rest of this paper we consider that extent proprieties are not crisply defined.

The basic constructs of the FSM are extensions of the Unifying Semantic Model (or USM) (see [20][21][19])—itself is an extension of traditional semantic models; especially SDM [10], IDEF1X [13], NIAM [16], and OSAM* [23]—and which are here enriched with new concepts enabling the database system to support fuzziness of real-world. They are illustrated and discussed in the following paragraphs.

2.1 Fuzzy Entities

A *fuzzy entity* is a natural or artificial entity that we cannot be assign to an exact class. In other words, a fuzzy entity verifies only some extent proprieties of one or some classes. Classic entities are a particular case of fuzzy entities because they are assigned exactly to one class. Here, however, all entities of real-world (fuzzy or not) are referred to fuzzy entities. The legitimacy of doing this is that fuzzy paradigm supports well exact entities by associating 1 for the d.o.m relative to their exact classes, and 0 for any other d.o.m (i.e. other classes).

2.2 Basic Classes

2.2.1 Fuzzy Classes

A *fuzzy class* is a semantic collection of fuzzy entities. Each fuzzy class is uniquely identified with a name. The elements of a fuzzy class are called *members*. Each class has a list of characteristics or proprieties, called *attributes*. Some of these attributes along with other common semantic phrases are called the *extent* and form the set P_K defined above. To be a member of a fuzzy class K, a fuzzy entity e must verify (fully or partially) at least one of the extent proprieties, i.e., $\mu_K(e) > 0$.

We should note that FSM fuzzy classes are well and exactly defined because even that their extent proprieties may change over time; they keep the same identity (or name). In this paper we suppose that these proprieties are constant over time. However, incorporation of temporality in FSM formalism is in process and will be the concern of a forthcoming paper.

There are seven types of fuzzy basic classes in FSM formalism (Figure 1):

1. A *complete fuzzy class K* (Figure 1.*c*) is a fuzzy class that all its members have a d.o.m equal to 1; i.e., $\mu_K(e) = 1 \;\; \forall \;\; e \in K$.
2. A *non-complete fuzzy class K* (Figure 1.*d*) is a fuzzy class that at least one of its members has a d.o.m strictly inferior to 1; i.e., $\exists \; e \in K$ such that $\mu_K(e) < 1$.
3. A *strong fuzzy class K* (Figure 1.*e*) is a fuzzy class whose members can exist on their own, i.e., they are not depending on other classes.
4. A *weak fuzzy class K* (Figure 1.*f*) is a fuzzy class whose members depend on the existence of other (strong and/or weak) classes for their existence.
5. A *compact fuzzy class K* (Figure 1.*a*) is a complete and strong fuzzy class.
6. A *non-compact fuzzy class K* (Figure 1.*b*) is a complete and weak fuzzy class.

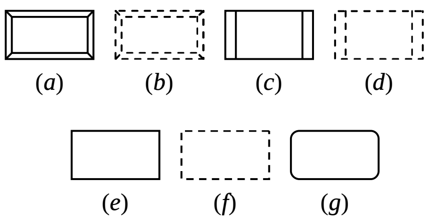

Figure 1: FSM basic classes symbols

2.2.2 Domain Classes

A *domain class* (Figure 1.*g*) is the space to which all attributes' values are mapped. Operations between attributes are possible only if their values map to the same domain, or eventually, to overlapping domains. The elements of a domain are all of the same datatype. Here, we keep the same datatypes defined in the USM, which are: integer, count, measure, currency, real, scaled, boolean, enumerated, name, text, datatime, and bit or byte-string (see [19] for the descriptions of these datatypes).

2.2.3 Fuzzy Entity-Class

A *fuzzy entity-class* is a new entity that cannot be assigned to any pre-existing fuzzy class. Therefore, this entity is transformed into a (compact) fuzzy entity-class containing initially only one element with a d.o.m equal to 1. A fuzzy entity-class can evolve to form a new fuzzy class whenever some new similar entities are introduced. It can also be eliminated whenever new attributes' values and/or semantic proprieties are discovered enabling it to be assigned to one or many other pre-existing fuzzy classes.

2.3 Members

As it is mentioned above, the elements of a fuzzy class are called *members*. They may be also termed *occurrences* or *instances*. Each fuzzy class K may have any number of three types of members:

- *True-Member*: is an entity e with a d.o.m equal to one, i.e., $\mu_K(e) = 1$.
- *Pseudo-Member*: is an entity e with a d.o.m greater than 0.17 and strictly inferior to 1, i.e., $0.17 \leq \mu_K(e) < 1$.
- *Weak-Member*: is an entity e with a d.o.m strictly less to 0.17 and strictly greater to 0, i.e., $0 < \mu_K(e) < 0.17$.

A true-member is a member of one and only one class. Pseudo and weak members are at least members of two fuzzy classes.

2.4 Relationships

Four types of relationships are defined in FSM formalism. They are depicted in the following paragraphs.

2.4.1 Propriety Relationships

A *propriety relationship* associates a fuzzy class to a domain class. Each propriety relationship defines an attribute (see §2.5). We distinguish two types of attributes: (*i*) simple attributes, which are defined by themselves (Figure 2.*a*), and (*ii*) derived attributes, which are obtained from other attributes (Figure 2.*b*). As it is defined in USM, propriety relationships are always binary and they are always seen only from the point of view of the entity class (i.e. only entities can have attributes [19]).

2.4.2 Decision Rule Relationships

Two new relationships for defining fuzzy classes are introduced in FSM formalism. The first is a ***semantic decision rule relationship*** (Figure 2.*c*), which is a semantic phrase used to decide whether or not a fuzzy entity is a member of a specific class. The second is a ***propriety decision rule relationship*** (Figure 2.*d*), which is an attribute-based decision rule used to decide (through a binary comparison, for instance) whether or not a fuzzy entity is a member of a given class. Decision rule relationships are in fact an implementation of the extent set P_K. Any fuzzy class must have at least one decision relationship. But there is not any limit number of decision relationships for a given class. However, one prefers to have a moderate number of decision relationships in order to keep the model comprehensive.

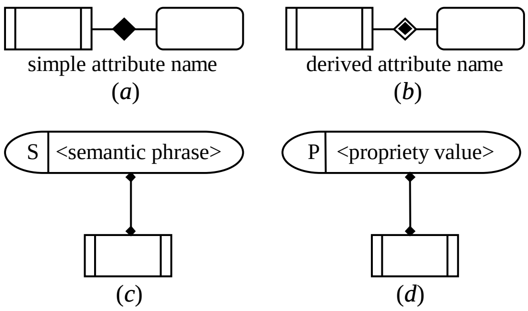

Figure 2: FSM propriety and decision rule relationships

2.4.3 Membering Relationships

The ***membering relationships*** relate fuzzy entities to classes. Along with the member's typology, three types of membering relationships are defined. A ***true membering relationship*** (Figure 3.*a*) is binary and relates one entity to exactly one fuzzy class. ***Pseudo*** and ***weak membering relationships*** (Figure 3.*b*) relates entities to one or several fuzzy classes. The letters T, P, and W in Figure 3 refer respectively to the terms True, Pseudo, and Weak, and the values in the parenthesis are the different d.o.m.

2.4.4 Interaction Relationships

An ***interaction*** (or ***association***) ***relationship*** relates members of one fuzzy class to other members of one or many fuzzy classes. The interaction relationship may be of binary or higher order and is identified uniquely with a name. The association relationship creates attributes for relating each participant member to each of the other participant members. This permits to consider the interaction relation from the viewpoint of any participant member. It may also require (Figure 4.*b*) or not (Figure 4.*a*) the creation of new attributes that describe the interaction relationship. In the former case, a new (obligatory weak or non-compact) ***fuzzy interaction class*** is generated. The d.o.m of members of a fuzzy interaction class is equal to the product of the related members. For example, a member e of a binary fuzzy interaction class K generated by associating two members, say e' and e'', of two fuzzy classes, say K' and K'', has a d.o.m $\mu_K(e)$ equal to $\mu_{K'}(e') \cdot \mu_{K''}(e'')$. When the binary fuzzy interaction class requires no new attributes, the class name may be omitted since the relation is totally identified by its two members' attributes. An interaction relationship may relate one member to other members of the same fuzzy class and forms a ***recursive interaction relationship*** (Figure 4.*c*).

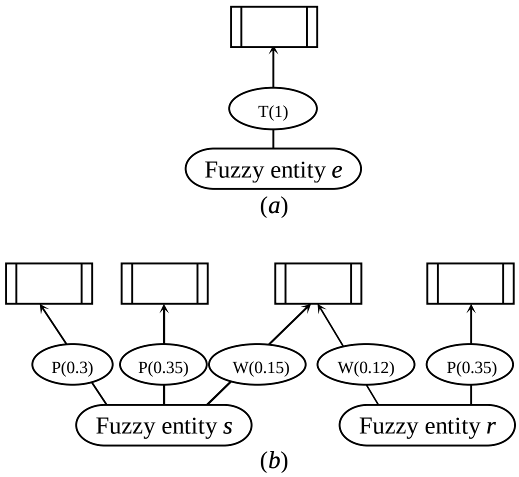

Figure 3: FSM membering relationships

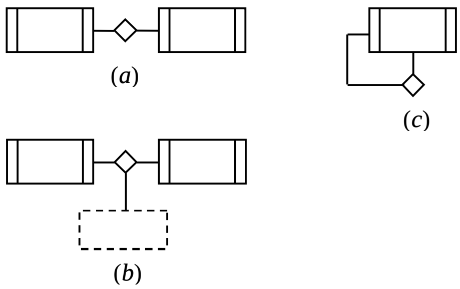

Figure 4: FSM interaction relationships

2.5 Attributes

As it is underlined above, a propriety relationship relates a fuzzy class to a domain class. This relationship creates an ***attribute*** associated to members of the fuzzy class. Attributes may also be created through interaction, composite (see §2.7) or grouping (see §2.8) relationships. Each attribute has a unique datatype and may be single or multi-valued. Values may be exactly defined or not. Accordingly, an attribute value may have one of the following natures:

- *SingleValued*: means that the attribute cannot have more then one value in a given time.
- *Unknown*: means that we cannot decide which is the value of the attribute among several plausible values.
- *Undefined*: means that there is not any defined value that can be assigned to the attribute.
- *Null*: means that we cannot even know whether the attribute's value is unknown or undefined.
- *MultiValued*: means that the attribute can have different values.

In FSM formalism, attributes as entities are affected with fuzziness. That is, these attributes are allowed to take imprecise values. As is underlined above, in this paper we do not intend to focalize on the representation of fuzziness at attribute level since it has been well discussed in most of fuzzy database literature (see, for e.g., [6][25][17][18][7][24]).

Each attribute has a name and many other characteristics. Several ones of these characteristics are enumerated in [19]. In the following list we just add two new ones, which are not defined in USM:

- *Exact*/*Fuzzy*: An exact attribute is a single or multivalued. Otherwise (i.e. undefined, unknown, or null) is a fuzzy attribute.
- *Relevant*/*Not-Relevant*: In FSM, it is not necessary that a member has all the attributes of his fuzzy superclass (see §2.6). Attributes that are not obligatory are said to be not-relevant ones. Note that this propriety must be seen from the point of view of members and not classes.

2.6 Class Relationships

FSM supports two types of inter-classes relationships: generalization and specialization. The ***generalization relationship*** relates a ***fuzzy superclass*** to one or several simple or composed *fuzzy subclasses*. Such relation advocates that all members of the *fuzzy subclass* are members of its fuzzy superclass with the same d.o.m., i.e., for any entity ***e*** of a fuzzy subclass ***S***, the d.o.m of ***e*** relatively to the fuzzy superclass ***P*** of ***S*** is $\mu_P(e) = \mu_S(e)$. Any generalization relationship creates implicitly a ***specialization relationship***, which relates a fuzzy subclass to a fuzzy superclass. The same fuzzy class may be the subclass of one or many fuzzy superclasses. A specialization relationship advocates that the fuzzy subclass ***inherits*** all the attributes of its fuzzy superclass(es).

A fuzzy subclass may be attribute-defined, semantically-defined, set-operation-defined or roster-defined. An ***attribute-defined fuzzy subclass*** (Figure 5.***a***) has one or several attributes' values that are in accordance with some discriminative values that characterize perfectly the members of the fuzzy superclass. A ***semantically-defined fuzzy subclass*** (Figure 5.***b***) verifies one or several semantic phrases used as decision rules for determining the members of the fuzzy superclass. Both of attribute and semantically-defined fuzzy subclasses inherit all the attributes of their fuzzy superclasss. A ***set-operation-defined fuzzy subclass*** may be defined as the difference (Figure 5.***d***) or the set-intersection (Figure 5.***e***) of two or more fuzzy classes. Members of difference fuzzy subclass of two fuzzy superclasses are those that are members of the first fuzzy superclass that are not members of the second fuzzy superclass. Members of a set-intersection fuzzy subclass of two or several fuzzy superclasses are members of each of these fuzzy superclasses. The set-intersection fuzzy subclass inherits all the attributes that are common to all the participant fuzzy superclasses while the difference fuzzy subclass only the attributes of the first fuzzy superclass will be inherited by the fuzzy subclass. A ***roster-defined fuzzy subclass*** is simply defined by an explicit enumeration of its members (Figure 5.***c***). These subclasses inherit all the attributes of their superclass.

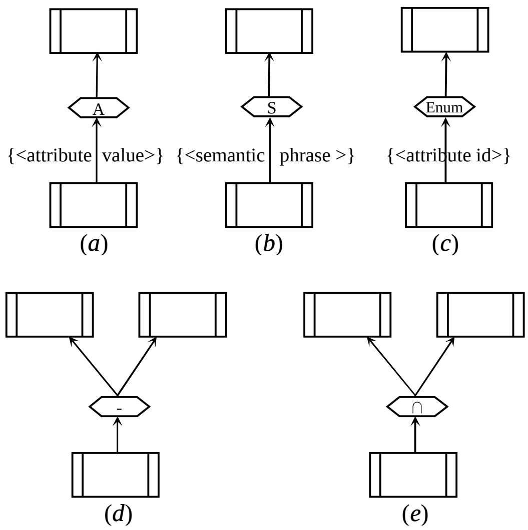

Figure 5: FSM inter-class relationships

Fuzzy subclasses of a common superclass may be equal, mutually exclusive or overlapping. ***Equal fuzzy subclasses*** represent fuzzy subclasses that have synonym names and have exactly the same members. ***Mutually exclusive fuzzy subclasses*** are those in which members of the first fuzzy subclass cannot be members of the other fuzzy subclasses. Those fuzzy subclasses that can have some common members are said to be *overlapping fuzzy subclasses*.

Finally, we just mention that generalization and specialization relationships may be defined on any basic fuzzy class, and that they do not have names and do not generate any new fuzzy class.

2.7 Composite Fuzzy Classes

A *composite fuzzy class* is a fuzzy class that has other fuzzy classes as members. It is uniquely identified with a name. If the members of a composite fuzzy class are subclasses of the same fuzzy superclass, they are said to be *homogenous*. Otherwise, they are *heterogenous*. Composite relationships are not generalization or specialization ones. Indeed, the utility of composite fuzzy classes is to maintain general attributes that describe common proprieties of all the members of a fuzzy class (or subsets of a fuzzy class). To avoid redundancy, the members of a composite fuzzy class are kept defined at their initial fuzzy classes but we associate to this composite fuzzy class a multivalued attribute called *contents*, which permits to identify all of its members. Composite fuzzy classes may be defined on any basic fuzzy class and can be generalized or specialized.

A composite fuzzy class may be defined basing on a collection of attributes, a collection of semantic phrases or simply by enumerating its members. Those, which are defined on a collection of attributes, share the same values for a subset of attributes (Figure 6.*a*). These attributes are called ***fuzzy selection attributes*** of the composite fuzzy class. Fuzzy selection attributes form also the attributes of the composite fuzzy class and they constitute the identifier of the members of this composite fuzzy class. Those that are defined on a collection of semantic phrases verify one or several semantic phrases, which serve as decision rules for determining the members of the composite fuzzy class (Figure 6.*b*). These phrases are called *semantic selection phrases* of the composite fuzzy class. A composite fuzzy class can be also defined by the enumeration of its members (Figure 6.*c*). These members may be homogenous or heterogenous.

Finally, we remark that each member of a composite fuzzy class may have their own attributes in addition to the common ones.

2.8 Grouping Fuzzy Classes

A *grouping fuzzy class* is a collection of members from other fuzzy classes. We may distinguish two types of grouping fuzzy classes: aggregate or grouping fuzzy classes. A member of an *aggregate fuzzy class* is an heterogenous collection of fuzzy classes, in which each member (or *aggregate*) is composed of one member from different fuzzy classes that are called *components* (Figure 7.*b*). A *grouping fuzzy class* is an homogenous collection of members (or *groups*) from the same fuzzy class that is called component (Figure 7.*a*). In both cases, members of the grouping or aggregate fuzzy class are unique collections of the component class(es). In other words, the addition or the elimination of one member from the collection creates a new group or a new aggregate.

Groupings and aggregates are nor generalization or specialization of fuzzy classes neither a composition of one or more fuzzy classes. In addition, they are weak ones and fuzzy subclasses, superclasses and/or composite fuzzy classes may be defined on them. Moreover, each grouping fuzzy class has at least a multivalued attribute called *contents* that refers to the members of each of its groups.

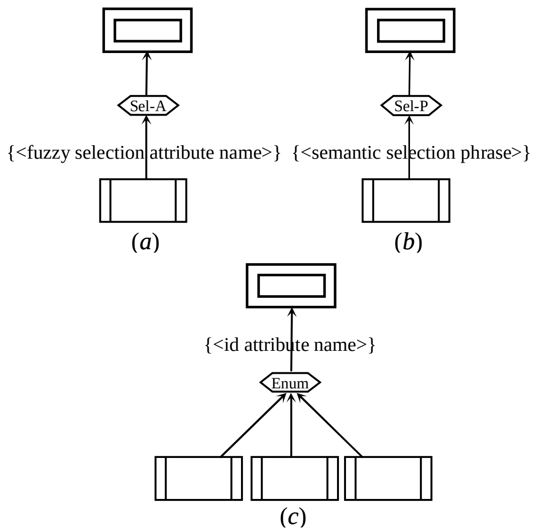

Figure 6: FSM composite fuzzy classes

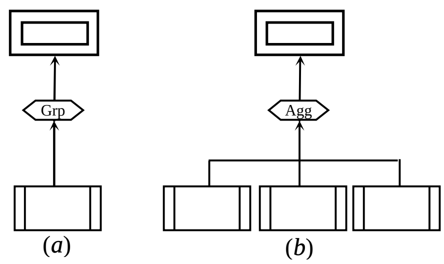

Figure 7: FSM grouping fuzzy classes

3 CONCLUSION

In this paper we have presented a new fuzzy semantic model that permits to formalize and conceptualize real-world within a manner adapted to human perception of and reasoning about this real-world. FSM is useful in several real-world applications in which the assignment of an entity to exactly one class may introduce some deformation of human perception of real-world and may eliminate several substantial information that may be very useful in several of these applications. One of the novelties of FSM is that it authorizes an entity to be a member of several classes at the same time and according to different degrees of memberships that reflect the extent to which the entity verifies the attribute-based and/or semantic proprieties of these classes.

Currently, an implementation of FSM is in process. Furthermore, an elaboration of an extended fuzzy semantic querying language is also in process. In future time, we intend to add the temporal dimension to our FSM in order to handle the evolution of facts and of human perception of real-world across time.

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