Possible-World and Multiple-Context Semantics for Common-Sense Action Planning

Maria J. Santofimia [a], Scott E. Fahlman [b] Xavier del Toro [c] and Francisco Moya [a]
Juan C. Lopez [a]

[a] *Computer Architecture and Network Group. University of Castilla-La Mancha*
[b] *Carnegie Mellon University*
[c] *School of Industrial Engineering. University of Castilla-La Mancha*

Abstract. Event management and response generation are two essential aspects of systems for Ambient Intelligence. In this regard, the context notion does also play an essential role, not only in determining the set of activities that take place in it, but also in devising the most appropriate response to those situations. Context is also essential for disambiguating knowledge and meaning. This work therefore proposes handling these issues by means of an approach with which to model and reason about actions and events which, under the umbrella of a philosophical and common-sense point of view, describes what actions and events are, how they are connected, and how computational systems should consider their meaning. Actions and events occur in the frame of situations. In order to leverage Ambient Intelligence systems to autonomously manage their environment these situations need to be characterized and understood. This work also describe an approach to tackle this challenge.

Keywords. Common sense, Ambient Intelligence, Context model

Introduction

The notion of context is at the heart of the Ambient Intelligence paradigm because of its role in narrowing down the meaning of the environmental events and in determining suitable means to react to undesired situations. Despite the importance of context, this concept has not yet been universally formalized. On the contrary, the fact that the notion of context is a relevant issue for different fields of knowledge such as natural language understanding, linguistics, context-awareness, or knowledge representation among some, makes it difficult to provide a common and unique definition of what context is. Some authors such as McCarthy [33] echo this peculiarity, deciding not to offer a definition of context since, under their perspective, it is as pointless as asking about the definition of a group elements [2].

Rather than trying to provide a definition of context, John Sowa in [46] distinguishes three different functions for the notion of context, as known: collecting the syntax of a given context; semantically mapping linguistics to physical situations; and pragmatically concerning the convenience or the purpose for a context to be considered in isolation. The confusion therefore lies in using the notion of context as though it simply refers to one of such functions.

In addition to its three-dimensional character, the notion of context when considered under the perspective of Ambient Intelligence pursues a twofold aim. On the one hand, the context notion should encompass the required information for recognizing and understanding undergoing situations. On the other hand, the context notion should also be devised as a set of devices and services accounting for the environmental acting capabilities. Context is then expected to implement responses to environmental situations by means of the tools available in it.

Traditionally, those responses have been devised as static recipe reactions that trigger whenever context information seems to match any of the considered situation patterns. In this regard, the majority of the contributions found in the literature make the assumption that those systems will only be facing previously considered scenarios, therefore overlooking unforeseen ones. On the contrary, even the scenarios described in [14], where the concept of Ambient Intelligence was firstly proposed, were also being constrained to dealing with those scenarios that fell into what one might reckons as *normality*. But, how are those systems then expected to behave when context does not evolve as it was expected? Or in other words, how are they expected to handle *novelty*?

Before being able to provide a solution to these questions, it is mandatory to devise a mean to capture and model the semantics of "*normality*", extending it to consider "*abnormalities*". Partially, this endeavor has already been addressed by the *context-awareness* paradigm [42]. Context-awareness is referred as the systems capability that entitle them to gain knowledge about their surrounding and adapt their behavior to autonomously act on behalf of users. Nevertheless, the lack of consensus reflected in the multiple meaning of context has also affected the context-awareness theory. Motivated by the need to provide a domain-independent notion of context, Dey and Abowd in [12] reaches a wide consensus on their definition and categorization of context and context-aware computing. However, according to the Sowa's work [46], rather than consolidating an integral definition of context, the work of Dey and Abowd basically contributes to consolidate the syntactic dimension of the context. From the perspective of the context-awareness and Ambient Intelligence, the semantic and pragmatic dimension of the context notion seem to be relegated to a second position, since, to the best of our knowledge, they have not been directly addressed by any of the approaches found in the literature.

Aware of these shortcomings, this work is intended to provide a comprehensive approach for context modeling that encompasses the three dimensional view of context and the twofold aim that characterizes it when considered under the perspective of Ambient Intelligence. Furthermore, this holistic approach should also take into account that context modeling is not only restricted to considering expected situations, but rather it should be enhanced with the required means for recognizing and understanding unpredicted or unforeseen scenarios.

The remainder of this work is structured as follows. First, a revision of the state of the art for context modeling and reasoning is presented. The next three sections are concerned with the description of the three dimensional views of the context concept: syntax, semantics, and pragmatics. Section 5 describes the proposed approach for characterizing the different types of situations that might take place in a context: normal, abnormal, and unknown. On the basis of the characterized situation, Section 6 describes the proposed mean to understand what is going on in the characterized situation. This mechanism is thoroughly described in Section 7 using the possible world theory to support the proposal. Due to the fact that there are many different aspects involved in the characterization and understanding process, Section 8 presents a clarifying description of how such processes are undertaken. Finally, Section 9 presents the most relevant conclusions of this work.

1. Previous works

A context model for Ambient Intelligence comprises the rules that establish how to map sensor data values into high level knowledge. These rules, far from being unique and common to context-aware systems, they tend to be tailor made solutions that prevent context-aware systems from sharing and leveraging the knowledge they hold. Context models are therefore characterized for their lack of interoperability.

The work in [5] provides an appropriate starting point for surveying the existing modeling techniques. In [5] authors split context into three levels of granularity. First level deals with raw sensor data, second level concerns about interpreting those data, as they were all knowledge about an on-going situation, and finally, third level surveys those works that extract information from establishing relationships among the situations of the second level. Despite the fact that much attention is paid to what Sowa named the *syntactic dimension of the context*, little is paid to the *semantic* and none to the *pragmatic* one.

The first of the surveyed approaches is the Context Modeling Language (CML) [24] [22] [23], which on the basis of a database modeling technique is intended to capture the concepts that are present in the context, along with the relationships established among those. CML claims to provide support for reasoning, however, rather than doing so, one might reckon that it simply consists in answering SQL-like queries. Inferences or deductions are therefore out of the scope of the provided functionality.

Context information can also be modeled with regards to the location, in a geo-spatial sense. The approach in [17] proposes different conceptualization of the world by constructing a multilevel model of the world. The model proposed inside the Nexus project consists in the Augmented World Model [37]. This proposal adopts an object-based approach in which multi-inheritance is supported by the context objects. It has to be highlighted that this model was motivated by the need to overcome the interoperability issues that characterize context-aware applications.

Similarly, the Equator project [19] models the context by means of an OWL class model in which ontology entities are symbolic spaces, arranged in a hierarchical fashion and whereas properties represent the relationships established among these spaces. In this sense, as it might be inferred from revising the context modeling state of art, the most commonly used approach is that of ontologies, especially, the ones based on OWL.

The main strength of an ontological approach is a direct consequence of using a standard language, as it is OWL. This language provides support for interperoability and information sharing. Additionally, a more restricted version of OWL language, as it is OWL-DL performs well when it comes to reasoning about the context knowledge. Some examples of successful frameworks for pervasive applications that have resorted to this approach are CoBrA[9], SOCAM[20], SOUPA[10], or Gaia[40].

As one might notice, the works presented so far have only been concerned about the knowledge that could be directly inferred from the raw sensor data. However, the semantic level goes one step forwards and gets engaged in interpreting or understanding the scenario that is taking place in the considered context. Although addressed to the field of meaning in natural language, the theory of *situation semantics*, proposed by Barwise and Perry [4] has been extrapolated to context-awareness. However, as stated in [46], situations cannot be completely described by propositionally enumerating all the aspects involved in the situation since, aspects such as intuitions about context escape from that modeling strategy.

Sowa also proposes his own theory [45] for context modeling, based on conceptual graphs of semantic networks. Under this theory, contexts are modeled as propositional containers of additional conceptual graphs. In [44] Sowa proposes the use of context so as to split knowledge bases into small pieces of knowledge. Please, notice that Guha in [21] founds his work in that premise, and from there he proposes the notion of microtheory as a mean to organize knowledge in Cyc [30].

McCarthy's *ist(c, p)* predicate [32], which can be read as "*proposition p is true in context c*" was his attempt to provide an universal mechanism to overcome the large number of arising logics for different reasoning theories. McCarthy's theory was also implemented in Cyc by his student Guha [21]. However, in spite of its great success with regard to supporting the construction of large knowledge base, the distinction among syntax and semantics is not clearly stated in the context model. As stated by Sowa in [46] the *ist* proposition mixes these two dimensions, in the sense that the *ist* predicate hold the meaning of the proposition *p* being contained in context *c* but also, the semantic dimension of proposition *p* being true in context *c*. A possible way of decoupling both dimensions is to resort to the Barwise and Perry's notion of *situation*, already mentioned above. As stated in [47], if it is possible to stablish a connection between a given proposition and a certain situation, in such a way that all the propositions encompassed in that situation are considered to be true.

Additionally, the meaning of that propositions is unavoidable associated to the context in which they are being considered. In this sense, *meaning* is expected to be something more elaborated that just mere conventions about what other concepts state their significance. On the contrary, the meaning associated to a proposition has to be provided in terms of how it affects the context. A plausible way of doing so is by means of the "*possible world*" theory. As stated in [39] there are two possible ways of describing what a *possible world* is. On the one hand it can be described as a set of consistent propositions that are true in a given *world*. On the other hand, a *possible world* can also be explained as an account for how things can be interpreted in a given *world*. The same author states the following, regarding the existing relation in between context and possible worlds:

> " *contexts are possible worlds in which judgments are derived, so that each judgment stated true by the theory is true in a certain world, namely the one providing all the informational data needed in order to acquire the knowledge contained in that judgment (i.e. the information which expresses the conditions to verify the propositional content of the given judgment). This world is namely expressed by a context*[1]."

---

[1] PRIMIERO, G., Information and Knowledge. A constructive Type-theoretical Approach.Logic, Epistemology, and the Unity of Science, Vol. 10. ISBN 78-1-4020-6169-1, pp. 152

Later on this chapter, it will be described how possible worlds can be formalized by means of the Kripke structures.

2. The context syntax

After having revised the state of the art for context modeling, this and the following sections are devoted to describing the insights of the proposed strategy for modeling Ambient Intelligence contexts. To this end and, inspired in the three-dimensional view of the context notion advocated by Sowa, the description of the proposed modeling approach is organized in terms of the aforementioned dimensions.

Consequently, this section concerns about capturing the context syntax, and to this end, the lexicon of the proposed context model has to be provided, along with the rules that determine how these symbols can be combined, by means of a context-free grammar.

The identification of the context lexicon starts by establishing all the categories or entities comprising the vocabulary of the proposed language. The revision of some of the most successful and widely accepted categories for context-aware systems, such as the ones proposed by Ryan in [41], Schilit in [43], or Dey and Abowd in [12], lead to the conclusion that despite being right in the insights, the proposed categories fail to comply with the requirement of low-coupling between the different context dimensions. Whereas categories such as *location* and *time* are part of the lexicon, some other such as *activity* or *identity* escape from the syntax dimension and should be part of the semantic one. However, this poses an arising question, as it is the identification of what should be part of the lexicon and what should be kept outside it? For the sake of preserving the independence of the three context dimensions the proposed approach adopts the convention of considering that just the information directly extracted or related to sensors should be considered part of the lexicon.

The fact that Ambient Intelligence systems are fed with raw information, directly gathered from sensors, simplifies the vocabulary lexicon needed to describe such contexts. In contrast to what it might happen in Natural Language Processing, in which the considered vocabulary must be the whole language itself, in Ambient Intelligence, vocabulary is limited to those items that handle actions and events and those that hold the environmental sensed data.

The context syntax is intended to strictly enumerate the domain concepts that are considered in the modeled context. High level knowledge is therefore left for the upper dimensions (semantics and pragmatics), preserving the low-coupling requirement between this and the remainder context dimensions. The main advantage of achieving a non-coupling model is grounded in the benefits of addressing each dimension with the modeling approach that better fit the features of each dimension.

Regarding the syntactic dimension, the modeled approach basically consists in describing the symbols and the rules that determine how these symbols can be combined. Despite the fact that OWL, or OWL-DL have traditionally been elected for modeling the context syntax, more basic and efficient mechanisms can also be used so as to cope with the task of capturing and modeling the syntactic dimension. Recall Sowa's definition of the syntactic dimension which only ascribes it the responsibility for enumerating the symbols that are required for expressing the knowledge about contexts, along with the rules that determine how those symbols can be combined. At this level nothing has to be said about the meaning of those symbols or their relationships. These are responsibility of the upper context dimensions, and therefore, they will be addressed in the following sections.

Similarly to how lexicon of formal languages is established and bearing in mind both the need for simplicity and efficiency restrictions, the proposed approach for modeling the syntactic dimension of context follows the formal language theory.

Using the notation and definitions of such theory, a context-free grammar is postulated as a mean to capture the context syntax. The following definitions presents the foundations of a formal language for modeling Ambient Intelligence contexts.

Definition 1: A context-free grammar is defined as a four-tuple, such that:

$$G = (\mathcal{B}, \mathcal{E}, \Gamma, S_0) \tag{1}$$

where:

S_0: is the initial axiom or symbol.

$\mathcal{B}$: is the alphabet or lexicon. It is also known as the set of terminal vocabulary of the grammar.

$\mathcal{E}$: is the set of non-terminal symbols of the grammar.

Γ: is the set of production rules, such that:

$$\Gamma : \mathcal{E} \rightarrow X_1, ..., X_n \text{ where } X_i \in (\mathcal{B} \cup \mathcal{E})^* \tag{2}$$

Definition 2: $\mathcal{L}$ is the language such that $\mathcal{L} = L(G)$, whose grammar $G = (\mathcal{B}, \mathcal{E}, \Gamma, S_0)$ is defined as follows:

$\mathcal{E} = \{S_0$, Definition, Predicate, Statement, Type, Device-id, Service-ID,
Action-ID, Object-ID, Event-ID, Place-ID, Time-ID$\}$

$\mathcal{B} =${event, action, device, service, object, place, value, time, provides,
performs, at, in, upon, has-value, is-a, causes, identifier }

Γ = {
(1) $S_0 \rightarrow$ Predicate in-context *C*
(2) Predicate $\rightarrow$ Definition | Statement
(3) *Definition* $\rightarrow$ identifier is-a Type
(4) *Statement* $\rightarrow$ identifier has-value value
(5) *Statement* $\rightarrow$ Device-ID provides Service-ID
(6) *Statement* $\rightarrow$ Service-ID performs Action-ID
(7) *Statement* $\rightarrow$ Action-ID upon Object-ID
(8) *Statement* $\rightarrow$ Event-ID at Place-ID
(9) *Statement* $\rightarrow$ Event-ID in Time-ID
(10) *Statement* $\rightarrow$ Device-ID causes Event-ID
(11) *Device-ID* $\rightarrow$ device
(12) *Service-ID* $\rightarrow$ service
(13) *Action-ID* $\rightarrow$ action
(14) *Object-ID* $\rightarrow$ object

(15) *Event-ID* → event
(16) *Place-ID* → place
(17) *Time-ID* → time
(18) *Type* → event | action | device | service | object | place | time
}

At this level, Ambient Intelligence contexts are characterized only in terms of statements that describe the devices and services deployed in there. The followings are valid statements of the language that correspond to a simplified description of a room in which a presence sensor is deployed:

```
sensor is—a device
presence—sensor—1 is—a sensor
room—1 is—a place
presence—sensor at room—1
presence—sensor—service—1 is a service
presence—sensor—1 provides presence—sensor—service—1
detection is—a action
presence—sensor—service—1 performs detection
moving—object is—a object
detection upon moving—object
current—time—instant is—a time
event—detected—presence—1 is—a event
event—detected—presence—1 in current—time—instant
presence—sensor—1 causes event—detected—presence—1
```

Please, refer to [50] and [49] for further information regarding how this syntatic model have been extrapolated to real Ambient Intelligence scenarios.

3. The context semantics

The semantic dimension of the context notion, built upon the syntactic one, concerns about the identification of the situations that are referred by the statements of the lower layer. Inspired by the work of Knuth in [27], this work has sought to assign meaning to the lexicon vocabulary by connecting those symbols to entities of a common-sense knowledge base, instead of by associating attributes to such symbols.

Common-sense knowledge can be described as the common knowledge, hold by humans, that explains how the "*the world works*". In this regard, the impact that capturing such knowledge has on achieving intelligence systems was long time ago envisaged by McCarthy and Minsky, as related by the latter in [34]: "*In 1959, John McCarthy came to MIT from Dartmouth, and we started the MIT Artificial Intelligence Project. We agreed that the most critical problem was of how minds do common-sense reasoning. McCarthy was more concerned with establishing logical and mathematical foundations for reasoning, while I was more involved with theories of how we actually reason using pattern recognition and analogy*"[1]. Since then, there have been several attempts to build a knowledge base for managing the vast amount of information involved in formalizing common sense. Among the most promising approaches to building common-sense knowledge bases it is worth mentioning the efforts of Cyc [30], WordNet [16], or Scone[2].

Building the semantic dimension of a context modeling approach is a task that has to be supported on top of a knowledge-based system. The devised knowledge base should supports not just semantic ascription to syntactic knowledge but also higher level functionalities such as reasoning, deductions, or inferences. On the basis of these requirements, we resort to a common-sense knowledge-base system that not only captures the context semantics but also leverages human-like reasoning capabilities.

Based on the syntactic dimension, in which concepts and rules have been enumerated, the semantic dimension is captured and formalized by means of a semantic model for actions and events. Considering that Ambient Intelligence contexts are mainly intended to supervise ongoing events and generate behavioral responses to those events, the notion of *action* and *event* should occupy a central role in the proposed model. Before addressing the computational aspects of how the semantic model should be formalized, an analysis of how the philosophical discussion have addressed the representation of actions and events is compulsory.

Actions and events have commonly been treated as being equivalent, or as having the slight difference of considering actions as events which have been intentionally generated [25]. On the contrary, the theory of action for multi-agent planning [18] advocates for a distinction between actions and events, although it hints that actions are accomplished by agents in their endeavor to achieve a goal.

Davidson's theories, particularly those regarding the philosophy of action, also identify actions with events, as is argued in [11]. Actions are described as a combination of two views. On the one hand, actions can be seen as causal explanations of body movements and on the other hand, actions can also be seen as the justifying reason that leads the action to take place. Davidson considers events to be equivalent to actions. The sole difference is that when an action is considered as an event, it is re-described in terms of its effects.

The model proposed here for actions and events adopts the Davidsonian view. It should be highlighted that Cyc [30], through its language CycL, represents actions and events using a Davidsonian approach. Actions are described as events but are carried out by an agent. The approach implemented in Scone has been extended to include the notion of primary reasons for an action, along with its temporal and location aspects.

Apart from the concept of action and event that concern us here, some other relevant entities must also be considered in relation to actions and events so as to capture their semantics. The following definitions state the foundation of the proposed model for actions and events:

Definition 3. A Context is a set $\mathcal{C}$ composed of statements which, when used together, describe knowledge about the world. There may be multiple contexts describing each of the different views of the world. The meaning or truth value of a statement is a function of the context in which it is being considered.

The function $meaning : \mathcal{T}, \mathcal{C} \rightarrow \mathcal{M}$, where $\mathcal{T}$ is the set of statements describing the world, $\mathcal{C}$ is the set of possible contexts, and $\mathcal{M}$ the set of possible meanings, $meaning(s, c)$ therefore returns the meaning or truth value of the statement s in the context c. This can be formally stated as:

---

[2] http://www.cs.cmu.edu/ sef/scone/

$$\forall c_i \in C \forall s_i \in \mathcal{T} : m_i = meaning(s_i, c_i) \iff s_i \subseteq c_i \tag{3}$$

The meaning or truth value of a given statement depends on the contexts in which it has been declared.

Definition 4. An Action $\mathcal{A}$ is causally explained from the perspective of their relation to the primary reason that rationalizes them. The function $AG : \mathcal{A} \rightarrow \mathcal{G}$, such that $\mathcal{A}$ is the set of possible actions, $\mathcal{G}$ is the set of possible agents, and the function AG returns the agent performing the given action. Furthermore, the function $PR : \mathcal{A}, \mathcal{G} \rightarrow \mathcal{E}$ is the primary reason for an agent performing an action to seek the effects of the event caused. Finally, the function $PA : \mathcal{A} \rightarrow \mathcal{O}$, such that $\mathcal{O}$ is the set of possible objects, and the function returns the agent that performs the action upon the given object.

$$\exists g \in \mathcal{G} \exists a \in \mathcal{A} \exists o \in \mathcal{O} : (AG(a) \wedge PR(g, a)) \iff PA(a, o) \tag{4}$$

Therefore, an action is performed upon an object, if and only if there exists an agent with a primary reason to perform the action.

Definition 5. An Event $\mathcal{E}$ is the individual occurrences that cause changes in the world. The criteria followed by the Davidsonian doctrine on individuation of events argues for the equality of events when the same effects occur. The Davidsonian view is here adapted to internalize the multiple contexts approach. In this paper it is therefore considered that two events are equivalent when the same effects are caused by different actions. The effects of events are captured in the *after context*, while the preconditions for an event to take place are described by the *before context*. The functions $BC : \mathcal{E} \rightarrow \mathcal{C}$ and $AC : \mathcal{E} \rightarrow \mathcal{C}$, such that $BC(e)$ and $AC(e)$ respectively return the statements of which the before and after context of a given event are composed. Furthermore, the function $\mathit{effect} : \mathcal{A}, \mathcal{O} \rightarrow \mathcal{S}$, such that S represents the set of statements that describe the world after the event took place.

$$\forall e \in \mathcal{E} : (BC(e) \cup effect(a, o)) \rightarrow AC(e) \tag{5}$$

Given the events e_1 and e_2, it can be said that e_1 is equivalent to e_2 when they have equivalent *after contexts* or when they cause the same effects:

$$\exists e_1, e_2 \in \mathcal{E} : e_1 = e_2 \iff AC(e_1) \subseteq AC(e_2) \tag{6}$$

Definition 6. A Service $\mathcal{S}$ is provided by a device $\mathcal{D}$ and it performs a set of actions upon an object or a set of objects. The function $PD : \mathcal{S} \rightarrow \mathcal{D}$, such that $\mathcal{D}$ is the set of available devices, and the function returns the device or devices that provide a given service.

$$\exists s \in \mathcal{S} \exists d \in \mathcal{D} \exists a \in \mathcal{A} \exists o \in \mathcal{O} : (PA(a, o) \wedge PD(s)) \rightarrow AG(a) = d \tag{7}$$

The definition of service therefore implies that the agent of an action provided by a service is a device.

Definition 7. An Object is the set $\mathcal{O}$ of possible environmental objects upon which actions are performed. The function $OA : \mathcal{A} \to \mathcal{O}$ returns the set of possible objects that can receive a given action.

$$\exists o \in \mathcal{O} \exists a \in \mathcal{A} \exists e \in \mathcal{E} : OA(a) \wedge PA(a, o) \to e \tag{8}$$

The occurrence of an event e implies the existence of an object o upon which the action a is performed.

4. The context pragmatics

Both semantics and pragmatics concern about meaning, however, semantics assume that there exists a precise meaning for every concept, while pragmatics goes one step forwards and concerns about how that meaning may vary depending on the surrounded circumstances [26].

Humans can hold multiple meanings of a concept, even inconsistent ones, with little efforts. For example, humans do not find any inconvenience in concurrently holding the propositional knowledge that states the fact that Bill is a dog and that other stating that there also exists a person named Bill. Saying now that *Bill barks* is obviously a statement that is referring to Bill, the dog. Not so obvious is the following fact: *I told Bill to stop barking at me, it was not my fault*, but even so, humans would easily identify that the Bill referred here is the person.

The logical or computational representation of both facts reaches an incongruence since Bill cannot be a dog and a person at the same time. On the contrary, people do not seem to have problem in dealing with this sort of information. Therefore, this situation poses the following question: how do people manage to deal with such an incongruent knowledge? Philosophers have pointed out to the theory of "*possible worlds*".

The meaning of the theoretical concept of "*world*" is used to analyze a set of key concepts, so called "*worldmate concepts*" [13], from their respective domains [8] and preserving the existing meaning differences. One world could be used to represent Bill, as Bill being a dog, while some other world could be used to represent Bill, now as a person. Either worlds are plausible although incongruous, however, this way of representing information as isolated worlds, enable the representation of inconsistent information in a logically consistent manner. This is how humans are capable of reasoning and making inferences about different situations, some of which might be inconsistent with previous knowledge. Humans only consider those worlds that are more plausible or typical on the basis of the knowledge they hold at that moment [48]. This is also the way that permits humans to easily deal with the vast amount of knowledge comprised by common sense.

Addressing modality has traditionally been the primary target of the theory of possible worlds [13]. The truth value of a certain proposition is evaluated in terms of the proposition being possible, impossible, necessary or contingency. However, the possible world theory can also be used for modeling the pragmatic dimension of [38] .

Possible worlds can be interpreted as both, the set of sentences evaluated to true in a given context, or in relation to the signification assigned to a given context. In either case, a possible world comprises the constitutive sentences, in an ordered manner, as though they were part of a knowledge process. This idea is supported in the Kripke structures [29], devised as a mean to formalize semantics in terms of possible worlds.

Definition 6. Context semantics can be described by means of the Kripke models such that:

$$M = (S, R, \Pi)$$

in which S is a nonempty set of states or possible worlds, R is the relation between the possible worlds, and Π is the function that tell us which propositions or statements are true in each of the possible worlds, such that:

$$\forall s_i \in S, \Pi(s) : \Theta \rightarrow \{\text{true}\}$$

where Θ is the set of propositions or sentences that are true in the possible world s_i.

Time and location are the two main sources of incongruency when asserting knowledge in a knowledge base. For example, the fact that represents the cabinet door being opened is incongruent with that other fact that states that the door is closed. Obviously, someone can tell that attaching the time-stamp to those occurrences avoids the incongruence problem without requiring possible worlds. However, what if instead of a cabinet door, the fact to be modeled is that one in which the stopper is put in the sink and the faucet is turned on. Modeling the state of the world after these two actions take place requires a more expressive mean than just two time-stamped facts stating that the stopper is put in the sink and that the faucet is turned on. If a person is asked to model the state of the world after these two actions take place, s/he will depict a world in which the sink water level will be increasing until the sink height is reached, then, water will start spilling onto the floor. These are the sort of situations that cannot be modelled by simple statements in a knowledge base, therefore demanding more expressive mechanisms. The work in [6] advocates the convenience of enhancing commonsensical reasoning mechanisms with qualitative representation and reasoning techniques to deal with space and location issues [7].

Common sense is what enables people to perform non-trivial inferences, such as those involving delayed effects of actions, as it is the spilling water scenario. Similarly, the proposal presented in this work is grounded in capturing such common-sense knowledge into the pragmatic dimension, using to this end an approach based on the possible worlds theory. This approach can be formalized by means of the aforementioned Kripke structures. This can be best illustrated by a simple example, making the most of that Kripke structure property that allows its representation using the graphs, where nodes represent states or possible worlds, with their corresponding propositions, and edges depict the connections among those worlds.

The pragmatic dimension is build upon the semantic dimension and therefore, the Kripke model proposed here is grounded in the semantic model presented in the previous section. Action and event concepts of the semantic model are here imbued with the pragmatism of the possible world semantics. Both actions and events are described as though they were knowledge process where milestones are used to separate the enclosed worlds. Those actions and events, labelled here as basic actions[3] will do with just two

---

[3] Those which are not involving fluents. Fluents are time-varying properties of the world, where more than the traditional milestones (*before* and *after worlds*) will be identified.

worlds, one for the context before the action or event takes place and other for the context afterwards.

Let the Kripke model for the *turn on faucet* action be:

$M_{turn.on.faucet} = (S, R, \Pi)$
$S = \{s_0, s_1, s_2, s_3, s_4, s_5, s_6\}$
s_0 = before turning on the faucet with empty sink and stopper put on
s_1 = before turning on the faucet with empty sink
s_2 = before turning on the faucet with non-empty sink
s_3 = after turning on the faucet without having put the stopper on
s_4 = after turning on the faucet level-of-faucet-drain equals (flow*(elapsed-time/ base-area)
s_5 = after turning on the faucet with water level having reached the sink height
s_6 = after turning on the faucet with faucet-liquid being dropped-off
Θ = $\{p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8, p_9, p_{10}\}$
$p_0 \rightarrow$ faucet valve is turned off
$p_1 \rightarrow$ faucet valve is turned on
$p_2 \rightarrow$ stopper is put on the drain
$p_3 \rightarrow$ stopper is not put on the drain
$p_4 \rightarrow$ the sink is empty
$p_5 \rightarrow$ level of faucet liquid contained in the sink is non-empty
$p_6 \rightarrow$ level of faucet liquid contained in the sink is full
$p_7 \rightarrow$ liquid contained in the sink is being dropped-off
$p_8 \rightarrow$ put the stopper on the drain
$p_9 \rightarrow$ turn on the faucet
$p_{10} \rightarrow$ level of faucet reaches the sink height
$p_{11} \rightarrow$ turn on the faucet
$\Pi(s_0) = \{p_0, p_2, p_4\}$
$\Pi(s_1) = \{p_0, p_4\}$
$\Pi(s_2) = \{p_0, p_5\}$
$\Pi(s_3) = \{p_1, p_3, p_4\}$
$\Pi(s_4) = \{p_1, p_2, p_5\}$
$\Pi(s_5) = \{p_1, p_2, p_5, p_6\}$
$\Pi(s_6) = \{p_1, p_2, p_5, p_6, p_7\}$

From the description of the *turn on faucet* action we can easily construct a Kripke structure that describes how possible worlds are interconnected on the basis of the happening events. Figure 1 depicts the Kripke structure for such scenario. Each structure node is labelled with the set of worlds that are considered possible given the previous state of the world and the happening events or actions. The structure edges represent the occurrence of events that trigger migrations to different possible worlds.

5. Situation characterization

One of the main challenges of context-aware systems is that of having to understand and recognize context activities with the sole information of sensor data. This complexity manifests when having to model raw sensor data in such a way that, not only isolated actions can be spotted but also higher level combination of them, referred here as *activities*

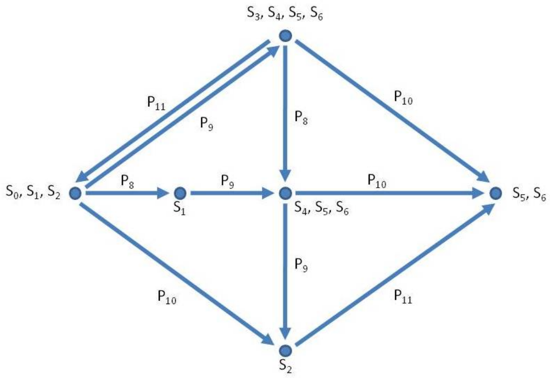

Figure 1. Kripke model for the *turn on faucet* action

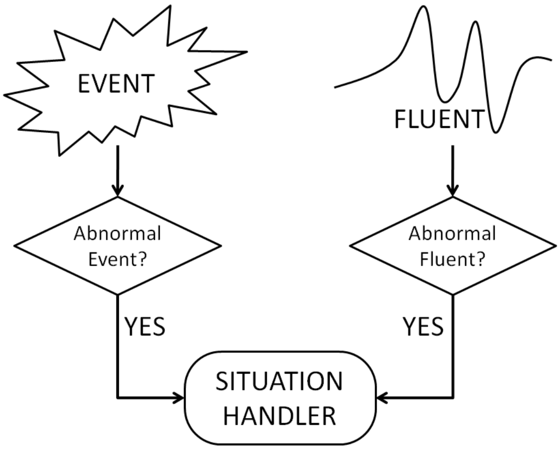

Figure 2. Overview of the process for abnormal situation identification

or *situations*. To this end, approaches originally thought for fields such as human activity or pattern recognition can be adapted to work in situation understanding and recognition systems. Thinking of activities or situations as sequence of actions that occur at a give location and at a specific time, entails a primary identification of the involved individual actions, ignoring time and location. Secondly, those actions are globally considered so as to recognize a pattern of an ongoing situation or activity.

Among the different activities or situations that are taking place in the context of Ambient Intelligence special attention is paid at identifying *abnormal* situation. Objectively, situations cannot be labeled as *abnormal* in isolation. On the contrary, situations need to be contextualized in order to determine if they match any of the abnormal situations to which the Ambient Intelligence context should be susceptible. Commonly, these situations, which do not fall into what one might reckon as a normal situation for the considered context, demand some sort of response from the system in charge of supervising

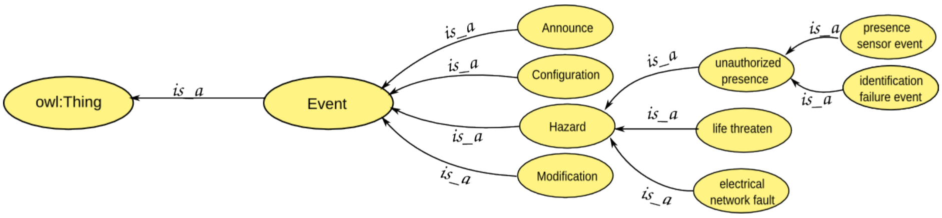

Figure 3. Extract of the taxonomy for an abnormal event characterization.

the environment. It is therefore particularly important to devise a mechanism that support the system in the task of identifying these situation that can be potentially abnormal.

The proposed approach for identifying potential abnormal situation is grounded in a double strategy, as depicted in Figure 2:

1. Some particular events suggests the occurrence of abnormal situations.
2. Properties that change along time (*fluents* in the Event Calculus) can be used to characterize abnormality.

There are some situations that can be characterized by the occurrence of certain events, in such a way that the single occurrence of one of those events provides a likely evidence that the situation taking place. Therefore, the first strategy consists is characterizing those events, in a sufficiently abstract manner, so that their occurrence can be identified under whatever circumstances. For example, an unauthorized presence alarm might suggest that a subversive actions is taking place in the context. The *unauthorized presence* event has to be characterized in such a way that it matches different types of events, such as for example the triggering event of a presence sensor located at a restricted access room, or the event that performs some sort of biometric identification resulting in a failed identification.

However, it cannot be established that there exists a direct relation in between the occurrence of these events and the existence of an unauthorized presence because it might be possible that they are due to human errors, different context conditions, or system errors. It is therefore necessary to discern between any of them, and for that reason, whenever any of these events are detected further analysis are required in order to conclude whether the undergoing situation fall into the category of *normal*, *abnormal*, or *unknown* situation.

Additionally, the event characterization is a task that depend on the domain knowledge of the considered context. For example, the aforementioned example, would correspond to a context dedicated to surveillance purposes. It is also a matter of the type of sensor and services deployed in the contexts, since they are likely to constrain the type of events that are going to be generated. However, due to the fact that new services and devices might appear in the context, this circumstance cannot be used as a sole strategy to characterize the different types of events.

A compelling approach for stating the different types of events that are suggestive of abnormal situations consists is using taxonomies. The higher concepts in the taxonomy trees are the ones used as the abstract event types that required further analysis whenever matched in the context. Figure 3 depicts a brief extract of an OWL taxonomy devoted to characterizing the most characteristic events of a given set of abnormal situations.

This strategy for abnormal situation identification based on the occurrence of characteristic events can be implemented by means of a Multi-Agent System approach. A *Context Manager* agent is in charge of translating raw sensor and service data into the appropriate lexicon devised for the syntactic dimension of the context model. Additionally, the *Context Manager* can also be responsible for matching event occurrence that might be suggestive of an abnormal situation. The BDI (Belief-Desire-Intention) model of agency seems to be a compelling approach to cope with the demands involved in dealing with the identification and management of abnormal situation. Therefore, the occurrence of the featured events trigger the goals that have been devised to cope with the abnormal situation. For example, whenever an unauthorized presence event takes place, one of the goals that triggers is intended to perform an intruder identification for the purpose of eliminating sensor errors. This goal has associated a plan or set of plans so as for the goal to be achieved. The details concerning the planning strategy will be described later on this article.

The second strategy consists in analyzing the value of those properties that change along time, the so called *fluent* in the Event Calculus [28]. In this sense, it has to be highlighted that the proposed approach presents many similarities with Event Calculus, but it is not completely an implementation of it. The proposed approach extend the Event Calculus by considering time in a more tree-like fashion, and also considering the conceptual abstractions extracted from the Situation Calculus [31].

Given that abnormal situations typically involves changes along time, and considering that fluents model how properties change along time, it is possible to characterize abnormal situation in terms of fluent values and changes. For example, think of an abnormal situation that poses a life threaten hazard whenever the temperature levels increase very quick to a very high values. More likely, these values are suggestive of an undergoing fire and therefore it requires the system to react in some way intended to extinguish the fire and to prevent people integrity from being compromised. In any case, temperature sensors have not been devised to alert quick increases or high temperature, and therefore it is necessary to implement this functionality at a different level.

Additionally, bear in mind that a quick increase can have different meanings depending on the context. For example, when this temperature increase occurs in a kitchen, it might be due a cooking activity taking place. Therefore, once again, the fluent characterizations simply outline the possibility of an abnormal situation taking place, and further analysis are also required so as to determine whether or not it is occurring.

The approach followed for characterizing the fluents values and changes suggestive of abnormal situations is based on a commonsensical and qualitatively approach. Please, notice that not only fluent values are being considered, but also changes. In this last case, it is not always possible to determine the exact variation quantity, and therefore it is more appropriate to describe changes in terms of qualitative or relative measures. Both strategies, the commonsensical and qualitatively approaches, have to be implemented at the knowledge base level, so that additional knowledge can be used to reason about the normality of the situation. At the knowledge-base level, there should be a function intended to evaluate the normality of a fluent value and change. In order to do so, this function should answer the following questions:

1. How does the fluent normally evolve along time?
2. Is the sensed change compliant with the function of time that describe this fluent evolution along time?

3. Yet, is the fluent sensed value considered normal?

It is a fact that a person cannot be at two different places at the same time (given that those places are geographically independent). In this sense, the fluent that describes a person position cannot have two different values at the same instant, since it involves time to experiment a relevant change in space. Whenever a situation like that takes places, it might suggest that an abnormal situation is taking place.

This strategy is independent from the event taxonomy involved in the event characterization strategy. Given that the implementation of this approach works at the knowledge-base level, it is possible to query the knowledge base about which possible worlds are consistent with the context description at that specific time instant. Those possible worlds are therefore contrasted to the abstract descriptions with which the Context Manager has been provided. The possible worlds that are consistent with the context description and that at the same time matches the situations considered by the Multi-Agent System will cause goals to trigger and therefore, plans to be instantiated for managing and achieving those goals.

6. Understanding Context Situations

As a constituent part of human mental events, the ability to foresee, understand, and manage *possible-worlds* and *multiple-contexts* semantic is what enable human to cope with novelty. As mentioned in the previous section, the notion of possible worlds is used here to refer to those states of affairs or “worlds” in which, given an event ε, it is true at all the worlds considered possible. For example, a specific presence sensor has detected that there is someone in the kitchen. Therefore, in all the worlds considered possible at that scenario, there is someone in the kitchen. Among all those worlds, it might also be possible to consider that there is someone else in the living room, since the only well known fact is that there is someone in the kitchen. If presence at the living room can be determined, and it can be concluded that there is not anybody in there, the world in which there is someone in the living room is no longer considered possible.

Recalling the concept of context, it is here understood as the set of facts or propositional knowledge that describes a specific state of the world, in the same way that J. Allen’s refers to the concept of *world* in [3]. This concept is represented by a set of descriptions of both the static and dynamic aspects of the world, therefore modeling what is known about the past, present, and future. By using the J. Allen nomenclature, the static aspects of the world are easily captured as *properties* while dynamic aspects are captured by *occurrences* or *events*.

The notion of *multiple contexts* is closely related to that of possible worlds and it refers to the mechanism used to concurrently handle the possible-world semantics at the knowledge-base level. According to the model proposed for the semantic dimension of the context, the multiple-context mechanism supports action and event modeling by describing the state of the world before, during, and after the action or event took place. Provided that world changes, or the world dynamics, is determined by the events or occurrences that take place in it, it is therefore sensible to model actions and/or events in terms of the world-states that are involved, before, during, and after the event or action takes place. For example, a `person moving` event gives rise to a new world state in which the person that moves has changed his/her location. If a person moves from the kitchen to the living room, the world-state before the event takes place is described by the person being present at the kitchen, meanwhile the world state after the event takes place is described by the fact that the person is now located at the living room. Now, think for a moment that the person, before moving, decides to take up an object; given this scenario, could you be able of correctly answering where the object is after the moving event? Moreover, what if now, the object is known to be slippery, what will happen then?

Answering to these questions involves holding a great deal of implicit knowledge known as common sense. Ideally, this type of knowledge is contained at the pragmatic dimension of the context model, that not only involves implicit knowledge about how the world works, but also the explicit knowledge about the context domain. Further in this chapter, the difference between implicit and explicit knowledge is detailed analyzed. Meanwhile, for contextualization purposes think of the following scenarios extracted from [36] in which the implicit knowledge hold by humans, so called common-sense knowledge, plays an essential role in understanding the situation:

1. In the kitchen, Lisa picked up the newspaper and walked into the living room.
2. Lisa put a book on a coffee table and left the living room. When she returned, the book was gone.
3. Jamie walks to the kitchen sink, puts the stopper in the drain, turns on the faucet, and leaves the kitchen.
4. Kimberly turns the fan's power switch to "on".

In the first scenario, it is easily inferred that since Lisa was intially in the kitchen, she picked up the newspaper while she was there and then took it into the living room. It is also obvious to us that if Lisa is in the kitchen she cannot be in any other room at the same time, since we are considering rooms as non-overlapping spaces in a house. With regard to the second scenario, we can easily infer that if Lisa left the living room, she is no longer there, and that if the book is not there when she returns, something must have happened because things tend to remain in the state they are unless a partiuclar event affects them. The *frame problem* concerns about the determination of those things that can be assumed to stay the same from one moment to another. In the third scenario we easily conclude that, after a while, the water will start spilling onto the floor. Finally, with regard to the question of what will happen in the fourth scenario, we can assume that if everything works as it is supposed to, the fan will start up.

These examples make evident the need to involve common-sense knowledge when it comes to interpret context events. Analyzing in isolation, or even taking into account correlative patterns among context events might help in recognizing certain set of simple activities. However, when more sophisticated situations take place in the context, which by the way are those that have traditionally required from human supervision, only by resorting to the implicit knowledge can they be susccessfully addressed, resembling human responses.

7. Possible worlds and multiple contexts semantics

The task of understanding context situations is indubitably related to that of interpreting the information retrieved from the sensorial sources deployed at the supervised environment. Roughly speaking, it can be said that the context dynamics are captured by the

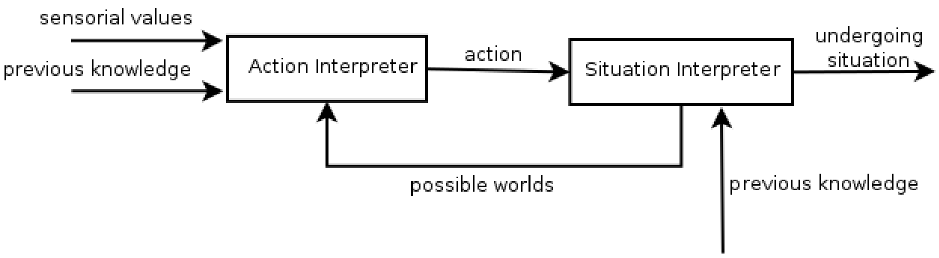

Figure 4. Overall view of the process of sensorial information understanding.

environmental sensors, in such a way that context changes are translated into new sensor measurements. The other way round, changes in the values sensed by the environmental sensors can be suggesting that changes are taking place in the context. Considering that context changes are produced by the undergoing actions or events, the task of translating context information into undergoing situations consists in devising the most appropriate set of actions that comply with the sense values and the knowledge that it is already known.

Figure 4 depicts the overall process involved in mapping context gathered data into situations that are likely to be taking part in the supervised context. As it can be noticed from the same figure, the first stage of the process consists in determining the actions that are occurring in the context, based on a combination of the sensed information and the implicit and explicit knowledge about the context. On the basis of the identified actions, and the previous knowledge, it can be feasible to determine the state of affairs that might be compatible with such information. In other words, provided the identified actions and the domain and implicit knowledge, it is plausible to determine the set of possible worlds that are compliant with such information.

The proposed approach for context understanding therefore consists in modeling actions and situations in terms of the possible worlds before, during, and after they take place. These descriptions are afterward employed in seeking for those actions or situations that match the current state of the context. Those worlds that comply with the context description are considered to be possible worlds. Finally, only those actions or situations that have been described to be compatible with those worlds considered possible are suggestive to be possible interpretations of the undergoing situation.

Despite the fact that the theory of possible worlds is undeniably associated to agents, yet nothing has been said about the role they played in the theory of possible worlds. Regardless of how agents are implemented, they are expected to hold the knowledge about both, the context dynamics and the previous and implicit knowledge that also describe the context domain. Particularly, the use of possible worlds for context understanding in Ambient Intelligence expects the environment itself to behave as an agent. In this sense, it is the sensorial devices responsibility to gather the new knowledge that evidence the occurrence of actions. Additionally, it is also its responsibility to combine this new knowledge, so called explicit knowledge, with the previous and implicit knowledge that could lead to more complex inferences. Finally, and what it is more important, that previous knowledge contains information that lead the environment behavior, as it is the information regarding the goals, intentions, and beliefs of the agent.

Having said that the agent previous knowledge do also hold information about the goals and intentions it pursues, it seems obvious that the most suitable approach for implementing this type of agents is that based on a BDI model of agency. Additionally, the previous chapter already did introduce the role of the *Context Manager* in charge of gathering the information provided by the environmental data. Consequently, this agent can easily assume the role of combining such information with the existing knowledge, resulting in a set of worlds that are considered possible for complying with the specifications of the current state of affair. Finally, those situations that lead to any of those worlds considered possibles are suggestive of matching the undergoing situation.

7.1. The multiple context mechanisms for describing actions and events

Before getting into the insights of the responsibilities attached to the Context Manager agent, it is necessary to describe how the formal theory of possible worlds is translated into a concrete implementation solution. In this regard, the intention of this subsection is to describe how knowledge should be stated using a possible world approach rather than adopting a propositional perspective, and how, when combined with common-sense knowledge, it can lead to the statement of an *accessible worlds* network. Summarily, this accessible world network supports the identification of those situations that might be compliant with the worlds that are considered possible at each different state of affair of the context.

The first steps therefore consists in identifying all the different possibles worlds. In order to do that, and provided that changes occur as a result of action or event occurrence, the task of identifying possible worlds is therefore addressed as a task of describing how actions cause those worlds to evolve from one state to a different one. This approach is inspired in the work of Moore, who in [35] presents a formalization approach for action description based on the theory of possible worlds. Such a formalization approach can be extrapolated and integrated into a different theory, as it the *multiple-context mechanism* proposed by Fahlman in [15].

The multiple-context mechanism is provided as an essential feature of the Scone Knowledge-Base system. As for the possible world theory, the multiple context mechanism allows the representation of different state of affairs, that simultaneously concur in the same knowledge-base, without leading to inconsistencies. Please, notice that one of the main objectives with which Scone was conceived for was to emulate humans' ability to store and retrieve pieces of knowledge, along with matching and adjusting existing knowledge to similar situations. To this end, the multiple-context mechanism implements an effective means to tackle this objective. The multiple-context mechanism also provides an efficient solution by which to tackle a classical problem of Artificial Intelligence, as it is *frame problem*. The multiple context mechanisms permits the instantiation of new context as *virtual copies* of existing ones. Additionally, in any of those context it is possible to state those aspects that do not hold as well as the new circumstances that might be relevant for the context description. The fact that a virtual copy behaves as a real copy but it does not requires to physically replicate such information provides a very compelling mean to address the aforementioned *frame problem*

In any case, the great potential of the multiple-context mechanism used by Scone can be better stated by using the example provided by Fahlman in [15]. The provided simile resorts to the Harry Potter novel, in which a fictitious world is presented in which, for example, brooms can fly. This example is specially descriptive because Harry Potter spends time in both worlds, the *wizarding* and the real (or *muggle's* world). Information about these two worlds have to necessarily be kept in the knowledge-base.

Since the "Harry Potter World" (or *wizarding* world) is quite similar to the real world, a new context, "HPW", can be created as an instance of the real world[4]. As it has been already mentioned, there are differences between these two contexts, such as the fact that in the "HPW" context a broom is a vehicle. This fact can be easily stated in the "HPW" without affecting real world knowledge, in the same way that knowledge of the real world could be cancelled so as to not be considered in the "HPW" context. The way in which Scone handles multiple contexts so as to avoid incongruence problems is by **activating one context at a time**. By doing this, only the knowledge contained in the active context is considered for the reasoning and inference task.

Unless otherwise stated, the knowledge described in a parent context is inherited by the child context. The context itself is also a node and, like the other the nodes, it stores a set of maker-bits. One of these marker-bits is the context-marker. This bit, when enabled, determines the activation of all the nodes and links that are connected to the active context.

Aside from the role that the multiple-context mechanisms plays in supporting the possible world theory, what it is more important, is the role it plays in describe actions and events. Representing actions and events in Scone simply consists of defining three new contexts, one describing the world before the action or event takes place and another that represents the state of the world afterward, and the one that describe the world properties that hold all along the action performance. In this sense, each of these context can be conceived as a possible world, in which the `after` context world is accessible from the `before` context goal when the described action takes place. The following example describes a simplified definition of the `move` event using a syntax similar to that employed by Scone.

```
NEW—EVENT move
  :roles
    origin is a place
    destination is a place
    moving—object is a person
  :throughout
    origin differs from destination
  :before
    moving—object is located in origin
  :after
    moving—object is located in destination
```

In accordance to the aforementioned representation of the `move` event, the propositional knowledge describing the explicit fact of Lisa moving, expressed as `Lisa moves`, can be also presented as an individual instance of the `move` event. This individual instance corresponds to the specific occurrence of Lisa moving from the kitchen to the living room.

---

[4] Using the Scone terminology, "general" is the context node that holds knowledge about the real world, and "HPW" would be an individual node, connected by an is-a link to the "general" node.

The declaration of a new instance of the type `move` event implies that, the new instance named `Lisa moves` inherits the implicit knowledge of the upper type, the `move` event. Provided that the origin and destination of the `Lisa moves` event have been set, respectively to `kitchen` and *living-room*, the Scone Knowledge-Base can be queried about the location of Lisa at two different time instant or at two different *worlds*, one before the action takes place and another, after it takes place. Please, notice how the Knowledge-Base consistency is not affected by that fact that Lisa's location is set to two different places. The use of multiple-context allows the Knowledge-Base to hold and manage *a priori* inconsistent information in an simple and efficient manner.

```
NEW—EVENT—INDV Lisa moves INSTANCE—OF move
THE origin OF Lisa moves IS kitchen
THE destination OF Lisa moves IS living—room
THE moving—object OF Lisa moves IS Lisa
IN—CONTEXT before
STATEMENT—TRUE? Lisa is in living—room
  => No
GET the location of Lisa
  => kitchen
IN—CONTEXT after
STATEMENT—TRUE? Lisa is in living—room
  => Yes
```

The answers provided by the Scone system depends on the context that is active at that moment. In this sense, when the active context is set to be the `before` context, the location of Lisa is therefore stated to the be the `kitchen`. Whenever the active context changes to the `after` context, the location of Lisa is also changed to be the `living-room`.

The most relevant feature of the multiple-context mechanism implemented by Scone is that it supports the construction of a context network along with a context activation scheme. It means that, depending on the desired information, different contexts are activated and deactivated. This feature is particularly important for implementing some of the key issues of common sense that are related to the effects of events.

As it has already been mentioned, the effects of events are described in the `after` context of the event description. However, this statement needs to be more elaborated when the considered event involves other than direct effects, as it might be, indirect, canceling, or delayed effects. The following subsections described the mechanism that have been implemented upon Scone in order provide support to these sort of complex effects.

7.1.1. Direct effects of events

In order to illustrate the Scone support for representing direct effects of events, one of the examples presented in [36] is recalled here:

> "*Given that Lisa picked up the newspaper, and this piece of common-sense knowledge, we should be able to infer that Lisa was then holding the newspaper.*"

The previous examples have used a syntax similar but not equal to the one proposed by Scone. However, the following examples are using the Scone syntax. It has to be clarified that the description of some events involves the statement of some additional elements, or *roles*, as they are called in Scone. For example, the description of the `take up` event involves several roles, as they are the role that represents the object being picked in the described action, or the place in which the object is being taken up. These roles should be instantiated whenever a new instance of such an event is created.

```
(IN-CONTEXT {general})
(NEW-EVENT-TYPE {take up} ’({event})
                         :ROLES
                         ((:TYPE {pickedObject} {thing})
                          (:TYPE {pickedObjectLocation} {place})
                          (:TYPE {pickerLocation} {place})
                          (:TYPE {picker} {person}))
  :THROUGHOUT
  ((NEW-EQ {picker} {person})
   (NEW-EQ {personlocation} {pickerlocation})
   (THE-X-OF-Y-IS-Z {personlocation} {picker} {pickerlocation}))
  :BEFORE
  ((IN-CONTEXT (NEW-CONTEXT {take up bc}))
   (NEW-STATEMENT {picker} {is located at} {pickedObjectLocation})
   (NEW-STATEMENT {pickedObject} {is located at} {pickedObjectLocation})
   (THE-X-OF-Y-IS-Z {pickerLocation} {take up} {pickedObjectLocation})
   (NEW-EQ {pickerLocation} {pickedObjectLocation})
   (NEW-EQ {personLocation} {pickerLocation}) )
  :AFTER
  ((IN-CONTEXT (new-context {take up ac}))
   (NEW-STATEMENT {picker} {is located at} {pickerLocation})
   (THE-X-OF-Y-IS-Z {pickedObjectLocation} {take up} {pickerLocation})
   (NEW-STATEMENT {pickedObject} {is located at} {pickerLocation})
   (NEW-EQ {pickedObjectLocation} {pickerLocation})
  (NEW-STATEMENT {picker} {is holding the} {pickedObject})))
```

The above code listing describes the `take up` event in terms of the possible worlds involve before, after, and thorough the event occurrence. For example, it can be mentioned that all along the action performance, the role assumed by the `picker` is equally treated to a person. Additionally, it can be said about the `before` context that the `picker` is located at the same place as the object that assumes the role of the picked object. Please, notice that the set of statements that comprise the `before` context description are basically devoted to describe a world in which both the person that is going to pick the object, and the object that is going to be taken up, are in the same location. In other words, in order for a person to take up an object, the person should approach the object to its proximity, so that s/he can reach it. The description of the `after` context shows a world in which the location of the picked object is now determined by the location of the person that has taken up the object. Additionally, it can be therefore stated that the person is holding the object.

The following code listing describes how an instance of such an event can be created, and how implicit knowledge is inherited from the upper event type, as it is the `take up` event, leading to important conclusions.

```
CL-USER> (NEW-EVENT-INDV {Lisa takes up} {take up})
{events:Lisa takes up}
```

```
CL-USER> (IN-CONTEXT {take up bc})
{events:take up bc}

CL-USER> (THE-X-OF-Y-IS-Z {pickedObject} {lisa takes up} {lisa
  newspaper})

CL-USER> (THE-X-OF-Y-IS-Z {picker} {lisa takes up} {lisa})

CL-USER> (STATEMENT-TRUE? {lisa} {is holding the} {lisa newspaper})
NIL

CL-USER> (IN-CONTEXT {take up ac})
{events:take up ac}

CL-USER> (STATEMENT-TRUE? {lisa} {is holding the} {lisa newspaper})
{events:picker is holding the pickedObject (0-2655)}
```

The first sentence is intended to create a new instance of the type `take up` event. Additionally, the roles involved in such an event are instantiated so as to assign the `Lisa newspaper` to the role of `pickedOjbect` and the role of `Lisa` to be the `picker`. Afterward, yet under the `before` context, the Scone system is queried about the truth value of the proposition that states that *Lisa* is holding the *Lisa newspaper*. As it can be noticed, Scone determines that this propositional statement is false at the `before` context. However, if the active context is changed to the `after` context, then the same query affirms that `Lisa` is holding the `Lisa newspaper`.

7.1.2. Context sensitive effects

A bit more complex to describe are those effects that change upon varying context circumstances. Think, for instance, in the example stated by Mueller in [36]:

> “*We should be able to represent that, if a person picks up a slippery object and is not careful, then the person will not be holding the object.*“

In order to achieve this requirement, the `take up` event needs to be described in such a way that an additional `after` context is described for each of properties that are leading to different effects. For example, one of these susceptible properties is the level of attention paid when holding the object. In this sense, the previous description of the `take up` event needs to modified in order to include a new context that describes the situation in which the slippery object is hold with careful attention.

```

:AFTER
   ((IN-CONTEXT {take up ac})
   (NEW-STATEMENT {picker} {is located at} {pickerLocation})
   (THE-X-OF-Y-IS-Z {pickedObjectLocation} {take up} {pickerLocation})
   (NEW-STATEMENT {pickedObject} {is located at} {pickerLocation})
   (NEW-EQ {pickedObjectLocation} {pickerLocation})
   (NEW-STATEMENT {picker} {is holding the} {pickedObject})

  (IN-CONTEXT (NEW-CONTEXT {take up slippery object ac} {take up ac}))
   (NEW-STATEMENT {picker} {is located at} {pickerLocation})
   (NEW-STATEMENT {pickedObject} {is located at} {pickerLocation})
```

```
   (NEW-NOT-STATEMENT {pickedObject} {is located at} {pickerLocation})
   (NEW-STATEMENT {pickedObject} {is located at} {pickerLocation})
   (NEW-NOT-STATEMENT {pickedObject} {is located at} {pickerLocation})
   (NEW-STATEMENT {picker} {is holding the} {pickedObject})
   (NEW-NOT-STATEMENT {picker} {is holding the} {pickedObject})

   (IN-CONTEXT (NEW-CONTEXT {take up slippery object with attention
     ac}  {take up ac}))
   (NEW-STATEMENT {picker} {is located at} {pickerLocation})
   (THE-X-OF-Y-IS-Z {pickedObjectLocation} {take up} {pickerLocation})
   (NEW-STATEMENT {pickedObject} {is located at} {pickerLocation})
   (NEW-EQ {pickedObjectLocation} {pickerLocation})
   (NEW-STATEMENT {picker} {is holding the} {pickedObject})))
```

Please, notice how the `take up ac` context describes those aspects of the `take up` event that satisfies independently of the circumstances that might affect some other effects of the event. Additionally, it is also worth mentioning the fact that it cannot be stated that the `picker` is holding the object in the `after` context due to the fact that attention has not been paid. On the contrary, when circumstances suggest that the `picker` is paying attention to the action, then it can be asserted that the effect of taking up the slippery object with attention is that of the person holding the object.

Creating a new instance of the `take up` event now involves determining the `after` context that should be applied, on the basis of the context sensitive property, that as stated above, is determined by the level of attention. The following code listing describes how to accomplish the election of the appropriate `after` context, by evaluating the truth value of the statement that describes the level of attention of the `picker`.

```
  CL-USER> (if (IS-X-A-Y? (GET-THE-X-OF-Y-IN-CONTEXT {pickedObject}
                {lisa takes up a slippery object})  {slippery object})
    (if  (STATEMENT-TRUE? {lisa} {pays attention to}
         {lisa takes up a slippery object})
         (THE-X-OF-Y-IS-Z {after context} {lisa takes up a slippery
           object} {take up slippery object with attention ac})
         (THE-X-OF-Y-IS-Z {after context} {lisa takes up a slippery
           object} {take up slippery object ac}))
         (THE-X-OF-Y-IS-Z {after context} {lisa takes up a slippery
           object} {take up ac}))

  {events:take up slippery object ac is the after context of Lisa
    takes up a slippery object (0-2696)}
```

Since, at this stage nothing has been said about *Lisa* paying attention to the action of taking up a slippery object, the `after` context that should be inherited is that of taking up a slippery object, without paying attention. On the contrary, something could have been said about the level of attention being paid, as it is shown in the following code listing:

```
CL-USER> (NEW-STATEMENT {picker} {pays attention to} {take up})
{events:picker pays attention to take up (0-2695)}

CL-USER> (if (IS-X-A-Y? (get-the-x-of-y-in-context {pickedObject}
              {lisa takes up a slippery object})  {slippery object})
```

```
             (if (STATEMENT-TRUE? {picker} {pays attention to} {take up})
                 (the-x-of-y-is-z {after context} {lisa takes up a
                   slippery object} {take up slippery object with
                   attention ac})
                 (THE-X-OF-Y-IS-Z {after context} {lisa takes up a
                   slippery object} {take up slippery object ac}))
             (THE-X-OF-Y-IS-Z {after context} {lisa takes up a
               slippery object} {take up ac}))

{events:take up slippery object with attention ac is the after
  context of Lisa takes up a slippery object (0−2697)}
```

The above code is particularly devoted to selecting the appropriate `after` context given the current context circumstances. However, this can be easily generalized so as to be applied to whatever the events that are subject to the value of changing context properties. In any case, the following code listing depicts how the changes suffered by those properties might affect the effects caused by the event.

```
CL-USER>(GET-THE-X-OF-Y {after context} {lisa takes up a slippery object})
{events:take up slippery object with attention ac}

CL-USER> (in-context (GET-THE-X-OF-Y {after context} {lisa takes up a
  slippery  object}))
{events:take up slippery object with attention ac}

CL-USER> (STATEMENT-TRUE? {lisa} {is holding the} {wet glass})
{events:picker is holding the pickedObject (0−2644)}
```

In this example, provided that a statement had been asserted about the fact that the `picker` is paying attention to the `take up` event, when the Scone system is queried about the truth value of a propositional fact stating that the `picker` is holding the object being taken up, it concludes that it is true due to the propositional knowledge it returns as proof of fact.

7.1.3. Nondeterministic effects

Sometimes, the effects of events cannot be determined beforehand for several reasons. For example, in the context sensitive effects, whenever the value of those properties that determine the effects are unknown, it is not possible to determine which context to apply. In this sense, Mueller proposes the following call:

> "*We should be able to represent that if a person picks up a slippery object, then the person may or may not be holding the object*"

In order to address such a requirement, the previous description of the `take up` action needs now to be enhanced with that general knowledge that affects the situation in which the `take up` event involves a slippery object, yet ignoring the context sensitive circumstances that might determine whether the `picker` is paying or not enough attention.

```
:AFTER
  (
```

```
  [...]
   (IN-CONTEXT (NEW-CONTEXT {take up slippery object ac} {take up ac}))
   (NEW-STATEMENT {picker} {is located at} {pickerLocation})
   (NEW-STATEMENT {pickedObject} {is located at} {pickerLocation})
   (NEW-NOT-STATEMENT {pickedObject} {is located at} {pickerLocation})
   (NEW-STATEMENT {pickedObject} {is located at} {pickerLocation})
   (NEW-NOT-STATEMENT {pickedObject} {is located at} {pickerLocation})
   (NEW-STATEMENT {picker} {is holding the} {pickedObject})
   (NEW-NOT-STATEMENT {picker} {is holding the} {pickedObject}))
```

There are several aspects that might vary in the world of which taking up a slippery from that in which the object is not slippery. As it can be noticed from the previous code listing, it cannot be stated beforehand that after the `take up` event, both the `picker` and the `pickedObject` are going to be located in the same place, since it might be possible for the object to drop off and end up on the floor.

The way of determining which `after` context to apply is similar to the one described above, although a new after context comes into play to describe the situation in which nothing has yet been said about attention.

```
CL-USER> *CONTEXT*
{common:general}

CL-USER> (if (IS-X-A-Y? (GET-THE-X-OF-Y-IN-CONTEXT {pickedObject}
              {lisa takes up a slippery object})  {slippery object})
               (if (statement-true? {lisa} {pays attention to}
                    {lisa takes up a slippery object})
                     (THE-X-OF-Y-IS-Z {after context} {lisa takes up a
                       slippery object} {take up slippery object with
                       attention ac})
                     (THE-X-OF-Y-IS-Z {after context} {lisa takes up a
                       slippery object} {take up slippery object ac}))
                     (THE-X-OF-Y-IS-Z {after context} {lisa takes up a
                       slippery object}  {take up ac}))
{events:take up slippery object ac is the after context of Lisa takes
  up a slippery object (0-2693)}

CL-USER>  (IN-CONTEXT (GET-THE-X-OF-Y {after context} {lisa takes up a
  slippery object}))
{events:take up slippery object ac}

CL-USER> (STATEMENT-TRUE? {lisa} {is holding the} {wet glass})
It cannot be predicted because: {events:Not picker is holding the
  pickedObject (0-2638)} AND  {events:picker is holding the
  pickedObject (0-2637)}

CL-USER> (STATEMENT-TRUE? {wet glass} {is located at} {living-room})
It cannot be predicted because: {events:Not pickedObject is located at
  pickerLocation (0-2636)} AND {events:pickedObject is located at
  pickerLocation (0-2635)}
```

The previous examples shows the mechanism that it has been built upon Scone in order to provide support for describing and managing the nondeterministic effects of events. As it can be seen from the previous code listing, the fact that the same statement is said to be true and false leads the system to conclude that the truth value of such statement cannot be determine given the knowledge hold by the system at that moment.

7.1.4. Effects of concurrent events

So far, the descriptions of the effects of event has been only concerned about describing events as occurring in isolation. However, this is not a realistic vision, and on the contrary, events need to be described considering the collateral occurrence of events. The majority of the events that are concurrently taking place do not have an impact on each other, although there are some other situations in which the effects of a certain event might be affected by the concurrent occurrence of a different event. In this sense, Mueller states the following:

> "*We should be able to represent that certain concurrent events are impossible; for example, a person cannot walk into two rooms simultaneously.*"

Firstly, it is necessary to describe a new event type as it is the `walk into` event, which inherits from the `walk` and `walk to` events, which for the sake of concreteness have not been listed here.

```
(IN-CONTEXT {general})
(NEW-EVENT-TYPE {walk into} ’({action} {walk} {walk to})
                :roles
                ((:type {enteringRoom} {Room}))

 :THROUGHOUT
 ((NEW-IS-A {enteringRoom} {enclosed space}))
 :BEFORE
   ((IN-CONTEXT (new-context {walk into bc}))
    (NEW-STATEMENT {walker} {is located at} {from})
    (NEW-STATEMENT {from} {is connected to} {enteringRoom})
    (THE-X-OF-Y-IS-Z {walkerLocation} {walk into} {from}))
 :AFTER
   ((IN-CONTEXT (new-context {walk into ac}))
    (NEW-STATEMENT {walker} {crosses across}
      (GET-THE-X-ROLE-OF-Y {doorway} {enteringRoom}))
    (NEW-STATEMENT {walker} {is in} {enteringRoom})
    (NEW-STATEMENT {walker} {is located at} {enteringRoom})
    (THE-X-OF-Y-IS-Z {walkerLocation} {walk into} {enteringRoom})))
```

The reason why a person cannot enter two different rooms at the same time is a direct consequence of the physical space property and the space and position that objects occupy in that physical space. In this sense, the following code listing describe how both rooms, the `kitchen` and the `living-room` are stated as two different rooms that cannot be considered equal.

```
(IN-CONTEXT {general})
(NEW-INDV {kitchen} {Room})
(NEW-INDV {living-room} {Room})
(NEW-NOT-EQ {living-room} {kitchen})

(NEW-EVENT-INDV {Lisa walks into} {walk into})
```

```
(IN-CONTEXT {walk into bc})
(THE-X-OF-Y-IS-Z {from} {Lisa walks into} {bedroom})

(IN-CONTEXT {walk into ac})
(THE-X-OF-Y-IS-Z {enteringRoom} {Lisa walks into} {kitchen})
```

Provided that both rooms are different, the following code listing describes the event of Lisa entering a room. Please, notice that this example is focused at describing how concurrent events can be addressed in Scone. For that reason, the examples showed here overlook some relevant aspects such as those involving time. Nevertheless, those aspects will be later on described in the following section.

```
CL-USER> (IN-CONTEXT {walk into ac})
{events:walk into ac}

CL-USER>(STATEMENT-TRUE? {lisa} {is located at} {kitchen})
{events:walker is located at enteringRoom (0-1946)}

CL-USER> (STATEMENT-TRUE? {lisa} {is located at} {living-room})
NIL

CL-USER>(STATEMENT-TRUE? {lisa} {is located at} {bedroom})
NIL

CL-USER> (THE-X-OF-Y-IS-Z {enteringRoom} {lisa walks into} {living-room})
{events:living-room} cannot be the {events:enteringRoom} of
{events:Lisa walks into}.  Continuing...
NIL
```

Having said that the previous sentences are considered to take place at the same time instant, the last sentence shows how the Scone system rejects to assert the propositional statement that would make Lisa to enter both rooms at the same time. In this sense, last sentence is intended to assert the fact that Lisa is walking into the living room. However, Scone fails to assert such statement because previously, the `enteringRoom` role of the `Lisa walks into` event had been set to `kitchen`. Since `kitchen` and `living room` are not equivalent, and since a person cannot enter two different locations at a time, Scone returns a message notifying of this failure attempt.

If both rooms would have been described as equivalent rooms, for example, a room working as a kitchen and living at the same time, it is possible for a person to enter both rooms at the same time, because these two rooms are spatially equivalent.

Besides from those effects of events that cannot take place concurrently, there are some other type of effects of events that, when globally considered produce a different result from the one that it would be expected if the event would have been considered individually or in isolation. One of those type of effects are the cumulative or canceling effects of events. In this sense, Mueller states that:

> "*We must be able to reason about concurrent events with cumulative or canceling effects. For example, if a shopping cart is pushed, it moves forward. If it is pulled, it moves backward. But if it is simultaneously pulled and pushed, then it moves neither forward nor backward; instead, it spins around.*"

In this sense, in order to determine whenever the effects of a certain event are getting canceled, it is necessary to state in first place, which other events are capable of producing canceling effects to the first one. In this sense, the a new relation type has been defined in order to enumerate those other events that are producing canceling events. The “`cancel effects of`” relationship is a transitive relation intended to establish those pair of actions that are producing canceling effects. Additionally, a new function needs to be defined in order to, not only determine whenever canceling or cumulative effects might take place, but also responsible for devising how the new `after` context would be as a result of these concurrent effects of events taking place. The following function is therefore intended to combine and produce the after context resultant from several concurrent events taking place.

```
(defun GET—THE—AFTER—CONTEXT—OF—CONCURRENT—EVENT (x y z)
  "Get the resultant after context of a compound event"
  (setq x_ac (GET—THE—X—OF—Y {after context} x))
  (if (not (IS—X—A—Y? x {compound event}))
      (format t "~A should be a compound event" x)
      (if (STATEMENT—TRUE? y {cancels effects of} z)
          (progn
            (format t "~A cancels the effects of ~A" y z)
            (setq current_context *context*)
            (IN—CONTEXT x_ac)
            (NEW—STATEMENT y {cancels effects of} z)
            (IN—CONTEXT current_context))
          (progn
          (with—temp—markers (m m1)
              (loop for i in (list—context—contents
              (GET—THE—X—OF—Y {after context} y))
                do(progn
                      (MARK—CONTEXT—CONTENTS
                      (GET—THE—X—OF—Y {after context} y) m)
                      (mark—context—contents
                      (GET—THE—X—OF—Y {after context} z) m1)
                      (loop for j in (list—marked m)
                         do (connect—wire :context (lookup—element j)
                         (lookup—element x_ac)))
                      (loop for j in (list—marked m1)
                         do (connect—wire :context (lookup—element j)
                         (lookup—element x_ac))))))))))
```

The following code listing describes how such function can be applied to an instance of an event of type`push` and `pull`, as it is `pullandpush` event, that concurrently occur.

```
CL-USER> (get-the-after-context-of-concurrent-event  {pullandpush}
         {push} {pull})
         {push} cancels the effects of {pull}
{common:general}

CL-USER> (list-context-contents {pullandpush ac})
({events:push cancels effects of pull (0−1996)})
```

As it can be seen from the previous code listing, a new `after` context has been created so as to include the effects of the two events, `push` and `pull`, when concurrently performed. In this particular case, it states that the `push` effects are canceled by the `pull` ones.

7.1.5. Indirect effects

There are some other type of events whose effects might also affects third party objects, in an indirect manner. In order to illustrate this aspect, Mueller recall the same example used for the direct effects of events, that of Lisa taking up an object. However, now the focus is at proving that, as an indirect effect of the `take up` event, the picked object changes its location along with the picker.

> *"Where did the newspaper end up? It ended up in the kitchen" We know that, if a person is holding an object, then the object moves along with the person.*

Scone has been enhanced with several functions in order to address the indirect effects of events. One of these functions is the one intended to provide a unique value to a property with changing values, which additionally can only hold one value at a time. For example, as mentioned above, the location property of an object is unique, and for that reason, assigning it a new value causes the previous one to be overwritten. In any case, the important aspect is here is the fact that only by changing the picker location property, it causes the picked object, that is the Lisa's newspaper, to also change its location, due to an indirect effect of Lisa holding that object.

```
CL-USER> (IN-CONTEXT {take up bc})
{events:take up bc}
CL-USER> (GET-THE-X-OF-Y-IN-CONTEXT {pickedObjectLocation}
  {Lisa takes up})
NIL
CL-USER> (GET-THE-X-OF-Y {pickedObjectLocation} {Lisa takes up})
{events:living-room}
CL-USER> (IN-CONTEXT {take up ac})
{events:take up ac}
CL-USER> (GET-THE-X-OF-Y {pickedObjectLocation} {Lisa takes up})
{events:living room}
CL-USER> (THE-ONLY-X-OF-Y-IS-Z {pickerLocation} {Lisa takes up} {Bedroom})
{events:bedroom is the pickerLocation of Lisa takes up (0−1901)}
CL-USER> (GET-THE-X-OF-Y {pickedObjectLocation} {Lisa takes up})
{events:bedroom}
CL-USER> (GET-THE-X-OF-Y {pickedObject} {Lisa takes up})
{events:Lisa newspaper}
```

7.1.6. Delayed effects and continuous change

Despite the fact that the description of the previous type of effects overlooks the role played by time, the description of the delayed effects and the continuous change can no longer obviate this issue. In this sense, the Scone approach for modeling and describing events needs to enhanced with the required capabilities to state how the effects of some events might take place all along a time interval, or at a specific time instant. Mueller proposes the following descriptive example:

"*Jamie walks to the kitchen sink, puts the stopper in the drain, turns on the faucet, and leaves the kitchen*".

In order to address this requirement, several functions proposed for the Event Calculus theory needs to be implemented. Recall that a the notion of *fluent* is used to describe those properties that change along time. Therefore, in order to determine the value of a fluent property, as it could be the height of the water level, it is necessary to describe how that fluent evolves along time, and at what specific time instant the property wants to be known. The following code listing describes the functions that have been provided to that endeavor:

```
(new—type {fluent} {thing})

(new—relation {holds at}
              :a—inst—of {fluent}
              :b—inst—of {time point})

(new—relation {releases at}
              :a—inst—of {fluent}
              :b—inst—of {time point})
```

```
(defmacro get-element-fluent (e fluent &optional
  (time-point *current-time-point*))
  (if time-point
     (setq fluent (read-from-string (concatenate
     'string (write-to-string fluent) "—at—" (remove #\} (subseq
     (write-to-string time-point) 1)))))) ‘(getf (properties ,e) ,fluent))
```

```
(defmacro eval—element—fluent (e fluent)
  ‘(eval (getf (properties ,e) ,fluent)))
```

These functions comprises an extract of the event calculus functions that have been implemented. Upon the description of the `turn on faucet` event, several conclusions can be achieved regarding the changing value of the water level property.

```
(NEW-EVENT-TYPE {turn on faucet} '({event} {turn on} {turn off faucet})
                                   :ROLES
                                   ((:INDV {turnedOnFaucet} {faucet}))
   :BEFORE
   ((IN-CONTEXT (NEW-CONTEXT {turn on faucet bc}))
    (NEW-STATEMENT {turnedOnFaucet} {status} {off}))
   :AFTER
   ((if(eq (GET-THE-X-OF-Y {sinkTapStatus} {faucetSink}) {opened tap})
       (progn
         (IN-CONTEXT (NEW-CONTEXT {turn on faucet ac}))
         (NEW-STATEMENT {turnedOnFaucet} {status} {on})
         (NEW-STATEMENT {faucetLiquid} {is being dropped through}
         (get-the-x-of-y {sinkPipe} {faucetSink})))
       (progn
         (IN-CONTEXT (new-context {turn on faucet ac}))
```

```
        (NEW-STATEMENT {faucetLiquid} {is contained in} {faucetSink})
        (IN-CONTEXT (new-context {turn on faucet DE}))
        (NEW-STATEMENT {faucetSink} {get overflowed with} {faucetLiquid})
        (NEW-STATEMENT {faucetSink} {is dropping} {faucetLiquid})))))
```

The following code listing shows how Scone can be enhanced with event calculus functions that entitle it to reason about the delayed effects of events and the continuous change.

```
CL-USER> (IN-CONTEXT {turn on faucet bc})
{events:turn on faucet bc}

CL-USER> (LIST-CONTEXT-CONTENTS *context*)
({events:LEVEL of faucetLiquid holds at instant T0 (0−2586)}
[...])

CL-USER> (in-context {turn on faucet ac})
{events:turn on faucet ac}

CL-USER> (list-context-contents *context*)
({events:LEVEL of faucetLiquid holds at instant T2 (0−2590)}
 {events:LEVEL of faucetLiquid releases at instant T1 (0−2589)}
 {events:faucetValve status on (0−2588)})
```

The activation of the `before` context describes a world in which, at a time instant labeled as `T0`, the water level does not change, since yet the tap has not been opened. Changing the active context to the `after` context, shows a world in which the water level will ultimately hold at time instant `T2`, however, it will be released from the common-sense law of inertia at time instant `T1`. It means that, at `T1` the water level changes its value according to function of time with which this fluent has been described. The following code listing shows an example of such function of time for the water level case.

```
CL-USER> (properties (lOOKUP-ELEMENT {faucetliquid}))
(:LEVEL-AT-INSTANT-T2 FULL :LEVEL-AT-INSTANT-T1 (* FLOW (/ T_S BASEAREA))
 :LEVEL-AT-INSTANT-T0 EMPTY :LEVEL FULL :ENGLISH-NAMES
 (("faucetLiquid" . :INVERSE-ROLE)))

CL-USER> *current-time-point*
{events:instant T1}

CL-USER> (GET-ELEMENT-FLUENT  (LOOKUP-ELEMENT {faucetliquid}) :level)
(* FLOW (/ T_S BASEAREA))

CL-USER> (GET-ELEMENT-FLUENT  (LOOKUP-ELEMENT {faucetliquid})
  :level {instant-t0})
EMPTY

CL-USER> (GET-ELEMENT-FLUENT  (LOOKUP-ELEMENT {faucetliquid})
  :level {instant-t2})
FULL

CL-USER> (GET-ELEMENT-FLUENT  (LOOKUP-ELEMENT {faucetliquid})
```

```
  :level {instant-t1})
(* FLOW (/ T_S BASEAREA))
```

As it can be seen from the previous code listing, the water level fluent changes its value depending on the considered time instant.

8. Description of the context understanding process

Figure 4 succinctly describes the overall process of understanding the activities that are being carried out in the context on the basis of the information retrieved from the environmental sensors and services. Basically, events take place in the context simultaneously causing the sensorial means to notice that changes. These changes result in new sensor values being populated and captured by the `Context Manager` agent. Recall that such agent is in charge of supervising all the information that is generated in the context by the sensorial mechanisms deployed in it.

Section 5 introduces the most relevant aspects of an approach intended to identify the occurrence of abnormal situations. In essence, the identification of abnormal situations is the first requirement that should be satisfy for a system intended to support Ambient Intelligence. Aside from the pre-coded reactions to foreseen situations, only when a situation has been considered abnormal is the system entitle to take some decisions intended to comply with the goals and intentions that have been enacted for that context. The decision about how to respond to that situation is also affected by the mechanisms that are available to implement the response.

This section therefore focuses at thoroughly describing the foundations of the situation characterization process. It has to be remarked that such process is mainly grounded in the distinction established among the different types of effects of events, described in the previous section. In this sense, the proposed approach does not only concerns about which events, in a direct manner, could be responsible for the captured effects, but rather, those effects have to also be analyzed from the perspective of the more complex effects caused by event occurrences, such as those involving delayed or canceling events, among some.

Despite the fact that a description of the characterization process is provided at the end of this section, for the sake of clearness, a case scenario is provided so as to illustrate the characterization process of some of the situations in which other than direct effects of events are involved.

8.1. A case scenario describing the understanding process

The following lines describe the events gathered by the `Context Manager` agent as a result of several sensors noticing the changes that are taking place in the context. At this point, it can be stated that the use of the word *event* has a twofold dimension. On the one hand, it refers to the general description of events in the sense of actions. On the other hand, it refers to a specific occurrence, and in this sense it is therefore assimilated to the effects noticed by a sensor device. Along this section, the following lines are indistinctly referred as events or effects of events, due to the twofold dimension already mentioned.

```
2011-05-02 00:59 presence-sensor-at-kitchen activated
2011-05-02 00:59 kitchen-lamp turned-on
2011-05-02 00:59 presence-sensor-at-bedroom activated
```

Whereas these events comprise the dynamic information of the context, the static dimension, so call the domain knowledge, has already been asserted to the Scone Knowledge-Base. It has to be mentioned that static information comprises several statements such as those describing that the above events take place in a house in which a single person lives. Let's say that Lisa is the person that lives in that house, and that she is an elder woman with some mobility problems that do not allow her to move too quickly along the house. Additionally, this is two-floor house in which the bedroom is located at the second floor and the kitchen at the first floor.

Provided the captured events and the information about the context domain, the characterization process is, at first, engaged at determining which set of events ϵ can lead the previous context situation, labeled as $\mathcal{S}_0$, to the situation in which presence is detected at both, the kitchen and the bedroom, and the kitchen lamp is turned on, also labeled as situation $\mathcal{S}_1$. In this sense, the purpose of the characterization process is to determine the unknown value ϵ, that refers to a set of events which, when applied to situation $\mathcal{S}_0$ results in the new situation or possible world equal or equivalent to $\mathcal{S}_1$:

$$effectOf(\epsilon, \mathcal{S}_0) = \mathcal{S}_1 \tag{9}$$

The method proposed for finding the value of ϵ consists in iteratively analyzing whether any of the different types of effects of events could explain the values gathered from the environmental sensors. The understanding process therefore consists in seeking for those events that respectively comply with both situations, $\mathcal{S}_0$ and $\mathcal{S}_1$, in their `before` and `after` context.

The first type of effects to be considered are the *direct effects of events*, with the purpose of determining whether there exists a single event that can connect the situation previously described as $\mathcal{S}_0$ to the one described in $\mathcal{S}_1$. In order to do so, Scone is queried about the existence of an event that complies with a `before` context equivalent to that represented by $\mathcal{S}_0$ and an `after` context equivalent to that represented by $\mathcal{S}_1$. Recall that situation $\mathcal{S}_0$ holds the following propositional knowledge:

1. Lisa is a person
2. Lisa's house is a house
3. Lisa habits Lisa's house

The situation $\mathcal{S}_1$ holds both, the propositional knowledge that describe situation $\mathcal{S}_0$, and the following statements:

1. A moving object is detected at the kitchen at time instant 2011-05-02 00:59
2. The kitchen lamp is turned on at time instant 2011-05-02 00:59
3. A moving object is detected at the bedroom at time instant 2011-05-02 00:59

The first step is therefore intended to seek for an events that match both situations with its `before` and `after` context, and for that endeavor the following function has been devised:

```
CL-USER> LIST-EVENTS(
        :BEFORE
          '(({Lisa} {is-a} {person}) ({Lisa house} {is-a} {house})
          ({Lisa} {habits in} {Lisa house}))
        :AFTER
          '(({movingObject} {is detected at} {kitchen} {2011−05−02 00:59})
          ({kitchen lamp} {status} {on} {2011−05−02 00:59})
          ({movingObject} {is detected at} {bedroom} {2011−05−02 00:59})))
```

The specificness of the propositional statements composing both worlds makes that no event satisfy the matching process. It is not surprising since the example has been purposely selected so as to show the potential of an approach that consider effects of events other than just direct ones.

The second stage of the characterization process consists in determining whether a concurrent effect of events are being involved in the situation described by both $\mathcal{S}_0$ and $\mathcal{S}_1$.

Due to the fact that considering the propositional knowledge of situations $\mathcal{S}_0$ and $\mathcal{S}_1$ as a whole has been unfruitful, the following approach consists in analyzing those events that could individually cause those events.

```
CL-USER> LIST-EVENTS(
        :AFTER
         '(({movingObject} {is detected at} {kitchen})))
```

As it can be noticed, the time stamp has been overlooked since, at this stage, the focus is at determining which events could cause an effect that is equivalent to the one just captured at the kitchen. The result provided by Scone enumerates a list of events that have such a statement in their `after` context. Those events are explored one by one, however, for the sake of concreteness, here, only the `walk into` event is described. In this sense, each of the resultant events are being activated and instantiated in order to evaluate whether they are or not plausible event occurrences. This means that the `walk into` event is instantiated by matching the roles defined for that event to the available individuals instantiated for that specific context, as they are `Lisa`, `Lisa house`, or `kitchen lamp` among some. The instantiation process results in the following individual event being proposed:

```
CL-USER> (NEW-EVENT-INDV {Lisa walks into} {walk into} {2011−05−02 00:59})
{events:Lisa walks into}

CL-USER> (IN-CONTEXT {walk into ac})

CL-USER> (THE-X-OF-Y-IS-Z {enteringRoom} {Lisa walks into} {kitchen})
```

Please, notice that nothing can be yet said about the location from which Lisa came from, since there is not any individual or statement that could lead to a match with the `from` role of the `walk into` event. The second events goes through the same process and leads to the statement of the same individual event, although matching the `enteringRoom` role to the `bedroom` rather than to the `kitchen` as happened with the previous event.

```
CL-USER> (NEW-EVENT-INDV {Lisa walks into} {walk into} {2011-05-02 00:59})
{events:Lisa walks into}

CL-USER> (IN-CONTEXT {walk into ac})

CL-USER> (THE-X-OF-Y-IS-Z {enteringRoom} {Lisa walks into} {bedroom})
```

Both individual events are two different instances of the same `walk into` event type that happen to occur at the same time instant. This example slightly differs from the one proposed when describing the impossible effects of events, in which, the same individual event role, the `enteringRoom`, was been assigned to two different and nonequivalent values. On the contrary, the current case scenario presents the existence of two different individual events which, at least `a priory`, do not seem to lead to any error or conflict. However, it seem obvious that Lisa cannot be at the kitchen and at the bedroom at the same time instant. Please, notice that only Lisa can assume the `movingObject` role since it is the only individual instance that can be equivalent to it.

Provided that both events can be *a priori* valid statements, there should be a mean to control this sort of situations. In this sense, and as it has already been mentioned in the previous chapter, this situation need to be controlled from the point of view of the common-sense knowledge about how certain fluents evolves along time. In this specific case, a person location is a fluent, since it is a property that change along time. The proposed approach for the determination of whether impossible effects of events are being involved is to turn the question into whether or not the fluents involved in the analyzed events are plausible.

The two instances of the `walk into` event which respectively state that Lisa walks into both the kitchen and the bedroom at the same time instant, are therefore evaluated from the perspective of the fluents that are involved in both events. The only fluent involved is the one concerning the person position. In this sense, at time instant t_0 Lisa position is at the kitchen, whereas at time instant t_1 Lisa is at the bedroom. Using the space utility implemented according to the OpenLS standard, the distance in meters in between the kitchen and the bedroom can be calculated, and it seems that there is a distance of 20 meters from the kitchen to the bedroom. The knowledge about Lisa that has been asserted to the Knowledge-Base does also include some information about the speed at which she moves, since, as it has already been mentioned she has some disabilities that makes hes to slowly move. In this case, Lisa is known to move at a speed of 1 km/h. Provided that Lisa is at kitchen at time instant t_0, she cannot be at 20 meter distant 0 seconds later, at time instant t_1, according to the function that describes how the fluent `person location` evolves along time according to her/his speed of movement.

After having explore the situation from the optic of the impossible effects of events, it can be concluded that the previous individual events cannot be asserted to the knowledge base due to the fact that they comprise two impossible effects of events. This failure means that the role matching process is not correct for the `movingObject` since it has lead to a impossible value of on of its fluents as it is the `movingObjectLocation`. Next step is therefore intended to seek for an additional instance of a `movingObject` type that can assume the role in the `walk into` event instance. If there would have been any additional instances of the `movingObject` type, such as for instance an animal or an additional person in the house, the same process had been carried out in order to determine the plausibility of the event instances in which they would enter the kitchen or the bedroom. However, there is not any additional instance of a moving object that can adopt the role in any of the two individual event. The followed approach then is to interpret these type of situations as though a moving object was present in the house. Therefore, a generic instance of a moving object is asserted to the Scone Knowledge-Base.

This changes the whole picture of situation t_1, that it is now faced from the perspective of a new statement, as it is the fact that a new moving object is present at the house. The assertion of a new statement causes the whole process to start from the beginning, at the light of the new information provided by the recently asserted fact.

Overlooking some aspects that do not lead to any relevant information, the characterization process reaches the point of determining which events are responsible for causing an `after` context in which a new moving object is present in the house. The `incoming guest` or the `overnight guest` events are two examples of events that cause the `after` context to assert that a person is present in the house. Now, the evaluation of the plausibility of those events do not bring into light any incompatibility, and therefore, a different context is created so as to hold the possibility of these events taking place. Each of these contexts are individually analyzed, undergoing through the same characterization process described in this section. It is omitted for the sake of conciseness, and just the most relevant aspects are being highlighted.

Following the same dynamics, the different effects of events are analyzed in order to determine whether they are or not involved in the situation being characterized. The last of the effects that is going to bring some additional light into the analysis are the context-sensitive effects of events. It seems obvious that it is not usual to receive a guest at past midnight, but how is that commonsensical knowledge articulated in this characterization process? Well, it could not be sensible to state that all guest arrives before midnight because it is not always true, so this fact needs to be state as a *typical* feature of the event. As it has already been mentioned, Scones provides an excellent support for dealing `typical` knowledge, that is, that type of common-sense knowledge that tend to be true but cannot be categorically affirmed since exceptions are possible. Making the most of the exception handling support by Scone, it is possible to assert information about the typical case without an additional cost, since it can be canceled by the specific instances. In this sense, it can be asserted that the typical `incoming guest` arrives before midnight.

This can be stated by resorting to the ability implemented upon Scone to handle the context-sensitive effects. An `after` context is defined to state that if it is past midnight, it is not true that a person enters the house. Otherwise, the `after` context that gets activated is that resulting in a new statement asserting that a person enters the house.

Due to the fact that it is past midnight the `after` context that applies is the one that states that in the typical case, a person does not enter the house. The fact that this event does not comply with the fact that there is a moving object in the house leads the process to abandon this path an explore other possibilities, such as the fact that a person is staying overnight. However, any of the explored path lead to a plausible justification of how a moving object is present in the house.

This example shows how after having explore all the possible worlds, the characterization process is not capable of determining the set of events ϵ that drives $\mathcal{S}_0$ to reach $\mathcal{S}_1$. In this cases, the situation is labeled as `abnormal` and the responsibility is delegated to the *Handler Agent*, which should adopts the most appropriate response to comply with the goals and intentions described for the considered context. These aspects are addressed in the following chapters. However, what does concerns the *Manager Agent* level is the responsibility of labeling the situation using any of the categories proposed for the different type of abnormal situation, recall the figure 5 in which an extract of the taxonomy is depicted.

9. Conclusions

This chapter has been devoted to proposing a comprehensive solution for context modeling and reasoning based on the impact that each level has on composing the final picture of the context. This proposal has been motivated by the conviction that the sole consideration of one of such dimensions does not suffice to capture the complete context picture. Nevertheless, most of the approaches presented to date focus in the semantic layer, using techniques such as ontologies or description logics. Overlooking the syntactic and pragmatic layer leads to poor context models. As result of such poor models, reasoning tasks are also very limited to the knowledge that can be extracted from the semantic layer. These shortages have motivated the need to propose an approach capable of dealing with the triple dimension of the context modeling.

The ultimate goal of this chapter is provide an holistic framework to be deployed in Ambient Intelligence, where a bottleneck is found at addressing unexpected situations. For that reason, not only foreseen situations or scenarios are considered here, but also unexpected ones. The context modeling strategy is specially concerned about how to characterize abnormal situations in such a way that they can be identified and addressed in terms of vague descriptions that are turning into concrete implementations.

Understanding the activities carried out in a context is a task that requires interpreting the effects of events captured from the sensors and services deployed at the context. In the most simple case, those effects are a direct consequence of an event occurrence, and therefore the understanding process basically consists in identifying all those effects that have been described to cause the captured effect. However, the most common case involves more complex effects of events, and therefore a more profound analysis is required so as to determine the set of events that have lead to a current situation.

An essential feature of the proposed approach is its foundation in the theory of possible world, and how it has been implemented by resorting to the multiple-context mechanism provided by Scone. With some enhanced function inspired in the possible world theory and a thorough description of the different types of effects of events it is possible to map effects into causing events as a mean to provide a plausible explanation of the situation that is taking place in the context.

It has to be remarked that unforeseen situations can be also addressed by means of this approach. In these situations, even when a plausible explanation cannot be provided, the system is capable of understanding that an abnormal situation is taking place.

References

[1] Varol Akman. V. lifschitz, ed., formalizing common sense: Papers by john mccarthy. *Artificial Intelligence*, 77(2):359–369, 1995.

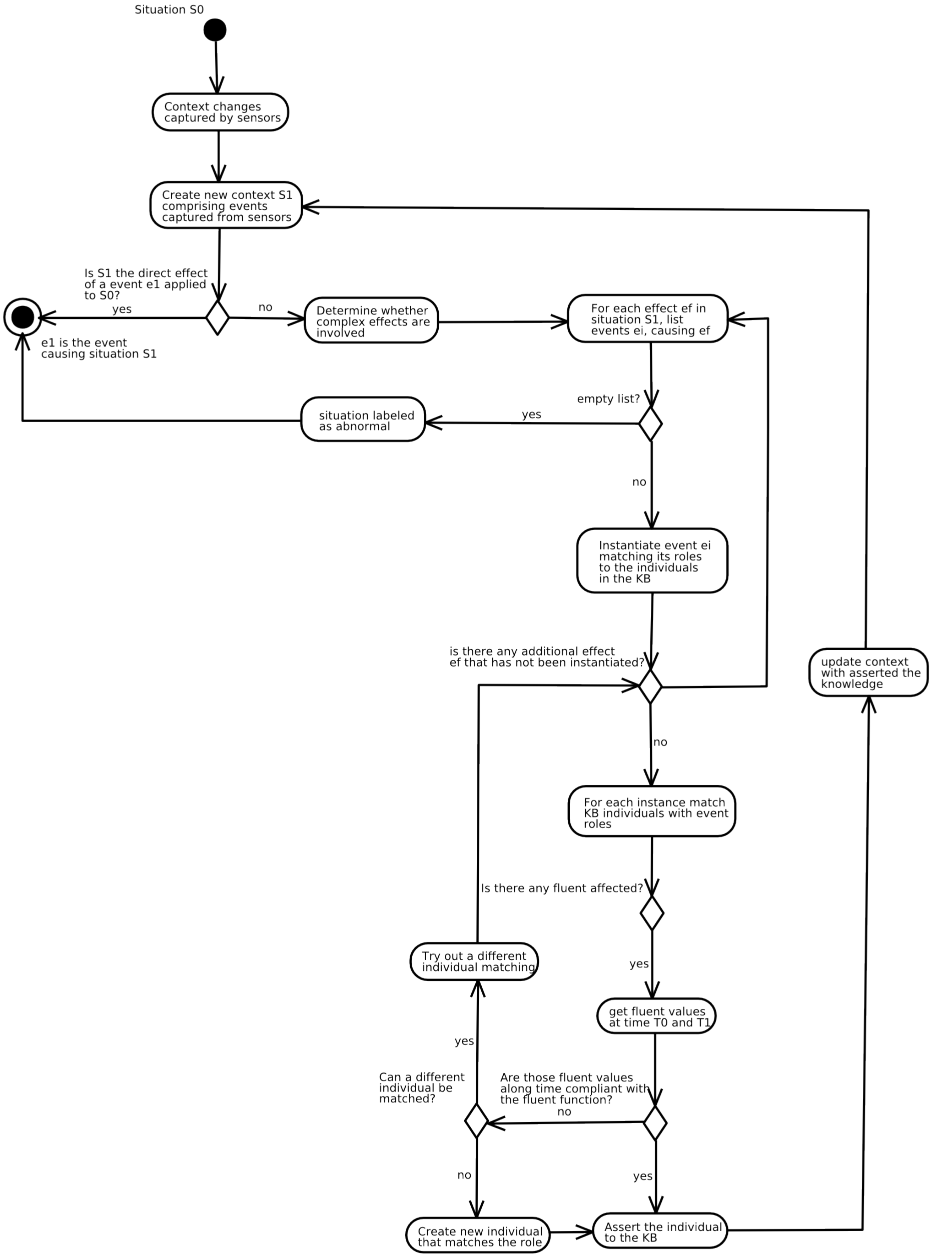

Figure 5. Process diagram that outline how the understanding process is carried out.

[2] Varol Akman and Mehmet Surav. The use of situation theory in context modeling. *Computational Intelligence*, 13(3):427–438, 1997.

[3] James F. Allen. Towards a general theory of action and time. *Artif. Intell.*, 23:123–154, July 1984.

[4] Jon Barwise and John Perry. Situations and attitudes. *Journal of Philosophy*, 78(11):668–691, 1981.

[5] Claudio Bettini, Oliver Brdiczka, Karen Henricksen, Jadwiga Indulska, Daniela Nicklas, Anand Ran-

ganathan, and Daniele Riboni. A survey of context modelling and reasoning techniques. *Pervasive Mob. Comput.*, 6:161–180, April 2010.

[6] Mehul Bhatt. Reasoning about space, actions and change: A paradigm for applications of spatial reasoning. In *Qualitative Spatial Representation and Reasoning: Trends and Future Directions*. IGI Global, USA, 2010.

[7] Mehul Bhatt, Hans Guesgen, and Shyamanta Hazarika, editors. *Spatio-Temporal Dynamics (STeDy 10)*. ECAI Workshop Proceedings., and SFB/TR 8 Spatial Cognition Report Series, August 2010.

[8] Phillip Bricker. David lewis: On the plurality of worlds. *Central Works of Philosophy. The Twentieth Century: Quine and After*, 2006.

[9] Harry Chen, Tim Finin, and Anupam Joshi. Semantic web in the context broker architecture. In *Proceedings of the Second IEEE International Conference on Pervasive Computing and Communications (PerCom'04)*, PERCOM '04, pages 277–, Washington, DC, USA, 2004. IEEE Computer Society.

[10] Harry Chen, Filip Perich, Tim Finin, and Anupam Joshi. Soupa: Standard ontology for ubiquitous and pervasive applications. In *In International Conference on Mobile and Ubiquitous Systems: Networking and Services*, pages 258–267, 2004.

[11] Donald Davidson. Actions, reasons, and causes. *The Journal of Philosophy*, 60(23):685–700, 1963.

[12] Anind K. Dey and Gregory D. Abowd. Towards a better understanding of context and context-awareness. In *In HUC99: Proceedings of the 1st international symposium on Handheld and Ubiquitous Computing*, pages 304–307. Springer-Verlag, 1999.

[13] John Divers. *Possible worlds. Problems of philosophy*. Routledge, 2002.

[14] K. Ducatel, M. Bogdanowicz, F. Scapolo, J. Leijten, and J. C. Burgelman. ISTAG: Scenarios for ambient intelligence in 2010. Technical report, ISTAG, 2001.

[15] Scoott E. Fahlman. Marker-passing inference in the scone knowledge-base system. In *First International Conference on Knowledge Science, Engineering and Management (KSEM'06)*. Springer-Verlag (Lecture Notes in AI), 2006.

[16] Christiane Fellbaum. *WordNet: An Electronic Lexical Database (Language, Speech, and Communication)*. The MIT Press, May 1998.

[17] A.U. Frank. Tiers of ontology and consistency constraints in geographic information systems. *International Journal of Geographical Information Science (IJGIS)*, 5:667–678, 2001.

[18] Michael P. Georgeff. A theory of action for multiagent planning. In A. H. Bond and L. Gasser, editors, *Readings in Distributed Artificial Intelligence*, pages 205–209. Kaufmann, San Mateo, CA, 1988.

[19] Matthias Grossmann, Martin Bauer, Nicola Honle, Uwe-Philipp Kappeler, Daniela Nicklas, and Thomas Schwarz. Efficiently managing context information for large-scale scenarios. In *Proceedings of the Third IEEE International Conference on Pervasive Computing and Communications*, pages 331–340, Washington, DC, USA, 2005. IEEE Computer Society.

[20] Tao Gu, Hung Keng Pung, and Da Qing Zhang. A middleware for building context-aware mobile services. In *In Proceedings of IEEE Vehicular Technology Conference (VTC*, 2004.

[21] Ramanathan Guha. *Contexts: a formalization and some applications*. PhD thesis, Stanford, CA, USA, 1992. UMI Order No. GAX92-17827.

[22] Karen Henricksen and Jadwiga Indulska. Modelling and using imperfect context information. In *Proceedings of the Second IEEE Annual Conference on Pervasive Computing and Communications Workshops*, PERCOMW 04, pages 33–, Washington, DC, USA, 2004. IEEE Computer Society.

[23] Karen Henricksen and Jadwiga Indulska. Developing context-aware pervasive computing applications: Models and approach. *Pervasive Mobile Computing*, 2:37–64, February 2006.

[24] Karen Henricksen, Jadwiga Indulska, and Andry Rakotonirainy. Modeling context information in pervasive computing systems. In *Proceedings of the First International Conference on Pervasive Computing*, Pervasive 02, pages 167–180, London, UK, 2002. Springer-Verlag.

[25] B. Hommel, Jochen Musseler, Gisa Aschersleben, and Wolfgang Prinz. The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, 24:849–878, 2001.

[26] Laurence R. Horn and Gregory Ward. *The Handbook of Pragmatics (Blackwell Handbooks in Linguistics)*. Blackwell Publishers, 2004.

[27] Donald E. Knuth. Semantics of context-free languages. *Theory of Computing Systems*, 2(2):127–145, June 1968.

[28] R Kowalski and M Sergot. A logic-based calculus of events. *New Generation Comput.*, 4:67–95, January 1986.

[29] Saul Aaron Kripke. A semantical analysis of modal logic I: Normal modal propositional calculi. *Zeitschrift für Mathematische Logik und Grundlagen der Mathematik*, 9:67–96, 1963.

[30] Douglas Lenat. Cyc: A large-scale investment in knowledge infrastructure. *Communications of the ACM*, 38:33–38, 1995.

[31] J. McCarthy and P. J. Hayes. *Some philosophical problems from the standpoint of artificial intelligence*, pages 26–45. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 1987.

[32] John McCarthy. Notes on formalizing context. In *Proceedings of the 13th international joint conference on Artifical intelligence - Volume 1*, pages 555–560, San Francisco, CA, USA, 1993. Morgan Kaufmann Publishers Inc.

[33] John Mccarthy. A logical AI approach to context. 1996.

[34] Marvin Minsky. *The society of mind*. Simon & Schuster, Inc., New York, NY, USA, 1986.

[35] R. C. Moore. A Formal Theory of Knowledge and Action. In J. R. Hobbs and R. C. Moore, editors, *Formal Theories of the Commonsense World*, pages 319–358. Ablex, Norwood, NJ, 1985.

[36] Erik T. Mueller. *Commonsense Reasoning*. Morgan Kaufmann, 2006.

[37] D. Nicklas and B. Mitschang. The nexus augmented world model: An extensible approach for mobile, spatially-aware applications. In *Proceedings of the 7th International Conference on Object-Oriented Information Systems*, pages 392–401, 2001.

[38] Giuseppe Primiero. *Information and Knowledge. A Constructive Type-Theoretical Approach. Logic Epistemology and the Unity of Science*. Springer, Berlin.

[39] Giuseppe Primiero. Information and knowledge. a constructive type-theoretical approach. In *Logic, Epistemology, and the Unity of Science*, volume 10. Springer, Berlin, 2008.

[40] Anand Ranganathan, Robert E McGrath, Roy H. Campbell, and M. Dennis Mickunas. Use of ontologies in a pervasive computing environment. *Knowl. Eng. Rev.*, 18:209–220, September 2003.

[41] N. S. Ryan, J. Pascoe, and D. R. Morse. Enhanced Reality Fieldwork: the Context-aware Archaeological Assistant. In V. Gaffney, M. van Leusen, and S. Exxon, editors, *Computer Applications in Archaeology 1997*, British Archaeological Reports, Oxford, October 1998. Tempus Reparatum.

[42] B. N. Schilit and M. M. Theimer. Disseminating active map information to mobile hosts. *IEEE Network*, 8(5):22–32, Sept 1994.

[43] Bill Schilit, Norman Adams, and Roy Want. Context-aware computing applications. In *In Proceedings of the Workshop on Mobile Computing Systems and Applications*, pages 85–90, 1994.

[44] J. F. Sowa. Crystallizing theories out of knowledge soup. In Z. W. Ras and M. Zemankova, editors, *Intelligent Systems: State of the Art and Future Directions*, pages 456–487. Ellis Horwood, New York, 1990.

[45] John F Sowa. *Conceptual Structures: Information Processing in Mind and Machine*. Addison-Wesley, Reading, MA., 1984.

[46] John F. Sowa. Syntax, semantics, and pragmatics of contexts. In *Proceedings of the Third International Conference on Conceptual Structures: Applications, Implementation and Theory*, pages 1–15, London, UK, 1995. Springer-Verlag.

[47] John F. Sowa. Peircean foundations for a theory of context. In *Proceedings of the Fifth International Conference on Conceptual Structures: Fulfilling Peirce's Dream*, ICCS '97, pages 41–64, London, UK, 1997. Springer-Verlag.

[48] Frank van Harmelen, Vladimir Lifschitz, and Bruce Porter. *Handbook of Knowledge Representation (Foundations of Artificial Intelligence)*. Elsevier Science, 2007.

[49] Felix Jesus Villanueva, Francisco Moya, Fernando Santofimia, David Villa, Jesus Barba, and Juan Carlos Lopez. Towards a unified middleware for ubiquitous and pervasive computing. *IJACI*, 1(1):53–63, 2009.

[50] Felix Jesus Villanueva, David Villa, Maria Jose Santofimia, Francisco Moya, and Juan Carlos Lopez. A framework for advanced home service design and management. *IEEE Transactions on Consumer Electronics*, 55:1246–1254, 2009.