# 缺省理论中一种获取优先序的方法*

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# A Method of Finding Priorities in Default Theories

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**Abstract**: An approach is introduced to derive specificity in default theories. Compared with other methods, the method handles priority quite well and has lower complexity. Then the prioritized stationary semantic for default logic is defined. The method can strengthen the cautious stationary default reasoning without increasing the computational complexity very much.
**Key words**: default logic; specificity; stationary extension; complexity

**摘 要**: 引进了一种在缺省理论中提取优先序的方法.与已有方法相比,此方法不仅具有合理性且具有低难度.进而定义了缺省逻辑的优先稳定语义.这种方法在不增加复杂性的情况下,增强了谨慎稳定缺省推理的能力.
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Reiter's default logic[1], DL for short, is one of the most popular nonmonotonic formulisms. In DL, a default theory consists of a set $W$ of propositional formulas and a set $D$ of defaults. Each default is of the form

$$\frac{A:B_1,\ldots,B_n}{C}.$$

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Extensions of a default theory are defined as fixed points of the operator $\Gamma$ which maps an arbitrary set $S$ of formulas to the smallest deductively closed set $S'$ such that $S'$ contains $W$ and that if $\frac{A:B_1,\ldots,B_n}{C}\in D$, $A\in S'$ and $S\nvdash\neg B_i$ for any $i$ then $C\in S'$. In default logic, two decision problems which are most relevant and have been extensively studied in the literature, are brave reasoning, deciding if a formula belongs to at least one extension, and cautious reasoning, deciding if a formula belongs to all extensions. The popularity of DL is basically due to two reasons. Firstly, the way defaults are represented is natural and intuitive[1]. Secondly, DL has great expressiveness[2]. This expressiveness makes DL as a powerful tool for knowledge representation and reasoning. Nevertheless, default reasoning suffers from some serious deficiencies. Firstly, brave reasoning is too strong, usually some conflicting formulas can be derived, while cautious reasoning is very weak. Sometimes we can get nothing by cautious reasoning except the initial knowledge.

*Example* 1.1. Let $W$ consist of the following formulas.

$$\text{penguin}(\texttt{tweety}),\quad \text{penguin}(\texttt{tweety})\Longrightarrow \text{bird}(\texttt{tweety}).$$

And let $D$ consist of the following defaults.

$$\frac{\text{bird}(\texttt{tweety}):\text{fly}(\texttt{tweety})}{\text{fly}(\texttt{tweety})},\frac{\text{penguin}(\texttt{tweety}):\neg\text{fly}(\texttt{tweety})}{\neg\text{fly}(\texttt{tweety})}.$$

Then both fly(tweety) and ¬fly(tweety) can be bravely deduced from ($D$,$W$). But nothing except formulas in $W$ can be cautiously deduced.

The second deficiency of default reasoning is its high computational complexity. Generally, default reasoning is at the second level of the polynomial hierarchy[2~4]. That is to say, default reasoning is much more harder than monotonic reasoning. Even in cases when the underlying monotonic reasoning can be done in polynomial time default reasoning is still intractable (see Refs.[4~6]). The high complexity is an obstacle to use DL as a tool of knowledge representation and reasoning.

Thirdly, a default theory may have no extensions, in this case, default reasoning is undefined. In 1994, Przymusinska and Przymusinsky introduced the stationary semantic for default theories[7]. A set $S$ of formulas is said to be a stationary extension if it is a fixed point of $\Gamma^2$, that is, $S=\Gamma(\Gamma(S))$. Stationary extensions have some nice properties[7]. For instance, every default theory has the smallest stationary extension. This makes cautious stationary reasoning a little bit easier (see Ref.[8]). However, cautious stationary reasoning is too weak, even weaker than cautious reasoning.

*Example* 1.2. Let $W=\{s,y\Rightarrow a\}$, and let

$$D=\left\{\frac{s:y}{y},\frac{s:\neg m}{\neg m},\frac{a:m}{m}\right\}.$$

It is easy to see that $y,a$ occur in every extension of $(D,W)$. But they do not occur in the smallest stationary extension (which is $Th(W)$) of $(D,W)$.

A partial reason why default logic has the above-mentioned drawbacks is that it does not prefer more specific defaults over more general ones. Specificity is a fundamental principle of commonsense reasoning, and it is commonly accepted that conclusions based one more general default rules should be given up when more specific conflicting rules are available. Default logic does not obey this principle. Let us take birds and penguins for instance (see Example 1.1). Intuitively, being a penguin is much more specific than being a bird, and in this case of conflict, we would like to use more specific default. But the default theory in Example 1.1 generates two extensions instead of preferring the more specific one.

In the literature there are several methods to find orders of specificity between defaults by using the information of the given default theories. Although these approaches handle specificity quite well, all of them suffer from some deficiencies (see section 1). In section 2, we present a new method to derive specificity. Based on this order of specificity we introduce the notion of preferred stationary extensions. The approach enjoys nice computational property. It can strengthen the cautious stationary reasoning without increasing the complexity very much.

## 1 Preliminaries and Realted Work

In this paper we shall restrict ourselves to normal default theories. And we will use somewhat simplified notations, for example we write default $\frac{A:B}{B}$ as $A \to B$. In order to show how the specificity can be defined we first split the initial knowledge *W* in our default theories into two parts, as is common in conditional approaches (see Refs.[9~12]).

A set *T* representing background knowledge, and a set *C* representing the contingent facts.

The background knowledge containing monotonic rules, like "penguin are birds", whereas *C* represents what is known about the current case or situation.

**Definition 1.1**. A default theory is a triple (*C*,*T*,*D*) where

(1) *C* is a set of literals

(2) *T* is a set of monotonic rules of the form $b_1 \wedge ... \wedge b_n \Rightarrow a$

(3) *D* is a set of default rules of the form $b_1 \wedge ... \wedge b_n \to a$

(4) $C \cup T$ is consistent.

We say *E* is an extension of $(C,T,D)$ if *E* is a Reiter extension of $(C \cup T, D)$ (see Ref.[1]).

Please notice that in the above definition we use $\to$ to denote a default implication. The material implication is represented by the symbol $\Rightarrow$. Intuitively, $b \to a$ means that "generally, if *b* holds then *a* holds", while $b \Rightarrow a$ means that "whenever *b* holds then *a* holds". Given a rule *d* (either monotonic or default), the set of the literals on the left is called the prerequisite of the rule, denoted as *pre*(*d*), while the literal on the right is called the conclusion, denoted as *c*(*d*). A rule is called Horn if its prerequisite consists of only positive literals (i.e. propositional atoms).

Let *D* be a set of default rules. $D^+$ is obtained from *D* by treating every rule in *D* as material implication.

### 1.1 System Z

In Pearl's system *Z* [11] a set of default rules is partitioned into an ordered list of mutually exclusive sets of rule $D_0, D_1, ..., D_n$. Lower ranked rules are considered less specific than higher ranked rules. More precisely, let $(C,T,D)$ be a default theory. A default rule is in $D_0$ if adding its prerequisite to $T \cup D^+$ does not lead to inconsistency, where $D^+$ is obtained from *D* by treating every rule in *D* as material implication. Similarly, a rule is in $D_i$ if it is not in $D_j$ for $j < i$ and adding its prerequisite to $T \cup (D - \bigcup_{j=0}^{i-1} D_j)^+$ does not result in inconsistency.

*Example* 1.2. Let $C = \varnothing$, $T = \{p \Rightarrow b\}$ and let $D$ consist of:

1. $b \to f$, 2. $p \to \neg f$, 3. $b \to w$

The partition contains two sets: $D_0 = \{1,3\}$, and $D_1 = \{2\}$. Then rule 2 is considered of higher priority.

The main problem of this method is that it will introduce unwanted priorities. Let consider the following example.

*Example* 1.3. Let $C = \varnothing$, $T = \varnothing$ and *D* consist of the following rules.

1. $a \to s$ 2. $b \to \neg s$ 3. $c \to t$ 4. $a \to b$

The partition contains two sets: $D_0 = \{2,3\}$ , $D_1$={1,4}. Intuitively, rule 4 tells us that $a$ is a more specific set than $b$, therefore rule 1 should get priority over rule 2. But since there is no information about the relative sepecificity of $a$ and $c$ , there should be no priority relationship among rule 1 and rule 3. However, system $Z$ gives rule 1 higher priority than rule 3.

### 1.2 Brewka's method

In Ref.[9], Brewka presented another method to derive priorities.

**Definition 1.4**. Let $(C,T,D)$ be a default theory. A subset $R \subseteq D$ is said to be conflicting if and only if for some $d \in R$ , adding the prerequisite of $d$ to $T \cup R^+$ leads to inconsistency.

**Definition 1.5**. Let $(C,T,D)$ be a default theory, $d_1, d_2 \in D$ . We say $d_1$ has priority over $d_2$, written as $d_1 < d_2$ , whenever

(1) $d_1$ and $d_2$ are contained in a minimal set $R \subseteq D$ which is conflicting, and

(2) Adding the prerequisite of $d_1$ to $T \cup R^+$ will lead to inconsistency, whereas adding the prerequisite of $d_2$ does not result in inconsistency.

Let us consider the default theory in Example 1.3. Clearly, rule 1 < rule 2, rule 4 < rule 2, but neither rule 1 nor rule 4 gets priority over rule 3.

The main drawback of Brewka's method is its high computational complexity of determining whether $d_1 < d_2$ for a given pair of rules $d_1$ and $d_2$ . To see if $d_1 < d_2$ , we have to at first guess a subset $R \subseteq D$ containing $d_1$ and $d_2$ , then check if $R$ is minimal conflicting. If this condition holds then check the condition (2) in Definition 1.5. If this condition holds then return yes. It is easy to see that the above procedure runs non-deterministically with polynomial many calls to the oracle of consistency checking. Thus the problem of determining if $d_1 < d_2$ is in $\sum_2^P$. Even if the default theory consists of only Horn rules, the problem will be in $NP$ . In another paper we shall present a precise analysis of the lower bound of this problem.

### 1.3 Dung and son's method

In Ref.[10], Phan Minh Dung and Tran Cao Son defined a specificity order $\prec_K$ between defaults with respect to a set $K$ of defaults. For simplicity we shall redefine the order using our own notations.

**Definition 1.6**. Let $(C,T,D)$ be a default theory, $d_1, d_2 \in D$ and $R \subseteq D$ . We say that $d_1$ is more specific than $d_2$ with respect to $K$ , denoted as $d_1 \prec_K d_2$ , if

(1) Adding conclusions of $d_1$ and $d_2$ to $T$ will lead to inconsistency.

(2) Every literal of the prerequisite of $d_2$ occurs in at least one extension of the default theory $(pre(d_1),T,K)$ .

(3) There is no literal $a$ , not only $a$ occurs in some extension of $(pre(d_1),T,K)$ but $\neg a$ occurs in some extension also.

The main difference between Brewka's method and Dung and Son's method is that the later does not consider default rules as ordinary rules. As Brewka's method, the deficiency of Dung and Son's method is its high complexity. Generally speaking, determining if a literal appears in some extension is $\sum_2^P$ -complete (see Refs.[3,4]). Thus, the problem deciding if $d_1 \prec_K d_2$ will lie in $\Delta_3^P$ . We will also analyze the lower bound of this problem in another paper.

Certainly, there are tremendous amount of literature on the notion of specificity in Artificial Intelligence (see Refs.[9,11,13~16]). Different intuitions lead to different approaches to define specificity. For example, Baader and Hollunder dealt with terminological systems and assumed to get the specificity information from the terminological reasoner. However, most of these approaches impose rather severe restriction on the syntax of the represented theories and for this reasoning we do not mention other methods here.

## 2 A New Approach to Derive Specificity

In this section we present a new method to derive specificity. Both Pearl's method and Brewka's Method consider default rules as ordinary ones during the definition of specificity. Whereas Dung and Son's method does not change the status of the rules. Our method will consider ordinal rules as default rules when defining the priority.

Given a set $T$ of monotonic rules, $T^-$ is obtained from $T$ by replacing each material implication by default implication.

**Definition 2.1**. Let $(C,T,D)$ be a default theory, $d_1,d_2 \in D$. We say $d_1$ is more specific than $d_2$, denoted as $d_1 \prec d_2$, if the following hold:

(1) Every literal of the prerequisite of $d_2$ occurs in some extension of $(pre(d_1),\varnothing,T^- \cup D)$.

(2) There is a literal in $pre(d_1)$ such that it does not appear in any extension of $(pre(d_2),\varnothing,T^- \cup D)$.

Let us consider the default theory in Example 1.2. According to Brewka's method, rule 2 does not get priority over rule 3. But according to our definition we have rule 2 $\prec$ rule 3. This is not unintuitive. Roughly speaking, the monotonic rule in $T$ says that $p$ is more specific than $p$. Thus, it is quite natural that rule 2 gets priority over rule 3.

*Example* 2.2. Let $C=\varnothing,T=\varnothing,D$ consists of the following defaults.

1. $a \to b$ 2. $a \to \neg c$ 3. $b \to c$ 4. $c \to a$

According to Brewka's order, we see that rule 1 has priority over rule 3. But in our opinion, there is no priority between rule 1 and rule 3. Intuitively, rule 1 tells us that $a$ is a more specific class than $b$. On the other hand, rule 3 and rule 4 tell us that $b$ is more specific than $a$. In this case we can not decide which of them is more specific. That is the reason why rule 1 $\not\prec$ rule 3.

Our method does not introduce unwanted priority. Let us consider the default theory in Example 1.3. Although system $Z$ gives rule 1 unnatural priority over rule 3, our approach does not, that is, rule 1 $\not\prec$ rule 3.

An advantage of our approach is its lower complexity. According to Definition 2.1, whether $d_1 \prec d_2$ can be decided on a deterministic Turing machine with polynomial many calls to the oracle determining if a literal occurs in some extension of a default theory $(C,\varnothing,D)$. By the results in Refs.[4,5], the oracle is a NP-complete problem. Therefore

**Lemma 2.3**. Let $(C,T,D)$ be a default theory, $d_1,d_2 \in D$. The problem deciding if $d_1 \prec d_2$ is in $\Delta_2^P$.

At this moment I am not able to show its $\Delta_2^P$-completeness. The next two theorems show that this problem is both NP-hard and co-NP-hard.

**Theorem 2.4**. Given a default theory $(C,T,D)$ and two defaults $d_1,d_2 \in D$. The problem determining if $d_1 \prec d_2$ is NP-hard.

*Proof.* We shall define a polynomial reduction from 3-CNF formulas. Let $\varphi = C_1 \wedge \ldots \wedge C_n$, where each $C_i$ is a clause $(a_i \vee b_i \vee c_i)$. For each $i$, $1 \le i \le n$, pick a new propositional atom $t_i$. Finally pick three fresh atoms $s,t,u$. Let $D$ consist of the following groups of defaults.

(I) For each propositional atom $x$ appearing in $\varphi$, the defaults $s \to x$, $s \to \neg x$.

(II) For each clause $C_i = (a_i \vee b_i \vee c_i)$, $1 \le i \le n$, the defaults $a_i \to t_i$, $b_i \to t_i$, $c_i \to t_i$.

(III) The single rule $t_1 \wedge \ldots \wedge t_n \to t$.

(IV) The single rule $t \to u$.

We fix a default rule in group (I) as $d_1$, and write the rule in group (IV) as $d_2$. The theorem follows from the following claim.

**Claim**. $\varphi$ is satisfiable if and only if $d_1 \prec d_2$ in default theory $(\varnothing,\varnothing,D)$.

Proof of the claim.

($\Rightarrow$) Suppose $v$ is truth assignment under which $\varphi$ is true. Define

$$S = \{x | v(x)=1\} \cup \{\neg x | v(x)=0\} \cup \{t_1,...,t_n\} \cup \{s,t,u\}.$$

It is not difficult to verify that $S$ is an extension of $(\{s\},\varnothing,D)$. On the other hand, $\{t,u\}$ is the unique extension of $(\{t\},\varnothing,D)$. By Definition 2.1, we know $d_1 \prec d_2$.

($\Leftarrow$) Suppose $d_1 \prec d_2$. Then $t$ occurs in one extension $E$ of $(\{s\},\varnothing,D)$. It is easy to see that $t$ is obtained by an application of the rule in group (III). That means, $t_1,t_2,...,t_n \in E$. By the same argument we know that for each $i$, at least one of $a_i$, $b_i$ and $c_i$ is in $E$. Consequently, $\varphi$ is in satisfiable.

**Theorem 2.5**. Given a default theory $(C,T,D)$ and two defaults $d_1,d_2 \in D$. The problem determining if $d_1 \prec d_2$ is co-$NP$-hard.

*Proof.* We shall define a polynomial reduction from 3-CNF formulas. Let $\varphi = C_1 \wedge ... \wedge C_n$, where each $C_i$ is a clause $(a_i \vee b_i \vee c_i)$. For each $i$, $1 \le i \le n$, pick a new propositional atom $t_i$. Finally pick two fresh atoms $s,t$. Let $D$ consist of the following groups of defaults.

(I) For each propositional atom $x$ appearing in $\varphi$, the defaults $s \to x$, $s \to \neg x$.

(II) For each clause $C_i = (a_i \vee b_i \vee c_i)$, $1 \le i \le n$, the defaults $a_i \to t_i$, $b_i \to t_i$, $c_i \to t_i$

(III) The single rule $t_1 \wedge ... \wedge t_n \to t$.

(IV) The single rule $t \to s$.

We write the rule in group (IV) as $d_1$, and pick a rule in group (I) as $d_2$. The theorem follows from the following claim.

**Claim**. $\varphi$ is unsatisfiable if and only if $d_1 \prec d_2$ in default theory $(\varnothing,\varnothing,D)$.

Proof of the claim.

($\Rightarrow$) Suppose $\varphi$ is unsatisfiable. It is not hard to see that $t$ can not occur in any extension of $(\{s\},\varnothing,D)$. Clearly, $s$ appears in some extension of $(\{t\},\varnothing,D)$. Thus, $d_1 \prec d_2$.

($\Leftarrow$) Suppose $d_1 \prec d_2$. Then $t$ does not occur in any extension of $(\{s\},\varnothing,D)$. This implies that $\varphi$ is unsatisfiable.

In some restricted cases, defining the priority order can be done in polynomial time. It has been shown in Ref.[5] that the problem determining if a literal occurs in at least one extension of a default theory $(C,\varnothing,D)$ can be solved in polynomial time provided that $D$ consists of only Horn rules. As a result, deciding if $d_1 \prec d_2$ in a default theory $(C,T,D)$ can be solved in polynomial time whenever $T$ and $D$ consist of only Horn rules. Another polynomial case is that the prerequisite of every (either monotonic or default) rule consists of only one literal (see Ref.[6]).

## 3 Prioitized Stationary Default Logic

Priority order can make default reasoning more reasonable, however, priority order can not generally decrease the complexity greatly (see Ref.[17]). To decrease the computational complexity one has to develop new reasoning formalisms. A particular interesting version of default logic was proposed by Przymusinska and Przymusinsky in 1994. Let us recall some notions.

**Definition 3.1**.[1] Let $(C,T,D)$ be a default theory. For any set $S$ of formulas, $\Gamma(S)$ is the smallest set $U$ satisfying the following three properties:

1. $C \cup T \subseteq U$.

2. $U$ is deductively closed.

3. If $b_1 \wedge ... \wedge b_n \rightarrow a \in D$ and $S \not\vdash \neg a$ and $b_i \in U$ for any $i$, then $a \in U$.

**Definition 3.2**.[7] Let $(C,T,D)$ be a default theory. A theory $S$ is called a stationary extension of $(C,T,D)$ if and only if

1. $S \subseteq \Gamma(S)$, and
2. $S \subseteq \Gamma^2(S) = \Gamma(\Gamma(S))$.

Stationary default logic has several advantages over classical default logic (see Refs.[7,8]). For example, every default theory has the smallest stationary extension which is the intersection of all stationary extensions. This property makes stationary cautious default reasoning much more easier (see Ref.[8]). Gottlob proved in Ref.[8] that determining if a formula appears in all stationary extensions is in $P^{NP[\log n]}$, that is to say, this problem can be solved on a deterministic Turing machine with $\log n$ many calls to the oracle of consistency test. However, cautious stationary default reasoning is too weak (see e.g. Example 1.2). Whenever a default theory $(C,T,D)$ contains conflicts, the smallest stationary is $Th(C \cup T)$, which is the deductive closure of $(C \cup T)$ (see Theorem 3.1 in Ref.[8]). In this section we shall introduce the notion of preferred stationary extensions.

**Definition 3.3**. Let $(C,T,D)$ be a default theory. Define $D_i$ by induction as follows.

$D_0 = \varnothing$.

Suppose $D_i$ has been defined. If $C \cup T \cup D_i^+$ is inconsistent or $D_i = D_{i-1}$ then let $N = i-1$ and stop. Otherwise, define

$$D_{i+1} = D_i \cup \left\{ d \,\middle|\, \begin{array}{l} d \text{ is } a \prec \text{- minimal default in } D - D_{i-1} \text{ such that} \\ C \cup T \cup D_i^+ \perp pre(d) \text{ and } C \cup T \cup D_i^+ \cup \{c(d)\} \\ \text{is consistent.} \end{array} \right\}.$$

Now we define $T_\prec = T \cup D_N^+$ and $D_\prec = D - D_N$.

We say a theory $S$ is a preferred stationary extension of $(C,T,D)$ if it is a stationary extension of $(C,T_\prec,D_\prec)$.

The following two theorems are not difficult to prove (see section 1 and Ref.[8]).

**Theorem 3.4**. Cautious prioritized stationary default reasoning, that is, the problem determining if a formula occurs in every preferred stationary extensions, is in $\Delta_2^P$.

**Theorem 3.5**. Given a default theory $(C,T,D)$. The smallest stationary extension is a subset of the smallest preferred stationary extension.

The above two theorems show that the priority can strengthen the cautious default reasoning without increasing the complexity very much.

## 4 Conclusions

In this paper we have given a new approach to derive specificity from normal default theories. Our approach when deriving specificity considers monotonic rules as default rules while existing methods consider default rules as monotonic rules. This difference makes our method much easier with respect to polynomial reduction. We have shown that the problem of deciding whether a default has priority over other one is in $\Delta_2^P$, that is, it can be solved in a deterministic Turing machine with polynomial many calls to an NP oracle. However, the question whether this problem is $\Delta_2^P$-complete is open. We have proved that it is both NP-hard and co-NP-hard. Some tractable cases have been indicated. Furthermore, we introduce the prioritized stationary semantics for default theories. The complexity of default reasoning based on this semantics has been also discussed.

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