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# Resolving Conflicts in Knowledge for Ambient Intelligence

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**Abstract**

Ambient Intelligence (AmI) proposes pervasive information systems composed of autonomous agents embedded within the environment who, in orchestration, complement human activity in intelligent manner. As such, it is an interesting and challenging application area for many computer science fields and approaches. A critical issue in such application scenarios is that the agents must be able to acquire, exchange and evaluate knowledge about the environment, its users, and their activities. Knowledge populated between the agents in such systems may be contextually-dependent, ambiguous, and incomplete. Conflicts may thus easily arise, that need to be dealt with by the agents in an autonomous way. In this survey, we relate AmI to the area of Knowledge Representation and Reasoning (KR) where conflicting resolution has been studied for a long time. We take a look on a number of KR approaches that may be applied: context modelling, multi-context systems, belief revision, ontology evolution and debugging, argumentation, preferences, and paraconsistent reasoning. Our main goal is to describe the state of the art in these fields, and to draw attention of researchers to important theoretical issues and practical challenges that still need to be resolved in order to reuse the results from KR in AmI systems or similar complex and demanding applications.

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# 1 Introduction

## 1.1 Background and Focus

The knowledge representation and reasoning research community contributed over the years a multitude of well-defined theoretical results, as well as practical solutions for engineering information systems tailored to the needs of diverse application domains that deal with knowledge. Recently, the domain of AmI emerged as an important future objective merging research trends from different disciplines; many of the problems relevant with respect to the handling of knowledge within AmI were studied in KR for a number of years. Although some solutions from this field already found their way to AmI systems, as intelligent environments move from the lab to the real world their behavior becomes more sophisticated and the development of viable holistic approaches requires a thorough reconsideration of the applicable tools and methodologies that need to be seamlessly combined within them.

The field of Ambient Intelligence (Zhelka, 1998; ISTAG, 2013) studies information systems embedded within the environment, sensitive to the human presence, that are able to facilitate distributed and networked computing machinery with the aim to accommodate and support human users with their everyday activities and tasks. Application domains of AmI range from ambient assisted living and health-care monitoring, to smart home and office automation, transportation services, classroom and education environments, smart shopping, and others (Cook et al., 2009; Chan et al., 2008; Rubel et al., 2004; Sadri, 2011).

The envisioned AmI applications materialize a long anticipated application objective for Artificial Intelligence (AI), and many of the subproblems studied within AmI can be addressed by AI methods, including: how to recognize activities, how to detect, anticipate and respond to users' needs and intentions, how to develop autonomous entities that can exhibit commonsense behavior, how to conduct distributed reasoning, etc. AmI systems need to be able to process knowledge about the environment in which they are embedded, but also about the users activities, goals and tasks. As the knowledge of the environment may be imperfect and ambiguous and the goals of diverse users may be contradictory, one particular issue, that has been long studied within KR, becomes relevant also in this domain: the problem of *conflict resolution*. The autonomous entities involved in an AmI application need to be able to handle conflicting knowledge, and to find (a form of) mutual consensus in their actions, in order to serve their users well, in consistent, and unobtrusive fashion. This issue was already recognized by the researchers within the AmI domain (Resendes et al., 2014).

In this survey we focus on selected KR approaches and formalisms that address conflict resolution. Each of the surveyed approaches address the problem with a specific motivation, following certain use cases. We do believe that the research in KR has now advanced to the stage, when it is useful to consider also more broadly defined problems, rooted in challenging real-world applications. For this sake we look towards AmI, as a model domain, that integrates a set of important features that need to be considered together, and not only in isolation: (a) distributed and decentralized nature of the system, with multiple autonomous reasoning entities (agents) and the need to resolve the conflicts reaching a certain consensus between the entities; (b) the need to recognize the context: the environment where the agent is placed, users within the environment, theirs preferences and needs; (c) being able to react appropriately to a possible change in the situation; (d) computational effectivity of reasoning and conflict resolution; (e) unobtrusiveness: the system should be able to work autonomously without calling for interference of the users.

## 1.2 Goals and Audience

The goal of this survey is to review and evaluate the relevant approaches from KR that can be applied on the conflict resolution problem, especially to which extent they can be applied on this problem in a complex setting as framed by the requirements (a)–(e) above. That is, our goal is to identify to which extent the KR approaches may possibly be applied, and to pinpoint important issues that still need to be resolved in the respective subfields in order to become applicable in such challenging domains as AmI.

Having this goal in mind we believe that the survey can be especially useful to the researchers in KR, who will get an overview of research directions relevant to the problem of conflict resolution, they will be able to compare the various approaches within the field, contrasting their applicability and open issues. Researchers will be able to compare how analogous issues were addressed in different subfields, and also where and how different approaches need to be combined in order to meet the given goals. The survey can also be useful to researchers who are looking for a suitable conflict resolution methodology for their application in AmI or a similar domain. They will learn about the approaches coming from the KR area and about their current status and potential applicability.

## 1.3 Survey Scope and Overview

In Section 2 we first introduce the necessary background from AmI and discuss how KR is relevant to AmI, where in the architecture of AmI systems KR methods can be best applied. Finally in Section 2.3 we take a closer look on the problem of conflict resolution, and we analyse the different kinds of conflicts that appear in AmI applications, especially from the point of view of different types of knowledge that necessarily have to be processed by AmI systems.

Then in Section 3 we survey a number of selected KR areas in which the problem of conflict resolution was pursued. The surveyed areas are as follows.

**Context Modelling** (Section 3.1) was long an important issue in KR, and it is a central problem for AmI as well, where *context recognition* is equally important to context modelling. Apart from answering the question which information is needed to capture the current situation of an agent, and how this contextual model should be organized, reasoning agents are challenged with uncertainty and ambiguity of the data on which they need to build their contextual models, and they need to resolve conflicts that may thus arise (e.g., in sensory data, or between the sensory data and background knowledge). We will discuss both more traditional KR-based approaches where the uncertainty and ambiguity are captured symbolically, and data-driven approaches where they are captured numerically. Hybrid approaches try to combine the results of the former two.

**Multi-Context Systems** (Section 3.2) and similar approaches in the area of distributed KR focus on the problem of combining multiple knowledge sources for reasoning. The combination is achieved with so called bridge-rules which allow to transfer conclusions from local reasoning in one knowledge source into another one as facts. Particularly relevant to AmI is the assumption that the knowledge sources may be distributed and heterogeneous, e.g., each coming from a different agent that may possibly be placed in a different context, and may even use a different representation language.

The knowledge between distinct sources may be conflicting, which the multi-context systems allow to resolve. The focus on distribution of knowledge is also relevant, as this is often required in real world applications.

**Belief change** (Section 3.3). Often referred to as *belief revision* is the problem of determining how to modify an agent's KB in the face of new, possibly contradictory information. The focus is on identifying and resolving problems before they actually creep into the KB. Belief change approaches could be used to prevent conflicts arising from conflicting sensor readings or from information provided by other agents that is conflicting with the context that the local agent understands. The conflicts considered by belief change approaches are logical inconsistencies, and many of the works in this area deal with the theoretical and philosophical aspects of the problem of updating a KB. Thus, the field is quite relevant for understanding the process of updating knowledge bases, and, consequently, the semantics that a rational agent should apply in order to prevent conflicts from creeping into its KB.

**Ontology evolution** (Section 3.4.1) refers to the process of modifying an ontology in response to a certain change in the domain or its conceptualization. Ontologies and ontology languages are being increasingly applied also by AmI applications, therefore this area is relevant. It is similar to belief change, in the sense that ontology evolution also tries to prevent conflicts from appearing in the KB. Ontology evolution has a more practical nature compared to belief change, in the sense that most approaches are dealing with the practical aspects of the problem of evolution, rather than understanding the evolution process per se. It deals with both the schema and the data of the ontology. It can thus serve to resolve conflict of various types, depending especially on the role the ontology is playing in the agent's knowledge.

**Ontology debugging** (Section 3.4.2), just like ontology evolution, deals with ontological languages at a practical level. The main difference is that ontology debugging is applicable after the conflicts have appeared in the KB, which can happen either because they were somehow allowed to appear, or because of reckless updating, or because the rules associated with the data had to be changed.

**Argumentation** (Section 3.5) aims to understand the process of exchanging rational arguments. More specifically, argumentation studies how arguments relate to each other, and how one can take decisions in the presence of possibly conflicting arguments. Argumentation was successfully applied to conflict resolution, because the resolution of a conflict can be modeled as the process of deciding which part of the evidence (arguments) is acceptable, given a complex evidence set parts of which support (or attack) conflicting information.

In Section 3.6 we further have a look on the existing body of work on the relation between argumentation and belief change, which we suggest as particularly interesting development w.r.t. AmI, as combining and revising argumentation systems will make them more applicable in complex and dynamic environments.

**Preferential reasoning** (Section 3.7). KR formalisms are employed to encode a problem in a formal language, and use reasoning capabilities of the formalism to compute the solutions to the problem. Often multiple solutions exist, e.g., due to the nature of a problem, or due to the use of general rules that are used to model the problem. Preferences are then used to select preferred solutions. Or preferences can be used to select from multiple conflicting rules that are applicable in certain situation.

**Paraconsistent reasoning** (Section 3.8) While most of the approaches above aims at resolving conflicts, e.g., by performing a repair, or revision of the knowledge base, or by deciding which arguments should be upheld and which should be rejected, paraconsistent reasoning studies logics which are able to derive meaningful conclusions also from inconsistent theories and data sets, e.g., by ignoring the inconsistent premisses and drawing conclusions only from the consistent part of the knowledge.

# 2 Ambient Intelligence, Knowledge and Conflicts

## 2.1 Ambient Intelligence

The advent and penetration of interconnected mobile devices into our everyday life has triggered a shift in computing towards sensor-rich environments with pervasive technologies, often referred to as smart spaces. Driven by the *ubiquitous computing* paradigm, a term coined by Mark Weiser's 1991 vision of a new generation of computer systems (Weiser, 1991), the new research area of AmI has emerged. AmI places the human user at the center of attention aiming at creating intelligent environments with the ability to adapt to human preferences, serve their needs and goals, and communicate with their inhabitants utilizing novel means. This paradigm implies a seamless medium of interaction, advanced networking technology, and efficient knowledge management, in order to deploy an environment that is aware of the characteristics of human presence and the diversities of personalities, and is also capable of responding intelligently and proactively to the users' needs.

AmI systems are intended to be (Zelkha, 1998; Aarts et al., 2001):

1. embedded within the environment: users do not need to be concerned with their operation,
2. context aware: they are able to recognize the user and the situation,
3. personalized: they can serve different users according to their own needs,
4. adaptive: they can change in response to the environment and users' actions,
5. anticipatory: they can understand users' needs and act upon them pro-actively, as opposed to only responding user generated requests.

The agent-based paradigm is commonly used to design and develop AmI environments. These contain embedded software entities, called agents, able to perceive and reason upon the current context, exploit the functionality of devices installed within the environment, and pursue specific goals while exhibiting autonomous behavior.

As variety of different elements and devices serving diverse purposes are typically installed in smart spaces, it is reasonable to assume that the agents may be rather heterogeneous in their implementation. Particularly, their cognitive skills may range from simple reactive agents whose behavior is based on the most recent sensor readings, to complex knowledge-based and deliberative agents that perform elaborate reasoning in order to infer relevant context, make estimates over the users' intentions, and communicate and negotiate with the other agents in collaborative manner.

Given the complex tasks that AmI applications are to carry out as a whole, we typically assume that a smart space hosts at least a small number of the latter type of agents. While often such rational agents are modelled using the BDI architecture (Rao and Georgeff, 1991, 1995; Cohen and Levesque, 1990; Bratman, 1987), comprising beliefs (i.e., some knowledge), desires (i.e., certain set of goals), and intentions (i.e., commitment to execute actions in order to meet a chosen set of the goals). Aiming to provide a suitable abstraction of agents for the need of this survey, we simplify

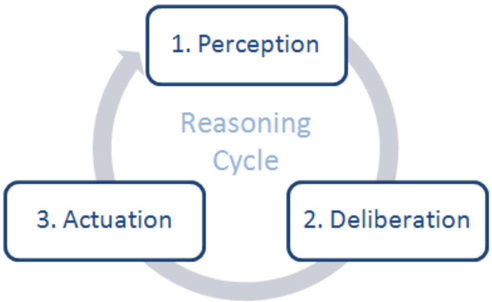

Figure 1: The reasoning cycle of autonomous devices in smart spaces.

the agent architecture and assume that the agents comprise especially the following components:

- A knowledge base (KB) of certain sort, comprising as a distinguished part the *context model* of the current situation respective to the agent, and possibly some additional background and domain knowledge used by the agent. There may be different kinds of beliefs that we may need to distinguish. Each agent may keep track of different aspects of the world and represent them differently than the other agents.
- A set of *goals* the agent is able to follow in all possible situations to serve its purpose, from which the agent selects some, depending on the current perceived context.
- Either some predefined plans of *actions* to execute to achieve each goal, or the ability to plan the actions accordingly when needed.
- Some way to *communicate* with other agents with the aim to exchange knowledge and cooperate the next actions (e.g., messages, queries, bridge rules, etc.).

It should be remarked that in AmI systems the general aim of an agent is to perceive and accommodate the goals of the users and to help them in carrying out actions to achieve these goals. For this reasons, agents may likewise model users simply as agents having goals and executing actions. This abstraction is indeed useful when studying AmI environments as a whole, however we must keep in mind that there is a distinction between the goals of an agent and that of a user, which are not always easily specifiable.

An abstract loop that can characterize the basic internal reasoning phases carried out by an agent is shown in Fig. 1 and involves the phases of perception, deliberation and actuation. This cycle is triggered by specific sensory inputs that the agent is monitoring (or the lack of them) and captures the ability to both deliberate about how best to *interpret changes* that occur in their dynamically changing world, as well as to *make decisions* about the most appropriate course of actions that needs to be taken to support the human users' activities. While many approaches have been proposed to study each phase alone, recent studies (e.g., Pecora et al., 2012; Chen and Khalil, 2011) argue about the need for a seamless integration of the tasks of perception, recognition and acting in a coherent loop, in order to synthesize support services in smart environments with proper and verifiable behavior.

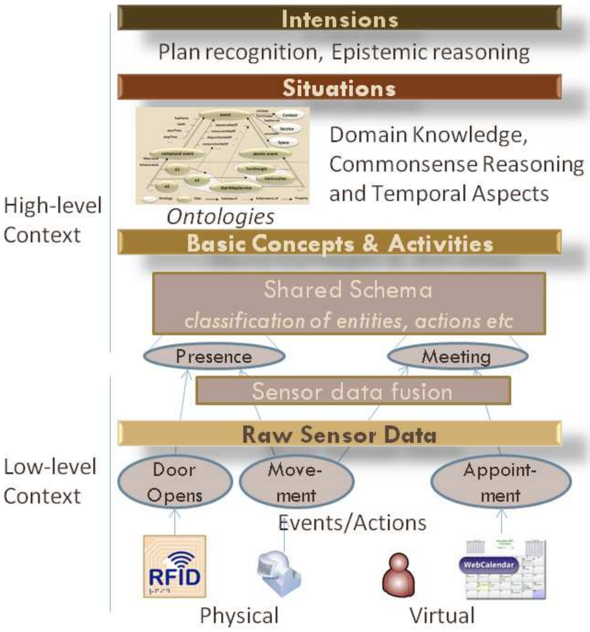

Figure 2: Conceptual Layers of Contextual Knowledge

In addition to its dynamic nature, the aspect of heterogeneity is an equally challenging factor for developing AmI services. Agents operating in smart spaces may possess different reasoning skills, obtain access to distinct knowledge repositories, local or shared, and evaluate incoming information based on different trust criteria. A real-world smart system needs to respect the fact that the way high-level context is inferred by each involved agent is not an objective process. Being highly distributed, these environments produce information that can be interpreted in a totally different manner by the various intelligent agents; as such, it is not uncommon for the latter to end up having incoherent and conflicting views of the current context. Devising intelligent automated mechanisms for identifying, preventing or resolving conflicts is of utmost importance, in order to appropriately balance between the two main design principles that have been set for the success of smart spaces: being as less intrusive as possible minimizing the need for user input, while still letting humans feel confident that they have control over their space.

## 2.2 Relevance of Knowledge Representation and Reasoning in Ambient Intelligence

A typical AmI application, as described in the previous section, needs to deal with a certain amount of knowledge, in order to evaluate the situation and to carry out the required tasks to serve its users. This knowledge must be represented, and processed within the system. In this section, we take a closer look into the types of knowledge that need to be represented and the kind of processing (i.e, reasoning) that is needed.

Many of the problems involved have been thoroughly studied for years in the area of knowledge representation and reasoning.

In Fig. 2, we observe the different conceptual layers of knowledge within an AmI system. As a first type of knowledge, the bottom layers is concerned with identifying the current *context* in which the AmI system is placed. Often, there are two layers of contextual knowledge distinguished – the lower level containing raw sensor readings, and the higher level in which these readings are interpreted on a more abstract level, using a set of concepts based on a commonly agreed schema. The context layer has been largely covered in the current AmI research and many approaches already rely on symbolic knowledge representation models (Bikakis et al., 2008), especially ontologies (Staab and Studer, 2004; Sowa, 2000).

Climbing up the levels of abstraction, the need to represent rich knowledge structures by means of expressive models becomes more apparent. User activities, such as the process of making coffee, are highly goal-driven, typically follow specific patterns, and pre-assume a significant extent of background and domain knowledge with respect to their causal effects and ramifications. In addition, their compositions, often referred to as *situations*, such as the preparation of breakfast, have rich structural and temporal aspects, as for instance location, duration, frequency, causality, and action. In order for AmI systems to fulfil complex tasks, they may need to consider also specific domain knowledge, and data from external data sources. Expressive symbolic modeling not only allows to combine all necessary reasoning tasks, but in addition significantly enhances the reasoning capacity of smart applications by enabling developers to hide the complexities and noise of sensor readings, while exploiting the implicit structure of the activities being observed and data that needs to be processed (Ye et al., 2012; Loke, 2004). Languages with expressive and formal semantics, dealing with commonsense reasoning (Mueller, 2010; Kuipers, 1984), spatio-temporal issues (Cohn and Hazarika, 2001; Gabbay et al., 2003), action and planning (Ginsberg and Smith, 1988; Lifschitz, 1999; Eiter et al., 2003b) have long been studied in knowledge representation.

AmI systems comprise autonomous entities, which need to act in synchronized fashion and collaborate in order to meet the users' goals. This inherently imposes the need of distributed processing of the knowledge involved in the overall application. Different agents may hold different viewpoints on the context, and they may have access to different knowledge resources. Therefore, ambiguity and conflicts frequently arise and must be resolved at execution time, in order to assure smooth operation of the system (Henricksen and Indulska, 2004). While current AmI implementations often take a simplistic and centralized approach to conflict resolution (Resendes et al., 2014), within KR a multitude of approaches have been devised with the aim to deal with distributed knowledge sources modelled from the perspective of distinct viewpoints (Giunchiglia, 1993), possibly inconsistent knowledge (Bertossi et al., 2005), and reaching agreement (Ossowski, 2013).

While many of the KR techniques presented above may not have achieved yet the requirement of scalability in an extent suitable for immediate application to AmI systems, they certainly focus on a number of issues that are central to AmI. Their further development will give them significant potential for improving the capabilities of AmI systems. In this survey, we concentrate our focus to the problem of resolving conflicts once they arise, and specifically consider the relevant KR approaches that address this problem in different settings and with different goals. Before presenting the surveyed areas in Section 3, we first take a look at the different types of conflicts that are met in AmI systems.

## 2.3 Conflicting Knowledge

to mention.

One of the problems that has long been studied in KR is how to deal with conflicting knowledge. This problem is particularly relevant in scenarios where multiple distributed knowledge sources that have to be combined for reasoning come into play. As we argued above, AmI systems and architectures often fall into this case, especially if they incorporate multiple autonomous agents that need to cooperate, in order to achieve common goals. Indeed, this has been noted by other researchers working in the field (Resendes et al., 2014; Henricksen and Indulska, 2004; Muñoz Ortega et al., 2010).

Table 1: Taxonomy of conflicts (Resendes et al., 2014)

| **Dimension** | **Possible types** |
|---|---|
| Source | resource<br>application<br>policy<br>role |
| Intervenients | single user<br>user vs. user<br>user vs. space |
| Time of detection | a priori<br>when it occurs<br>a posteriori |
| Solvability | conflict avoidance<br>conflict resolution<br>acknowledge inability<br>acknowledge occurrence |

Resendes et al. (2014) analyze different types of conflicts that may arise in AmI systems and organize them into a taxonomy, as listed in Table 1. They identify four basic broad categories of conflicts, which are dubbed *dimensions* in order to stress their orthogonality, i.e., the fact that one conflict can be independently classified with respect to each of them.

The *source* dimension indicates where/how each conflict originates – it may be the case that users (or applications) are conflicting over some resource allocation, or it is not possible to execute some action due to policy, or there are conflicting user profiles. Furthermore, following the *intervenients* dimension, there might be conflicting intentions within a single user, between multiple users, or between user and the space. The *time of detection* dimension sorts conflicts into those that are (can be) detected a priori, at the time they occur, or only a posteriori. Finally, the *solvability* dimension indicates at which level can conflicts be resolved – before they happen (i.e., to avoid them), or immediately when they happen, or, possibly, some conflicts cannot be resolved in sensible time, and these are further split into those which cannot be resolved at all, and those which cannot be resolved due to being detected too late.

Homola and Patkos (2014) propose an additional dimension to be added to the taxonomy of Resendes et al., namely *knowledge type*. As each type of knowledge is processed differently, and in a different point of the agents reasoning cycle (cf. Fig. 1), conflicts in distinct types of knowledge may need to be processed differently in AmI systems.

Table 2: Taxonomy of conflicts (Resendes et al., 2014)

| **Dimension** | **Possible types** |
|---|---|
| Knowledge type | sensory input<br>context<br>domain/background<br>goal<br>action |

The possible values of the knowledge type dimension are listed in Table 2 and in more details they are described as follows:

**Sensory input conflict:** if a conflicting reading of some sensors appears. Either multiple readings of the same sensor, or similar sensors may be conflicting. Or the reading may be of different sensors, however the outputs are mutually exclusive (the agents know that these outputs cannot occur at the same time). The conflict may arise within a single agent, but it may also be distributed between more then one agent (each containing part of the conflicting readings). The latter option may subsequently possibly cause a contextual conflict.

**Contextual conflict:** if two (or more) agents are part of the same situation, their models of the world are conflicting, implying, e.g., a different location, or perceived activity of the user, etc. This type of conflict may likely be caused by a previous unnoticed sensory input conflict. But it may also be caused by different evaluation of the situation.

**Domain and background knowledge conflict:** domain and background knowledge refer to the information the agent possesses and uses in order to fulfil its purpose. For instance, a calendar scheduling agent associated with a user records information about months in a year, days in a week, working days, holidays, etc. This is the knowledge respective to the domain of the agent's tasks. To contrast this with contextual knowledge, the fact that Monday follows Sunday is part of unchanging domain knowledge, respective to the calendar domain, while the current date and time, first day of week are in reality contextual knowledge, which changes from situation to situation. It is apparent, that conflict in domain and background knowledge should occur less frequently in AmI systems, in comparison to the remaining four kinds of conflicts discussed here. Also, if they occur, they may require a different kind of solution, due to domain and background knowledge being most typically considered unchanging and fully specified (to the extent required by the application). Hence redesign of the agent's knowledge base by its creator may be required, in contrast to automatic dealing with the conflict.

**Goal conflict:** if two (or more) agents are part of the same situation, their models of the world are compatible, but they have mutually conflicting goals. Note that we do not consider it a goal conflict if agents have conflicting goals in different models of the world, because it is natural to have different goals in different situations.

**Action conflict:** if two (or more) agents share a compatible model of the world, and a compatible set of goals, yet decide to follow a contradictory course of actions to carry out their goals.

As further observed by Homola and Patkos (2014) these five knowledge types can be sorted on the scale from lower to higher level of knowledge: (a) sensory input, (b) contextual, domain and background knowledge, (c) goals, and (d) actions, in the respective order. Distinguishing between these five types is important also due to the following conjecture: solving conflicts in a lower level knowledge may possibly prevent occurrence of further conflicts in the higher levels of knowledge. Consider an example in which two agents have a conflict in the contextual knowledge, that is, their interpretation of the situation in which they both participate is not compatible (e.g., they may have conflicting information about location). If the conflict is resolved at this level, it is less likely that the agents will come up with conflicting goals and consequently action plans.

In the remainder of this survey, we overview and compare different KR formalisms and tools that are suitable to resolve conflicts. Each formalism can be suitable for different type of conflicts, and the knowledge type dimension is often important to consider. As noted above, conflicts in domain and background knowledge most likely require a manual solution, and hence they are not in our main focus. There are however a few formalisms capable to address these conflicts, as we note below in the survey.

# 3 Conflict Resolution Approaches

In the previous section we have learned of the different types of conflicts that may arise in AmI scenarios. In this section, we will present different ways in which agents could resolve such conflicts. In particular, we will focus on the research areas of *context modelling*, *multi-context systems*, *belief change*, *ontology evolution*, *ontology debugging*, *argumentation*, and *preferential reasoning*. Each of these areas is relevant to the problem of resolving conflicts, however, each of them uses a different approach to resolve the conflict. Even though these fields were developed and motivated in different contexts, we feel that the ideas and approaches used there can be easily applied for AmI-related problems which we also highlight in this section.

## 3.1 Context Modeling and Recognition

There is a plethora of methodologies that investigate issues related to the recognition of context; these methodologies are distinct in the way in which they model, represent or reason over the involved information (relevant surveys include Ye et al., 2012; Chen and Khalil, 2011; Sadri, 2011; Yang, 2009). Among the different classifications that can be made, a commonly adopted one is related to how the information is being processed, which leads to the very broad distinction between *data-driven* and *knowledge-based* approaches. The former rely on a numerical characterization of the uncertainty in inferring context, while the latter apply symbolic reasoning techniques from the field of KR. In the sequel, we investigate the main advantages and weaknesses of methodologies in both categories, as well as recent approaches that attempt to combine prominent features in hybrid models. The main objective of these approaches is to process information from the lower levels of context and produce inferences on the higher levels, with the big majority of approaches focusing on activity recognition

(Figure 2). Although the topic of automatic conflict detection and recognition is inherent in the construction of smart spaces, addressing it as part of the context recognition research has only produced partial solutions, as we will see later on.

### 3.1.1 Data-Driven Approaches

Table 3: Characteristic features of Data-Driven Context Recognition Fields

| **Advantages** | **Weak Points** |
|---|---|
| • Effective handling of uncertainty and conflicts at the sensor level<br>• Learning process<br>• Under conditions, can deal with noisy sensor data<br>• Easily extract patterns and complicated associations | • Poor portability, scalability and reusability of the models<br>• Require large amount of training data<br>• Data annotation is a laborious task<br>• Lack of formal semantics<br>• Prone to domain-dependent performance |

Data-driven approaches adopt primarily a probabilistic and statistical view of information and widely rely on the enormous impact of machine learning techniques in real-world applications. Although further classification can be made, e.g., based on whether supervised or unsupervised methods are being used, one distinctive characteristic of data-driven activity recognition algorithms is their capacity to model uncertainty. They apply quantitative measures to evaluate plausibility of observed data, which renders them a popular solution for deciding how best to resolve contradictory sensor inputs. For instance, the problem of domestic activity recognition for a single user was approached by training multiple naive Bayesian models enhanced with ranking features and reliability factors to detect interleaved activities and unexpected sensor malfunction (Lu and Fu, 2009). The same topic for multiple users was investigated with the application of Hidden Markov Models (HMM) that can benefit the process of recognition taking into consideration temporal patterns of data (Singla et al., 2010).

The ability to learn from datasets is a big leverage for data-driven models for tackling conflicts at the sensor level, but often becomes their main point of weakness when attempting to address problems related to the recognition of high-level context. The performance of data-driven approaches is largely dependent on the availability of big amounts of - labelled or unlabelled - training data, thus compromising their capacity to offer scalable, reusable and portable solutions. Due to the pragmatic difficulty to monitor the behaviour of different humans for a long period of time while they perform everyday activities, the models produced exclusively from data-driven techniques are often prone to domain-dependent performance, limiting their reusability and portability (Ye et al., 2012).

Moreover, for abnormal or exceptional behaviours, such as for recognizing a heart attack, it is difficult to train a system properly, which is why for instance the applicability of certain approaches, like the one proposed by Jakkula et al. (2009), is limited to frequent and predictable behaviors only. For less common situations, there is also the problem of overfitting, i.e., when the training of a system is based on a small set of annotated data, which cannot be disregarded, as understood in the work of Lester et al. (2005).

### 3.1.2 Knowledge-Based Approaches

Table 4: Characteristic features of Knowledge-based Context Recognition Fields

| Advantages | Weak Points |
|---|---|
| • Semantically clear<br>• Enhanced interoperability, sharing and portability<br>• Verifiable and intelligible behavior<br>• Consistency checking<br>• Portability due to the incorporation of domain knowledge<br>• Flexibly extensive with new context types | • Treatment of fuzziness and uncertainty<br>• Learning capacity<br>• Quantified confidence weights of inferred models<br>• Scalability can be an issue in some approaches |

With knowledge-based approaches the rules of inference are modelled from first principles, rather than learned from raw data, and typically rely on formal specifications of their syntax and semantics, exploiting symbolic modelling and logic-based reasoning techniques. The expressive power, along with the capacity to verify the properties of their axiomatizations, are key advantages of these methodologies.

Among knowledge-based approaches for context recognition, ontology-based models are arguably the most popular ones.

Ontology languages have rich and formal semantics that enables them to express complex knowledge using a wide set of primitives. These languages are utilized in modelling high-level contextual information, due to their ability to incorporate rich domain knowledge and heuristics in a machine processable way, thus offering a number of advantages in terms of expressiveness and quality of representation, automation and interoperability, composition and level of formality (Bettini et al., 2010; Strang and Linnhoff-Popien, 2004). The most elaborate recent studies in the field of ontology-based context recognition are probably (Riboni and Bettini, 2011b) and (Springer and Turhan, 2009). Based on expressive languages (i.e., OWL 2 Description Logic (DL) and OWL DL, respectively) and decidable reasoners, they enable a context-aware system to detect inconsistencies, infer occurring activities and reproduce knowledge.

Although a multitude of pervasive computing systems have applied ontologies in modelling and reasoning on context knowledge (e.g., (Preuveneers et al., 2004; Patkos et al., 2010; Ye et al., 2007)), most of them try to avoid the generation of conflicts relying on centralized solutions, whereas only few try to explicitly incorporate a solution for resolving conflicts about context within a distributed environment. An early example is Semantic Space (Wang et al., 2004; Tan et al., 2005), a context infrastructure for building smart spaces that investigates a variety of issues, such as context modelling, storage, inference, querying and dynamic discovery of available context providers (wrappers). Context wrappers that obtain raw context information from various software and hardware sources transform them into semantic knowledge (markups) based on the system's context model and store this knowledge in the KB. As an attempt to avoid potential conflicts generated by application-specific inferences, the higher-level context inferred from markups using general purpose reasoners is not explicitly stored in the KB; instead, when needed, specific rulesets are applied to obtain the required knowledge on-the-fly. While this approach may be sufficient for restricted domains, it can be problematic for the general AmI setting, where the different entities often need to obtain a ubiquitous and commonly agreed view of the current situation, in order to decide the best actions to perform and support humans accordingly.

Similar approaches that perform rule-based reasoning are also proposed by Fuchs et al. (2005), as well as in the SOCAM system (Gu et al., 2005), where first-order logic (FOL) rules are applied to reason about the context data and resolve possible conflicts between data coming from different sources. Sets of rules are defined for the classification and evaluation of the quality of the observed context data.

One serious limitation and a key reason for the superiority of data-driven approaches over ontology-based ones, is the limited support for temporal reasoning by ontology-based languages, according to Riboni et al. (2011). Nevertheless, temporal extensions of Semantic Web languages start to become popular (Gutierrez et al., 2007; Batsakis et al., 2011). More importantly, the inherent uncertainty of the information that exists in ubiquitous domains is difficult to handle at the pure symbolic level. While context recognition with respect to coherent incoming information is where most of the aforementioned studies are focusing on, the resolution of information that is conflicting has not been extensively considered so far. Indeed, Semantic Web-based approaches mostly deal with the problem of context disambiguation up to the point of acknowledging that certain parameters can be regarded as unknown.

The problem becomes more pronounced when the recognition task involves high-level complex situations, which ultimately leads in having to resolve the two other types of conflicts defined in Section 2.3, namely goal and action conflicts. For instance, Sadri (2010) proposes an approach to recognize the intentions of a user by means of identifying plans using action graphs. Human intentions are often unclear, cannot be directly measured with physical devices and may be the result of controversial desires. Committing to specific potential human intentions typically means for an agent to decide which of the conflicting knowledge to keep and which to drop. Considering the fact that often multiple and heterogeneous entities are employed in a smart space to perform such reasoning tasks, it becomes evident that dealing with the resolution of the conflicting viewpoints adopted will be inevitable in the next generation of smart systems. This aspect is starting to become an important research topic by considering the integration of techniques from other fields, such as argumentation, as it often requires extra-logical information, as we will see in the following sections.

### 3.1.3 Hybrid and Other Approaches

Table 5: Characteristic features of Alternative Context Recognition Fields

| **Advantages** | **Weak Points** |
|---|---|
| • Can effectively overcome certain of the inherent problems of the previous categories | • For the time being, they have not been able to present a holistic solution to the problems<br>• Scalability is also an unresolved issue |

Although data-driven methods are currently the mainstream choice to activity recognition, with most effective being the supervised learning methods, numerous recent studies justify the attention that knowledge-based approaches have attracted over the last years. Yet, experience showed that both lines of investigation suffer from limitations that restrict the former to the lower levels of data abstraction and the latter to high-level knowledge. A seamless integration of methodologies for all levels is essential for the materialization of AmI objectives. Much of current research is working towards this end. The COSAR system (Riboni and Bettini, 2011a) for example loosely-couples ontological OWL DL reasoning with statistical inferencing, where the latter predicts the set of possible activities without considering context parameters, in order to make the task manageable, while the former is applied to refine the results. In a similar style, the approach by Roy et al. (2011) applies possibility theory to model qualitatively incomplete knowledge, coupled with a DL representation of context to characterize the subsumption relation of actions, whereas the one by Helaoui et al. (2012) presents a first attempt to use probabilistic DL for activity recognition. Still, these frameworks provide only limited or no support for temporal reasoning, inheriting some of the deficiencies of ontological reasoning in expressiveness, as discussed before.

A coupling of uncertainty with rich temporal relations is presented by Helaoui et al. (2011) that uses Markov Logic Networks (MLNs), a statistical relational framework, to introduce uncertainty measures in logical statements to recognize simultaneous and nested activities. Skarlatidis et al. (2011) go even further to combine MLNs with the Event Calculus, a theory for reasoning about action and change, in order to exploit certain properties of the latter, such as the persistence of activities, and soften them as appropriate. Closely related to MLNs is the approach presented by Augusto et al. (2008) that integrates confidence values to Event-Condition-Action rules. The authors define a new syntax for expressing temporal relations among events, with Dempster-Shafer theory being used to assign confidence values to both antecedents and conclusions of rules. The belief rules they define can be used both to monitor a user's interactions and to recognize exceptional situations.

### 3.1.4 Summarizing

Although the domain of AmI environments demands the generation of collective context-aware applications for group of users, where individual agents with personal goals seek collaborative execution of tasks (see for instance (Thais R.M. Braga Silva, 2011; Muñoz Ortega et al., 2010; Muñoz et al., 2011)), relevant literature on collective context conflict resolution is rather scarce. Contemporary approaches, summarized in Table 6, rely largely on centralized architectures, where a single reasoning entity handles conflict resolution. Those that deploy distributed settings on the other hand either try to avoid conflict occurrences (Muñoz Ortega et al., 2010) or focus primarily on policy conflict detection, i.e., establishing behavior schemes that guarantee acceptable system states (Resendes et al., 2014).

The heterogeneity of the reasoning entities inhabiting smart spaces, as well as the processing load required to reason about context renders unreasonable the assumption that full perception is owed by all agents in a smart environment for describing the world state and the situation the users are involved in. Similarly, the need to combine context inference with actuation cannot be overlooked. As evidenced by Pecora et al. (2012), inference, sensing and actuation must operate close cooperation, in order to manage an effective integration of the cognitive capabilities of an intelligent system to be both context-aware and proactive. As the various smart entities need to interact and negotiate with one another, individually or collectively, in order to make decisions and synchronize their actions, conflicts inevitably emerge at the actuation level as well, a topic that only recently started to attract attention by current research in smart spaces, as we see in later sections and especially in Section 3.5.

Table 6: Context Modeling approaches

| **Methodology** | **Uncertainty** | **Formal Semantics** | **Learning Capacity** | **Interoperability** |
|---|---|---|---|---|
| Naive Bayes and Bayesian Networks (Lu and Fu, 2009; Wu et al., 2007)<br>HMM (Singla et al., 2010; Jakkula et al., 2009)<br>Case-based (Knox et al., 2010)<br>Others (Neural Networks, Support Vector Machines, Suffix trees) | Yes, especially for low-level context | No | Yes | Limited |
| Ontology and rule-based (Riboni and Bettini, 2011b; Springer and Turhan, 2009)<br>Classic Logic-based (Artikis et al., 2010; Mastrogiovanni et al., 2011; Rugnone et al.; Sadri, 2010)<br>Defeasible Logic (Ferrando and Onaindia, 2012; Bikakis and Antoniou, 2010) | Limited, usually in the form of non-determinism | Yes | Very limited | Yes |
| Hybrid (Riboni and Bettini, 2011a; Roy et al., 2011; Augusto et al., 2008)<br>Markov Logic Networks (Helaoui et al., 2011; Skarlatidis et al., 2011)<br>Evidence Theory (Mckeever et al., 2010; Sebbak et al., 2012; Hong et al., 2009)<br>Constraint-based reasoning<br>(Pecora et al., 2012; Cirillo et al., 2009) | Can handle quantitative and qualitative uncertainty | In some cases | Yes | Still limited |

## 3.2 Multi-Context Systems and Distributed Knowledge Representations

AmI systems are particularly peculiar in that they are inherently distributed and decentralized, and their components are supposed to act autonomously. The agents should be able to carry out their tasks in cooperation with other agents, but also independently, e.g., if communication, or perhaps other parts of the system are broken. Such assumptions pose increased requirements on knowledge processing, particularly reasoning, which was traditionally investigated especially for the single KB/single agent case. Although reasoning agents (e.g., based on BDI architecture (Rao and Georgeff, 1991, 1995)) were investigated in the context of distributed multi-agent systems (Wooldridge and Jennings, 1995; Jennings et al., 1998), the concern was usually about how should the agents process the newly acquired knowledge (e.g., possibly by revising their KB, see Section 3.3) and what should the resulting knowledge state of the agent be, upon which they would then act. However, it was not traditionally investigated what should the resulting knowledge state of the whole system be, and how the knowledge of one agent can influence the others, etc.

### 3.2.1 Multi-Context Systems

This interesting problem was pursued by Giunchiglia (1993), and Giunchiglia and Serafini (1994b), who proposed Multi-Contexts Systems (MCS). In MCS, we deal with a collection of knowledge bases $\mathcal{K}_1, \dots, \mathcal{K}_n$. Each of the knowledge bases $\mathcal{K}_i$ is a collection of formulae in its own language $\mathcal{L}_i$. The knowledge bases of an MCS, commonly called *contexts*, represent different pieces of knowledge that are to be combined in a unified reasoning system. The contexts may represent different knowledge sources, knowledge bases of communicating and cooperating agents, etc. The issue of multi-contextuality is captured by MCS in various ways. Not only with different languages that the contexts may possibly use, but also with the fact that each context may be respective to a different situation and, therefore, may contain diverse facts. Each context may even represent similar information differently. The combination of these assumptions renders MCS very flexible in modelling scenarios of diverse levels of knowledge heterogeneity, from completely homogeneous, up to ones involving largely heterogeneous knowledge sources/agents.

Logical semantics of the contexts is assumed, in the sense that we have either entailment or a proof system by which we can derive when a formula $\phi \in \mathcal{L}_i$ is true in $\mathcal{K}_i$. The knowledge from different contexts is combined with *bridge rules* of the form $i : \phi \leftarrow j : \psi$, meaning that if the formula $\psi \in \mathcal{L}_j$ is true in $\mathcal{K}_j$ then also the formula $\phi \in \mathcal{L}_i$ must be true in $\mathcal{K}_i$. That is, bridge rules allow to derive consequences in one context (target context) based on premises previously proven in some other context (source context). Hence, bridge rules allow to characterize knowledge transfer between contexts, but also to translate from the language used in one context to that of another, which may be necessary given their possible heterogeneity. That is, given the bridge rule $i : \phi \leftarrow j : \psi$, the recipient agent $\mathcal{K}_i$ upon receipt of information $\psi$ from the sender agent $\mathcal{K}_j$ concludes $\phi$, where $\phi$ represents the recipient's own representation and interpretation of the senders statement $\psi$. A more general form of bridge rules allows more assumptions coming from different contexts on the right hand side (e.g., $i : \phi \leftarrow j_1 : \psi_1, \dots, j_n : \psi_n$). Such rules fire if $\psi_k$ is derived in $\mathcal{K}_{j_k}$ for all $j_k$.

Inference in MCS was first characterized by a proof theory, where bridge rules are used as calculus rules, that are combined with the local calculus of each context

(Giunchiglia, 1993; Giunchiglia and Serafini, 1994b). A model theoretical semantics for MCS, called *local model semantics*, was introduced by Giunchiglia and Ghidini (1998; 2001). In this semantics, the model of a whole MCS is a collection of local models over which additional semantic constraints are asserted that are derived from the bridge rules. Local model semantics was particularly influential and formed the base for further research. We will now survey the main areas of research associated with MCS.

### 3.2.2 Distributed Logics and Distributed Ontologies

Due to their capacity to combine logical reasoning over multiple knowledge sources, MCS have been used to formalize Distributed First Order Logic (DFOL) (Ghidini and Serafini, 1998), and later Distributed Description Logic (DDL) (Borgida and Serafini, 2003). The latter approach, in particular, proved to be influential and sparked considerable interest in distributed ontologies, where the power of MCS is used either to make alignments between heterogeneous and possibly ambiguous ontologies that are to be combined in reasoning (Ghidini et al., 2008; Ghidini and Serafini, 2008), or to facilitate truly distributed inference (Serafini and Tamilin, 2004; Serafini et al., 2005; Homola and Serafini, 2010). Both directions may be useful in AmI systems, in cases when more then one ontology is employed within a system, possibly governed by independent agents. Other related approaches to distributed ontologies include $\mathcal{E}$-connections (Kutz et al., 2002, 2003; Cuenca Grau et al., 2004), Context OWL (Bouquet et al., 2004), Integrated Distributed Description Logics, and Package-based Description Logics (Bao et al., 2009). For a comparison of their expressive power, we refer the interested reader to Homola (2010, chap. 6).

### 3.2.3 Non-Monotonic Multi-Context Systems

Logic-based multi-agent systems often rely on non-monotonic logics, in which the agents are able to reason with assumption, and derive new consequences from assumptions as long as they are not disproven. In order to plug non-monotonic contexts into MCS, it was desirable to enable also non-monotonic bridge rules. Such rules are of the from $i : \phi \leftarrow j_1 : \psi_1, \dots j_k : \psi_k, \mathbf{not}\ k{+}1 : \psi_{k+1}, \dots \mathbf{not}\ l : \psi_l$, and they allow to assert consequences in some context also based on the fact that some evidence is *not* proven in a source context of the bridge rule. For example, consider a situation in which the control agent is instructed to switch lights on during the night if a person is present and switch them off if a person is not present, using knowledge from the calendar and detector agents. While the former case is easily captured by a monotonic bridge rule (1), the latter is not; we need a non-monotonic bridge rule (2) for that:

$$\mathit{ctrl} : \mathit{lights\_on} \leftarrow \mathit{cal} : \mathit{night}, \mathit{det} : \mathit{preson\_present} \tag{1}$$

$$\mathit{ctrl} : \mathit{lights\_off} \leftarrow \mathit{cal} : \mathit{night}, \mathbf{not}\ \mathit{det} : \mathit{preson\_present} \tag{2}$$

Local model semantics was not sufficient to handle non-monotonic bridge rules. First steps towards such extensions were taken by Roelofsen and Serafini (2005) and Brewka et al. (2007), but the semantics which later became generally accepted as a defacto standard for non-monotonic MCSs is the equilibrium semantics given by Brewka and Eiter (2007).

The expressive power of MCS is further increased in Managed Multi-Context Systems (mMCS) Brewka et al. (2011). While so far we dealt with bridge rules, which always result in addition of a formula into the target context, mMCS introduce new operations, such as deletion of a formula, revision by a formula (in the sense of belief revision, cf. Section 3.3).

### 3.2.4 Contextual Knowledge Representation

While bridge rules allow us to change and accommodate information transfered between contexts in arbitrary way, they do not suggest how this should be done. The reason is that MCS allow to put different contexts into each component, but do not provide any means to capture the characteristics of these contexts. Already in his early work on contextual reasoning McCarthy (1993) described transfer of information between contexts as knowledge lifting. This operation, which in MCS is implemented with bridge rules, was also studied under the names, such as knowledge push and pop (Benerecetti et al., 2000). It is understood that the knowledge is changed or adjusted during the transfer, in order to fit into the target context. What is more, these changes are influenced by the characteristics of the source and the target context, sometimes also called contextual meta knowledge. This meta knowledge may refer, e.g., to a particular location, period of time, topic, etc., associated with a context. Once such meta information is assigned to contexts, contextual relations between them are studied, e.g., one context preceding another in time, or, is associated with a broader topic, an so on. Thanks to these relations, contexts can be organized into a contextual space (Lenat, 1998; Benerecetti et al., 2001). Thus, for instance, the statement $President(Bill\_Clinton)$ associated with the context of US in year 2000 may be changed to $ExPresident(Bill\_Clinton)$ when lifted into another context associated with some future period of time.

Contextualized Knowledge Repositories (CKR) (Serafini and Homola, 2012) can be seen as extension of MCS that addresses this issue. In CKR, user may initialize a number of contextual dimensions, with respective values and their relations. Such dimensional values are then assigned to contexts as a form of meta knowledge. Thus, we can have a context associated with, e.g., US politics 2000, similarly as illustrated above. CKR relies on the mechanism of knowledge importing, which enables to reuse the knowledge of a context in another one. For example, in any context we can access the predicate $President_{US,politics,2000}()$, which will import relevant instances respective to $President()$ from the context of US politics in 2000. This way, the user does not deal directly with bridge rules. Further versions of CKR (Bozzato and Serafini, 2013) allow for more expressive meta theories than just simple dimensional properties. Similarly, Description Logics of Context (Klarman and Gutiérrez-Basulto, 2013) allow to model a set of context and a meta theory that describes their relations, and information between contexts is then accessed using dedicated modal operators.

CKR and similar formalisms may particularly be useful to AmI applications to develop agents which need to combine numerous amounts of knowledge imported from various sources. This can be information from sensors and other agents, or external knowledge available in the form of linked data datasets from the web. Each peace of information can be associated with respective contextual meta data and then seamlessly combined in reasoning.

### 3.2.5 Conflict Resolution and Argumentation in MCS

Apart for resolving sensory input conflicts, MCS can potentially be applied to resolve any types of conflicts that may arise between the agents in AmI environments. However, their main efficacy lies with resolving or avoiding contextual conflicts between the agents, as documented by the studies of (Serafini and Homola, 2012; Bikakis and Antoniou, 2010; Benerecetti et al., 2000; Ghidini et al., 2008). It is also apparent from the foundational works that MCS were built upon (Lenat, 1998).

MCS immediately allow for localized conflict resolution, i.e., if a context $\mathcal{K}_i$ imports mutually conflicting information from some other contexts $\mathcal{K}_j$, $\mathcal{K}_l$, this can be resolved within $\mathcal{K}_i$. For instance, we may choose to prefer the information from $\mathcal{K}_j$ and neglect the one from $\mathcal{K}_l$, or vice versa, or we may decide to ignore it entirely, or to react in some other appropriate way.

A global view on inconsistency handling in MCS was studied by Eiter et al. (2010b) who look at MCS systems which have no equilibrium and propose possible explanations why this happens. Confining local inconsistencies and preventing them from polluting the entire system was also one of the design goals of DDL (Serafini et al., 2005) and CKR (Serafini and Homola, 2012).

The problem with localized conflict resolution is that two separate, autonomous agents may face the same conflict differently, choosing two different resolutions and act upon them. This may possibly disturb the overall coordination of agents in the system. Negotiating about conflicting knowledge between autonomous entities has been studied in the argumentation theory (see Section 3.5). Combining MCS with argumentation therefore seems to be a particularly promising direction in this respect. Already Parsons et al. (1998) propose to use argumentation within an MCS-based agent architecture in order to resolve conflicts that arise between agents. More recently, Bikakis and Antoniou (2010) study an application of MCS and argumentation in the context of AmI systems. They built an MCS with defeasible logic used inside contexts that uses argumentation to resolve conflicts in each context. Such an approach, however, is still localized: each context resolves the conflicts locally, based on its local preferences. Brewka and Eiter (2009) introduce Argumentation Context systems. This approach takes further steps towards reaching a certain level of agreement between the agents, in order to resolve mutual conflicts: MCS are enriched with so called mediators, which import relevant information from other contexts using bridge rules that resolve any conflicts relying on an argumentation semantics.

### 3.2.6 Towards Applicability of MCS in AmI

Some of the systems described above were also developed into working prototypes. A distributed reasoner prototype for DDL was released under the name DRAGO (Serafini and Tamilin, 2005). It enables to combine and reason with OWL ontologies with expressive power up to $\mathcal{SHIQ}$ DL (Horrocks et al., 2000). It was developed as an extension of the Pellet reasoner (Sirin et al., 2007). Also, $\mathcal{E}$-connections are supported by Pellet (Sirin et al., 2007). An implementation of an RDF-based CKR was showed by Joseph and Serafini (2011). It is an extension of the OWLIM semantic data store (Bishop et al., 2011).

A working prototype of an MCS system was developed by Bögl et al. (2010), in order to demonstrate the method for finding explanations for inconsistency in MCS by Eiter et al. (2010b). This implementation is based on the tool named dlvhex (Eiter et al., 2006).

Regarding the question of what role should MCS actually play in AmI applications, they were proposed as basis of agent architectures. Parsons et al. (1998), Casali et al. (2005), and Sabater et al. (2002) use MCS to develop the internal architecture of an agent. While Parsons et al. and Casali et al. essentially design an MCS imple-

Table 7: MCS: Comparison of approaches

| | **Local Language** | **Interconnection** | **Non-monotonic** | **Practicality** |
|---|---|---|---|---|
| MCS | various | bridge rules | no | – |
| DFOL | FOL | bridge rules | no | – |
| Distributed Ontologies | DL/OWL | bridge rules<br>links<br>imports | no | reasoners available |
| Contextual Representations | DL | imports<br>modalities | no | reasoners available |
| MCS/equilibrium semantics | various | bridge rules | yes | implemented and evaluated |
| mMCS | various | bridge rules with operations | yes | – |
| argMCS | various | mediators | yes | – |
| Bikakis and Antoniou (2010) | defeasible logic | bridge rules | yes | implemented and evaluated |

mentation of the BDI architecture, Sabater et al. propose a more elaborate, modular architecture which extends BDI. Other works (Cimatti and Serafini, 1995; Bikakis and Antoniou, 2010) use the notion of context to encapsulate an agent and exploit bridge-rules to implement inter-agent exchange of knowledge. This enables to reason about the knowledge distributed in the whole MAS. While such an approach can be used within each agent to model its perception of the other agents' knowledge, Parsons et al. (1998) envisaged that bridge rules could potentially be exploited also for capturing the actual inter-agent communication and thus the MCS would take the role of a fully fledged multi-agent architecture.

Above, we highlighted the application of MCS in resolving conflicts, especially when referring to contextual conflicts. Recently, work has been done towards integrating also normative reasoning into MCS (Knorr et al., to appear), which can further enhance the capabilities of AmI systems relying upon the MCS architecture.

As mentioned above, Bikakis and Antoniou (2010) studied AmI applications of MCS, and proposed an MCS based on defeasible logic, which is capable of conflict resolution using argumentation. This approach was also experimentally evaluated by an implementation (Bikakis et al., 2009), in which various conflict resolution strategies were studied. The communication complexity of these strategies was evaluated, shown to be ranging from polynomial to exponential, depending on their expressiveness.

## 3.3 Belief Change

### 3.3.1 Classical Belief Change

Belief change is important in the context of conflict resolution, because it prevents inconsistencies (and therefore conflicts) from arising, by taking appropriate actions during changes, i.e., during the process of adding into the KB the new knowledge that came from sensors or other agents. Thus, following the classification of Resendes et al. (2014), belief change falls under the "conflict avoidance" type. A recent survey of the field (Ferme and Hansson, 2011) shows that the problem is very challenging, both from the theoretical and the practical perspective.

In terms of the classification of conflict types appearing in Section 2.3, one could say that belief change can, in principle, deal with all types. However, belief change approaches are most suitable for contextual conflicts, as they were designed to deal with conflicts in agents' models and beliefs. Some types of conflicts, namely goal and action conflicts, would require special variations or applications of belief change theories into languages that they were not in their original focus, e.g., BDI models or action languages, whereas others (e.g., sensory input and domain and background knowledge conflicts) may require assumptions that are usually considered in subfields of belief change (rather than the mainstream), such as the assumptions considered in non-prioritized belief change.

As far as the theoretical perspective is concerned, the main challenges arise from the fact that it is often difficult, even in toy examples, to identify the appropriate result of a change operation, and several philosophical considerations need to be taken into account (such as the debate related to the adoption of coherence or the foundational viewpoint (Gardenfors, 1992), the use of belief sets or belief bases (Hansson, 1991), the differences between static-world and dynamic-world changes (Katsuno and Mendelzon, 1992), the semantics of minimal change (Fuhrmann, 1991; Hansson, 1996; Makinson, 1987), and others). As already mentioned, most of the belief change field is focusing on understanding and resolving those challenges, i.e., identifying the optimal way to resolve conflicts (logical inconsistencies) arising due to the introduction of new, conflicting information.

From the practical perspective, the main challenges are related to the fact that belief change algorithms are usually intractable. This is partly attributed to the types of languages considered (propositional and first-order logic) whose reasoning problems are intractable (at best). However, intractability should also be attributed to the inherent difficulty of the problem itself and the difficult challenges that it poses. Unfortunately, most of the works in belief change are not dealing with the practical aspects of the problem.

All the works related to belief change can be broadly classified in three different categories: *postulation approaches*, *construction approaches* and *explicit definition of concrete operators*. These are defined in detail below:

- *Postulation* amounts to defining a set of formal requirements (postulates) that determine whether any given operator behaves in a "rational" manner. Depending on the application at hand, the engineer can choose the exact semantics of the operator to use; as long as the postulates are satisfied, the operator is guaranteed to produce rational results and have certain desirable properties. Not surprisingly, there is no single set of postulates that works well for all cases (Flouris et al., 2004; Ribeiro et al., 2013), even though there are some proposals that are more widely accepted than others (Alchourrón et al., 1985; Hansson, 1991).

- A set of postulates tells us the desired properties of a rational change operator, but gives us no clue as to how to construct one. The latter is the role of *construction approaches*, which essentially define a construction methodology for change operators satisfying a particular set of postulates. At the heart of such approaches is usually a representation theorem that proves that the constructed family coincides with the family of operators that satisfy the intended postulates.

- The *explicit definition of concrete operators* is a more direct approach to belief change, where a specific change operator is provided, often for use in a certain application or context. Such operators usually employ some kind of application-specific hard-coded or parameterized methodology to define the result, as this usually involves extra-logical considerations. In addition, such operators are often shown to satisfy certain postulates or are based on some construction method.

The most seminal work on belief change is that of Alchourrón et al. (1985), a postulation attempt for the operators of contraction and revision. These postulates are often referred to as *the AGM postulates* by the initials of the authors. The AGM postulates formed the cornerstone of later approaches on belief change. Alchourrón et al. considered three operators: *expansion*, which is the trivial addition of information without regards to possible inconsistencies that could arise; *revision*, which deals with adding information consistently; and *contraction*, which deals with removing information.

These operators deal with the assumption of a static world, i.e., in cases where a new observation, experiment or other information forces us to change our conceptualization of the world; the world itself does not change, but our modelling of the world does. On the other hand, under the dynamic world assumption a belief change operation is caused by a change in the world itself; in this case, there is nothing wrong with our original conceptualization, but the world itself is evolving and we need to keep our conceptualization up-to-date. These two settings have different semantics, so another pair of operations (*update* and *erasure*), along with a set of postulates, were defined by Katsuno and Mendelzon (1992). These are the dynamic counterparts of revision and contraction respectively. Note that the dynamic setting is more relevant for the AmI domain.

The presence of postulates allowed to formally show a number of interesting results for these operators. In particular, the operations of contraction and revision, were shown to be interdefinable in the presence of the postulates (Alchourrón et al., 1985). Further results showed that update and erasure are also interdefinable, and revealed connections between the static-world operations and their dynamic-world counterparts (Katsuno and Mendelzon, 1992). In most contexts, including the AmI context, revision and update are the most relevant operators; however, due to contraction/erasure being simpler, and in the light of the above results, most works in the literature deal with contraction.

Obviously, the intuition behind the AGM postulates is not valid for all settings. The most controversial postulate in the AGM set was the postulate of recovery, which captures the informal *principle of minimal change* for contraction; this principle states that change operators should have the minimal possible effect (or "impact") on the original KB. The recovery postulate was criticized as non-intuitive by several authors (Fuhrmann, 1991; Hansson, 1996), and its status was the subject of several debates (e.g., Makinson, 1987). Alternative postulates were proposed, the most prominent one being the postulate of relevance (Hansson, 1991), which captured the intuition of minimality in a different way. Surprisingly, relevance, despite being proposed as a more intuitive alternative to recovery, was formally shown to be equivalent to recovery in the presence of the other postulates under the assumptions considered by the AGM work (Hansson, 1991).

All the above works (and most of the works related to belief change in general) are dealing with *prioritized belief change*, i.e., they assume that the new information is unconditionally accepted (an assumption known as the *principle of primacy of new information* (Dalal, 1988) or the *principle of success* (Alchourrón et al., 1985)), and this is also captured in one of the AGM postulates. The effects of dropping this assumption were studied in the subfield of *non-prioritized belief change* (Hansson, 1997; Hansson et al., 2001). Non-prioritized belief change is important for the AmI setting, where the cause of a conflict may be found in the input, e.g., a faulty sensor reading (sensory input conflict), and not in the agent's KB.

Most construction approaches are based on the AGM postulates, in the sense that they show that the resulting family of operators coincides with the family of operators satisfying the AGM postulates. One such construction was provided by Alchourrón et al. themselves in their original paper (Alchourrón et al., 1985), but others were proposed as well (Gardenfors and Makinson, 1988; Grove, 1988; Alchourron and Makinson, 1985; Hansson, 1994; Rott, 1992).

Works that explicitly propose a concrete belief change operator are rather scarce in the belief change literature. Unfortunately, this makes the application of belief revision methods to practical domains (like AmI) more difficult. Works that propose an explicit belief change operator are based on the idea of "closeness" between (sets of) models: they view a KB as a set of models (i.e., those that the KB satisfies), and the result of a change application (e.g., contraction or revision) is the KB (i.e., set of models) that satisfies the required postulates, while being the "closest" to the set of models satisfied by the original KB. The difference in these works stems from the different definition of "closeness' between models. Two of the most important concrete operators that have been proposed are those of Dalal (1988) and Chou and Winslett (1994).

Another family of works, known as Truth Maintenance Systems, provide explicit operators via a step-wise, formula-based approach, where a set of rules determines the facts to be added/removed from the KB in each step, towards reaching a KB satisfying a set of conditions (i.e., requirements that correspond to the considered postulates). Eventually, a state is reached where no more facts need to be added/removed to achieve the required properties, at which point the result is returned (Doyle, 1979).

Note that most of the above works are not touching practical issues such as efficient implementation of the related algorithms. This is an inherent problem of belief change methods, as they are dealing with logics which are intractable at best. However, most of the employed techniques are also problematic when used in less expressive logics, as they involve identifying minimal sets of formulae that cause conflicts and selecting one of them in an optimal manner, a process that is also (usually) intractable.

An additional drawback of belief change techniques, as related to their applicability in the AmI setting, is the fact that they do not deal with distributed, multi-agent settings, but consider scenarios where a single agent autonomously collects information from its environment and incorporates some information in its own KB, without regards to the existence (or not) of other cooperating (or competing) agents.

For these reasons, belief change techniques were only rarely considered in AmI settings so far, e.g., by Bosse and Sharpanskykh (2010). Nevertheless, we argue that belief change techniques should be viewed (and used) for what they offer, namely a robust understanding of the process of change and evolution (which includes conflict resolution as an integral process) and a rich set of theoretical results that describe this process. Under this light, belief change literature could be re-used to understand and describe the intricacies of the conflict resolution process in AmI settings, but this would require revisiting existing belief change approaches under this prism.

### 3.3.2 Belief Change in Semantic Web and Other Non-Classical Logics

The AGM approach, as well as most belief change approaches, are based on some relatively strong assumptions regarding the underlying language; this essentially limits their applicability to KBs represented using the so-called *classical logics*, which basically amount to propositional and first-order logic. For a complete list of these assumptions, as well as their effects on the supported languages, see the works of Alchourrón et al. (1985) and Ribeiro et al. (2013).

However, changes also happen in different settings, where other knowledge representation languages are used. For example, we could mention handling of changes in logic programming (Lloyd, 1987), multi-context systems (Giunchiglia and Serafini, 1994a), horn logics (Horn, 1951), or datasets based on Semantic Web languages (such as Description Logics (Baader et al., 2003) or OWL (OWL Working Group, 2009)).

For addressing dynamicity in logic programming, different approaches have been considered, some of which consider a non-standard set of postulates that is more suitable for the characteristics of logic programming (Leite and Pereira, 1997; Alferes et al., 2000; Leite, 2002). In multi-context systems, different variants have been proposed addressing changes in the knowledge itself (Goncalves et al., 2014b), or in the corresponding bridge rules (Goncalves et al., 2014a). The field of belief change for horn KBs has been addressed in various papers (Delgrande and Wassermann, 2010; Langlois et al., 2008; Booth et al., 2011, 2009; Delgrande, 2008; Zhuang and Pagnucco, 2010, 2012; Adaricheva et al., 2012), where most approaches are again trying to adapt belief change ideas to apply for the reduced expressiveness of horn KBs.

The latter (changes in Semantic Web datasets and ontologies) is much more relevant for this survey, as there is an increasing volume of works that employ Semantic Web languages to address AmI-related problems and/or exploit data in the Linked Data cloud for AmI applications (Celino et al., 2012; Emaldi et al., 2012; Lecue et al., 2012; Daly et al., 2013). For this reason, this subsection is mostly focusing on the dynamics of Semantic Web datasets. In that context, the problem has been addressed in the field of ontology evolution, where it has been argued that the adaptation of belief change methods and ideas in ontology evolution would provide several benefits (Flouris and Plexousakis, 2006).

The idea of applying belief change theories in the ontological setting was introduced in a series of works that studied the feasibility and consequences of applying the AGM postulates in the ontological setting (Flouris, 2006b,a; Flouris et al., 2006a; Flouris and Plexousakis, 2006; Flouris et al., 2004, 2005). Even though the AGM postulates can be easily reformulated to apply for ontological languages, it so happens that most DLs are not closed with respect to updates, in the sense that one can find examples where none of the "expected results" (per the postulates) is expressible in the underlying DL.

Subsequent work by the same authors proposed new postulates, like *optimal recovery* (Flouris et al., 2006b) or a generalized form of relevance (Ribeiro et al., 2013), which share most of the good properties of the standard AGM postulates, while being more widely applicable. The latter (generalized relevance) was shown to be applicable for a large class of logics, which includes all compact logics (Ribeiro et al., 2013). Given that most Semantic Web languages are compact, this work is very relevant for the AmI domain (and non-classical logics in general). Other works provided further insights on why certain Semantic Web languages cannot comply with belief change methods (that were developed for classical logics), resulting in the so-called *inexpressibility results* (Cuenca Grau et al., 2012). Other similar negative results appear in (De

Giacomo et al., 2007; Liu et al., 2006; Calvanese et al., 2010).

These result motivated the search for ways to circumvent this problem. One approach used approximation techniques, i.e., evolution approaches resulting to an ontology whose set of models is as close as possible to the desired one (De Giacomo et al., 2007; Wang et al., 2010). Others chose to develop new DLs which provably avoid such problems (De Giacomo et al., 2009; Liu et al., 2006).

Some works adopt a more direct approach by proposing specific operators (inspired by belief change ideas), which are applicable for certain DLs. For example, Lee and Meyer (2004) deal with ontologies represented in the $\mathcal{ALU}$ DL fragment; OWL ontologies are handled by Halaschek-Wiener and Katz (2006); Qi and Du (2009) propose three different revision operators for DLs; and Ribeiro and Wassermann (2007) deal in general with knowledge representation formalisms that do not support negation (making it applicable to RDF/S ontologies, as well as ontologies represented using certain DL fragments).

The maxi-adjustment algorithm (Benferhat et al., 2004), is an approach for repairing inconsistencies in stratified propositional KBs in a minimal manner; the works by Qi et al. (2006b,a), based on this approach, develop evolution algorithms that guarantee the validity of the result in the context of stratified ontologies. Note however that this line of work assumes that ontologies are expressed using disjunctive DLs (Meyer et al., 2005), an extension of standard DLs that supports disjunction of axioms.

Gutierrez et al. (2006) consider the operator of erasure for RDF/S ontologies. Due to the simplicity of the underlying language, the main problem considered by Gutierrez et al. (2006) is how to prevent the removed triple from reappearing in the ontology as the result of RDFS entailment. The approach of Gutierrez et al. (2006) addresses this problem using a technique inspired by belief revision.

The resolution of conflicts in the Semantic Web languages is a critical task for the AmI setting, as more and more works are employing such languages to address AmI-related problems. In addition, the wealth of information existing in the Semantic Web (as Linked Open Data), is increasingly being exploited in various AmI applications, especially in the context of Smart Cities (Celino et al., 2012; Emaldi et al., 2012; Lecue et al., 2012; Daly et al., 2013). As a result, resolving the conflicts that appear in the underlying data, represented using Semantic Web languages, will become increasingly important, and one possible approach in this direction is the application of belief change technologies in such languages (as advocated by the works presented in this subsection).

The works related to the generalization of belief change approaches to Semantic Web (or other) languages, are mainly focusing on the feasibility of such an application, and are thus not concerned with the tractability properties of the corresponding approach. More work is needed in this respect to verify that these approaches can scale when applied to practical situations. Therefore, as with classical belief change approaches, one should view the works presented here as a means to understand the process of change and conflict resolution in representation languages that are useful in AmI settings.

## 3.4 Ontologies and Belief Change

### 3.4.1 Ontology Evolution

Ontology evolution deals with the process of modifying an ontology in response to a certain change in the domain or its conceptualization (Flouris et al., 2008), and its main objective is to prevent conflicts from appearing in the ontology during the evolution process (where the term "ontology" refers to both the data and the schema). Thereby ontology evolution falls under conflict avoidance with respect to the classification of conflicts given by Resendes et al. (2014). Given the popularity of ontology-based methods in the AmI field, ontology evolution is highly relevant for this survey, as it could be directly adapted for conflict resolution in smart spaces. Recent surveys on ontology evolution were done by Flouris et al. (2008) and Zablith et al. (to appear).

As with belief change, all the conflict types appearing in Section 2.3 are relevant for ontology evolution. However, since goals, plans and action effects cannot be described well using ontological knowledge, it is highly unlikely that ontology evolution methods will be applicable in such types of conflicts. Since many of the approaches are dealing with the data part of the ontology, they are only applicable to sensory input and contextual conflicts, but some of the more recent works are also dealing with the schema part, making them applicable for domain and background knowledge conflicts as well.

In ontology evolution, two different types of conflicts are considered, namely *incoherency* and *inconsistency*. Incoherency appears when a class is unsatisfiable (Flouris et al., 2006a). Inconsistency is closer to the notion of logical inconsistency and appears when an ontology has no models (Flouris et al., 2006a).

In early approaches to ontology evolution, the application of changes upon ontologies was performed manually by the editor/curator using ontology editors (e.g., Protégé (Noy et al., 2006, 2000), OilEd (Bechhofer et al., 2001)) and reasoners used to pinpoint conflicts. Later on, more specialized tools appeared, which can identify the changes to be performed to guarantee validity, possibly with some user interaction. User interaction may be direct, through an intuitive interface (e.g., Lam et al., 2005), or indirect through parameters, like evolution strategies (e.g., Stojanovic et al., 2002). Examples of such tools are KAON (Gabel et al., 2004), OntoStudio (formerly OntoEdit, Sure et al., 2003), and ReTax++ (Lam et al., 2005). It is obvious that such approaches cannot be applied in the AmI setting, because it is assumed that agents should resolve conflicts (and inconsistencies/incoherencies) in an automated manner.

RUL (Magiridou et al., 2005) is a declarative language for data updating in RDF/S ontologies, which takes into account RDFS semantics, as well as a fixed set of constraints on the resulting RDF/S ontology. For every change requested by the user, the language automatically checks whether the application of said change would cause any problems related to the above constraints (taking into account RDFS semantics), and, if so, it automatically adds further changes (side-effects) to guarantee that the end result will have no conflicts.

In EvoPat (Riess et al., 2010), the identification of conflicts is performed using SPARQL queries; each conflict is associated with one or more SPARQL Update statements that resolve it. The same idea of identifying conflicting patterns (in various ways) and resolving them (in a user-defined way, or using some hard-coded, predetermined process) was employed in various works (e.g., Djedidi and Aufaure, 2009, 2010; Liu et al., 2006; Roger et al., 2002).

A formal method for applying changes in the presence of custom validity rules was proposed by Konstantinidis et al. (2008a,b) and Flouris et al. (2013), where the incorporation of changes is performed automatically, taking care that the validity rules are not violated at the end of the process (see also the discussion on invalidity in Section 3.4.2).

Ontology evolution approaches are, by conception, meant to be applied in real settings where ontologies are used, and often the intended application area is the Semantic Web. As a result, scalability and tractability is generally an objective for these approaches, and sometimes applicability and formal rigour are sacrificed to achieve good tractability properties. The main drawback for many evolution approaches is the fact that they rely on manual or semi-automatic processes, which makes them unsuitable for the AmI setting. Therefore, further research efforts towards a fully automated ontology evolution process would be highly relevant for AmI.

Table 8 shows the works related to the evolution of ontologies and includes works presented in this section, as well as related works presented in Section 3.3.2. The referenced works have been grouped according to their properties.

### 3.4.2 Ontology Debugging

The field of ontology debugging addresses conflicts after they have already appeared in the KB (cf. Section 2.3). In contrast to ontology evolution, the reason that caused the conflict is unknown (or irrelevant) in this field, i.e., it is not considered during the resolution of the conflict. Works in ontology debugging are not only dealing with inconsistencies and incoherencies, but also with *invalidities*, which are violations of one or more custom validity rules that express application- or domain-specific requirements on the underlying ontology (Roussakis et al., 2011). For a related survey see the one by Flouris et al. (2008).

Several recent works have acknowledged the need for imposing such custom, application-specific or user-defined requirements (in the form of validity rules) upon ontologies (Lausen et al., 2008; Motik et al., 2007; Serfiotis et al., 2005; Tao et al., 2010). Thus, identifying and resolving cases where an ontology violates the imposed requirements, either after a reckless change or for other reasons, is paramount for the seamless functionality of the associated applications. Such validity rules are also important for smart spaces, where agents can employ commonsense background knowledge (in the form of rules) to improve their performance in supporting the user in the smart space, for context recognition, or to overrule unreasonable data (e.g., sensor readings); such rules should be respected by the agents' KB at all times.

Validity rules are often encoded as part of the ontological schema (e.g., as OWL rules (Horrocks et al., 2005)); however, in some cases the ontological language is not rich enough to encode the necessary rules, so another "rule layer" is considered on top of the ontology, encoded in some more expressive logical language. In both cases, an important invariant in ontology debugging is that the rules are considered fixed and do not change. Thus, in the former case (rules in the schema) ontology debugging only applies changes in the data part (instance level) of the ontology to resolve a conflict, whereas in the latter (rules in an external layer) it may affect both the schema and the data. Due to this invariant, ontology debugging is not suitable for resolving conflicts related to the rule level, which typically encodes (parts of) the domain and background knowledge. Furthermore, as with ontology evolution, goal and action conflicts cannot easily be addressed via ontology debugging methods, as ontological languages are poor at representing goals, plans and actions.

There are two main problems associated with the field of ontology debugging, namely *diagnosis* and *repair*. Diagnosis refers to the identification of the conflicts, as well as the possible causes behind such conflicts, whereas repair refers to the determination of the best way to resolve the identified conflicts.

Standard reasoners are of little help for the task of diagnosis, because, even though they can identify the existence of a contradiction, they provide little support for resolving and eliminating it (cf. Section 2.3, the solvability dimension (Resendes et al., 2014)). On the other hand, manual identification of the sources of a conflict (contradiction) is not feasible, especially in a smart space setting. Therefore, a more powerful approach is required in order to identify the part(s) of the ontology that led to the contradiction (Flouris et al., 2008).

Repairing is even more difficult, because, in addition to identifying the causes of a conflict (diagnosis), one must determine the “optimal” (under some measure of optimality) way to resolve such a conflict. This process is very similar to the process of identifying the “minimal change” in the belief change/ontology evolution context, and often requires some kind of user feedback, as the choice involves non-logical considerations. Due to this fact, most of the works related to the field of ontology debugging actually deal with the problem of diagnosis only, leaving the problem of repairing to human experts. However, this is not enough for most AmI applications.

Many approaches use some tableau-based algorithm for diagnosis. One of the most influential approaches was given by Schlobach and Cornet (2003), where a tableau-based algorithm for identifying the causes of an incoherency for a specific DL was presented. Similar tableaux-based algorithms for diagnosis were also proposed (Plessers and de Troyer, 2006; Meyer et al., 2006; Wang et al., 2005). In all these techniques, diagnosis reports the axioms responsible for a conflict; a more fine-grained approach would be to identify the parts of the axioms that are responsible for the conflict (see the works of Kalyanpur et al. (2006) and Lam et al. (2006) for such approaches).

As already mentioned, the process of repairing usually employs some kind of user interaction. In some cases (e.g., in ontology editors such as Protégé (Noy et al., 2006, 2000)), this interaction is direct, i.e., the user is presented with the conflicts (possibly with some support regarding the results of the diagnosis) and asked to manually resolve them. In the ORE tool (Lehmann and Buhmann, 2010) a similar interactive approach is used, where the system presents the user with a set of suggestions for resolving the conflict. Such approaches are not useful in the AmI context, where agents need to decide how to resolve conflicts in an automated manner.

Automated approaches for repairing either employ ad-hoc solutions for resolving conflicts, or take advantage of some kind of implicit user feedback. For example, Qi and Pan (2007); Meyer et al. (2005) take into account external information related to the stratification of knowledge to identify the optimal resolution option, whereas Roussakis et al. (2011) relies on user feedback that is provided at input time via a set of user-defined “preferences”. These preferences act as high-level declarative specifications for the “ideal” repair, based on which the system is able to automatically determine the optimal resolution of conflicts in order to produce a repair that is as close as possible to the “ideal” one, as specified by the preferences. The same technique, using preferences based on metadata (such as trust or provenance) was applied in a real setting by Flouris et al. (2012).

A rather original approach for repairing, proposed by Moguillansky et al. (2008), employs ideas from argumentation frameworks to identify and resolve conflicts. In particular, a conflict is defined as an “attack” between arguments (which can be easily identified using logical reasoning), whereas repairing consists in determining accepted/rejected ontological axioms based on the standard acceptability semantics of argumentation frameworks. This approach can be used both for ontology evolution and for ontology debugging.

Ontology debugging approaches are also concerned with the scalability properties of the proposed algorithms. In most of the works presented, one can find experimental results, as well as theoretical analysis of their computational complexity. Of course, the scalability of approaches for ontology debugging is greatly depending on the expressiveness of the considered underlying language and integrity constraints; when considering expressive DLs or expressive integrity constraints, the problem of diagnosis/repair is inherently intractable.

Ontology debugging is very relevant to the AmI setting where agents should make sure that their KBs satisfy the imposed validity rules at all times; this is especially relevant for recognizing the context and for reacting appropriately to its changes. For the same reason, ontology debugging is mostly useful for contextual conflicts, but also for the other types of conflicts which are identifiable through a set of rationality constraints (validity rules) based on the background knowledge about the domain.

Table 9 shows the works related to the problem of ontology debugging (diagnosis and repair). As with Table 8, the referenced works have been grouped according to their properties.

## 3.5 Argumentation

Argumentation is nowadays a very popular conflict resolution approach. Its semantics can be adapted to both centralized and decentralized distributed settings and some solvers have already been implemented, making it relevant also for the AmI domain.

The research on argumentation covers a wide range of disciplines: from psychology, philosophy and social sciences in general, to cognitive science and AI (Rahwan and Simari, 2009; Besnard and Hunter, 2008; Prakken and Vreeswijk, 2002). In the latter in particular, the focus of relevant research is devoted to formal models of argumentation. One of the main challenges is to design a formal system that enjoys desirable semantic properties and tractable computational complexity, while being theoretically easy to understand.

In this section, we overview existing approaches and discuss how argumentation can be suitable for dealing with conflicting information in AmI environment.

Formal models of argumentation can be divided according to whether they focus on a specific logical language and the structure of arguments, or not. Thus, we usually distinguish between *abstract* and *structured* argumentation (Prakken and Vreeswijk, 2002).

### 3.5.1 Abstract Argumentation

The most influential work on abstract argumentation is by Dung (1995), where *abstract argumentation frameworks* (AFs) have been introduced. Abstract argumentation does not consider any structure of arguments or conditions defining conflict (attack) between arguments.

*Argument* in abstract argumentation is an atomic term that is understood as anything that a rational agent can argue with/about and *attack* between arguments is an arbitrary binary relation denoting any inconsistency between these arguments. The advantages of this abstract approach are simple elegant semantics and generality. The main issue in abstract argumentation is to determine which arguments are accepted, which are rejected, and which are left undecided. Generally, if an argument $a$ attacks an argument $b$ then arguments $a$ and $b$ cannot be accepted together, and $b$ is rejected whenever $a$ is accepted.

Intuitively, semantics prescribes a set of sets of arguments, called extensions, for each argumentation framework. Different semantics have been proposed by Dung (1995), based on the notion of *admissibility*, and several of them have been defined with different motivations in mind. An argument $a$ is *defended* by a set of arguments $S$ if $S$ attacks all arguments attacking $a$. An extension is said to be admissible if it is

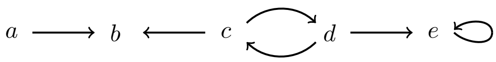

Figure 3: Nodes denote arguments and arrows denote the attack relation (e.g., $a$ attacks $b$).

*conflict-free* (i.e., it does not contain any pair of attacking arguments) and defends all its members. For example, given the AF shown in Figure 3, the admissible extensions are $\emptyset$, $\{a\}$, $\{c\}$, $\{d\}$, $\{a, c\}$, and $\{a, d\}$.

In our example, not all admissible sets are relevant as an intended meaning of argumentation framework and various semantics based on admissibility have been proposed. For example, admissible extensions $\{c\}$, $\{d\}$ do not provide intuitive meaning, since they do not contain all the arguments they defend (argument $a$ namely). The semantics requiring such property is called *complete*. There are three complete extensions $\{a\}$, $\{a, c\}$, $\{a, d\}$ for AF. As it can be seen, complete extensions can be included in one another resulting in two different semantics: skeptical and credulous. The skeptical semantics is the most careful one, where arguments cannot be defended by themselves. The extension corresponding to skeptical semantics is called *grounded* and we can see that $\{a\}$ is the grounded extension. On the other hand, there are two credulously accepted extensions $\{a, c\}$, $\{a, d\}$ called *preferred*. The last semantics proposed by Dung (1995), which is the most aggressive, is called *stable* and requires all arguments outside of an extension to be attacked by an argument in the extension. The only stable extension of AF is $\{a, d\}$. Note, however, that stable semantics is not always defined – there may exist AF with no stable extensions, such as the AF consisting of only one self-attacking argument. As sometimes this is unsatisfactory, weaker semantics called *semi-stable* have been defined (Caminada et al., 2012) which is universally defined and coincides with stable semantics if stable extensions exist.

Given an arbitrary complete extension $E$, justification status $in$, $out$, $undec$ can be assigned to arguments. Intuitively, an argument is:

- $in$ if it is defended by $E$,
- $out$ if it is attacked by $E$,
- $undec$ otherwise.

Arguments that are $in$ are included in the extension and are always accepted. Rejected arguments (status $out$) are attacked by the extension and, consequently, are never accepted. Finally, the acceptance of undecided arguments (status $undec$) is not determined, since they are attacked by undecided arguments only.

Argumentation can be described as a discussion between two players: a proponent trying to justify his claim and an opponent who counterargues. The inclusion of an argument in some of the semantics described above can be decided procedurally by creating and evaluating discussions called *argument games*. Intuitively, a player wins a discussion if she has the last word.

Dung (1995) also studied the relationship of argumentation with other non-monotonic formalisms, such as default logic (Reiter, 1980), inductive defeasible system (Pollock, 1995), stable (Gelfond and Lifschitz, 1988) and well-founded (Van Gelder et al., 1988) semantics for logic programming. Furthermore, significant research has been conducted on studying proof theories (Modgil and Caminada, 2009), on complexity analysis (Dunne and Wooldridge, 2009) (see Table 10) and on various extensions of AFs including support – in addition to attack – relations (Cayrol and Lagasquie-Schiex, 2009), preferences (Amgoud and Vesic, 2011) or weighted attacks (Coste-Marquis et al., 2012).

### 3.5.2 Structured Argumentation

For certain application areas (such as reasoning in the legal domain), Dung's approach may be too abstract to be directly used in practice. The usual methodology is then to instantiate Dung's AF. Structured argumentation formalisms are usually described by defining four notions: a logical language, the structure of an argument, an attack relation and the status of an argument (Prakken and Vreeswijk, 2002). Each one of these notions can be expressed by means of the previous. The status of an argument depends on the notion of argument and attack relation, attack relation depends on the notion of argument and underlying logical language, and the structure of arguments is defined with respect to underlying logical language. To justify some conclusion (i.e. formulae of an underlying logical language) it is sufficient to defend some argument deriving it.

If the status of arguments is computed with respect to some of Dung's semantics, we say that the structured argumentation formalism is an instantiation of Dung's AF.

As for the logical language, usually a classical propositional language (Besnard and Hunter, 2001) or the language of Defeasible Logic Program (DeLP) (Prakken, 2010; García and Simari, 2004; Governatori et al., 2004; Prakken and Sartor, 1997) is considered. A system using classical logic (Besnard and Hunter, 2001) is also called *deductive argumentation*. The language of DeLP is particularly interesting, as its semantics is usually derived from argumentation frameworks. Two kinds of rules are distinguished in the language of DeLP: strict $\rightarrow$ and defeasible $\Rightarrow$. While strict rules are used to represent some kind of deductive reasoning (i.e., whenever the preconditions hold, we accept the conclusion), defeasible rules formalize tentative, uncertain knowledge, where a validity of the precondition of a rule usually (but not necessary) implies a validity of the head of the rule. Thus, defeasible rules can be defeated. An example containing both strict and defeasible rules is shown next:

$$\begin{array}{rclcrcl} & \rightarrow & penguin(tweety) & \quad & penguin(X) & \rightarrow & bird(X) \\ bird(X) & \Rightarrow & fly(X) & \quad & penguin(X) & \rightarrow & \neg fly(X) \end{array}$$

In DeLP, arguments are actually constructed through the chaining of the rules. For example, in the program above, $A_1 = [\rightarrow penguin(tweety)]$, $A_2 = [A_1 \rightarrow bird(tweety)]$, $A_3 = [A_2 \rightarrow fly(tweety)]$, $A_4 = [A_1 \rightarrow \neg fly(tweety)]$ are arguments. We can see that arguments have inherently recursive structure, i.e., argument $A_1$ is a subargument of argument $A_2$, $A_2$ is a subargument of argument $A_3$, etc.

García and Simari (2004) deal with the language of defeasible logic. The semantics is determined by the set of literals, which is computed procedurally via an argument game. However, the argument game is not admissibility-based and, therefore, departs from Dung's semantics. It is interesting to note though that an online solver has been implemented (DeL).

On the other hand, Prakken and Sartor (1997) directly instantiate Dung's AF. They define an argument as a sequence of derivations and apply argumentation games to compute the grounded semantics. According to the authors, several non-standard design decisions were motivated by the legal domain.

A more recent work by Prakken (2010) introduces argumentation framework with structured arguments, called ASPIC+. It is basically a framework for structured argumentation rather than a particular system, where particular language and argument ordering (preferences on arguments used in conflict resolutions) is left to be determined by the user. The online Java system TOAST that implements ASPIC+ has been developed Snaith and Reed (2012).

A different methodology was applied by Baláž et al. (2013), where the status of an argument does not depend on attacks between arguments, but on attacks between conflict resolutions. Intuitively, a conflict resolution is a recipe describing how a conflict is resolved. Within the language of DeLP, a conflict may be resolved by either attacking a default literal or a defeasible rule.

However, as Caminada and Amgoud (2007) pointed out, several existing DeLP based approaches (García and Simari, 2004; Governatori et al., 2004; Prakken and Sartor, 1997) fail to meet the so called *rationality postulates*, specifically consistency (i.e. conclusions of extensions must be consistent in a meaning of classical logic) and closure under strict rules (i.e. conclusions of extensions must satisfy all strict rules in a meaning of classical logic). Violation of these postulates can result into justification of absurdities or incomplete results, where some conclusions are missing.

Note that both approaches by Prakken (2010) and Baláž et al. (2013) satisfy the aforementioned postulates. Proposing new techniques for satisfying rationality postulates as well as for studying the relationship of argumentation-based semantics of DeLP and more traditional semantics of logic programming are still an open research topics in structured argumentation. Table 11 summarizes several approaches and their properties.

### 3.5.3 Applications in Ambient Intelligence

Argumentation has already been applied in AmI as a KR paradigm for dealing with both incomplete (partial) and inconsistent (contradictory) knowledge (Ferrando and Onaindia, 2012; Bikakis and Antoniou, 2010; Moraitis and Spanoudakis, 2007; Muñoz et al., 2011; Muñoz Ortega et al., 2010; Muñoz et al., 2010). The approach presented in (Muñoz et al., 2010), for instance, uses argumentation techniques, in order to tailor services to the preferences of multiple users that share the same resources (i.e., a TV set). An internal dialogue is structured whenever conflicting preferences arise. In our survey, this corresponds to action conflict. Notable are also the studies described in (Ferrando and Onaindia, 2012; Bikakis and Antoniou, 2010; Moraitis and Spanoudakis, 2007) that respect the distributed nature of contextual information, where different entities possess locally a partial and tentative view of the actual world state. In these studies, defeasible rules are defined to represent uncertainty during context recognition, while techniques from the argumentation theory are applied in an attempt to resolve conflicts and reach a consensus about the actual context. Argumentation techniques are well tailored to resolving such types of *contextual* conflicts. In particular, Ferrando and Onaindia (2012) implemented and experimentally evaluated a DeLP Multi-Agent Partial Order Planning framework, which computes plans whose actions are unlikely to misfire at execution time according to the knowledge of the agents. Their objective is to choose a plan respecting both the desire to minimize the computational overhead and to maximize the quality of the solution plan. Bikakis and Antoniou (2010) aimed primarily at representation and reasoning issues. They defined a contextual defeasible logic (MCS instantiated with defeasible logic in each of the contexts), providing a decentralized platform and a set of distributed algorithms for query evaluation. To resolve all possible conflicts, a total preference ordering on the system contexts is assumed. Although not directly applied in an AmI setting, an interesting application of argumentation techniques was proposed by Leite and Martins (2011) in the Social Web area where the social voting determine arguments strength and consequently also the semantics of the system (valuation of all arguments).

To conclude, argumentation is a well-investigate field and one of its advantages over the other KR formalisms is its user-friendliness; argumentation-based semantics can be intuitively explained for both researchers in the KR domain and people not familiar with formal logic.

## 3.6 Belief Change and Argumentation

In the previous sections we noted that the area of belief change, may amplify AmI systems with the ability to deal with newly acquired information and to accommodate changes in the current situation. Moreover, the field of argumentation has emerged works, that enable agents with contrary beliefs or goals, to achieve agreement.

In this section we survey some works proposed recently, that investigate the interrelations between these two fields. This issue is gaining an increasing research attention: three recent events, Madeira Workshop on Belief Revision and Argumentation (Ferme et al., 2013), Luxembourg Workshop on the Dynamics of Argumentation, Rules and Conditionals (DARC 2012) and Dagstuhl Seminar on Belief Change and Argumentation in Multi-Agent Scenarios (Dix et al., 2013), are focused on the relations of these fields.

Being a relatively novel research direction, it has mainly developed theoretical models so far. Even so, it can be considered relevant to the current survey as it may extend the state of the art in both fields of belief change and argumentation. In realistic multi-agent settings as is AmI, these two important capabilities of agents need to be combined to ensure that the changes in beliefs and goals are executed in a mutually compatible way.

### 3.6.1 General Considerations on Interrelation of Argumentation and Belief Change

Standard argumentation theory deals with a set of arguments and an attack relation. However, when argumentation becomes dynamic by adding or removing new arguments/attacks, interesting problems arise. Belief change methods are helpful in such situations. On the other hand, a variety of argumentation semantics exist, representing different views on compatible sets of arguments, which set the base for a more flexible approach to belief change.

In Baroni et al. (2013), Ferme et al. (2013), argumentation and belief change are considered as reasoning process and are thoroughly compared for commonalities and differences. They conclude that both fields capture partially distinct but overlapping research problems, and identify a number of interesting open research questions, posed by their comparison (e.g., they note the rising importance of postulates in argumentation which were long considered central in belief change, and call for proposals of "reasoning benchmarks" which could be used to evaluate different approaches in both fields).

According to Falappa et al. (2011), some argumentation formalisms can be used to define belief change operators, and belief change techniques have been used for modeling the dynamics of beliefs in such argumentation formalisms. Complementary roles of belief change and argumentation in understanding and modeling complex reasoning processes are stressed. The analysis of connections between argumentation and belief change within a complex reasoning process is based mainly on the ideas of Falappa et al. (2009). A complex reasoning process consists usually of the following basic reasoning steps: (1) reception of new information, (2) evaluation of it, (3) change of beliefs, and (4) inference. Basically, argumentation can be used mainly in step 2 and belief change can be used in step 3. However, a more detailed analysis shows that there are complex interrelations between argumentation and belief change within the different reasoning steps.

Rotstein et al. (2010) propose Dynamic Argumentation Framework (DAF), in which a new feature, *evidence*, is introduced. Evidence enables to distinguish valid arguments. Change is represented at different levels: change on evidence, on arguments, on conflicts, or on a preference relation.

The works surveyed so far, study the general connections between belief change and argumentation. Next, more technical approaches follow, categorized in two directions: those, applying methods of belief change to argumentation and those, that use the argumentation viewpoint to introduce some new features about belief change.

### 3.6.2 Belief Change Applied to Argumentation

Computational aspects of argumentation frameworks updating are studied by Liao et al. (2011). A modular approach to updates is implemented as follows: if an update operation is specified for a given argumentation framework, the updated argumentation framework is divided into three parts: arguments affected by the update, arguments unaffected, and conditioning arguments. The latter are unaffected arguments, which attack affected arguments.

The role of conditioning arguments is essential from the computational point of view. Computation of the status of arguments can be divided in two parts. The status of unaffected arguments is the same as in the original argumentation framework, as well as it is not changed by the update. The status of affected arguments is computed in a Conditioned Argumentation Framework (CAF), where attacks of conditioning arguments against affected arguments influence the status of the second. An algorithm implementing this method is described.

The next works, focus on elementary change operations in abstract argumentation frameworks. They provide a view on the change of basic components of argumentation frameworks. Different basic change operations are considered.

Cayrol et al. (2010) defined four basic change operations on argumentation frameworks: adding an attack between arguments, removing an attack, adding an argument together with attacks involving it and removing an argument together with the involved attacks. The case of adding one argument is studied in details. The main focus is on the impact that the changes cause on the structure of extensions and on the status of some particular arguments.

Boella et al. (2009b) are focused on impact from adding attack relations to the semantics of an abstract argumentation framework. The work is continued in Boella et al. (2009a), where the removal of attacks and arguments is studied. Only the case of a semantics with precisely one extension is considered. The main focus is on principles for the argumentation dynamics.

Coste-Marquis et al. (2013) and Mailly (2013) study revision of attack relations in argumentation as minimal change of the arguments status. The principle of minimal change plays an important role in the belief change research: it states that it is appropriate to preserve as much from the given knowledge set as possible. It is further shown, how AGM belief revision postulates (Alchourrón et al., 1985) can be translated to the case of argumentation systems.

A different approach was undertaken by Baumann and Brewka (2010; 2012; 2013). The, so called *enforcing problem* was posed and solved by Baumann and Brewka (2010). It poses the question whether it is possible, given a specific set of allowed operations, to modify a given argumentation framework $\mathcal{A}$ into $\mathcal{A}'$ such that a desired set of arguments $E$ is contained in some extension of the modified AF. Some conditions, under which enforcements are possible, were identified.

An important special case of the enforcing problem – how to reach that goal by a minimal change – was studied by Baumann (2012). Given an argumentation framework $A$ and a set of arguments $E$, the minimal number of additions or removals of attacks needed to reach an enforcement of $E$ is called the *characteristic of* $E$. This number depends on the underlying semantics and the type of allowed modifications. It was shown that in certain cases there are local criteria, allowing to determine the characteristic. Local in the sense that the criteria are based on properties of the underlying argumentation framework and they enable to determine the characteristic in a finite number of steps.

The *spectrum problem* is studied by (Baumann and Brewka, 2013). Given a set of semantics and a modification type, the task is to determine for the pairs $(\sigma, \Phi)$, where $\sigma$ is a semantics and $\Phi$ is a modification type, the set of all natural numbers which are characteristics of arbitrarily argumentation framework $A$ and a set of arguments $E$. Surprisingly, this rather abstract problem yields interesting insights into relations of stable, semi-stable and preferred semantics: it may be arbitrarily more difficult to enforce arguments using stable rather than semi-stable semantics, and also using semi-stable rather than preferred semantics.

Some researchers addressed problems connected to belief change in instantiated argumentation systems (structured argumentation frameworks with a subargument relation). Moguillansky et al. (2011) studied argumentation within Defeasible Logic Programming (DeLP). They defined prioritized argument revision operators for a given DeLP. The newly inserted argument becomes undefeated after the revision, hence its conclusion becomes warranted. In order to ensure this warrant, the program has to be changed in accordance with a minimal change principle.

### 3.6.3 Argumentation Applied to Belief Change

A relatively smaller part of research is devoted to this aspect of interrelations between belief change and argumentation. As already mentioned, Moguillansky et al. (2008) employed argumentation to belief change in ontologies (particularly, ontology debugging). They build an argumentation framework, in which mutually inconsistent ontological axioms attack each other, and argumentation semantics thus determines possible repairs.

Liao (2013) constructed a layered (abstract) argumentation framework with subargument relation (AFwS). The semantics of AFwS provide a basis for the study of updating a layered AFwS and its properties. Among motivations for this research is a scenario as follows. An argumentation component is put before a belief revision component. Suppose that a new piece of (updating) information is given. The argumentation component serves as a filter: a set of accepted arguments (and therefore, their conclusions) is obtained by means of argumentation. As a consequence, only new information justified by argumentation inputs into the process of belief change. This can serve as a contribution to standard implementations of belief change.

Krümpelmann et al. (2011) proposed a way, how to distinguish whether new information should be accepted. Deductive argumentation (Besnard and Hunter, 2001) is used to assess the value of new information. Hereby is obtained a revision operator which accepts new information only if the new information is justifiable.

### 3.6.4 Summary

Understanding the mutual interrelations between belief change and argumentation, presents a contribution to both these fields, which we previously found relevant for AmI applications. In particular it may contribute to develop more flexible argumentation frameworks, capable of updating and necessary changes that may be required by a change of a situation faced by a particular AmI application. On the other hand it may contribute to the development of more flexible and more effective belief change operators implemented with argumentation procedures.

Given that this research direction is fairly new, most of the proposal are yet at the theoretical level, lacking reasoning support and implementations. We see this as a notable research challenge, especially for the KR community. Out of these theoretical works we would like to particularly highlight the notion of complex reasoning processes (Falappa et al., 2009), which highlights interactions between related reasoning tasks of a rational agent and which is fairly in line with the reasoning cycle of agents in AmI systems (cf. Figure 1). The only work with more practical implications in this area is that of Liao et al. (2011). For more detailed comparison, see Table 12

## 3.7 Preferential Reasoning

The notion of preferences is part of the everyday human reasoning. For example, two laws giving conflicting instructions, the instructions given by the law with more "power" precede. Another example is that doctors usually prefer non invasive procedures over invasive ones.

Almost every KR formalism was extended to support preferences. However, the term "preferences" is too abstract, and means slightly different things in different approaches. Common underlying intuition is that preferences select between multiple options. In this section, we focus our attention to logic programming, a widely used non-monotonic formalism. Logic programming uses if-then rules to express the knowledge about a domain. In contrast, e.g., with production systems, which also use if-then rules, logic programming is purely declarative. Logic programming is very relevant for AmI, as it a generic knowledge representation formalism, which was applied in many areas, e.g., agent programming (Köster et al., 2009), assisted living (Mileo et al., 2008a,b) decision support (Nogueira et al., 2001), diagnosis (Balduccini and Gelfond, 2003), multi-agent planning (Son et al., 2009), planning (Dimopoulos et al., 1997), policies (Son and Lobo, 2001). For additional references to applications we refer the reader to Schaub (2011). For the survey of preference handling approaches in other non-monotonic formalisms we refer the reader to Delgrande et al. (2004b). In the context of logic programming, preferences are used in the following ways:

- Preferences on rules are used to control the applicability of rules. Having two conflicting rules that are both applicable, we use the preferred one.
- Preferences on literals are used to prefer answer sets containing some literals over answer sets containing others.

### 3.7.1 Preferences on Rules

Consider we have a rule encoding that an agent should execute an action $A$, and a second rule encoding that the agent should not execute the action $A$. If the 'if' parts of the both rules are satisfied, we have a conflict. Given a conflict resolution principle, e.g., the second rule is based on more specific information, we want to prefer one rule over the other, i.e., we want the first rule to be inapplicable if the second one is applicable. Preferences on rules allow exactly this kind of reasoning.

One of the standard semantics for logic programming is the answer set semantics (Gelfond and Lifschitz, 1991). It assigns to a logic program a collection of answer sets, alternative beliefs an agent can accept. So called *selective* preference handling approaches, studied, e.g., by Brewka and Eiter (1999), Wang et al. (2000), Delgrande et al. (2002), Zhang and Foo (1997), Sakama and Inoue (2000),Šefránek (2008), and Šimko (2013), select a subset of standard answer sets as *preferred*. They do so in order to stay compatible with the answer set semantics, instead of inventing a completely new semantics.

The approaches studied by Delgrande et al. (2002), Wang et al. (2000), and Brewka and Eiter (1999) can be characterized as *prescriptive* (Delgrande et al., 2004b). Preferences on rules are interpreted as the order, in which rules are applied. As a consequence, a less preferred rule cannot defeat a preferred rule. Each of the approaches puts slightly different conditions on the order in which rules have to be applied. Schaub and Wang (2003) showed that the approaches form a hierarchy. The biggest difference between the approaches is that the approach by Brewka and Eiter (1999) handles only direct conflicts, while the approaches by Delgrande et al. (2002) and Wang et al. (2000) handle indirect conflicts. Delgrande et al. (2002), Eiter et al. (2003a), Grell et al. (2005), and Asuncion and Zhang (2009) deal with the issue of computing the semantics.

On the opposite side of prescriptive approaches lie *descriptive* (Delgrande et al., 2004b) approaches. They do not see preferences as the order of rule's application. Preferences are handled in more declarative fashion. Zhang and Foo (1997) view preference handling as a removal of less preferred rules. Sakama and Inoue (2000) define preference handling as a comparison of the rules that generate answer sets. Šefránek (2008), Šefránek and Šimko (2011), and Šefránek and Šimko (2013) look at preference handling as a form of argumentation. Šimko (2013) uses preferences to transform conflicting rules, to rules defining exceptions: a preferred rule defines exception to a less preferred rule, but not the other way around.

From the computational point of view, the decision problems for the aforementioned semantics are hard (NP-complete, or lie on a higher level of the polynomial hierarchy).

Besides the answer set semantics, the well-founded semantics is the second standard semantics for logic programs. It can be computed in polynomial time. Brewka (1996), Schaub and Wang (2002), and Wang et al. (2000) defined preferred well-founded semantics for logic programs with preferences, which can also be computed in polynomial time.

Delgrande et al. (2002) and Zhang and Foo (1997) consider *dynamic preferences*. Preferences not only change the semantics of logic programs, they are also subject of reasoning.

The main shortcoming of the literature in the field is that it provides little or no inside into which semantics to use in a domain at hand. The study of principles for preferential reasoning can help to fill this gap. Some development was done by Brewka and Eiter (1999), Šefránek (2008), and Šefránek and Šimko (2013). Ideally, given an application domain, a suitable semantics is selected based on a subset of relevant principles. However, work in this direction is still needed. So far, existing principles do not sufficiently differentiate between the approaches and are unable to guide in selecting a right semantics for a task at hand.

Table 13 summarises the approaches for reasoning with preferences on rules. The values in the column "practicality" have the following meaning: (i) native – a solver with an algorithm specifically tailored for the approach is implemented, (ii) algorithm – there is an algorithm specifically tailored for the approach, but no implementation is available, (iii) reduction – reduction of an approach to logic programming without preferences exist.

### 3.7.2 Preferences on Literals

If the answer set programming methodology is used, a problem is encoded into a program in a way that the answer sets of the program correspond to the solutions of the problem, e.g., using answer set programming for planning, each answer set of the program corresponds to a possible plan. Sometimes we want to prefer some solutions over others, e.g., we want to prefer the plans containing non-destructive actions. Preferences on literals allow exactly this kind of reasoning. Usually, an order on answer sets is computed based on the preferences, and maximal answer sets w.r.t. the order are selected.

Sakama and Inoue (2000) extend logic programs with a preference relation on literals. The preference relation on literals is then transferred to relation on answer sets, and maximal answer sets are selected as preferred. In this way, preferred answer sets contain preferred literal. Sakama and Inoue also showed how preferences on literals can be applied to various forms of commonsense reasoning: minimal abduction, prioritized abduction, default reasoning, prioritized default reasoning, circumscriptions and prioritized circumscriptions.

Brewka (2002) introduces logic programs with ordered disjunction, in which preference of a literal is given by its position in a disjunction. The intuition behind the rule with ordered disjunction $A \times B \leftarrow C$ is as follows. If $C$ is contained in an answer set $S$, then $A$ is in $S$ if possible. But if it is not possible, then (at least) $B$ is in $S$ (Brewka, 2002). Brewka also shows how programs with ordered disjunction can be used in the configuration domain.

Brewka et al. (2003) consider answer set optimization programs consisting of two parts. The generating program produces answer sets representing solutions of a problem. The preference program expresses user preferences. A preference relation on the answer sets of the generating program is based on the degree in which the rules of the preference program are satisfied.

From the computational point of view, the decision problems of the semantics are at least NP-complete.

Table 14 summarises the approaches for reasoning with preferences on rules. The column "practicality" contains a unique value "algorithm" – there is an algorithm specifically tailored for the approach.

### 3.7.3 Summary

We have given an overview of the approaches for preference handling in logic programming. In this section we give some pointers how the approaches can be used in

AmI.

In Section 2.3, five types of conflicts w.r.t. knowledge type were introduced. With a suitable encoding, all conflicts seem to be solvable using preference handling. However, some might feel little unnatural, and probably other approach would be more appropriate.

Preferences on literals are especially suitable for handling conflicting goals and plans. If answer sets correspond to different goals/plans, we can select preferred ones. Preferences on literals can, e.g., prefer literals representing non-destructive actions over destructive ones, or actions using less expensive resources. For the issue of incorporating domain-specific preferences in planning systems we refer the reader to Delgrande et al. (2004a).

Preferences on rules are usable for handling both conflicts inside an agent and conflicts between agents. One way at looking at preferences on rules is as a handy way of encoding exceptions between rules. When writing logic programs, we usually use general rules with exceptions. Preferences on rules allow us to express exceptions in a more easily and change tolerant way. Preferences on rules were already used in AmI. Bikakis and Antoniou (2010) use trust level of agents to determine preferences on conflicting rules, although they use different formalism than we discuss in this section.

Regarding the applicability of the approaches in real environments, algorithms and prototypical solvers exists. However, additional work needs to be done as no production ready solver for preferences exists.

## 3.8 Paraconsistent Reasoning

One of the key features of AmI systems is the ability of agents operating in them to handle knowledge that originates from multiple sources, that may be incomplete, ambiguous, or even inconsistent. AmI systems are not supposed to halt or report errors when they face such problematic situations, instead they should be able to react to such situations appropriately, reconstructing and reusing the consistent and reliable parts of the knowledge at hand. In this section, we give an overview of *paraconsistent reasoning*, sometimes also called *inconsistency tolerance* (Bertossi et al., 2005); the area of KR that comprehensively addresses the problem of reasoning with inconsistent knowledge.

Inconsistency is a challenge for classical logic-based systems, as in classical logics meaningful reasoning is not possible once inconsistency arises – typically the *ex falso qodlibet* principle is applied, i.e., all possible consequences are derived. Therefore, studies in the area of paraconsistent reasoning focus on identifying the sources of inconsistency in the knowledge and on developing methods to constrain and isolate inconsistent knowledge, as well as derived facts that are only supported by inconsistent knowledge and there is no way to derive them from consistent premises, thereby avoiding this derivation explosion. Consequently, also the goal of proposing repairs and removing the inconsistencies from the affected knowledge sources is often considered (Bertossi et al., 2005).

Goals related to inconsistency tolerance are indeed addressed by a number of approaches that we already reviewed: belief revision, ontology repair, and argumentation. All these approaches aim at conflict resolution, or at least avoidance. In this section, we will focus on *paraconsistent logics* which, instead, focus on derivation of sound conclusions from knowledge that may possibly contain inconsistencies, without necessarily attempting to repair the knowledge base. This is usually achieved by isolation of the inconsistent parts and drawing conclusions only from the consistent parts of the knowledge base. Such approaches may be beneficial if we an agent is acting based on the currently available knowledge, without the need to store it for later reuse.

### 3.8.1 Propositional Case

Paraconsistent logic can be split into several types (Bertossi et al., 2005): *signed systems*, which involve the renaming of literals and then restoring the non-conflicting part of the original theory by adding equivalences with their renamings; *weakly-negative logics* and *quasi-classical logic*, which use a restricted subset of classical proof theory, or rely on natural deduction to apply the proof rules more carefully, in order not to avoid the explosive derivation of all conclusions; and *multi-valued logics*, which employ a dedicated semantics, in which the truth and the falsity of each statement are considered independently.

Besnard and Schaub (1998) define a paraconsistent semantics for propositional theories by a signed system, in which they represent each positive literal $a$ as $a^+$ and each negative literal $\neg a$ as $a^-$. They employ default logic (Reiter, 1980) which allows to interpret $a^+$ as $a$ and $a^-$ as $\neg a$, but only as long as the equivalence between $a^+$ and $\neg a^-$ can be assumed. Thus, a consistent part of the original theory is effectively reconstructed. Unlike some other paraconsistent logics, in the consistent case the entailment within such a system coincides with classical entailment. Decision procedures for default logics (e.g., Junker and Konolige, 1990; Ben-Eliyahu and Dechter, 1991; Niemelä, 1995) can be used, although even in propositional case default entailment is known to be complete with respect to the second level of the polynomial hierarchy (Gottlob, 1992). This stream of development has largely gave way to (answer-set) logic programming, with relevant paraconsistent extensions being discussed in Section 3.8.2.

Besnard and Hunter (1995) and Hunter (2000b) proposed and developed quasi-classical logic, which they show to possess useful properties to reason with inconsistent knowledge. A number of interesting applications have been studied (e.g., Hunter, 2000a; Byrne and Hunter, 2004), and the logic is known to be decidable Hunter (2000b), however no implementations are known.

The four-valued propositional logic was developed by Belnap (1977). This logic works independently with truth and falsity, yielding two new truth values of a statement (apart from the classical *true* and *false*), namely *unknown* and *inconsistent*. This approach was later generalized for more than four truth values (Ginsberg, 1988; Fitting, 1991a). Translations of this logic into first-order logic are known (Rodrigues and Russo, 1998), which enable the use of classical first-order provers (e.g., VAMPIRE (Riazanov and Voronkov, 2002)) for reasoning.

Arieli and Denecker (2003) also investigate on paraconsistent propositional logic with multi-valued semantics and its translation to classical logic. In addition, they employ preferential reasoning (cf. Section 3.7), with the help of which they accept only models in which the inconsistent part of the knowledge base is minimized. They provide a polynomial translation, yielding a first-order theory with an addition of circumscriptive second-order formulae (McCarthy, 1980) representing the preferential criteria. This allows to use known translations of circumscriptive formulae (Ohlbach, 1996; Doherty et al., 1997; Gustafsson, 1996), finally yielding a first-order theory and again enabling to resort to classical first-order provers.

Besnard et al. (2005) encode various paraconsistent systems (maximal-consistent subsets, signed systems, and multi-valued approaches) into quantified propositional logic (QBF). This enables their comparison, but also the use of QBF solvers (e.g., Feldmann et al., 2000; Giunchiglia et al., 2001; Letz, 2002) for reasoning. This paves the way towards more practical applications, given the recent increased interest and developments in the area of QBF solvers.

### 3.8.2 Paraconsistent Logic Programs

The logic programming paradigm has been successfully applied in agent-based applications. Development of paraconsistent semantics for logic programs has been driven by the ability of agents (and other systems) to deal with situations, in which inconsistent information simply cannot be ruled out. Real-time applications, and distributed systems with autonomous entities and decentralized information sources fall under this category.

Paraconsistent semantics for logic programming was largely built on top of the multi-valued logic paradigm (Belnap, 1977; Ginsberg, 1988; Fitting, 1991a). First, such semantics for logic programs was developed by Blair and Subrahmanian (1987, 1989); other early studies in this area include those of (Fitting, 1991b) and (Kifer and Lozinskii, 1992). All use four-valued semantics and only work with classical negation.

Sakama (1992) concentrates on extended logic programs (ELP, Gelfond and Lifschitz, 1991), which feature both classical and default negation, and possibly negation in the head. Sakama (1992) proposes a paraconsistent version of the well founded semantics (Van Gelder et al., 1991) for this class of logic programs, where in order to distinguish between the classical and the default negation he resorts to the seven-valued semantics of (Ginsberg, 1988).

This work is further extended by Sakama and Inoue (1995) who developed a paraconsistent stable-model semantics for extended disjunctive logic programs (EDLP). This semantics was also implemented on top of the MGTP reasoner (Inoue et al., 1992). Further evaluation of this semantics was done by Alcântara et al. (2004) and Odintsov and Pearce (2005).

An alternative paraconsistent version of the well-founded semantics for extended logic programs, dubbed $WFSX_p$, was proposed by Alferes et al. (1995). This semantics is based on the principles of coherence and introspection (Damásio and Pereira, 1995), ensuring, e.g., that the default negation of an atom (i.e., the weaker one) is always entailed from the classical negation of the same atom. A dedicated decision procedure called SLX, which uses a procedure similar to the standard PROLOG SLDNF procedure (Lloyd, 1984) was described and implemented (Alferes et al., 1995). Further extensions of $WFSX_p$towards other common logic programming semantics are proposed by (Damásio and Pereira, 1995).

In the same paper discussed above, Sakama and Inoue (1995) proposed also the so called semi-stable semantics, which has the feature that is able to derive consequences in cases when the classical stable-model semantics has no model, but coincides with it in cases when it has models. Such an approach, dubbed *paracoherent* is not intended to draw conclusions from truly inconsistent knowledge bases, but merely to overcome non-existence of models in some cases due to some rather technical reasons (e.g., cyclic dependencies). This line of work was further extended by (Eiter et al., 2010a) who provided a model-theoretic characterization, and proposed several improvements. They show the complexity of reasoning, which is one level up in the polynomial hierarchy when compared to classical stable-model semantics. Finally, they briefly described a prototype implementation.

### 3.8.3 Other Paraconsistent Logics

Given the popularity of Semantic Web ontology languages, such as RDF and OWL 2, in AmI applications, their paraconsistent variants may contribute to the ability of AmI systems to deal with inconsistent information sources. Four-valued paraconsistent extensions of description logics (i.e, the family of logics which provides the formal semantics for OWL 2) were already investigated by Patel-Schneider (1989) and Straccia (1997). The approach of Ma et al. (2007), who propose $\mathcal{ALC}4$, a four-valued extension of $\mathcal{ALC}$ (cf. Baader et al., 2003), is particularly interesting to us, as paraconsistent reasoning is obtained with no additional computational cost by reduction to classical description logic. In the follow-up work, Ma and Hitzler (2009) extended this approach towards the $\mathcal{SROIQ}$ DL (Horrocks et al., 2006), reaching the full expressiveness of OWL 2. They also investigate the tractable fragments of OWL 2. Their approach has been implemented into RaDON plug-in Ji et al. (2009) of the NeOn ontology engineering toolkit (Haase et al., 2008).

A quasi-classical variant of description logic was developed by Zhang and Lin (2012). A tableau algorithm was also described by Zhang et al. (2009). These studies carry over the quasi-classical approach into the area of ontologies.

In argumentation systems (see Section 3.5), conflict resolution is typically addressed by the argumentation mechanism, and only consistent extensions are returned. As argued by Wakaki and Nitta (2013), inconsistent extensions are often filtered out, in order to satisfy the rationality postulates for abstract argumentation (Caminada and Amgoud, 2007). Therefore, Wakaki and Nitta (2013) proposed a paraconsistent semantics for argumentation based on multi-valued logics, that is able to reconstruct useful information also from these inconsistent extensions. An ASP-based implementation is said to appear in a future paper.

### 3.8.4 Applicability of Paraconsistent Reasoning

Paraconsistent reasoning has found applications in databases (Arieli et al., 2004), including medical knowledge bases (da Costa and Subrahmanian, 1989), and its applications in spatial databases were also conceived (Rodríguez, 2005).

Paraconsistent reasoning has been further applied for inconsistency management in areas, such as software engineering, and on problems, such as combining inconsistent specifications (Hunter and Nuseibeh, 1998) and requirements (Ernst et al., 2012).

Quasi-classical logic has been applied in dealing with inconsistency in structured text excerpts (Hunter, 2000a), e.g., structured news reports (Byrne and Hunter, 2004). A similar approach may be valuable in AmI applications with the need to process textual inputs from multiple users. An interesting observation in these works is that the presence of inconsistency need not necessarily be an indicator of error; for instance, if multiple news reports are found inconsistent with background knowledge, then this may be an indicator of interesting new developments in the domain, that have to be accommodated and processed (Byrne and Hunter, 2004).

We are not aware of any direct application or case study of paraconsistent reasoning in AmI. Nevertheless, these approaches can be applied to any type of conflict resolution, most notably sensory input conflicts, and also for resolving conflicts between new observations and background knowledge (Byrne and Hunter, 2004; Ernst et al., 2012).

As already noted above, current AmI applications already make use of ontologies. If inconsistency handling of ontological data becomes needed, paraconsistent OWL (Ma et al., 2007; Ma and Hitzler, 2009) may become handy (or alternatively some of the ontology debugging approaches surveyed in Section 3.4.2 may be applied).

While all the approaches surveyed in previous Sections mostly aim at removing conflicts and repairing the knowledge base, paraconsistent reasoning shifts the point of view into simply being able to reason also with inconsistent knowledge, without necessarily requiring some kind of repair. This point of view may be useful in certain AmI scenarios, where agents need to react on their inputs, while maintaining the knowledge base is of secondary interest. Many of the logics which we surveyed have favourable (polynomial) reasoning complexity of reasoning (Coste-Marquis and Marquis, 2005). Many of the paraconsistent logic programming extensions have developed into experimental implementations, and some of them are also known to be tractable (e.g., $WFSX_p$ (Alferes et al., 2003)). Further research may be however needed in order to make them effective enough for realtime AmI applications.

# 4 Summary

In this work, we surveyed a number of research areas in KR that we believe to be relevant to the problem of conflict resolution, that, as we noted, is crucial in AmI, and in many other knowledge-intensive application scenarios.

The body of research concentrating on modelling context within AmI, also addresses conflict resolution to a certain extent. The main attention is given to resolving conflicts within context, originating, for instance, from faulty or incompatible sensor readings, or as a result of situation change. This part is well elaborated in the literature, and it is also efficiently handled, for example by resorting to hybrid techniques integrating KR and machine learning methods. The field, however, relies mostly on centralized context models, which may not be sufficient in real world AmI environments, as we discussed above. Therefore, this branch may largely benefit from cross-fertilization with the other KR branches discussed in the paper.

Multi-context systems (MCS) and related approaches allow to represent heterogeneous and interconnected systems composed of knowledge bases, each of which may be modelled in different language and from a different contextual perspective (therefore they are called contexts). As such, MCS allow to resolve conflicts that may arise between the contexts, although mostly in a localized fashion, i.e., each context is capable to resolve the conflicts locally and independently from the other contexts. Some recent efforts may help to make conflict resolution more shared (Brewka and Eiter, 2009) and its understanding global (Eiter et al., 2010b). In this respect, cross-fertilization between MCS and argumentation seems to be a promising approach (Brewka and Eiter, 2009; Bikakis and Antoniou, 2010). Some studies related to MCS also considered resolving, or, at least isolating conflicts inside contexts; this can be seen as some limited way how to handle background or domain knowledge conflicts. The research in MCS has been advanced to the point, where multiple implementations and evaluations are known and even for experimental applications in AmI settings (Bikakis and Antoniou, 2010).

Conflict resolution has long been studied in the area of belief revision, where knowledge bases are combined with newer, or more important knowledge, and conflicts need to be resolved in order to yield a consisting result. As such, belief change methodologies mostly fall under conflict avoidance, as they prevent the conflict from creeping into the knowledge base. The main body of research in this filed focuses mostly on foundational research, trying to characterize suitable conflict resolution strategies with postulates and devising revision operators, that behave accordingly. The area may contribute to AmI as a foundation for suitable conflict resolution strategies to be applied in AmI systems. More practical approach is undertaken in ontology evolution and ontology debugging fields, where real algorithmic support, feasibility and effectiveness are considered relevant. Nevertheless, further research will be needed before the results can be applicable at real time, as most of the current methodologies, especially in ontology evolution, are semi-automatic and require human intervention. In ontology debugging several approaches are known, which go in the fully-automated direction (Qi and Pan, 2007; Meyer et al., 2005; Roussakis et al., 2011).

Argumentation is a representation technique that formalizes notions of argument, attack, and support, and enables to resolve conflicts by identifying sets of arguments that are consistent, ruling out any possible attacks. The notion of argument is rather abstract, which enables to resolve conflict between beliefs, goals, actions, etc. The increasing popularity of argumentation is given by its rich and flexible formalism with a family of semantics with well established theoretical properties, some of which also enjoy feasible complexity results. It was applied on a number of practical problems, and notably, also in AmI (Ferrando and Onaindia, 2012; Bikakis and Antoniou, 2010; Moraitis and Spanoudakis, 2007), especially as a decision making technique for autonomous agents in the presence of conflicting information.

The position of argumentation as essential and effective conflict resolution technique is further assured by the fact that researchers from the other fields try to integrate argumentation into their approaches when conflicts need to be resolved. We noted such attempts in multi-context systems (Brewka and Eiter, 2009) and ontology debugging (Moguillansky et al., 2008), but the interchange between argumentation and belief change seems to be especially fruitful, as we documented in Section 3.6. This line of research is only very recent, and mostly theoretical results were yet achieved, though we believe its possible future impact on practical applications, including AmI, is quite likely.

Preferences are sometimes combined with different reasoning formalisms, in order to select a rule to be applied in a given situation from a set of possibly conflicting rules, or in order to distinguish between multiple possible derivations. The former case can be seen as conflict avoiding, while the latter case is a more delicate indirect conflict resolution method, as it allows to choose from the set of all possible solutions, some of them possibly conflicting, based on predefined preferences. As we have argued, such a strategy may be useful in resolving conflicts in goals and actions, if preferences are paired with a formalism that can capture planning such as, for instance, logic programming. Algorithms for reasoning with preferences were devised, and prototypical reasoners were implemented. Preferential reasoning was also already applied in AmI (Bikakis and Antoniou, 2010).

While most of the above approaches work by removing or avoiding conflicts, paraconsistent reasoning takes a slightly different direction and concentrates on identifying and isolating the inconsistent parts of the knowledge base and carefully drawing conclusions only from the consistent knowledge. In this area, different approaches were theoretically studied, however, especially paraconsistent logic programming and paraconsistent ontologies were developed also in practice and prototypical reasoners have been implemented. We believe that they can be potentially useful in AmI, especially when the AmI environments are to react to the current situation (which may feature inconsistencies) without the need to necessarily store all the current information for future processing.

A summary of our observations is presented in Table 16. We conclude that indeed KR has been fruitful in addressing the problem of conflict resolution from many different points of view and with diverse applications in different use cases. The different approaches to conflict resolution are very well theoretically developed, in the sense that the semantics is established and its properties are investigated. But, as we saw, for number of the approaches also effective (in the sense of polynomial) algorithms were developed, and some of them were implemented and experimentally evaluated. Finally, we have also pointed out a number of works that are already trying to apply KR methods in AmI (Moraitis and Spanoudakis, 2007; Mileo et al., 2008b; Muñoz et al., 2010; Bikakis and Antoniou, 2010; Muñoz et al., 2010; Muñoz Ortega et al., 2010; Ferrando and Onaindia, 2012).

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Table 8: Summary of Ontology Evolution Approaches

| **Referenced Work(s)** | **Supported Language** | **Properties Considered** | **Resolution Method** |
|---|---|---|---|
| Protégé (Noy et al., 2006, 2000)<br>OilEd (Bechhofer et al., 2001) | OWL | Custom | Manual (Editors) |
| KAON (Gabel et al., 2004)<br>OntoStudio (Sure et al., 2003)<br>ReTax++ (Lam et al., 2005) | OWL | Coherence<br>Consistency | Semi-automatic |
| EvoPat (Riess et al., 2010)<br>(Konstantinidis et al., 2008a,b; Flouris et al., 2013)<br>(Djedidi and Aufaure, 2009, 2010) | RDF/S | Custom | Automatic |
| RUL (Magiridou et al., 2005) | RDF/S (Data Only) | Custom | Automatic |
| (Liu et al., 2006; Roger et al., 2002) | DL | Coherence<br>Consistency | Automatic |
| (Lee and Meyer, 2004) | $\mathcal{ALU}$ DL | Consistency | Belief Change |
| (Halaschek-Wiener and Katz, 2006) | OWL | Consistency | Belief Change |
| (Ribeiro and Wassermann, 2007) | Without Negation | Principle of Success | Belief Change |
| (Gutierrez et al., 2006) | RDF/S | Principle of Success | Belief Change |
| (Flouris, 2006b,a; Flouris et al., 2006a; Flouris and Plexousakis, 2006; Flouris et al., 2004, 2005, 2006b)<br>(Ribeiro et al., 2013)<br>(Cuenca Grau et al., 2012) | General | Consistency | Belief Change |
| (De Giacomo et al., 2007)<br>(Wang et al., 2010)<br>(De Giacomo et al., 2009) | DL | Consistency | Approximate |
| (Qi et al., 2006b,a) | Disjunctive DL (Stratified) | Consistency | Maxi-adjustment |
| (Qi and Du, 2009) | DL | Consistency | Belief Change |

Table 9: Summary of Ontology Debugging Approaches

| **Referenced Work(s)** | **Supported Language** | **Problem Considered** | **Approach** |
|---|---|---|---|
| Protégé (Noy et al., 2006, 2000) | OWL | Diagnosis<br>Repair | Manual (Editors) |
| (Lehmann and Buhmann, 2010) | OWL | Diagnosis<br>Repair | Semi-automatic |
| (Plessers and de Troyer, 2006; Meyer et al., 2006; Wang et al., 2005)<br>(Kalyanpur et al., 2006; Lam et al., 2006) | DL | Diagnosis | Tableaux-based |
| (Qi and Pan, 2007; Meyer et al., 2005) | DL | Diagnosis<br>Repair | Automatic (Stratification) |
| (Roussakis et al., 2011)<br>(Flouris et al., 2012) | RDF/S | Diagnosis<br>Repair | Automatic (Preferences) |
| (Moguillansky et al., 2008) | $\mathcal{ALC}$ DL | Diagnosis<br>Repair | Automatic (Argumentation) |

Table 10: Complexity of abstract argumentation (Dunne and Wooldridge, 2009)

| | *admissible* | *grounded* | *complete* | *preferred* | *stable* |
|---|---|---|---|---|---|
| Credulous | NP-c | P | NP-c | NP-c | NP-c |
| Skeptical | trivial | P | P | $\Pi_2^P$-c | coNP-c |

Table 11: Argumentation-based formalisms.

| | language | satisfies postul.? | complexity | implementation |
|---|---|---|---|---|
| (Prakken and Sartor, 1997) | defeasible | no | P | - |
| (Besnard and Hunter, 2001) | propositional | irrelevant | PSPACE-c | (Vasiliki Efstathiou, 2010) |
| (García and Simari, 2004) | defeasible | no | P | (DeL) |
| (Governatori et al., 2004) | defeasible | no | P | (Dei; Aceto, 2010) |
| (Prakken, 2010) | defeasible | yes | P/$\Pi_2^P$-c | (Snaith and Reed, 2012) |
| (Baláž et al., 2013) | defeasible | yes | P/$\Pi_2^P$-c | - |

Table 12: Belief change and argumentation: Comparison of works

| | **BC of AF** | **BC by AF** | **Studied Problem** |
|---|---|---|---|
| Baroni et al. (2013) | | | general comparison |
| (Falappa et al., 2009),(Falappa et al., 2011) | Yes | Yes | general comparison, inter-applicability |
| (Rotstein et al., 2010) | Yes | | dynamic evidence-based argumentation |
| Conditioned AFs (Liao et al., 2011) | Yes | | update of AF |
| Cayrol et al. (2010), Boella et al. (2009b,a) | Yes | | addition/removal of attacks/arguments |
| Coste-Marquis et al. (2013), Mailly (2013) | Yes | | revision in AF, minimal change |
| Baumann and Brewka (2010; 2012; 2013) | Yes | | enforcing and related problems |
| Moguillansky et al. (2011) | Yes | | prioritized revision of arguments |
| Moguillansky et al. (2008) | | Yes | ontology debugging |
| Liao (2013) | | Yes | belief revision |
| Krümpelmann et al. (2011) | | Yes | non-prioritized belief revision |

Table 13: Preferential Reasoning: Preferences on Rules.

| | **Type** | **Underlying semantics** | **Complexity** | **Practicality** |
|---|---|---|---|---|
| (Brewka and Eiter, 1999) | prescriptive | answer set | NP/worse | reduction |
| (Delgrande et al., 2002) | prescriptive | answer set | NP/worse | native |
| (Wang et al., 2000) | prescriptive | answer set | NP/worse | reduction |
| (Zhang and Foo, 1997) | descriptive | answer set | NP/worse | – |
| (Sakama and Inoue, 2000) | descriptive | answer set | NP/worse | algorithm |
| (Šefránek, 2008; Šefránek and Šimko, 2011, 2013) | descriptive | answer set | NP/worse | – |
| Šimko (2013) | descriptive | answer set | NP/worse | reduction |
| (Brewka, 1996) | prescriptive | well-founded | P | – |
| (Schaub and Wang, 2002) | prescriptive | well-founded | P | – |
| (Wang et al., 2000) | prescriptive | well-founded | P | – |

Table 14: Preferential Reasoning: Preferences on Literals.

| | **Preferences as** | **Complexity** | **Practicality** |
|---|---|---|---|
| Sakama and Inoue (2000) | a relation on literals | NP/worse | algorithm |
| Brewka (2002) | rules with ordered disjunction in the head | NP/worse | algorithm |
| Brewka et al. (2003) | a preference program | NP/worse | algorithm |

Table 15: Paraconsistent reasoning: Comparison of approaches

| | **Language** | **Type** | **Practicality** |
|---|---|---|---|
| Besnard and Schaub (1998) | propositional | signed | reduction to default logic |
| Belnap (1977); Arieli and Denecker (2003) | propositional | multi-valued | reduction to FOL |
| Arieli and Denecker (2003) | propositional | quasi-classical | decidable |
| Besnard et al. (2005) | propositional | multi-valued/signed | reduction to QBF |
| Blair and Subrahmanian (1987, 1989); Fitting (1991b); Kifer and Lozinskii (1992) | LP | multi-valued | – |
| Sakama (1992); Sakama and Inoue (1995) | EDLP | multi-valued | implemented |
| Alferes et al. (1995) | ELP | multi-valued | implemented |
| Sakama and Inoue (1995); Eiter et al. (2010a) | EDLP | multi-valued/paracoherent | implemented |
| Paraconsistent OWL (Ma et al., 2007) | DL | multi-valued | implemented |
| Quasi-classical DL (Zhang and Lin, 2012) | DL | quasi-classical | reasoning algorithm |
| Paraconsistent argumentation (Wakaki and Nitta, 2013) | ELP | multi-valued | implementation<br>“to appear” |

Table 16: Summary of Conflict Resolution Fields

| **Field** | **Conflict types** | **Resolution method** | **Theoretical focus** | **Tractable variants (complexity)** | **Applications in AmI (and elsewhere)** |
|---|---|---|---|---|---|
| **Current Context Modelling Approaches** | Contextual<br>Sensory<br>Bckg./Domain<br>Goal<br>Action | Mostly Prevention | – | – | Yes |
| **Multi-Context Systems** | Contextual<br>(Sensory)<br>(Bckg./Domain) | Resolution, Isolation | Yes | – | Yes |
| **Belief Change** | Contextual<br>Bckg./Domain<br>(Sensory)<br>(Goal)<br>(Action) | Prevention | Yes | – | – |
| **Ontology Evolution** | Contextual<br>Bckg./Domain<br>Sensory | Prevention | – | Yes, depending on underlying Description Logic | – |
| **Ontology Debugging** | Contextual<br>Bckg./Domain<br>Sensory | Repair | – | Yes, depending on the expressive power of the constraint language | – |
| **Argumentation** | Contextual<br>Bckg./Domain<br>Goal<br>Action | Resolution | Yes | Grounded semantics<br>(P) | Yes |
| **Preferential Reasoning** | Goal<br>Action | Prevention, Indirect | Yes | Preferred well-founded semantics<br>(P) | (in planning, configuration) |
| **Paraconsistent Reasoning** | Sensory<br>Context<br>Bckg./Domain | Isolation | Yes | Multiple<br>(P) | (in data integration) |