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Summary

1 Motivation

In everyday life, we need to make decisions to solve various problems. In the ideal case, we would have all relevant information about the problem. Then we would reason to draw conclusions. Unfortunately, this is not usually the case. We must often make decisions based on *incomplete* and *inconsistent* knowledge.

The goal of artificial intelligence is to create intelligent machines. But what does it mean to be *intelligent*? Although there exist many definitions, we could say that intelligent machines think and act rationally, resp. think and act at least as well as humans do (Touring, 1950; Newell and Simon, 1956; Russell and Norvig, 2010). It means that they face the necessity of dealing with incomplete and inconsistent knowledge as well.

The ability to create *representations* of the domain of interest and *reason* with these representations is a key to artificial intelligence (McCarthy, 1959). In the logic-based approach to intelligent machines, *logic* provides both the language for the representation of the domain of interest and also the inference engine for reasoning with those representations. The question still remains what kind of logic is appropriate to represent incomplete and inconsistent knowledge.

2 Background

Knowledge representation and reasoning is the field of artificial intelligence dedicated to representing knowledge about the world in a form that machines can utilize to solve various problems. It includes default reasoning, defeasible reasoning, and reasoning with arguments.

In *default reasoning*, we can express default assumptions like "some statement is true resp. false unless there is an exceptional situation". By contrast, *classical reasoning* can only express facts like "some statement is true resp. false". Domain-specific knowledge has usually exceptions. For example, birds usually fly but there are species like ostrich that do not fly. Also birds with broken wings do not fly and so on. The set of possible exceptions is typically not limited. In classical reasoning, for each possible exception, we would need to have explicit knowledge that it is not that case. If we have incomplete knowledge, we fail to draw conclusions. In default reasoning, we can assume by default that it is the typical case and we can draw conclusions.

There exist many logics based on default reasoning like logic programming (Gelfond and Lifschitz, 1988; Przymusinski, 1990; Dung, 1991; Gelder et al., 1991), default logic (Reiter, 1980), autoepistemic logic (Moore, 1985), or non-monotonic modal logic (McDermott, 1982). Assumption-based frameworks generalize all mentioned logics and can be seen as an abstraction of default reasoning (Bondarenko et al., 1997). In assumption-based frameworks, each assumption has its contrary – a sentence representing that it is an exceptional situation in which that assumption cannot be assumed. The semantics of assumption-based frameworks assigns to each framework sets of assumptions which we will call contexts. The extension of a context is the set of all consequences of that context with respect to the deductive system in the background.

In the assumption-based approach to default reasoning, extensions are determined by interaction between sets of assumptions (Bondarenko et al., 1997). There exists an alternative approach to default reasoning, in which extensions are determined by the interaction between arguments (Dung, Kowalski, et al., 2009). An argument is a proof for a conclusion that can be retracted since it is constructed by applying inference rules on default assumptions that are retractable too. The argumentation-based semantics assigns to each framework sets of arguments which we will also call contexts. The extension of a context is the set of all conclusions of arguments in that context.

Classical reasoning uses only strict inference rules of the form "if preconditions are true, then the conclusion is also true". Such rules are applied without exception. In *defeasible reasoning*, we can use in addition defeasible inference rules of the form "if preconditions are true, then the conclusion is also true unless there is an exceptional situation". Defeasible inference rules can be defeated by concluding that we have an exceptional situation. Like in default reasoning, we will call such statement the contrary of a defeasible rule. Defeasible reasoning is closely related to default reasoning since a defeasible rule can be viewed as a strict rule with the additional assumption that the original rule is not defeated.

In frameworks that incorporate both default and defeasible reasoning, arguments are usually built from default assumptions by applying strict or defeasible inference rules. Three kinds of conflicts among arguments were identified – undermining, undercutting, and rebutting. Undermining is when the conclusion of an argument is the contrary of an assumption of another argument, undercutting is when the conclusion of an argument is the contrary of a defeasible rule of another argument, and rebutting occurs when conclusions of two arguments are inconsistent. Rebutting is usually symmetrical, but preferences among arguments can be used to decide whether only one argument is rebutted by the other or both arguments rebut each other.

There exist many defeasible systems like defeasible logics (Nute, 1994), abstract argumentation systems (Vreeswijk, 1997), extended logic programs with defeasible priorities (Prakken and Sartor, 1997), defeasible logic programs (García and Simari, 2004), or ASPIC$^+$ (Prakken, 2010; Modgil and Prakken, 2013). They differ in many aspects, both syntactic and semantic. Although all mentioned systems use argumentation-based semantics, no single defeasible system is nowadays accepted as a standard.

In Dung, 1995, abstract argumentation frameworks were introduced as a pair consisting of a set of arguments and a binary attack relation among the arguments. They are abstract since they do not assume any structure of arguments. The status of arguments is determined on the abstract level only in terms of the attack relation. Semantics of many structured argumentation systems are defined on top of abstract argumentation frameworks. After what arguments and attacks among the arguments are instantiated, the semantics of abstract argumentation frameworks can be used to determine extensions.

Assumption-based frameworks (Bondarenko et al., 1997), some defeasible systems (Prakken and Sartor, 1997; Vreeswijk, 1997; Prakken, 2010), and also abstract argumentation frameworks (Dung, 1995) use so called admissibility-based semantics. Admissible contexts, that are sets of default assumptions resp. arguments, are defined on top of the attack relation among contexts. There exists the whole family of admissibility-based semantics like complete, grounded, preferred, ideal, semi-stable, eager, and stable semantics.

3 Problem Identification

Language with default assumptions and knowledge base containing both strict and defeasible inference rules over that language look promising for representing knowledge that is incomplete and inconsistent. Default and defeasible reasoning provides an inference engine that is non-monotonic hence close to human reasoning. However, we show in the thesis that there are still fundamental problems with existing formalisms that should be addressed.

The semantics of assumption-based frameworks, as defined in Bondarenko et al., 1997, is restricted to closed contexts. A set of assumptions is closed, if it contains all assumptions derivable from it. The status of assumptions is then determined by interaction only between closed contexts. Such restriction has various consequences. First, the semantics has unintuitive results and does not follow the generate-and-test paradigm of default reasoning. Inference rules, that do not contain default assumptions as consequences, usually generate candidates for the semantics. Contexts, that do not satisfy inference rules containing default assumptions as consequences, are filtered out. This is not the case of the semantics of assumption-based frameworks as we show in the following example.

Example 1. Consider the assumption-based framework F_1 for the logic program P_1

$$b \leftarrow \mathrm{not}\, a$$
$$c \leftarrow \mathrm{not}\, b$$

and the assumption-based framework F_2 for the logic program P_2 obtained from P_1 by adding the inference rule

$$\mathrm{not}\, c \leftarrow \mathrm{not}\, a$$

The context $\Delta_1 = \{\mathrm{not}\, a, \mathrm{not}\, c\}$ is the only context complete in F_1. It is complete also in F_2 as expected. The problem is that there is another context $\Delta_2 = \{\mathrm{not}\, b\}$ complete in F_2 but not in F_1 which does not comply the generate-and-test paradigm.

Next, the semantics of assumption-based frameworks restricted to closed contexts are not related in the usual way. For example, preferred or semi-stable contexts are not in general complete, or the existence of complete or preferred contexts is not guaranteed (Bondarenko et al., 1997). Many results for assumption-based frameworks hold only under the assumption that frameworks are *flat*, i.e., that they do not contain inference rules containing default assumptions as consequences. Such assumption is too restrictive hence not acceptable in our setting. Although there exist knowledge bases like normal logic programs (Gelfond and Lifschitz, 1988; Przymusinski, 1990; Dung, 1991; Gelder et al., 1991) or default theories (Reiter, 1980) that are flat, the deductive system of assumption-based frameworks should also contain objective, domain-independent inference rules that are sound and complete with respect to the consequence operator of a logic in the background. For example, the coherence rule for logic programming (Alferes and Pereira, 1992) or the modus ponens rule for non-monotonic modal logics (Marek and Truszczyński, 1993) contain default assumptions as consequences.

Finally, even if we would drop the restriction to closed contexts, the skeptical semantics of assumption-based frameworks implode when there exist two complete extensions with inconsistent sentences. This problem was the first time identified for default theories in Pereira et al., 1992.

Example 2. Consider the default theory $(\emptyset, D)$ where

$$D = \left\{ \frac{\mathrm{M}\, a}{a}, \frac{\mathrm{M}\, \neg a}{\neg a}, \frac{\mathrm{M}\, b}{b} \right\}$$

It has two default extensions $E_1 = \{\mathrm{M}\, a, a, \mathrm{M}\, b, b\}$ and $E_2 = \{\mathrm{M}\, \neg a, \neg a, \mathrm{M}\, b, b\}$ (Reiter, 1980). Both the well-founded semantics (Pereira et al., 1992) as well as the least stationary semantics (Przymusinska and Przymusinski, 1994) identify $E_0 = \{\}$ as the least extension instead of the expected extension $\{\mathrm{M}\, b, b\}$. The source of the problem lies in the fact that two inconsistent sentences a and $\neg a$ are potentionaly true. Since any sentence follows from $\{a, \neg a\}$, any sentence is potentionaly true including b. Therefore $\mathrm{M}\, b$ and consequently also b do not belong to E_0.

If the deductive system of an assumption-based framework contains not only domain specific rules, but also domain independent inference rules that are sound and complete with respect to the consequence operator of a logic in the background, and the assumption-based framework has two complete contexts with two inconsistent consequences, the grounded context representing the skeptical view is always empty.

As we mentioned earlier, the argumentation-based semantics of frameworks with default assumptions and defeasible inference rules usually distinguish three kinds of conflicts – undermining, undercutting, and rebutting. An argument is undermined by another argument on its default assumption. Similarly, an argument is undercutted on its defeasible inference rule. The problem may occur when an argument is rebutted without specifying which defeasible element is defeated.

Example 3. Consider a logic program containing one defeasible rule (denoted with $\Leftarrow$) and two strict rules (denoted with $\leftarrow$):

$$\neg a \Leftarrow \qquad\qquad a \leftarrow \qquad\qquad b \leftarrow r$$

Let r be the contrary of $\neg a \Leftarrow$, i.e., let r represents the knowledge that the defeasible rule can not be applied. If we resolve the conflict between two arguments $A = [\, \Rightarrow \neg a]$ and $B = [\, \rightarrow a]$ by defeating A without specifying on which defeasible element, neither r nor b are concluded.

Another problem with rebutting is that in general, it does not properly resolve indirect conflicts between arguments. Desired properties regarding both direct and indirect conflicts were formulated in Caminada and Amgoud, 2007. It is quite surprising that all defeasible systems mentioned in the previous section do not satisfy them. ASPIC$^+$ is the only exception, but only under assumptions that are not acceptable in our setting, including the condition that the deductive system is flat.

Example 4. Consider a logic program containing two defeasible rules (denoted with $\Leftarrow$) and two strict rules (denoted with $\leftarrow$):

$$a \Leftarrow \qquad b \Leftarrow \qquad c \leftarrow a \qquad \neg c \leftarrow b$$

Arguments $A = [[\ \Rightarrow a] \rightarrow c]$ and $B = [[\ \Rightarrow b] \rightarrow \neg c]$ rebut each other. It is not enough to resolve the direct conflict between A and B by defeating one of the conflicting arguments. There is also indirect conflict between arguments $C = [\ \Rightarrow a]$ and $D = [\ \Rightarrow b]$ if we take into account strict rules.

4 Problem Solution

Although the fixpoint characterization of admissibility-based semantics of abstract argumentation frameworks and assumption-based frameworks is already well-known, proper proofs in the original papers are either missing because of limited space or too specific for particular framework. Therefore we present in Preliminaries a consistent summary of existing results in order theory that can be applied to prove various properties of admissibility-based semantics. The shift from a specific framework to more abstract order theory helps to better understand not only why some propositions are true, but also why there are problems with some design decisions like the restriction of assumption-based frameworks to closed contexts. We also introduce in Preliminaries a universal logic together with consequence operators, knowledge bases, and an example of a proof system.

Then we present three frameworks – assumption-based frameworks for default reasoning, defeasible frameworks for defeasible reasoning, and abstract argumentation frameworks that represent reasoning with arguments. For all three frameworks, we present in a uniform declarative way the family of admissibility-based semantics that assign to each framework a set of contexts. A context is a set of defeasible elements – default assumptions, defeasible rules, resp. arguments.

In order to provide the fixpoint characterization of admissibility-based semantics for all three frameworks at once, we introduce non-monotonic frameworks. They consist of the set of defeasible elements and the attack operator on the set of defeasible elements. At this level of abstraction, defeasible elements are atomic concepts. We apply the results from order theory to prove properties of admissibility-based semantics like the existence or uniqueness of a context in particular semantics, and specialization or the subset relation between contexts of various semantics.

Then we introduce restrictions to contexts of non-monotonic frameworks. In restricted non-monotonic frameworks, the status of defeasible elements is not determined by interaction between any contexts, but only between contexts from a given class. Each context in the class has usually some desired property. We show that contexts in the admissibility-based semantics of restricted non-monotonic frameworks do not always belong to the given class. In other words, they do not have the required property. If we require the membership to the class by definition, we break useful semantical properties like in the case of assumption-based frameworks restricted to closed contexts.

In order to solve the problem with the implosion of the grounded semantics, we focus on the restriction of non-monotonic frameworks to attack-free contexts, i.e., to contexts that do not attack themselves. We show that for a reasonable wide class of non-monotonic frameworks, contexts in the restricted semantics remain attack-free. It means that the usual properties of admissibility-based semantics remain untouched after the restriction, and that the grounded semantics is not too skeptical as in the unrestricted case.

Finally, we introduce the structured argumentation frameworks consisting of the language containing default assumptions and deductive system containing both strict and defeasible inference rules. We show why rebutting causes problems in argumentation-based semantics of structured argumentation frameworks. Instead of rebutting we propose different handling of conflicts. When the deductive system contains inference rules sound and complete with respect to a logic in the background, two arguments with inconsistent consequences can be used to construct another argument concluding the contrary of any defeasible element they contain. Hence we move from resolving conflicts among two arguments to resolving conflicts in self-attacking arguments. We show that in spite of rebutting, the new approach satisfies properties inspired by Caminada and Amgoud, 2007.

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Abstract

Humans must often make decisions based on incomplete and inconsistent knowledge. Intelligent machines face the necessity of dealing with such knowledge too. The question arises what kind of logic provides the language for the representation of the domain of interest and the inference machine for reasoning with those representations.

In recent decades, great efforts have been devoted to research default and defeasible reasoning with argumentation-based semantics. Classical reasoning can express facts like "some statement is true resp. false" and uses strict rules of the form "if preconditions are true, then the conclusion is also true". By contrast, default reasoning can express default assumptions like "some statement is true resp. false unless there is an exceptional situation". Defeasible reasoning uses in addition to strict rules also defeasible rules of the form "if preconditions are true, then the conclusion is also true unless there is an exceptional situation". If we conclude that there is an exceptional situation, previous knowledge may be retracted. Such kind of reasoning is non-monotonic and is close to how people think.

Arguments are proofs for conclusions built by applying strict or defeasible rules on default assumptions. They are defeasible since assumptions and inference rules they are constructed from are defeasible too. Arguments can attack each other. One argument may conclude that it is an exceptional situation for an assumption or defeasible rule in another argument, or conclusions of two arguments may be inconsistent. The status of arguments is then determined by the attack relation among the arguments. Conclusions of accepted arguments represent a possible state of the world we are reasoning about.

There exist many systems incorporating default and defeasible reasoning with argumentation-based semantics that are possible candidates for representing incomplete and inconsistent knowledge. They differ in many aspects like the level of abstraction, language, structure of arguments, attack among arguments, or the status of arguments. It is expected that the set of accepted arguments is consistent, not only directly, but also indirectly with respect to the set of strict rules in the knowledge base. It is surprising that existing systems either do not meet those expectations or only under unacceptable assumptions. In this thesis, we propose a new argumentation-based approach to default and defeasible reasoning that satisfies those requirements.